11th Indian Particle Accelerator Conference

InPAC 2023

March 13-16, 2023

Book of Abstracts

Organised by

Bhabha Atomic Research Centre, Mumbai

Program Schedule InPAC-2023

Day 1: 13 March 2023 (Monday)

09:30 - 09:40	Opening remarks	
09:40 - 10:00	Address by Chief Guest	
10:00 - 10:10	Closing remarks	
10:10 - 10:30	Inauguration of Industrial Exhibition	
10:30 - 11:15	**HIGH TEA**	
	PLENARY SESSION - 1	
11:15 - 11:45	Pellatron and SC Linac (IUAC)	Avinash Pandey
11:45 - 12:15	LEHIPA (BARC)	Rajesh Kumar
12:15 - 12:45	ARPF (RRCAT)	Jishnu Dwivedi
12:45 - 13:15	Superconducting Cyclotron (VECC)	Atanu Dutta
13:15 - 14:15	**LUNCH**	
14:15 - 14:45	Indian Institutions & Fermilab Collaboration	Purushottam Shrivastava
14:45 - 15:15	Future Accelerators at CERN	Frank Zimmerman
15:15 - 15:45	High Brilliance Light Sources	John Byrd
15:45 - 16:15	**TEA**	
16:15 - 16:35	Industry Talk : Pfieffer Vacuum	
16:35 - 16:55	Industry Talk : JAPS Inc	
16:55 - 17:15	Industry Talk: Rosalina Instruments	
17:30 - 18.30	**ISPA GBM**	
19:30 - 21:30	**Dinner (DAE Convention Centre)**	

Day 2: 14 March 2023 (Tuesday)

	PLENARY SESSION - 2				
09:30 - 10:00	INDUS-2 (RRCAT)	Tushar Puntambekar			
10:00 - 10:30	IR-FEL (RRCAT)	K K Pant			
10:30 - 11:00	HCI (IUAC)	Rajeev Mehta			
11:00 - 11:30	**TEA**				
11:30 - 11:50	RIB (VECC)	Vaishali Naik			
11:50 - 12:10	Pellatron Linac Facility (BARC/TIFR)	Vandana Nanal			
12:10 - 12:30	FOTIA (BARC)	Arun Agarwal			
12:30 - 12:50	1 MV DC accelerator (BARC)	P C Saroj			
12:50 - 14:00	**LUNCH**				
	PARALLEL SESSIONS				
	PAS - 1: Accelerators and Beams			**PAS - 2: RF Systems**	
14:00 - 14:20	Beam Trial Experiments of 9300 MHz 6 MeV X-Band Linac	Jayanta Mondal	**14:00 - 14:20**	RF characterization of 32 kW and 40 kW, 650 MHz Solid State RF Power Amplifiers	Kriti Pathak
14:20 - 14:40	Status report on the 10 MeV superconducting electron linac at VECC	Siddhartha De Choudhary	**14:20 - 14:40**	Kalman Filter as detuning estimator for experimental RF cavity	R Keshwani
14:40 - 15:00	Design of Superconducting Linac for Radio Active Ion Beam Generation	Asavari Dhavale	**14:40 - 15:00**	Operational experience of Digital LLRF system for particle accelerators at RRCAT	Nitesh Tiwari
15:00 - 15:20	RF characterization and tuning of DTL tanks 3 & 4 for LEHIPA	Elina Mishra	**15:00 - 15:20**	Development of pulse and event synchronization system for LEHIPA	Deepak N Mathad
15:20 - 15:40	Four Dimensional Transverse Phase Space Reconstruction Technique using multiple 2D Profiles	Sanket Haque	**15:20 - 15:40**	Design, Fabrication and Characterization of HOM Damped RF Cavity	M Prasad
15:40 - 16:00	Simulation of Transverse Single Bunch Instabilities in HBSRS Booster synchrotron	Abdurrahim	**15:40 - 16:00**	Design and Testing of components for High Power RF Systems for LEHIPA 20 MeV acceleration	B V Ramarao
16:00 - 16:30	**TEA**				
16:00 - 18:30	**POSTER SESSION - 1**				
19:00 - 21:30	**Ghazal Night and Dinner (DAE Convention Centre)**				

Day 3: 15 March 2023 (Wednesday)

	PLENARY SESSION - 3				
09:30 - 10:00	Radio-isotope production using the VECC medical cyclotron	Sumit Som			
10:00 - 10:30	Cancer Treatment using Proton Cyclotron at Apollo Hospital, Chennai	D Sharma			
10:30 - 11:00	Societal applications of electron Accelerators	R I Bakhatsingh			
11:00 - 11:30	**TEA**				
11:30 - 11:50	High power RF systems for future accelerators	M. Lad			
11:50 - 12:10	Challenges in Cavity Processing	S. Raghavendra			
12:10 - 12:30	Cryogenics for superconducting accelerators	Anindya Chakravarty			
12:30 - 12:50	Beams in cavities	Vinit Kumar			
12:50 - 14:00	**LUNCH**				
	PARALLEL SESSIONS				
	PAS -3: Superconducting Cavities and Cryogenics			**PAS -4: Accelerator Technologies**	
14:00 - 14:20	Development of Elliptically Shaped High Beta 650 MHz Superconducting RF Cavity: An Overview	Vikas Jain	**14:00 - 14:20**	Design and characterisation of anodised aluminium strip solenoids	Gautam Sinha
14:20 - 14:40	Frequency Measurement of Halfcells,Dumbbells and Subassemblies of Low Beta 650MHz 5-cell SCRF (LB650) Cavity	Sudeshna Seth	**14:20 - 14:40**	Development, fringe field optimization & cryogenic qualification of pre-series 6 T conduction cooled magnet assemblies for High Intensity Proton accelerators	Kumud Singh
14:40 - 15:00	Study and Development of Various Dissimilar Metal Joints of Superconducting Radio Frequency cavities	Syed Moulali	**14:40 - 15:00**	Measurements of a gas-sheet based beam profile monitor	Sherry Rosily
15:00 - 15:20	Dark Current calculation in SRF Elliptic Cavities	Ram Prakash	**15:00 - 15:20**	Beam-diagnostics at LEHIPA	Jose V Mathew
15:20 - 15:40	Development of SHP20: 2 K Cryo-plant for MEHIPA	Naseem Ahamed	**15:20 - 15:40**	Beam profile and emittance measurement using scintillation screen and solenoid scan method.	Hitesh Kewlani
15:40 - 16:00	Status of High Energy Electron linac development for medical isotopes production at SAMEER	Tanuja Dixit	**15:40 - 16:00**	Development of a Prototype Fast-ramp Power Converter with Grid Power Control	Abhishek Srivastava
16:00 - 16:30	**TEA**				
16:00 - 18:30	**POSTER SESSION - 2**				
18:30 - 19:00	Medical Accelerators at CERN	Maurizio Vrettner			
19:30 - 21:30	**Banquet (Golden Banquet Hall, Deonar)**				

Day 4: 16 March 2023 (Thrusday)

	PLENARY SESSION - 4	
09:30 - 10:00	Future Accelerators at RRCAT	S. V. Nakhe
10:00 - 10:30	Future Accelerators at BARC-MEHIPA	Srinivas Krishnagopal
10:30 - 11:00	Laser wakefield accelerators	Anand Moorti
11:00 - 11:30	**TEA**	
11:30 - 11:50	IUAC-DLS	Subendhu Ghosh
11.50 - 12.10	LLRF system for Superconducting Cavities	Gopal Joshi
12.10 - 12.30	Future Accelerators at BARC- PLF Upgradation & R&D towards SUBHIR	Anit Gupta
12:30 - 13.30	**LUNCH**	
13.30 - 16.00	**POSTER SESSION - 3**	
15.30 - 16.00	**TEA**	
16.00 - 16.15	Young Scientist Award presentation	
16.15 - 16.30	Young Engineer Award presentation	
16:30 - 16:45	Best Thesis presentation	
16:45 - 17:00	Award Ceremony	
17.00 - 17.15	Concluding Remarks	

Contents

Design, fabrication and testing of fin tube heat exchanger for 1MeV DC Electron beam accelerator

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Compact fin tube heat exchangers are used in many industrial heat transfer processes where at least one of the fluids is gas and large heat transfer area is desired. 1MeV DC electron beam accelerator is being developed in BARC for industrial applications. The accelerator high voltage column, electron emitter, and accelerating tubes are assembled inside pressure vessel at 6 bar nitrogen gas pressure. There is a continuous heat generation inside vessel from high voltage column and other electronics. Suitable compact plain fin tube heat exchanger is designed to remove the heat inside vessel. Process water is used as coolant in heat exchanger tubes. The heat transfer capacity, gas side pressure drop are calculated using suitable heat transfer correlation and friction factor after formulating the fin tube configurations. This design has been validated by CFD modeling of heat exchanger in ANSYS Fluent. Heat exchanger is fabricated with all quality control to make system as per specification compliance. The preliminary testing of heat exchanger assembly is done in open atmosphere. Fan capacity, water flow rate are adjusted to match as per design. Water temperatures are kept on lower side and rise in air temperature are recorded when passed through the heat exchanger tubes, therefore verified heat transfer design. The capacity of heat exchanger from CFD model gives 4.95kW which is very close to 4.84kW capacity calculated by suitable heat transfer correlation. The pressure drop across gas side from model comes to 2.81Pa which is also near to the 2.78Pa from the correlation used.

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Data Acquisition system for transient analysis of EBWWT Accelerator

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APPD is developing an electron beam DC accelerator of up to 1 MeV 100 KW rating for textile effluent water treatment. This accelerator, known as electron Beam Waste Water Treatment (EBWWT) Accelerator is based on symmetrical Cockcroft Walton topology powered by 10 kW solid state inverter based power supply. During restoration of the system after its pressure vessel is opened and the multiplier has been exposed to environment, the machine has to undergo high voltage conditioning. In conditioning process, the voltage of the HV multiplier column is slowly raised and some discharges are allowed so that dust particles and sharp corners are eliminated. It is essential to register these discharges and to analyse the trend of the trips during conditioning. To satisfy this purpose, a data acquisition system of up to 100 ksps sampling rate, on Linux based embedded platform has been developed and implemented in the accelerator. It has been programmed to obtain data at user defined sampling rates. The data obtained are instantaneously displayed in graphical mode and also stored with timestamp in the database. These data are being used for analysis of transient performance of the machine during high voltage conditioning and also to determine the suitable rate at which the voltage can be raised during this period.

High beam power operation of DC Accelerator: Opportunities and Challenges of 1MeV/100kW DC EBA at Electron Beam Centre, Kharghar

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High power DC accelerators of 1.5-3.0 MeV Beam energy and 50-150 kW beam power find applications in Electrical cable industry, Paint curing, Teflon degradation, Food preservation etc. Accelerators in 3-5 MeV energy range are widely used for gem-stones value addition, Food preservation, sterilization of medical products and in automobile Industry.

Accelerator and pulse power division of BARC, Mumbai has taken up design and development of a 1MeV/100kW DC electron beam accelerator for treatment of waste water from dye industry, sewage effluents and Tannery water.

High Voltage generator of the DC accelerator comprises of 500V/125kW DC power supply, 120kW/10kHz Inverter, 500Vp/90kVp, 120kVA step-up transformer and a 1MV/100mA, Symmetrical Cock-croft Walton generator for acceleration of high power e-beam. Electron beam is generated by an LaB6 cathode electron gun and accelerated in accelerating column under high vacuum medium, which is transported using focus, steer, and scan magnets and extracted through a Titanium Foil window to fall on a 4mm thick,1500mm wide Jet of waste water for e-beam treatment.

The Voltage generator has been tested at 1.0MV voltage and electron beam trials are conducted upto 0.95MeV/ 66mA beam parameters. Accelerator has been tested for prolonged duration of 3.5hours at 40kW beam power as well as uninterrupted 24hours at 25kW beam power for checking the reliability of various subsystems.

We have found several challenges while raising beam power. Beam diameter is found be 40-50 mm, which imposed limitations in full beam scan and associated overheating related issues. The elevated heating of titanium foil window restricted the further power raising beyond 63kW. Also, the higher temperature of exit window and surrounding areas has deteriorated the vacuum level putting additional restrictions on further power raising. All the forthcoming challenges are being addressed for testing the DC Accelerator at 1MeV/ 100kW rated beam power.

Study of 30 MV High Energy Electron Linear Accelerator Technology for Medical and other Applications

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Medical radio-isotopes are an important part of medical practice which are used in non-invasive nuclear diagnostic imaging techniques. The most widely used medical radioisotope is Technetium-99m. Ageing of reactors is leading to shortage of ^{99}Mo isotope and hence ^{99m}Tc. Therefore an alternative technology using Electron Linear Accelerator is proposed [1]. The X-rays from LINAC can be shined on target of ^{100}Mo discs to knock out a neutron to create ^{99}Mo which eventually decays to ^{99m}Tc.

SAMEER is successful in developing 15 MeV S-Band side coupled standing wave Linear Accelerators (LINAC) which gives an average output current of ~70μA when operated in π/2 mode with resonant frequency 2998 MHz [2]. The structure's quality factor (unloaded) is ~15000, with a shunt impedance value of ~90MΩ/m. Given the current LINAC specifications and the need to produce the medical radioisotope ^{99m}Tc, it is conceivable to construct a significantly higher energy LINAC for ^{99}Mo generation [3]. Study suggests that 30MeV energy electrons will give sufficient bremsstrahlung photons to knock out neutron from ^{100}Mo to produce 99Mo [4]. Therefore, 30 MeV LINAC with a high average current of 350 μA is proposed as a prototype development for medical isotopes generation. When developing the structure, the idea of two distinct 15 MeV LINACs joined back to back is proposed rather than one single structure, taking into account the brazing constraints. A Klystron with a peak power of 7.5 MW and an average power of 38 kW serves as the RF source for individual LINACs. Individual LINAC resonant frequencies are carefully tuned so that the π/2 of the second LINAC is within the bandwidth of the first.

Also for the beam to pass from one LINAC to other without loss proper synchronization is required. The dimensions and drift spaces are varied and simulations are performed to check the synchronization of the beam in two LINACs to ensure that the particle phase at the exit of the first LINAC matches the particle phase at the entrance of the second LINAC. Only for a certain length and multiple of lambda is the beam allowed through with maximum efficiency. The energy distribution studies within the resonant cavities is simulated and the energy gain is obtained by an iterative approach in each cell of the structure. Furthermore, input power estimations are computed in the two LINACs to get a consistent electric field. Beam power calculations are performed using the RF parameters obtained from each LINAC test, such as shunt impedance and electron beam current. The beam loading characteristics are studied and an optimal coupling factor 'β' is achieved for maximum energy gain and minimum reverse power. Transient response of cavity to incident RF pulse upon critical coupling is obtained through calculations. A detailed report of the simulations and other parameters will be covered in the paper.

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Beam Trial Experiments of 9300 MHz 6 MeV X-Band Linac

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X-band low energy accelerators are compact in size, light weight, which make them highly superior over S and C band Linacs, with applications in medical radiation therapy/non- destructive testing. BARC has developed a 9300 MHz, 6 MeV, 0.48 kW standing wave type X-Band Linac (XBL) cavity-based x-ray source. The 6 MeV XBL comprises of dispenser cathode based thermionic e-gun, an on-axis coupled cavity linac with 49 cells (25 accelerating and 24 coupling cells) and water-cooled tungsten target. The Linac is designed to be operated in the pulsed mode with a pulse width of 3-4 is at 200 Hz repetition rate. This paper describes the E-Gun characterization in 15-25 kV, RF conditioning at 1.5 MW, 2-4 μs, 25-100 Hz, initial beam commissioning experiments for overall functionality of this novel X-Band Linac.

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Thermal-Structural Analysis and Creep Life Estimation of PMMA Insulator Support in HV Transformer of DC Accelerator

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The high voltage transformer of 1 MeV DC Accelerator at Electron Beam Center consists of an Insulator support of PMMA (Poly Methyl Metha Acrylate) material commonly known as Acrylic Perspex. The purpose of this Insulator is to isolate and support the transformer weight along with covering the hot transformer oil in the tank. A thermal-structural analysis of the Perspex Insulator has been carried out in ANSYS software to evaluate the stresses generated in the insulator material due to transformer load and differential expansion of tank and insulator at elevated operational temperature. The PMMA material is sensitive to stresses at elevated temperature and can fail via creep deformation. In this paper, we have used various models of creep life estimation and have evaluated the creep life at evaluated stresses and operational temperature of the insulator material. Also, a parametric study has been carried out to evaluate creep life using various models at different combinations of stresses and temperatures of insulator material so as to provide a guide for range of allowed parameters for further design and developments.

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Integration and Commissioning of 150kV Solid State Pulse Modulator

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Pulse Modulator generates high voltage rectangular pulses at specified repetition rate. Traditionally in Pulse Modulators a thyratron switch, Pulse Forming Network (PFN) and high voltage transformer is used to convert High voltage DC into high voltage pulse to drive a klystron. Such designs are for fixed pulse width and fixed frequency moreover it requires frequent tuning. This configuration is bulky at the same time expensive. The input side DC voltages are in the order of tens of kilo Volts in thyratron modulator.

Solid State Pulse Modulator (SSPM) was developed to demonstrate the feasibility to replace the Pulse Forming Network (PFN) type pulse modulator. In SSPM solid state devices are used such as Thyristor, MOSFET, IGBT and high voltage pulses are achieved while switching DC at comparatively very low voltage. SSPM is more reliable.

A solid-state pulse modulator was developed using fast IGBT, fast diode, low inductance capacitor and a fractional turn pulse transformer. Modulator is made up of four major subsystems a) DC source b) control electronics c) solid state switching power modules and d) HV pulse transformer. All the interface signals are optically isolated to provide HV isolation. In the event of any fault control electronics inhibits the trigger pulses to the switching power devices. A self integrating air core Rogowski coil was employed for current sensing and protection. SSPM was tested with simulated load as a qualification test prior to integration with klystron.

Once the performance on simulated load was found to be satisfactory, the SSPM was integrated and commissioned with Klystron (TH2163) at Klystron Test Facility (KTF), EBC, Kharghar. Test trials were carried out with RF water load. Similar performance was observed with klystron.

Acknowledgements: We would like to thank P C Saroj, Project Manager, EBC Kharghar and Awadhesh Kumar, Sushant S Bhange & Anand M Bankar, CnID, BARC for their timely support during commissioning of SSPM.

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Deflection Magnet Configurations for Exit Foil Protection

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The high power accelerated beam in an accelerator can be used for various environmental application like flue gas treatment and waste water treatment. EBWWT is designed for textile waste water treatment, where the high power beam is scanned over large area to distribute its energy and utilize the beam. The scanning topology used is two dimensional scanning over a 50µm thick titanium foil window with an area of 1500mmx100mm. In case the X-X scan magnet fails, the beam will fall on titanium foil at a spot till AC source to the accelerator is switched off. Even after switching off of source voltage, stored energy in the HV system will be dumped in the titanium foil, thus raising its local temperature, deteriorating the vacuum with the probability of foil rupture. Foil rupture will lead to contamination of accelerating tubes and electron gun. To prevent this, various configuration for deflector magnet has been studied through simulation. The concluding design was developed to deflect the beam as soon as possible after scan magnet failure. The beam is deflected towards scan horn thick sidewalls (material SS). The configurations studied include window frame structures and C shaped structures aiming at least beam distortion and beam density uniformity. The deflector magnet is compensated magnet with electromagnet and permanent magnet. The simulation results compare different arrangements of coil and permanent magnets. The detail design of configurations will be discussed in this paper.

Status of High Energy Electron linac development for medical isotopes production at SAMEER

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A very high energy and high average power electron linac system is under development at SAMEER for medical isotopes production viz. Technitium-99m. A study of Moly target design under different irradiation mechanism shows a high yield for direct Moly target irradiation [1]. An enriched Moly target will be irradiated to get Moly-99 and Technetium-99m will be eluted from it. INMAS will establish the process to extract Tc-99m from Mo-99 and carry out quality assurance of the extracted Tc-99m and thereafter clinical trials of Tc-99m. The status of various subsystems developed is described in detail below.

Electron Linac with 30 MeV energy and ~10 kW beam power will be realized by placing two linacs of 1.2 m length in series, each having an acceleration gradient of 20 MV/m on an average [2]. High beam power will be achieved by running the system at high duty. The first linac has a low Z material exit window for the electron beam to come out and enter second linac without much loss and divergence. The second linac distance/drift spaces are adjusted so as to match the phase of the incoming electron beam. The linacs are ready for high power testing. Linac1 is tested at 2.0 MW peak power and a peak beam current of 40 mA is measured on a faraday cup. Very precise frequency tuning has resulted in less than 100 kHz of difference between the operating frequency of both the linacs. Thus reducing the margins of operation for the RF system, chiller system and thereby control system. Since very high duty ~0.5% operation of the entire system is envisaged, therefore very high precision chillers are installed to achieve ±1°C accuracy.

Modular shielding cube around the target will ensure minimum leakage radiation of both photons and neutrons. One side of the shield can be moved to open cavity inside the cube for placing Moly target. A robotic arm arrangement will help in loading and unloading of the Moly target. This robotic arm will be placed on an automotive guided vehicle. The systems are already procured and installation and commissioning is ongoing. Trials of beam line assembly with gate valves, bending magnet and beam dump is carried out. Final alignment with linacs will be carried out after linac individual testing is done. Safety gadgets for radiation and system are installed and tested. Test results of subsystems mentioned above will be covered in detail in the paper.

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Residual Stress Distribution in Titanium Alumina Brazing Joint with Effects of Thermal Cycles in Accelerating Tube of DC Accelerator

Ajit Singh*[1], R. Barnwal[1], S. Nayak[1], M. Kumar[1], Kumar Sajal[1], S. R. Ghodke[1], P. C. Saroj[1], R. I. Bhaktsingh[1] and Archana Sharma[1]

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A 1 MeV 100 kW electron beam DC accelerator has been designed and developed for waste water treatment at EBC, Kharghar. Accelerating tubes are an inevitable requirement items in beamline assembly for the high energy electron beam production. These tubes consist of ceramic rings which are bonded with titanium electrodes for generation of high potential difference electric field in beamline and to accelerate the electron beam. In fabrication of accelerating tubes brazing process is required for joining two base dissimilar materials, i.e. alumina and titanium. These materials express different response to thermo-mechanical conditions during heating and cooling phases of brazing process. Due to different coefficient of thermal expansion (CTE) of ceramic and titanium, induced residual stresses are developed during brazing process. Such residual stresses can lead failure in brazing joints of accelerating tubes before design limits if not addressed properly. The failure of brazing joint leads to vacuum breakdown in beamline which can cause to severe damage to high voltage components of accelerator. The purpose of study to assess residual stresses with effect of thermal cycles by performing thermo-mechanical analysis of brazing process in ceramic titanium assembly through finite element analysis (FEA) technique.

Thermal Analysis of Beam Locating Aperture for Beam Diagnostics in Electron Beam DC Accelerator

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A beam locating aperture (BLA) is an essential non-destructive diagnostics part of electron beam DC accelerator which provides information about the beam size and its misalignment in beamline. It is composed of SS and copper brazed parts with recommended aperture size for Gaussian profile beam. It also has 6 numbers of equally spaced thermocouples in 360^0 to sense position of beam by measuring temperature. There is a water convective cooling channel to control the temperature of BLA. The purpose of this study is to find out temperature distribution in BLA at different positions (offset values) of beam in beamline using finite element methods (FEM) simulations. The temperature distribution profile in BLA helps in determining the position, path deviation and misalignment of beam. In fabrication of BLA brazing joint is required for joining SS and copper. Due to hitting of beam during misalignment problem of beam, the higher temperature on BLA can lead failure in brazing joint of BLA. This problem can lead to vacuum breakdown in beamline and severe damage to high voltage components of accelerator. The purpose of study is to assess temperature distribution in BLA using FEM simulations at optimum water flow rate in cooling channel.

Design and Development of Pulsed data acquisition system for industrial RF Linac

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The 10 MeV, 5kW horizontal RF Linac is being developed at Electron Beam Centre, Kharghar. The RF Linac has various sub-systems including Electron gun and its associated pulsed power supplies, S-band pulse high power klystron and its power supply, accelerating cavities, scanning system and Vacuum system etc. The Linac is operated in pulsed mode and the design specifications of the accelerator are 10 MeV Energy, 225 mA (peak) beam current, 7.5 μs pulse width and repetition rate of 300 Hz. The pulsed signals are required to be measured, monitored, and controlled for desired operation of accelerator. The measurements of interest are flat-top values of Klystron current, E-gun extraction high voltage, RF forward power, RF reflected power and Beam current.

The pulsed data acquisition system has been designed and developed. Noise reduction techniques have been implemented at the point of acquisition of the pulsed signals. The output of the acquisition system is given to central control system for monitoring, interlocking and control purpose **Chavan [1]**. The sampling duration and sample time for each channel can be adjusted separately. The paper will discuss the nature of pulsed signals, signal conditioning and acquisition techniques used in detail.

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Design, Development, Installation, Safety compliances and Testing of 10MeV, 5kW Horizontal RF Electron Linac being developed for Industrial Applications

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High energy electron beams have played a key role in the field of basic and applied sciences. Over the last few decades, various industrial, medical and strategic applications using high energy electron beam have been developed. 10 MeV Electron beam is found to be suitable for food irradiation, medical sterilization, cross linking of polymers for agriculture, cable & tyre industries, semiconductor characteristics modifications, electronic waste management, radiation hardening studies etc. In view of the enormous potential of EB and to exploit their industrial uses, BARC/APPD/ EBC has taken up a project for developing a new 10 MeV electron accelerator having horizontal assembly. The main sub-systems of the linac include the electron gun, linac cavity, klystron-based RF power source, scan system, vacuum systems, beam diagnostics, control system and auxiliary systems such as DM water cooling system and ventilation systems. Paper will present details of design, development, installation, safety compliances and test results of high power testing.

Dosimetry characterization of dual energy electron accelerator for energy and spot size verification

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Abstract

Cargo scanning systems are employed to inspect cargos at ports/boarders to prevent the transport of contraband objects. The inspection is done with high energy x-ray produced by energetic electron beam generated with an RF electron linear accelerator (Linac). The electron beam hits the tungsten target, mounted inside a cylindrical collimator having a trapezoidal planar slit to slices the x-ray lobe in a plane. Material discriminations with high energy x-ray require two spectrums with different extreme energies [1, 2]. In this reference the verification of tail energies of x-rays as well as measurement of beam spot size are very crucial to achieve desirous quality of internal image of cargo. A dual energy Linac is indigenously designed and developed by EBC, BARC with flair of energy variation in alternating pulse. Attenuation method is adopted to get the energy verification under proper combination of beam current and forward RF power of the Linac. It works under concept of half value layer (HVL) and steel plates are used as attenuator. HVL conditions are satisfied with 2.80 cm and 2.54 cm of steel for 6 MV and 4 MV x-ray respectively [3]. Hence electron beam energy verified as 6 MeV, called high mode operation and 4 MeV, called low mode operation with respective combination of peak beam current and RF forward power. X-rays spot sizes, for both high mode as well as low mode, have been measured using pin hole camera and dosimetry film. Full width at half maxima (FWHM) of x-ray intensity profile implies the actual beam spot size and in each case it concludes that x-ray spot size is around 1 mm or less. Full x-rays intensity profile concludes that complete beam sizes are 1.75 mm and 2.2 mm for 6 MV and 4 MV x-rays respectively. These results decide the operating parameters of dual energy Linac and based upon it cargo scanning with material discrimination is realized.

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Design and development of pulse transformer for Pico-second Electron Accelerator Klystron modulator at RPCD, BARC

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The pulsed modulator for A 10MW peak power S-band RF system operational for a Pico-second Electron Accelerator at BARC as a part of Ultrafast Pulse Radiolysis [1] setup is being upgraded. The RF system consists of a 25MW S-band (2856MHz) Peak Power Klystron powered by a line-type modulator with a pulse transformer rated for 250kV, 250A, and 4.5us pulse width at a 10 Hz repetition rate. In a line-type modulator topology, the pulse transformer is an important component of the pulsed modulator because it not only matches the klystron impedance with the pulse forming network (PFN) for maximum power transformer but also results in reduced operating voltage of PFN. For maximum power transfer and to reproduce the pulse shape at its input with minimum distortion, the pulse transformer should have very low leakage inductance and distributed capacitance and high magnetizing inductance [2]. These parameters affecting the pulse shape are the function volume enclosed between primary & secondary winding, the number of turns in the secondary winding, the volume of core employed and the maximum flux density of the core material. Optimization of these parameters is therefore important to arrive at an optimum design. In addition to the optimization of parameters, the design of a pulse transformer with a reset core (the transformer core held in negative saturation using DC bias current) and cone winding further improves the pulse performance by reducing core volume and the volume enclosed between windings. Thus, the design of the pulse transformer is crucial for the modulator's performance. This paper discusses the design details – "core selection, bobbin design, mechanical design, electrical isolation, corona ring at high voltage end" – and operating results obtained during the testing of the pulse transformer with the Klystron.

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Upgradation, Modification and RF Testing of line type modulator of 7 MeV Electron LINAC used for Pulse Radiolysis Experiments at RPCD, BARC

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A 7 MeV pulsed Linear Electron Accelerator was procured from M/s Radiation Dynamics, U.K in 1985 for research in pulse radiolysis experiments and radiation chemical research, & which has now become part of Radiation & Photochemistry Division, BARC. The accelerator was commissioned in April 1986.

7MeV Electron LINAC for pulse radiolysis experiments [1] at RPCD, BARC is being upgraded for better dose stability and pulse to pulse electron beam energy stability. Nanosecond 7MeV electron LINAC [2] modulator is line type modulator, using a Pulse transformer rated to operate at 43kV, 100A, 2.6us pulse width at 50Hz repetition rate to generate 2MW peak power with a pulse-forming network (PFN) employing Hydrogen thyratron high voltage electrical switch. In conventional 3-phase variac and step-up HT Transformer and rectifier-based power supply lacks the pulse-to-pulse stability in high voltage accuracy. Stability in high voltage power supply is crucial to achieve stable electron beam energy in every pulse. Therefore, high voltage power supply upgraded to constant current power supply (CC) and the upgraded version of Line type pulse modulator has been tested for RF power with M5125, 2MW magnetron ~2998MHz. In the earlier version of LINAC modulator, the mains power from the 3-phase stabilizer is fed to the primary of the step-up transformer. The secondary voltage from the transformer is rectified by the bridge rectifier circuit. The high voltage (D.C.) thus generated is passed through the filter circuit. This voltage is used to charge the pulse forming network (PFN) through a charging choke and a charging diode. A high voltage thyratron tube is used to discharge the PFN voltage through the thyratron and primary winding of a pulse transformer (turns ratio 1:4.3) on applying a trigger pulse to the grid of the thyratron, thereby generating 43 KV pulses at the secondary terminal of the pulse transformer. This paper discusses the installation, commissioning and testing of 30 KV, 200 mA CC Power Supply in Main Modulator with all necessary modifications needed to incorporate the new power supply and restoration of all required interlocks in the system. Pulse to pulse stability reported in the specifications has been obtained with low noise when compared to earlier modulator.

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Upgradation, Modification & Testing of High D.C. Current Power Supplies used for Main Focus and Buncher Focus Coils of 7MeV Electron LINAC used for Pulse Radiolysis Experiments at RPCD, BARC

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Nanosecond 7MeV Electron LINAC was procured in 1986 from Radiation Dynamics Ltd., UK for carrying out experiments in Radiation Chemistry. It was commissioned.in.1986 at Mod.labs.BARC. Since then it has been working however due to aging of components, modifications were done as per the required specifications. It is being upgraded for better dose stability and pulse to pulse electron beam energy stability.In this accelerator, the RF waves tend to defocus the beam and this effect is counteracted by strong solenoidal focusing fields generated when 200 Amp DC Current flows through Buncher focus coil and Main focus coil. Therefore, very stable high current DC power supply is required for pulse-to-pulse electron beam energy and dose stability in single shot mode operation and also in repetative mode operation of the electron LINAC. Thus, power supplies have been upgraded with Constant Current SMPS based programmable high current DC Power Supply.

New programmable DC Power Supply having input voltage three phase, 50 Hz and Output 0-15 V DC & Output Current 0-400 A DC is installed, commissioned and tested successfully with the Accelerator. All necessary modifications needed to incorporate the new Power Supply were carried out and interlocks in the system were restored properly. Earlier version of this Power Supplies were based on conventional transformer and thyristor circuits.

This paper discusses the power supplies upgradation for focus coils, interlocks incorporation for safe and stable operation, and the performance result i.e., reduction in noise, energy stability, current regulation and efficiency.

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Design studies for a pill box type accelerating structures with beam ports and coupling loop using analytical and perturbation techniques

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Radio-Frequency (RF) cavities are employed in accelerating facilities to play different roles: as pre-bunchers, bunchers, accelerators, deflectors etc. The important RF properties that qualify these cavities are their resonant frequency, Quality factor, Shunt Impedance, and the accelerating electric field to be supported by the structure. Making a functional RF cavity requires the design of the cavity along with the essential openings for the electron beam propagation through the cavity, for vacuum pumping if required in the cavity, and for the coupling of RF power into the cavity. The simplest RF cavity that can be designed precisely by employing analytical formulae is a pill-box type cavity without any openings. A freely available RF code like SUPERFISH can be employed to design an azimuthally symmetric RF cavity with the beam ports on axis [1]. However, the presence of openings on its side walls for vacuum pumping or for RF coupling, or for RF pickup, cannot be treated analytically, and usually require design codes normally not available freely.

For a simple accelerating structure like a single cell pre-buncher with a coupler loop, analytical formulae can be employed to design the pill-box structure, and perturbation techniques can be employed to determine the effect of port openings on its resonant frequency and for the dimensional modifications required to compensate this perturbation to achieve the designed resonant frequency. Analytical formulation can also be employed to design RF power coupling and pickup loops to achieve the desired RF coupling coefficients for the structure.

In this paper, the design and development of a prototype, single cell, pill-box type, S-band pre-buncher structure resonant at 2856 MHz will be discussed. An Aluminum prototype has been built and systematic studies have been performed to study the agreement between the designed RF properties and those measured using a Vector Network Analyzer (VNA) at different stages of the development, viz. pill box without any ports, perturbations due to beam ports of different sizes, dimensional modifications to compensate the perturbation by taking a machining cut. The perturbation in resonant frequency due to presence of RF coupling and pickup ports on its cylindrical surface, and the design of a RF coupler loop to achieve a desired RF coupling coefficient is also discussed and compared with measurements made on the Aluminum prototype. The implications of mounting an RF coupler loop on the cylindrical wall versus on a side wall adjacent to a beam port will also be discussed, considering the deployment of such structures as part of injector linac system with air-core solenoids in the low energy beam transport region of the injector system. The study is motivated by the ongoing design of an injector linac system for a proposed Tera Hertz Free Electron Laser (THz-FEL) [2].

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Development of a Computer Program for Longitudinal Beam Dynamics Studies in a Traveling Wave Constant Impedance Electron Linac

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Industrial electron linacs utilizing Traveling Wave (TW) accelerating structures have been developed at RRCAT for societal applications, and there are efforts to develop more such linacs with desired improvements in terms of RF to beam power conversion efficiency and beam transmission efficiency. Towards the aim to develop an indigenous computer code for design of TW linac structures, a computer program for longitudinal beam dynamics has been developed in Python. First-order coupled differential equations in energy and phase have been solved, using the fourth order Runge-Kutta method. Macroparticles are tracked through the electric fields in the bunching-cum-accelerating structure, with the given input beam energy distribution, and phase distribution. The program considers a particle as lost, if either its velocity becomes zero, or its longitudinal phase exceeds the value specified in the computer program. Program calculates the beam transmission based on longitudinal beam dynamics studies, and can be used to optimize the bunching section of the bunching-cum-accelerating structure. The output value of energy and phase of each particle are exported into a text file for post-processing. Space charge has not been considered in this calculation. The code generates the plots of evolution of energy and phase of particles along the linac length. This code is capable of dealing with both CW as well as bunched beams. The effect of beam loading is explicitly considered in the code through the calculation of accelerating field gradient profile in the linac (for fixed beam current), which is utilized during dynamics calculations. The code can perform calculations for fixed, as well as, variable phase velocity structures. The electrodynamical parameters of the cells are specified as the input. This code can be conveniently used for quick optimization of TW structure geometries, as it does not require the 2D/3D field maps. After completing the quick optimization based on longitudinal dynamics, commercially available codes for transverse beam dynamics and space charge calculations can be used for further optimization, which will make the overall design optimization process fast. The computer program has been validated by simulating the case of the 9.5 MeV, 10 kW constant impedance traveling wave electron linac that has been designed and commissioned by RRCAT, and comparing the output rms energy spread and phase spread calculated using the in-house developed computer program with those obtained using commercial beam dynamics code [1]. For a CW beam with fixed input energy, analytical calculations have been performed for evaluating the beam transmission efficiency and threshold value of accelerating gradient for capture, in a constant phase velocity structure [2]. These values have been confirmed using the in-house developed code. The capabilities of the program can be extended to include a pre-buncher cavity before the bunching-cum-accelerating section, and also for other traveling wave structures like constant gradient structures etc.

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Optimisation of Titanium foil thickness for electron beam irradiation applications of DC Accelerator

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The DC Accelerated electron beams can be effectively used for a wide range of irradiation applications. A Titanium (Ti) foil window is used at the end of scan horn that acts as a barrier between atmosphere and vacuum inside the accelerator while it allows the transmission of majority of accelerated electrons through it. A part of the energy of high energy electrons gets deposited on the Ti foil hence increasing its temperature which may puncture the foil and cause its permanent failure. To prevent this, scanning of electron beam is done in both mutually perpendicular directions (X & Y) for uniform distribution of heat on a Ti foil. It is important to have optimum thickness of Ti foil as larger thickness will lead to larger power dissipation in the foil while thinner foils are susceptible to damage due to pressure difference. Simulation studies using FLUKA [1,2] Monte Carlo code are carried out to estimate the total energy deposited by incident electrons of 1MeV energy in Ti foils of different thicknesses. The cross-section of the foil is 1500 mm (length) x 100 mm (width). The profile of electron beam is taken as gaussian (FWHM = 2.0 cm) along X & Y axis in the plane perpendicular to direction of electrons(z-axis). The variation of total energy deposition for Ti foil of different thicknesses is shown in Fig. 1. The energy deposited values given in the figure corresponds to single incident electron. The thermal power deposited in the foil as obtained from FLUKA simulation is used as an input to carry out Thermal-Structural analysis in ANSYS software. Hence the optimum thickness of Ti foil is obtained which can sustain the thermal and structural stresses.

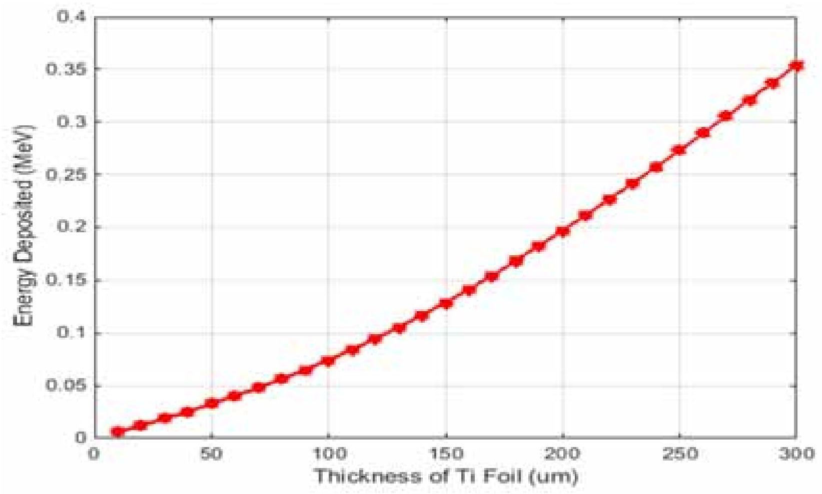

Fig. 1: Variation of total energy deposition in Ti foil of different thicknesses

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Numerical studies for evolving measurement methodology for characterization of single cell in constant gradient traveling wave linac

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Low power RF measurements are very crucial for the characterization of RF cavities/cells before installing or brazing them in a linac structure. These measurements are used to estimate the resonant frequency, quality factor etc. of RF structures. We had earlier designed disk loaded, constant impedance (CZ), traveling wave (TW) electron linacs, operating in 2π/3 mode at 2856 MHz [1, 2, 3]. Recently, design of a 9.5 MeV, disk loaded, constant gradient (CG) type, TW electron linac structure has been done for industrial applications [4, 5], which is presently being fabricated. In addition, we have also designed CG TW accelerating structure for a 200 MeV electron linac for injector applications [6]. The CG structure has a higher RF to beam power conversion efficiency, compared to a CZ structure. In a CZ structure, geometrical dimensions of all the cells, which are designed for the same phase velocity, are identical. Hence, resonant frequency of desired operating mode for a TW structure, i. e., 2π/3 mode, can be measured directly, using a single measurement set-up comprising of stack of identical cells. One of the configurations used for the characterization of cells of CZ structure is "Half Cell-Full Cell-Full Cell-Half Cell" configuration. In this configuration, the measurement set-up is fabricated in such a manner that one of the full cells, which is the test cell for which frequency is to be measured, is detachable. Different cells are positioned one by one at the place of test cell in the measurement set-up for characterization. On the other hand, in a CG structure, the aperture radius and cavity radius of each cell, even though designed for the same phase velocity, are suitably varied such that group velocity varies linearly, to obtain constant electric field along the structure, in the absence of beam loading. Due to variation in the geometrical dimensions of different cells, the direct method used in the CZ structure for measurement of the resonant frequency of the desired operating mode is not applicable for CG structure. Hence, indirect methods to estimate the frequency of 2π/3 mode are preferred for the cells of CG structure. Single-cell measurement method is one of the methods, which can be used to characterize the cells, using a single measurement set-up [7]. However, detailed explanation of the method and the measurement set-up are not readily available in the literature. In this paper, we describe the details of single cell method for low power RF characterization of cells. Single-cell measurement method is used to measure the frequency of zero-like mode of a single cell with a beam pipe. It is used to indirectly estimate the resonant frequency of 2π/3 mode, as there is a systematic difference between the two frequencies (zero-like mode and 2π/3 mode). To calculate this difference (Δf), extensive 2D electromagnetic simulations using SUPERFISH have been performed for different cells in test set-up. Each cell has different value of β_g (group velocity in unit of speed of light), according to the aperture radius and cavity radius of that cell, and Δf has linear dependence on β_g. Detailed 3D electromagnetic design studies have been performed to design the measurement set-up. Simulations have been performed to estimate the dimensions and effects of crucial components like choke flange and position of measurement probes to pick up the sensing RF signals, without perturbing the cavity frequency. In this paper, details of the measurement set-up, from physics design aspect, are also provided.

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Design of Superconducting Linac for Radio Active Ion Beam Generation

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Radioactive isotopes are essential for the basic research and medical applications. High energy electron accelerator can produce radioactive ion beams by photo-fission. An electron beam is incident on the Converter Target made up of high Z material like Tungsten or Tantalum that produces high energy Bremsstrahlung photons. Photons are incident on the Production target made up of Uranium or Thorium oxide that produces various fission fragments which are radioactive ions. Generation of radioactive ions require an electron beam of energy greater than 25 MeV while the photo-fission yield saturates beyond electron energy of 50 MeV. Thus an accelerator that can deliver electron beam of energy up to 50 MeV is required for this application. Since the production target is porous in nature, to avoid the physical damage of target due to excessive heating, an accelerator operating in continuous mode is preferable [1]. A superconducting (SC) linac that can deliver 50 MeV electron beam of power 100-500 kW is suitable for this application. A photo-fission yield will be ~ $10^{13\text{-}14}$ fissions/sec.

The SC linac will be made up of 150-300 keV electron gun followed by a room temperature pre-buncher. The main accelerating structure will be made up of TESLA shape (β=1) cavities made up of Niobium. A single cavity will be made up of 9-cells of elliptical shape [2]. Five such cavities are required to accelerate electron to final energy of 50 MeV. RF power will be fed to cavities by a Fundamental power coupler (FPC). The accelerator cavities are immersed in LHe inside cryo-module at 2^0 K.

The paper presents results of a 9-cell TESLA shape cavity simulated using SUPERFISH and the CST microwave studio codes. The end cell and the accelerating cell dimensions are optimized to get π-mode at resonant frequency of 1.3 GHz. The beam loading calculations show that to get beam current of 10 mA at electric field gradient of 10 MV/m, Q_{ext} ~ 1.15 x 10^6 is required. A coaxial type of FPC is designed taking into account effect of beam loading. Beam dynamics simulations are carried out using CST particle studio. Transmission of beam is studied at various input parameters like input energy, divergence and energy spread.

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Status report on the 10 MeV superconducting electron linac at VECC

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At Variable Energy Cyclotron Centre (VECC), we have taken up a project to develop ANURIB - a facility to produce neutron-rich RIB using a superconducting electron linear accelerator (e-linac) of 50 MeV, 2 mA. In the first phase, the 10 MeV injector that comprises an RF-modulated thermionic electron gun (e-gun), low energy beam transport (LEBT) line, and an Injector Cryo-Module (ICM) housing a beta = 1, 9-cell 1.3 GHz niobium cavity operating at 2 Kelvin is being developed at VECC. The RF modulated thermionic gun operating at 100 kV along with LEBT line has been commissioned and is being upgraded for operation at 250 kV. The ICM has been built jointly with TRIUMF Canada and tested by accelerating 10 MeV electron beam. The current status of activities towards commissioning of the injector will be presented.

Dose calculation program on Windows platform for pulse radiolysis experiments at RPCD, BARC

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Nanosecond 7MeV Electron LINAC was procured from Radiation Dynamics Ltd., UK for carrying out pulse radiolysis experiments in Radiation Chemistry. It was commissioned in 1986 at Mod. Labs. BARC. For data acquisition & processing of experimental data for Kinetics studies, subsequently a program was developed in 1987 in Pascal programming language with those days prevalent computers running on DOS platform. To calculate dose during experiments, calculations done using calculators was tedious, time consuming and prone to errors. Hence, for dose calculations, program was developed in BASIC programming language. These programs developed for computers running on DOS platform were incompatible with present day computers based on Windows platform.

Hence, for data acquisition & processing of experimental data for Kinetics studies, a LabVIEW based program was developed in 2009 . However, program for dose calculations on Windows platform remained to be done.

This paper discusses program developed in LabVIEW for dose calculations to be incorporated with the already existing LabVIEW program for data acquisition & processing of experimental data for Kinetics studies.

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Development of Pinger Magnets for Indus-2 Electron Storage Ring

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Pinger magnets are used to find important linear and nonlinear dynamic characteristics of magnet lattice by exciting betatron oscillations of the stored beam in horizontal and vertical planes. This paper reports development and installation of two such magnets (one horizontal and the other vertical pinger magnet) in Indus-2 (2.5 GeV) electron storage ring. These magnets can provide 1.5 mrad and 2.0 mrad deflection to the electron beam in transverse plane of motion [1]. The betatron oscillations induced by the pinger magnets are measured turn by turn using beam position monitors installed over the entire storage ring. The measured turn by turn data are used to calculate betatron tunes, betatron function, dynamic aperture etc of the lattice [2]. These magnets are required to produce a magnetic field pulse which is half sinusoidal in shape and less than 1µs wide. The required peak field of magnets are 596 G and 650 G. The field uniformity is better than 2×10^{-3} in the good field region. Magnetic field simulations were performed using Opera 3D Elektra Solver [3] and parameters of the magnets were optimized. These magnets have window type geometry with single turn copper coil. High frequency Ni-Zn ferrite is used as core material. The design, fabrication and pulsed magnetic characterization of these magnets are discussed in this paper.

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Electromagnetic Simulation of 107.5 MHz Co-axial RF Cavity and Its Higher Order Mode identification.

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RRCAT has developed and installed 10 MeV, 6kW Linac at ARPF for bulk radiation processing. This is the first step on the roadmap for reaching on industrially viable level of electron beam power for bulk processing. For economic viability, the electron beam power of 100 KW or higher is required for radiation processing applications. The next step on this roadmap include increasing the beam power to 30-50 KW level. Accelerator schemes making use of a large single cavity for repeated acceleration can work in cw mode and are capable of providing very high beam power with well defined energy and narrow energy spread. Considering this fact an electrodynamic design of 107.5 MHz coaxial recirculating cavity was carried out. In this paper we will be presenting electromagnetic simulation of λ/2 coaxial resonant cavity and identification of its higher order modes.

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Modification of Loop Control PCB of FOFB Power Supplies to Simplify Tuning Procedure and Provide Interchangeability between Horizontal and Vertical Coil Power Supplies

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Indus-2 is a 2.5 GeV Synchrotron Radiation Source (SRS) with 17 beamlines operating in the round the clock (RTC) mode [1]. Various causes that include dipole field errors, magnet alignment errors, slow power supply drifts, ground settlements, ground vibrations, thermal expansion of components open/close operation of insertion devices, etc. affect the electron beam orbit in the Indus-2 SRS. The disturbed orbit is detrimental to the performance of the SRS as it changes the position of the synchrotron radiation light spot at the front end of the beam lines which in turn reduces the effective flux and brightness of the light going into the beam lines. This affects the experiments being conducted in the corresponding experiment station. To counter this, a correction scheme is employed wherein the beam position data from all the Beam Position Indicators (BPI) is fed to the controllers which in turn provide the feedback to a corrector mechanism which corrects the electron beam orbits in the Indus-2 ring. This is known as the Global Fast Orbit Feedback (FOFB) Corrector mechanism. The FOFB corrector mechanism employs 40 nos. of air core magnets connected in the Indus-2 ring. Each of these magnets has a pair of horizontal and vertical coils. Both the horizontal coils of a single magnet unit are connected in series and powered by a single unit of FOFB corrector bipolar current controlled power supply [2]. Similarly, both vertical coils of a single magnet unit are connected in series and powered by a separate FOFB corrector power supply. The loop control PCBs (Printed Circuit Boards) developed for each of the 80 power supplies had a tiresome tuning procedure involving control loop gain adjustment by using 3 sets of potentiometers on each PCB to achieve optimal performance in terms of rise time and overshoot for the applied step input. The presence of three tuning components in each PCB severely limited the inter-operability of the same loop control PCB for the power supplies for the horizontal and the vertical coils of the magnet. Therefore, the loop control PCBs of the FOFB power supplies were upgraded to simplify the tuning procedure of the loop control PCBs and inter-usability of the same loop control PCB for both the horizontal and vertical coils power supplies with minimum modifications. This upgradation was implemented for the last 56 FOFB power supplies pending commissioning. Therefore, a total of 56 loop control PCBs (28 nos. for horizontal coil powers supplies and 28 nos. vertical coil power supplies) were upgraded under this scheme. Following this a detailed testing and tuning procedure for the loop control PCBs was developed and implemented. The tuned response data for each of the loop control PCB for horizontal and vertical coils of the magnets was recorded for future tuning reference. In addition to this, a recurrent phenomenon of noise inflicting into the reference signal of the control loop PCB, resulting in DC offset in the final load current waveform, was identified and resolved by modifying the output capacitive filter of the power converter.

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RF characterization of 32 kW and 40 kW, 650 MHz Solid State RF Power Amplifiers

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This paper presents RF characterization and high power RF measurements carried out for 32 kW and 40 kW amplifier systems working at 650 MHz which are developed under R& D phase, as deliverables to Fermi Lab, USA. These amplifiers were tested and characterized for required specifications at rated RF power on dummy load. These high power amplifiers comprise around hundred numbers of high power amplifier modules; similar numbers of directional RF power sensors, 48/64 way power dividing and combining structures, cooling water distribution system, RF protection unit, electrical power sub-system etc. Along with these, control and interlock sub-system is there to ensure proper functioning of various sub-systems. Both 32 kW [1] *and 40 kW amplifiers are realized in the foot print of two racks, outputs of which are combined to give the rated power. Divide and combine strategy is followed in both the amplifiers wherein the input RF is divided and fed to individual racks. Each rack of 32 kW amplifier consists of forty eight numbers of 500 W power amplifier modules and outputs of these are combined through a 48 way RF power combiner. In 40 kW amplifier, 64 way RF power combiner is used. Measurement sequence includes cold testing, output measurement set up calibration at 1 kW RF power and eventually high power testing* [2]. *In cold testing different checks like water leakage check, electrical testing, assembly and integrity check and control and interlock functionality check are performed. Output measurement set up which needs to be calibrated comprises high power directional coupler and RF cables. High power testing includes amplifier gain and efficiency measurement, spectral response measurement, bandwidth measurement, group delay measurement and radiation mapping. This measurement sequence is followed for individual racks first. After optimizing individual racks, outputs of these racks are combined via a 2-way RF power combiner and high-power testing is performed along with the configuration of alarm and trip limits for RF power and amplifier heat-sink temperature. Developed amplifiers were tested in pulsed mode also and suitable pulsed RF measurements like rise time and fall time measurement, droop and pulse to pulse amplitude variation measurements were carried out. In addition to these tests, amplifiers performance was observed for increased inlet cooling water temperature as per requirement of Fermi Lab specifications. Spectral response of both these amplifiers were measured where the harmonic content was found below -30 dBc and spurious below -55 dBc. 3-dB bandwidth of both the amplifiers was beyond ±2 MHz. Radiation mapping in the complete amplifier zone within a distance of 1 m from the amplifier was carried out with radiation maxima inside the rack within prescribed safety limits. Amplifiers were tested and characterized successfully at rated power with AC to RF efficiency better than 40 %.*

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Three-dimensional Electromagnetic Simulations of a Constant Gradient Traveling Wave Accelerating Structure Integrated with RF Couplers

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An S-band Constant Gradient (CG) Traveling Wave (TW) accelerating structure has been designed [1] for the injector linac for a High Brilliance Synchrotron Radiation Source (HBSRS), to accelerate the 15 MeV electron beam to 200 MeV. The linac is designed with four sections, each having a length of 3.793 m. Each section will consist of 114 regular cells, with β_p (phase velocity of operating electromagnetic mode in unit of speed of light in vacuum) of each cell as 0.999 [1]. As the structure is CG type, the cell radius and aperture radius are varied for each cell, such that a constant electric field profile is obtained along the linac length, in the absence of beam. The cell-to-cell variation in inner radius is 4–8 μm, while the cell-to-cell variation in aperture radius is 16–33 μm. The RF power will be fed into the structure through an input RF power coupler, and the remnant power at the end of the structure will be sent to a matched load through an output power coupler. The power coupler will consist of a coupling iris, and a tapered waveguide that connects the iris to the WR-284 transmission line. Since different cells are designed independently, using a 2D EM code SUPERFISH [2], it is prudent to perform end-to end three-dimensional (3D) electromagnetic (EM) simulation of TW linac section, integrated with input and output RF power couplers, to confirm that the design works as desired, in totality. With this aim, 3D EM simulations have been performed using frequency domain solver module of 3D EM computer code [3]. The finite resistivity of copper has been considered explicitly in the 3D simulations. At the operating frequency of 3 GHz, the reflection coefficient of −36 dB, and average phase advance per cell of 120° is obtained. Voltage Standing Wave Ratio (VSWR) is less than 1.22 in a frequency range of 2.998–3.003 GHz, which corresponds to power reflection of less than 1%. A constant electric field profile is obtained for this linac, which validates the 2D design of this linac, and design of the RF power couplers. The RF power coupler is generally designed, using Kyhl's method [4], considering only the coupling cavity and the adjacent cell of the linac. In our study, the design of input and output RF couplers is verified also for the operation mode, when the couplers are together connected to the full linac. Error and tuning studies have also been performed for random errors in cell radius and fixed error in output coupling iris, using Steele's bead-pull perturbation technique. An in-house developed tuning program has been used for tuning this linac in simulation environment. It has been explicitly shown that after applying the cell corrections and output coupler tuning, the field profile is restored to a constant value, and the reflection coefficient improves from −11 dB to −33 dB. The phase advance error reduces from ± 42° to ± 2°, except at one point, where it is +6°. The average phase advance per cell improves from 123° to 120°, which is the design value.

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Design and Development of Ultrahigh Vacuum Compatible Upgraded Synchrotron Light Monitor for Indus-1 Upgrade

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Abstract

Synchrotron light monitor (SLM) is used to obtain continuous visual information of stored beam using visible part of synchrotron radiation (SR) emitted from the beam. It facilitates the machine operation crew members to know the successful storage of injected beam during the beam injection process. The SLM presently installed, in 450 MeV, 100 mA Indus-1 SR source at RRCAT, Indore is about 23 years old and has almost completed its useful life. An ultrahigh vacuum (UHV) compatible upgraded SLM has been designed and developed, which will be installed during the upgradation of Indus-1 in coming months. The upgraded SLM is 231 mm long UHV compatible assembly mainly made of SS316L material. It incorporates a special mirror developed in-house using silver plated, Ø80 mm x 12 mm thick, oxygen free copper. The mirror has ~200 nm thick silver layer on it deposited by pulsed DC sputtering. The mirror is mounted on a vertical shaft rotary motion feedthrough for the adjustment of its angular position with respect to the direction of SR light. The mirror position is locked during laser alignment to get the visible light through the centre of viewing port of SLM. A CCD camera has been used to capture visible portion of SR light after reflection from the mirror. Due to SR power loss, the estimated temperature of mirror will be ~104 °C during the operation which will give ~141 µm thermal expansion in its diameter. The suitable relief has been provided in its holding arrangement in order to minimize the deterioration in flatness of the mirror. Recorded reflectance curve of silver plated mirror of SLM shows more that 94% absolute reflection for visible part of spectrum. During the vacuum qualification, the upgraded SLM assembly has been leak tested for helium in the range of ~2.0 x E10-10 mbar-l/s. The ultimate vacuum ~5.5 x 10E-10 mbar and specific out gassing rate ~1.0 x E10-12 mbar l/s/cm^2 (after 65 h running of sputter ion pump; tested without the mirror to prevent the deterioration of reflective characteristics of mirror due to baking temperature) have been measured after bake out. RGA spectrum attained in UHV condition was found satisfactorily. The developed SLM is ready for installation at 10° port of dipole chamber DP-4 of Indus-1 upgrade. The mechanical design and development of upgraded SLM have been described in detail in this paper.

Design and Development of Ultrahigh Vacuum Compatible Upgraded Fluorescent Screen Monitor for Indus-1 Upgrade

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Abstract
With regard to the present upgradation requirement of beam diagnostics devices in 450 MeV, 100 mA Indus-1 synchrotron radiation source (SRS) being operated for last 23 years at RRCAT, Indore, the design and development of ultrahigh vacuum (UHV) compatible upgraded fluorescent screen monitor (FSM) have been carried out for Indus-1 Upgrade. This upgraded FSM is ready for the installation replacing the already installed old monitor which has almost completed its useful life. The FSM is being used in Indus-1 in S-2 straight section to monitor the relative electron beam position and beam spot size of a 450 MeV electron beam for injection optimization and trouble shooting, if any. A chromium doped alumina ceramic is inserted into the beam path, and fluorescence produced is monitored by a video camera. The resulting image is captured using a frame grabber and analysed. The upgraded FSM incorporates improved features as thicker side plate of SS316L vacuum chamber in order to limit the deflection due to motor-feedthrough sub-assembly, holding frame made of Al alloy in order to protect the 1 mm thick fragile fluorescent ceramic screen (AF995R), in-situ screen position checking arrangement by using machined reference blocks, provision for alignment posts, self centered camera stand and multi featured holding and supporting base stand. The laser alignment of the ceramic screen has been carried out with the accuracy of 0.3 mm with respect to the mechanical axis of vacuum chamber of FSM. The total length of FSM is 231 mm including 21 mm thick x Ø152 mm outer diameter rotatable knife edge sealing (DN100-CFR) SS316L end flanges at both ends. During the vacuum qualification, helium leak rate <1.5 x 10E-10 mbar.l/s and ultimate vacuum ~5.7 x 10E-10 mbar have been recorded. The residual gas analyser (RGA) spectrum attained in UHV condition was satisfactory. The specific out gassing rate ~7.0 x 10E-13 mbar.l/s/cm^2 (after ~65 h running of sputter ion pump) was measured after bake out. The developed FSM is ready for installation. The mechanical design and development of upgraded FSM have been described in detail in this paper.

HOLISTIC APPROACH FOR DESIGN AND CONSTRUCTION OF THz-FEL BUILDING AT RRCAT

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The Accelerator Technology development in the field of FEL requires specific infrastructure facilities for component development, testing and commissioning. The THz-FEL (Tera Hertz Free Electron Laser) complex has been designed with integrated approach to enable the technology development ensuring fulfillment of specific requirements of radiation shielding, precision alignment, environmental conditions, man and material transport arrangement, provision for supporting arrangement for heavy undulator, electron beam transport system, optical cavity system and electrical power etc.

The THz-FEL lab building is extension of existing LPCL building and in- house the shielded vault for free electron laser experiments to carry out research and development programs in the area of material science, magnetism, superconductivity, and other associated R & D activities.
The facility is designed to be operated at two electron beam energies and power: 15 MeV, 55 W (average) and 50 MeV, 0.5 W (average). Dose rate due to bremsstrahlung x-ray photons and photo-neutrons are calculated for several reference points outside the shielded enclosure including the roof. Shielding adequacy was checked after considering the beam loss at beam dump and beam slit location. On the basis of functional use the building has three major zones viz.The Control and Equipment zone having Klystron room, LLRF room, Laser room, Control room, and Services zone having Electrical room and AHU room , and the radiation shielding vault which will in house two injector systems: (1) a thermionic electron gun based conventional injector linac system and (2) a laser photocathode RF gun based linac system. The overall dimensions of the building is 33.80m x 20.1m and height is 9.4m from FFL . The vault is situated inside the building and having dimension of 20.5 x 10.2x 4.5m.The thickness of walls of RCC shielded vaults is 1500mm and roof slab and foundation raft are of 1000mmthick.

The structural design for the building with requirement of radiation shielded area has been accomplished by considering appropriate structural configuration, FEM modelling of shielded vault, and design for seismic loads and thermal stresses.
The construction of the complex has been undertaken in phase manner and comprehensive planning has yielded an efficient layout fulfilling AERB stipulations for the project.

The paper highlights the salient features of the planning, design & construction of THz-FEL building which includes isolation of shielded area, integration of building with existing lab, appropriate use of ground topography, well planned man and material movement network. The implementation of good schemes and quality assurance plan is of great concern for the important structures especially which houses radiation shielded area. The quality control plan was implemented using mock up test in addition to lab test on material ingredients.

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Final Commissioning of the high-power RF system for Conditioning of the RF photocathode gun at higher field gradient

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Delhi Light Source (DLS), a compact, pre-bunched Free Electron Laser facility is being commissioned at IUAC [1]. This facility is expected to produce electron beam of maximum energy up to 8 MeV by a 2.6 cell normal conducting RF photocathode gun operating at 2860 MHz for pulse operation up to 4 μs duration with estimated field gradient of 110 MV/m. The high-power RF system for the gun consists of a solid-state modulator-based Klystron system rated for 25 MW peak RF power for the desired pulse duration at 50Hz repetition rate [2]. The RF System was installed and tested up to full rated power with a vacuum based wave guide connected to water cooled matched load. When the matched load section was replaced with the actual RF gun, the RF power was limited up to 1 MW for RF conditioning of the gun due to high value of the reflected power during conditioning in absence of the high-power Circulator [3]. In place of high vacuum-based Circulator as planned initially, SF_6 Gas based circulator is installed in the wave guide system. Additional RF windows are installed to isolate the vacuum-based wave guide system and SF_6 gas-based circulator. Additional interlocks using arc detection in the circulator section and monitoring of SF_6 gas pressure is incorporated. After installation of the Circulator the RF conditioning of the photocathode gun carried out at high RF power level, The VSWR is found to be better than 1.1 for the entire 4us pulse duration and RF gun could be conditioned at high field gradient up to 65 MV/m (calculated). The dark current along with the pick up from the RF gun was monitored and measured during the conditioning process. The photo-electron beams are also generated from the electron gun using a nanosecond UV laser beam. The energy calibration of the electron beam at different field gradients of RF gun is being planned using a dipole magnet. In this paper we will report the status of the final commissioning of the high-power RF system along with conditioning status of the RF gun.

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Performance Optimization of the IR-FEL at RRCAT

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*The **I**nfra-**R**ed **F**ree **E**lectron **L**aser (IR-FEL) at RRCAT is designed to lase from 12.5–50 µm wavelength, with a Continuous Wave (CW) average out-coupled power ~ 30 mW at 10 Hz pulse repetition rate (PRR) [1-3]. Wavelength tunability from 12.5 – 40 μm has been achieved by varying the electron beam energy from 19 – 24 MeV, and by varying the Root Mean Square (RMS) undulator parameter from 0.54 to 1.26. Saturation of lasing was achieved in 2020 with an out-coupled power ~ 7.3 mW at 2 Hz PRR. [4,5], which increased in 2021 to ~ 20 mW at 24.6 µm wavelength for 2 Hz operation in 2021[6,7].*

Performance optimization of the IR-FEL setup has been done to achieve 30 mW CW average out-coupled power at 24.6 µm wavelength, and a detailed characterization of the optical beam has been performed. The wavelength of the FEL beam, predicted by using values of the experimental beam energy and undulator parameter in the standard FEL wavelength equation, has been verified by comparing the transmission spectra of a standard TPX window material obtained using the FEL radiation in a wavelength range of 16-30 µm with the spectra obtained for the same TPX window with a lab source and FTIR spectrometer. FEL simulations considering experimental parameters for the beam energy and wavelength show a reasonably good agreement with the experimental measurements of the CW average out-coupled power, optimum detuning length, width of the detuning curve and start-up time, considering 0.6 nC charge per micro-pulse and 0.5% rms energy spread. The FEL start-up time of ~ 1.8 μs from simulations is in good agreement with the measured startup time of 2.2 µs.

Recent experiments with improved charge per micro-pulse in the electron beam and with lower energy spread have resulted in a detuning curve with a larger width as compared to the results obtained in 2021, which is also predicted by FEL simulations. Hitherto, the electron beam emittance was measured in standalone experiments and the obtained emittance was used in FEL simulations to interpret experimental results. Recently, the emittance measurements have been repeated for the optimum injector system and transport line settings leading to saturation of lasing, and FEL simulations repeated considering these electron beam parameters for a better interpretation of experimental results.

FEL light from the radiation shielded area has been transported to the user laboratory over a distance of ~ 55 m by employing an optical transport line constructed earlier with 13 mirrors. The observed high loss in power during the optical beam transport has been studied through *simulations considering the size of optics presently employed in the setup, and a revised design of the transport system has been prepared considering larger size optics to significantly reduce the transmission loss.*

Experiments are currently underway to obtain operational regimes for saturated lasing at longer wavelengths up to the design value of 50 μm, and to improve repeatability and operation for the machine. This paper discusses the present status and the future plans of the IR-FEL project at RRCAT.

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Performance of 40 kV electron gun with beam trials in a 10 MeV Rf Linac system

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A 40 kV, 1.6 A LaB_6 cathode based thermionic diode electron gun is designed and developed keeping modified Pierce configuration for the focusing electrode. The gun is tested on test bench and then connected to the 10 MeV RF linac system. After initial beam trials, there were problems due to arcing and the extraction voltage had to be reduced. The problem was solved without removing the electron gun by using a triode mode operation with a positive bias. The desired output beam current of 225 mA is achieved.

This paper presents the design of the electron gun, its testing on test bench and its performance during beam trials with 10 MeV Rf linac system.

Experimental study of performance of a LaB_6 cathode thermionic electron gun after long shutdown

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A 40 kV 1.4 A thermionic diode LaB_6 cathode based thermionic electron gun was designed and developed using the Pierce configuration for the grid (focusing electrode). The LaB_6 cathode housing the LaB_6 cathode pellet consists of cups and heat shields made out of Tantalum and Rhenium sheets.

The gun is tested on test bench. After long shutdown if the electron gun is operated, we expect to get the beam extraction performance as was during regular operation.

This paper presents the design of the electron gun, its testing on test bench and the experiment to study its performance after long shutdown and to verify the above assumption.

Effect of Wehnelt potential on the beam parameters of a 20 keV strip type DC electron gun and its initial beam trials

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Photon absorbers (crotches) are used to absorb unused heat of synchrotron radiation emitted in a storage ring and their performance is interlocked with machine operation. It is planned to test these crotches in laboratory under vacuum environment using electron beam from an electron gun as an equivalent thermal power source. The physics design of a 20 keV/100 mA thermionic, DC electron gun delivering rectangular beam of power density 11 W/mm^2 at a throw distance of 300 mm for the above work had been reported previously using CST particle studio to test photon absorbers by Monika Rana et al. [1]. In the present work, we report the simulation studies that have been carried out for studying the effects of Wehnelt potential on the beam parameters and subsequent to the fabrication of this gun as per the design specifications, the preliminary results of beam trials in the laboratory with a crotch are summarized.

An electron gun is a current controlled device whose beam current can be controlled by varying the temperature of the cathode. This method of controlling beam current is very sensitive to the heating current of the cathode and hence it is difficult to maintain stable beam current in the temperature dependent region of the electron gun. In order to obtain a stable beam current, the electron gun is converted into a voltage-controlled device by applying negative bias to the Wehnelt. The bias voltage acts as a beam current adjustable shutter that controls the emitted current density from the cathode surface and its maximum operating value for the desired footprint of the beam landing on crotch surface. The emitted current is finally limited by the geometrical perveance of the gun. In the simulation, the geometry of the gun components was first evolved for the diode configuration at 130 mA beam current in space charge mode [1]. In the present simulation the requirement of bias voltage to the Wehnelt is optimised to vary the beam current from 50 mA to 100 mA from the gun. Further, the effect of bias voltage on the beam sizes in both the planes have been optimised to produce the desired beam size at the throw distance of 300 mm. The gun has been fabricated and preliminary beam trials have been carried out in the laboratory with a crotch. This paper will also report the measured data of beam current variation with the Wehnelt bias voltage. Fabrication details of the electron gun will be reported separately [2].

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Compact Hollow Cathode plasma source for high current electron beam generation

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Electron guns have wide application in the fields such as Accelerators, Vacuum electronic devices, X ray generation, welding, melting, heat treatments of materials, surface treatments, sterilization etc [1-4]. When thermionic cathodes are employed as electron gun, it has a limited life and also it cannot operate in poor vacuum. Thus plasma cathodes are better choices when long life of the source is desirable for uninterrupted operation and where ultra high vacuum is not attainable. Keeping the wide applicability in consideration, a compact high current hollow cathode plasma based electron gun is under development at VECC. This self sustained plasma system has a cylindrical hollow cathode geometry and do not use any filaments and magnets. The plasma cathode assembly measures 70 mm long and 5 mm diameter. Plasma discharge is achieved by 1KV/1A power supply while -4kV power supply is used for acceleration of the electron beam. Beam is measured using a faraday cup which is at ground potential. Argon, Neon and Oxygen plasmas were generated and the extraction of electron beam was carried out through 1 mm extraction aperture in the anode. Break down voltage for various operating pressure noted and observed that it follows Paschen curve(5). 650 mA of electron beam was extracted at 7.0x10^{-5} mbar Oxygen pressure with discharge voltage of 700 V. The design and the experimental results are discussed here in this article.

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Development of a computer program for design of diode type electron gun

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For designing an electron gun, several computer codes, such as $EGUN$ [1] and CST particle tracking solver [2] etc. are commercially available, which simulate the physics of electron guns. $EGUN$ is a two-dimensional (2D) software that simulates axi-symmetric structures, whereas CST is a three-dimensional (3D) software. $EGUN$ is old software, which has been widely used by the accelerator community to design electron gun. Simulating the beam dynamics in an electron gun is of somewhat different nature compared to that in downstream accelerating structures. This is because in an electron gun, the beam formation takes place; and the space charge field seen by an electron, and hence its dynamics depends on the overall distribution of charge between the cathode and the anode, which in turn depends on the electron dynamics. This problem thus needs to be solved in a self-consistent manner. After the beam is formed in the electron gun, and it enters downstream in the accelerator, the beam dynamics needs to evolved, taking the space charge field for a nearly known charge distribution of the formed beam. Manual of the EGUN software describes the procedure for several calculations, such as calculation of voltages on grid points and ray tracing in the space inside the gun structure, calculations of charged density on grid points and beam emittance calculations, etc. However, the manual does not provide the procedure for perveance calculation with adequate clarity, and also it gives different values of emittance at different places in the output file. In order to develop a better understanding of the physics of electron gun and its simulation procedure, along with the capability to be able to add new features in the calculation, an indigenous $MATLAB$ [3] based computer program is developed. The Poisson equation inside the electron gun is solved for an axisymmetric system with an appropriate boundary, and the five point difference technique is used to calculate voltage at grid points for a specified domain. As in the software EGUN, ray optics approach is used to evolve the electron dynamics, for which the relativistic equation of motion is solved in cylindrical coordinates, using four-step Runge-Kutta method. A self-consistent charge distribution between the cathode and anode is evolved in an iterative manner. In the first iteration, calculations are performed without space charge, and later, the charge distribution obtained in the previous step is used to update the electron dynamics in the presence of updated space charge field. After a few iterations, a self-consistent charge distribution is obtained. Program calculates the beam parameters at the output of the electron gun, and also the perveance. For the calculation of perveance, the program calculates the space charge limited current for a given cathode voltage, which is the beam current for which the electric field at the cathode becomes zero. The indigenous program is benchmarked with the code $EGUN$ for case study of 50 keV/90 keV electron gun design. The voltage distribution, ray positions and beam parameters, calculated using the indigenous program are found to be in close agreement to the results obtained using $EGUN$. The further scope of upgrades is also discussed in the paper.

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Study of on-axis Longitudinal Beam Injection in Storage ring of High Brilliance Synchrotron Radiation Source

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A High Brilliance Synchrotron Radiation Source (HBSRS) based on storage ring is being planned based on multi bend achromat lattice with strong quadrupole and sextupole magnets to achieve ultra-low beam emittance. These strong non-linear magnets with even small errors may significantly reduce the dynamic aperture of the storage ring lattice as compared to a 3rd generation light source. Thus, this configuration generates a great challenge for the beam injection by conventional 4 kicker scheme. To relax the dynamic aperture requirement in transverse plane, on-axis longitudinal injection scheme is studied.

In this injection scheme, a bunch is injected in the longitudinal plane with suitable energy and time offset, with respect to the stored bunch [1]. This injected bunch gradually merges into the stored bunch through synchrotron radiation damping phenomena. For this, a very fast dipole kicker with a pulse length shorter than the bunch spacing is required to keep stored bunches undisturbed [2, 3]. With the help of this kicker, the off energy injected beam is placed on the dispersive orbit of the storage ring, which is longitudinally separated from the stored beam. Appropriate placement of the kicker demands a phase advance of an odd multiple of $\pi/2$ from the injection point and finite dispersion in horizontal plane.

In this paper, the feasibility of longitudinal injection scheme for the storage ring of HBSRS is studied and reported. For this, the optimum placement of the kicker is chosen according to the availability of space in the lattice and injected beam energy offset is chosen according to the available momentum acceptance of the storage ring.

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Beam profile and emittance measurement using scintillation screen and solenoid scan method.

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Low Energy High Intensity Proton Accelerator (LEHIPA) is a 20 MeV proton accelerator developed at BARC. Currently, LEHIPA has been commissioned up to 11 MeV, and an acceleration trial of 20 MeV is underway. The front end of LEHIPA is a 50 keV, 10 mA ECR ion source. In LEHIPA, ECRIS with three electrodes has been commissioned so far. However, an upgrade of five ECRIS electrodes was developed to further improve the quality of the beam and its characterization is ongoing at ECRIS test lab.

The five electrode Electron Cyclotron Resonance (ECR) ion source characterized in terms of beam profile and beam emittance. The characterization was carried out at 50 keV and a beam current of 10 mA. The CCD camera and quartz scintillation screen have been used to observe the beam profile of pulsed beam in transverse *x* and *y* planes. Measurement of beam emittance is accomplished with solenoid scans in a beam line. In solenoid scan emittance measurement, series of beam profile is measured for different strengths of focusing magnets in order to determine the beam size minima for a 50 keV H^+ beam. From the knowledge of beam optics, focusing solenoids strength and beam profile, beam emittance measurement has been carried out.

The paper discusses a five electrode ECR ion source, experimental setup for beam profile measurement, experiments and analysis of beam emittance. Measured beam emittance is also verified by Allison scanner results. The measured rms beam size is in the range of 8~11 mm and rms normalized beam emittance is ~0.24 π.mm.mrad for 50 keV, 8~10 mA beam.

Status Report of FOTIA Facility at BARC

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A 6 MV Folded Tandem Ion Accelerator (FOTIA) was commissioned in 2000 at BARC. Since then it is in operation and has been used both for basic and applied research. The facility has been delivering various ion beams to users from BARC and universities for PIXE, PIGE, RBS, material irradiation and radiation biology experiments. During the year 2022, FOTIA has been operational in round the clock shifts and achieved 3176 hours of beam time.

FOTIA facility has been delivering variety of ion beams for last twenty three years reliably for performing various kinds of experiments and contributed immensely to various programs of DAE and other research institutes and universities. As there is continuous user demand for high energy beams, High Voltage conditioning has been carried out for attaining a stable terminal voltage of 3.75 MV. The 180^0 bending magnet power supply has been upgraded to 110A for carrying out user experiments. Some of the major experiments carried out at FOTIA facility are Quantification of low Z elements in geological samples using External PIGE, Exposure of CR-39 detector to 3-5 MeV, 20 nA Proton beam, Study of effect of H+ ion on InAs quantum dots, Determination of (n, Y) cross sections of fission products and structural material elements for fast neutrons in 0.5 -2.0 MeV, Study of neutron capture cross sections for ^{nat}Mo, ^{nat}Sb and ^{nat}Ta with covariance analysis & Quantification of low Z elements like B, F, Li in reactor material using external PIGE etc.

FOTIA is one of the safest accelerators in operation and received safety shield for three consecutive years earlier. Many of the FOTIA practices are recommended by ULSC-PA to other accelerator facilities to adopt, which is an indication of very high safety standard of FOTIA. In this paper, we will discuss operational status of the FOTIA in detail.

Studies of the PIG ion source behavior in *K*130 cyclotron at VECC

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K130 room temperature cyclotron (RTC) at VECC, Kolkata has been delivering light and heavy ion beams for various experimental purposes as a national facility. The hot cathode PIG ion source placed at the center of the cyclotron produces light ions (protons or alphas) that are subsequently accelerated in the cyclotron. The filament of the ion source is made of tantalum, operating in the range of 300-500 A. Two water-cooled copper tubes supply the necessary filament current. A separate tube carries the gas to be ionized. The grounded copper anode is made in the form of a chimney, which is also water-cooled. A tantalum insert with a rectangular slit is fitted to the anode. There is an insulated tantalum anticathode on the top of the ion source that reflects the drifted electrons towards it. This whole assembly is mounted on a shaft, which runs all the way through the lower yoke of the magnet to the Dee-tank. A puller assembly at Dee potential extracts the ions to be accelerated.

The beam current obtained from the PIG ion source and the lifetime of the filament depend upon several factors, such as the magnetic field, pressure inside resonator tank, filament current, ARC voltage, gas flow etc. In this work, the behaviour of the ion source for a given species has been studied under different operating conditions of the ion source parameters in order to investigate the reason behind the significant reduction in filament lifetime. A MATLAB based image processing graphical user interface (GUI) has been developed for the measurement of variation of beam spot with the ion source parameters. The internal beam profile is also measured using Dee probe. A detailed study of the ion source characteristics will be described in this work.

Physics Design of a 50 MeV Proton Cyclotron for Rare Ion Beam Production

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A 50 Mev 200 micro-Ampere Proton cyclotron is being designed in VECC to produce Rare Ion Beams (RIBs) for the ANURIB project using ISOL (Isotope Separation On Line) post accelerator method. This will provide neutron deficient RIBs using fusion evaporation reactions and neutron rich RIBs using fission reactions. The RIBs produced using thick targets will diffuse out, ionised in an online ion source, mass separated to select the RIB species of interest. The low energy RIBs (typically 1-1.5 KeV/u) will be further accelerated according to requirement of the experiments.

A volume type multicusp ion source will be used to produce negative hydrogen ions (H-) in CW mode. These ions will then be injected inside the cyclotron. A spiral inflector will be used to launch the ions in the central electrode geometry. A four sector magnet with optimised hill profile will be used as the main magnet of the machine. Two triangular shaped RF cavity resonators connected in phase and situated at two opposite valleys will be used for accelerating the ions. These ions will be extracted using carbon stripper once they achieve the desired final energy. A switching magnet will be used to steer the beam towards the beam line.

This cyclotron will be operated for hydrogen ions (H-) at fixed frequency. It is possible to vary the energy of the extracted ions by adjusting the radial and angular position of the carbon stripper. Physics design of the main cyclotron magnet is underway. Maximum operating hill field, hill and valley gap, average magnetic field, axial and radial betatronic tune values, frequency error are the major parameters which decide the optimum shape and size of any cyclotron magnet. In this paper estimation of these parameters from hard edge calculation as well as from three dimensional simulations using a finite element based commercial software (OPERA) will be presented. Thicknesses of the iron return paths were adjusted in such a way that magnetic field inside the iron return path remains well below saturation magnetisation. Average magnetic field at the median plane of the cyclotron at different radii was optimised by shaping the pole profile in such a way that isochronism is maintained up to the extraction radius. Simulated result of this isochronous magnetic field will be presented in this paper. Static equilibrium orbit properties of the ion were analysed using Fortran based code GENSPEO and which was used to control the pole profile. Another Fortran based code SPIRALGAP was used to generate the central trajectory. Knowledge of this central trajectory will be used to design the central region of the cyclotron. Basic beam dynamical behaviour based on these codes will also be presented in this paper.

Simulations of frequency correction of Quarter Wave Resonator using electropolishing

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To widen the mass acceptance of the Superconducting LINAC booster at the BARC-TIFR Pelletron LINAC Facility located at TIFR, Mumbai, it is planned to retrofit the first cryo-module with four low velocity (β=0.07) superconducting Niobium Quarter Wave Resonators (QWR). A QWR is a transmission line terminated at one end by a drift tube which supports the high accelerating voltage and shorted at the other end. The basic electromagnetic design of the resonator was reported in an earlier conference [1,2]. These resonators are being fabricated at CDM, BARC with the required sheet metal work being handled by M/S. Veekay Industries, Mumbai. Dimensional inaccuracies which are inevitable during fabrication will shift the electromagnetic resonant frequency away from the design value. Electropolishing of the surfaces of the QWR exposed to the RF field/current removes material from the surfaces which in turn changes the cavity volume and hence the resonant frequency. This procedure was previously used to adjust the resonant frequency of the OFHC copper resonators used in the Superconducting LINAC booster. However in the present case since the geometry of the resonators is different, studies have been undertaken to adapt the process for the niobium QWRs.

If we uniformly etch a few micrometers of material from the inner and outer conductors, then to a first approximation the transmission line characteristic impedance changes, but the overall resonant frequency will be unaffected. However, due to the tapered geometry of the central conductor in the low beta cavity the resonant frequency keeps on increasing linearly with thickness of material removal.

Electropolishing of the bottom half (high electric field end), causes the capacitance to decrease and consequently the resonant frequency increases. In general, the capacitance between the drift tubes of the QWR is much higher than the capacitance between the central drift tube and the end plate. In the simulations, the full volume from the bottom plate to above the drift tubes is included to simulate the variation of frequency. On the other hand if electropolishing is done in the upper half (high magnetic field end) the inductance increases leading to a decrease in resonant frequency. These opposite effects on the resonant frequency depending upon which end of the resonator is being polished implies the existence of an inversion length which defines the height of the column of electropolishing solution or the length of electrode to be used.

Simulations of the material etching have been performed using COMSOL Multiphysics software to study the rate of frequency change with material removal under the various scenario described above and also for the full length of the cavity. For electropolishing at the capacitative end a rate of frequency change of 3.5 Hz/μm is obtained and for electropolishing at the inductive end the corresponding value is -2.8 Hz/μm. For full length electropolish of the QWR we get a value approximately 0.7 Hz/μm.

Details of the simulations will be presented during the conference.

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Dark Current calculation in SRF Elliptic Cavities

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In RF cavities, dark current is formed by the field emitted electrons, which originate from the regions of very high electric field (~ 10^4 MV/m) on the cavity surface, and exit through the beam pipe [1]. Such high electric field occurs because of large field enhancement factor due to irregularly shaped contaminants that may be remnant at some locations of the cavity surface, even after following a rigorous procedure of cavity processing [2]. The dark current electrons gain large kinetic energy, when they exit from the beam pipe of the cavity, and can attain even higher energies, when they pass through the downstream or upstream elliptic cavities [3]. The highly energetic dark current beam can be harmful for accelerator operation, and it limits the maximum operable acceleration gradient of a superconducting RF (SRF) accelerator [4] [5]. In this paper, we have studied the process of dark current buildup in the medium and high energy accelerating sections of a 1 GeV pulsed H^- linac, for which we developed computer programs for analyzing the motion of charged particles under the influence of electromagnetic field inside the elliptic cavities. For this purpose, we calculated the electromagnetic field, using the code SUPERFISH [6], and exported it to our self-developed program. It was observed that the charged particles, which exit through the beam pipe, and can be interpreted as dark current, were mainly emitted from the iris region of the elliptic cavity. Therefore, performing the trajectory calculations only around the iris region, up to an optimally selected radial distance from cavity axis, the particle tracking analysis was performed for the medium and high beta elliptic cavities [7]. The medium beta cavities have been used for acceleration in the medium energy section of the 1 GeV H^- linac, which accelerates the 3 MeV beam to ~ 500 MeV. In our baseline design, this section consists of total 12 cryomodules, where each cryomodule is made of three elliptic cavities. In between two cryomodules, a quadrupole triplet is placed to provided transverse focusing to the H^- beam. In the high energy section, which further accelerates the beam to ~ 1 GeV, six high beta elliptic cavities form a cryomodule, and total six such cryomodules have been used for acceleration. Similar to the medium energy section, quadrupole triplets are used to provide transverse focusing to the beam in this section too. When the dark current propagates through the medium and high energy section of the linac, it can get amplified with the help of contributions from the several elliptic cavities installed in these sections. On the other hand, a fraction of the dark current can get lost due to transverse kicks by the electromagnetic field of the RF cavities and the quadrupole triplet magnets. After accounting these two competitive processes, we have estimated dark current build-up in the mid and high beta accelerating sections, and an overall amplification factor for the dark current at the exit of these accelerating sections was calculated.

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Development of a 3D Particle in a Cell (PIC) solver for multipacting study

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Multipacting is a resonant process that occurs in the RF structures, when electrons repeatedly strike the surface in synchronization with the RF field, and multiply their numbers exponentially [1]. Typically, in very few RF cycles, a large number of electrons are accumulated in this process. These electrons start consuming almost all the energy, which is supplied to the RF structure [2]. As the number of electrons increase, space charge forces among them starts becoming significant in comparison to external RF fields. Eventually, the space charge repulsion among these electrons becomes so high that a fraction of these electrons fall out of resonance with the RF fields. A steady state is achieved, when increase in the number of electrons during multipacting is balanced by the loss of electrons due to above mentioned process [3]. In the present work, we have developed a 3-dimensional (3D) particle in a cell (PIC) module to simulate the space charge effects during the multipacting process. To make the problem numerically solvable, we have used the concept of macro-particles in our calculations. Each macro-particle has charge to mass ratio similar to an electron, however, it accommodates a charge, which is equivalent to a large number of electrons. The macro-particles are moved in the electromagnetic field of the cavity by solving Lorentz's equation of motion, using leap-frog based Boris scheme [4]. In this step, electromagnetic field from the nodes of Cartesian mesh is interpolated at the particle's location, using the tri-linear interpolation method in 3D [5]. The PIC module calculates electric field due to the macro-particles by solving Poisson's equation, using the Fourier transform method [6]. To solve the Poisson's equation, charge on the macro-particles is proportionally distributed on the nodes of the Cartesian mesh, using the reverse of tri-linear interpolation method. In order to study the problem of multipacting, apart from the PIC module, we required a secondary emission module to simulate the secondary emission process. In this module, we assumed that the secondary particle, which is emitted after a macro-particle strikes the surface, holds the charge similar to the charge of the primary macro-particle. The secondary emission module is based on the Furman model [7], which provides an event-by-event detail of the secondary macro-particle generation i.e., number of secondary macro-particles, their emission energy and corresponding angle of emission. Using this PIC code and the secondary emission module, the process of multipacting is studied in a parallel plate structure. The results from the in-house developed code are benchmarked with the results from the standard commercially available code [8]. The in-house developed PIC code has a general structure, and can be modified and repurposed for other studies, such as study of beam dynamics with space charge effects.

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Study of cumulative beam breakup instability in spoke resonator section of a 1 GeV pulsed H^- linac

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Beam instabilities due to the higher order modes (HOMs) have been a concern for the superconducting linacs worldwide. Due to HOMs, the beam breakup (BBU) [1] instabilities can occur in transverse and longitudinal planes. It can be of regenerative type [1] or cumulative type BBU [2]. The regenerative BBU occurs in a single multicell structure, where the cells are strongly coupled electromagnetically. Here, a dipole mode gives transverse kick to a particle that is on-axis at the cavity entrance to make it off-axis, while it travels in the cavity, which regenerates the dipole mode and enhances its strength further. On the other hand, the cumulative BBU dominates in case of a linac, which consists of an array of electromagnetically independent cavities. Here, if a bunch enters off-axis in a cavity, it generates deflecting modes, which gives a transverse kick to the following bunches, and the transverse displacement of a bunch may grow as it moves downstream in the linac. In this paper, we present a study of cumulative transverse BBU instability for the single spoke resonator (SSR) section for a 1 GeV pulsed H^- linac. For this, the difference equations for transverse displacement and angular kicks imparted to beam bunch due to deflecting mode of cavities, coupled with the equation for evolution of amplitude of most prominent deflecting mode due to interaction with the beam are solved for SSR sections. Here, each cavity is treated as a thin lens and matrix method is used to derive these equations. Kick imparted by each cavity depends on the strength of deflecting mode in that cavity. Calculations have been performed for the baseline lattice [3] of the 1 GeV H^- injector linac. The transverse displacement and angular kick imparted on beam bunch are functions of initial offset of beam bunch, initial angular displacement, transverse shunt impedance to quality factor $\left(\frac{R}{Q}\right)_\perp$ ratio of cavity, field strength of magnetic lenses and distance of successive elements in a period. The HOMs study for each type of cavity in SSR section was earlier carried out using a three-dimensional electromagnetic design computer code [4], and for deflecting HOMs, $\left(\frac{R}{Q}\right)_\perp$ and their respective frequencies were calculated. A computer program in $MATLAB$ [5] has been written for solving the difference equations of BBU for all three sections of SSRs, to calculate the transverse displacement of the beam at the end of SSR sections. In the worst case scenario, i.e., ignoring external focusing magnetic field effects, and taking the case of those deflecting HOMs for which their $\left(\frac{R}{Q}\right)_\perp$ is maximum for each cavity type, the beam displacements for 2000 beam bunches are calculated at the end of SSR section for two cases: (i) when only the first bunch is offset by 1 mm at the entry of first cavity, and (ii) when all 2000 bunches are offset by 1 mm at the entry of first cavity. The obtained beam bunch displacement due to HOMs in both cases at the end of SSR section is found to be insignificant. Moreover, the effects of the frequency, the frequency spread, and the R/Q value of the HOMs on the cumulative BBU have been studied, which are also presented in the paper.

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Numerical studies and simulation of field stabilization and tuning of a 325 MHz Drift Tube Linac

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For the 1 GeV pulsed H^- injector linac for the envisaged Indian Facility for Spallation Research (IFSR), RRCAT is developing a 325 MHz, Drift Tube Linac (DTL) in the low energy section of the linac. The DTL will accelerate the 3 MeV H^- ion beam from a RFQ accelerator to ~ 12.7 MeV. Since the electric field direction is same in all the accelerating gaps at any instant, DTL is said to operate in the 0-mode. The group velocity of the electromagnetic (EM) wave in 0-mode is zero, which makes the frequency separation between operating mode and its adjacent mode very small. Due to this, the electric field in DTL is very sensitive to errors that can arise due to manufacturing tolerances, power dissipation, beam loading, etc [1]. These errors can disturb the field profile of the DTL. In order to make the field profile less sensitive to these perturbations, an ingenious technique that utilized post-couplers (PC) was invented in 1967 by Knapp et al. [2], which has since then been routinely used in DTLs. Insertion depth of each post-coupler in the DTL tank must be optimized to reduce the error sensitivity of a DTL to its minimum value. Role of post-couplers for field stabilization of DTLs was earlier understood in terms of confluence of post-coupler mode PC_0 with operating mode TM_{010}. Once having found the confluence length, the optimum PC insertion depth has to be found in an iterative manner, so as to reduce the error sensitivity. More recently, in 2016, a new understanding was developed by Khalvati and Ramberger in terms of equivalent circuit model [3]. In this paper, we present the three-dimensional (3D) simulation studies that have been performed using a 3D EM computer code for field stabilization of 1.82 m long DTL module designed at RRCAT. The new methodology for field stabilization, as given in Ref. 3, has been implemented, with an aim to evolve the optimized PC insertion depths, so as to reduce the tilt sensitivity slope, by nullifying the coupling admittance due to post-coupler and stem. It is seen that stabilization using equivalent circuit model results in better field flatness and better tilt sensitivity, as compared to stabilization by achieving only the confluence. The tilt sensitivity has been reduced from 47 %/MHz to 8 %/MHz upon implementation of new technique. In this paper, we also present the tuning studies that have been performed for this module. A tuning program has been written in Python to estimate the optimum insertion depth of each tuner. This program has been evolved on the basis of linear dependence of the normalized electric field and resonant frequency of the DTL on the insertion depth of tuner [3]. It has been explicitly shown through 3D simulations that error in field flatness reduces upon the implementation of this tuning algorithm, and frequency can be restored to its design value. Such extensive simulation studies will be useful during experimental implementation of the stabilization and tuning strategy, with reduced number of iterations, once the DTL is fabricated.

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Cold test and RF tuning of the first section of 3 MeV, 325 MHz RFQ at RRCAT

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A 325 MHz, 3 MeV four-vane Radio Frequency Quadrupole (RFQ) linear accelerator has been designed and is under fabrication at RRCAT, Indore [1] for front end studies for Indian Facility for Spallation Research (IFSR). Total length of RFQ is 3.49 m, and it consists of three sections, which will be directly coupled to each other. The first section is 1.162m long, and recently, the final machining and assembly of the first section has been completed, after which its low power characterization and RF tuning experiments have been performed. This section does not have provision of vane-end cutback at the exit end, which is necessary to satisfy the boundary condition of the operating fundamental quadrupole mode, while testing it standalone. Therefore, a 55 mm long unmodulated attachment piece of aluminum, which includes vane-end cutback, was designed using 3D EM code, and fabricated. After attaching this piece to the exit end of the first section, low power characterization of the first section of RFQ was performed. Sampling port in one of the quadrants of RFQ was used to feed a small RF power from VNA, and the sampling port in another quadrant was used to pick up the RF signal. Reflection and transmission measurements were performed to determine the frequency of the resonant modes in the structure, as well as to identify these modes. With the tuners kept at their nominal position, i.e., 9.8 mm inside the cavity, the two polarizations of the fundamental dipole mode were found to be resonant at 320.8 MHz and 322.6 MHz, whereas the desired fundamental quadrupole mode was found to be resonant at 325.1 MHz, which is very close to the simulation result. Further, the bead pull measurements were performed to determine the off-axis electric field profiles in each quadrant of the RFQ section. These measurements were carried out using the bead-pull set-up developed earlier for the characterization of the 3 MeV prototype RFQ [2], and in-house developed LabVIEW program for the bead-pull set-up [3]. Initially, the fractional field error in the fundamental quadrupole mode due to mixing of dipole mode was found to be 35%. Tuning iterations have been performed using in-house developed tuning program [4] based on transmission line model of the RFQ to minimize the fractional field error in the fundamental quadrupole mode. After tuning, the fractional field error in the operating mode due to dipole mode mixing was reduced to 4%, which is less than the maximum acceptable value of 5%. It was also checked that the repeatability in the field profile was better than ± 2% in the measurement. In this paper, we present the details about the methodology and results of cold test and RF tuning experiments for the first section of the RFQ.

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RF characterization and tuning of DTL tanks 3 & 4 for LEHIPA

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A Low Energy High Intensity Proton Accelerator (LEHIPA) is being built at BARC, Mumbai. This will serve as pre-injector to proposed Indian ADS program [1, 2]. LEHIPA mainly consists of 3 MeV Radio Frequency Quadrupole (RFQ) and 20 MeV, 12 m long Drift Tube Linac (DTL) [3]. The DTL was fabricated in 4 tanks of 3 m length each. Recently the LEHIPA was commissioned up to 11 MeV using RFQ and first two DTL tanks. Each DTL tank consists of several Permanent Magnet Quadrupole (PMQ) based Drift Tubes, Tuners, Post Couplers, RF ports and Vacuum ports amongst others. RF qualification, characterization and tuning of DTL cavity is paramount for determining & tuning the key performance indices of the cavity. These include determination & tuning of resonant frequency of the cavity, achieving the electric field flatness and tilt sensitivity in each RF gap within the required specifications, determination of loaded & unloaded quality factor, and spectrum of all the post coupled modes of the cavity, etc [4]. The resonant frequency of the TM_{010} mode of DTL cavity needs to be tuned to 352.115 MHz. While fabrication of the cavity at room temperature, several factors that lead to changes in resonant frequency have to be taken into consideration [5]. This in turn decides the dimensions and geometrical tolerances of DTL cavity. Tuners are provided to adjust the resonant frequency of the cavity. These are copper structures that change the inductance of cavity in magnetic field zone and thus changes the resonant frequency [6]. Tuners are also responsible for maintaining field flatness in the DT gaps within the desired limit (< ± 2 %). Field flatness in each DT gap determines the average electric field in each gap. Post couplers introduce TE modes in the cavity by introducing a capacitance between PC and DT. These TE modes help in increasing separation between the consecutive modes. Also, the group velocity of the EM waves generated inside the cavity increases which improves the energy flow in the axial direction in the cavity, hence stabilizing the cavity in case of introduction of any perturbations leading to change in resonant frequency of the cavity [7]. PCs are therefore essential for maintaining tilt sensitivity in each DT gap within the desired limit (± 20 %/MHz).

For carrying out the RF measurements, a bead-pull setup was developed. A spherical aluminium bead of 8 mm diameter was used for perturbing the field and carrying out the measurements. As the bead traverses through the cavity, the fractional change in the resonant frequency ($\frac{\delta\omega}{\omega}$) is given by the equation below [8].

$$\frac{\delta\omega}{\omega} = \frac{\Delta\varphi}{2Q_l} = \frac{\alpha E^2}{U}$$

Where α depends on the shape of the bead (for spherical bead of radius r, $\alpha \propto \frac{4}{3}\pi r^3$), U is the stored energy and E is unperturbed field. This paper describes complete RF characterization and tuning methodology and results of DTL tanks 3 and 4 to achieve the above key performance indices within the required specifications.

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Super-conducting Resonators as post-accelerators of RIB facility at VECC

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An ISOL (Isotope Separator On-line) type Rare Ion Beam (RIB) Facility has been developed at the Variable Energy Cyclotron Centre (VECC) ***[1]****. The RIBs are produced using primary ion beams from the K130 Cyclotron , transported to an ECR ion source, ionised and the RIB of interest is selected using an Isotope Separator. Thereafter the beam is accelerated to higher energies using a radio frequency quadrupole (RFQ) linac and three heavy-ion Linear accelerator modules to 415 keV/u. Two more linac modules will be used to accelerate the RIBs up to about 1 MeV/u and further acceleration will be done using super-conducting Quarter Wave Resonators (QWRs)* ***[2]****.*

The QWR cryomodule has been designed and developed jointly with TRIUMF laboratory in Canada. The cryomodule houses four bulk niobium QWRs operating at 113.61 MHz for accelerating the ions and a superconducting solenoid for the transverse focusing. The QWRs have been optimised for β_0 of 5.5% and will operate at 4K. In this design, the beam space vacuum is hermetically sealed from the cryo-module vacuum which is expected to retain the performance of the QWRs in the long run. The test results of the first cryo-module will be presented in this paper.

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Design and Development of low frequency high voltage switching system for ISOL to study Charge Exchange Collisions

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The existing isotope separator online (ISOL) system [1, 2] in RIBFG, VECC has been used to accelerate both beta-stable isotope beams ($^{39}K^+$, $^{85}Rb^+$, $^{87}Rb^+$, $^{115}In^+$) and radioactive ion beams (RIB) ($^{42}K^+$,$^{43}K^+$) [3]. The system has already been used for using Collinear Laser Spectroscopy (CLS) of stable ion beams ($^{85}Rb^+$, $^{87}Rb^+$) [4]. Currently the CLS system is being further optimized for the study of RIB. Of particular interest is the beams of alkali species. Optimization of the Charge Exchange Cell design is one of the key modification, which is to be incorporated in the system. Here we are working on a new dynamic characterization technique for studying charge exchange collisions based on the work by Rai et al. [5] where low frequency pulsing of ion beam is required.

For this purpose a bunching electrode has been installed downstream of the cathode disk of the surface ion source. A high voltage pulser, connected to the bunching electrode is slaved [6] to a master oscillator. The communication between master and slave is done through an optical fiber network. The network acts in a 'TALK-LISTEN' configuration between HV pulser and master oscillator. The duty cycle, frequency of the HV pulser can be changed as per setting of master oscillator. The optical transmission system allows us to operate the HV pulser (floating at 30kV) by manipulating the master oscillator (placed at ground voltage) [7,8]. It adds flexibility to the system to generate low frequency bunched beam, which will be introduced in the new charge exchange cell of CLS for optimization purpose and to execute collinear laser spectroscopy, where a high (photon/atom) ratio can be achieved. The details and test results of the newly installed system will be discussed.

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Estimation of neutron yield from the interaction of ~ 7 MeV/nucleon ^{7}Li beam on Cu and Ta target for safety analysis and shielding design of ANURIB project

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Introduction: The availability of heavy-ion (HI) beams (A > 4) has made an enormous impact on nuclear reaction study, particularly in understanding the fusion mechanism. The fusion phenomenon, which refers to the total amalgamation of the projectile (P) and target (T), has been a long-standing topic of research due to the presence of a variety of mechanisms, viz., evaporation/equilibrium (EQ), pre-equilibrium (PEQ), breakup fusion or incomplete fusion (ICF), quasi-fission, etc., all of which contribute to the reaction cross section of the fusion process at moderate beam energies. The present study focuses on the estimation of neutron yield due to interaction of ~ 7 MeV ^{7}Li beam on Cu and Ta target for source term estimation related to the safety analysis and shielding design for high energy section of the ANURIB project at VECC, Kolkata. In nucleus-nucleus collisions, FLUKA **[1,2]** relies on three distinct models, each operating in a different beam energy range EB:

- EB < ~ 0.1 GeV/n: The Boltzmann Master Equation (BME) model
- ~ 0.1 GeV/n < EB < 5 GeV/n: Relativistic Quantum Molecular Dynamics Model (RQMD)
- EB > 5 GeV/n: Dual Parton Model (DPM): DPMJET-III.

In present case, the BME model is used by FLUKA since the 7Li beam energy is ~ 7 MeV/n. In the BME model, the nucleons are distributed in binned momentum space according to their energies, and the energy level occupancies follow the Pauli principle. Time evolution is given by numerical integration of the so-called Boltzmann Master Equation, and a range of mechanisms, depending on the spatial offset of the beam direction to the target particle, may lead to the emission of secondary fragments. The BME model always adopts the complete fusion mechanism, followed by the PEANUT pre-equilibrium and Weisskopf-Ewing evaporation model. Several benchmarking studies have been carried out over the years to validate FLUKA physics models. Similar estimations have also been carried out with GEANT4 for validation of the model.In the present case, two simulations have been carried out using FLUKA and GEANT4. Experimental values were available for 46 MeV ^{7}Li beam incident on a thick Cu target. The outputs from both FLUKA and GEANT4 are in the range of 2.3E-3. The experimental results in this energy domain are very less, and often suffer from large uncertainty. However, FLUKA community has benchmarked their model for ^{7}Li + nat Cu reaction channels at ~40 MeV with the experimental results given by Rishabh Kumar, Moumita Maiti et al, 2021 **[3]**.
From Table 1 and after comparing with available experimental values, it can be concluded that since FLUKA/ GEANT4 results are comparable and higher than the quoted experimental values, these codes can be used for radiation protection purposes, the shielding efficiency as simulated by these codes will be on the safer side.

Table 1: Total neutron yield/primary

Cases	FLUKA	GEANT4
Beam: 46 MeV ^{7}Li beam Thick target: Cu	2.32E-3 $\pm$ 0.334	2.26E-3
Beam: 49 MeV ^{7}Li beam Thick target: Ta	1.65E-3 $\pm$ 0.533	2.09E-3

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Operational experience of heavy ion beam acceleration with phase and amplitude tuning of RF cavities in VECC RIB facility

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An ISOL type radioactive ion beam (RIB) facility has been developed at VECC with the K130 cyclotron as the primary accelerator. After mass separation, the low energy 1.75 keV/u heavy ion beam is accelerated first in a 37.8 MHz radio frequency quadrupole (RFQ) linac to 100 keV/u. This is followed by three heavy-ion linac modules (L1- L3) for further acceleration of the beam to 415 keV/u. The final beam energy will be 1 MeV/u using another two linac modules (L4, L5). Apart from the accelerators, the beam-line comprises five rebunchers and several focusing as well as analyzing magnets installed in various sections. Currently, the entire beam-line upto L5 has been installed while the beam commissioning and acceleration has been carried out up to the exit of L3. In this paper, we report the operational experience with the accelerated beam and tuning of the RF cavities with amplitude and phase locked LLRF system developed in-house. The energy-phase scan of the individual accelerator modules has been carried out to ascertain the required RF power and subsequently the designed phase. The tuned parameters are in close agreement with beam dynamics calculations.

Optimization of Operating Parameters of ECR Proton Source in Pulsed Mode

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An electron cyclotron resonance (ECR) ion source operating at microwave frequency 2.45 GHz was designed and developed at RRCAT. The source was commissioned and operated in CW mode (magnetron - adjustable up to 2 kW). Ion beam current is extracted using three-electrode extraction geometry and is measured using 1.5 kW water cooled standard pneumatic controlled Faraday cup. Proton beam current up to 10 mA at 35 keV beam energy was extracted **[1,2]**. *This source has been modified and upgraded to operate in pulsed mode. For this, a RF source has been designed and developed indigenously based on solid state RF pulsed amplifier of 1 kW (peak power), 2.45 GHz, pulse width 1-5 ms, duty factor up to 10% and integrated with the ion source* **[3]**. *The RF power is fed through coaxial adapter to waveguide and coupled to plasma cavity via rectangular open ended waveguide (WR-284). The microwave power transfer line consists of isolator, directional coupler, triple stub tuner, microwave window and high voltage DC break. The directional coupler is used for the measurement of forward and reflected RF power. Three water cooled solenoid coils are used to produce magnetic field to meet the ECR resonance condition inside the plasma cavity. The hydrogen pulsed ECR plasma has been obtained by varying pulsed power from 10 W to 850 W, magnetic field configuration and hydrogen gas flow from 1 to 10 SCCM, to investigate the optimized operating condition. The reflected power behavior was also studied at the different operating parameters and minimized using triple stub tuner This paper presents the optimization of operating parameters of ECR proton source in pulsed mode for the extraction of pulsed proton beam current.*

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Characterization of a multi-cusp ECR plasma source for different power coupling schemes

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LEHIPA is a 20 MeV, Low Energy High Intensity Proton Accelerator with includes an ECR-Ion Source of 50 keV, RFQ (50 keV-3 MeV) and DTL (3 MeV-20 MeV) cavities. There have been further efforts to improve the ion source parameters by improving the different operational parameters of the ECR ion source. In view of this, a compact 2.45 GHz, 14-pole permanent magnet multi-cusp ECR plasma source is being developed in-house to study the microwave power coupling to ECR plasma source. Three different power coupling schemes have been studied. 1) The plane waveguide-based coupling; 2) the 4-step ridge waveguide-based coupling and 3) an optimized one step λ/4 ridge coupler scheme. The λ/4 ridge coupler has been able to improve the microwave coupling to the source thereby enhancing the electric field amplitude at the center of cylindrical resonator cavity operating at TE111 mode. A novel wave cut-off probe and Langmuir probe are indigenously developed for the plasma diagnosis. The plasma parameter measurements are done for analyzing the different power coupling schemes. The optimized λ/4 ridge coupler is found to improve the plasma density as compared to the other power coupling schemes. The details of the multicusp configuration for plasma confinement, plasma parameter measurements using Langmuir probe for different power coupling schemes will be presented.

Study of beam dynamics in a superimposed solenoid and dipole magnet

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In accelerators, several magnetic elements (such as quadrupoles, solenoids, dipoles etc) are used in beamlines for transporting a beam of charged particles. Solenoid magnets are most commonly used for focusing and matching in low energy beam transport lines of any accelerating systems. In a cylindrically symmetric system like solenoid magnet, a beam is influenced only by the uniform axial magnetic field and two hard-edge fields at both the ends. These fields provide simultaneous focusing in both the transverse planes and at the same time produce a rotation of the beam around the axis. The trajectory of a particle in a bending magnet or dipole is well known, it is used to bend the path of charged particles during beam transport. Usually the dipole magnet is placed symmetrically about the arc of the particle's path. The guide field inside a dipole magnet is uniform and the ideal motion of the particle is simply an arc of a circle. Superposition of a dipole field with the solenoidal field, makes the trajectory of the ions bend along the curved reference orbit determined by the dipole magnetic field. This combined function magnet with focusing can be used for beam focusing and bending simultaneously in a low energy beam transport system.

In the present work we have first obtained the paraxial ray equations of motion starting from the Hamiltonian in the combined fields of solenoid magnet and dipole magnet. Knowledge of transfer matrix is essential for studying beam dynamics. The transfer matrices of solenoid, dipole, quadrupole as well as combinations of those magnets are available in literature. Sometimes, it is desirable to get infinitesimal transfer matrix for beam dynamics and to study the space charge dominated beam transport. So, from these paraxial equations of motion we have obtained the infinitesimal transfer matrix of the combined system and at the same time we have also calculated the beam envelope as a function of path length through the magnet by employing the well-known sigma matrix method. We have made detailed study of the emittance evolution that results from the coupling between the two transverse planes for different input beam conditions. We have also discussed how the combined system can be utilized to focus as well as shifting of the beam in a low energy beam transport line. In addition, we have studied the feasibility of using this combined magnet in a solenoid based low energy beam injection line of a compact cyclotron to match the beam of circular cross-section to the input of a spiral inflector which requires well focused and centred beam in the transverse planes for optimum transmission of the beam.

Proposed closed orbit correction scheme for indus-1 storage ring

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Indus-1 synchrotron radiation source is a 450 MeV, 125 mA electron storage ring, emitting synchrotron radiation from mid-IR to soft X-rays with a critical wavelength of ~ 61 A°, is operational at RRCAT. Its injector system consists of a 20 MeV Microtron as a pre-injector and of a 450 MeV Booster Synchrotron as an injector, which provides the electron beam for injection into the Indus-1 storage ring. Present closed orbit correction scheme consists of four beam position indicators (BPIs), and 7 correctors for the horizontal plane (out of seven correctors, 4 correctors are integrated on dipole magnets) and 3 correctors for the vertical plane [1]. Simulation results indicate that present closed orbit correction scheme shows poor closed orbit correction at BPIs in vertical plane and at the dipole centre in both planes. In view of this, two closed orbit correction schemes are proposed with different configuration of BPIs and correctors in terms of their location and numbers. Simulation studied are carried out for correction efficiency for both the schemes considering various quadrupoles and dipoles alignment error sets, and maximum corrector strengths required for correction are evaluated. Based on the simulation studies, a scheme in which 8 correctors in horizontal and vertical planes (CHVs) integrated on sextupoles, and 8 BPIs four at old locations and four at new proposed locations, is finalized. Simulation results indicate that the proposed closed orbit correction scheme is efficient to control the closed orbit at all BPIs and at the dipole magnet positions, from which the beamlines are connected to tap the photons. In this paper, results of the simulation studies are presented for existing and proposed closed orbit correction schemes for Indus-1 storage ring.

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Preliminary simulation studies on closed orbit correction in HBSRS storage ring

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A high brilliance synchrotron radiation source (HBSRS) based on electron storage ring is proposed at RRCAT, Indore, India which will be a 6 GeV and kilometer scale machine [1]. The lattice of HBSRS storage ring is designed based on hybrid seven-bend-achromat concept, which has very strong focusing quadrupoles and a relatively smaller vacuum chamber. The HBSRS storage ring consists of a large number of magnetic elements such as dipoles, quadrupoles, octupoles etc., distributed all over the ring. In a practical storage ring, several errors such as magnet-to-magnet field errors, calibration errors in power supplies, alignment errors in placing magnetic elements etc are expected. As a part of error analysis, reported literature indicate that tolerable alignment errors in such machines are very small (~10-15 μm) which is difficult to achieve with present technology [2,3]. Therefore, there is a need for relaxing the tolerable alignment errors to 60-100 μm, in the magnets [3,4]. However, with such relaxed errors, beam injection and beam accumulation may become very difficult. Even in some cases, first turn beam circulation will not be possible, and therefore commissioning is expected to be a significantly challenging task [4]. To keep the commissioning period as short as possible, it is necessary to understand how realistic errors will affect the machine operation. The initial tasks during commissioning of a storage ring include: a) to achieve first turn beam circulation, b) establish closed orbit and c) to carry out the required orbit corrections. Preliminary studies on first turn beam circulation in HBSRS has been reported by V. K. Meena et al. [5]. Thus, in this paper, we present a detailed simulated commissioning studies to achieve both first turn beam circulation and closed orbit correction in presence of various errors. To carry out simulation studies, we have used a simulation-commissioning package, which consists of high-level scripts written in MATLAB [6]. In the HBSRS storage ring, for measurement of beam trajectory/closed orbit 320 beam position monitors (BPMs) and for its correction, 320 combined function dipole correctors are assumed. The first turn beam circulation is achieved by correcting the trajectory of the beam which is injected on-axis. After achieving first turn beam circulation, the trajectory in horizontal as well as vertical plane is found to be within ~1.5 mm. In addition, the rms values of corrector strengths are less than 30 μrad in both the transverse planes. The multi-turn pass in linear lattice is achieved by matching the co-ordinates of centroid of beam at first few BPMs in second turn with coordinates of centroid with first turn at the same BPMs using two-turn response matrix. Further, the sextupoles and octupoles are switched on in a ramped manner and correction is performed to achieve multi-turn pass. By switching on the RF cavity, beam can survive for a longer time and the measurement of closed orbit become possible. After performing pseudo beam-based alignment to reduce the offsets in BPMs to 50 μm level, the closed orbit is further corrected down to 140 μm rms from an uncorrected value of ~300 μm rms in both horizontal and vertical planes. The resulting rms corrector strengths are less than 130 μrad in both the transverse planes.

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Design and development of unipotential Electrostatic focusing element for heavy metal ion beam isotopes

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A magnetron sputtering based ion source has been developed for concentrating isotopes of medical significance on the principle of electromagnetic separation of momenta. The ion optics of high-current beams is as critical as a high current ion source for efficient beam transmission up to the ion beam collector. Thermal velocity distribution, convex plasma meniscus and space charge forces cause divergent ion beams. Beam focusing at the exit of ion source is important to increase the beam transmission and decrease the loss at the entry slit. A divergent ion beam can be focused either by magnetic viz. solenoid or electrostatic focusing elements. Electrostatic lens are widely used in charged particle optics in lower energy region, where they are more effective than magnetic lenses. Magnetic elements focusing properties depend on mass to charge ratio and energy of ion beam but electrostatic elements focusing depend on energy of ion beam and independent of mass of beam.The exciting features of these lenses, such as their small size, relatively low power consumption, fast response times, and fabrication simplicity have made them suitable choices for many applications in low energy region. A unipotential electrostatic element (Einzel lens) is used for effective radial focusing of Lutetium ion beam. The einzel lens is a variant of the immersion lens often encountered in low-energy electron guns. It consists of three colinear tubes, with the middle tube elevated to high potential. The einzel lens consists of two immersion lenses in series. An Indigenous electrostatic element for high current ion source for Electromagnetic Isotope separation experimental facility is designed with SIMION and CST particle studio code. Various geometrical design parameters, focusing properties and fabrication for proper alignment of three coaxial hollow cylindrical lens are discussed in this paper.

The optimized geometry was selected for development. The effects of different particle beam parameters such as initial size and energy distribution on the performance of the proposed lenses are investigated. Einzel lens for ~1mA of extracted current o Heavy ion beam was designed, developed and installed in the beam line and its operational parameters were measured. This paper presents the design, construction, and characterization of the Einzel lens.

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Physics design of MEHIPA LEBT for 30 keV proton beam

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The Medium Energy High Intensity Proton Accelerator (MEHIPA) is proposed to be built at BARC Facility, Vizag. MEHIPA will be a 40 MeV, 10 mA, superconducting accelerator, with a 10 MeV normal conducting front-end. Based on experimental observations, for an improved beam quality especially in-terms of beam emittance, the energy of the ECR ion source is reduced to 30 keV from earlier 50 keV. Accordingly, the first accelerating structure, RFQ has been redesigned for an input beam energy of 30 keV. The Low Energy Beam Transport (LEBT) channel for transporting and matching the 30 keV, 10 mA CW proton beam having transverse emittance 0.2 $\pi . mm - mrad$*, from the ECR ion source to the RFQ has therefore been re-optimized. In order to reject the molecular ions like* H_2^+*,* H_3^+ *from the ion source and to keep the option of dual ion source for redundancy, a conceptual design of the LEBT, consisting of a bending magnet has been proposed. The LEBT design consists of three solenoids and four drift sections in between the solenoids. Compact solenoid of physical length 142 mm with field maps obtained from magnet designs have been used in the simulations. The first solenoid is placed just after the ion source to limit transverse size of the beam and the other two solenoids are used for the matching and focusing of the beam in the LEBT. The beam injection into the RFQ with minimum transverse emittance is achieved by optimising the magnetic fields of the three solenoids and the drift spaces between these solenoids. The drift spaces are optimised such that beam steering magnets and the beam diagnostics can be included. The optimisation of the LEBT design is done by iterative method where initially, the magnetic field of the last two solenoids are tuned for minimum emittance with a fixed field in the first solenoid. Beam dynamics of the LEBT has been done to ensure the transportation and matching of the realistic phase-space ellipses, obtained from the ion source simulations, to the RFQ. The various simulation results of the MEHIPA LEBT design will be presented.*

Analytical calculation of pole profile for combined function magnets with Enge-type fringe field

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Non-Scaling Fixed Field Alternating Gradient (FFAG) based achromatic bending section for transporting multiple charged state ion beams has been optimized using ZGOUBI code. The beam radius after the bend is around 5 mm at the target location for input beam of momentum spread of around ±16 % about mean energy of 6 MeV/u. The combined function FFAG magnets are having components up to octupole and the Enge-type fringe field for additional vertical focusing. The optimization of these magnets has been done in ZGOUBI. Subsequently, the pole profile has been analytically formulated to achieve the optimized coefficients of multipoles and the Enge coefficients. The details of the design are discussed and the design of the magnet with the achieved pole profile has also been studied using a 3D magnet code.

A multi electrode system for deceleration of 1^+ ions entering a Charge breeder source

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A charge breeder is being developed for the production of multiple charge state radioactive Ion Beams (RIB). It consists two ECR ion sources (ECRIS) in tandem. Radioactive recoils produced by the action of primary beam from k130 cyclotron on suitable targets are first transported to a 2.45 GHz ECRIS [1] by Gas Jet Recoil Transport (GJRT) method. Because of high dynamic gas load on this source, it mainly produces 1^+ ions which are then charge bred after injection into a 6.4 GHz ECRIS after sufficient deceleration, for the production on n^+ RIB. The 6.4 GHz ECRIS has been operational at the facility for many years whereas the 2.45 GHz ECRIS has been commissioned and tested for the online production of RIB recently [2]. This paper discusses the beam optics optimizations of injection of the 1^+ beam from the first ion source into the breeder source after the required deceleration.

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The injection of the 1^+ beam into the breeder source and their capture is a critical part of the charge breeder scheme. For efficient capture, the energy of the incoming 1^+ beam should be little higher than the plasma potential of the breeder source. Since plasma potential of such sources are known to be in the range of few tens of eV, focusing optics needs to be carefully tuned to avoid beam loss because of emittance growth at such low energies. To calculate the design goal of final 1^+ beam energy entering breeder plasma, a Langmuir probe was developed and used to find out the breeder source plasma potential. These measurements dictated the final energy of the 1^+ beam after passing through a 26 mm aperture at the entrance of the breeder source to be in the range of 25 – 35 eV for efficient capture of the beam. Two types of deceleration systems have been studied for this purpose. The first one is a multi-electrode deceleration comprising of three electrodes preceding the 6.4 GHz source for gradual deceleration and focusing of the beam. The second configuration studied is the conventional grounded electrode decelerator preceding the breeder source. The final beam parameters at the edge of theoretical plasma zone of breeder source have been studied for both the cases. From the obtained parameters, the capture efficiency of the 1^+ beam by the breeder plasma has been calculated for the two cases using an in-house developed code based on Monte Carlo simulations [3]. The details of the deceleration optics simulation of the incoming beam as well as the results of capture efficiency for the two cases will be presented.

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Analogy of particle-core model with a variable-length nonlinear pendulum

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High intensity accelerators have variety of applications like in ADS, SNS, RIB and so on. For such accelerators, even a small percentage of the beam, when lost, can deposit significant amount of beam power which can lead to activation/damage of the beam line. In order to allow hands-on maintenance of the accelerator, average beam loss in the linac, for beam energies above 100 MeV should not exceed 1 W/m. Therefore, it becomes crucial to understand themechanism of beam halo formation, which isa major cause for beam losses in such accelerators. Beam halo is a loosely defined low-density distribution of particles with large oscillation amplitudes, which can reach the beam line aperture dimensions, thus creating uncontrolled beam loss. The particle-core model is a simple means to study the halo formation. In this model, a bunch of beam particles is treated as a "blob" of charge (beam core) with distinct boundaries, which then interacts with a single particle crossing the core, where the oscillations of the beam core drive the single particle oscillation.In this paper, an analogy of the particle core model has been made with a variable-length pendulum. For this, the non-linear equation of the pendulum oscillation has been solved, considering a sinusoidal variation of the pendulum length with time.Sinusoidal oscillation of thelength with time excites higher order resonances in the pendulum oscillations in theta with time. It has been observed that the amplitude oscillation becomes most signification for 2:1 resonance. This is very similar to the 2:1 parametric resonance which is responsible for the halo formation in the particle-core model. Further, this simple variable-length pendulum is compared with the particle-core model analysis for a uniform focusing channel. Poincare map technique has been used to understand the resonance observed in both the cases. For the particle-core model studies, a mismatch has been introduced to excite the core oscillations, which further drives the single particle oscillation and if 2:1 parametric resonance gets excited, the single particle leads to the halo formation.

Study of bifurcations in beam envelope trajectories due to nonlinear perturbations

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In intense particle beams propagating through a periodic focusing channel, the space-charge force can induce nonlinear resonances and chaotic behaviour of the envelope. The strength of the nonlinearity depends on the beam current. As it increases, the stable trajectories bifurcate and gradually turn chaotic. Correlation between vacuum phase advance and envelope instability is well known. In the predicted regions of instability, different bifurcations of trajectories and transition to chaotic behavior is expected. The stable trajectories undergo period doubling with increase in the (nonlinear) perturbation. This leads to stochasticity as the separatrices merge.

The properties of the bifurcation are studied using bifurcation diagrams and Poincare surface of section plots. The nonlinear resonances, classified in terms of vacuum phase advance and beam perveance, are correlated to regions of unstable envelope oscillations. The bifurcation of matched envelope trajectory is seen to be correlated with the unstable vacuum phase advance condition of 90 degrees. The bifurcations of the trajectories lie in the region of the envelope instability stop band. Thus, the envelope stability is linked with the bifurcation of its trajectories and rise of resonant islands.

The nonlinearity of space charge forces causes particles to have resonant trajectories even for matched envelope beams. The fourth order resonance of particles is also excited in the envelope instability region. Higher order resonant islands are seen to grow more rapidly for a Gaussian distribution compared to a uniform one.

The particles evolving under resonant envelope conditions can be transported to large distances and can form a halo around the core. These effects are more prominent for Gaussian distributions due to its larger nonlinearity than uniform distribution. The particles trapped at large distances from the center are seen to undergo resonances other than the prominent 1:2 parametric resonance. Nonlinearity is a major destabilizing force for high intensity beams along with a mismatched envelope. These effects are shown to cause beam emittance growth along the channel.

Understanding the RF coupling, beam loading and wake field in accelerator physics

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Beam Loading and RF coupling are important topics in accelerator physics, which are inter-related, and typically explained in the text-books, using the circuit theory approach [1]. Interestingly, another approach based directly on Maxwell equations, was proposed by the famous physicist Condon (of "Frank-Condon principle" fame!), way back in 1940 [2]! Unfortunately, this approach did not find much place in the text-books, and it appeared in few references only [3]. In this paper, I will show that by further refinement and extension of the Condon approach, it becomes very useful for transparent, and hence, easy and clear understanding of beam loading, RF coupling, space charge and wakefield. The total electromagnetic field in the cavity can be expressed as a sum of a linear combination of empty cavity modes or cavity electromagnetic modes (EM) modes, plus a sum of linear combination of space charge modes [3]. In this approach, evolution of an EM mode supported by the cavity is analyzed, using Maxwell equations, where the driving current comes from the current excited in the coupling loop or iris (as the case may be) by the RF generator, and also from the beam current; and the current flowing on the cavity surface gives rise to damping of the mode. Equations are written for the case of loop coupling, and are generalized to include the iris coupling too. The space charge mode is driven by the beam charge density, and the boundary conditions, which takes care of image charge. After setting up of Maxwell equation, it is clearly seen that the equation for evolution of EM modes is in the form of a damped driven harmonic oscillator, for which an equivalent circuit model can be constructed. Using this model, transient as well as steady state solutions can be obtained. Following this approach, simple derivation of some useful beam loading and RF coupling formulas, which are needed during various design calculations, will be presented for the most general case of off-resonant excitation. The concept of optimum coupling coefficient (β_{opt}) and optimal cavity detuning (δ_{opt}) for maximum power transfer to beam is elaborated for the most general case. It is clearly shown that in principle, RF generator and beam can excite multiple EM modes in the cavity. Using this approach, as a special case, a formula for cavity voltage in fundamental and higher order mode (HOM) excited by a single charge particle passing through the cavity is obtained, which is similar to the famous Wilson formula [4]. Connection of the fundamental and HOMs excited by a charge particle to the concept of wakefield and impedances [1] is elaborated in the paper. Although most of the formulas derived in the paper are there in the text-books, the paper gives a fresh and easy insight of the basic concepts involved.

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Simulation of Transverse Single Bunch Instabilities in HBSRS Booster synchrotron

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There is a proposal to design a booster synchrotron as a pre injector for top up injection of energy 6 GeV in a High Brilliance Synchrotron Radiation Storage ring. In booster synchrotron, the energy of the beam coming from LINAC will be ramped from injection energy of 200 MeV to 6 GeV. At injection energy, in booster synchrotron, even at lower stored current in a bunch, the motion of electrons may become unstable due to the transverse single bunch instabilities. In this work, simulation studies are carried out to find the effect of transverse single bunch instabilities on beam motion in booster synchrotron. We have considered the resistive wall impedance as an input impedance in our simulation study as in low aperture ring, it is one of the major contributor to the transverse impedance. The resistive wall impedance of the booster synchrotron is evaluated by analytical formula [1] considering the vacuum chamber radius varying from 13mm to 18mm at different locations in the ring. In simulation, the linear one turn transfer map is extracted from the booster synchrotron lattice. It is represented by the ILMATRIX element in Elegant code [2]. Particle tracking is carried out with the ILMATRIX element to find the effect of transverse instabilities on beam centroid motion and also on beam emittance in both the transverse planes. Particle tracking is also carried out considering different positive chromaticities to control the effect of transverse single bunch instabilities on beam motion. The effects of lattice nonlinearities on instabilities are also studied after including the nonlinearities in the one turn transfer map [3]. The nonlinear terms include the second order momentum compaction factor, first and second order amplitude dependent tune shifts, first and second order amplitude dependent path length difference, and the second and third order chromaticities. The corresponding simulation results are analyzed and presented in the paper. As the beam energy ramping starts in booster synchrotron, the radiation damping becomes strong, therefore, a simulation is also carried out to study how the ramping process influences the beam centroid motion as well as the emittance, in presence of resistive wall impedance.

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Coherent and Incoherent Space Charge Resonances in a Drift Tube Linac

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In recent years, there has been a lot of interest in the development of high intensity proton accelerators for applications like Accelerator Driven Systems (ADS), Spallation Neutron Sources (SNS), Radioactive Ion Beam (RIB) production, Neutrino factories etc. These accelerators are required to operate at high beam currents of the order of milli-amperes for the various applications. At these currents, the non-linear space charge forces are very high and can lead to increase in beam emittance and formation of beam halos. The main design goal in high intensity accelerators in order to allow hands on maintenance is to minimize the beam loss by avoiding or minimizing contributions of various halo forming mechanisms. Among the various mechanisms for beam loss, there are two main mechanisms which can cause significant halo formation: Incoherent and coherent effects due to the nonlinear space charge forces of the high intensity beam. These can lead to beam degradation causing increase in beam size, beam emittance and halo formation. In this paper, we study these effects on the beam through a Drift Tube Linac (DTL) that accelerates proton beam from 3 MeV to 40 MeV. The coherent effects represent the collective behaviour of the beam as a whole. These are excited by beam mismatch and can lead to resonances and instabilities of the beam envelope. The incoherent effects, on the other hand, represent the single particle behaviour of the beam and can be seen as single particle resonances. The single particle resonances are excited when the resonance condition $mk_{xy} = 360°$ *is satisfied. Here, m is the order of the resonance and* k_{xy} *is the single particle phase advance per focusing lattice period. The incoherent effects are excited even in the absence of beam mismatch. Studies are done with uniform and Gaussian beams to study these effects and their effect on beam emittance growth and halo formation. The transverse phase advance per period in the DTL is varied from 60 degrees to 130 degrees for a fixed beam current and the effect on beam emittance is seen. We see emittance growth at around 60 degrees, 90 degrees and 120 degrees. On careful analysis, we see that the increase in beam emittances is associated with the* 6^{th} *order,* 4^{th} *order and* 3^{rd} *order single particle resonances respectively. The coherent effects are studied by introducing an initial mismatch in the beam for different values of phase advances per period. These resonances are identified by seeing the evolution of the beam trajectory and the beam in transverse phase spaces.*

A review of calculation of emittance growth for some common cases in accelerator physics

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Emittance is one of the crucial parameters in charged particle beam dynamics. Fundamentally, emittance is defined as the area/volume occupied by the beam in phase space, and physical picture given by this definition is very useful, while visualizing its evolution. In addition to the phase space definition, the concept of rms emittance is also defined, which is more useful for mathematical analysis. Since the phase space of a charge particle will in general be six-dimensional (6D), one can define the emiitance either in a 6D, or its projection on four-dimensional (4D) volume, or two-dimensional (2D) plane, which is known as the projected emittance. This is applicable to the phase space picture, as well as, to the rms concept. The transverse and longitudinal emittances are thus defined, and in the more general case, where the charge particle undergoes acceleration, the normalized emittance is introduced. One of the key concerns, while designing an accelerator, or a particle source such as electron gun or ion source, is to control the growth of emittance. Although the phenomenon of emittance growth is complex in nature, approximate formulas for quantifying the growth in rms emittance can be derived for some cases [1-2]. In this paper, we present a review of such calculations, and present simple derivations of formulas for growth of rms emittance, starting from the scratch, for a wide variety of cases. Growth in rms emittance is generally attributed to nonlinear forces. We show that that a more prominent reason for emittance growth is the coupling of motion in different directions, which is practically always present in case of nonlinear forces. This can be explicitly seen for space charge forces of an axisymmetric beam and ideal sextupole and higher multipole fields in accelerator magnets. For these cases, in the phase space picture, it is very easy to visualize the emittance growth due to coupling in motion in different directions. Emittance growth is expected to occur in a skew quadrupole (where the forces are linear) due to coupling. Skew quadrupole can however be visualized as a normal quadrupole, by rotating the coordinate axes by 45°, and in which case, no growth should occur in rms emittance. This seemingly counterintuitive result is explained in the paper by analyzing the beam envelope. Formulas are then derived for other cases, where forces are still linear, such as for beam transport in an ideal solenoid and an ideal RF cavity [3]. Under thin lens approximation, formulas are derived for the cases with nonlinear forces, such as beam transport through sextupoles, octupoles etc., and also due to nonlinear space charge forces. Finally, approximate formulas are also derived for the emittance growth due to field errors in magnets [4]. Such formulas are quite useful for estimating the estimating the emittance and controlling the growth while designing an accelerator.

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Four Dimensional Transverse Phase Space Reconstruction Technique using multiple 2D Profiles

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A Python based algorithm has been developed for characterizing the four dimensional (4D) transverse phase space of a complete beam ellipsoid. The main advantage of this method is that it does not require a priori information regarding the nature of distribution of the initial beam or coupling introduced by intermediate beam line elements such as solenoids or skew quadrupoles. Compared to other indirect 4D phase space measurement techniques, it is computationally faster. Further, tagging with a particle in cell (PIC) code, for example, the General Particle Tracker, (GPT), makes the reconstruction method independent of beam intensity as opposed to any transport matrix based formalism. In this paper, we discuss the algorithm and results of the 4D reconstruction technique.

Particle-in-Cell Simulation Studies of Rod Pinch Diode at 250 – 500 kV Voltages

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Flash X-ray (FXR) [1] sources for dynamic radiography operate in different electron beam diode geometries depending on the applied voltage and impedance of the pulse power systems driving them. For energies from few hundreds of keV, industrial FXR diode geometry is generally used. This configuration is similar to Rod Pinch (RP) diodes but they operate in the space charge limited (SCL) region at lower voltages. The X-ray source size axial spread will be more compared to an RP diode where the current is magnetically limited (ML). The FXR source figure of merit (FoM) is inversely proportional to the square of its size and it is feasible to attain electron beam pinching even at lower voltages by increasing the cathode emission length [2]. Three dimensional Particle-in-Cell simulation studies were carried out to evaluate the I-V characteristics of the RP diode at voltage levels 250 – 500 kV by varying the diode gap parameters like anode extension length and separation between multidisc cathode to check the feasibility of beam pinching and subsequent improvement of the FoM. For compact portable FXR sources in the voltage range of 300 -550 kV, further improvement in FoM is realizable if a double disc cathode RP diode is implemented.

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Beam Characterization of 2856 MHz Reentrant Single Cell Pre-Buncher RF Cavity

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A 10 MeV, 3kW RF electron linac is in operation at EBC, Kharghar. It has been planned to develop a new horizontal linac rated for 10 MeV, 5 kW at EBC, Kharghar. The components of 10 MeV linac beam line are electron gun, a standing wave (SW) single cell pre-buncher cavity and a SW main linac cavity of length 0.9 m. In order to enhance the beam capture efficiency and to reduce the energy spread a pre-buncher cavity along with focusing elements is introduced between the electron gun and the main linac cavity. This paper presents the design, fabrication, RF measurements and beam experiments of the 2856 MHz pre-buncher cavity **[1,2].** Pre-buncher cavity is designed at 2856 MHz having loaded quality factor of 600. Beam dynamics simulation with pre-buncher cavity shows that the transmission is increased to 67% from 25% **[3].**

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Stress linearization for MEHIPA superconducting spoke resonator SSR-B

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*Phase 1 of the Medium Energy High Intensity Proton Accelerator (MEHIPA-1), is a high current 40 MeV proton accelerator, being proposed in India. It will use single spoke resonator, SSR-B, cavities for the energy range 10-40 MeV. Superconducting cavities are made of high grade Niobium (RRR>300) sheets and are surrounded by Titanium made helium jacket. For cryogenic operations, liquid helium is filled into space enclosed between Niobium cavity and Titanium jacket. Niobium sheet cavity is subjected up to 2 bar pressure at room temperature during liquid helium filling and up to 4 bar of pressure at 2K temperature during cryogenic operation. Preliminary FEA linear elastic analysis result **[1]** shows that at 2 bar pressure and room temperature, equivalent stresses are higher due to superior mechanical properties at 2K that at room temperature and their value breach yield strength at few isolated points.*

*In order to limit maximum equivalent stresses, cavity material thickness can be increased or more stiffeners can be added. However, cavity thickness has an upper limit due to tuning range of cavity and material cost. Therefore, there is need to switch to failure criteria which is more accurate than von-Mises yield criteria, which is very often conservative, to make design optimum and safe. To investigate possibility of local failure, linear elastic analysis result is post processed through stress linearization technique which provides alternate method to qualify complex state of stress without involvement of plasticity model. Stresses have been separated into components of membrane, bending and peak stresses, which are basically average, linearly varying and remaining component of stress respectively normal to a line called stress classification line (SCL). Niobium thickness and stiffener design have been varied to minimize highest equivalent stress and subsequently, linearized stresses along SCL at those locations have been found within allowable limits as prescribed by ASME Annex 5.A of Section VIII, Division II. The paper presents the basic procedure of analysis and discussion of result which forms basis of the SSR-B cavity prototype development. Results gives better understanding of margin of failure in the design over linear elastic analysis done earlier **[1]**, using triaxial limit criteria.*

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Characterisation of the effect of unbalancing coil on the developed ion source

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The effect of the unbalancing coil (UBC) on the indigenously developed magnetron sputtering based ion source was characterised by Langmuir probe and optical emission spectroscopy. In the balanced magnetron sputtering the magnetic field lines of magnetron confine plasma near the target. The introduction of the unbalancing coil distorts the magnetic field lines of traditional magnetron and form a closed trap for electrons between the unbalancing coil and magnetron which decrease the transverse field component. This limiting transverse mobility of electron leads to the extension of plasma volume along the axial direction [1]. The extension of plasma results in enhancement of the extracted current and also an improvement in ion to neutral atom ratio [2]. The plasma comprising of inert gas and sputtered metallic ions was ignited using glow discharge method and critical plasma characteristics of interest such as electron temperature, Debye length, electron density and ion density were mapped in the plasma volume and their dependence with discharge parameters were analysed in depth. Optimal magnetic field for extending the plasma for obtaining enhanced ion density was measured and ionisation states beyond first ionisation were not detected in the measured emission spectrum of the plasma. The absence of the higher ionisation states and an increased ion to atom ratio will result in an increased extracted ion current per sputtering target which will increase the efficiency of the developed ion source. The introduction of the UBC resulted in an increase in ion density in the vicinity of the probe which indicate increase in the plasma volume.

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Design, Development and Characterization of three electrode ion beam extraction system for Magnetron Sputtering Ion Source

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Ion extraction systems are crucial beam handling component for ion beam formation at the exit of an ion source. It determines the beam properties such as ion current and beam quality. Primary requirement of an ion extraction system is to optimize the beam focusing for desired beam current and energy with low emittance and high perveance. Electrode shaping and design optimization shall focus on maximizing the number of ions extracted with low divergence and minimize the losses on various electrodes to enhance the electrical efficiency and lengthen the lifetime of the electrodes. In the case of space-charge-limited surface-emitted electrons, there is a perfect solution (Pierce Geometry [1]) for providing a parallel electron beam accelerated from the cathode. However, for the plasma ion sources it does not provide a perfect solution, as the ions do not start from a fixed surface, but from plasma with varying starting conditions.

A three-electrode extraction system is designed for extraction of Lutetium ion beam at the exit of a magnetically confined ion source for electromagnetic isotope separation experimental facility. Optimization parameters like separation between electrodes and the aperture diameter of extraction and screening electrode were investigated in addition to influence of space charge on beam quality. Numerical analysis of electrodes was done in SIMION software to optimize geometrical parameters to maximize beam current while minimizing the divergence of beam. Trajectory simulations were performed for charged particle dynamics. Formation and shape of plasma meniscus near extraction electrode aperture is discussed. Plasma meniscus serves as a source of ions, therefore factors affecting its shape such as argon flow rate and ion source pressure are investigated. Interaction of ion emission current density and space charge limited current density is mainly responsible to determine the shape of plasma meniscus [2]. For different shapes of plasma meniscus e.g., concave, convex and flat, beam trajectory was estimated using numerical simulations. Beam size and divergence were also assessed. Triode extraction system with features for precise alignment was developed as alignment of the electrodes is a key parameter for performance of the extraction system. Thermal management of the extraction system has been incorporated in the design to limit the rise of the operating temperature of the electrodes resulting in increased lifetime. The developed extraction system is integrated with the beam line of electromagnetic Isotope separator. High Voltage conditioning of electrodes was done to obtain stable operation of extraction system. Beam parameters are determined using wire scan method. Experimental results are summarized and analyzed.

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Design of Three-electrode Beam Extraction System for ECR Ion Source using IBSimu code

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Three-electrode extraction system has been simulated using IBSimu ion optical code for ECR Ion Source (IS). Previously, the ion source for LEHIPA was designed for 50 keV beam energy. But various experimental studies have shown that the emittance of the extracted beam is minimum when the extraction voltage is around 30 kV. The MEHIPA linac has been designed for an input beam energy of 30 keV. It requires an ECR IS extraction system, which will provide 30keV, 10mA proton beam. Moreover, the experimentally measured values of beam emittance in our ECR Ion Source is found to be higher in compared to its estimated values from simulation. To understand the discrepancies between simulation and experimentally measured values of emittance, a simulation study of the beam extraction is necessary. Accurately predicting the behaviour of extracted proton beam from the ECRIS is important, both for estimation of beam transport through subsequent lattices as well as high current operation of the linac. Here, we present the preliminary simulation results of the ion beam extraction, which was performed using the ion optical code IBSimu. The shape of the electrodes has been kept same as that of the existing LEHIPA IS. For simulation the best values of mesh sizes and iteration number have been obtained. Simulation has been done up to 250mm distance from the exit hole of the plasma electrode. Beam emittance and Twiss parameters of the rms ellipse are calculated at various locations. Different parameters of the extraction system such as extraction gap (distance between plasma and puller electrode), suppressor voltage, electrodes aperture, extraction voltage has been optimized to get minimum rms emittance at 200 mm distance from the exit hole of the plasma electrode. The extraction gap has been changed in the range of 16-30 mm; it is seen that the emittance is minimum at 25 mm extraction gap. The extraction voltage is varied from 20 kV to 50 kV, and minimum emittance is found at 30 kV of extraction voltage, which is in compliance with various experimental results. The dependence of emitted beam on the suppressor voltage has also been tested. It is found that, though the emittance has almost no dependence on suppressor voltage, the angular divergence increases slightly as the voltage is varied from 2 to 4 kV. Additionally, in simulation a huge beam loss is observed after 400mm distance from the plasma electrode.

Beam dynamics simulation of 300 keV RF modulated gridded triode electron gun

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Superconducting resonant cavity based high average current electron injector systems are required for the photo fission process to produce radioactive ion beams. The injector system requires a 300 kV, 10 mA electron gun to emit and accelerate beam up to β value necessary for the optimal capture and acceleration in the superconducting cavity section. A thermionic gridded cathode is an ideal candidate for such electron gun since beam bunching as well as current modulation can be achieved by feeding RF power at the grid of the cathode. In this work we present design and beam dynamics simulation of 300 kV electron gun with grid modulation at 650 MHz RF frequency. Analytical and numerical simulations were carried out to design a 300 keV electron gun. The gun geometry was optimized using "CST particle studio". For beam dynamics simulation, PIC code "GPT" was used to determine the bunch length, beam emittance and other beam parameters at the gun exit.

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Optimization of Electron Beam Deflection using Particle Tracing Mechanism

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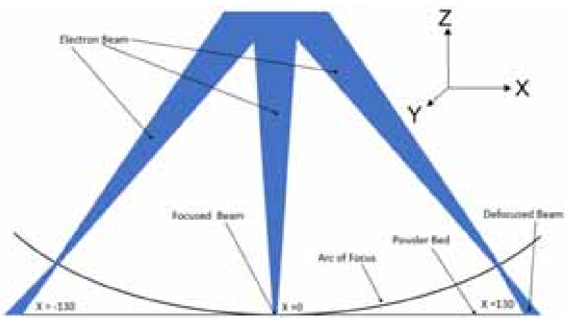
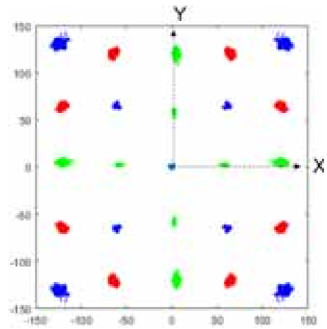
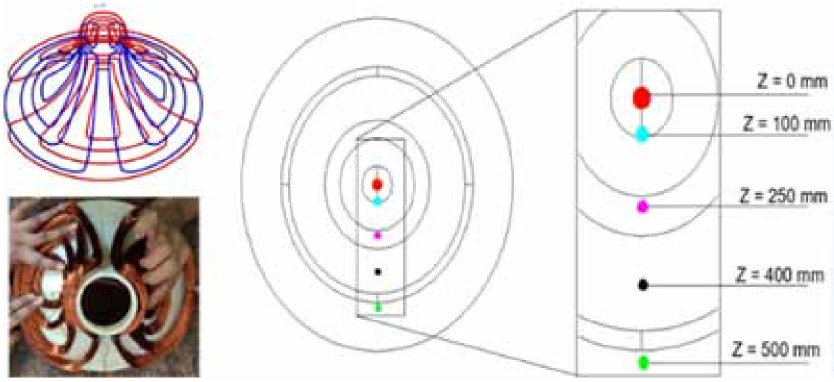
Electron Beam (EB) is a bunch of negatively charged particles moving together. EB can be accelerated to a higher velocity (Up to 0.7x speed of light) by applying acceleration voltage. This high-Velocity EB can be used for several applications, such as manufacturing, medical, metrology, electronics, etc. According to the type of applications, The EB can be used for scanning, melting, heating, microstructure analysis, surface treatments, medical treatments, lithography, etc. Electron Beam Additive Manufacturing (EBAM) is an emerging technology for creating complex and precise metal parts for direct end use. In the powder-based EBAM process, a high-speed EB is used to scan and melt powder particles and deposit them using various motion systems. To Control the part accuracy and built quality, the EB has to deflect over the powder bed precisely to scan and melt the powder. This positioning and shaping of EB are achieved through a magnetic field system. Precise deflection of EB is challenging because of the interfering magnetic fields, which cause aberration. Also, Beam gets defocused when the EB moves away from its axis. Figure 1a shows the mechanism of defocusing. Both the above reason results in distorted and larger EB. Figure 1b shows the shape and size of the EB at different locations of the bed. Here different colors have been used to differentiate the various angular zones of the bed, such as green for 0^0 & 90^0 locations, blue for 45^0, and red for 22.5^0 & 67.5^0. Therefore, the EB should be traced very accurately for the precise functioning of the powder-based EBAM system.



(a) Defocusing mechanism of EB



(b) Different shapes and sizes of EB at various locations of the bed



(c) Modified deflectuion coil and its optimized results

Figure 1: Particle tracing results obtained using COMSOL Multiphysics

In this work, a detailed study has been carried out to trace the path of the electrons for optimization of the shape and size of the EB. Simulation has been performed using COMSOL Multiphysics to analyze the EB trajectory along equally spaced planes perpendicular to the direction of motion of electrons. The two approaches have been used for tracing the path of the EB. In the first approach, ten equally spaced electrons have been released vertically downward from the periphery of a circle of 1mm diameter. In the second approach, 500 converging electrons have been released from a circular face with diameter of 2.2mm. Various magnetic coils with proper current and potential values have been used for required beam deflection. Based on the simulation output and literature study available on the deflection yoke of CRT [1-3], a unique saddle-type deflection coil has been designed to deflect the beam by $\pm 15^0$ from the axis accurately. Also, instead of a single winding, discrete winding is preferred as the deflection of the EB is subjected to the shape of the coil, and there has to be a varying magnetic field to encounter the electrons at various locations. Two pairs of coils have been used for deflection in X and Y directions, with each coil consists of 4 discrete subsections connected in series. The shape and size of the coil have been optimized using an iterative approach to avoid beam drift and defocusing issues. Figure 1c shows the designed and fabricated deflection coil as per the simulation results (left side) and the shape of the EB at different heights during deflection.

Keywords: Electron Beam, Particle tracing, Electron Beam Additive Manufacturing (EBAM), Beam Deflection.

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Thermal Characteristics and Frequency Tuning Methodology for 325 MHz RFQ structure

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Abstract

RRCAT is involved in the development of a 3 MeV, 325 MHz Radio Frequency Quadrupole (RFQ) structure as a part of front end for high energy proton accelerator. During operation, Radio Frequency (RF) induced heating in the RFQ results in temperature rise, deformations and subsequent frequency shift from designed value. A water cooling scheme is designed to take away RF heat from RFQ structure. Beside heat removal, cooling water will also be used to tune the cavity frequency close to the designed value. Detailed three dimensional multi-physics finite element analyses of RFQ structure have been carried for various duty factors. Parametric studies are performed to investigate the effect of cooling water temperatures on RFQ frequency. Based on thermal characteristics of RFQ, the cooling water temperatures will be adjusted to achieve the designed frequency during steady state operation. Results of numerical studies and frequency tuning methodology for RFQ is presented in the paper.

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Design and Development of PLC Based RF Cavity Tuner System for 31.6MHz RF Cavities in Indus complex

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At RRCAT, Indus-1 and Indus-2 are two Synchrotron Radiation Sources (SRS) at RRCAT, having stored electron energies of 450 MeV and 2.5 GeV respectively. Both these rings are filled using a common Booster synchrotron. Both Booster synchrotron and Indus-1 SRS are filled using a 31.6 MHz RF systems, which consist of RF signal generator, RF Amplifier, Circulator and RF Cavity along with Low-Level RF (LLRF) system. LLRF systems mainly have subsystems like Amplitude Control Loop (ACL)-Phase Control Loop (PCL), Power monitoring and Interlocks and RF Cavity Frequency Tuning loop (FTL). Resonance frequency of RF Cavity may drift due to change in dynamic conditions like RF cavity water temperature, beam loading and ambient temperature etc. This causes detuning which results higher RF reflected power from the RF cavity. For faithful operation of machine and effective utilization of RF power, RF Cavity shall be kept tuned near to the RF generator frequency under all operating conditions. Booster and Indus-1 RF 31.6 MHz cavities are equipped with three plungers each for frequency tuning. To keep the RF cavity automatically tuned, a Programmable Logic Controller (PLC) based RF cavity tuner system is designed and developed for Booster and Indus-1. Amount of RF cavity detuning from operating frequency is obtained by measuring the phase difference between forward and RF cavity sense signal using RF phase detector. Based upon this detuning in RF cavity, PLC system moves the plungers via stepper motor driver following a stepper motor to keep RF cavity tuned throughout machine operation. Algorithm for appropriate movement of plunger for tuning of RF cavity has been successfully implemented in PLC. This development is an upgraded system of earlier system used in Indus complex that have extra features like "Auto/Manual" mode selection and limit switch interlock status in local, "Home" position during trip and Detuning in kHz etc. During machine experiment, Plungers are required to operate manually, considering this "Auto/Manual" mode selection option in local mode has been additionally implemented. This new FTL system will also have the feature of displaying the detuning in kHz which shall be helpful in normal operation. Limit-Switches are implemented to keep plungers in safe range and their live status can be monitored in HMI in local. This system also has one new feature of "Home Position" that ensures in case of any fault and RF trip, all the plungers automatically placed in to manual mode and parked to predefined safe positions (i.e. "Home" positions). This system is designed in such a manner that it shall be able to tune either Booster or Indus-1 RF cavity precisely in its entire bandwidth range. A Human Machine Interface (HMI) has also been developed to display Real-Time positions of plungers, Auto/Manual Mode status, Tuning Compensation etc. along with the provision of operating FTL in local mode. This new system has additional feature of data storage which could be used for post mortem analysis and machine learning applications.

In this paper, experience of design and development of "PLC Based RF Cavity Tuner System" will be presented.

Multipacting Analysis of the Radio Frequency Cavity for Compact Superconducting Medical Cyclotron

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VECC has planned to design and develop a 13MeV Compact Superconducting Medical Cyclotron(CSMC). CSMC will accelerate H- ions to an energy of 13 MeV with beam current of 50 μA. Radio frequency Cavity of the CSMC is one end short circuited quarter-wave (λ/4) coaxial transmission line, consisting of inner conductor called Dee stem, which is terminated by an accelerating electrode called Dee where accelerating Dee voltage at 54 MHz, will be produced. This paper presents the multipacting analysis of the RF cavity as it can produce vacuum degradation, localized heating etc. in the RF cavity. Multipacting is a phenomenon of resonant secondary electron emission from metal surfaces inside vacuum, which can lead to exponential growth of secondary electrons. The analysis of multipacting is carried out using 3D code CST-Particle Studio and the results are discussed in the paper. Simulation results shows that when no DC magnetic field at the Dee region is present, multipacting exists at only lower input RF power while when the DC magnetic field is applied, multipacting is not observed at any input RF power.

Design, Fabrication and Characterization of HOM Damped RF Cavity

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Synchrotron storage ring has many beam based longitudinal modes depending upon the RF frequency and ring parameters. Significant growth in any of these mode can cause beam instabilities and in turn increase in the beam emittance. One of the main cause of these instabilities is when any of beam harmonic mode coincides with the Higher Order Modes (HOM) of the RF cavities. These instabilities can be reduced in many ways, shifting the HOM frequency of the RF cavity away from the beam harmonic frequency is one of them. In SRS Indus-2, HOM frequency shift is being achieved by precisely changing the RF cavity temperature and moving the HOM frequency shifter plungers of cavity. Difficulty with these schemes is that, if we tune away one HOM in RF cavity, other HOM may come closer to beam harmonics and can still drive the instabilities. This will be tedious task if there are large number of cavities and HOMs, like in the case of low emittance machines. It also becomes a very serious issue in large diameter storage rings where the orbital frequency is small or comparable to the bandwidth of the modes. For trouble free operation at higher currents single cell HOM damped cavity is preferred. In this cavity HOMs are damped by only ridged waveguide dampers followed by 50-ohm coaxial transition. This cylindrical cavity is nose cone in its shape and is equipped with three HOM dampers. These dampers are in the form of ridged Circular Waveguide to Coaxial Transition (CWCT).

A prototype pillbox type 500 MHz Higher Order Mode (HOM) damped RF cavity [1][2] with nose cones has been designed towards capacity building for High Brilliance Synchrotron Radiation Source. For ease of fabrication development of HOM damped RF cavity is done in three parts, namely hexagonal body, end plates and three HOM dampers. HOM damper is ridged circular waveguide to coaxial transition (CWCT) [3] consisting of a tapered circular double-ridged waveguide, a transformer section and a 7/8” coaxial line of 50Ω impedance. This damper will ensure the propagation of HOMs out from main cavity. To build up confidence in fabrication of complex RF accelerating structure this prototype HOM damped RF cavity and all the parts have been fabricated in Aluminum alloy. Before assembly in the RF cavity, characterization of HOM dampers was carried out. This paper describes RF design, challenges faced in the fabrication and assembly of RF cavity with three HOM dampers along with test results of important RF cavity parameters.

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Design, Development and RF Characterization of Tunable RF Cavity for LLRF Control Systems

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RF Cavities are one of the most important components of any particle accelerator. It not only imparts the energy to the charge particles but also the overall response of the RF system is strongly governed by the RF cavity due to its high Quality factor. These RF cavities are not readily available for testing and optimization of Low Level RF control (LLRF) systems. Different accelerators operate at different RF frequencies; accordingly their LLRF systems are designed. In order to reduce the installation time of LLRF systems, their characterization and optimization has to be done. Availability of RF cavity helps in optimization of PI parameters in close loop operation. Considering this a wide band capacitive loaded tunable aluminium RF cavity in the range of 320 MHz to 725 MHz, has been designed and developed for testing of LLRF systems in lab. This cavity can be tuned to any frequency in its tunable range for LLRF system testing. Electromagnetic simulations for this cavity have been performed with the help of SUPERFISH and 3D-CST Studio Suite. Tuning of the RF cavity to required frequency is achieved by varying the length of tuning plunger inside the RF cavity. Change in fundamental frequency and unloaded quality factor with change in penetration length of plunger have been computed. Five ports are provided on the cavity which can be used as feed and sensing ports. Also by terminating these ports appropriately, the loaded quality factor at desired operating frequency can be controlled. This provides flexibility in characterization of LLRF system for a wide range of response time. Simulated unloaded quality factors at resonant frequencies of 325 MHz, 505 MHz and 650 MHz are 9100, 10600 and 12900 respectively. Low power RF characterization of cavity has been carried out over a frequency range of 320 MHz to 725 MHz. By tuning this cavity to 325 MHz, Digital LLRF system at 325 MHz for RFQ has been tested and optimization of LLRF parameters was done. By tuning this cavity at 476 MHz, adaptive feed forward based pulsed Digital LLRF system for IRFEL was optimized before installation in IRFEL. This cavity is being used in Lab for the characterization and optimization of LLRF systems at different frequencies and applications.

This paper describes the design, electromagnetic simulations, development and RF characterization results of the tunable RF cavity. Optimization of PI parameters carried out in Lab for different LLRF systems using this cavity along with results will also be presented in this paper.

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Design and simulation of a VHF band directional coupler for high accuracy power measurement of 150 MHz, 300 W Solid State Amplifier

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BARC has developed a prototype 150 MHz, 300 W solid state RF amplifier (SSA) as a part of up-gradation of the BARC-TIFR Pelletron LINAC facility (PLF). As a part of the indigenization of the power measurement system of the LINAC, it had been planned to develop directional couplers for accurate measurement of forward and reflected power. Directional couplers are passive, reciprocal four port devices that couple part of the transmitted power by a known amount through another port, often by using two transmission lines set close enough together such that power passing through one is coupled to another. The typical parameters of a directional coupler are coupling factor, insertion loss, isolation and input and output port return loss. For the 150 MHz, 300 W SSA, the performance requirements of the directional coupler are strong coupling (<35 dB) to minimize the effect of noise on the coupled samples, particularly reflected power sample. Another requirement is that of high directivity (>25 dB) for limiting interference between the forward and reflected samples at the respective coupled ports to ensure accurate power measurement. Based on the power handling requirement (300 W CW max.) and the need for compactness, it had been planned to design a microstrip line type directional coupler for the present requirement. However, high directivity requirement poses a design challenge and it is difficult to obtain directivity>25 dB in such structures. Therefore, certain modifications in the typical geometry of the microstrip type directional coupler have been adopted to meet the dual requirements of coupling and directivity. The modifications include the use of suitable bend cutting methods for the coupled section as well as impedance mismatch compensation [1]. The microstrip type directional coupler has been implemented on a dielectric substrate having thickness 1.6 mm and dielectric constant 2.2. The metal track thickness on the substrate is 70 microns. The simulation of the directional coupler has been done using CST microwave studio and the measured parameters at 150 MHz are coupling factor: 33 dB, insertion loss <0.1 dB, directivity>30 dB and input /output match>30 dB. The measured parameters of the directional coupler are in agreement with the design requirements and provide a high accuracy compact solution for power measurement in the VHF band.

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Integration and testing of 150 MHz, 300 W solid state RF amplifier with superconducting cavity of BARC-TIFR PLF Superconducting LINAC

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As a part of up-gradation of the BARC-TIFR Pelletron LINAC facility (PLF), existing 150 MHz, 150 W amplifiers have been planned to be replaced with high efficiency, compact and air cooled 150 MHz, 300 W solid state RF amplifiers (SSA). Therefore a prototype 300 W, 150 MHz air-cooled SSA has been designed, developed, tested and integrated with the superconducting cavity at TIFR. The 300 W SSA has been designed around the LDMOS device MRFX600H as a class AB amplifier [1][2]. The SSA has a protection and diagnostics card designed to offer protection against high reflected power, over-current and over-temperature. Forward and reflected powers are sensed and processed via on-board ICs of the card. The SSA along with its other sub-systems such as DC power supplies, driver amplifier, protection sub-system, display unit etc. has been enclosed in a 19", 4U cabinet having a depth of 650mm. The SSA has been tested on a 50 ohm load and some of its important specifications are: Rated power (CW): 300 W at 150 MHz, 1 dB BW: > 3 MHz, DC to RF Efficiency: 65%, gain flatness: 2.3 dB over 10 dB dynamic range, harmonics: < -30 dBc and warm up time within 20 seconds. The SSA has the option of remote as well as local RF ON/OFF and reset. On the front panel, RF forward and reflected power are displayed and the fault indications for reflected power, temperature and DC power supply eases the diagnostics process during accelerator run.

The SSA has been integrated with one of the resonators M3R4 of the superconducting LINAC at TIFR. It has been tested in closed loop via the low level RF (LLRF) system for amplitude and phase locking with the other cavities of the LINAC. The amplitude and phase stability of the closed loop were 0.1 % and 0.1 degree respectively. The integrated system has been operated with the SC LINAC for more than 72 hours before accelerator facility was shut down as its objectives were completed. The entire system had been operational without any problem in amplifier or its integration with LLRF and cavity.

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Design of high-power ridge Waveguide couplers for MEHIPA

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Warm front end of MEHIPA (Medium energy High Intensity Proton Accelerator) is proposed to be consisting of a RFQ and two Drift Tube Linac (DTL) cavities which accelerates beam to 10 MeV. Each cavity will be connected to the waveguide power distribution system by two RF couplers designed for 250 kW CW power at 325 MHz. Hence a total of six high power RF couplers are required in the warm accelerator cavities.

The proposed design evolved from 352 MHz RF Couplers previously developed for LEHIPA [1,2]. However, several changes and further improvements stemming from operational and assembly experience are incorporated in design. The coupler assembly consists of an iris, ridge section and a 45-degree waveguide bend. The iris opens to the cavity wall and provides magnetic coupling to the cavity at desired mode. The ridge section provides mechanical size reduction from the large waveguide to a ridge waveguide with much smaller dimensions while acting as a matching transition. It also enhances coupling coefficient at the succeeding iris. The 45-degree bend connects the coupler to the waveguide distribution system while absorbing certain length of the ridge section thereby reducing the overall length of the ridge section.

Basic requirements for an RF Coupler are to provide optimum coupling coefficient to cavity, induce minimum frequency change to the cavity, provide ultra-high vacuum performance and to have adequate power handling capacity. The coupler should have sufficient thermal management to avoid over-heating damage, to maintain structural integrity of the coupler and its joinery and to provide consistent high power RF performance. But other factors such as such as fabrication cost, material consumption, easiness of fabrication, assembly, and testing are also important while designing an RF coupler.

Similar to LEHIPA couplers, the irises and the ridge sections will be made with OFE copper and brazed in a vacuum furnace. The 45-degree bends will be made in Aluminium. LEHIPA couplers contain two tuners and a diagnostic port in the ridge section [2]. However, the tuners were never used as the design coupling was obtained during measurements and did not require any fine tuning. Hence possibility of removing tuners is being studied. The proposed design also aims to remove any vacuum pumping ports from the coupler assembly unlike LEHIPA couplers. This rooted from operational experience as the vacuum pumping from windows will suffice for the entire coupler assembly.

This paper describes basic design procedure followed and results obtained. It also explains changes adapted such as elimination of tuner ports, vacuum port and physical dimensions in comparison to previous LEHIPA coupler design. Design simulations for coupling coefficient are done using CST Microwave Studio [3] on a smaller re-entrant cavity model and are scaled for actual cavity parameters. Return loss of better than -20 dB is obtained.

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Advances and Challenges in development of high power solid state RF power amplifier for accelerator applications

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Solid state RF power Amplifiers (SSAs) will drive RF cavities of future RF accelerators. Research in particle physics, high energy physics, accelerator for medical applications, for research and development in energy frontiers requires high energy/intensity or both accelerators depending on requirements. These accelerators require stable output from these high power amplifiers with efficient, reliable and economically viable RF power. Solid state RF power amplifiers technology is one of the most explored option by accelerator community now a days. Most of the new accelerators are being built/planned using solid state RF power technology. Moreover, this trend has also been complimented by innovations and exemplary progress of superconducting radio frequency (SRF) technology for acceleration of charged particle.

SSAs have been increasing their footprint in RF accelerators due to their unique advantages, i.e. modularity, graceful degradation, low voltage operation, high availability/reliability, stable/quality RF, scalable, easy maintenance among many others. However, SSAs are challenged by other technologies like klystrons, tetrodes etc. on the performance fronts like size, cost and efficiency. Below few tens of kWs of power, SSAs are efficient and compact compared to other technologies. But for power in excess of 100 kW, SSA technology is either comparable in size or a bit bulky with lower efficiency and higher costs. However, other advantages of SSA technology have outweighed these evolving features of SSA. This has led to decision makers around the world to choose SSAs for current and future particle accelerators. Despite this, researchers in the field of SSAs development are working hard on improvement of SSAs characteristics and performance to match or even exceed to those of other alternatives/challenger technologies.

Efficiency of an amplifier depends on efficiency of its various components which are involved in supplying of energy/power, conversion of power, its conditioning/transportation up to the output port of the amplifier. Efficiency of the SSAs can be improved at conversion stage where DC power is converted to RF and then improvement is required at conditioning/transport level where power from multiple amplifier modules are combined and transported to output. We are working on these two components of SSA for improvement on efficiency. High overall SSA efficiency can be achieved by incorporating amplifier module with efficiency in excess of 75% and efficient combining technique with better graceful degradation properties. This approach helps in reduction of size and cost of the amplifier too.

Another approach that needs to be followed by SSA researchers is to adapt innovative SSA topology that can help reduce DC power supply size and cost without compromising on its modularity and reliability aspect. This can be achieved by using efficient, compact and water cooled DC power supply. Authors would like to present their theoretical work with practical experience on development of SSAs.

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Design upgrade and characterization of 200 W, 325 MHz driver amplifier with high gain for 20 kW solid state amplifier

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BARC has been developing 20 kW solid state amplifiers for Indian accelerator program. BARC has developed a prototype 20kW, 325 MHz solid state amplifier [1]. In [1], the driver and pre driver stage were separate. The driver was a 200W indigenously designed water cooled amplifier whereas the pre-driver was a 20 W Mini circuits air cooled amplifier, which was not optimum both in terms of power as well as footprint. As a technological advancement and as part of the indigenization drive, an integrated 325 MHz, 200 W amplifier combining the pre-driver and driver stages as a single driver module has been indigenously designed, developed and tested up to 200 W power output.

The 20 kW solid state amplifier (SSA), requires a minimum gain of 53 dB and 200 W CW power output from the driver stage to meet the overall gain and output power requirements. Additionally, the gain and phase variation of the driver amplifier over 30% to 90% output power must be ≤1dB and ≤2° respectively to meet the overall technical requirements of the 20 kW SSA.

The predriver has been designed around the RF5110G amplifier and has been tested on a 50 ohm load up to 1.1 W power output (@325 MHz).The driver amplifier has been designed around the LDMOS device as a class AB amplifier. The standalone driver amplifier has also been initially tested on a 50 ohm load up to 200 W power output. Subsequently the pre-driver and driver amplifier have been assembled on a water cooled heat sink and tested up to 200 W power output. The driver stage in [1] had not been tuned for the gain and phase variation over 30% to 90% output power. Since this is a crucial requirement for the 20 kW SSA, the driver stage has been tuned to optimize the gain and phase variation. The tested parameters of the integrated driver assembly at 325 MHz are: gain(@200 W output power):54 dB, gain variation (over 30% to 90% output power):<1 dB, phase variation(over 30% to 90% output power):<1 degrees and gain variation at 200W output power (from peak gain):<0.1 dB. Thus, these values are in line with the overall technical requirements of the 20 kW solid state amplifier and the driver acts as an effective high gain frontend amplifier for the 20 kW amplifier.

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Automatic frequency tuning of LINAC and Re-bunchers during high power RF conditioning and beam operation in the RIB facility

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Charged particle beams are being accelerated by the RF accelerators at RIB facility at VECC. During RF conditioning and beam operation, high power RF is applied to the RF accelerators, which may cause the RF cavities to get detuned. To mitigate the detuning, cavity tuner control mechanism employing feedback for automatic operation has been developed for the RF accelerators and re-bunchers in the RIB beam line. Tuner controllers have been tested and their performances optimized for LINAC-2, Re-buncher-2 and Re-buncher-3 operating at 37.87 MHz and LINAC-3 operating at 75.74 MHz.

Each RF cavity is fitted with a mechanical tuner for resonant frequency tuning of the cavity [1]. The mechanical tuner is moved using a high torque stepper motor coupled to the tuner. In the automatic mode of operation, the movement of the stepper motor is controlled by the tuner controller, based on a feedback signal derived from the forward power and cavity pick-up. For efficient movement of the tuner when the cavity is in high vacuum, a mechanism using a high-torque stepper motor (22 Nm) and ball screw has been devised. The control system is an ADuC841 microcontroller based feedback control system and can be operated in either manual or automatic mode [2]. The phase difference between the forward power and cavity pick-up serves as a measure of the detuning of the cavity from its original resonance position. Minimum frequency shift possible is around 15 Hz for LINAC-3 for a minimum linear movement of 10 µm. Feedback phase difference detection resolution is less than 1°.

Very high Q of the RF cavities makes it necessary that maximum power is transmitted into the RF cavity and reflection is minimized. Maximum power transmission is also desirable during beam acceleration to obtain required accelerating voltage at the calculated RF power. Automatic frequency tuning has been employed during high power conditioning of LINAC-2, Re-buncher-2, Re-buncher-3 and LINAC-3. Charged particle beam acceleration has also been done using the RF cavities tuned to their resonant frequencies at all power levels. The tuner controller functions in synchronism with the LLRF controller during beam operation. Reflected power has been maintained at levels below 1% of the forward power in the tuned condition. In this paper, the design, fabrication and performance during RF conditioning and beam operation of the RF cavity tuners is presented. Future scope of development is also discussed in brief.

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Synchronized high power feeding system of RF accelerator modules in RIB facility at VECC

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The various accelerator modules of RIB facility are installed for accelerating beam up to 1 MeV/u [1-3]. This comprises RFQ linac, five heavy-ion linac modules (L1-L5) and five rebunchers (RB1-RB5) operating at 37.8 MHz and 75.6 MHz. Currently, facility is commissioned up to energy of 0.415 MeV/u. All the cavities have separate RF power amplifiers with a low level RF control system. To achieve efficient beam transmission and acceleration, all these RF cavities needed to be operated in phase synchronism with respect to a reference RF signal. A RF distribution system has been developed to divide the signal from the signal generator to the respective phase and level controllers of the individual transmitters. A single oscillator at 37.8 MHz drives all the RF power amplifiers through RF distribution system. The forward and reflected power samples and pick-up signal from each of the RF accelerator cavities are fed to the low level RF control modules of the RF amplifiers. The amplified signals are fed to the cavities. The phase and power level for each cavity could be varied using the respective phase and level controllers of the individual transmitters.
The developmental work as well as measurement results during beam line operation will be presented in this paper.

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High power (30 kW) testing of resonant ring in traveling-wave mode

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Many high power (20 kW at frequency of 325 MHz) coaxial RF couplers are being fabricated in BARC under IIFC collaboration. To check high power performance of these couplers, high power RF source is required. So, design and development of 30 kW resonant ring high power RF test facility has been taken up in BARC. Such type of couplers will also be used for future DAE projects like MEHIPA. Resonant ring has advantage of providing high power by using passive low cost RF components. It is cost effective, simple in design and doesn't require very high voltage for operation.

The main components of the ring are Directional couplers (13 dB and 50 dB), waveguide transmission lines, tuners, bends, RF amplifier and RF load etc. The performance of the resonant ring depends on many variables like coupling coefficient of the directional coupler, return loss, attenuation in the ring and electrical length of the ring [1]. The resonant frequency of the ring has been set to 325 MHz with the help of tuners. The low level gain obtained earlier was about 11 dB 2]. After optimization this has been increased to about 13 dB at 325 MHz [2].. After low power characterization high power testing of the resonant ring has been done. The RF source has been connected at the input of resonant ring via transmission lines. Slowly input power has been raised to get high travelling power in the ring. With input of about 1.1 kW we obtained RF power of about 30 kW in the ring. The ring has been operated at high power for about 75 hours. This paper presents the results of the high power test of the resonant ring. The MEHIPA SSR RF couplers requires more power (about 40 kW) for testing and for 200 MeV accelerator further higher power couplers will be required. So, it is planned to increase the input amplifier power to 7 kW. This will give around 200 kW in the ring without couplers as the gain will be same. In future few waveguide sections of the ring will be replaced by two coaxial RF couplers with a cavity in between for testing. The two couplers will be part of the closed resonant ring. Thus with the help of the resonant ring setup two 325 MHz RF couplers will be tested simultaneously at high power.

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Development and Commissioning of a Thermal Profile Data Logging and Protection Subsystem for Indus-2 RF Cavity

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Indus-2 RF system at Raja Ramanna Centre for Advanced Technology (RRCAT) Indore, is equipped with six 60 kW, 505.8 MHz, CW RF power stations [1] feeding to normal conducting elliptical RF cavities generating over 1.5 MV of gap voltage. Among these, the RF cavity installed in RF station #5 is developed inhouse by RFSD, RRCAT indigenously. In a synchrotron radiation source, it is essential to keep the resonant frequency of the RF cavity constant. Hence for the proper filling of electron beam current and smooth energy ramping to 2.5 GeV level, a precision chiller unit for each RF cavity is used which keeps the thermal profile of RF cavity precisely stable during full operation. A Thermal Profile Data Logging and Protection Subsystem for Indus-2 RF Cavity system was installed and commissioned in the Indus-2 RF system to display and log the thermal profile data, as well as to provide thermal protection to the RF cavities. This protection is against any incidental excessive rise in RF cavity surface temperature during the round 'O' clock operation of Indus-2 synchrotron Radiation Source.

The system uses–a Hioki make 60 universal channel data logger, K type and T type thermocouples suitably customised for proper mounting upon the surface of the RF cavity, interface cables and connectors compatible for the used thermocouples. As the mechanical mounting of the thermocouples upon the surface of RF cavity is not recommended due to various reasons, customised thermocouples having flat square shaped copper strip brazed on the junction tip were mounted, using thermally conductive epoxy adhesive paste which can withstand high temperature of the surface without loosing its properties. Around 7 numbers of K type thermocouples are fixed at suitable places upon the surface of the RF cavity, so that a comprehensive data of the RF cavity thermal profile may be obtained. As the cavity is installed in the extremely high radiation area (zone # 3), K type thermocouples are used due to their high relative radiation hardness. Connectors and cables used for the interfacing of the thermocouples with the data logger placed in RF equipment hall area are also made up of the similar material to maintain the compatibility. In total, approximately 200-meter length cable has been routed through the trenches to provide interface between thermocouples and datalogger unit. One T type thermocouple is also mounted upon the cavity surface at appropriate place which is used for the reference temperature purpose.

The 60 universal channel datalogger has been programmed with OR logic to generate a potential free contact to trip the interlock unit [2] of the respective RF station in case the temperature of any thermocouple exceeds the safe limit. The system was tested okay after installation and has been working properly since it's commissioning in 2017.

This paper presents about the scheme, technical considerations and issues related to maintenance of the subsystem.

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Frequency Measurement of Halfcells,Dumbbells and Subassemblies of Low Beta 650MHz 5-cell SCRF (LB650) Cavity

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In India, DAE laboratories are now actively involved in research and development activities on SRF cavities and associated technologies for high current, high energy proton linear accelerators, which is essential for development of ADSS and Spallation Neutron Source by DAE and also for the FERMILAB PIP-II Project. These activities are being carried out under Indian institutions- Fermilab collaboration (IIFC). As part of these activities, VECC, Kolkata, has been involved in the design and development of 650 MHz, β=0.61, 5-cell elliptical shape Superconducting RF linac cavity(LB650 cavity). After the completion of design , fabrication of two 5 -cell LB650 niobium cavities has started. To validate the process of fabrication of 5- cell LB650 niobium cavity , a prototype 5- cell copper LB650 cavity has been developed before the development of 5- cell LB650 niobium cavity. Subsequently, all the niobium halfcells for two 5-cell niobium LB650 cavities have been developed and electron beam welding of the halfcells are going on ,at present, for development of niobium dumbbells. The fabrication process of a 5 -cell cavity consists of fabrication of halfcells and stiffener rings , welding of halfcells and stiffener rings, to develop four sets of dumbbells and two sets of End groups, subsequent welding of the dumbbells and end groups, to fabricate sub-assemblies and final welding to fabricate the 5-cell cavity. To take care of the frequency deviation introduced during forming of halfcells and during welding process, frequency measurements are carried out for halfcells, dumbells, end group and subassemblies and depending on the measured values , dumbbells are trimmed in the equator region. Frequency measurements set up have been developed for measurement of halfcells, dumbells, end group and subassemblies of 5-cell LB650 cavity.

Simulation and development of 650 MHz high power dummy coupler of superconducting RF cavity for Q_{ext} measurement

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Superconducting RF cavities are formed using materials like niobium or Nb3Sn, which become superconducting at cryogenic temperatures. These cavities have a very high quality factor (10^{10}) and require qualification and testing at several stages before final use. Under the Indian Institutions' Fermi Lab Collaboration (IIFC), RRCAT is developing 5-cell, β0.92, 650 MHz SCRF cavities for Fermi Lab, USA. The external quality factor Q_{ext} of a cavity with a high power coupler is a critical parameter that must be measured before the cavity can be used. The high power coupler-to-cavity coupling factor is calculated from the measured Q_{ext}. As the actual high power coupler of the cavity is bulky& delicate and needs a Class 100 clean room for installation & measurement, a dummy coupler is being developed for Q_{ext} measurement of the cavity. For RF coupling and hence Q_{ext} measurement, the dummy coupler behaves like an actual high power coupler but does not require a clean room for installation. Dummy coupler measurement allows for the calculation of the SCRF cavity's power requirements during machine operation.

The output impedance of dummy coupler is designed to be the same as that of the actual 50 kW 650 MHz coupler, which, in this case is 105 ohms. The output impedance is kept high to minimize/restrict the power loss in the outer conductor, as power loss on the outer conductor decreases the efficiency of the RF coupler. After the output section, the impedance of the coupler is transformed and matched to 50 ohms. Matching is necessary for obtaining accurate Q_{ext} value. The structure has been simulated using an electromagnetic simulation software CST'. The results of the convergence study have been completed and they are as expected. The real coupler has also been simulated. The inner conductor with goosefoot has been rotated 360° with a 30°step size, and Q_{ext} values have been computed using the software. Simulation data shows variation of Q_{ext} values with respect to inner conductor angles. The variation in Q_{ext} values at different angles is due to the asymmetry in the electric field distribution at the location of the coupler position, which is mounted on a beam pipe.

After the fabrication of the dummy coupler, a dimensional inspection will be performed to verify the dummy coupler's geometry. The Q_{ext} values of the dummy coupler, which are expected to be close to those of a 50 kW high power coupler, will be measured. Q_{ext} of the coupler will be measured using two methods. In the first method, the 'reflection' method, only a dummy coupler is required. In the second method, an additional antenna will be used for measurement using the transmission parameter method. The results of both methods will be analyzed and compared with the simulation data. This paper presents the simulation, analysis, development, and Q_{ext} measurement methods of a high power dummy coupler whose fabrication is in progress.

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Bead Pull Test Setup for low beta Niobium Cavity

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A Superconducting Linear Accelerator, employing lead plated copper cavities of β_{opt}=0.1, has been indigenously developed as a booster to the 14 MV Pelletron accelerator and is operational since 2002 [1]. The Linac is routinely used for acceleration of beams of ^{12}C to ^{37}Cl as per the user requirements. To widen the mass acceptance of the linac, the development of low β Niobium QWR cavities (β_{opt}=0.07) has been initiated. A prototype of SS for qualification of electromagnetic design is under fabrication [2,3]. The design qualification of the prototype, mainly the resonant frequency and field mapping using a bead pull test, is an important step in the cavity development process [4]. A small teflon bead is used to perturb the resonant cavity, which consequently changes the electromagnetic fields within the cavity and the resonant frequency of the cavity. Frequency modulation technique is used to measure the change in frequency accurately, which is directly proportional to the change in electric field. To qualify the design and performance of the low beta cavities, a precision bead pull test setup is developed at TIFR employing a teflon bead of 6 mm diameter.

In this setup, the displacement of the bead in precise steps of 1 mm is achieved using a gear assembly and a stepper motor. The microstepping stepper motor driver A4988 is incorporated in the stepper motor controller design. To test the setup, the field mapping was carried out in the lead plated copper cavity (β_{opt}=0.1). Multiple sets of readings are taken using a high precision signal generator (R&S make SMB100A, 1.1 GHz) and data was recorded using 500 MHz digital oscilloscope (Tektronix DPO4054B). Further, tests are underway to measure the phase shift with Vector Network Analyzer (VNA). The field inside the cavity can be deduced from the measured angle. It is proposed to automate the measurement setup. The details of setup and preliminary results will be presented.

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Development of Transfer Function Measurement System for Elliptical High Beta Superconducting RF Dressed Cavity

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RRCAT is developing elliptical high beta dressed superconducting RF cavity for domestic as well as international projects. Due to high quality factor, superconducting RF cavities are very sensitive to external vibrations generated from vacuum pumps, AHU, motors etc. Generally, superconducting RF cavities are designed to have mechanical resonance frequency above 100 Hz for avoiding resonance with external vibrations [1]. The mechanical resonance frequency of the cavity depends on its material of construction, design, type of mounting/ support, tuner stiffness etc. In order to check the performance of superconducting RF cavity towards external vibrations, transfer function measurement system has been developed.

This paper describes development of transfer function measurement system. Developed system excites the cavity by a set of sinusoidal signals through piezo-actuators. These piezo actuators are part of cavity tuning system. Cavity response to these excitations is measured by change in phase by RF measurements system. Developed system consists of function generator and piezo-driver for set of sinusoidal signal generation and phase detector for cavity response measurement. Change in phase is digitalized by NI based DAQ system. FFT of the phase signal gives transfer function of the dressed cavity. The transfer function measurement system is mounted with 5-cell 650 MHz dressed cavity. The setup is initially tested on a rotary fixture and tested for 1 Hz to 500 Hz piezo excitation. During this test, two most strong mechanical modes were observed at 231 Hz and 460 Hz and no mechanical modes were observed below 100 Hz. The results are compared with FE analysis results which show a close matching of the excited modes [2].

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Mechanical Design of Spoke Resonator Cavity for High Energy Pulsed Proton Accelerator

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Abstract

Superconducting single spoke resonator cavities to accelerate H^- ions are under design and development at RRCAT. There are three families of single spoke cavities for accelerating the beam from 3 MeV to 168 MeV energy. These superconducting RF (SCRF) cavities have high quality factor for efficient acceleration of charged particle. The high quality factor needs stringent control of resonant frequency of the cavity. The SCRF cavity gets detuned by Lorentz Force Detuning (LFD), df/dP and micro phonics. Also, the cavity should qualify for various operating load conditions. This paper will discuss the design of 1st family of single spoke dressed cavity i.e. SR011, for various requirements such as Lorentz Force Detuning (LFD), df/dP, leak testing load to the bare cavity and 2 bar MAWP load (at room temperature). Issues related to cavity tuning such as cavity stiffness, tuning sensitivity and tuner range will also be presented in this paper.

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Design Methodology for Forming Tooling of SCRF cavities

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Abstract

RRCAT is involved in the design and development of various superconducting RF (SCRF) cavities for high energy proton accelerator. SCRF cavities have a very high-quality factor and are very sensitive to any dimensional changes. These cavities are generally fabricated by deep drawing and it is very difficult to achieve required tight tolerances due to spring-back, thickening, and thinning.

Using finite element analysis die and punches have been designed to get RF profile very close to the required RF profile for SR011 cavity. The main components of spoke cavity are end wall, spoke and shell. These components are manufactured by the deep drawing of thin sheets of niobium. This paper will elaborate on the procedure of estimation of spring-back, thinning, thickening and other forming parameters for the End Wall using finite element method. Based on forming simulations, the profile of die and punches has been varied iteratively to get the RF profile of the formed component close to the physics RF profile.

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Study and Development of Various Dissimilar Metal Joints of Superconducting Radio Frequency cavities

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The Superconducting Radio Frequency (SCRF) cavities are a prominent element of the modern linear proton accelerators. Technological developments in the manufacturing of SCRF cavities are on-going at Raja Ramanna Center for Advanced Technology (RRCAT). RRCAT is developing high beta (HB) 650 MHz five-cell cavities for PIP-II project under IIFC. The Superconducting Radio Frequency bare cavities are fabricated mostly with high RRR Niobium (Nb), and except the flanges and transition spools, which are made of Niobium-Titanium (Nb-Ti) material. The dressing/jacketing of the cavity (integration of bare cavity to helium vessel) vessel is fabricated with Titanium (Ti). The joining Nb cavity to Ti vessel, added a transition material Nb-Ti in between these two dissimilar materials to make weld joints of Nb to Nb-Ti and Nb-Ti to Ti. Also these dissimilar materials have close thermal contraction coefficients and will not generate high mechanical stress, during cavity cools down from 300K to 2K.. The five-cell HB 650 MHz SCRF cavities were joined using Electron Beam Welding (EBW, jacketed and dressed by Gas Tungsten Arc Welding (GTAW) in a controlled environment glove box to prevent titanium from oxidization [1]. The welding of Nb to Nb-Ti and Nb-Ti to Ti material were challenging for developing a desired weld joint of these dissimilar materials, despite having good solubility of Nb to Nb-Ti, Nb-Ti to Ti materials. This is mainly due to wide difference in the thermal properties like thermal conductivity, melting temperatures and specific heat. The developments of these joints were carried out in EB and GTAW by optimizing the electron beam and GTAW heat source offset to make the stable joint respectively. To the Study and estimate of maximum temperature of the fusion zone and cool-down time cycle (thermal cycle plot) of these dissimilar metals weld joints, was carried out by finite element analysis in Simufact weld software. The weld pool in the simulation was constructed with help of weld bead test coupons and also used predefined heat sources of GTAW in welding FEA software [2]. Further, the experimental studies were conducted on various joints samples for these dissimilar metals for 650 MHz SCRF cavities to optimize the weld parameters by varying the heat source offset. The test samples of the welded seam micrograph studies, it was observed that the variation in the welded metal compositions of Nb and Ti and its hardness. By varying the weld parameters and beam offset, a stable weld joint of these dissimilar materials was developed and implemented in welding of HB 650 MHz five-cell cavities successfully. The paper describes the study of these dissimilar materials metallurgical compositions, solubility, development & optimization of EB welding, TIG welding parameters, micrographs of the weld joints, hardness etc. Also discussed in paper, the simulation results of the dissimilar metal weld pool peak temperatures and cool down time etc.

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Design and Construction of an ISO Class-4 Cleanroom Facility for SRF Cavity Processing and Assembly

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At RRCAT, a programme has been initiated for development and production of Superconducting RF (SRF) cavities and infrastructure development for cavity string assemblies for future high power pulsed superconducting proton accelerators. After fabrication, superconducting RF cavities needs to be inspected, processed and assembled under controlled environmental conditions. Any particulate impurity on the superconducting cavity surface can influence its maximum achievable accelerating gradient, hence contamination by particulates has to be avoided. For achieving the controlled environment, a cleanroom has been planned and constructed at RRCAT. The cleanroom has zones of various cleanliness ranging from ISO Class - 4 to Class - 8 cleanroom as per ***ISO 14644 Part-1[1]****. The cleanroom has a footprint of 35 Sqm with ISO class – 4 area of 4.0 m x 3.8 m (~ 15 Sqm). General operating parameters of the cleanroom are as follows; a) Temperature - 22° ± 2° C, b) Relative Humidity - 50% ± 5%. The cleanroom is equipped with automatic control via Facility Control and Monitoring System (FCMS) which can automatically track and control various parameters viz. temperature, pressure, humidity, air flow etc. The supply air of the cleanroom is provided from ceiling and the return air is taken from bottom below the raised floor to achieve laminar flow. Two numbers of cleanroom compatible Air Handling Units (AHU) have been provided with Variable Frequency Drive (VFD) to separate different class of cleanroom in zones. The cleanroom has been designed based on plenum concept to maximize the filter coverage. The cleanroom is intended for SRF cavity processing activities which include High Pressure Rinsing (HPR), component & hardware preparation, assembly, evacuation and vacuum leak testing. With the emerging scope of high power accelerator technology in various fields, the demand for cleanrooms is ever increasing.*

The paper highlights the layout planning, salient design features and construction details and validation of the cleanroom facility for SRF cavity processing. Construction of cleanroom is project specific and significantly depends on the process requirement. Moreover the design requirement influences the HVAC system apart from the enclosure elements. A holistic approach towards fulfilment of the desired environment condition is essential. The paper also highlights check points which shall be followed at various stages of cleanroom projects to consistently achieve intended class of cleanroom.

Major topics which would be covered in the paper are as follows:-

1. *Design and detailed engineering of the cleanroom - This includes the details of design parameters, HVAC design, facility monitoring and control system planning, civil structural design etc. in accordance with* ***ISO 14644 Part – 4 [2]****.*
2. *Construction planning and management - This includes the sequencing of various activities, quality assurance, construction safety etc.*
3. *Testing and commissioning of the facility – This includes the testing of constructed cleanroom as per* ***ISO 14644 Part – 3 [3]****.*
4. *Challenges encountered during the work and the measures taken to overcome those challenges.*

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Digitally Controlled Precision RF Signal Synthesis for LLRF Applications

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Next generation particle accelerators using superconducting RF (SCRF) cavities for high energy acceleration have demanding requirements for cavity field generation and control. The RF fields inside the SCRF cavities must be precisely generated and controlled, for maintaining the stability of the particle beam in an accelerator and, also for cavity characterization in cavity test stands like Horizontal Test Stand (HTS). To cater to the stringent requirement due to very high quality-factor (Q) there is a need for highly stable and precise RF signal synthesis as well as advanced control algorithms that can quickly respond to changes in the cavity field and its resonance frequency. The digital Low-Level RF (DLLRF) system plays a critical role in meeting these requirements, by providing a precise generation and control of the RF field needed for stable and efficient operation of the accelerator and during SCRF cavity characterization. Using the advanced digital signal processing (DSP) & RF signal processing techniques a high-performance digital LLRF (DLLRF) system can precisely generate, control, and stabilize an RF signal and hence the RF field inside the cavity. To realize such a DLLRF system the hardware typically consists of Field Programmable Gate Array (FPGA), high speed Digital-to-Analog (DAC) devices, RF filters and upconverters. The FPGA can implement complex synthesis and control algorithms to generate RF signal with high resolution of its amplitude, phase & frequency along with low noise and fast modulation capabilities. Such FPGA algorithm generates a sine wave by either looking up values in real time from a lookup table containing values of a sine waveform which are pre-calculated or using real time computation algorithms like coordinate rotation digital computer" (called CORDIC). Frequency of the sine wave is precisely controlled by a digital control word. The generated digital sine wave inside the FPGA is given to DAC for obtaining a precisely controlled low frequency analog signal. This signal is processed through an RF up-converter circuit. RF up-conversion typically involves mixers where the low-frequency signals are mixed with high-frequency signal from a local oscillator (LO) to obtain the desired RF frequency. By using a low-frequency signal generated from DAC as the input, this method provides fine adjustment and high precision control of synthesizing the high-frequency RF signal. RF filters are used to remove unwanted harmonic frequencies that are generated because of the discrete values in the low frequency signal from DAC, which can cause unwanted interference and reduce signal's signal-to-noise ratio (SNR). This paper represents such a scheme and its implementation on modular PCI eXtensions for Instrumentation (PXI) platform, along with an indigenously developed RF up-down converter PCB board to generate RF signal which is digitally controlled and provides fast & precise control over its amplitude, phase, and frequency.

Design and development of setup for 650 MHz β=0.92 SCRF cavity to study the effect of trapped magnetic flux on cavity performance

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Superconducting radio frequency (SCRF) cavities play a vital role in high energy particle linear accelerators. In Department of Atomic Energy (DAE) SCRF cavities will be required for the proposed high energy (1GeV) superconducting proton linear accelerator. Silmilar cavities are also required as deliverable to Fermi National Accelerator Laboratory (Fermilab), USA for their Proton Improvement Plan-II (PIP-II) project under Indian Institutes Fermilab Collaboration (IIFC). RRCAT has been developing dedicated in-house infrastructure and expertise for fabrication, processing and qualification of SCRF cavities. Worldwide research and technical advancements are aimed to enhance the operational (cryogenic) efficiency by improving the quality factor (Q_0) of these SCRF cavities. In order to make these cavities qualify the stringent functional and technical requirements, it is required to work precisely on optimized procedures for fabrication, processing and testing of these cavities. Worldwide niobium SCRF cavities in particle accelerators are operated at temperature around 2K. Niobium cavity, when cooled down below its transition temperature (9.3K) must expel all the external magnetic field. However due to certain factors like material defects, grain size, dislocation density, spatial thermal gradient during cavity cool down, high temperature treatment, Nitrogen doping etc. the cavity traps a fraction of the external magnetic field. This trapped magnetic field that persists below transition temperature degrades the quality factor of the cavity that results in poor cryogenic and operational efficiency [1, 2].

A set up has been established at RRCAT, Indore, to study the phenomenon of magnetic flux trapping in the β=0.92 650 MHz SCRF cavities. This paper presents the details of the flux expulsion setup. The setup comprises of an electromagnet, a set of stratigically mounted sensitive temperature and magnetic field detectors and a data acquisition system. In order to generate uniform magnetic field of the order of few milli Gauss in the volume enclosing the cavity under test, a pair of coaxial air core Helmholtz coils has been designed and fabricated. The magnetic field mapping at room temperature was performed to ensure the required field uniformity. RTDs and fluxgate sensors compatible to cryogenic environment are used to detect temperature and magnetic flux density respectively with fine resolution. A multi channel data acquisition system was used to acquire and analyze data from different detectors. Iterative attempts were made to acquire data during cavity cool down across the transition temperature. The paper also presents the preliminary test results obtained from the experiments performed at Vertical test stand facility at RRCAT on a β= 0.92 650 MHz, single cell SCRF cavity. The data acquired during testing was found repeatable and precise . The experimental setup is scalable and can also be deployed on the 650 MHz five cell cavity.

In future study of flux expulsion data from a large number of cavities will be required in order to categorize the processes that contribute strongly to the magnetic flux trapping phenomenon in high RRR Niobium cavities. This study will also help to identify treatment required to transform a cavity showing weak flux expulsion characteristics to strong flux expulsion. Avoiding the flux trapping in SCRF cavities will enable us to achieve the desired cavity performance characteristics of high quality factor, better operational and cryogenic efficiency.

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Processing and Cleanroom Preparation of SCRF Cavities for Performance Testing in VTS Cryostat

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RRCAT is pursuing research and development activities related to high beta 650 MHz superconducting radio frequency (SCRF) cavities which shall be major component in high intensity superconducting proton LINAC for future Indian Facility for Spallation Research (IFSR). Under this program, development and setting up of infrastructure facilities for fabrication, processing & testing of superconducting RF (SCRF) cavities are taken up. Development of SCRF cavities and infrastructure is also useful for Indian Institution Fermilab collaboration (IIFC) for PIP-II (Proton Improvement Program)**[1]**. Superconducting RF cavities after fabrication, need to be inspected and go through several steps of processing like ultrasonic cleaning, electro-polishing, high pressure rinsing etc. to conform to the desired surface quality. Any particulate impurity on the superconducting cavity RF surface can influence its maximum achievable accelerating gradient and limiting its performance, hence contamination by particulates has to be avoided. The processed cavities are assembled under controlled environmental conditions and prepared for performance test at 2K in Vertical Test Stand (VTS) Cryostat. A dedicated ISO class 10 cleanroom facility is used for assembly and preparation of cavity. Cleanroom preparation of SCRF cavity includes component and hardware cleaning, High Pressure Rinsing (HPR), drying after HPR, assembly of end flanges, assembly of RF feed ports, burst disk and all metal angle valve with the cavity, evacuation and vacuum leak testing. Preparation of components and hardware before assembly requires exhaustive cleaning steps which include ultrasonic rinsing using special solvent, ultrapure water rinsing, drying with high purity ionized nitrogen gas. For nitrogen purging of components cleanroom compatible nitrogen purge line made of polished stainless steel tubes has been set up. High Pressure rinsing with ultrapure water is the final cleaning procedure before vertical test. It removes the micro contaminants from internal surfaces of cavities and helps in improving cavity performance by reducing field emission. In high pressure rinsing, all parts of cavity internal surface are scanned by high pressure (80-100 bar) jets of ultrapure water (Resistivity $\geq$ 18 MΩ.cm). The jets emerge from a rotating wand coaxial with the cavity traversing around it. First round of HPR is carried out for 10 hours. After drying the cavity in clean room air overnight, assembly of end flange and RF feed port is carried out. After first assembly, second round of HPR for about 17 hours is performed. Cavity is dried for 48 hours and second assembly of bottom flange with burst disk and angle valve is carried out. Cavity is evacuated using clean vacuum line and oil free pumping station. Vacuum leak testing of cavity is done using RGA and cavity is finally sealed at pressure < 7E-7 mbar. Cavity is moved out of cleanroom and further prepared for VTS test. It is shifted to VTS staging area and assembled with instrumentation like temperature sensors, second sound sensors and inserted in VTS cryostat for performance testing at 2K. The cavity high pressure rinsing and assembly procedures have been modified and upgraded to improve the process and cavity performance. The paper described various facilities developed and processes involved in preparing the cavities for testing in VTS Cryostat.

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Development of Titanium gr-2 Bellows for HB 650 MHz 5-cell SCRF cavities

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R & D activities are going on at RRCAT for development of high energy regime (HB) 0.92, 650 MHz, five-cell superconducting radio frequency (SCRF) cavities required for proposed high energy superconducting proton accelerator. In addition, these cavities will be a part of deliverables from RRCAT to Fermilab under Indian Institutes Fermilab Collaboration (IIFC) ***[1]****. Each SCRF cavity is enclosed within titanium vessel containing liquid helium. Titanium bellows joins helium vessel with cavity at field probe (FP) end. Titanium was chosen for its low temperature toughness, weldability and closeness of linear coefficient of thermal expansion with high RRR niobium. The bellow has to deal with axial displacement for cavity tuning and compensates the differential expansion/contraction between niobium cavity and titanium vessel due to cooling from 300K to 2K temperature and vice versa. Also, the bellows must be stiff enough circumferentially to withstand the liquid helium pressure and flexible enough to facilitate axial displacement. Titanium bellows development involves challenges of thin sheet forming, titanium welding and qualifications for rated parameters and no manufacturer in India was qualified for SCRF applications. A two way prolonged approach, to develop these from US vendor to meet the short term goal of meeting the IIFC deliverable timelines as well as its development in India for long term goal, was taken up. After exhaustive market survey few vendors were identified. Details technical specification with stringent qualification and acceptance criteria were prepared and Order was placed on M/s Ameriflex, Inc. Vendor's design report was reviewed and design validation of bellows conforming to EJMA10/Appendix 26 of ASME section VIII has been carried out suggesting several corrections. Inspection reports were reviewed (including decolouration of sample to qualify Ti welding procedure) in remote mode. Ti gr-2 bellows are fabricated by seam welding and hydro-forming of 0.4 mm thick sheet/blank* ***[5}[6]****. Later, machined end rings were welded at either ends. Welding was carried out by micro-TIG Welding process using ERTi-2 filler. After ends machining to remove distortion and bellows cleaning, vacuum leak rate measurement was carried out. Necessary forming, machining and welding fixtures were designed and fabricated. All the weld joints have been qualified as per ASME section IX. To ensure sufficient toughness/ductility of welds at 2K temperature, as per AWS G2.4M, the oxidations (discoloration) of welds were minimized* ***[4]****. Later, these were qualified for designed parameters.This paper covers the design, forming and welding of bellows using micro TIG with extra argon purging, acceptance (as per AWS G2.4M) and testing of bellows to qualify for cavity requirements* ***[2][3]****. Three cavities, dressed utilizing theses bellows have been qualified for HTS test parameters at Fermilab and have been assembled in cryomodule significantly helping DAE/India to meet their deliverables to Fermilab in the R&D phase of IIFC. The experience thus gained is very helpful for their indigenous development.*

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EB welding of Helium Vessel Assembly for 650 MHz SCRF Dressed Cavities

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Superconducting Radio Frequency cavity is very important component in High intensity proton accelerators. 650 MHz β=0.92 SCRF dressed cavities are required to be devloped as deliverables under Indian Institutes Fermilab Collaboration (IIFC) for Proton Improvement Plan-II (PIP-II) project at Fermi National Accelerator Laboratory (Fermilab),USA.These cavities are also required for proposed high energy(1 GeV) Superconducting Proton linear accelerator research and development at RRCAT Indore. RRCAT has developed dedicated in-house infrastructure and expertise for fabrication, processing and qualification (2K testing, dressing and HTS testing) of SCRF cavities, cavity dressing components and SCRF cavity dressing.Titanium helium vessels have been used for housing Superconducting Radio Frequency cavities due to its compatible thermal expansion coefficient with niobium cavities. Dressing of bare cavity is challenging as it has pressure boundary joints working at 2K temperature.Titanium is a highly reactive material and needs to be welded in vacuum controlled atomphere.Helium vessels have been fabricated using Electron Beam welding method which is first of its kind, as conventionally it is done in Welding Glove box using TIG welding.The EB welding route offere several advantages like faster and automated process with possibility of making several joints in one setting and low distortion which is very helpful as cavity support bracket are used as reference for precision alighment of dressed cavity in the cryomodule. Electron beam welding of different components like Titanium cylinder, chimney Adaptor, lifting lugs, tuner mounting support bracket and cavity support bracket have twenty six weld joints. All these joints has been designed suitable to EBW process.Chimney Adaptor is very crucial full penetration 3D joint. EB welding is very useful here due to low heat input to protect possible damage with an explosion bond welded joint in close vicinity. All the joints of the Helium Vessel were welded by 15 kW (150 kV, 100 mA) electron beam welding (EBW) facility available at Superconducting Cavities Development Division (SCDD) at RRCAT Indore.Crucial weld parameters like beam current, accelerating voltage, beam focusing, beam oscillations, weld speed, gun to work distance etc, plays an important role for finalizing the quality of weld. These paremeters were optimized by carrying trials on linear and circular test coupons/ samples. Linear test coupons have been tested for micrograph of weld cross-section and mechanical strength. Circular coupons have been welded and examined for micrograph of weld cross-section and the beam current is ajusted for getting good bead. Quality assurance and control plan was made to control the dimensions, parellelism and weld shrinkage during welding. Further, welding of actual Titanium vessel joints was performed using optimized parameters.This paper discusses the various steps and precaution followed, difficulty faced and their remedies performed in welding for theHelium vessel joints of the 650 MHz β=0.92 multi cell SCRF cavities.RRCAT has successfully fabricated five numbers of 650MHz β=0.92 Titanium Helium vessel assembly for SCRF cavity dressing. The vessel assembly has successfully qualified Helium leak test for the leak rate of 1E-10 mbar l/s at Room Temperature .Three 650MHz β=0.92 Titanium Helium vessel with ID 502,503 and 504 which are fabricated at RRCAT and dressed at Fermilab and qualified for prototype cryomodule(pCM) string assembly PIP-II Project.

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Experience of Dumbbells fabrication for five-cell HB 650 (β=0.92) SCRF cavities in Indian Industries

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Large numbers of 650 MHz (β=0.92) Superconducting Radio Frequency (SCRF) cavities are required to be fabricated under Indian Institutes Fermilab Collaboration (IIFC) for PIP-II project at Fermilab,USA and for envisaged high intensity superconducting proton accelerator in Department of Atomic Energy (DAE). RRCAT has developed dedicated in-house infrastructure and expertise for fabrication, processing and qualification of SCRF cavities [1]. In order to cater large scale production of multi-cell SCRF cavites, it is planned to develop Indian Industries under Atmanirbhar Bharat. Internationally only few industries makes SCRF cavities on 'built to print' basis and not on 'built to performance' basis. Dumb-bells make an important part of any multi-cell SCRF cavity. Hence, RRCAT has initated the development of dumbbells at Industries. The formed half cell, stiffening ring, dedicated welding & machining fixtures are issued to Industries for fabrication of dumbbells.The Electron Beam Welding (EBW) machine at Industries was qualified for retainment of RRR on high RRR Niobium samples. The half-cells were etched by buffered chemical polishing (BCP) up to 20 μm to remove the impurities, contamination and oxidized layer just before welding.This was followed by rinsing in ultra-pure water. During niobium welding vacuum chamber pressure of <3x10^{-5} mbar was maintained. Weld parameter like beam current, accelerating voltage, welding speed and focusing current were optimized on various weld samples.Quality control plan was made to control the dimensions, parellelism and weld shrinkage during outside, inside & steffening ring machining and welding. In first step the two half cell are joined back to back by EB welding at IRIS to form a dumbbell (First from outside a.nd then from inside) and in second step, stiffening ring is machined as per measured gap and welded to the dumb-bells from outside with full penetration weld.The steffening ring EB welding is crucial weld with full penetration from outside which leads to large deformation in dummbell [2]. The weld shrinkage leads to deformation in half cell geometry which needs to be corrcted by tuning and trimmming. Eight number of Dumbbells for two five-cell SCRF cavities have been fabricated at Indian Industries with development of special tooling, fixtures and weld parameters.These dumbbells have also been pre-qualified for dimensional measurement, radiography test and radio frequancy (RF) testing. The Dumbbells tuning were performed in-house by special tuning fixture to get the right length, right frequency and required parellelism.The dumbbells triming at Equator were performed at Industry. Special machining fixture were designed for equator machining and machining was performed on dedicated CNC machine,dedicated cutting tool with optimized machining parameter and appropriate coolant was used thoughout the machining process. The paper presents the lesson learned and experience gained during fabrication of these dumbbells with manufacturing process sequence plan,forming of half cell, weld joint design,chemical cleaning, weld parameters optimization, machining, dumbbell tuning and equator machining at final stage of fabrication. The experience gained in fabrication of dumbbells will be useful for for large scale production of SCRF cavities.

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Development Journey of Elliptically Shaped High Beta 650 MHz Superconducting RF Cavity: An Overview

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RRCAT is pursuing the development of superconducting cavities for more than a decade and has established the infrastructure for superconducting cavity development. The purpose of developing superconducting cavity facilities is twofold; one is to cater the deliveries under the Indian Institution Fermilab collaboration (IIFC) for PIP-II (Proton Improvement Plan - II) and another one is to develop strength for future Indian proton accelerator projects [1]. RRCAT has developed complete in-house infrastructures for superconducting cavities such as forming, machining, electron beam welding, CMM inspection, material characterization, RF stations, processing, testing at 2K temperature, dressing, etc. The development work includes physics design, engineering analysis [2], procurement of high RRR niobium and other materials, manufacturing prototypes, high RRR niobium fabrication, field flatness correction, processing and 2 K testing until bare cavity reaches its qualification parameters. Further, these bare cavities are dressed and reprocessed for final qualification for the string assembly of cryomodule.

During the R&D phase of IIFC, an important milestone towards this development has been achieved when three RRCAT high beta 5-cell 650 MHz cavities (designated as HB650-RRCAT-502, HB650-RRCAT-504 and HB650-RRCAT-506) qualified for HB650 (High beta 650MHz) pCM (prototype Cryo-Module) of PIP-II. Superconducting cavities are fabricated using high RRR niobium sheets by forming, machining, inspection, RF measurement and chemical cleaning which is followed by electron beam welding. All the joints of the superconducting RF bare cavity components were welded by a 15 kW (150 kV, 100 mA) electron beam welding (EBW) facility available at RRCAT. There are total of 54 various types of weld joints having more than 25 m of welding length. Most of these joints are not only vacuum boundary joints but also fall in RF boundary joints, which make these joints most critical. The bare cavities, after leak testing at room temperature and at LN_2 temperature, are corrected for a uniform electric field in each cell which is followed by processing (electro-polishing and high-pressure rinsing). The bare cavities are tested at 2K in VTS (Vertical Test Stand) and are reprocessed if required. HB650 cavity has operating voltage gradient (E_{acc}) of 18.8 MV/m and quality factor (Q_0) of 3.3E10 as per PIP-II HB650 cavity technical requirements. Once the bare cavity is qualified in VTS, it is dressed with a titanium helium vessel in environment controlled glove box. These cavities are pressure-tested and vacuum tested before the final qualification test cycle at 2K. This paper elaborates the lessons learned during the entire process from design to final stages of qualification.

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Thermo-mechanical analysis of MEHIPA couplers

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RF coaxial couplers are required to provide high RF power (maximum 40 kW at 325 MHz) to the SSR cavities of MEHIPA. Each SSR cavity requires different power. The power requirement varies from 6 kw to 40 kW. The coupler design has been optimized so that the same type of coupler can be used to feed all the cavities. This coupler has 6-1/8" input line, inner and outer bellows for flexibility, ceramic window, air cooled inner antenna for capacitive coupling etc. CST simulation of this coupler has been done [1]. It has been designed provide good match at input. After RF simulation thermal simulations has been carried out for different reflections and phases at the output port of the coupler. Along with RF and thermal simulations it is necessary to know the stresses at the alumina window brazing joints [2]. During full power operations these brazing joints may break if the temperature and stresses are too high. So, preliminary level simulations have been carried out in 2D-comsol software to calculate stresses at the inner and outer side of the alumina brazing joints. This paper describes this thermo-mechanical analysis of the coupler.

The most weak places of coupler is places of brazing ceramic to copper sleeves and brazing of copper sleeves to flange and to antenna. There are two reasons of stresses during operation: atmospheric pressure to the window and change of size due to heating/cooling. According to literature available in any case the stress has be below 100 MPa at the joint for increased life cycle of ceramic [2]. To reduce the stress it is required to reduce the temperature gradient at the brazing joints. For this generally some design changes are done which includes increasing the size of the alumina disk, improving the cooling etc. To study this behavior first thermal analysis was carried out in CST for different phases with full reflection as well as 20% reflection cases. Temperature profiles were obtained along the radius of the ceramic for these different conditions. These temperature profiles were exported to comsol 2D for mechanical stress analysis. This analysis is being carried and results will be presented.

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Design and development of 100 kW, 325 MHz tetrode tube based high power RF pulse amplifier

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Modern pulse power tetrode tubes, equipped with pyrolithic graphite grids and advanced filament cathode - offer a very attractive option of having a high power pulse RF power amplifier in VHF band. These devices offer inherent advantages like mechanical and electrical robustness, compact size, energy efficient high power operation and overall cost effectiveness of radio frequency power amplifier (RFPA). This paper discusses design of a high power pulsed RFPA based on tetrode tube TH391, which is specially designed for high power pulse operation in extended VHF band, and required interlocking system. This amplifier system is being developed as an alternative to solid state RFPA for energizing pulsed radio frequency quadrupole (RFQ). This RFPA is designed to deliver 100 kW output power at 325 MHz for 5% duty cycle. Tube is rated for a gain of 15 dB, but with consideration of aging, a gain of 12 dB is assumed while estimating the required input RF power of 7 kW. Trade off among efficiency and harmonics is decided by class of operation. It is designed to operate the tetrode tube TH391 in grounded grid configuration under class AB mode. RFPA will be biased with a pulsed power supply (-250V/-150V) at control grid, thus minimizing power loss during off state of RF input pulse cycle. 14 kV anode voltage and 1 kV screen grid voltage are selected as operating point of tetrode tube. For 100 kW output RF power and 12 kV RF swing at anode, required value of peak anode pulse current is around 34 A, along with optimum impedance of 720 Ω at anode. This impedance is matched to 50 Ω output load by a tunable rectangular cavity with magnetic loop. At input side, a coaxial transmission lined based matching structures is used to realize matching of 50 Ω impedance of source to 12 Ω at cathode of tube. Mechanical plunger based tuning strategy is implemented for realization of ±5 MHz tunable RF bandwidth. For the purpose of control and protection of RFPA, a control, monitoring and interlock (CMI) systems is designed as an integral part of this amplifier. With tetrode tube systems, biasing supplies and RF input are required to be switched ON and OFF in a predefined sequential manner for safety of tube, amplifier structure and other subsystems. A Siemens make S7-CPU-315-2DP (CPU) based programmable logic controller (PLC) system is designed for execution of pre-programmed operation sequence and interlocking of currents and voltages of all biasing supplies along with cooling system. Siemens make human machine interface (HMI) KPT1000 is being used for command input and status cum alarm display unit. The CMI system is developed with the feature of balckheat mode to prevent multiple on off cycle of tetrode filament for better life expectancy. Sequential standby and transmit modes of CMI system put tetrode tube in ready stage for high voltage operation and amplification of RF input power respectively, thus minimizing RFPA idle time. CMI unit has been deployed for testing of tetrode tube TH 391 under DC pulse operation for a pulse current of 40 A.

Design Study on Solid-state RF power system for 10MeV Re-circulating High Power Accelerator (RHPA)

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Design & development work for realization of 107.5MHz solid-state RF power system is taken up which is required for feeding coaxial accelerating cavity of 10MeV re-circulating EB accelerator capable of delivering maximum beam power of 30kW. The maximum RF power of 150kW as required, is to be delivered to the coaxial accelerating cavity with help of three RF power transmitter; wherein the each one connected exclusively to a cavity feed port, excite the cavity in same phase and capable of delivering 50kW RF power to the cavity at 107.5MHz with required isolation between transmitter outputs. The 50 kW/107.5MHz transmitter is to be developed using solid-state device technology in alternative to RF power systems based on tetrode tube. It is being realized by combining 32 nos. of 1.6KW RF power modules with help of simultaneously matched N-way RF power combiner at the operating frequency of 107.5MHz as designed. Each RF power module based on MRFX1K80H LDMOS, is developed for rated output power of 1.6KW at 107.5MHz. The combiner output port is be coupled to the coaxial cavity feed port via 60kW, 107MHz junction-circulator and 61/8" EIA coaxial line system. All the ports of the combiner are simultaneously matched to 50 ohm system impedance, therefore drop-in circulator will not be required at the outputs of the RF power modules for feeding the combiner which is otherwise too bulky to be part of the RF power module at 107.5MHz/1.6kW. A 32way RF power combiner is designed using Gysel network topology in multi-layer configuration using suspended stripline. This novel design of high power N-way combiner provides matched load to connected RF power modules even when there is an amplitude & phase mismatch among outputs of the amplifiers modules feeding the combiner. This will assure isolation between RF power modules and stabilize the performance; also should some RF power module fail, performance of healthy module remains unaffected. Performance of the RF combiner structure is evaluated with help of 3D full wave EM simulator done on CST MWS and optimized in terms of S parameters. Its Compatibility to high power operation is evaluated in terms of E-field & H-field values at various points which is found to be well below the safe operating level. S-parameters results as obtained confirmed simultaneous matching of all its input ports to better than 28dB, isolation between port to be better than 30dB and insertion losses to be less than 0.1dB in frequency range of 107.5+/-5MHz in worst case of phase and amplitude mismatch among inputs. The sum-output-port is a 50 ohm, 6-1/8" EIA coaxial port. Coaxial-line directional coupler is to integrated with solid-state modules as a single unit which is designed, fabricated and tested; which meet all our design parameters of coupling factor, isolation, matching to be 50dB, 32dB and 35dB respectively at the design RF power level of 1.6kW at 107.6MHz. RF power amplifier module based on LDMOS device MRFX1K80H is developed and tested at 1.6kW power level with required performance. This paper will give brief account of design requirements & satisfactory performance as obtained and also progress made in the realization..

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Conditioning, testing and phase measurement of 1 MW, 352 MHz klystron system for 20 MeV DTL of LEHIPA

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Low energy high intensity proton accelerator (LEHIPA) is final stage of commissioning of 20 MeV DTL. LEHIPA has Drift Tube Linac (tank-1&2, and tank-3 &4) that accelerates the 3 MeV proton beam from RFQ to 20 MeV. Both DTL tank-1 & 2 and DTL tank-3 & 4 require around ~ 850 kW at 352 MHz RF power to accelerate the beam up to 20 MeV. This RF power is supplied by 1 MW klystron based RF system. Proton beam is already accelerated up to 11 MeV using DTL tank-1 & 2. 2nd klystron system is fed around 830 kW RF power to 11 MeV DTL. Third klystron system for powering 20 MeV DTL tank-3 & 4 is recently tested and commissioned.

Third klystron vacuum was deteriorated with time beyond normal operating range, so it is not simple to powering the klystron. A poor vacuum in a klystron will cause breakdown between cathode and body or anode during powering klystron and damage itself permanently. Conditioning of klystron has been carried out in systematic way to improve the vacuum of the klystron. Biasing condition of the klystron is optimized each HV power level. Klystron conditioning was started form low DC power to high DC power in pulse mode with low repetition rate. The DC power has been increased in steps by optimizing the biasing parameters at each step. The klystron vacuum was also monitored and noted during operation. After the DC conditioning, the klystron has been tested up to 850 kW (RF output) in pulse mode on dummy load.

This paper discusses the details of klystron conditioning, RF testing and output power phase measurement w.r.t to input of klystron. This paper also describes the sub-system of 1 MW, klystron based RF system.

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Power Combining topology for CW 32kW-650 MHz Solid State RF Amplifier (SSPA) installed at Horizontal Test Stand (HTS) facility, RRCAT

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For the characterization and qualification of superconducting RF cavities at HTS facility, RRCAT, 32 kW-650 MHz CW water-cooled Solid-State high power RF Amplifier (SSPA) has been designed, developed and deployed [1]. Fully dressed, high beta, elliptical, super conducting RF cavity AES-010, from Fermilab, USA was tested at HTS facility, RRCAT successfully with the help of this SSPA. 32 kW of SSPA RF output power is obtained by combining two nos. of 16 kW SSPA Racks using lossless, junction type, 2-way RF Power Combiner with power handling capacity of 70 kW. This Power Combiner has two inputs as well as output on 6 1/8-inch rigid coaxial line interface. Cascaded stepped impedance coaxial line sections have been designed, for impedance matching of the junction of the 2-way power combiner to system impedance of 50 ohm, at center frequency of 650 MHz. Return loss better than 25 dB has been measured with the help of Rhode & Schwarz make Vector Network Analyzer (VNA) for this 2-way RF power combiner. Also, Amplitude and phase symmetry better than ± 0.05 dB and ± 1° respectively in coupling coefficients have been achieved for this 2-way RF power combiner, resulting in power combining efficiency better than 98%. To achieve 16 kW of RF output from single SSPA Rack, 48 nos. of 500-watt solid state RF amplifier modules have been power combined by novel 48-way RF Power Combining-Power Dividing Structures at 650 MHz.These lossless structures are based upon radial power combining/dividing scheme. These 48-way Power combiner-Power Divider structures have two sperate combining/dividing electromagnetic (EM) planes on either side of radial line, making these RF structures compact by factor of two. Due to this, coupling coefficients of these structures become inherently asymmetrical in amplitude as well as phase [2]. A suitable shorting stub has been designed and suitably placed in these RF structures to achieve amplitude symmetry of coupling coefficients. This stub also helps in removing heat from center conductor by water cooling. For phase compensation, 48-way RF Power Combiner and RF Power Divider are used in cross fashion in 16 kW SSPA rack. 48-way RF Power Combiner has output on 6 1/8-inch rigid coaxial line interface and 48 nos. of input on N-type Connectors. 48-way RF Power Divider has input as well 48 nos. of output on N-type connectors. Return loss better than 20 dB has been achieved for both the RF structures. Amplitude and phase symmetry better than ± 0.2 dB and ± 2° respectively for coupling coefficients have been measured with the help of VNA, resulting in power combining efficiency better than 95%. Phase deviation of 50° has been measured between the two separate combining/dividing EM planes. Port to Port RF isolations ranging from 13 dB to 32 dB have been measured with the help of VNA, depending upon the position of ports. This paper discusses detailed RF design methodology including design of input impedance matching sections, design of shorting stub for amplitude compensation, thermal management and RF measurements for the 70 kW 2-way RF Power Combiner, 48-way RF Power combiner and 48-way RF Power Divider.

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Indigenous development of 13.56 MHz RF amplifiers

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*Internationally, portions of the radio spectrum is reserved for industrial, scientific, and medical (ISM) purposes. So under ISM, various scientific activities require 13.56 MHz RF power systems, which are mostly imported in our country. At BARC, indigenous standalone radio frequency (RF) power system comprising of 13.56 MHz, 250 W solid state amplifier and 50 W solid state amplifier have been designed and developed.*The *major design objectives / goals are compact size, good efficiency (70 %), moderate gain (20 dB),cost effectiveness and plug & play type RF power system with stringent performance features as an import substitute for 13.56 MHz RF source.This RF system consists of 13.56 MHz signal synthesizer, a driver amplifier, a 250/50 watt power amplifier stage, a bi directional coupler [1] and an external impedance matching network (IMN) for cold plasma device. In addition to above it consists of DC bias supplies, directional coupler based RF power meter and interlock and protection system for overall protection and control of entire system. Forced air cooling is provided for driver amplifier and power amplifier. Each of these sub systems are explained in detail in the paper. Both these RF systems have tested for long term and their performance parameters have been noted. Important & critical performance parameters achieved of these RF system are:*

I. *Efficiency (DC to RF) %: > 70%*
II. *Efficiency (AC to RF) %: > 64%*
III. *Gain (dB):21 dB*
IV. *Withstanding short and open load conditions without use of circulator*
V. *Modular, Portable & Field deployable*

A novel protection scheme based on reflected power and MOSFET junction temperature is used to protect RF amplifier against continuous high reflected power. An interlock and protection system has been used for sequential 'ON/OFF', control and protection of system against over voltage, over current and over temperature. Another innovative development is an indigenously designed high directivity directional coupler for simultaneous measurement and monitoring of both forward and reflected RF power. These directional couplers are very much cost effective and compact as compared to imported RF directional couplers,which are highly expensive.

Design details and test results are discussed in the paper.

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DEVELOPMENT OF 8-WAY HIGH RF POWER COMBINER AT 75.6MHz

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In Variable Energy Cyclotron Centre (VECC), development of high RF power solid-state amplifiers and power combiners at 75.6 MHz is under progress for feeding Linac Cavities of Radio-active Ion Beam (RIB) project. Efficient power combining is basic requirement for high power Solid State Amplifier design. The present work illustrates design and implementation of an equal split 8-way Radial RF power combiner/divider to generate combined 1KW RF output power at 75.6MHz. The combiner exhibit negligible insertion loss leading to no efficiency degradation and lesser heat dissipation. Measured performance of the power combiner is in excellent agreement with theoretical results at 75.6MHz with 1% desired bandwidth. A Gysel combiner type configuration has been incorporated with the 8-way combiner for achieving good peripheral port isolation. Finally, peripheral port isolation of better than 40dB has been achieved and the system was tested with 95% power combining efficiency.

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Prototype Development of Digital Controllers for Multi-Module Current Sharing Power Supply for RF Amplifiers

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Accelerator systems are designed to be functionally accurate and reliable with many considerations taken into account. Any subsystem associated with particle accelerators are designed and engineered taking aspects of reliability and redundancy into consideration. It is also very important to design any subsystem with very low Mean Time Before Failure (MTBF) and very high availability for its designed life. Radio Frequency (RF) System is one of very critical subsystem of accelerator which needs to perform very precisely and fault free. Many aspects are taken into consideration during engineering design for ensuring fault free operation of RF Systems including low level RF, amplifiers, RF delivery, RF Cavity etc. DC Power supplies which powers RF amplifiers plays very crucial role in the overall performance of RF system. The DC power supply performance and reliability is important hence design of controller for power supply has to be robust and reliable. The prototype development scheme have multiple module DC power supply to bias solid state RF amplifiers, current sharing approach with redundancy and monitoring features. Considering the scheme, systematic design of prototype controller for DC power supply is being done so that very high availability is ensured. Current sharing in power supply is achieved using multiple power supply modules connected in parallel which communicates with central controller and maintain the desired voltage and current at the output which powers the RF amplifiers. Modular approach for power supply helps in reducing bulky hardware and also reduce the maintenance time. Systematic diagnostics of power supply, online health monitoring along with modular current sharing are few techniques which helps in improving reliability and availability of power supply. Redundant, reliable & fast communication between central controller and module controller has to be ensured. Differential signal, optical fiber along with robust communication protocol with error detection, are techniques implemented for making communication, immune from very high electrically noisy environment. A prototype digital controller is being designed for power supply to work in redundant, modular current sharing mode and have fast communication interface. Incremental design implementation and testing has proven very useful approach for development of the digital controller. The present scheme have single master and multiple slave modules. Provision for multi-master and redundant central controller is also taken into consideration in the design. This paper will discuss design scheme, status of communication protocols, its performance and present limitations. The prototype development is done using Real Time Operating System (RTOS) and Field Programmable Gate Array (FPGA).This paper will also highlight implementation of key feature on the digital controllers.The incremental prototype development is being successfully done and its test results are highly encouraging, this paper will also have a brief discussion on road map ahead and various possible combinations of implantation in final design of the digital controller in multiple module (current sharing) DC power supply to bias solid state RF amplifiers.

Design and Testing of components for High Power RF Systems for LEHIPA 20 MeV acceleration

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The LEHIPA project is under development at BARC for acceleration of proton beam to an energy of 20 MeV. The LEHIPA basically consists of three accelerating cavities and one buncher cavity. The accelerating cavities are Radio Frequency Quadrupoles (RFQ), and two stages of Drift Tube Linacs (DTLs). Recently, proton beam acceleration up to 10.8 MeV has been commissioned through RFQ, buncher, and DTL-1. The three acceleration cavities RFQ, DTL-1, and DTL-2 are driven by a high-power RF klystron working at 352 MHz. The corresponding RF power required for these structures are 500 kW for RFQ, and 900 kW for each for DTL-1 &2. In between the high-power klystrons and the RF accelerating structures, there required a high-power waveguide transmission line at 352 MHz. These waveguide transmission systems have various high-power RF components in WR2300 waveguide like straight sections, E/H plane bends, directional couplers, magic tees, phase shifters, windows etc. All these waveguide transmission line components have been indigenously designed, tested. The waveguide systems for RFQ and DTL-1 are commissioned. The waveguide systems for DTL-2 are characterized and ready for installation. A waveguide matched load at 352 MHz is desired at various places in the waveguide distribution to terminate the un-balanced or reflected RF power in the system. The main locations of the RF waveguide loads are at the magic tee's balanced ports (4th port of the Magic Tee). A waveguide with salt columns are used as absorbent for a RF wave energy. The salt concertation has been varied to optimize the absorption coefficient. The length of the salt column, size, spacing of the columns have been designed for maximum absorption. The designed load has been connected to the output of the klystron and tested for maximum rating 800 kW in pulse mode. A high-power RF window has been designed to operate at 352 MHz for Low Energy High Intensity Proton Accelerator. It has been designed in a WR2300 half height waveguide. The Alumina ceramic make circular window is embedded in a cutoff mode of a circular waveguide. On either side of the window a rectangular waveguide is used. The window is matched to a rectangular waveguide using a pair of posts on each side of the window. The RF performance parameters of the window have been optimized. The designed window has an input return loss better than 20 dB and an insertion loss less than 0.28 dB. The design has been implemented using Alumina ceramic material of low loss tangent of 0.08 and dielectric constant of 9. The waveguide made of Al is used on air side and whereas SS made waveguide with Cu plating used for vacuum side. The fabricated window has been characterized for its RF & vacuum performance. The developed window met the design parameters and also passed the vacuum leak test. Five such windows have been fabricated and tested for Drift Tube Linac-2 (DTL-2) of LEHIPA. The windows are in the process of installation in DTL-2 of the LEHIPA system. The paper presents the analysis, design, implementation, and test results of the various waveguide components including the critical components like Waveguide matched load and RF window. The paper also presents the present status of commissioning of these waveguide systems.

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Status of Design and Testing of 20 kW solid-state RF Power Amplifier for Buncher Cavity of LEHIPA

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The LEHIPA project is under development at BARC for acceleration of proton beam to an energy of 20 MeV. The block diagram of the LEHIPA system is shown in Fig. 1. The LEHIPA basically consists of three accelerating cavities and one buncher cavity. The accelerating cavities are Radio Frequency Quadrupoles (RFQ), and two stages of Drift Tube Linacs (DTLs). Recently, proton acceleration up to 10.8 MeV has been commissioned. These accelerating cavities are driven by a high-power RF klystron working at 352 MHz. A waveguide distribution systems couple RF power output of Klystrons to accelerating cavities. A 3-1/8” coaxial waveguide couples the solid-state RF power amplifier (SSPA) to a buncher cavity.

Presently, the buncher cavity is operating at 10 kW at 352 MHz. A new CW/pulse RF solid-state power amplifier is planned to be designed. In future, the LEHIPA may operate at increased CW/peak currents. To mitigate the requirement of increased beam parameters, the buncher may require the power output >20 kW at 352 MHz from SSPA. As the present operating power amplifier is designed way back in 2014, and it’s operation and maintenance is costly and time consuming in future. Many technologies of the RF devices have been changed over the years and availability of electronic parts are difficult. In order to avoid the down time of LEHIPA, in future it needs an innovatively designed SSPA. In view of these a 20 kW Rf power amplifier design is taken up. It consists of 24 RFPAs which are combined using 24-way power combiner. The paper present the deign details of RF power amplifier of 20 kW at 352 MHz.

Design and Development of Pulse 2 kW Solid State amplifiers for Energizing S-Band Pre-Buncher Cavity of 10 MeV, 10 kW LINAC developed at RRCAT

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RRCAT Indore has developed 10 MeV,10 kW Electron LINAC named KIRTI-1010, for electron beam radiation processing. The LINAC will be installed at M/s. Microtrol Sterilisation Services Pvt. Ltd. Bangalore under incubation agreement presented in ref [2]. A 2856 MHz, 2 kW pulse amplifier has been designed and developed to energize S-Band pre-buncher of the LINAC. The amplifier is developed by combining two 1 kW amplifier modules previously fabricated using a LIM-EOM based planar RF combiners, the details of which were presented in ref [1]. The amplifiers supersede our earlier 2 kW amplifier design presented in ref [3]. The earlier design utilizes 8 LDMOS devices combined via 3 stage 8:1 Wilkinson combiner while the new design requires only 6 LDMOS devices.

The S-Band amplifier provides a peak power of more than 2 kW, at an operating pulse width of 16 µs and a pulse repetition rate in excess of 300 Hz. The amplifier provides a gain greater than 57 dB, 0.1 dB bandwidth of 2856 MHz ± 5 MHz and operates in class AB mode. The amplifier has 4- stages of amplification starting with a Low Noise Amplifier (LNA) followed by a pre-driver, a driver stage and finally the high-power stage consisting of two 1 kW modules combined via hybrid combiner. A dual directional coupler is incorporated in the high-power combiner eliminating the need for a separate coupler. The output of each 1 kW amplifier module is protected by a co-axial circulator providing protection against reflection from pre-buncher. An RF switch is used before the LNA to provide pulse width modulation, synchronized with trigger signal. Two such amplifiers have been installed in the S-Band RF system for the KIRTI-1010, with one functioning as a spare for quick replacement. Both the amplifiers have been extensively tested during the LINAC operation at RRCAT. The amplifiers have performed satisfactorily during the trial operation with no failure during nearly two months of operation. Development of more amplifiers of same design is also being carried out to meet future requirements of upgrades and spares at other accelerator facilities at RRCAT.

The present paper describes the design details and test results of the amplifiers.

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Design and Development of S-Band Low Level RF System for 10 MeV, 10 kW Electron Linear Accelerator KIRTI-1010

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RRCAT is a premier center for development of various accelerator technologies in India, and has recently developed a 10 MeV, 10 kW electron LINAC named KIRTI-1010 for electron beam radiation processing. A 2856 MHz, 6 MW klystron is used to energize the LINAC. The S-Band LLRF system consists of a2 kW S-Band pulse amplifier for energizing the PB cavity of LINAC, a 350 W amplifier for driving the 6 MW klystron, a power display and distribution unit (PDDU), an optical to TTL converter and an RF signal generator. The PDDU is the heart of the system, and it consists of a power splitter, a voltage-controlled phase shifter, a four channel RF pulse power meter, and pre-buncher fault detection system all developed in-house.

The power splitter divides the incoming RF signal from generator into two parts one for klystron driver and the other for PB amplifier. The phase shifter is incorporated into the PB arm and provides a mechanism to adjust phase between the PB and LINAC for maximizing electron beam performance. The 4-channel power meter consists of in house developed RF detector cards and a microcontroller based power measurement and display system which provides readout in user selectable units and has facility to add offset to the displayed power. The PDDU also displays the phase set via phase shifter in degrees for ease of operation. The PDDU also features an adjustable marker for reading the power level at a particular point on the pulse waveform which is shown on a DSO. The RF detector cards convert the incoming pulsed RF signals into a DC pulseenvelope, a precision Sample and Hold (S/H) circuit designed in house is used along with 10-bit, ADC of microcontroller (Arduino Mega) to measure the RF power with precision. Arduino based microcontroller is used to take advantage of large libraries available for the platform.

The PDDU power measurement accuracy is within 0.1dB with respect to the reference power meter. A python-based application has been developed for automated calibration of power measurement system. The complete LLRF system has been installed in a 42 U Rack Enclosure and has been used extensively during performance evaluation of LINAC at RRCAT. This paper presents the details of the developmental efforts made in the engineering design and implementation of S-Band LLRF system of the machine.

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Design and Development of a 1 kW Pulse RF Amplifier with Integrated Power Meter and Pulse Generator for ECR Proton Source

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Radio Frequency System Division at RRCAT has recently designed and developed a 2450 MHz, 1 kW pulse RF amplifier for plasma discharge in electron cyclotron resonance (ECR) proton source set up at RRCAT. The amplifier can provide a peak power of up to 1 kW with pulse width, variable from 1 ms to 5 ms and duty cycle of up to 10%. The amplifier is a four-stage amplifier comprising of an LNA, a pre-driver, a driver followed by a high-power stage. The high-power stage is developed by combining the outputs of two 500 W dual LDMOS devices via planar hybrid combiner, which are fabricated on Arlon make 30 mil thick, 3.5 dielectric constant RF PCB. A directional coupler is also incorporated in the design to provide a sample of forward power. The drain efficiency of the high-power stage is53%. The overall gain of the amplifier is greater than 50 dB. The amplifier system features an integrated peak power meter and a pulse generator. The power meter consists of an in house developed RF detector with a microcontroller based DAQ system which measures and displays sampled output power of the amplifier on an LCD display. The pulse generator controls the pulse width and duty cycle of the amplifier and provides a synchronized TTL compatible output. The amplifier has been thoroughly tested for its performance and stability and has been subjected to heat runs of more than a week. The amplifier has been installed at the ECR proton source as a replacement of a magnetron based imported source, and the system is being used to study hydrogen plasma discharge in pulsed mode.

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3. Praveen Mohania et al., “Design and Development of S-Band Low Level RF System for 10 MeV, 10 kW Electron Linear Accelerator KIRTI-1010”, this conference.
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Design and development of 24 way power combiner with direct interface with PA modules avoiding the use of high power RF cables for Indian accelerator program

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High power solid state RF power amplifiers (SSA) uses combining technique to scale output power from relatively low power amplifier module compared to required output power. RF accelerators require high power amplifier to increase energy of beam of charged particles. Solid state RF power amplifier technology is one of the most explored options to power RF cavities by accelerator community now a day. Most of the new accelerators are being built/planned using solid state RF power technology. Moreover, this trend has also been complimented by innovations and exemplary progress of superconducting radio frequency (SRF) technology for acceleration of charged particle. SSAs have been popular and increasing their footprint in powering RF accelerators due to their unique advantages, i.e. modularity, graceful degradation, high availability/reliability, stable/quality RF, scalable, easy maintenance among many others.

Power combiner is one of the important components in the SSA design and development. There are various combining topologies available e.g. corporate combiner/divider, Wilkinson power combiner, Gysel power combiner, radial power combiner, cavity type power combiner etc. Corporate combiner will be highly lossy and gysel is bulky and not practical with this much power and ports. Cavity combiner is bulky for 20 kW output at 325 MHz frequency and hence not chosen. Wilkinson topology has been chosen for 20 kW 325 MHz SSA due to its efficient design but simple implementation features. For the power rating of PA module as 1 kW @ 325 MHz and final combined power requirement as 20 kW, design calculation shows that 24 way power combiner will ensure 20 kW SSA operation with suitable operational margin of more than 10% for reliable operation.

Design of 24-way Wilkinson combiner, as described by Mishra in [1] uses quarter wave spline lines of 24 nos. with their impedance equal to $\sqrt{24}\, Z_o$ *where* Z_o *is 50 Ohm. These 24 spline lines are joined together at one end by a metallic disc. Each spline is connected to output of one of the PA module at other end. This structure is matched on combining port to 50 Ohm system. This structure is simulated using CST microwave studio. A 24 way combiner has been constructed based on this design. Constructed combiner has 3 1/8" as output port and 24 nos. of 7/16" input ports. This combiner has been tested using Vector Network Analyzer (VNA) as low power characterization. It shows a output port match of 25 dB, transmission 13.9+/- 0.1 dB and phase variation of +/-0.8 degrees. Minimum isolation without isolation resistors is 20 dB which is observed in adjacent ports, however for rest of the ports it is more than 25 dB. This combiner has been integrated in 20 kW SSA at 325 MHz for its power testing and validation. Power amplifier combining process was very smooth and amplifier has successfully delivered 20 kW output power. Combiner has functionality has been tested under non ideal conditions like few PA modules not feeding power to the combiner and power measured at the combiner output shows very close relation with theoretically calculated power under same input conditions. Authors would like to present these results in this manuscript.*

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Design and development of steerer magnet for extraction beam line of superconducting cyclotron

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The present external beam line of the K500 Superconducting Cyclotron consists of series of quadrupole magnets and two steering magnets. During beam trial with N^{4+} and Ne^{6+} beam, it is found that extracted beam coming out from cyclotron through magnetic channel M9 is inherently defocused horizontally and also beam centroid shifts is more than 7.0 mm. Beam dynamics study has been revisited that reveals the need of extra steering magnet to be installed just after the first Faraday cup (FC1) to match the extracted beam with existing beam line elements with a total of three steering magnets in 21 meter long external beam line. Considering the space constraint in the existing beam line, a small X-Y steering magnet of 1.25 degree in either direction for a 2.4 T-m beam rigidity has been designed, developed and tested. Design features and measured magnetic field data of the magnet is prsented in this paper.

Development of B-H Curve Measurement System Using Rowland Ring Method

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The design of an iron-dominated magnet, especially for particle accelerators, beamlines, spectrometer, and other allied areas largely depend on the correlation of the magnetization curve or relative permeability in terms of magnetic flux density (B) and magnetic field strength (H) (B-H or $\mu_r - H$ data) of the magnetic steel used. The Pole profile of accelerator magnets such as cyclotron main magnet and beam line magnets like dipole magnets, quadrupole magnets, etc. are optimized considering a particular grade of magnetic steel or its B-H curve. However, the B-H property of magnetic steel largely depends on its composition and metallurgical process of heat treatment. Even if one follows a stringent metallurgical process of steel ingot production, it is very difficult to predict its magnetic performance unless measured. Many a time, using the wrong B-H data of the ferromagnetic core at an early stage of magnet design, there is a large impact on the design performance of accelerators in terms of field quality. Therefore, it is essential to use measured B-H data to ensure the magnetic performance as desired. The conventional Rowland ring method that employs primary and secondary windings on a toroidal core has been used for B-H curve measurement.

This paper discusses an experimental setup for the characterization of different magnet cores by measuring their magnetization (B-H) curves. Different ferromagnetic materials e.g. ferrite, silicon iron, mild steel, etc. have been used to cross-verify the measured data. During the testing process, a precision current source is used to produce the magnetizing force (H) in the primary coil of a toroidal electromagnet. A Precision Digital Integrator (PDI) is used to measure and record the B-H loop data. One channel of the PDI records the instantaneous current in the primary coil whereas the second channel integrates the time-varying voltage signal, developed across the secondary coil. A detailed calibration method is used to find the relation between the Volt-second (V-s) value and the integrated counts obtained from the PDI. The dimensional parameters of the coil are used to calculate the magnetic field intensity B from the measured V-s value and the magnetizing force H from the instantaneous current in the primary coil. The obtained B-H data will be compared with the standard data used in FEA software like OPERA, ANSYS, etc. for different grades of iron steel commonly used for accelerator magnets. The details of the measurement set-up, the calibration method for V-s calculation, and the measured data will be described in this paper.

Keywords:
B-H curve, Magnetic material, Rowland Ring

Effect of Dy Substitution at Nd Sites in Melt-spun Nd-Fe-B Permanent Magnet Ribbons

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New materials and techniques are being used to attain extremely high magnetic fields in permanent magnet-based accelerator magnets that may offer a viable alternative to their conventional electromagnetic counterparts for many applications, especially where strong gradients, low power consumption and less radiation damage are needed [1]. Rare-earth magnets are characterized by high energy product {$(BH)_{max}$}, high intrinsic coercivity (H_{ci}) and reasonably high remanence (B_r). Sm-based and Nd-based magnets are commonly used rare-earth systems. Of these, Sm-based alloys have high temperature stability and high resistance against demagnetization at high temperature, while Nd-based alloys have high remanent field/energy values but poor temperature stability [2]. Material processing techniques often plays a vital role in enhancing magnetic properties of Permanent magnets. Controlling the cooling rate during the material processing (rapid solidification) is very important in order to improve the microstructure and magnetic characteristics of the material. Melt-spinning is the mostly used technique among the numerous rapid solidification procedures since it allows for a high degree of material property control and hence improves the coercivity and remanence of the permanent magnets. The melt-spun ribbon develops Nano-structure as a result of rapid solidification which enhances its properties as compared to the bulk samples. Moreover, the Nd-Fe-B melt spun ribbon forms an in-situ Nano-composite with Alpha-Iron and $Nd_2Fe_{14}B$, with the former being a soft magnetic phase, while the latter being a hard magnetic phase. The exchange coupling between the soft and the hard magnetic phases helps in significant increase in the remanence value. Melt-spinning also helps in cold working of the metal introducing a preferred orientation which increases the anisotropy, thereby enhancing the magnetic properties.

In this study the effect of adding Dy as an alloying element to the Nd-Fe-B magnetic system was evaluated by preparing the samples via Rapid Solidification (melt-spinning) process. Micron-thin Ribbons of composition $Nd_{2-x}Dy_xFe_{14}B$ (x=0 and 0.6) were synthesized, keeping the spinning wheel speed at 30 m/s. Thereafter, the rapidly solidified ribbons were studied by various characterization techniques. X-Ray Diffraction study along with the Rietveld refinement was performed to understand the phase formation behavior and phase fraction quantification. SQUID measurements were done to investigate the magnetic properties of the ribbons. Dy addition increased the maximum energy product [$(BH)_{max}$] 2 fold, while the coercivity values were observed as 2.4 kOe and 8.1 kOe for $Nd_2Fe_{14}B$ and $Nd_{1.4}Dy_{0.6}Fe_{14}B$ ribbons, respectively. Microstructural observation with the help of Field Emission Scanning Electron Microscope (FESEM) revealed that the increased coercivity by Dy addition can be attributed to the segregation of Dy at the interface between the matrix phase and the grain boundary phase which opposes the nucleation of reverse domain during demagnetization.

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Electromagnetic Design of Bending magnets for LBNF beamline

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Abstract:

The Long baseline neutrino facility shall use the primary proton beam(60-120GeV) from the MI-10 section of the main injector at FNAL for high energy physics experiments. The high energy proton beam shall be directed to interact with sold target to produce mesons which will be subsequently focused by magnetic horns onto a decay pipe where they decay into muons and neutrinos. The Beamline facility is designed for initial operation at a proton-beam power of 1.2 MW, with the capability to support an upgrade to 2.4 MW[1]. At MI-10 there is no existing extraction enclosure and the impact is minimised on the MI by introducing a beam carrier pipe to transport the beam through the MI tunnel wall into the new LBNF enclosure. The extraction and transport components send the proton beam over a man-made embankment/hill and further directed towards the target. The reference design envisages several 4m and 6m long fast cycling bending magnets to direct the beam along the designed trajectory. To handle proton beams of various energies(60-120GeV) from the main injector, the bending magnets of the proposed lattice needed to ramp from 1-1.6T in few hundred milliseconds and needs to possess operational interchangeablility with main injector magnets and power supply. The paper shall present the electromagnetic design of these bending magnets using Opera TOSCA software. 2-D Shimming of the pole faces were carried out to achieve the desired magnetic field uniformity within the good field region. Magnetic field estimates were sampled in the good field region to calculate the higher order harmonics coefficients of the magnetic field. The dependence of the higher order harmonics on the exciting currents were also studied and sextupole component caused the dominant field inhomogeneity errors over the operating range, largely attributable to saturation effects of the pole shims. Due to the large size of these magnets, Sensitivity analysis were required to be performed in order to evaluate the impact of dimensional error resulting from acceptable manufacturing allowances, deviations in the magnetic properties of the material and its contributions towards higher order harmonics. The electromagnetic design of the pole shims were found to be fairly tolerant towards hysteretic properties of the material and fabrication allowances. Electromagnetic transient analysis were also carried out to comprehend the temporally response of the magnetic field with the applied current, as these magnets operate in fast cycling mode. An optimal thickness of the laminations from commercial available silicon steel(CRNO) was selected based on the outcome of the transient analysis to evaluate the design. The laminated end packs of the magnets were optimised extensively to evaluate the sensitivity of the effective magnetic length through out the operational range of the magnet. An optimal design was obtained using particle swarm optimisation algorithm with the effective magnetic length remaining unperturbed in the design range.

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Design and development of an improved 270 degree dipole magnet for energy filtering system for the Linac at RRCAT

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An improved 270-degree dipole magnet of 0.175 T peak central field has been designed, developed and characterised for the proposed linac at RRCAT. The operating energy of the linac is to be restricted up to 9.5 MeV for irradiation of the food products as per the safety norms. So, an improved achromatic 270 degree dipole magnet system is designed for analysing the electron energy and restrict the higher energy electrons which trace at higher radii in the dipole magnetic fields. This achromatic system consists of two dipoles and make a double achromatic system. An improved mechanical design of the core assembly has been made using thick low carbon steel plates. This new design has the features of dis-assembly/ assembly of the magnet core assembly from its mid plane for placement of vacuum chamber, removal of central support that constraints the accessibility of hall probe during measurements etc. The excitation coils of the magnet were fabricated from enamelled copper strips and epoxy resin impregnated. The deflection of the magnet poles due to force acting on it is restricted with a tolerable limit in order to meet the specified magnetic field uniformity. Magnetic measurements of such dipoles are difficult because both the dipoles are placed only at 175 mm apart from each other on a common base plate and there will be a coupling of magnetic fields. Both the dipoles were magnetically characterised successfully as a system and analysed the measurement results. The magnetic field measurement results satisfy the achromatic condition of the magnet system and suitable for energy filtering system of the Linac. The details of magnet design, development and its measurements results will be discussed in this paper.

Design and characterisation of anodised aluminium strip solenoids

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RRCAT has developed 9.5 MeV, 10kW electron Linac for food irradiation. Solenoids are used to focus charged particle beams and increase the transmission in the Linac. Earlier the solenoids are made using hollow OFHC copper which were imported. Now solenoids are made using anodised aluminium strip which are available in the country as an import substitution. Solenoids are designed, fabricated and characterised to meet the requirement of the Linac. Two smaller solenoids are placed in the LEBT section and rest 4 are in the Linac section. Out of these 4 solenoids, three are of one type and the fourth is of different type. Details of magnetic field design and measurements of both types of the solenoids are presented in this report. Comparison between design and measured data are reported. Various important parameters of the solenoid like coefficient of spherical aberration, effective length, peak field are calculated. Demountable iron disks on the outer jacket are used and advantages of such arrangements are explained.

Field produced by a circular current loop can be analytically expressed in terms of elliptic integrals. The ideal solenoid can be treated as a stack of such current loops and its magnetic field can be obtained by performing the integration. Alternatively, the field may be derived by solving a boundary value problem with cylindrical symmetry using FEM code. Both the procedures are explained here. In any practical solenoid error field is present. Experimentally, error field is measured and minimized. In addition to this a set of horizontal and vertical steering coils are placed inside each solenoid for beam steering, if required. These coils can generate 180 Gcm integrated field in each direction. These are made in such a way that it can be removed if not required without disturbing the set up. In any solenoid, axial field, B_z is maximum at the center of the magnet and decreases towards the end. Centre of the solenoid can be found out by taking the derivative of the field. However, the off-axis radial magnetic field is maximum at the ends. These radial field is responsible for focusing action of the solenoid magnet. These are water-cooled magnets and cooling arrangements are made at both the ends. The magnet is energized with different currents varying from 47.5 A to 80 A and allow to stabilize for 45 minutes before measurement. Characterization of the magnetic field plays a significant role for the qualification of the magnets. Magnetic field is measured using a 3-axis motion system and SENIS make 3-D Hall sensor and digital tesla meter. Magnetic field sensitive volume of the sensor is (0.1x0.01x0.1) mm^3. A special holder is designed to maneuver the Hall sensor which can manipulate the sensor in 3 possible directions. The magnetic field is measured along the length in a grid. Horizon, vertical and the length along the axis of the magnet is defined as X, Y and Z axis. On axis field means the field is measured from -Z to +Z for X and Y both zero. Experimentally magnetic axis is determined from the measured field. Measured field profile is in good agreement with the design values and satisfy the field requirement. This is not only the import substitution but reduce the power loss and price considerably.

The current and resistance of the solenoid using hollow OFHC copper to generate 1500G central magnetic field are 180A and 0.159 Ω. However, to generate the same field using the aluminium strips solenoids the required current and resistance are 54.27 A and 0.46 Ω. Therefore, the power loss in copper and aluminium solenoids are 5.15 kW and 1.35 kW, respectively. Lower current density used in aluminium solenoids resulted in low power loss. The cost of the material and fabrication of aluminium strip solenoid is around 50 % lower than the OFHC solenoid.

Design, development and testing of 1.5 Tesla Superconducting magnet for compact MRI

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Magnetic Resonance Imagining (MRI) is the biggest commercial application of superconductivity. MRI is a noninvasive powerful diagnostic tool used by medical community for examination of soft tissues diseases such as tumor's in cartilages, musculoskeletal, deformities in CTL spine etc. A 1.5 Tesla multi coil superconducting magnet is designed and developed for compact MRI applications for human extremities such as wrist, ankle etc. The developed superconducting magnet is cooled by two stage Pulse Tube Cryocooler in a closed cycle mode and hence do not require liquid Helium for its operation. The heat removal capacity of a cryocooler is limited to 1.5 W at 4.2 K which makes thermal design quite challenging in nature. The multi coil superconducting magnet is designed for uniformity better than 10 ppm in a Diameter of Spherical Volume (DSV) of 160 mm. Nonlinear integer optimization such as fmincon and Nomad algorithms were used to achieve the required uniformity.

Developed superconducting magnet has a working bore of 300 mm and a length of 700mm. Spatial magnetic field uniformity is achieved by deploying multi coil design (6 main coils & 2 buck coils). Nb-Ti wire 1.65mm×1mm is used for magnet development. Temporal stability of the magnetic field is obtained by operating the magnet in persistent current mode. Persistent current joints and switches for this magnet were developed and tested for its rated current. The developed superconducting magnet system is integrated and is tested for its rated performance.

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Development and characterization of persistent current joints for superconducting magnets

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1.5 Tesla multi coil superconducting (SC) magnet is designed and developed for Magnetic Resonance imaging applications for human extremities. SC magnet is designed for uniformity better than 10 ppm in a Diameter of Spherical Volume of 160 mm. Temporal stability of the magnetic field is obtained by operating the magnet in persistent current mode. Persistent current joints and switches for this magnet were developed and tested for its rated current. The developed SC magnet system is integrated and is tested for its rated field.

Niobium-titanium (Nb-Ti) with a critical temperature (Tc) of 9.2 K is used to fabricate 1.5 Tesla multi coil superconducting magnet. One of the distinct features of Nb-Ti that makes it ideal for most commercial applications is the possibility to produce true “superconducting joints”. The superconducting joints allow the Nb-Ti magnet to operate in the persistent-mode to attain an ultra-stable magnetic field (drift in the magnetic field should be of the order of 10 ppm/year).

To achieve persistent-mode operation, two ends of an Nb-Ti superconducting magnet should be connected with a persistent-current switch (PCS) using superconducting joints without any electrical loss. Superconducting joints were fabricated by using a solder matrix replacement method with lead-bismuth (Pb-Bi) solder.

In this paper, we discuss about the superconducting joints of Nb-Ti superconducting wire which are embedded in copper or copper nickel matrix. The developed superconducting joints were characterized in self field operation in a cryogen free characterization system and by current decay measurements while operating the superconducting magnet in persistent mode. The measured resistance of fabricated superconducting joints using solder matrix replacement method is of the order of $10^{-10}\Omega$ which is required for the persistent mode operation. Persistent mode operation of the system is demonstrated in a compact coil assembly with a persistent current switch in a cryogen free magnet setup.

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Development, fringe field optimization & cryogenic qualification of pre-series 6T conduction cooled magnet assemblies for High Intensity Proton accelerators

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ABSTRACT:

Medium beta cryomodules for High Intensity Proton accelerator envisages using superconducting solenoids as transverse focusing elements. Electromagnetic, thermal and mechanical design of the compact magnet assemblies equipped with focusing solenoid, corrector coils and active shielding coils has been carried out at Bhabha Atomic Research Centre (BARC) [1 & 2]. With the transition to a new superconducting magnet technology based upon conduction cooling, it is important to have a quantitative understanding of the stability limits and the quench behavior so that magnets can be effectively protected [2]. Transient behavior and design margin of such magnets needs to be analyzed for predicting the quench behavior. A cryogenic test stand using closed cycle cryocooler was designed & developed for cryogenic qualification of conduction cooled magnets [2, 3]. Axial magnetic field mapping for integral field strength calculation and fringe field measurement demands a clear bore for magnetic field probe placement. Hence the cryogenic test stand is equipped with a warm bore for scanning of the field in magnet aperture. The test stand is equipped with multiple current feedthroughs for simultaneous excitation of main coil and corrector coils. Warm section and the cold portion of the current leads in the test stand have been optimized to reduce steady state heat in-leaks as well as dynamic heat load during ramping. Cryogenic test stand is being used for quench training, ramp rate testing and axial magnetic field mapping of the conduction cooled magnet at various excitation currents. Thermal design of the system has been carried out to reduce conduction, radiative heat load and thermal contact resistance between the heat sink plates and cryocooler cold head [4] . 4 no.s of 6T pre-series superconducting solenoid magnet assemblies have been integrated with the test stand and tested for its performance. Cool down and warm up rates were measured as well as peak temperature of first stage and second stage heat sink plates were recorded during magnet quench. This paper reports the design, assembly, and commissioning of the cryogenic test facility, and presents results of the test performed on the pre-series magnet assemblies.

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Design and simulation studies of 40 kV, 80A solid state magnetron modulator

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Magnetron as a source of microwave is extremely popular in the field of RF accelerators that are used for industrial & medical applications. High power pulsed modulators are widely used for driving magnetron sources. A Solid state switch based PFN (pulse forming network) type magnetron modulator is designed for driving Nelson made VE2093 tunable X-band magnetron. This modulator consists of five parallel PFN modules and each module contains fourteen capacitors connected in double layer structure. All the PFN modules are discharged simultaneously using IGBT switches into the primary of a fractional winding pulse transformer. While discharged, 40 kV 5µS pulse voltage appears across the matched load of 500 Ohm. Details of the design, optimization and simulation of PFN structure and fractional winding transformer are narrated in this paper. Experimentally measured voltage waveforms are found to be in close agreement with simulated results.

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Design and Development of 3 kW, Active PFC Pre-regulator for Super Conducting Wavelength Shifter Magnet Power Supply.

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The synchrotron radiation sources Indus-1 and Indus-2 are continuously operating in round the clock mode at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The insertion device (superconducting wavelength shifter (WLS), peak field - 5T) is being developed for Indus-2 to increase the spectral brightness of the emitted radiation which is indispensable for energy dispersive X-ray diffraction (ED-XRD) beam line applications. The insertion device is to be installed in Indus-2 storage ring and to meet the requirement of high stability radiation flux for ED-XRD, the high stability current controlled wiggler magnet power supply is required.

An SMPS based high power, high stability (< 50 ppm) magnet power supply is also being developed to energize the superconducting WLS magnet for Indus-2 accelerator at RRCAT, Indore. The input diode rectifier of the SMPS without PFC behaves as a non linear load to the ac utility resulting in poor input power factor and higher harmonic current in ac input current. For shaping the ac input current from utility grid and reduction of harmonics current, an active PFC converter is needed as a front end of the dc- dc converter based magnet power supplies. The active PFC is also essential to meet the regulatory requirement of low harmonic current in input current from utility grid for high power systems. Passive PFCs are generally very bulky in size & have poor dynamic performance, so are not suitable for high power systems.

A boost converter based active PFC high power pre-regulator operating in continuous conduction mode (CCM) is proposed and presented in this paper. The boost converter is very attractive for PFC applications since it has low part count, high efficiency, is compact in size and operates as a step up converter which is quite suitable for wide ac input range. Moreover, it has an input inductor which smoothens the input current and operates in CCM. The PFC boost converter is operated in closed loop control with multiple control loop architecture using power factor corrector IC circuits. The high bandwidth fast inner current loop in average current mode control and a low bandwidth slow voltage loop is used with feed forward of ac input. SiC Mosfet and SiC Schottky diodes are used in boost converter power circuit which are switched at frequency of 100 kHz. The design parameters, formulations and experimental results of the developed 3 kW prototype of the active PFC pre-regulator are presented in this paper. The input power factor of 0.99 and THD < 6.1 % with efficiency ≥ 94% is achieved.

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Design and Development of 125 A, 25 V Power Converters for Combined Function Corrector Magnets in Indus-1 Storage Ring

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Due to the space limitation in the Indus-1 ring, it is proposed to develop a set of eight combined function multipole magnets to facilitate closed orbit distortion (COD) correction. Each magnet will produce four required magnetic field components, namely, sextupole component to correct the chromaticity, skew quadrupole component to reduce the coupling (between the horizontal and vertical planes), and vertical & horizontal dipole components for steering the beam in both the planes. For chromaticity correction, sextupole coils of four magnets will be connected in series and energized by one power supply. Thus, in total two power converters of maximum output rating 125 A/25 V, with output current stability within ± 100 ppm are required. This is a new requirement for performance enhancement of Indus-1.

The power converters are developed based on switch-mode, two-switch forward converter (TSFC) topology. The converter is operating at 25 kHz switching frequency. IGBTs are used as switching devices. The main features of the new design are: high efficiency, smaller size, less cooling requirement, low audible noise, high stability, better maintainability, etc. The power converters are designed and developed in modular fashion. The power converter is divided in three modules: the power module, the breaker module and the control rack. Each module is developed and tested separately. All the modules are integrated in cabinet. Open and closed loop testing at low as well as high power testing has been carried out. Apart from these functional tests, heat run test and special endurance tests, such as current cycling tests, etc., have been carried out. Stability for eight hours of continuous operation has been recorded to be well within the specification of ± 100 ppm. The paper reports the design details and test results.

Design and Simulation of Upgraded 800 A, 140 V Power Converter for Indus-1 Dipole Magnet

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The existing power converter for Indus-1 dipole magnet (800 A/140 V) is based on 12-pulse thyristor based rectifier scheme and is in operation for more than 25 years. Hence, most of the power components like magnetics, electromechanical components, electrolytic capacitors, etc. are reaching to their end of life. Maintaining spares for these components also becomes difficult as some of the components have become obsolete and retrofitting the available components in the running machine becomes difficult due to time and layout constraints.

For these reasons, it is planned to develop a new power converter for the Indus-1 dipole magnet following switch-mode power converter scheme having smaller size, faster dynamic response, better power factor, better maintainability, etc. The new power converter is planned to be developed not as a single unit delivering 800 A / 140 V, but as an appropriate number of modules operating in parallel with current sharing control, with N+1 redundancy. In case of failure of any module, the remaining modules will continue the operation. This will significantly increase the overall availability of power converter and reduce the machine down-time.

The switch-mode converter based scheme will be capable of achieving fast dynamic control and will be smaller and lighter. Each module consists of two stages of two-switch forward converter operating in Input Parallel Output Series (IPOS) configuration. Similar module, rated for 20 kW maximum output power, has been used in new power converters for Indus-2 quadrupole magnets [1]. The power converter architecture consists of five 200 A / 140 V modules operating in parallel with 4+1 redundancy. So even if one fails then the remaining 4 power converter modules would be able to share the load and deliver maximum rated output current of 200 A each at 140 V. In normal operation, when all the 5 converters are in healthy condition then each one operates at part load of 160 A. The design and layout of the power converter module is significantly updated to improve power density as well as maintainability. These aspects, along with the design details and simulation results of the power converter are discussed in the paper.

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Simulation Studies on Series Connected Fast-Ramped Power Converter Modules for Booster Synchrotron

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In booster synchrotron, magnetic field needs to be ramped up at a fast rate (typically within 100s of milliseconds) in synchronism with energy of the particle. For this purpose, fast-ramped power converters (FRPC) are used, which are capable of operation in two or four quadrants, to energize series string of electromagnets. High peak power, having a large reactive component, needs to be handled by the power converter to energize and de-energize the magnets at a fast rate. During ramping up, energy is transferred to magnet; during ramping down, energy is transferred back by magnet. Large reactive power fluctuations are undesirable due to resulting various power quality issues, most notably the voltage flicker. The studies reported in this paper used a FRPC that uses DC link capacitor for energy storage and a two-switch forward converter (TSFC) in the front-end feeding to a two-quadrant power converter (TQPC). With this arrangement voltage across DC link capacitor can be programmed to vary in such a way that only active power is drawn from the source. In large accelerators, number of electromagnets to be energized in series are large. The peak voltage encountered by power converter is prohibitively large during ramping. To reduce this voltage within feasible limits, the total number of magnets are divided into number of smaller sections of magnets in series and each section of magnets is energized by separate power converter. The power converter, depending on the power levels involved, itself may need to be developed not as a single unit but by connecting suitably rated modules in series.

Circuit simulation of switch-mode converters operating at kilo-Hertz frequencies for longer times (of the order of seconds) is computationally intensive and time consuming task for commercial simulation platforms. Therefore, simulation studies reported in this paper are carried out using equivalent circuit models of TSFC and TQPC, which provides important circuit parameters that are averaged over one switching period of the switch-mode converters. While this method does not provide information on high-frequency parameters, it speeds-up the simulations to a great extent. The studies are carried on equivalent circuit models of two FRPC modules connected in series. The effect of various non-ideal conditions, for instance unequal input DC voltages of TQPCs on individual and overall output voltages of series connected TQPCs, is presented. DC link capacitor is used to store the energy that is transferred to and fro from electromagnet and DC link capacitor. Mechanism of energy flow between DC link capacitor and electromagnet is validated by simulation. This validation is achieved by computing voltage across DC link capacitor by energy conservation principle for various values of capacitors. Results of simulation studies regarding operational safety aspect in the series operation of FRPCs are also presented.

Development of High-Stability True-Bipolar Power Converters for Upgraded Closed Orbit Distortion Correction Scheme in Indus-1 Storage Ring

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An upgraded closed-orbit-distortion (COD) correction scheme in Indus-1 storage ring will have new magnetic elements, better diagnostic devices, systems and capabilities to facilitate stable and repeatable operation of the machine. A set of eight combined function multipole magnets will be installed to facilitate COD correction. To produce skew quadrupole component to reduce the coupling (between the horizontal and vertical planes), and vertical & horizontal dipole components for steering the beam in both the planes in these magnets, in all 24 high-stability, output-current-controlled power converters rated for output current of +/- 12 A and output current stability within +/- 100 ppm are required. The bipolar power converters need to have smooth zero-current-cross-over, with precise control while operating near zero. The design of these power converters is also space-constrained owing to severe space limitations in the Indus-1 Magnet Power Supply Hall. These power converters are developed based on the high-frequency switch-mode power converter technology, satisfying functional specifications as well as practical constraints. The converter, with its power circuit, feedback control electronics and remote interface electronics, has been developed on a single, four-layer, 6U printed circuit board. The power circuit is based on four-quadrant, non-isolated, switch-mode power conversion scheme that uses MOSFETs operating at 50 kHz with unipolar PWM scheme. With this scheme, the ripple frequency is doubled that reduces size of filter components and facilitates miniaturization. The output current feedback control electronics uses precision current sensing resistor, and, low-drift operational amplifiers with precision resistor arrays, the latter being kept inside on-board oven for constant temperature operation.

The prototype converter was first developed and tested rigorously for long-duration continuous operation under different modes, namely, dc operation at positive/negative maximum current; cyclic bipolar operation with sinusoidal and triangular output currents, etc. Subsequently, series manufacturing of 30 power converter cards, that included spare power converters, was carried out with industry support. As these power converters normally operate in remote mode, a test simulator was developed for testing of these power converters in local mode. A detailed document providing testing guidelines was prepared to facilitate simultaneous testing of these cards on multiple testing setups. A test report template was also prepared for documentation of test results for individual cards.

Five such power converter cards are housed in one 19-inch 6U rack. Similar to the testing of individual power converter cards, a test simulator, testing guideline document and a test-report template was prepared to qualify the correctness of wiring of the racks.

The paper discussed the design and development activities and salient results of these high-stability true bipolar power converters for upgraded COD correction scheme in Indus-1 storage ring.

Design and Development of Ethernet based Remote Card for generation of Programmable Reference for Bipolar Current Controlled Power Supply

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An electron linear accelerator is widely used for irradiation of food products and sterilization of medical equipment. In a linear accelerator a time varying magnetic field, which is generated by a scanning magnet, is needed to make the electron beam scan the product for uniform distribution of the dose. A programmable current controlled bipolar power supply excites the scanning magnet for generation of time varying magnetic field. The dose delivered to the product is controlled by variable ramp up time and the beam current. The scanning width is controlled by varying the magnet current through the magnet. This bipolar current controlled programmable power supply needs a suitable reference for generating the required output current profile. Operation of electron beam accelerator is associated with radiation hazard and to overcome this, power supply needs to be operated from a remote place where radiation dose is minimum. This paper focuses on development of an ethernet based remote controlled programmable reference for the bipolar current controlled power supply. A 32 bit ARM Cortex M4F based microcontroller has been used for the development of programmable reference board. This microcontroller has inbuilt ethernet controller which conforms to the IEEE-802.3 specifications. The programmable parameters like ramp up time, ramp down time and voltage peak for the reference of power supply is selected either by user friendly touch screen interface or ethernet based remote interface. A generic 3.2" HMI TFT intelligent LCD touch display module is used for the local control of the power supply. The development of user friendly GUI for the touch interface is carried out in compatible HMI editor. In local mode bipolar voltage reference, programmable ramp up time and ramp down time are selected by HMI. In the development of GUI several protection features like selection of parameters within pre specified limits have been incorporated and it also alerts user through pop up window. The HMI interacts with microcontroller using a serial port. In remote mode these parameters are selected by open source software through TCP/IP. The development of software is done using suitable compiler in C language and for TCP/IP based ethernet software a suitable light weight TCP/IP protocol suite has been used. Open source software has been used for transmitting data from desktop PC to microcontroller and for receiving data from microcontroller. Several interrupts like ethernet, timer and serial interrupts have been used for the generation of reference in both local and remote mode. A 20-bit, serial input and voltage output single Digital to Analog converter (DAC) has been used for generating voltage reference for scanning magnet power supply. External voltage reference to DAC is generated by the highly stable external reference. This DAC communicates with microcontroller through Serial Peripheral Interface (SPI) bus. The bipolar reference with programmable ramp up and ramp down time has been successfully tested with power supply and meets all intended parameters.

Design and fabrication of cold plates for dipole power converter of Indus-2 at RRCAT.

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Abstract:

The cooling of electronic devices is essential to guarantee their functional performance and operational lifetime. Diodes, IGBTs, MOSFETs, transistors and integrated circuits generate considerable amounts of heat during operation. Extreme heat can damage or significantly affect the performance of the semiconductor devices and therefore, supplemental cooling is necessary to maintain the temperature within the limits. Among the various devices which are used for thermal management of electronic equipment, the cold plate is a primary tool. A cold plate is a fluid flow space that is contained within bounding metallic walls.The key task is to design fluid flow passages within the space such that the heat dissipated by the electronic equipment is extracted while maintaining temperatures at a level compatible with high performance. This paper discusses the selection of material, design, development and fabrication techniques of cold plates for cooling of SCRs of bridge assembly for Indus-2 dipole power supply which is rated as 800 A/800 V. This power supply energizes all the seventeen dipole magnets of Indus-2. The cold plates of SCR bridge assembly have been designed for 2 kW heat load with maximum surface temperature of cold plate at 50˚C. Geometrical tolerances of cold plates have been measured and achieved as specified. Steady state thermal analysis has been performed in ANSYS to estimate maximum temperature of cold plate. This paper also discusses the mounting techniques of SCR bridge assembly.

Development of a Prototype Fast-ramp Power Converter with Grid Power Control

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In Indus Accelerator Complex, booster synchrotron is used to boost the energy of electrons to the desired levels required to fill Indus-1 and Indus-2 storage rings respectively. Presently, the series connected main windings of dipole and quadrupole magnets in the booster are energized by a single power converter, which is based on 12-pulse thyristor controlled rectifier scheme. As the magnetic field of these electromagnets need to be ramped at a fast rate (typically few 100s of milliseconds) in synchronism with the energy of electrons, the magnet power converter is required to handle large power swings during ramp-up (energizing) and ramp-down(de-energizing) transitions. The existing power converter scheme is able to meet the specified requirements. However, it poses certain limitations such as operation at low power factor and voltage flicker due to repetitive power fluctuations. Further, as the power converter scheme has inherent slow dynamic response, a control scheme that has multi-loop feedback and feedforward control is used to achieve the desired tracking accuracy. Being operational over many years, the power converter is also due for upgradation in near future. Therefore, it is planned to develop a new power converter using switch-mode power conversion technology with grid power control that would result in high power factor operation as well as relieve the ac mains from periodic power fluctuations and consequent voltage flicker. The technology development would also be essential to energize magnets in the booster synchrotron of the next-generation synchrotrons, wherein power swings of the order of few MVAs are envisaged.

As a first step in the developmental process of this complex technology, a prototype fast-ramped power converter with grid power control was developed and tested. The converter is rated to deliver trapezoidal current of 100 A flat-top value at the ramp rate of 350 A/s to a magnet load with inductance of 54 mH and resistance 0.165 Ω available in the laboratory. It consists of two stages: a two quadrant converter is used to provide the output current, with a two-switch forward converter at the front end to vary the voltage across the intermediate dc link storage capacitor in a specified manner in order to draw only resistive power from the input.

Analysis, Design and Development of High Voltage Surge Protection for High frequency Transformer and IGBT Inverter of 1MeV, 100kW DC Accelerator

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Electron Beam Centre (EBC), Beam Technology Development Group (BTDG), BARC is developing 1MeV, 100kW DC Accelerator for electron Beam Waste Water Treatment (EBWWT). The accelerating potential of 1MV DC is generated by symmetrical Cockcroft Walton multiplier column pressurized at 6kg/cm^2 N_2 gas for HV insulation. The accelerated electron beam passes though graded accelerating column with vacuum better than 10^{-6} mbar. The multiplier column is powered through high voltage high frequency transformer (HFT) alongwith IGBT based inverter and DC Power supply (DCPS). During HV conditioning, due to arcing inside the high voltage multiplier column or inside accelerating column, a typical surge of about 100-150kV and 1-10MHz frequency is estimated across HV terminal of HFT. This surge enters to the inverter and DCPS through HFT inter-winding capacitance. A suitable surge limiting inductor alongwith spark gap & common mode bypass filter has been designed and developed for the surge protection. This papers describes about the simulation analysis, design basis, prototype testing of the surge protection system. The fabrication and test results are also presented.

Design, Development and Commissioning of Series Regulator based High Voltage Regulated RF Screen Power Supply for VECC K-130 Room Temperature Cyclotron Kolkata

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A novel scheme incorporating SCR based AC voltage control type pre-regulator followed by in-house developed step-up transformer and solid-state series regulator has been designed and developed. This was done to replace the older vacuum tube based power supply with a compact and rugged solution for the existing system. The design includes the development of an analog control system for the pre-regulator as well as a dual loop control architecture for the output voltage regulation of the said power supply. The multiple inner current loops ensure equal current sharing of the individual series pass elements as well as better control dynamics in terms of overcurrent protection of the load (EIMAC 4CW150000). Low output storage energy, better line ripple rejection, better line and load regulation etc. were also the major concerns during the design, development and optimization of the control scheme. The power supply additionally features protection against overcurrent, over-temperature, mains fault etc. and also provision for remote interfacing with the existing supervisory control system for upgradation of the power supply with minimum shut-down time of the system. This paper reports the design of the power converter stage, control system modelling, controller design, and the important results obtained at various stages of the development.

Prototype development of four channel 2kV/5A power supply using pulse step modulation technique

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Abstract

A 2kV/5A power supply is designed and tested utilizing Pulse Step Modulation (PSM) which comprises of 4 individual power supply modules (SPM) based on Pulse Width Modulation (PWM). A power supply with PSM techniques is used in the accelerator technology in order to avoid crowbar, ease of maintenance. The PSM uses phase shifted PWM for producing final output. There are various ways to obtained phase shifted PWM like using FPGA, DSP etc. In this paper, the phase shifted switching pulses are obtained by using analog IC LTC6994 which can produce a delay of 1µs to 33.6s. The use of analog IC eases the complexity of design. Each phase shifted PWM pulse is used to turn ON and OFF the IGBT connected in each module as a Buck converter mode which is fed from a 600 VDC source. A free-wheeling diode connected at the output of the modules bypasses the current even it is in standby or non-function mode. Each SPM can produce 60V to 540V with maximum 5A depending upon duty cycle of switching pulse. After Simulation of prototype design experiment is performed which matches the simulation profile. Load regulation is obtained using PI controller fabricated on an externally SG3524 IC, which act as a master controller. The final output is the summation of voltages of modules connected in series resulting very less ripple at higher ripple frequency and thus the requirement of filter capacitor is very less. The main advantages of PSM based high voltage power supply are smaller size, easy maintenance and low stored energy.

Power factor correction techniques employed with DC power supplies of various RF amplifiers in Indus-2

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The input performances of DC power supplies such as input power factor (IPF) and current total harmonic distortion (THD) must be improved for minimizing the total apparent power consumed from electrical utility. In order to improve these input performances, DC power supplies incorporate active or passive power factor correction (PFC) techniques. Input performances can also be improved by employing multi-pulse input system. All these power factor correction techniques are used in DC power supplies employed for biasing various RF amplifiers in RF system of Indus-2 and analysis of these techniques is presented in this paper. An active power factor correction approach entails the use of a full power converter stage in between the diode bridge and the isolated DC/DC converter. This power factor correction technique is employed in 50 V, 700 A modular DC power supplies, used for biasing solid state RF power amplifiers in RF system of Indus-2 [1]. Under this technique, a Vienna rectifier is used at the input of 50 V, 100 A DC module employed in these power supplies. Vienna rectifier is a three phase, three switch and three level rectifier, which provides controlled output voltage. Its topology is a mix of a boost DC-DC converter and a three-phase diode rectifier. By controlling the turn-on and turn-off of its switches, the input current is made to follow the input voltage, which results in very high IPF as well as low current THD. With incorporation of Vienna rectifier, IPF > 0.97 and current THD < 6% have been achieved. Eight units of these power supplies are operating in 24x7 mode in indus-2. Passive power factor correction approach places reactive components such as capacitors and inductors across the input line. This power factor correction technique is employed in -20 kV, 5 A DC power supply of klystron amplifier in RF system of Indus-2. Under this technique, a detuned passive filter network is connected across the input line along with series limiting inductors for improving input performances. The tuning frequency of this detuned filter is kept as 228 Hz, which is below the lowest harmonic generated by nonlinear load connected across this power supply i.e., 5th harmonics, to avoid harmonic amplification with the input, due to parallel resonance. With incorporation of both detuned filter network and series limiting inductors, -20 kV, 5 A DC power supply achieves current THD < 15% and IPF > 0.97 at nominal 415 V, 50 Hz AC input. A 24-pulse input system is incorporated in -36 kV, 24 A DC power supply for biasing Inductive Output Tube (IOT) amplifier in Indus-2 [2]. It receives input from 11 kV, which is applied to two numbers of input transformers, whose secondary windings are connected in star and delta configuration. Their primary windings are shifted by ± 7.5º to realize 24-pulsed input system. This power supply achieves current THD < 6% and IPF > 0.97. Details of power factor correction techniques employed in these power supplies and experimental results for current THD and IPF are presented in this paper.

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Installation and commissioning of high voltage DC power supply with electron gun for power testing of photon absorbers

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An AC regulator based -25 kV, 5 A high voltage DC (HVDC) power supply has been installed, commissioned and integrated with electron gun for testing of photon absorbers [1]. The control of this power supply has been implemented though silicon-controlled rectifiers (SCRs) in AC regulator configuration [2]. The controlled voltage output of SCRs is given to the primary winding of star connected 3-phase step-up transformer. The secondary winding of this transformer has been split into two windings, one connected in star and other in delta configuration. These secondary windings are feeding to corresponding 3-phase diode bridge and rectified output is filtered to obtain -25 kV, 5 A high voltage DC output. The transformer, rectifier and filter inductor of this power supply are kept in an oil filled tank. The SCRs along with input switch gear and various control cards are housed in AC voltage regulator (ACVR) panel of this power supply. Before installation, the functioning of various control cards was checked and voltage levels at various test points were monitored. Functioning of SCRs and other components was also checked. During installation, the health status of high voltage transformer was checked through megger. Afterwards, the output of ACVR panel was connected with transformer-rectifier unit & filter capacitors and power supply was energized. A 100 kΩ bleeder resistor was connected across the output terminals of this HVDC power supply and its performance parameters were checked. Various safety and protection features have been implemented in this HVDC power supply by using protection cards for over temperature, over voltage, over current, under voltage, transformer oil over temperature and phase failure. In order to ensure smooth operation of power supply with electron gun, its preventive maintenance is carried out at regular intervals. This includes multiple checks such as testing dielectric breakdown voltage of transformer oil, checking moisture content of silica gel in transformer breather, checking integrity of power circuit connections and dust-cleaning of various components of power supply. Functioning of various protection cards used in power supply, is checked along with the calibration of multiple meters. During operation of power supply, several performance parameters such as output voltage, output current etc. along with voltage levels of multiple signals in interlock cards are monitored. The power supply can be operated in local mode as well as in remote mode. This power supply has been operating satisfactorily with 20 keV strip electron gun for qualification testing of photon absorbers. The details of installation, commissioning and integration of -25 kV, 5 A DC power supply with electron gun are given in this paper. During testing with electron gun, this power supply is operated at -20 kV, 100 mA operating point and output voltage ripple ≤ 0.5% and output voltage stability ≤ 0.5% have been observed. These experimental results are also presented in this paper.

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Control protection interlock system of 50 V, 700 A DC power supply for solid state RF amplifier in Indus-2

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A microcontroller based digital control protection interlock system has been employed in 50 V, 700 A modular DC power supply for biasing solid state RF amplifiers in Indus-2 RF system at RRCAT, Indore. This power supply consists of seven numbers of 50 V, 100 A AC-DC converters which operate in parallel to share the load current [1]. Hot swappable features and active redundancy are implemented in the power supply to reduce the down time as well as increase availability of the overall system significantly [2]. The control system consists of Microchip made ATMEGA644P microcontroller and DSPIC30F5011 digital signal processor. ATMEGA644P microcontroller communicates with controller of individual AC-DC converter via RS232 interface and ensures equal sharing of load current among the healthy AC-DC converters. Suitable optical isolation has been provided for communication between the controller of individual AC-DC converter and control system. DSPIC30F5011 is responsible for ON/OFF operation of DC contactors, which provide 50 V DC bias to 32 numbers of 500 W, 505.8 MHz RF amplifiers. The control system also enables the operating personnel to specify the trip limits for RF amplifier bias currents, individual converter currents, total power supply current, output overvoltage, under voltage, independently for effective protection of the overall system. If any RF amplifier gets short circuited, the control system isolates it by switching off its DC contactor, keeping remaining RF amplifiers in operation. Hot swappable feature incorporated in AC-DC converter enables online isolation of faulty converters without affecting the operation of remaining AC-DC converters and RF amplifiers. The control system also monitors the healthiness of 7 numbers of AC-DC converters and 32 numbers of RF amplifiers and displays crucial parameters of the power supply including input AC voltages and currents, output DC voltage and current, AC-DC converter currents, RF amplifier currents on LCD. In case of external interlock, it trips the entire power supply by sending shut down command to AC-DC converters and tripping the DC contactors. Emergency OFF button is also provided on the power supply for tripping it in case of any abnormal condition. A DC OK status signal is given from the power supply to the RF amplifier system. Once the RF amplifier system is ready, it sends turn ON command to the three phase 415 V input A.C. contactor through this control system. The control system has capability to operate the power supply in remote mode via PC connected through Ethernet communication. With this control system, eight units of 50 V, 700 A DC power supplies are commissioned with RF amplifier in Indus-2 RF system at RRCAT, Indore and are working satisfactorily in round the clock mode. Current total harmonic distortion ≤ 6.4%, input power factor ≥ 0.97, output voltage stability ≤ 0.5% and output voltage ripple ≤ 0.2% have been achieved. This paper presents details of the digital control protection interlock system, scheme of power supply in brief along with experimental results.

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Evaluating the Design Performance of HV & HF Transformer of the High Power DC Accelerator

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Abstract: HV & HF 125 kVA Transformer with high step-up ratio of 180 has designed for feeding power to high power DC Accelerator based on Symmetrical Cockroft Walton multiplier scheme. Regulation and efficiency are the two important performance tools of the transformer for exploring the 15 stage SCW with line regulation and ONWF cooling scheme for heat removal respectively. This paper presents the detail theory with calculation insight for explaining the gaps of the design and test result. The complete frequency response of the HV & HF Transformer explains the reason behind the question, why step up is coming higher than the designed value. This paper demands the focused and detail study for the skin and proximity effects because the gap between theory and test result are very wide. The performance of noncondenser type bushing concludes satisfactory result due to No HV discharge between the terminals during the test up to rated voltage.

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Design, development and testing of 200V, 1A power supply for grid electrode of RF amplifier tube of MC18 cyclotron

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Abstract

Medical Cyclotron 18MeV (MC18) is under development in VECC, Kolkata. Radio frequency (RF) system is most vital part of cyclotron which is also under development. The grid biasing plays most critical role in triode power amplifiers. A linear regulated power supply rated 200V/ 1A is designed, developed and tested with resistive load for biasing grid electrode of RF amplifier tube. This power supply is developed by incorporating single-phase step-down transformer, single phase full bridge rectifiers, LC filters and a bipolar transistor as a shunt regulating element. The output voltage is controlled and regulated by feedback technique. This is achieved by first sampling output voltage and compared it with a reference voltage to generate an error signal. This error signal is given to an analog proportional and integral (PI) controller that controls the base current of transistor to put the output voltage within desired limit. The power supply has features of over voltage, over current and over temperature protection with one external interlock. Simple control circuit, no EMI and high reliability are main advantage of liner regulated power supplies. Also, short circuit proof is added advantage of shunt regulated linear power supplies due to use of series resistance. The simulation of the designed is performed in PSIM to analyses the circuit performance. In this paper, circuit topology, function of system components, simulated and experimental result of power supply are discussed.

Comparative exergetic and paramertric evaluation of an existing helium liquefier with a simulated model in mixed mode operations

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Superconducting magnets and radiofrequency cavities are being applied in a variety of sectors, including medical accelerators, MRI magnets, NMR equipment, mass spectrometers, magnetic separation processes, etc. in addition to research accelerators. In order to keep the superconducting coils and cavities at the superconducting state, a superconducting system requires liquid helium plants. Helium plants, used for diverse accelerator projects are highly energy-intensive due to operation of the accelerator components at very low temperature range of 4.2 K to 20 K. Depending on the operation philosophy of the magnet/cavity, these plants are either constructed as a liquefier or a refrigerator or for various mixed-mode activities. It has been observed that the majority of liquid helium plants, whether built as liquefiers or refrigerators, really operate in mixed mode for superconducting system operation. The operating condition (% of liquefaction) of liquid helium plants determines their performance under mixed-mode operation, and any off-design operation typically lowers its performance efficacy. It has been found that there are a very few studies on the operation of liquid helium plants under off-design conditions and there is paucity of information on this subject. The modern liquefiers are made to operate optimally within narrow operating margins, however there occurs instability in their performance on account of wide fluctuations in off-design thermal loads **[1]**. The performance of mixed-mode multistage helium plants for design and off-design operations is evaluated in only one available publication by Kundu et al. **[2]** using the commercial process simulator ASPEN HYSYS. The current study has attempted to simulate a model liquefier using Aspn Hysys, experiment with an existing helium liquefier operating in mixed-mode using an exergy analysis, and examine its performance in mixed-mode operations under various off-design scenarios. The experiment's liquefier (model: HELIAL 50, manufacturer: Air Liquide, France) has a 50 liter/hour capacity without liquid nitrogen precooling and has been working for the Superconducting Cyclotron at the Variable Energy Cyclotron Centre (VECC).

Comparing the simulated model to the actual liquefier while considering that both have an equal capacity for liquefaction at pure liquefaction mode, it was found that the variation of the capacity at mixed modes happens less than +12%. The current investigation also demonstrates that the exergy efficiency and SPC of the existing liquefier depart from the simulated model by less than +10%. Interestingly it has been observed that the deviation of exergy efficiency is a maximum of 7.80% at 75W@4.5K mixed mode refrigeration load. This occurs due to the fact that although the existing plant has been sold as liquefier, but actually it has been optimized at a mixed mode refrigeration load of 75W@4.5K. For the pure liquefaction and pure refrigeration modes, the variations, however, are less than 1%.

The current experimental study suggests that the parameter exergy efficiency is the most important factor in determining a helium liquefier's performance in off-design mixed modes. This investigation validates the approach of the simulated model and shows how a designer can use it to forecast off-design properties of a real liquefier. Another interesting observed aspect is that the JT valve and turbine flow control valve have percentage exergy destruction of about 8%, which is pretty significant and is supported by the simulated model. This examination also reports on the thermal characteristics of the heat exchangers operating below 20 K at mixed modes.

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Design Methodology of a Vertical test cryostat in BARC for testing of superconducting cavities

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BARC Mumbai is working towards development of a high intensity proton accelerator as a part of the accelerator driven subcritical systems plan. This envisages the use of superconducting cavities for acceleration of a proton beam to the present energy target of 40 MW. A test facility is therefore proposed to be setup in BARC for testing and qualification of the superconducting cavities. This paper describes the design methodology for the Vertical test cryostat of the test facility. The requirements are taken w.r.t. the largest cavity to be tested which is ~700 mm diameter. The dynamic heat load is ~ 20 W with a testing period of ~ 8 – 16 hours at a temperature of 2K. The heat in-leak computations result in a value of ~ 10 W of static heat load. The cryostat grossly consists of a cylindrical vessel containing liquid helium bath which is enclosed by a vacuum jacket with a thermal shield in between. The cryostat is planned to be tested by transfer of helium from storage dewars. The cavity is suspended from the top cover by support rods and immersed in the liquid helium bath. The bath temperature is reduced below 4.2K by evacuation up to 2K at saturation pressure of 31 mbar. Other components of the cryostat include cryogenic valves, piping interconnections, flanges, etc. The piping is designed using ASME B31.3. The basic scheme is followed by sizing of the cryostat based of the inventory requirement, vacuum pumping and experimentation procedure. It consists of iterative calculations of static heat load, vaporization during pumping initial filling and design of the cryostat inserts. Height of the cryostat is ~4.5 m. The material of construction is SS 304L. Flanges, Inner vessel and outer vessel are designed as per ASME Sec VIII Div 1 [1] and is detailed in the paper. The cryostat is designed for transportation with the help of temporary internal supports. Fabrication and assembly procedures have also been discussed. The insert of the cryostat consists of an assembly supported by threaded support rods. The upper part consists of foam insulation to reduce radiation heat transfer from the flange. The lower part supports the cavity which has other connections such as vacuum line, RF input line, temperature sensors, etc. upto the top flange.

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Control and Instrumentation system of Indigenous LHP100 Helium Liquefier Plant at BARC

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Cryo-Technology Division, BARC is developing a 100 l/hr helium liquefaction system [1] (LHP 100) [2]. The process design of LHP100 is based on modified Claude cycle [3]. In contrast to the LHP50 [4, 5], the LHP100 makes use of liquid and vapour nitrogen precooling to enhance the refrigeration capacity. LHP50 helium liquefier has been manually operated extensively. The operational experience from the LHP50 cryo plant has been utilized in the development of control system for the LHP100 liquefier. The major components of the LHP100 system consist of a process screw compressor with gas management system, cold box with vacuum system, high effectiveness plate-fin type heat exchangers, high speed turboexpanders, charcoal absorbers, bellow sealed control valves and helium Dewar with interconnecting cryogenic pipelines. Present article describes the detailed philosophy of the control system for the LHP100 liquefier along with details of the supervisory control system. The control system consists of independent feedback loops for some of the above component systems and plant automation according to an elaborate flow control diagram implemented through PLC and supervisory control system. The complete automation/control system of the LHP100 plant is being developed by Reactor Control Division and Cryo-technology Division, BARC. The high speed turboexpander brake control system and precision pressure control loops have already been developed using microcontroller and PC based system and have been reported earlier [6]. The present article reports the PLC implementation and simulated testing of these systems. The PLC system has been integrated with EPICS SCADA software using Channel Access (CA) protocol.

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Design, Development and testing of 1 Kelvin refrigeration test setup.

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Quantum computers made up of superconducting qubits must operate in ultra-low temperature (50mK or less) to reduce thermal energy which could excite vibration motion of quantum states disturbing the quantum computing operations. These systems must operate under high vacuum and stable mechanical environment to prevent unwanted excitation of qubit state. The steady state low temperatures required for quantum computers are achieved using dilution refrigerator.

Considering the imperative requirement of dilution refrigerators for Quantum computers based on superconducting qubits, EmA&ID, BARC has initiated indigenous design and development of cryogen free dilution refrigeration system. As a step towards indigenization, a 1K cryogen free system is designed, developed and tested for its performance.

This refrigeration system consists of a closed cycle cryo-cooler, heat exchangers, gas handling unit and JT impedance. Closed cycle cryo-cooler is required to maintain the base temperature of plates connected to first stage (50K) and second stage (4.2K) of the cold head using flexible copper braid joint. The gas handling unit is designed to evacuate the vacuum vessel of the refrigeration system before cool down of the plates connected to first and second stage of cryo-cooler and main helium loop. Gas handling unit automates the precooling of system to reduce the cool down time. Once the base temperature of the first stage and second stage plate is reached due to cryo-cooler and precooling system, the system evacuates the helium gas from the precooling loop and automatically transfers helium gas to the main helium loop. The still (helium-pot) of the refrigeration system is evacuated after liquefaction of helium in the main loop. High purity helium-4 gas precooled to 40K, using heat exchangers attached to first stage of cryo-cooler, is liquefied using condenser at 4.2K cold head stage. The liquefied helium is passed through a Joule Thomson (JT) Impedance valve into a cylindrical vessel, which is evacuated to decrease the vapor pressure and achieve low temperature. As He-4 becomes superfluid at temperature less than 1.8K, proper design of the still/He-4 evacuation chamber is carried out to reduce creeping of the superfluid helium. Proper surface finishing of evacuation chamber is carried out to reduce the critical velocity of helium liquid film. A stable temperature of 1.04K is achieved by proper optimization of the still chamber.

Process modeling and thermodynamic performance evaluation of a turboexpander based helium liquefier

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A small-scale radial expansion turbine is characterized by its ease of production, higher efficiency, and reliability. These expansion turbines are successfully used in cryogenic turboexpander to cool the process gas. This work presents the insight for an optimal design procedure of a radial expansion turbine, the most essential and expensive component of a cryogenic turboexpander. The initial investigation starts with the preliminary design of a radial expansion turbine and nozzle (turboexpander) employing helium as a working fluid. Initially, different losses of the turboexpander have been determined using an optimum set of loss correlations which is incorporated with the design process. After that, three turboexpander systems are designed and a comparative numerical analysis has been conducted to study the fluid flow phenomenon and their thermal performance at different operating conditions using ANSYS CFX®. The results illustrate that the predicted performance from the numerical simulation shows good agreement with the experimental results.

The process simulation of the designed helium liquefaction system has been illustrated for different operating modes. The typical flow rate of the warm and cold turbines is 36 g/s with the minimum cooling power of 3060 W and 1070 W respectively. The cooling power for the warm turbine is achieved for inlet and outlet pressures of 13.2 bar and 5.4 bar, respectively and the outlet temperature achieved is 58.3 K for inlet temperature of 74.2 K. The equivalent pressures for the cold turbines are 5.3 bar and 1.13 bar whereas equivalent temperatures across this turbine are 17.4 K and 11.4 K respectively.

The experimental test set-up of helium liquefier is under developing phase. There is a separate control system for the turboexpander based on Siemens make S7-1200 series PLC. A separate control system will be made for the process Siemens make S7-300 series PLC. Profinet bus communication is there for command and feedback using PUT/GET functions.

The performance of the turboexpanders can be evaluated by its cooling capacity for a particular temperature and pressure difference at a particular flow rate. The process requirement is determined by the opening of the inlet valve of the turboexpander. As the required heat exchangers would not be available, simulation has been performed for the available heat exchangers to understand the pressure and temperature distribution across the overall system so that the thermodynamic performance and off-design characteristics of the turboexpanders can be realized.

Horizontal Test Stand for the Testing of Single Spoke Resonator Superconducting RF Cavities at BARC

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Single spoke resonator (SSR) superconducting radiofrequency (SCRF) cavities are planned for the proposed Medium Energy High Intensity Particle Accelerator (MEHIPA) [1] at BARC. The cavities, before assembly into cryomodule, will be qualified for cryomodule worthiness. The required tests, among others, include high power RF testing at 2 K. These tests will be done in a purpose built cryostat called horizontal test stand (HTS). The cryostat will provide the same process conditions which will exist in the cryomodule, but for a single cavity. Tuner, high power coupler and other auxiliary components required for testing will be installed with the jacketed SSR cavity for testing in the HTS. The cryostat have three independently operable cryogenic fluid circuits. The liquid nitrogen circuit will serve to remove the heat load of the thermal shield maintained around 80 K. Helium incoming circuit, 4.5 K @ 1.2 bara, will be used to cool down the cavity . The third fluid circuit is of sub-atmospheric saturated 2-phase helium at 2 K. This sub-atmospheric circuit will cater to the 2 K refrigeration load of the cavity. Provisions are also made for 80 K thermal intercepts to mitigate the conduction heat load to the components and regions maintained at 2 K. The supply of cryogenic fluid will be controlled by an existing feedbox. The feedbox was developed earlier by BARC. Long stem bellow sealed valves and a JT heat exchanger along with cryogenic piping, dedicated thermal shield and check valves are the major components of the feedbox. The required liquid helium and liquid nitrogen will be supplied to the feedbox from respective Dewars. The facility is being planned to cater to a maximum isothermal heat load of 30 W at 2 K. Cryostat will also have room temperature magnetic shield to maintain the required magnetic hygiene near SSR cavity during tests. The required instrumentation to measure the cryogenic load shall be provided. Q_0 will be determined by experimental measurement of 2 K isothermal heat load. The performance of tuner, piezo and high power coupler will also be investigated at cryogenic temperatures during the cavity performance test. This work presents the preliminary cryogenic process scheme and the mechanical design of the HTS.

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Development of SHP20: 2 K Cryo-plant for MEHIPA

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BARC is involved in the development of 200 MeV and 10 mA, Medium Energy High Intensity Particle Accelerator (MEHIPA) [1] arming to the Demo ADS and spallation research. In order to cater to the cryogenic requirement of MEHIPA and to test various cryogenic equipment mainly very low pressure heat exchangers and subsystems, SHP20, a 20 W at 2 K cryo-plant is being designed and developed [2][3]. The SHP20 cryo-plant will be coupled with the existing indigenously developed liquid helium plant LHP50 [5] or LHP100 [3]. Supercritical 4.5 K helium is been supplied to the SHP20 cryo-plant from the LHP100 plant. The SHP20 plant consists of helium pre cooler, VLP heat exchanger, cryogenic valves and sub-atmospheric bath to produce 2 K helium. The 2 K sub-atmospheric bath pressure is maintained to 30 mbar using a warm compression. Since the full sensible heat of the cold stream is not utilized in the JT Heat exchanger, a cryogenic radiator has been incorporated in the design. Thermal insulation design of the 2 K system is critical and uses copper thermal shields, thermal intercepts and vapor cooling. The present article details the process, thermal and mechanical design of SHP20 cryo plant. Design of the cryogenic equipment such as pre cooler, 2 K vessel and bayonets have been briefly discussed along with relevant design codes. The VLP heat exchanger development along with the cryogenic testing is also reported in the present article.

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Design and fabrication of cryogenic distribution box for Horizontal Test Stand at RRCAT

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Horizontal Test Stand (HTS) facility has been setup at Raja Ramanna Centre for Advanced Technology (RRCAT) for high power testing of dressed 650 MHz Superconducting Radio Frequency (SCRF) cavities at 2 K temperature and it is used for final qualification of dressed SCRF cavity before integration/installation in a cryomodule. Presently HTS cryostat is directly interfaced with cryogenic plant through cryogenic transfer lines. A distribution box is being planned to be interfaced between the HTS cryostat and cryogenic plant for better cryogenic operational flexibility and reliability. The distribution box consists of the vacuum vessel , Liquid Nitrogen (LN_2) cooled thermal shield , Liquid Helium (LHe) transfer line , LN_2 transfer line , 2 phase helium return line , cryogenic control valves , check valves , temperature and pressure measurement instrumentation , safety valves , isolation valves etc. This external cryogenic distribution system will be a set of cryogenic components to feed and return the cryogens via vacuum insulated pipelines to the various components of horizontal test stand which need cryogens.

Distribution box will provide the path for 4.5 K helium supply,5 K intercept and bridge cooling helium return, LN_2 supply for radiation shield cooling , accidental release of helium in circuit , pressure and temperature measurement of supply and return helium. Vacuum insulation space of distribution box has been designed for continuous sealed vacuum operation and it will be able to be maintained without active continuous mechanical pumping during normal operation. HTS distribution box has also been designed in such a way that it can perform all required cryogenic operations safely with in-built design safety features. Total 16 ports have been provided for operational requirement of HTS and 1 spare port has been provided for any future needs.

The HTS facility has been set up , commissioned and a dressed 650 MHz Superconducting Radio Frequency cavity is successfully tested at RRCAT, with required pressure stability. During this testing, the cavity was conditioned for more than 20 hours, at pulse repetition rate of 20 Hz with duty cycle upto 40% and power up to 22 kW. 2 K temperature was maintained with required stability for more than 48 hrs continuously . Present paper describes the mechanical design of distribution box vacuum vessel and fabrication aspects of this vessel along with LN_2 shield including trace tubing. The mechanical design of vacuum vessel consist of the buckling analysis of the shell , stress analysis of bottom support and top flange etc. In addition to this, the various fabrication and qualification aspects of vacuum vessel and LN_2 shield such as helium leak testing , vacuum testing , cold shock etc. have been described in this paper.

Design, development and installation of cryogenic safety system of Horizontal Test Stand

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Horizontal Test Stand (HTS) facility serves as a final-qualification test of dressed Superconducting Radio Frequency (SCRF) cavities at 2K temperature before integration/installation in a cryomodule. Cryogenic operation of HTS is a quite complex process, due to its stringent requirement of simultaneous filling and pumping of helium to achieve 2K temperature while maintaining constant liquid level with required pressure stability. HTS safety system has been designed and installed to ensure safety of equipment, personnel in case of emergency. This safety system is a combination of spring operated relief valve and rupture disc. Designed safety system alone or in combination will serve as emergency relief for loss of vacuum with helium lading, fire condition and loss of vacuum with air condensation and will protect helium vessel and cavity for all these emergency scenarios.

The lay-out of safety system, consisting pipelines and safety valves, is able to take safely the static and dynamic stresses (reaction forces) occurring due to quickest opening and closing of safety valves. All cross sections of pipelines have been designed and installed to ensure the necessary discharge and undisturbed functioning of the safety valve without frequent popping. Rupture disk is being installed in series of spring loaded safety valve and will vent the same mass flow rate as the spring loaded safety valve. The venting requirements for the burst case scenario has been taken into account. The corresponding heat load for the loss of vacuum of cryostat vacuum jacket and loss of 650 MHz cavity vacuum with air condensation are 128 kW and 83.6 kW respectively. Calculation shows that loss of cryostat insulating vacuum with air condensation is the worst case pressure rise situation for the Horizontal Test Stand and will release 6.24 kg/s mass flow rate of helium through the relief valve at 15 psig set pressure.

These safety devices have been placed indoor at atmospheric pressure and ambient temperature. Any accidental venting has been routed to the outside of building to avoid any oxygen deficiency hazards (ODH) in HTS Vault. All these safety devices have also been installed close to the HTS as possible to limit the heat flow into the helium temperature environment while venting. The attention has been paid for required leak tightness and necessary process has been incorporated to prevent any possible leakage from ambient to the helium vessel during 2 Kelvin operation. The volume between safety valve and bursting disk has the provision to maintain the atmospheric pressure during sub-atmospheric operation and also has the provision to release the excess pressure rise build-up in the space during the top fill and bottom fill operation.

Present paper describes the design of safety system of HTS cryogenic system and it's installation for eliminating any probable accidental scenarios, analysis and mitigation plan for safe operation of HTS is also presented.

Cryogenic Transfer Line for Cryomodule of e-LINAC at VECC

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It is planned to generate Rare Isotope Beam (RIB) using the photo-fission route at Variable Energy Cyclotron Centre (VECC), Kolkata [1]. To achieve this, VECC is constructing an electron linear accelerator (e-LINAC) facility comprising of a number of cryomodules having superconducting cavities inside. The proposed Cryogenic Transfer Lines (CTL) will transport liquid helium (LHe) to cryomodules from Dewar of helium liquefaction plant. 4K LHe from Linde 280 LHe plant will be fed to the Cryomodule via LN2 cooled and Multi-Layer Insulation (MLI) shielded cryogenic transfer lines (CTL). Vacuum-jacketed LN2 CTL provides LN2 to the actively cooled shield of the LHe line as well as to the thermal radiation shield of the cryomodule. Inside the cryo-modules, 4K helium is brought into a reservoir and 4K to 2K cool-down is done internally. 2K LHe is distributed to individual niobium cavities via a common distribution pipe connected to annular shells of the cavities. This pipe is evacuated using sub-atmospheric helium pumps via vacuum-jacketed sub-atmospheric (SA) line, to maintain an internal pressure of around 30 mbar thereby maintaining the LHe at 2K. The total length of cryogenic transfer line is about 300 m including the 100 m long LN2 shielded LHe line & the vacuum jacketed sub-atmospheric line and 200 m long LN2 line. Hence, the cryogenic transfer line is divided into multiple transportable segments. These segments are connected to each other by means of vacuum insulated field joints. The heat in-leak calculation has been carried out for a typical pipeline segment as well as field joint separately. The estimated heat in-leak values are 0.08 W/m for a typical segment and 1 W for a typical field joint. Phase separators are used for separating gas from liquid nitrogen so that bubble free LN2 is supplied to the cryo-modules and LHe transfer lines. Finned aluminium tube vaporizers with natural convective air cooling are used. The cryogenic transfer line is equipped with different sensors for monitoring the operation, viz., Si diode temperature sensor, thermocouple, RTD, pressure transmitter etc. Its control system is SCADA based for facilitating supervision and control through LAN from a remotely located Central Control Room. The PLC will continuously monitor values of all the cryogen delivery system process parameters and primarily use these signals to control the cryogen delivery system. The PLC requires the following I/Os - Digital Input: 48; Digital Output: 12; Analog Input: 12; Analog Output: 16; RTD input: 7. All the spools / segments of cryogenic transfer line have been fabricated at M/s Shell-N-Tube, Pune. The spools have been rigorously inspected at their factory; spools in which leaks were found, have been repaired and then retested. The installation and commissioning of the cryogenic transfer line will be carried out at the RIB facility at VECC, Kolkata.

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Design analysis of strongback and cavity support for high beta 650 MHz cryomodule at RRCAT

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Design and development of cryomodule for High Beta (HB, Beta= 0.92) 650 MHz Superconducting Radio Frequency (SCRF) cavities is being pursued for 1GeV pulsed proton Linac R&D at RRCAT in collaboration with Fermilab. This cryomodule will be a part of high beta section of the superconducting proton LINAC. Major subsystems like vacuum vessel, strongback, 70K thermal shield, cavity support etc. have been designed at RRCAT [1].
Strongback is main supporting frame, maintained at room temperature, which supports cavity string from bottom inside vacuum vessel of HB 650 MHz cryomodule. Its main function is to withstanding complete cold mass load including thermal shield. It facilitates assembly of the cold mass outside vacuum vessel. Cavity support structure holds the cavity and string assembly in place above strongback. Cavity support transfers the load of the cavity string maintained at 2K temperature to strongback through cryogenic support post. Strongback and cavity support also maintains alignment of the cavity string. Alignment of cavity string will be done outside of vacuum vessel. Strongback and cavity support should be rigid enough to maintain alignment during insertion of cavity string inside vacuum vessel as realignment cannot be done once string is inside vessel.
This paper discusses design efforts for strongback and cavity support at different loading conditions. Structural analysis for load conditions during operation and during insertion, has been performed to find out stresses and deformation. For operating load condition, strongback support location is fixed on studs and has been modeled as fixed support. String assembly load is distributed on strongback through cryogenic support posts. For load condition during insertion, strongback support has been shifted from fixed studs to wheels on rail step-by-step and all conditions has been modeled and analyzed to obtain stresses and deformations during each step of insertion of cavity string in vacuum vessel. Cavity support thermal contraction analysis also has been performed to ensure maintaining alignment after cool down to 2K. The paper discusses all the results for different load cases analyzed for strongback and cavity support.

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Selection of HB 650 Cryomodule Control Valves & Development of Excel VBA Program

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Design and development of cryomodule for High Beta (HB, Beta= 0.92) 650 MHz Superconducting Radio Frequency (SCRF) cavities is being pursued for 1GeV pulsed proton Linac R&D at RRCAT in collaboration with Fermilab. This cryomodule consists of six numbers of SCRF cavities. SCRF cavities are maintained at temperature of 2K during normal operation. There are various operating modes of cryomodule like cool down from room temperature to 2K, pulsed mode operation, CW mode operation, standby mode at 2K etc. This requires modulation of helium flow rates through cryogenic circuit for these different modes. This cryomodule has two cryogenic control valves namely JT Valve and Cooldown Valve to cater to these requirements.
This paper presents calculations for pressure drops, flow rates and valve C_v requirement for various operation modes. Helium flow rates required to cool cavities with required cool down rates have been calculated and C_v requirement for these cases at different temperatures are also calculated. Temperature varying material properties are used while calculating required flow rates through cooldown valve. Valves have been selected to cater to various operating modes and their opening percentage and percentage of maximum C_v have been presented in this paper. Cool down and JT valves of DN15 size have been selected. Maximum C_v for Cool down and JT valves are 3.5 and 0.2 respectively with Rangeability of 100. Operating points for various cases with different values of maximum C_v are also presented and compared in this paper.
An Excel VBA program has been developed for calculation of required valve C_v as per ISA75.01 code. This excel program has been interfaced with Hepak for helium properties which can be called from excel worksheet like any other excel function and calculates required C_v for given set of inlet and outlet conditions. Developed code will be useful for valve calculations in future as well.

Design of Vacuum Vessel for HB 650 MHz Cryomodule at RRCAT

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Design and development of cryomodule for High Beta (HB, Beta= 0.92) 650 MHz Superconducting Radio Frequency (SCRF) cavities is being pursued for 1GeV pulsed proton Linac R&D at RRCAT in collaboration with Fermilab. The cryomodule is a large cryostat and is basic building block of superconducting Linac. The length of cryomodule is ~10 m, housing six numbers of HB β=0.92, 650 MHz SCRF cavities. The cylindrical vacuum vessel of cryomodule provides insulating vacuum and structural support to cold mass which comprises of SCRF cavities, thermal shield, support system, internal piping etc. Vacuum vessel has various ports for tuner, RF coupler, cryogenic instrumentation, vacuum pumping and transport access, strongback support posts, relief valve, side extension, top hat for heat exchanger and pressure transducers on vessel shell. Vacuum vessel for HB650 MHz cryomodule has been designed and an engineering note has been prepared as per ASME Boiler and Pressure vessel code, Section VIII, Div. 1.

This paper describes structural design of vacuum vessel.The design calculations has been performed for vessel shell thickness for both internal and external pressure, flanges & end covers, reinforcement requirements for openings, large openings of shell, reinforcement for multiple openings on flat head and out of roundness calculations. FEA has been performed for different loading conditions and results for stresses and deformation are presented.

Development of a 20 KeV, 2 kW DC strip type electron gun system for testing photon absorber of Indus-2 SRS

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A 20 keV, 2 kW DC triode thermionic emission strip type electron gun is designed with tungsten cathode of size 0.7 mm x 20 mm, producing strip electron beam foot print of size 3 mm x 60 mm [1]. The electron gun system is developed to extract desired beam current of 100 mA at average power density of 14.5 W/mm^2 at water cooled photon absorber surface for its qualification testing. In Synchrotron Radiation Sources (SRSs), photon absorbers are used to absorb unused synchrotron radiation (SR) power emanating from bending magnets. In next generation SRS, the SR power density to be absorbed by such devices is in the range of 10-100 W/mm^2. Such photon absorbers, being designed indigenously, need to be tested with an alternative power source simulating identical power density. To meet this requirement, an indigenous test setup is developed with electron gun depositing heat load in vacuum environment on water cooled photon absorber as thermal power source. This paper describes design, development, manufacturing, hardware architecture and initial optimization of test set up parameters for desired beam power density.

Keywords: *Synchrotron Radiation Source, Photon absorber, electron gun, Thermionic emission.*

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Design and simulation analysis of vacuum system of SWLS insertion device for Indus-2 Synchrotron Radiation Source

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Indus-2, 2.5 GeV Synchrotron Radiation (SR) source at RRCAT, Indore is a dedicated national facility for synchrotron users. In long straight section (LS-4) of Indus-2, Superconducting Wavelength Shifter (SWLS) is planned to be developed indigenously at RRCAT and to be installed in Indus-2 LS-4. Ultra-high vacuum (UHV) system compatible to SWLS has been designed to operate at ~1E-9 mbar under dynamic condition for having sufficient long beam lifetime. Due to narrow pole gap of SWLS magnets, corresponding vacuum chamber is conductance limited hence achieving this order of UHV is quite difficult with conventional lumped pumping system. Distributed pumping in the form of non-evaporable getter (NEG) coating is proposed to be applied on the vacuum exposed surface of SWLS vacuum chamber for effective pumping. Monte-Carlo simulation based software was used for the pressure profile simulation of proposed system. Structural and thermal stability of SWLS vacuum chamber against atmospheric loading and SR respectively were studied using Finite Element Method (FEM) based software. This paper describes design, pressure profile simulation and analysis of the UHV system of SWLS. Structural and thermal simulation results of vacuum chamber and peripheral components are also discussed and analyzed.

***Keywords**: Long Straight Section-4, Superconducting Wavelength Shifter, Ultra High Vacuum, Monte-Carlo, Non Evaporable Getter, Finite Element Method*

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Design, simulation, development and UHV testing of upgraded prototype dipole vacuum chamber for Indus-1 SRS at RRCAT

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Indus-1(a 450 MeV, 100 mA) Synchrotron Radiation (SR) source is a dedicated national facility for synchrotron users. Implementation of closed orbit distortion (COD) correction scheme in Indus-1 ring is planned to be implemented as part of up-gradation program. Accordingly, new UHV system compatible to COD correction scheme has been designed and development of all the new components are in advanced stage of progress. Operating pressure <1E-09 mbar is required for good beam life time. Dipole vacuum chamber is one of the major UHV components of the ring. A prototype dipole vacuum chamber with new design features was designed, fabricated and tested for its UHV performance prior to batch production of the actual chambers. Salient upgraded design features of new dipole vacuum chamber are simplified geometrical design, incorporation of ion clearing electrode and new UHV pumping scheme [1]. Finite Element (FE) simulation was carried out for structural design optimization under atmospheric loading condition. CNC water jet cutting machine was utilised first time for cutting the profiles of the SS316L sheets for its fabrication. Manual GTA welding process was deployed for UHV compatible helium leak tight (<2E-10 mbar-l/s) welding of the vacuum chamber [2]. This paper describes design, structural FE simulation, manufacturing and UHV performance testing of prototype dipole vacuum chamber for Indus-1 SRS ring.

Keywords: *Synchrotron Radiation, Closed Orbit Distortion, UHV, Dipole vacuum chamber, Ion clearing electrode, Finite Element simulation.*

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Design and Impedance Simulation of RF-Shielded Bellow and Pumping Manifold for Indus-1 Upgradation

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Abstract

Indus-1(a 450 MeV, 100 mA) Synchrotron Radiation (SR) source is a dedicated national facility for synchrotron users. Implementation of closed orbit distortion (COD) correction scheme in Indus-1 ring is planned to be implemented as part of upgradation programme. Accordingly, new UHV system compatible to COD correction scheme has been designed and development of all the new components are in advanced stage of progress. Hydroformed metallic bellow made of SS316L is an important component which is installed in the ring to compensate for fabrication & alignment tolerances and to take care of thermal expansion of vacuum chambers during baking. Corrugations of bare bellow generate impedance for the circulating bunched beam in the ring and requires rf-shielding to minimize the impedance to acceptable range. Pumping manifold is another in-line important component in the ring which is required to connect Ultra High Vacuum (UHV) Pumps. Pump port hole again creates impedance for the beam and requires rf-screen type design to facilitate pumping together with low impedance for the beam.

In view of above requirements, impedance simulations of rf-shielded bellow and rf-screen pumping port have been carried out using CST Particle Studio wake field solver for optimizing their designs. Before embarking on the actual design simulation, software simulation result was first validated comparing with analytical solution and measurement data for simplified geometry of bellow. Measurement of impedance was carried out by co-axial stretched wire method [1]. The simulated results show a covariant behavior w.r.t the theoretical as well as measured results over a large frequency range.

This paper summaries layout of the UHV system of upgraded Indus-1 ring, engineering design of the rf-shielded bellow assembly & UHV pump manifold their impedance simulation results and analysis

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Vertical Pinger Magnet Power Supply for Indus - 2

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A set of Pinger magnets is required to study linear and nonlinear beam dynamics in Indus-2. With these magnets, the beam can be excited vertically or horizontally, and the response to these magnets will be measured with BPMs. Half sine current pulse with peak current of 5600 Amps and pulse width < 1µs was required to generate a deflection angle of 2 mrad in Vertical Pinger magnet. The half sine current pulse is generated by a highly underdamped LC circuit formed by HV capacitors and Vertical Pinger magnet which acts as an inductor. Power supply specifications were achieved with a low inductance, high voltage compliant pulser unit with Thyratron as a switch. As a means of reducing the charging voltage to a minimum value, low ESL capacitors (ESL ≤ 50nH) were used and compact coaxial thryratron assemblies are fabricated, to reduce the path inductances. Additionally the PFN assembly was fabricated on site based on the available space and it was placed very close to the pinger magnet to reduce stray inductances. Besides reducing the charging voltage to minimum value this step also aids in achieving the current pulse width < 1µs. The control unit, capacitor charger, thyratron auxiliaries, trigger unit were housed in 36U rack. To overcome the problem associated with thyratron switch namely slow recovery characteristic, which will lead to significant negative current and reverse arcing due to highly under damped circuit, a snubbed diode stack was used in series with thyratron. Toroidal saturable reactors (Ni-Zn ferrites, T 150) are used to limit di/dt of current. With the use of saturable reactors, clean up current and amplitude of reverse voltage were reduced. The power supply was installed and commissioned in Indus -2 and is ready for beam dynamics experiments.

Design and Development of Digitally Controlled Power Converter for Thyratron Auxiliary Power Supplies

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In particle accelerators, pulse magnets are energized using pulsed power supplies to generate fast pulsed magnetic fields. Performance requirements for these power sources are stringent. Peak amplitude stabilities, jitter, repeatability and pulse shapes are of prime importance. For high voltage, high current switching applications, Thyratron is used as a switch due to its ruggedness but Thyratrons suffer from anode delay drift. In precision pulse power applications, it is desirable to control the anode delay drift. This paper presents the design and development of a Digitally Controlled Power Converter to power Thyratron auxiliaries. It also discusses measuring and controlling thyratron auxiliaries remotely with digitally controlled power converter. A prototype two switch power converter with switching frequency of 24.41 kHz was developed for experimental validation. The digital controller and Digital Pulse Width Modulator (DPWM) was implemented in FPGA. This paper presents the generation of DPWM using counter based DPWM technique, controller and it's implementation in FPGA. The developed power converter has been used to power thyratron in a prototype pulser in lab. It has been demonstrated that the developed power supply can be used to manipulate thyratron anode delay remotely. Experimental results of anode delay with thyratron reservoir voltage have been presented.The design, development and testing have been elaborately discussed in this paper.

Deisgn and Development of HV Pulsed magnetron modulator for Dual Energy Linac Applications.

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A typical 6/4 MeV electron Linac is used for CARGO Scanning application. Pulsed Electron beam with alternate pulses of 6MeV and 4MeV is used for material discrimination. In-order to make the compact RF Source of the same, Pulsed Power Magnetrons are typically used as an RF Source. The magnetron is powered by a pulse modulator whose output pulse power varies from pulse to pulse so as to achieve interlaced RF Pulse power output for feeding the linac.
The paper describes the design and development of the pulsed magnetron modulator rated for 38kV (-ve), 168A, 3.4μs, (flat top) and Pulse Repetition Frequency of 200 pps.
The modulator has been tested on Resistive load followed by magnetron load. The pulse to pulse current stability of within +/- 1% has been achieved for the same. In conclusion the paper also discusses the future scope of improvement and scalability of the technology.

Development of Test stand for Performance Evaluation of High Voltage PFN Capacitors

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The pulse forming network (PFN) capacitors of the HV pulsed modulators are required to be capable of simultaneously handling the high voltages, high peak and RMS currents, and high repetition rates. Proper testing and qualifying the capacitor's performance for their peak design values is crucial for such applications. The manufacturers (OEM) generally do not have the facilities for testing the capacitors at high peak currents and voltages at high repetition rates. OEM conducts usual tests of viz capacitance, peak voltage, leakage current, peak current, equivalent series resistance (ESR) and equivalent series inductance (ESL). ESR parameter directly indicates the loss within the capacitor. The measured ESR and ESL values are highly affected by the measurement test set up and do have large measurement errors. Local industries are not equipped with set up for testing of energy storage capacitors for high repetition rate applications. Also, direct loss calculation based on the inference of the test data may lead to wrong conclusion. Hence, a test stand has been designed and developed for the performance evaluation of high voltage PFN capacitors at parameters very close to real application parameters. The test stand consists of a HV capacitor charging power supply (CCPS), thyratron based switching unit and resistive load. The CCPS linearly charges the "capacitor under test (CUT)" to the desired voltage. The CCPS has the output voltage and current capability of 25 kV_{max} and 1.5 A respectively. The supply is based on high frequency switched DC-DC converters using series L-C resonant topology. The switching frequency of the DC-DC converter is chosen as ~10 kHz. The stored energy in the CUT is discharged to the resistive load using a HV switch unit. The HV switching unit consists of a hydrogen thyratron (CX1154) and associated grid drive unit to turn on the thyratron switch. Low cost heating elements have been used to construct the resistive load. The test stand serves as a qualification set up of PFN capacitors for loss estimation at parameters close to real application before its usage in the modulator. The test stand operates at maximum charging voltage, peak current and repetition rate of 25 kV, ~800 A and 400 Hz, respectively. The design, construction details and results of the test stand will be discussed in the paper.

Design and development of floating pulse power supply for triode electron gun

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Abstract

Triode type pulsed electron gun of 90 kV cathode voltage has been developed at RRCAT, Indore as a technology demonstration. This electron gun source is proposed to be used for 10 MeV electron LINACs for irradiation of industrial and agricultural products. The control electrode of the electron gun requires positive pulsed voltage up-to 2 kV floating at cathode voltage. A 2 kV pulsed power supply of 15 μs pulse width has been developed to bias the control electrode. This power supply floats at -90 kV cathode voltage and provides 0 to +2 kV pulse between cathode and control electrode in synchronism with the cathode pulse of electron gun. By varying the pulse voltage of control electrode, it is possible to vary the electron gun current.The input ac voltage to this pulse power supply is derived from the isolation transformer used for filament heating of electron gun. DC power supply has been switched through an IGBT switch and a pulse transformer. The DC voltage is controlled by applying optical signals to motorized auto-transformer. The maximum and minimum value of control electrode is set by an optical limit switch of auto-transformer. The control electrode voltage is monitored by sensing DC voltage at the rectifier output and converted into proportional frequency signal for optical transmission. This frequency signal is converted back to voltage signal for measurement and read-back of control electrode voltage. At present, this power supply has been tested and qualified on a resistive load of 10 kΩ up-to pulse repetition rate of 300 Hz. Also it is integrated with the electron gun test stand and tested up-to 2 kV control electrode voltage at 90 kV cathode voltage. This paper presents design, development and test results of the pulse power supply for triode type electron gun.

Design and Development of Isolated Two Winding Bouncer Scheme for Droop Correction in Hard Switched Modulator

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Abstract

Pulse modulators provide high voltage pulses at required pulse repetition rate (PRR) for the Klystron based microwave amplifiers. The pulse modulator generates high voltage pulses by discharging the energy stored at lower voltage, in energy storage capacitor into the primary of a step-up pulse transformer using a controlled switch. In pulsed modulator applications, droop of the output pulse is an important parameter. The output pulse droop of less than 1 % is generally acceptable for most of the applications. The droop of the output pulse depends on the load, capacity of the energy storage capacitor and pulse transformer parameters. A novel scheme based on two-winding bouncer for droop correction has been developed which has resulted in reduction in the capacity of the energy storage capacitor of hard switched modulator by about 50 times. The droop correction technique uses LC oscillations setup between bouncer capacitor and magnetizing inductance of the bouncer transformer to compensate the droop in HV output pulse of the hard switched modulator. A transformer having step up ratio of 1:5 has been designed and fabricated in-house using amorphous metal cores. The transformer of this scheme provides galvanic isolation from HV pulse modulator circuit. This scheme reduces the requirement of current rating of the switches in the compensation circuit and allows for maximum utilization of voltage rating of available switches as the level of voltage compensation can be adjusted due to transformer action. A pulse modulator has been designed and developed for generating 10 kV, 10 A, 100 Hz, 20 µs pulse with 10 % droop. The pulse transformer of this modulator consists of multiple parallel windings in primary to achieve lower leakage inductance and fast rise time. The two winding bouncer scheme is integrated with 10 kV pulse modulator to compensate droop from 10 % to 1 %. The trigger pulses for switches in pulse modulator and compensation circuits are generated by an FPGA. Interlocks are also provided to stop triggering of switches in case of any unsafe condition. Trigger pulses are transmitted from FPGA to HV circuit by optical signals which provide optical isolation to FPGA. The scheme is tested at 10 kV, 10 A, 20 µs with resistive load up to pulse repetition rate of 100 Hz and droop of 1% has been achieved in output pulse.

Our Experiences in Establishing and Managing Reliable and Secure Network Connectivity Over Public Communication Channels for Mission Critical Accelerator Applications

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Many large research and development organizations have departments located in geographically remote locations that need access to the internet and intranet resources for effective collaboration. Leased link services provided by telecommunication service providers can be used for extending computer network to these remote facilities. However, these leased links use public networks, which are known to be vulnerable to cyberattacks ***[1]****. Thus a proper security framework must be deployed to secure network traffic* ***[2]*** *flowing across remote locations. Virtual Private Network (VPN) solutions* ***[3]*** *provide a secure network tunnel to a remote location using modern encryption technologies over the internet to protect the data from malicious entities. Internet Protocol Security (IPsec)* ***[4]*** *is a suite of protocols and services that provide security for IP networks. It is a widely used virtual private network (VPN) technology* ***[5]*** *that uses encryption and authentication algorithms to ensure the security of VPN connections.*

Agriculture Radiation Processing Facility (ARPF) ***[6]*** *is a national level facility for carrying out irradiation of research samples for the development of new crop varieties, colour modification of gem stones, the development of novel materials, the modification of semiconductor properties, etc. using electron accelerators. ARPF site of Raja Ramanna Centre for Advanced Technology (RRCAT) is located at a distance of about 5 Kms from the main campus. RRCATNet,* ***[7]*** *is the campus wide computer network in RRCAT, which facilitates collaboration and information sharing among scientists and engineers at RRCAT.*

RRCATNet connectivity is extended up to remote ARPF site for controlling, monitoring of the radiation facility and administrative coordination of the ARPF activities by scientists and engineers working for the facility. The extended communication channel transports confidential and sensitive data related to linear accelerator administration and dose management for sample irradiation. Since mission critical data is flowing between two different locations via a public network, hence network security ***[8]*** *is of utmost importance. The best approach is to provide the protection at the lowest level of network and do not expect users to know anything about it. There are a number of solutions with pros and cons to protect the data during transit against tapping and eavesdropping* ***[9]****. Thus it is challenging to choose a solution which provides reliable and secure network connectivity over public communication channels. The continuity management of such a solution is also a big challenge.*

In this paper, we discuss the design and development of an IPsec-based ***[10]*** *secure VPN setup* ***[11]*** *for providing internet and intranet facilities to users at ARPF site of RRCAT. OpenBSD-based setups were developed and deployed and measured to obtain throughputs of approximately 75 Mbps over 100 Mbps leased line using IPsec protocol. Network security measures implemented inside RRCAT are also applied on the developed setup. The setup has been designed, developed, and deployed at ARPF, RRCAT, Indore, and is in regular use for last three years with 99.98% up time. We will also be discussing the continuity management aspect of such network* ***[12]*** *for mission critical accelerator application* ***[13].***

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Development of a prototype induction heating system For solid and metal ion beam generation in ECR ion sources.

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Recently in VECC, metal ion beam was generated and delivered from one of the two 14.45GHz ECR ion sources using MIVOC facility and has been successfully accelerated by K130, room temperature cyclotron. Although being a simple method, MIVOC has several disadvantages like contaminating the ECR chamber and poor transport efficiency. To overcome these, a prototype induction heating system along with temperature monitoring facility has been developed to explore the possibilities of solid and low melting point metal ion beam generation in ECR. This method is a cleaner, efficient and alternative technique to MIVOC. Here,a ZVS, parallel resonant type inverter generating 250 kHz frequency has been designed and developed for this purpose along with a thermocouple based temperature monitoring system which monitors the workpiece temperature. The sample metal or solid is taken in a ceramic crucible which is placed inside a cylindrical shaped, hollow iron work piece. Successful in vacuum experiments have been carried out in prototype arrangement for different metal sample evaporation. Mg, Bi, Zn. Pb, Ag and Cu are the few metals which have been evaporated. The efficiency of the system is found out to be around 78%. This paper describes the development, vacuum evaporation and performance analysis of the system developed.

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Development of Helmholtz Coil based Measurement System for Characterization of Permanent Magnet Blocks

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A majority of insertion devices used in synchrotron light source are undulators. Permanent magnet blocks made of Samarium Cobalt or Neodymium Iron Boron are used in undulators for getting spatially varying magnetic field. The quality of the magnetic field is related to the variation of magnetic properties of the individual permanent magnet blocks. Therefore, at the first step the magnetic properties of each block should be measured precisely to be able to sort them to minimize the field integrals and the phase error of the device [1,2]. This paper reports development of a Helmholtz Coil based measurement set up to characterize the permanent magnet blocks for the above purpose.
The measurement setup consists of a Helmholtz coil, a suitable holder for the magnets, a mechanical system for rotating the magnet holder, a rotary encoder for measurement of angular position of the magnet, electronics for acquisition of the emf signal and its integration. In the Helmholtz coil setup, two identical circular coils are placed coaxially and separated by a distance equal to the radius of the coils. This pair of coils produces nearly uniform magnetic field in the central zone when same current is carried by the coils in the same direction. Therefore, if a magnetic dipole (magnet sample) is placed and rotated in the central zone of the coils, the information of its magnetic properties can be retrieved from the voltage induced in the coils due to change of flux. The flux w.r.t. the rotation angle can be found out by integrating the voltage signal over time. By fitting the signal with a sinusoidal function, the two components of the magnetic moment (e.g. M_x and M_y) of the sample in the plane of rotation are found out. To find out the third component of the magnetic moment (M_z) , the magnet sample is rotated and the above procedure is repeated.
In the present setup, the two identical circular coils of radius 400 mm have been developed and placed co-axially at a distance equal to the radius of the coils. The magnet holder made of Aluminium alloy is driven by DC motor. The voltage induced in the coils is sampled and integrated digitally to give information about the magnetic properties of the magnet being characterized. The Helmholtz constant i.e. the *k* value was measured using high precision Keithley 6430 source meter and Mag-01 Bartington Fluxgate Magnetometer (magnetic field sensor). A rectangular coil of 8300 turns of known dimension is made to qualify the setup by comparing its measured magnetization with the estimated value. The precision of the measurement setup in terms of repeatability should be very high because the setup would be used for sorting of permanent magnet blocks of identical properties as stated in the beginning, A repeated measurement of a NdFeB permanent magnet block was used to get repeatability of the measurement. Data so collected reveal that the system provides a repeatability of better than 0.1 % in total strength and better than 0.1^0 in angular orientations of the components of magnetic moment w.r.t. the total moment.

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Improvement in Indus-2 Coolant Temperature Stability During Beam Energy Ramp up with Flooded Evaporator Type Chiller System

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The process heat of machine components in the Indus-2 Synchrotron Radiation Source (SRS) is transferred to secondary cooling loop by circulating low conductivity process water through plate heat exchanger units. The electric current in SR magnets such as dipole, quadrupole, sextupole etc. is required to be increased in a short duration of time, typically of the order of 10 minutes, during beam energy ramp-up from ~ 550 MeV to 2.5 GeV which causes the surge in the demand for cooling. The existing air-cooled chiller of 1 MW cooling capacity with dry expansion (DX) type evaporator was not able to match the requirement of fast cooling demand in Indus-2 during beam energy ramp-up. This response lag was causing the increase in chiller tank temperature by nearly 5 °C. Hence, an improved chiller unit with flooded evaporator was installed and connected to existing cooling loop.

The flooded evaporator unit has more uniform temperature profile in heat transfer **[1]**. *The new chiller evaporator contains refrigerant is sub-cooled liquid form and it has handled the higher cooling rate demand during beam energy ramp-up condition* **[2,3]**. *Even when the chiller starts during the subsequent load cycle, the sub-cooled liquid refrigerant present in the evaporator starts absorbing the heat load immediately. This characteristic has been suitably utilized for getting the improved chilled water temperature stability during thermal transient condition. This paper reports the developments carried out for improvement in supply water temperature stability better than ± 0.5 °C compared to the previous stability of more than ± 1 °C during beam energy ramp-up. The upgradation has also improved the supply water temperature stability to better than ± 0.2 °C during stored beam condition at 2.5 GeV energy which was earlier around ± 0.5 °C. The experience gained in this development will also be useful in design of cooling system for proposed High Brilliance Synchrotron Radiation Source.*

Key words: Cooling, Chiller System, Accelerator.

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Design and Development of NiAlCo Ferrites for High Power Circulator at S-Band

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NiAlCo spinel ferrites are promising materials as non-reciprocal ferrite phase-shifter owing to their high-power handling capability with tailorable magnetization and high Curie temperature [1]. Since a high magnetization is undesirable at high power microwave application, we have designed and developed a range of spinel ferrites ($Ni_{0.94}Co_{0.03}Mn_{0.03}Cu_{0.04}Al_zFe_{1.97-z}O_4$) of optimum saturation magnetizations ($4\pi M_S$: 300-500 Gauss) by selective doping of aluminium in the specific sub-lattices of nickel ferrite and processing the ferrites using solid state ceramic process techniques. Introduction of 0.03 Co^{2+}/ f.u. leads to indirect spin–orbit coupling which raises the power handling capability by raising the peak-power threshold [1,2]. Temperature dependent magnetization studies of sintered (1250°C) disc samples using a pulse magnetometer show Curie temperature (T_C : 350-400°C) with significantly low temperature coefficient of magnetization (α_M : –0.19% to –0.25%) thus offering excellent temperature stability of device in the operating temperature range (25–100°C). Field emission scanning electron microscopy studies of sintered samples reveal granular microstructures. The measured dc resistivity is of the order of $10^7 \Omega$-cm. Electromagnetic measurements of co-axial cylindrical samples using a vector network analyzer show FMR linewidth (Δ_H) in the range 300-600 Oe.

This paper presents the dependence of $4\pi M_S$, T_C, α_M and Δ_H of the developed spinel at various Al concentration. The observed thermo-magnetic, electromagnetic, electrical and microwave properties are promising for pulsed high power circulator application at S-band.

Using the ferrite properties, electromagnetic modelling and simulation of S-band rectangular waveguide phase shifter has been carried out for stable operation at 2856 MHz. The simulated result shows non-reciprocal differential phase shift between scattering parameters S_{12} and S_{21}. The results can be implemented in the development of 4-port differential phase shift circulator at S-band using two magic tees and a ferrite phase shifter.

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PLC based centralized control system for 1MeV DC Accelerator control

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A DC electron beam accelerator of 1MeV @100mA is being developed at electron Beam Center , Navi Mumbai. The accelerator has high voltage multiplier sub-system operating at 10khz cockroft walton type. It has many subsystems such as beam scanning power supply, beam sterrer, beam position monitor, solid state invertor controller etc. All these subsystems requires central monitoring and control of each of the sub-systems besides controlling machine and human safety signals.

A commercial (Schneider Electric) PLC based control system has been developed for the operation and control of the accelerator. The user interface for the accelerator has been provided using the touch screen panel. All the important parameters are monitored and controlled from the touch screen panel. The parameters are logged at fix interval of 1 second each and the past data can be retrieved by putting the date and time of start and end time. The accelerator with current configuration has been tested up-to 1MeV @50kW of beam power. Important parameters of the accelerator are logged in a SCADA based data logger.

Transient protection of low voltage systems in DC accelerator

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Treatment of industrial effluents using accelerators are helpful in decomposition of complex molecules resulting in reduction of time required for the biological treatment process before disposal. The basic mechanism has been identified as the reactions induced by reactive species originating from water radiolysis [1]. Being a cost sensitive application, accelerators deployed for waste water treatment has to be highly power efficient. A DC electron accelerator rated for 1 MeV, 100 mA is being developed at Electron Beam Centre, Kharghar for waste water treatment applications. High voltage supply of this accelerator uses symmetrical Cockcroft Walton multiplier driven by a high frequency power supply operating at 10 kHz. In order to achieve high efficiency power conversion, the high frequency power supply is realized by means of IGBT based solid state inverter in place of the conventional design using Triodes. High frequency generated by inverter at 500V peak is stepped up to 45kV-0-45 kV using a ferrite-cored step up transformer to achieve desired input voltage for the multiplier.

The accelerator operates under the supervision of a closed loop control system to maintain energy and beam current level. The operating voltage of the multiplier is sensed by means of a voltage divider located in the multiplier structure. The beam current is measured by means of a current shunt connected in the return line of the high voltage multiplier. There are many other measurement circuits in the system like capacitive voltage divider for measuring high frequency input voltage to the multiplier, isolated electron gun filament current measurement, inverter DC input voltage and current feedback, inverter output voltage and current monitoring etc. In all measurement circuits, the output is brought down to 0-10V analog or pulse width modulated (PWM) form for further processing.

The high voltage system is designed to operate under high electric field in the order of 100 kV/cm in N_2 atmosphere at 6kg/cm^2 pressure. During conditioning and vacuum failures, discharges can happen in high voltage system. The resulting transient currents can vary in amplitude from 580A to 40kA and the frequencies generated vary from 23 kHz to 26 MHz. If these transients are not adequately handled, it can result in damage of power supplies driving the accelerator and upset control electronics. Spark gaps deployed to protect the system produces secondary oscillations leading to interference in sensors used for spark detection resulting in false spark identification. This paper describes electromagnetic interference and methods used to mitigate effect of transients in DC accelerators.

There are two main pathways the transients can reach low voltage systems. Firstly through the step up transformer in the power feeder line and the second through measurement circuits connected to the transformer and multiplier. Transients coupling through the power feeding lines is minimised by means of surge limiting inductors, shielding and filtering. In order to minimise transient voltage levels in the control electronics, coordinated surge protection scheme is deployed in the accelerator [2,3]. Atmospheric pressure or pressurised spark gaps are used as the primary surge limiting element followed by low pressure gas discharge tubes and Transzorbs at second level of suppression. Radiated pickups are minimised by adequate shielding.

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Development of Prototype Serial Bus Communication Analyzer System

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Indus-2 Control System is built around three layer architecture. Various Equipment Controllers at Layer-3 are distributed over a large area and communicate with the Supervisory layer through RS 485 serial bus using PROFI protocol. Performance of serial bus communication has vital role in monitoring and control of Synchrotron machine sub-system parameters as well as beam parameters for reliable and uninterrupted delivery of beam to the beam-line users.

A prototype Serial Bus Communication Analyzer (SBCA) system is developed, which can detect the communication errors at protocol level and electrical signal level. This system continuously monitors the data over these serial bus links and records and validates them in real-time. Serial bus data in this case are transmitted at maximum 1Mbps, causing the corresponding electrical voltage transitions on the bus link. SBCA system consists of a High-Speed Data Acquisition Module (HSDAM), which captures and stores the actual voltage levels of RS485 serial bus at 10 MSPS with 12-bit resolution and stores an event of ~6.4ms length of data. A Signature Based Analysis Module (SBAM), measures and records the time profile of various transmission packets (telegrams) with a time resolution of 1 µs, using event based handshaking with the high-speed data-acquisition system. Retrieval of digitized data of RS485 line voltage signals is done in synchronism with event generated by signature based analyses module which is configurable. Software is developed to identify and classify the type of communication errors like start delimiter error, frame length, frame checksum error, parity error etc. This system can be configured for the analysis of standard as well as for the custom made protocol. This system is installed at the location of Supervisory Layer (Layer-2) of Indus-2 Magnet Power Supply system. Using this system telegrams were recorded for setting the reference voltage of magnet power supplies during Slow Orbit Feedback (SOFB) for detection of abnormalities in one of the I/O boards during feedback corrections. The *Serial Bus Communication Analyzer (SBCA) system has been* qualified for its functions and capabilities using simulated test conditions. Various development aspects will be discussed in the paper.

Development of Area Radiation Monitor Readout at PLF

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Area Radiation Monitors (ARM) are installed in and around the Pelletron Linac Accelerator building to monitor neutron and gamma yields during beam operation. The neutrons are detected using a BF_3 gas filled proportional counters (V_{bias}=1.1 kV), while the gamma detectors use a Geiger Muller (GM) counter (V_{bias}=0.5 kV). The development of modern, efficient readout electronics for ARM has been initiated, since many electronics components in the existing readout have become obsolete and some detectors do not have remote monitoring capability.
The bias voltage for BF_3 is generated using a miniaturized AGH series high voltage module from EMCO, which generated a variable high voltage up to 1200V. A trans-resistance amplifier is designed around the operational amplifier AD 817 to convert the detector pulse to a voltage signal. The output signal of the preamplifier is filtered and fed to a voltage amplifier to boost the signal to the required level, and the amplified output signal is fed to a comparator designed around LT1016 high-speed comparator IC. The TTL output of the comparator is fed to a microcontroller-based logic circuit to process and display the parameters [1]. The PCB cards are made very compact, thereby minimizing the interconnections between the cards, detector and the processing circuits, in order to reduce the noise pickups.
In the case of the gamma ray detector (GM counter), the output of the detector is fed to an amplifier and passed to a comparator. The TTL output of the comparator is buffered and fed to the microcontroller based in-house developed processing card, which has the provision to connect to the internet, and the data can be monitored remotely on a centralized monitoring system. Detail designs will be presented.

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Development of Beam Position based Interlock System for Indus-2

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Indus-2 (2.5 GeV, 200 mA) is a Synchrotron Radiation Source (SRS) at RRCAT, Indore. Three Insertion Devices (IDs) have been installed in Indus-2 ring to have high intensity Synchrotron Radiation (SR) beam. Normally the electron beam in Indus-2 revolves closely around the designed orbit, and the SR produced in the IDs passes through the vacuum chamber without any obstruction. Any deviation of the electron beam from its designed orbit in the ID section may cause SR beam to hit the vacuum chamber. This direct interaction of the SR beam from IDs with the vacuum chamber results in the excessive spot heating, which may damage the chamber walls. For the safety of ID vacuum chamber, a beam position based interlock system has been developed and deployed in Indus-2. Beam Position Indicators (ID-BPIs) [1] are installed at the entry and exit of each ID to measure the beam position in the vacuum chamber. In addition, these ID-BPIs generate 'beam cross-over' signals when the beam crosses the safe beam position limits which are set in the digital beam position measurement electronics [2] of ID-BPIs. The cross-over signals are used as inputs to the interlock system to interrupt the RF stations of Indus-2 and consequently dump the beam.

The developed interlock system is modular. For each ID, an interlock module has been developed which takes in the beam cross-over signals from the ID-BPIs and status signal of the position of jaws of the corresponding ID. When the jaws of an ID are moved inwards for high intensity SR based experiments, a 'jaws close status' signal is asserted and the corresponding interlock module gets enabled. In this condition, if the 'beam cross over' is detected in the associated ID interlock module, an 'ID-BPI interlock' signal is generated. The interlock signal is opto-isolated open collector type signal. For each ID, there is a dedicated interlock module. A separate master interlock module, takes in the 'ID-BPI interlock' signals of each ID and qualifies them with the 'beam at 2.5 GeV' status signal. When the interlock conditions are met, an 'RF trip signal' is generated from the master interlock module to dump the beam immediately. The status of interlock signals from all the interlock modules are provided for logging of the events on the Indus server. The total propagation time of the interlock system to dump the beam is less than 300 μs. An application program has been developed on MATLAB platform which configures the electronics of all the six ID-BPIs over TCP/IP interface and sets the safe beam position limits. The software acquires and displays the real time beam positions of ID-BPIs along with set beam position limits on the developed GUI. The available margin of the real time beam positions to the set position limits are also displayed on the GUI. The interlock system has been deployed and tested with Indus-2 beam. The development and deployment of the interlock system is presented in this paper.

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Control and Monitoring of Steerer Power Supply on EPICS Platform

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The control system for linac at Pelletron Linac Facility, Mumbai TIFR has a modular structure catering to various subsystems, namely, the RF control, beam transport devices (magnets, steerers), and beam diagnostic devices (Faraday cups and Beam Profile Monitors). The software is written as a client-server architecture using JAVA. As is well known, Experimental Physics and Industrial Control System (EPICS) is the preferred choice for complex, large scale distributed control system applications like accelerators [1]. The efforts have been initiated towards development of the EPICS based control system [2,3]. In this paper, we report the development of the control interface for Delta make Steerer power supply (ES030-10) using EPICS stream protocol. The application Input Output Controller (IOC) is built on EPICS base 7 platform, with asyn module and stream devices using the standard IP protocol. The Python interface for the Channel Access EPICS library (PyEpics) is used to develop the front end GUI in Python with QT designer support. A tabular user interface, analogous to the existing operational system, is desirable for the ease of migration. The remote operations, control and monitoring, are tested and found to work well. It is proposed to carry out in-beam tests in near future and to integrate various beam diagnostic/control instruments into the EPICS framework. Details will be presented in the paper.

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Design and Development of FPGA based data acquisition card for Hydrogen ion source beam current measurements

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Abstract - This paper presents simulation, design, development and prototype testing of an FPGA based data acquisition card for hydrogen ion source beam current measurements. This can measure 100 mA (maximum) beam current with 2ms pulse duration up to 50Hz repetition rate.

The beam current is measured and controlled during the operation of hydrogen ion source in order to make it compatible for transmission through Low Energy Beam Transport (LEBT) line and further injection into Radio Frequency Quadrupole (RFQ). Simulation of the data acquisition card such as ADC and Ethernet interfacing with FPGA was carried out in Vivado software. Design of a ferrite core current transformer has been carried out by simulating in FEMM. A Graphical-User Interface (GUI) is developed in Python using Tkinter library for displaying and logging real timebeam current data.The prototype of data acquisition card was tested using a function generator, generating pulses of 2ms duration up to 50 Hz repetition rate. The samples were generated by the Successive Approximation Register (SAR) ADC working at 2.56 MSPS sampling rate which were transmitted through Ethernet and subsequently displayed and logged in by the GUI.

Key words: Data Acquisition card, FPGA, Ethernet, Tkinter

Development of Energy Measuring Device and the Measurement of Energy and Energy Spread for the Industrial Linac

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An Energy measurement device has been developed for the measurement of Energy and Energy spread of electron beam after the accelerating structure of Industrial Linac, LINAC-3 developed at RRCAT. Spectrometer (Dipole) magnet based method [1] is used to measure the energy and energy spread of the electron beam. The electrons having different energy follow different circular paths under the influence of dipole magnetic field and therefore, the profile of the beam at any cross section is the function of energy distribution. In this method of measurement of energy and its spread, a Slit & Faraday Cup is used to measure the profile (current vs position) of the beam after the dipole magnet. Position of slit corresponds to the unique energy of electrons for a given magnetic field and the current recorded using the Faraday cup behind the slit at that position is proportional to the number of particles at that energy.

The slit and Faraday cup set-up of energy measurement solely depends upon slit position, to predict the profile of energy of particles in the beam. Any deviation in initial conditions of the beam, angle of incidence of the beam, and inaccuracy in magnetic field will lead to the error in measured profile and thus the energy by the set-up. An error analysis has been carried out to estimate the error associated with various parameters like beam position, Incident beam angle, beam size, divergence of the beam and accuracy of slit movement etc. Error analysis has suggested that the beam position at the entrance of the dipole magnet has significant effect on measured maximum probable energy and have almost no effect on measurement of energy spread. Transverse beam size has less significant effect on measurement of maximum probable energy however; it has significant effect on energy spread measurement. The order of inaccuracy is inversely proportional to energy spread.

This paper presents the development of movable slit & Faraday cup type energy monitor, and measurement carried out using this device.

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Key words: Beam Diagnostics, Linac, Energy, Energy Spread

Measurement of Electron Beam Size by using Synchrotron Radiation Interferometer in Indus-2

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The measurement of transverse beam size in new generation Synchrotron Radiation Sources (SRSs) is a challenging task due to their small beam emittance and low couplings. Beam size measurement by imaging of visible Synchrotron Radiation (SR) is mainly limited by diffraction. Synchrotron Radiation Interferometry (SRI) is a very useful technique for the measurement of small beam size of charge particle beams in various accelerators/SRSs. It is based on Van Cittert-Zernike theorem, which relates transverse source profile to its spatial coherence. The particle beam size is inferred from the measured fringe contrast. SRI system has a superior spatial resolution and can measure transversal beam size down to few microns with visible light. Transverse emittance can also be evaluated from the measured beam size by using Twiss parameters of machine at source point. SRI systems with reflective optics, intensity imbalance, and rotating pinholes designs have shown huge diagnostics potential of this technique.

A quad slit SRI system is optimized to measure the horizontal and vertical beam size of electron beam in 2.5 GeV, 200 mA SRS, Indus-2 at RRCAT, Indore. It can measure electron beam size with spatial resolution of few microns at various beam current and energies viz. at injection energy, during energy ramping and at stored beam current. After optical alignment of various components with laser, SRI system is installed at the sighting beamline port (BL-27) in Indus-2. Initial results of the beam size measurement at different energies and beam currents have shown repeatability within few microns in vertical plane. Beam size changes were also measured during operational testing of Indus-2 in low beam emittance mode. SRI technique of measurement of beam size will be very useful in measurement of small beam size of charge particle beam in the envisaged High Brightness Synchrotron Radiation Source (HBSRS). The SRI based beam size measurement system and the measurement of beam size in Indus-2 using this system have been discussed in this paper

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Tomographic reconstruction of the phase-space distribution

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In particle accelerators, non-linear forces can enhance the higher-order moments of the beam distribution in phase space. The elliptical beam distribution in the phase space, defined by Courant-Snyder parameters, therefore becomes an approximation and hence it is important to understand the real distribution of the beam. The non-elliptical features like halo particle tails in the beam distribution, due to non-linear effects such as space-charge, magnetic field imperfections etc., can lead to beam losses in a high-intensity beamlines. Phase-space imaging techniques are used for re-constructing realistic phase space beam distributions. In general, the technique by which n-dimensional image is reconstructed from various n-1 dimensional projections is referred to as computed tomography. The one-dimensional projection of a two-dimensional image as a function of viewing angle, θ, is described by the Radon transformation. The computed tomography is an attempt to achieve an inverse Radon transformation. In order to make an algorithm for the beam phase-space reconstruction, general Radon transformation equation is expressed in terms of transfer matrix. Here, beam profile at different viewing angle is basically the beam profile for different transfer matrix, which can be achieved by changing the focusing strength of the magnet. Varying transfer matrix will lead to the varying beam profiles in x or x' (number of particles vs x or x'). Further an algorithm has been written in Python, which can reconstruct a two-dimensional phase-space beam distribution (in x-x') using several one-dimensional beam-profiles. This is referred as back-projection of the beam. Further, in order to generate a more accurate depiction of the actual beam, each projection is filtered before reconstruction. Various filtering techniques have been compared to understand which filter will lead to the reconstruction close to the actual initial distribution. After standardization of the code, we plan to extend the study to reconstruct the two-dimensional beam distribution from measured one-dimensional profiles.

Design and development of high voltage amplifier communication system using optical fiber

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Abstract

An optical fiber based communication system is designed and developed for high voltage amplifier system (HVAS). This high voltage amplifier/pulsar is used in the isotope separator on line system of VECC. The amplifier uses bipolar pulse with varying frequency and pulse width as an input signal. This signal is then further amplified and given to the additional electrode after the extractor. The HVAS is floated up to 30kV, so there is a need to use optical fiber communication. In order to communicate the bipolar communication two electronic card were made OS1 (Optical Setup 1) and OS2 (Optical Setup 2). The signal generator is used as a master for generating pulses to HVAS. This bipolar pulse is first converted into unipolar signal using OS1 and then transmitted optically to OS2 situated at high potential (~30kV). The OS2 is then used to convert this unipolar signal back to bipolar signal and sent it to HVAS. Feedback signal coming from HVAS is then again converted to unipolar signal using OS2 and then optically converted and transmitted to OS1 at ground potential for monitoring. The present paper will highlight the detailed design and development of the present scheme and the challenges that are faces.

Development of Camera Triggering Setup for Beam Diagnosis of e-LINAC at RIB and its integration with EPICS based control system

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Presently electron gun has been installed and is operational at VECC, delivering electron beam of 100 keV. The source is a DC thermionic gun, floating at -100 kV and RF modulated at 650 MHz. To measure the transverse beam size, we have installed YAG:Ce scintillator screen along with Charged Coupled Device (CCD) camera in the beam line. The Ce doped YAG screen acts as fast scintillator material. This scheme though is simple but has sources of error like background illumination from nearby light source. Tuning of the exposure time to trigger camera only when the electron beam hits the screen can reduce such background effects. Moreover, being a pulsed beam, timing synchronization is required to observe the same set of pulses in the pulse train corresponding to the macro-bunch. We have developed a setup for timing synchronization of camera triggering with pulsed beam illumination.

The hardware setup of Camera trigger unit involves an Atmega328P microcontroller based master control board with RS-232 communication link for configuration and control purpose. The controller generates a modulation pulse with adjustable duty cycle for RF signal generator and a camera exposure pulse to control the exposure time of CCD camera. The delay between modulation pulse and camera exposure pulse is remotely adjustable and is necessary to synchronize electron beam emission during RF modulated pulse and its scintillation on YAG:Ce screen.

Experimental Physics and Industrial Control System (EPICS) is used to develop the supervisory control system of the camera trigger system for remote operation. EPICS Input Output Controller (IOC) has been developed using asyn tool for interfacing the hardware setup through serial link. A Graphical User Interface (GUI) has been developed using Control System Studio (CSS) for configuration of various parameters like delay and exposure time. In this paper we are going to present the schematic setup, triggering unit design, its integration with EPICS based control system and effect of triggering on beam spot capture.

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NoSql based Data Archiving system for LEHIPA

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Low Energy High Intensity Proton Accelerator (LEHIPA) is a 20 MeV, 10 mA Proton Accelerator is currently under commissioning at common facility building (CFB), BARC, Mumbai. Commissioning is nearing its completion. This accelerator consists of an ECR ion source(ECRIS) , Radio Frequency Quadrupole(RFQ), Drift Tube LINAC(DTL) as the main component to produce and accelerate proton beam.Electromagnetic field, generated in Klystron is transported via waveguide and fed in the cavities to set up electromagnetic field to accelerate proton beam. Klystron once again is driven by a high voltage regulated power supply.

Proton Beam of Energy 11 MeV is successfully accelerated in this accelerator.Experimental Physics and Industrial Control System(EPICS) is used as the control system middleware in this accelerator.LEHIPA Control system extensively uses Raspberry Pi as the IOC hardware for various subsystems such as Vacuum System,Timing system etc.Apart from Raspberry Pi various other kind of hardwares such as cPCI ,mini PLCs are also used for data acquisition and interlocking purpose. All these data are assigned to hundreds of EPICS process variables (PVs) and interlocking actions are carried out taking a cue from the EPICS alarm generation system.All these PV values , alarms need to be stored in the archiever on a periodic basis to undertake data analysis and to carry out post mortem analysis in case of a partial and/or complete system failure.

Even though EPICS has an excellent data archiving system, a new archiver and ELogbook system is designed and developed in the LEHIPA, which is currently working very satisfactorily and archiving data and alarm of EPICS PVs. This new archiver uses noSql database to store EPICS Pvs and alarms and Elogbook logs. MongoDB is chosen to use as the nosql database.A python script,using pyepics, scraps data from main control network and keep on updating database system periodically. Periodicity of the various Pvs can be individually set in the configuration file.

A web based data fetching and visualization system is also integrated with the archiever, which is used by multiple users simultaneously to fetch the historical archival data for their analysis. This tool is also used to broadcast vital parameters of the LEHIPA (such as beam current, cavity power , vacuum etc) in near real time for anyone interested to watch it by entering a web address in their browser from anywhere inside BARC Trombay campus.

In this paper we present the design and performance details of archiver system used in LEHIPA.

Measurements of a gas-sheet based beam profile monitor

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Ion Accelerator Development Division is developing high intensity proton accelerators for various application such as Accelerator Driven Sub-critical System (ADSS) and isotope production. Accelerators require beam profile monitors as feedback for beam control and beam quality measurement. Traditional beam profile monitors such as solid scintillators and wire scanners are invasive methods in which solid material has to be introduced into the beam path. The wire scanners partially stop the beam whereas the solid scintillators fully stop the beam. The beam will not be available at the target during measurements. However, applications like ADSS require high beam availability. In addition, the entire energy of the beam is deposited on the solid material, which can cause thermal damage, and in high-energy beams, it can cause radio-activation. For these reasons, we require exploration of new techniques for non-invasive beam profile monitoring. Many labs have reported gas based beam profile monitoring techniques based on Beam Induced Fluorescence (BIF) and Ion Profile Monitors (IPM). In 2018 KEK, Japan has reported a method to generate a gas sheet in vacuum, which they had tested with a beam of 7.5 µA average current 400 Mev H-beam [1].

Presently, we have developed a gas sheet generator using the same method and viewed the beam profile of an intense proton beam of average current above 1 mA at 20 keV. The test bench consisted of an ECR proton source, which provided a 14 mA beam with pulse width of 100 ms and pulse repetition rate of 1 Hz. The beam was focused using a solenoid magnet with 0.12 T. The gas sheet generator used two sheet sources 10 cm apart for a uniform density distribution at the center. In each gas sheet source, the gas from a reservoir passes through a long thin slit to form a gas sheet due to the positional beaming effect of gases in molecular flow. The directional core of the sheet then passes through a skimmer to generate a thin gas sheet of ~1 mm. As the beam was intense and of low energy, large amount of energy was deposited on the gas producing intense scintillation, which was visible to the eye. A CMOS imaging camera system could capture the scintillation without requiring an image intensifier. The results will be presented in this paper.

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Prototyping of FPGA Based Timing and Interlock System for ECR Ion Source

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For pulsed operation and characterization of Electron Cyclotron Resonance (ECR) ion source, a timing and interlock system has been designed and developed. The timing system generates user programmable synchronizing pulses which are used to trigger various subsystems such as magnetron, high voltage pulse, diagnostics and data acquisition system in the correct sequence. The fast interlock system is designed for quick shutdown of the ion source within ~50 μs.

Xilinx make zynq 7010 SOC has been used along with a graphical programming language. The graphical program gets translated to HDL code and finally to a binary file that can be downloaded on the FPGA. The code is optimized such that the processing of the inputs and the generation of corresponding output completes in the clock period of 25 ns.

The five-channel timing system generates pulses with duration ranging from 200 μs to 200 ms at frequency of 1-10 Hz. A GUI is developed with control of individual channel on-off, master on-off, pulse width and its delay input from user. The interface has been designed with inbuilt range limit, thereby assuring the system safety.

The five input channel interlock module generates an active low interlock with a response time of 25 ns. The GUI for interlock system has indicators for individual channel showing if interlock is generated on any of the channels. The timing system has been tested for varied values of pulse width, delay and frequency. The FPGA output pins are by default pulled to ground which ensure in case of any power failure the outputs are automatically pulled to ground and fail safe condition is ascertained.

Development and Preliminary Evaluation Results of Prototype 100 nm Spatial Resolution Digital Beam Position Monitor Envisaged for High Brilliance Synchrotron Radiation Source

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Envisaged Indian High Brilliance Synchrotron Radiation Source (HBSRS) is expected to be a key enabler for the scientific and technical community to carry out advanced scientific and technological investigations in India. Precise measurement of electron beam position in the HBSRS will be a very challenging and important requirement for commissioning and smooth operation of the machine.

FPGA based Digital Beam Position Monitoring (DBPM) electronics has been indigenously developed for the HBSRS. This processing electronics determines the position of electron beam using four-electrode capacitive pick-up device. The processing electronics consists of RF Front End (RFFE) electronics and FPGA based digital processing electronics. The RF processing electronics built on a 6-layer PCB has been designed and developed for simultaneous signal conditioning of all the four pickups at 505.8 MHz FPGA based digital processing electronics designed and developed on a 16-layer PCB houses four high speed ADCs, ultra-low jitter PLL based reconfigurable sampling clock generator, dual Gigabit Ethernet controller, dual USB controller, Gigabit optical fiber link, 144 Mb FIFO, 512 Mb SRAM, EEPROM, on board temperature sensor etc. The Gigabit optical fiber link will be used for grouping of fast acquisition (FA) data at 10 kHz for fast orbit correction. The processing electronics provides Turn-by-Turn (TBT), post-mortem data, Fast Acquisition (FA) data, Slow Acquisition (SA) data at 10 Hz and 1 Hz. It also provides configurable interlock facility (trigger out) for machine protection in case the measured beam position is out of the stable zone. The processing electronics has been developed in 1U size 19" sub-rack.

The rms positional uncertainty in the beam position has been measured for different power levels of simulated beam conditions in the laboratory. Measured uncertainty is less than 100 nm for signal power level of -48 dBm and higher at the input of processing electronics for SA data. This power level (-48 dBm) is equivalent to measured power level of pick-up electrodes of TWIN BPI system [1] at beam current of 2 mA and 550 MeV beam energy in Indus-2. The beam current dependency for positional measurement is within ±1 μm for the signal power level of -41 dBm to 0 dBm and the temperature dependency is ≤ 0.2 μm/ °C. Measured sensitivity of the processing electronics is -90 dBm.

The DBPM electronics is installed at Indus-2 instrument gallery and interfaced with TWIN BPI system. The TWIN BPI system installed at long straight section 6 (LS-6) of Indus-2 ring has two sets of closely mounted pickup electrodes in single housing. One set of electrodes of TWIN BPI system is connected with sub-micron resolution DBPM and another set of electrodes is connected with commercial DBPM (Libera brilliance+) [2]. A data logging software has been developed to acquire the data from both the processing electronics into a single file for comparative study. Responses of indigenously developed sub-micron resolution DBPM and Libera brilliance+ are in close agreement. Performance of indigenously developed DBPM on Indus-2 will be presented under different operating modes and operating conditions of Indus-2 in this paper.

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A Digital Beam Position Indicator Design and Development on VME Platform for Orbit Control Applications in Indus-2

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The beam position indicators (BPI) are used for measuring the beam position in particle accelerators. The digital BPI in Synchrotron Radiation Source (SRS) uses the high-speed, high-resolution analog to digital converters to directly under-sample the radio-frequency (RF) signal between 300 MHz to 600 MHz in two orthogonal streams (In-phase and Quadrature-phase) by precisely adjusting the sampling clock frequency. This method simplifies the analog and digital processing circuit development and testing. The orbit control applications in modern SRS are divided in two systems viz. slow orbit control system (SOFB) that works with loop rate up to 10 Hz and fast orbit control system (FOFB) that operate upto 10 KHz. Both the systems work together to suppress the disturbances covering frequency spectrum from milli Hertz to few hundred Hertz. A digital BPI (DBPI) has been developed for use in Indus-2, a 2.5GeV SRS machine. This DBPI has been designed to generate slow acquisition(SA) data at 10 Hz update rate, fast acquisition(FA) data at 10 kHz update rate. The Turn-by-Turn data sampled at bunch revolution frequency (~ 1.73 MHz) and raw ADC data sampled at sampling frequency (~ 120 MHz) have been made available on demand. VME platform has been chosen for the digital BPI development so that the slow and fast orbit feedback control algorithms can be developed with minimum latency and can run on the Digital BPI CPU with RTOS thus simplifying their overall implementation. The development is aimed towards integration of multiple BPIs in one VME crate so as to save space through system integration comparable to the commercially available digital BPI platforms. The digital domain signal processing for all the four channels has been implemented in one FPGA chip with configurable digital filters and sampling clock modules. The sampling clock PLL has been synchronized to accelerator RF using the standard 10 MHz clock method as employed in commercial DBPIs. The channel to channel gain and phase equalization method has been used for improved long term stability. Automatic gain control and piece-wise linearization methods have been provided to get the improved accuracy over large dynamic range of input signal.

For testing in Indus-2, the developed DBPI electronics was connected to Undulator-3 exit BPI (BPI-31) electrode cables. It was then interfaced with Indus-2 Digital BPI server application and Indus-2 Slow Orbit Feedback Control system. The test results showed very good beam position control ability at the Undulator location with this BPI in SOFB. Also the integrated operation of SOFB with this DBPI, passes the beam position interlock requirements for Undulator normal operation. This paper discusses the overall digital BPI design, test and characterization results and the Indus-2 machine performance with developed BPI included in SOFB operation under different operating conditions.

DC Current Transformer for Pulsed Beam Current Measurements

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DCCT (DC Current Transformer) is a widely used non-intrusive method of beam current measurement in particle accelerators [1,2]. Based on the principle of the Flux-gate magnetometer [3], DC magnetic parameters (magnetic field or current) can be measured using search coils and a magnetic modulator. Two balanced cores are deep-magnetized in phase opposition with an AC current of suitable frequency which has a common search coil. When the current being measured, passes through the bore, the cores get imbalanced which is reflected in the generation of the second harmonic, which is a direct function of the current being measured. To get linear relation between the current and second harmonic, the magnetic material of the core needs to have a square B-H curve (B_{rem}~$0.95B_{sat}$) with a low remanence field [4]. The choice of core material plays an important role in the desired functioning of DCCT [5]. The electronics of DCCT consist of a precise AC current source, high order narrow bandpass filter at the second harmonic frequency, and RMS voltage measurement circuit. The complete measurements are carried out in the analog domain. The design optimizations are carried out using the ELECTRA module of OPERA FEA software. The B-H curve of the actual core was measured in the in-house facility and was used in simulations. The cores with the best-matched properties were used for the construction of the magnetic modulator. Subsequent to the winding of the cores using a special torus winding machine, the inductance of the cores was matched at the rated frequency. Turns in the core were altered to match the parameter. Each core contains tertiary winding for future usage. A common search coil was wound after providing sufficient electrical insulations. An automatic application software was developed for measuring the transfer function of the DCCT at a different frequency and excitation current. This helped in the optimization of the operating parameters. A sub-routine of this software was used for the calibration of the DCCT. The developed DCCT measured for DC and pulsed current. For DC current, the DCCT is having a range of 30 mA with a resolution of 50 uA and 200 uA accuracy. The calibration curve was used for overcoming the linearity issues in full range. In sub-ranges of 10 mA, the DDCT gave a linear response. A six-order bandpass filter centered at 2000 Hz was designed, developed, and used for reading the second harmonic of the measured signal. The RMS value at the output of this filter is proportional to the beam current. The DCCT successfully measured up to and more than 2.5 msec pulse-width beam current with a peak value of 10 mA. The existing design is being upgraded with promising results to measure beam current with a pulse width of 200 usec. This paper details the design, construction, calibration, and testing of the DCCT.

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Beam Diagnostics at LEHIPA, BARC

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Low energy high intensity proton accelerator (LEHIPA), BARC has been commissioned to 11 MeV by acceleration through the RFQ and two DTL Tanks. A variety of beam diagnostic devices have been developed for the transverse and longitudinal beam measurements at different stages of LEHIPA commissioning. The longitudinal beam diagnostics include Fast Faraday cups (FFCs) to measure the time structure of the beam bunches; time of flight (ToF) based beam energy measurement techniques and beam emittance measurements. Two types of wide bandwidth (>7 GHz) FFCs – Stripline and Coaxial- have been used to measure the beam bunch structure of the RFQ and DTL operating at 352 MHz. Two different ToF based beam energy measurement techniques have been used in LEHIPA. The dual FCT based ToF measurement provides a quick data on beam energy, while the movable beam position monitor (BPM) based ToF method provides better accuracy in beam energy measurements, averaged over several beam pulses. A buncher amplitude scan technique for longitudinal emittance measurement by using buncher cavity and FFC combination has been tried in LEHIPA MEBT. The details of various measurement devices with measurement results will be presented.

FPGA Based VMEbus Compatible Location Monitor Board

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Equipment controllers and Supervisory controllers in Indus-2 control-system are VME bus-based embedded systems. System diagnostics and monitoring facilities are required in such complex digital systems to improve availability and serviceability and to minimize the downtime. This paper explains design methodology and functional qualification of FPGA-based VME bus compatible Location Monitor board which monitors the address bus activity on the VME bus. 'Location Monitor' according to VME bus specification is a functional module that monitors the data transfers over the Data Transfer Bus (DTB) to detect accesses to the location it has been assigned to watch. The developed Location Monitor described in this paper generates an on board trigger signal on the access of respective monitored location. It also records the time stamp of access with a fine time resolution of better than 3 µs. Time stamp of access of any monitored location can be retrieved through VME bus read cycle and through serial communication port. It can also list the sequence of access of different monitored locations along with the time stamps of its access. It will help in estimating the time elapsed in execution of hardware functional blocks, software functions and software loops running in the CPU of Equipment Controller, which can greatly help in monitoring and improvement of the system performance and optimization. Generated trigger signals will be useful in synchronization of data acquisition and data setting.

For this work, design of Location Monitor is implemented using Verilog- Hardware Description Language (VHDL) in Xilinx Spartan-3 FPGA which also includes the design of VME bus interface for A32:D16 data transfer cycles, design of I2C interface for DS1307 real-time counter for time stamping, design of UART and serial interface Finite State Machine (FSM) to communicate to the PC. It also includes the design of a complete mechanism which can store time stamps and generate trigger signal on the access of monitored location, etc. A 6U size PCB of VME Location Monitor is designed and developed which houses Xilinx Spartan-3 FPGA, VMEbus buffer ICs, RTC, serial port, opto-isolators, line drivers, etc. Along with hardware development, a GUI software utility is also built using LabVIEW. The GUI lists out all the monitored location addresses, time-stamps of access of different monitored locations in descending order of time and sequence of access of different monitored locations. Monitored Location addresses are reconfigurable. These can be updated using VMEbus write cycles and also using GUI.

At present, it can monitor 16 different VMEbus address locations. For each monitored location, a memory segment is fixed which can store at least 31 time-stamps. Once the segment fills out, it starts overwriting from the start. At last, testing of this hardware cum software solution has been done for different test cases and reported in this work.

EPICS-based Embedded Control System for Deflector Conditioning System of K-500 Superconducting Cyclotron

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The extraction system of the K-500 Superconducting cyclotron is comprised of two electrostatic deflectors and nine magnetic channels. The deflectors are used to extract the accelerated beam from the outer radius of the cyclotron by applying a strong DC electric field of the order of 10^2 KV-cm. In order to achieve such an electric field, a high DC voltage is applied across a small gap between the deflector plate and the septum kept inside a high vacuum ***[1]****. After prolonged operation inside the cyclotron, the surface of the deflector plate develops micro-level surface irregularities due to interaction with the beam. These irregularities lead to high discharge current and a reduced operational voltage between the septum and deflector plate. This reduces the extraction efficiency of the deflectors. It is reported* ***[2]*** *that controlled pre-conditioning of the deflector before cyclotron operation reduces the surface irregularities on the deflector plate and hence enhances its operational life. Therefore, a deflector conditioning setup consisting of a deflector power supply, magnet power supply, vacuum system and interlocks is developed in VECC. This paper describes the implementation of an EPICS (Experimental Physics and Industrial Control System)* ***[3]*** *based embedded control system for the operation of the system. A RaspberryPI* ***[4]*** *module is chosen as the controller hardware for the embedded control system. The deflector power supply and the magnet power supply with embedded serial communication are interfaced with the controller through a serial server. A MODBUS-TCP-based data Acquisition module is used to interface the turbo-molecular pump and vacuum gauge via analogue voltage channels. The EPICS Base is built on Raspbian (Linux distribution provided by RaspberryPI) and an EPICS IOC application is developed for control and monitoring the system. A customized device driver for the CALC record is developed for implementing the automated conditioning operation of the deflector. Deflector conditioning modes such as Ramp, Ramp to Zero, Auto, Conditioning and Halt are implemented based on required voltage ramp rates. Just before conditioning, the leakage current limit can be configured through the OPI. The operational interface (OPI) of the system is developed using CS-Studio which is a readily available open-source tool for EPICS-based OPI development. The system interlock status and the Real-Time plots of deflector voltage and leakage current are shown in the OPI. System parameters such as deflector voltage, leakage current, vacuum level, turbo molecular pump speed and armature current are continuously monitored from the control room. A local GUI is developed on RaspberryPI for debugging purposes. This GUI is developed using an upgraded version of CS-Studio called Phoebus* ***[5]*** *which supports ARM-based computers such as RaspberryPI. JavaFX, a dependency of Phoebus was installed on Raspbian prior to the GUI development. The detailed design of the hardware setup, software implementation and the operational experience of the system are described in this paper.*

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Remote Control Applications for operation of Hydrogen Negative Ion Source

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To control and operate negative hydrogen ion source remotely, a GUI based control applications have been developed in LabVIEW. A high voltage deck for the Ion source houses instruments viz. mass flow controller, 13.56 Mhz based RF ignitor, 10 kV/1 A pulsed extraction power supply, 2 MHz RF source for main plasma generation etc, These instruments have RS 232/485 and ethernet digital communication ports. The high voltage deck instruments are communicated through duplex fiber optic converter. The ground side instruments are high voltage acceleration power supply, turbo molecular pumps, roughing pumps, vacuum gauges, beam current measuring instruments etc. Communication ports of both, the ground side instruments and high voltage side instruments, are interconnected though ethernet switch to computer. A LabVIEW based GUI has been developed to control and monitor the operation of these instruments. The developed control application features supports in optimizing the performance of ion source by varying different parameters like gas flow rate, 2 MHz RF power, extraction voltage at different acceleration potential etc. The developed user interfaces has been successfully used for generation of negative hydrogen ion current of 26 mA at 50 KV energy up to repetition rate of 50 Hz with pulse width of 2 ms. This paper presents the brief description of remote operation of ion source using designed control application, GUI and high voltage optical isolation communication architecture.

Design, Development and Implementation of C&I System for X-Band LINAC

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Linear accelerators are used inmany applications ranging from radiation therapy, food irradiation, agriculture, waste water treatment to other industrial applications and metallurgical applications. One of its main application which is very much in demand is generation of X rays for radiation therapy for cancer treatment. X-Band LINAC is compact and can be easily fit into portable machines/equipments used for therapy. Aprototype6MeV X-Band LINAC has been developed at EBC, Kharghar. LINAC is installed in a shielded cell area and operated from control room. PLC & HMI based C&I System is designed and developed for control and monitoring of X-Band LINAC remotely. Process parameters are monitored and controlled from touch screen-based HMI during operation. Control system is developed using Schneider PLC and there are 24 DI, 19 DO, 19 AI and 7 AO signals. In addition, parameters to and from Magnetron Modulator unit which installed in field, are communicated to Control system on MODBUS TCP Protocol. Graphical user interface (GUI) is designed and developed to monitor and control signals from PLC IOs as well as Magnetron Modulator.All Safety aspects related to LINAC operation are taken into consideration in design. Safety and process interlocks are implemented in PLC program. Hardwired trip for critical subsystems is provided as additional safety feature.Main sub systems which are monitored and controlled by Control System are Gun Modulator, Magnetron modulator, Trigger Controller unit, Vacuum System, Magnet System and field signals from sensors. In order to meet regulatory and safety aspects of LINAC operation, signal from Search and Secure System and Radiation Monitoring System are displayed always on Control Panel and used in trip logic as well. Based on various safety conditions, sub systems are tripped automatically using a fail-safe trip logic implemented in PLC program.

Simulation of feedback control of beam position and an implementation of algorithm for beam focusing in BARC-TIFR Pelletron Accelerator

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The 14UD Pelletron Accelerator is an electrostatic tandem accelerator operating round-the-clock since 1988. Various ions of specific mass, energy and current can be accelerated by employing several electromagnetic quadrupoles and steerers located across the accelerator. A well-focused and non-steering beam of a particular energy and current is delivered as per the user requirements for carrying out experiments pertaining to nuclear physics and allied areas.

At present, the beam focusing and steering is performed manually. For beam tuning, the beam position and focusing information is obtained from a rotating wire Beam Profile Monitors (BPM). The working of the BPM, a non-intrusive diagnostic element employed to estimate the position and intensity distribution of the beam, is briefly described. It is proposed to implement a basic linear feedback system to control the beam position along with the algorithm for focusing in one section of Pelletron accelerator. The feedback system for beam position control will generate the output position according to the reference or set point position. The algorithm for focusing will set the current values to quadrupoles at the point of maximum focus. The knowledge of plant that is to be controlled with closed loop feedback is estimated through recorded input-output data in the form of transfer function model. The controller transfer function is obtained from linear design techniques like Root locus and frequency response methods.

This paper describes the identification of plant transfer function (in the forward path) model through the obtained time domain input-output data. Data for estimating the transfer function is obtained by varying the steerer power supplies and measuring the corresponding position through BPM. The time domain input-output data is utilized in estimating plant transfer function. The data-driven modelling of plant is carried out utilizing MATLAB routines. The obtained plant transfer function is utilized to estimate the controller transfer function for position control in beamline. The closed loop feedback system is simulated in SIMULINK. The LABVIEW routines employed for automating the process of focusing the beam are also described. The results of simulation for position control and the routines for focusing the beam of one section of the quadrupole-steerer section shall be presented.

Study of the effect of location of laser tracker on alignment uncertainty of components in circular particle accelerators

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The alignment of components in particle accelerator machines has always been of primary importance for their smooth operation. Imperfections in the position of components such as accelerating structures, magnets can perturb the motion of beam of charged particles. These perturbations may limit the performance of these machines and in the extreme case of misalignment, the operation of machines may fail. In these machines, specified alignment tolerances are of the order of ± 100 µm or less over the large dimensions from few tens of meters to hundreds of meters to get a beam of extremely low emittance. The local smoothness of the best-fit trajectory is needed to be of still better relative accuracies. Considering the large measurement volume of particle accelerator machines along with the very tight alignment tolerances, it is necessary to achieve the best possible performance using state-of-the-art instruments and best technique feasible for given site conditions.

Presently, laser tracker is a common choice in the particle accelerators for precision survey and alignment activities due to the recent advancements in opto-electronic and computation technologies, making it affordable and best choice for high measurement accuracy over the large distances along with the high-speed data acquisition. Laser tracker acts as a 3D portable coordinate measuring machine which determines the coordinate of a point in polar coordinate system and these coordinates are transformed to cartesian coordinate system using the data processing software. In an accelerator machine, the location of laser tracker station is generally fixed randomly or by considering the line-of-sight obstructions, sources of disturbance etc.

Angular inaccuracies govern the uncertainty in coordinates of points measured by the laser tracker due to its better measurement capability for distance as compared to the angle. Also, the alignment tolerances for position-sensitive components of an accelerator are more stringent in the radial direction as compared to circumferential direction. With this directionality in mind, the effect of location (w.r.t. the machine) of laser tracker stations on the measurement uncertainty in radial direction is studied for a nearly circular accelerator machine.

A mathematical model based on the probability theory was developed and implemented in MATLAB to investigate the effects. One location of laser tracker can be used for aligning the multiple components which are in its measurement range having different combinations of distances and angles. Thereafter, the study will guide in limiting the working volume of a measurement station to the extent uncertainty is maintained within the specified alignment tolerances in the large low emittance accelerators. Synchrotron radiation (SR) source- Indus-2 at RRCAT was chosen as a case study to analyze the effects of location of laser tracker. Distance of laser tracker station from the accelerator machine was varied from 1 to 3 m, on both - inside and outside of it. In the present study, it is found that the location of laser tracker station inside the machine results in lesser uncertainty in measured coordinates of the points for the same component. In addition, it covers wider working volume while maintaining the required tolerances though the visible area which may be larger from the outside of the machine. The present study will be a guide for the precision positioning activities of future SR sources in RRCAT and other the circular particle accelerators.

Development of Simulator for 10MeV RF Linac

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A 10 MeV Industrial RF Electron Linac, for radiation application (Electron Beam mode or X-Ray mode) is installed at Electron Beam Centre, Kharghar, India. The accelerator is being regularly operated at 3kW average beam power for industrial and experimental irradiation applications. Accelerator is complex system consisting of various sub-systems like Electron Gun, Modulators, RF Cavity, RF source, Vacuum System, Cooling water system etc. To handle such sophisticated system trained personnel's are required. The simulator developed will be utilized for training of personnel for operation of 10 MeV RF LINAC. The simulator is built on the same platform as the actual control system in use for this accelerator. It uses SCADA interface developed in Movicon by Progea. The field variables in the accelerator are simulated with memory locations of PLC (Schneider make). The trainer PC works on runtime Labview 8.5 platform. The trainer PC is capable of creating various known error conditions for the accelerator and its sub-systems.

Remote Monitoring system for high-temperature Vacuum Furnace

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A custom-built high-temperature vacuum furnace has been installed at TIFR in the Pelletron Linac Facility (PLF) for heat treatment of Niobium resonator cavities~[1]. The furnace is designed to operate at 1200^0 C with a vertical hot zone of 600mm diameter x 1000mm high. During the heat treatment, crucial parameters like vacuum and temperature need to be monitored continuously to ensure the safe and secure operation of the vacuum furnace. For this purpose, four vacuum gauges are deployed at different locations in the furnace. Further, the monitoring of auxiliary support systems like chilled water temperature are also important to avoid accidental malfunctioning and prevention of the job damage. Therefore, a remote monitoring system is designed and developed to read the parameters from the system, and to transmit the data through the android-based telegram messenger application. Additionally, an alert message is generated to the designated phone number if the parameters exceed the set values.

The monitor system is built around Espressif ESP32, which is a low-cost, low-power system-on-chip (SoC) 32-bit microcontroller and also works well with the Arduino IDE. This is equipped with IO ports, analog-to-digital converters (ADC), serial ports, Wi-Fi, and Bluetooth. The analog output of vacuum gauges read with the Pfeiffer vacuum controller unit (MaxiGauge™) is fed to the ADC channels of the ESP32. The water temperature is measured using a PT100 sensor and its output is also fed to one of the ADC channels. The ESP32 is programmed to connect to a Wi-Fi network and a telegram bot is created to communicate with the ESP32-based monitor system. The digitized values can be accessed through the telegram group by sending the relevant command and are also displayed locally on a 4 X 16 LCD unit. Whenever the vacuum level or water temperature breaches the set threshold level, the ESP32 sends the alarm message to the telegram group. The message is continuously transmitted at a specified time interval until it is acknowledged. The design is general and can easily be adapted to monitoring of other subsystems of Linac or other crucial equipment.

The ESP32-based monitor system is tested with the vacuum furnace and performance is found to be satisfactory. The details of the design will be presented.

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Design of FPGA based RF Interlock system and Power Monitoring

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The design of FPGA based RF power monitoring and interlock system has been done based, on the results of the prototype microcontroller-based fast interlock system developed earlier at LEHIPA and on the studies performed to calculate the time required for generating the RF interlock signal for preventing the beam from damaging the cavity. The response time of the system is improved as fast comparators are used and microcontroller is replaced with FPGA. RF power monitoring is also done using the ADC's that are interfaced to the FPGA. This system comprises of two units: front-end analog unit and a digital unit. This is a 9-channel RF power monitoring and interlock generation system. The Analog unit comprises of an RF band pass filter of 352 MHz center frequency to remove the noise. This signal is passed through a Power detector which provides voltage signal proportional to the RF power. A low pass filter has been placed at the output of power detector which is required for removing the peaks present in the reflected power signal at the start and end of the RF pulse. The low pass filter is an 8-th order bessel filter of variable cut-off frequency up to 50 kHz. A microcontroller is used to vary the cutoff frequency which generates digital clock of varying frequency required for the low pass filter IC. The low pass filter can also be bypassed by enabling/disabling it through the microcontroller. The communication to microcontroller is through serial communication - RS-232 which is done by the user through FPGA-SoC in Digital part. The Digital part consists of fast comparators, ADC's, FPGA and DAC's. The output of power detector is given to the comparators. The other terminal of comparator is connected to variable threshold voltage generated by DAC's through the FPGA-SoC by user. The 9 comparator outputs are presented to the FPGA as inputs where user logic is configured to generate the interlock signal when any of the RF power of the cavity pickup, forward or reflected powers are out of limits. The generated interlock signal is given to RF switches which turn off the RF input to the cavities. 10 such interlock signals are generated to cater to various cavities and other subsystems. The FPGA is an SoC which has both processing unit (PU) and programmable logic (PL). The PL is configured for generating interlock signals whereas the power monitoring is done through the PU.

Study of thermal effects of proton beam interaction with accelerating structures to derive the response time of fast protection system

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These studies have been carried out to derive the time response requirements of fast protection system. The fast protection system (FPS) provides the protection to accelerating components from beam hitting in case of any fault in subsystems. The maximum allowable response time of fast protection system is determined by time taken by full beam to start melting of accelerating structure. FPS should be able to protect equipment even when full beam loss occurs, for this response time of protection system should be lesser than the time taken by full beam to melt the structure. The response time of FPS is mainly function of beam parameters like energy, current and size. In this paper, it is assumed that the beam deposits energy in steel/copper accelerator components instantaneously and estimated the FPS time response required to prevent start of melting the steel/copper for a 10 mA beam with energies 3 MeV - 200 MeV. When a proton beam hits the structure, it deposits energy and heats it up. Energy transfer depends upon stopping power of material and energy of proton beam. For lower beam energies, the average energy transfer is larger and the energy transfer is even higher at the end of the proton range (Bragg peak). The stopping power data for steel/copper has been generated using SRIM/TRIM software. The number of protons required to melt the structure is calculated based on the amount of energy is required to change the temperature of the material from its initial temperature to melting point temperature. The time to melt the structure is derived using the number of protons to melt and the beam current. From these studies, it is understood that full uniform beam with 3 MeV energy and 10 mA current can melt copper and stainless steel in about 6 μs and 9 μs time respectively. Fast protection system should be able to protect the accelerating structures in case of full beam loss, so response time of protection system should be less than 6 μs .The calculation model, dependency of response time on beam energy, beam current ,beam size and non-uniform beam , and the effect of bragg peak will be discussed in this paper.

Disciplined Software Clock for New VME CPU

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Timing system is indispensable for any particle accelerator. Timing system is not only responsible for facilitating execution of various time critical tasks (e.g. triggering the pulsed power supplies of kicker magnets) in perfect sequence but also facilitating in timestamping various events and instants (e.g. parameter acquisition, setting etc.). The timestamped parameter values are subsequently used to know the state of the machine, at any given time which is not only required for smooth and continuous round the clock operation of machine but also for taking necessary preventive action for a possible untoward event in the future. Timed parameter settings and various event sequences are crucial for the desired behaviour and performance of the machine. Therefore, it is important to maintain high temporal accuracy among various events, clocks and parameters. The problem of time synchronization arises in spatially distributed systems due to the variation of crystal oscillator's resonant frequency with crystal ageing and with changing ambient conditions. The next-generation Synchrotron Radiation Sources would require a highly robust, reliable, flexible and scalable timing system. Various timing systems deployed in different accelerators have been reviewed. Among them the White Rabbit stands out as the most promising in terms of accuracy, flexibility, robustness and ease of scalability. In White Rabbit network, there is a master node (atomic clock or GPS disciplined clock) and the ordinary nodes (clocks synchronized with respect to master node). To begin with, the implementation of reference clock is targeted for the new VME CPU board that is designed and developed in house at RRCAT, Indore. This paper presents design, development and testing of the disciplined software clock using the GPS module and i.MX RT1062 micro-controller unit (MCU) present on the board. A brief overview of the present timing system deployed in Indus-2 is given in the paper, which is followed by the discussion on design, development and test results. Procedure followed to establish the communication between the GPS module (using NMEA, UBX, UART protocols) and i.MX RT1062 is discussed using the flow chart. Similarly, procedure followed to retrieve the time and date information from GPS is presented. Further, virtual disciplining of the oscillator's resonant frequency is discussed. The experimental setup and procedure followed in conducting the time stamping experiment (using commercial NI PXI-6683H timing module) for accessing the performance of the developed clock in terms of accuracy is explained. The experiment results show the improvement of accuracy from 22200 ns (free run mode) to 120 ns (control loop active mode).

Development of Multi-Channel Programmable Trigger Generator for Linac of Electron Beam Radiation Processing Facility

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The electron beam radiation processing facility (EBRPF) is being operated at Devi Ahilyabai Holkar fruit and vegetable mandi complex, Indore. The facility is based in-house developed 10 MeV, 6kW electron linear accelerators (Linacs) developed by Raja Ramanna Centre for Advanced Technology (RRCAT), Department of Atomic Energy. The electron beam, which is in horizontal direction, is moved up & down in vertical direction to get radiation field in vertical plane. The products which are to be irradiated, are transported in front of vertically scanning beam, with a roller conveyor in horizontal plane. This facility provides electron beam irradiation services for medical devices sterilization and irradiation of research samples for development of new crop varieties. The deliverable dose range is from few Gray (Gy) to several Kilo Gray (KGy) based on the product requirements.

A timing system for precisely time synchronization of subsystems is required for operation of Linac, measurements of various diagnostic parameters, irradiation process verification and process interrupt handling with several parameters & faults. Various delays are to be precisely adjusted in time domain with sub-system functions & measurements with respect to the master reference trigger. To realize this, a multi-channel programmable trigger generator module is developed.

The multi-channel Programmable Trigger Generator (PTG) Module for Linac is comprising in-house developed Field Programmable Gate Array (FPGA, Spartan 3, Xilinx) board and controller board with Optical Fiber transmitters. These trigger pulses will be provided for field device like RF modulator, Electron Gun, Beam Energy measurement system, Beam Position Indicator, Beam pulse current measurement system and BPM etc. The multi-channel PTG module is provided with front panel LCD display to indicate current status like Pulse Repetition Rate (PRR), operating mode, local/remote status, serial communication and system interlock status. A 4 x 4 metrics key pad is interfaced for setting of PRR, delay time and trigger on/off command in local mode. The selectable communication ports RS232 / RS485 are provided for remote operation from control room. The output trigger pulse generation is interlocked with the integrated healthy interlock of Linac system, so that in case of fault, the trigger pulse output stops. Sixteen trigger output channels are provided for different subsystems requirement and an input channel to synchronize with external sync pulse. The multi-channel PTG module is tested with the Linac system for proper operation. This paper describes an elaborated view of the multi-channel PTG module.

Development of pulse and event synchronization system for LEHIPA

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A multi-channel digital pulse synchronization system is developed for LEHIPA Facility, BARC. This system provides the timing pulses for various sub-systems of the accelerator like the high voltage power supply systems, ion source, RF systems and beam diagnostics. The hardware is based on cPCI backplane and the basic pulse structure is generated by three programmable timer cards (Adlink cPCI-8554). The timer card has an internal base clock of 8 MHz. Using this, auxiliary clocks of 2 kHz and 200 kHz are derived and these are used as the timebases for the primary master clock and secondary master clock, respectively. The primary master clock that sets the common time period (variable from 1 ms to 32 seconds) for all pulses and the secondary master clock that sets the common delay (variable from 10 µs to 327 ms) with respect to the primary master for pulses other than the RHVPS systems. The individual pulses can have the different pulse widths variable from 5 ms to 327 ms (200 kHz timebase) for RHVPS systems and from 1 µs to 8 ms (8 MHz timebase) for other sub-systems. This scheme with two timebases was used to effectively optimize the required range of delays / pulse widths and best possible jitter performance with the available counter width of 16 bits.

In-house designed digital electronics board is used with each timer card to implement additional functionalities such as external / internal interlocks and external triggering, providing ease of reconfiguration. The logic is implemented using discrete components. The output pulses can be TTL/LVTTL compatible as set by the jumpers provided on the individual channels. The interlock signal (ILK) must be high (logic 1) for the outputs pulses to be enabled. Absence of healthy ILK signal will force all the outputs to go low (logic 0). There can be a maximum of eight output pulses per timer card. Each output port has a corresponding optical transmitter integrated on the board. Sub-systems like RHVPS and pulse modulator that use optical timing signals are directly driven through these optical transmitters. The EPICS driver for the timer cards is written based on asynportdriver module. The EPICS IOC is hosted on the linux-based cPCI system controller. The system is completely modular and no modifications in the basic code are required for extending the system using additional timer cards. The GUI is developed using Qt-EPICS framework and the same is integrated with the main LEHIPA control panel. The system was tested in lab for all its functionality. The observed jitters in output pulses are about 5 µs and 125 ns for RHVPS and other sub-systems respectively. When an interlock condition occurs, all the output pulses are turned off simultaneously in about 250 ns. The timing system is deployed in the facility and all the sub-systems are integrated with it. Initial operations with the new system are successful and its performance is satisfactory.

FPGA based digital I/Q demodulator for LLRF control system at RIB Facility in VECC

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Radioactive Ion Beam (RIB) facility at VECC, Kolkata consists of a series of linear accelerating cavities [1]. All these cavities require RF power with precise amplitude and phase. The RF power is responsible for the acceleration of the ion beam to a higher velocity. Thus, the phase mismatch between RF voltage and ion beam may result in transmission losses. The low level RF (LLRF) control system plays an important role in maintaining the proper phase and amplitude of the RF voltage inside the accelerator cavity. Traditionally, conventional amplitude-phase control is being used at the RIB facility in VECC [2], which has inherent limitations due to the interdependency between the amplitude loop and phase loop. Thus I/Q (In-Phase and Quadrature) based LLRF control system is being developed at VECC. The I/Q demodulator is the first and the most crucial part of I/Q based LLRF control system. It is responsible for the measurement of the phase and amplitude of the RF pickup signal from the cavity and thus calculating the amplitude error and phase error from the desired set values respectively. Initiatives have been taken earlier for the implementation of I/Q demodulators with conventional analog RF components [3]. But the analog technique is susceptible to noise, drift, and other inherent errors that can degrade the I/Q Demodulator performance, including gain balance, quadrature-phase balance, DC offsets, impedance match, and carrier leakage. Recent advances in high-speed analog-to-digital converters allow the I/Q demodulator to be implemented digitally, greatly reducing these systematic errors [4].

The digital I/Q demodulator is designed for a 1.3 GHz RF superconductive cavity which is being used in the electron linear accelerator (e-LINAC) beamline at the RIB facility in VECC. Initially, the 1.3 GHz RF signal is down-converted to an Intermediate Frequency (IF) of 113 MHz. The IF signal is then sampled with a 90.4 MHz clock signal in order to obtain the In-phase (I) and Quadrature (Q) components. The phase and amplitude are computed mathematically from these I and Q components [5]. A 16-Bit, 250 MSPS Analog-to-Digital Converter (ADC) with a 1.6 GHz Voltage Controlled Oscillator (VCO) based clock multiplier and a Zynq-7000 SoC (System on a Chip) based development kit is used for hardware implementation of the I/Q demodulator. The Zynq 7000 SoC is selected for our application to take advantage of the software programmability of the Advanced RISC Machine (ARM) processor and hardware programmability of the Field Programmable Gate Arrays (FPGA) on a single chip. A LabVIEW based DAQ system is also developed for data acquisition and configuration of the I/Q demodulator over a Universal Asynchronous Receiver Transmitter (UART) communication link. This paper describes the design and hardware implementation of a digital I/Q demodulator for a linear accelerator cavity.

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FPGA based data acquisition and control for accelerators

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A mixed signal FPGA(Field Programmable Gate Array) Zynq RFSoC(Radio Frequency System on Chip) based board ZCU111 was used to generate RF signal of 150 MHz and simultaneously digitize an external RF signal of 150 MHz and display both RF generation and RF digitization signals on PC using GUI(Graphical User Interface) made in Labview. The RF generation was done by using inbuilt 14 bit 6 GSPS(Giga samples per second) DAC and RF digitization was done using inbuilt 12 bit 4 GSPS ADC. The Zynq RfSoC series of FPGA has inbuilt 8 channels of DACs and 8 channels of ADCs which are programmable through software and Hardware. A Hardware program was developed which used various inbuilt peripherals inside the FPGA like Gigabit Ethernet for communication with the PC along with customizable program in hardware description language like VHDL using the Xilinx Vivado software and software program in Labview was developed for communicating with the ZCU111 board through Ethernet using drivers from Xilinx Vitis suite. The GUI in Labview could display the digitized RF signal on PC and 21 samples per clock period was recorded after digitizing 150 MHz RF signal. Hence sampling frequency of 150 x 21 = 3.15 GHz was achieved after digitization. Also the same GUI was used to generate RF signal of 150 MHz which was displayed on digital oscilloscope. The ZCU111 board has capability to bypass the PC and can be used as standalone system with direct interfaces to keyboard/mouse and monitor which needs to be explored further.

The applications for this development are enormous ranging from LLRF (Low level RF) cavity control for accelerators, nuclear detector pulse digitization, RF power supply precise control, standalone system for data acquisition for accelerators.

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Kalman Filter as detuning estimator for experimental RF cavity

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In an operational accelerator, RF cavity operates in pulsed or CW mode. Due to various reasons, the resonance frequency of RF cavity may deviate from its designed value. Value of detuning needs to be known for tuning and tracking of cavity resonance frequency. However, direct sensor/s for measurement of cavity detuning are not available. Often model of RF cavity is employed to infer or estimate value of detuning from available measurements. This type of measurement is termed as secondary/inferential measurement. In this paper, RF cavity model based detuning estimation is discussed. Authors have reported RF cavity detuning estimation based on direct estimation technique in [3]. However, it has serious practical limitations. In this work, detuning estimator based on Kalman filter under stochastic state space framework is considered. Similar estimator is reported in [1], [2] and emphasized by various reported literatures. While design of such estimator scheme, one needs to address practical issues like those of measurement noise and model uncertainty. Experimental set up is made using lab prototype RF cavity of 650 MHz and KF algorithm based detuning estimator is evaluated. Specifically, paper would introduce need of detuning estimation and RF cavity state space model. Steps used in discrete Kalman filter operation are explained. Two steps involved in KF operation are prediction using model of system and correction using measurements. The basic advantage is that one could incorporate sensor noise and model inaccuracies into KF operation. At each computation step, a state estimation problem is solved for estimation of apriori and posterior states along with state error covariance's. Performance evaluation of discrete KF is carried out using experimental set up. Set up and its components will be described. Experimental results of direct estimated detuning at various RF frequencies in pulsed mode are described graphically. Mean of estimated detuning and its variance using KF and direct estimated methods will be bought out through graphical comparison. Improvements offered by proposed method will be bought out.

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Auto-configurable Clock Divider for Digital Low-Level Radio Frequency System of Infrared Free Electron Laser

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Digital Low Level Radio Frequency (DLLRF) system is developed and deployed in Infrared Free Electron Laser (IRFEL) at RRCAT, Indore for controlling the amplitude and phase of Radio Frequency (RF) signal inside the Sub-Harmonic Pre-Buncher (SHPB) cavity, within the required limits (±0.1% for amplitude and ±0.1° for phase) [1]. Various synchronized RF signals are required for operation of DLLRF and sub-systems of IRFEL. Signals such as clock (95.2MHz) to Analog-to-Digital Converter, signal (23.8MHz) for Local Oscillator (LO) frequency (499.8MHz) generation, signal (2856MHz) to Linear Accelerator (LINAC), signal (476MHz) for Electron Gun etc. are being generated for operation of IRFEL. For proper operation, all these RF signals must be synchronized in nature that is achieved by deriving these RF signals using a master clock and programmable multichannel clock divider. These signals are generated by changing/programming the division ratio of different channels of clock divider. RF signals are generated using AD9516 based programmable clock generator in IRFEL. Since, AD9516 chip is volatile in nature, all the essential settings (division ratio, output levels etc.) are erased out after power to the chip is turned off. Each time power to chip is turned on, AD9516 has to be programmed by Graphical User Interface (GUI) provided with the board for working of DLLRF system. An automated solution has been developed for programming of clock divider that configures DLLRF system automatically, without any manual programming. Automatic programming is carried out by a Raspberry Pi (RPi) that is installed and commissioned along with the AD9516 based board. RPi programs the board by sending the data frames to AD9516 through Serial Peripheral Interface (SPI). A script has been developed in python that automatically executes after RPi boots and all the essential settings (stored in a database on RPi) are being transmitted through SPI to program the AD9516. Two GUIs (remote and local) has also been developed in Python for changing the division ratios and other essential settings. Remote GUI runs on a window that sends command through Ethernet and local GUI runs on Raspberry Pi. GUIs are used to modify the division ratios and updated ratios are also stored in the database simultaneously. Updated division ratios are used for the configuration at the time of powering of the chip. This system for automated configuration will be installed in DLLRF system of IRFEL at RRCAT. Design Scheme, algorithm and result of auto-configurable clock divider for DLLRF system will be described in the paper.

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Unscented Kalman Filter as SC cavity detuning estimator

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In an operational accelerator, RF cavity operates in pulsed or CW mode. Due to various reasons, the resonance frequency of RF cavity may deviate from its designed value. Value of detuning needs to be known for tuning and tracking of cavity resonance frequency. However, direct sensor/s for measurement of cavity detuning Δω are not available. Often model of RF cavity is employed to infer or estimate value of Δω from available measurements. This type of measurement is termed as secondary/inferential measurement. Dynamics of Model of RF Cavity are linear in case of normal conducting cavity, thus methods of linear estimation suffice [1]. However, the model is nonlinear in case of superconducting cavity necessitating use of non-linear estimators. In this paper Unscented Kalman filter, a well-known estimator for non-linear system is described followed by its application as estimator for RF cavity Δω. Modelling & Simulation results are presented. Paper explains steps used in UKF operation. Unlike KF [1], UKF[2] makes use of the fact that it is easier to approximate a probability distribution than it is to approximate an arbitrary nonlinear function or transformation. The probability distribution function of the states (and parameters) is approximated by a sample points chosen appropriately. The sample points are propagated using the nonlinear state space model and the state estimates and its error covariance matrix are computed. After explaining UKF, application of UKF as Δω estimator is described. Simulations and results of estimation are discussed. Paper concludes stating that for SC cavity, one needs to assess performance of UKF as an estimator of cavity Δω under non-linear systems formulation. It is concluded that estimated states of RF cavity are close to true states i.e, in absence of noise. Sigma points in UKF formulation help capture the first two moments of underlying probability distribution function of noise. Due to nonlinear dependence of Δω on cavity electric field, a model based on UKF Δω estimator is expected to give better estimation results in case of SC cavity.

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Statistical Methods for assessment of RF amplifier linearization

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In design of particle accelerators, solid state RF power amplifier linearization has been one of the challenging areas. Among various available techniques, digital predistortion (DPD) based on least square estimation is one of the promising approach [1] [2] [3]. Design of such an estimator needs fitting a suitable model which has inverse characteristics to that of SSPA. Authors have described recursive least square estimation (RLS) method for DPD design in [4]. A designed digital pre-distorter is added in series at input of SSPA leading to overall linear I/O characteristics. However, success of such a linearization method depends how well estimated DPD coefficients represent inverse characteristics of SSPA. For assessment of goodness of fit, one has to often resort to statistical methods based on linear regression concepts. A linear regression exercise leads to random component representing misfit. Once problem is formulated as linear regression, many design issues may be seen from different perspective. This paper applies concepts of linear regression to problem of least square estimation to obtain confidence interval estimates of DPD coefficients. Many interesting issues pertaining to linearizer design and performance can then be addressed. Some of them are fixing number of parameters needed for arriving at ideal model of SSPA or DPD I/O, assessing value of modelling error w.r.t. to true response and ways to reduce it. Secondly, amount of confidence that can be associated with each DPD model parameter, Thirdly, goodness of fit of model output to experimentally obtained outputs and ways to quantify it, number of readings over I/O range of SSPA to obtain reasonably accurate DPD model, over a full I/O range, effect of resolution or spacing between readings. This paper explains concept of linear regression, followed by estimation of CI estimates for model coefficients. R2 measure for goodness of fit is used. Saleh model is used to generate SSPA I/O followed by DPD design. Simulation results to assess effect of number of model coefficients on CI estimates are described. It is concluded that Concept of linear regression could be used to look at LSE problem from error analysis perspective. The amount of error served as guide for R2 measure and also to selection of appropriate no. of coefficients in DPD model. In order to build confidence on model, CIs are found as useful tools. Values of CI help in choosing no. of total readings and their resolution while acquiring data during model building exercise for application of SSPA linearization using DPD.

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Development of Prototype LLRF System for 18 MeV Medical Cyclotron

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A low-level RF (LLRF) system has been designed for the 18 MeV Medical cyclotron, which will be used to deliver the requirements of medical radiopharmaceuticals in and around Kolkata. The LLRF system is used to feed the RF cavity having frequency of 65.6 MHz with the controlled amplitude of RF. A prototype LLRF system operating at 65.6 MHz is designed to stabilize acceleration voltage and control the resonance of the cavity. LLRF system broadly consists of a Dee Voltage Regulator (DVR), Spark detector, Ripple detector, Interlock protection system, and tuner control system. The RF amplitude is designed to be controlled by PI feedback control for keeping the voltage stability of the cavity within 0.1%. Spark detector will stop the RF power input to the amplifier within 1us as soon as the voltage in the cavity dips. Furthermore, the testing results and simulation of the LLRF prototype has been presented.

Operational experience of Digital LLRF system for particle accelerators at RRCAT

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RRCAT, Indore is involved in the development of different particle accelerators–providing synchrotron light to the users in India ~~and~~. Indus complex at RRCAT has Indus-1 (450MeV, 125mA) and Indus-2 (2.5GeV,200 mA) synchrotron radiation sources (SRS) and a common Booster synchrotron to inject the beam into Indus-1 and Indus-2 SRS. Both these synchrotron radiation sources have been operating in round the clock mode for more than 11 years. Booster and Indus-1 operates with 31.6 MHz RF systems each, whereas Indus-2 requires six RF stations of 505.8MHz. Low Level Radio Frequency (LLRF) control system ensures the amplitude and phase of the RF signal stability with in ±1% and ± 1° which is necessary for proper acceleration and storage of electron beam. Out of 6 RF stations of Indus-2, four are Solid state RF amplifier based where-as IOT and Klystron are used in one station each. Infrared-Free Electron Laser at RRCAT is another important accelerator facility at RRCAT, which accelerates the electron beam to 15-25MeV in linear direction which corresponds to the lasing in the tuneable range of 12 to 15 μm. A 476 MHz pulsed RF system for Sub Harmonic Pre Buncher is required to ensure bunching of electron before entering the 2856 MHz LINAC. Amplitude and phase stability requirement for this 476MHz Pulsed RF system of SHPB is ±0.1% and ±0.1˚ respectively and uses Tetrode Tube based RF amplifier. Maximum allowed RF Pulse width in SHPB system is only 50 Micro second, therefore a fast Digital LLRF system which is equipped with adaptive feed forward algorithm has been used in SHPB system of IR-FEL. Various RF system at RRCAT operating at respective operating frequency has different type of RF amplifiers, moreover the operating conditions of RF plants vary due to various reasons like beam loading, change/upgradation of active and passive components etc. For reliable and smooth operation of RF system optimization of LLRF system parameters along with some upgradations were carried out over the period of time. Since every RF station has different plant conditions therefore first the individual RF amplifier was characterized in open loop, then accordingly the PI parameters of amplitude and phase loop is separately optimized for each station. Response time of each station is optimized to ensure that loops don't act on the synchrotron frequency components sense signal. Similarly, the parameters of feedforward and feedback control loop of the IR-FEL systems were also optimized to ensure the repetitive performance and lasing. In this paper operational experience of Digital LLRF systems of particle accelerators like Booster, Indus-1, Indus-2 and IR-FEL will be discussed in details.

Upgradation of Low Level RF System for K500 Super Conducting Cyclotron

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Variable Energy Cyclotron Centre, Kolkata has commissioned K500 Superconducting cyclotron (SCC). The system consists of three identical RF cavities for beam acceleration in SCC. RF cavity is formed with two one-end short circuited λ/4 transmission line sections connected at central region operating in the frequency range of 9-27 MHz. Existing low-level RF (LLRF) system has been upgraded to meet the stringent requirement of amplitude and phase stability of 100 ppm and ±0.1°, respectively. Upgraded LLRF system has been designed which broadly consists of Dee Voltage Regulator, Phase Regulator, Spark detector, Fine Frequency (Trimmer) Control System, RF Tuning System and Interlock-protection system. The paper discusses detail insights into the various technical aspects of LLRF system for the K500 SCC at VECC, Kolkata. Furthermore, the test results of the upgraded design has been presented.

Design and Development of Up-Graded Digital RF Gap Voltage and Phase Regulation Control System

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Indus-2, a synchrotron radiation source at RRCAT, Indore is designed for beam energy of 2.5GeV at beam current of 200 mA. Indus-2 has 6 numbers of RF stations of 505.8MHz. Each RF system has an independent Low Level RF (LLRF) control system that keeps the RF gap voltage and phase regulated with in ±1% and 1 ° to minimize the beam loss. Initially all the LLRF systems were analogue in nature, over last 5-6 years they were replaced with Digital LLRF systems and were developed using distributed RF components and standard boards. Over the period of time four channel RF UP down converter and synchronized LO and Clock generation boards have been designed and developed indigenously at RRCAT. Four channel RF up down conversion board is developed using an active mixer for down conversion and I/Q modulator for amplitude and phase control. Synchronized LO and clock generation boards which uses a programmable clock generator and active mixer for synchronized Clock and LO signal generation has also been developed. This board has auto configurability feature which ensures the touch less auto configuration at the time of power cycling. Using these boards, a two channels RF gap voltage and phase regulation system (DLLRF) at 505.8MHz has been designed and developed to cater to two RF stations in one LLRF rack of Indus-2 RF system at RRCAT. Digital PI controllers for amplitude and phase regulation loops are implemented using LabVIEW FPGA in NI FlexRIO card, which sits in PXIe chassis. To communicate with supervisory controls system multifunctional Flex Rio card which sits in the same chassis has been used. This Up graded two channel Digital LLRF system was tested in the lab using RF system simulator, providing gap voltage and phase regulation of better than ± 1% and ± 1 ° respectively. This system has option of independently operating the amplitude and phase regulation loop in closed or open loop and also have two additional spare up-down converter and I/Q modulation channel for quick on the self-replacement to reduce the maintenance time. It is planned to replace all the existing Digital LLRF system of Indus-2 SRS with this new upgraded LLRF system. This system will reduce the size, number of RF connection and human intervention hence in turn reliability of the machine will be improved. First LLRF system of station #3 and #4 will be replaced then in phased manner other LLRF systems will also be replaced. In this paper designing and development aspects of this new upgraded Digital RF gap voltage and phase regulation control system and its results will be presented.

Implementation and testing of low power RF distribution system for RF transmitters in RIB facility

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A Radioactive Ion Beam (RIB) facility has been developed at VECC, Kolkata which has a beam line consisting of a series of RF linear accelerators. This comprises six RF cavities operating at 37.87 MHz [RFQ linac, three rebunchers RB1-3, two linac modules L1-L2] and five RF cavities [RB 4-5 and three linac modules L3-L5] operating at 75.74 MHz. The Low level RF (LLRF) control systems has been developed for RF cavities till L3, whereas for the remaing cavities, it is in advanced stage of development.

It is necessary to operate the RF cavities in phase synchronism with respect to a reference phase to obtain efficient beam transmission and acceleration. For this purpose, a RF distribution system has been designed and fabricated to deliver the RF signal generated from a single source to the respective LLRF systems. A master oscillator signal at 37.87 MHz is divided to obtain 6 output ports for 37.87 MHz signal and 2 output ports for 75.74 MHz signal. The maximum RF power output for 37.87 MHz is 0 dBm and all are in phase. The maximum RF power output for the 75.74 MHz signal is +10 dBm. Proper isolation between the channels has been implemented into the design of the system. Steps have been taken to eliminate electromagnetic interference. The design, development and performance results of the RF distribution system will be described in this paper.

Modelling and Simulation of Temperature Stabilization System for Voltage Reference to be used in Precision Magnet Power Supply

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The electromagnets are indispensable parts of any particle accelerator such as a cyclotron, linear accelerator, synchrotron etc. In particle accelerators, these magnets are used for bending, focusing and steering the beam of charged particles by inducing Lorentz force on them. The stability of the trajectory of beam particles is determined by the stability of the magnetic field of the electromagnets. The stability of the magnetic field in turn is decided by the stability of the coil current of the electromagnets. The high precision temperature stable current regulated power supplies are generally used for powering the electromagnets. In VECC, a magnet power supply with a 100 ppm stability class is being developed indigenously to replace the imported power supplies of various beamlines. It is reported ***[1]*** *that varying environmental factors such as a change in ambient temperature leads electronic component behaviour to drift from its ideal characteristic. One of the crucial components sensitive to temperature variation is the voltage reference IC present in the power supply controller. This voltage reference along with digital-to-analogue converter (DAC) is used to generate the analog set point for desired magnet current. This paper describes the modelling and simulation of a novel method for the temperature stabilization of the voltage reference IC to be used in indigenous power supplies. The SIMULINK from MATLAB is selected as the simulation software. The thermoelectric module* ***[2]*** *which works on the Peltier effect is selected as the final control element of the temperature stabilization system. An electrical equivalent model* ***[3]*** *of the thermoelectric system is developed using heat transfer equations for the Peltier Effect, Joule Heating and Fourier law of heat conduction. For example, thermal parameters such as heat flow and temperature were modelled using standard blocks of current and voltage sources available in the SIMULINK library. To develop a simplified model, heat flow due to natural convection, radiation and the Thomson effect was neglected on the basis of certain assumptions explained in this paper. The system parameters such as heat capacity, and thermal conductance was calculated on the basis of calculated mechanical dimensions and intrinsic parameters such as thermal conductivity and specific heat capacity. The temperature dependency of voltage reference output is modelled as a linear relation as per an associated temperature coefficient. Suitable closed-loop control algorithms* ***[4]*** *such as PI, ON-OFF and ON-OFF with an integrator are implemented on the developed model. The entire system is simulated after setting a suitable solver configuration to optimize between simulation step size and simulation time. The controller parameters are tuned to optimize the dynamic and steady state control parameters such as steady-state error, rise time, overshoot and settling time. The detailed flow of work related to modelling, simulation and analysis of results is mentioned in this paper.*

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Development of Protocol Converter for Lab Windows and EPICS

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LabWindows/CVI[1] *is an ANSI C software development environment with a comprehensive set of programming tools for creating test and measurement applications for the Microsoft Windows platform. It is a proprietary software. Lab windows support C (only partial support of C99, debugging tools and math libraries do not support complex or double precision math and no Unicode). There is no C++ support for object oriented programming which becomes a necessity while handling large control systems.* ***EPICS[2]*** *is Experimental Physics and Industrial Control system. It is a distributed SCADA framework which can run on various operating system for control and data-acquisition.* ***EPICS[3]*** *provides a set of open source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments. LEHIPA uses EPICS SCADA system which uses Channel Access protocol to communicate between IOCs(Input-Output Controllers) and CWSs(Client Workstations). Few of the system in LEHIPA are developed using Lab Windows. In order to integrate the system with LEHIPA control system it is needed to develop an interface between such systems and EPICS.*

In order to convert Lab windows based software into EPICS based project, a protocol converter is built. This protocol convertor is developed over TCP/IP protocol stack. Data is communicated between the Lab Windows and EPICS based CWS(Client Work Station) is sent over the LAN. This protocol can also convert the data stream format and allows waveform datatype. This protocol also ensures the network channel efficiency. Instead of sending separate packets for actual data value and corresponding metadata, one single packet is sent in a user defined datatype, structure. This structure accommodates data and metadata which corresponds and maps the field from Lab Windows GUI to appropriate EPICS record type. The result is returned to a GUI which is developed using QT, a cross-platform software for creating graphical user interfaces as well as cross-platform applications that run on various software and hardware platforms.

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Experimentation and Demonstration of Dual Energy with Klystron based Medical Linac

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Electron linear accelerators have a wide spectrum of applications ranging from high energy physics to medical, industrial, military and civilian purposes [1-8]. SAMEER has well established expertise in development of linear accelerators for medical applications with electron energies from 6 MeV to 30 MeV for high energy X-ray generation. Linac currently being developed at SAMEER has the capabilities of generating a 30 MeV electron beam with sub-picosecond bunches at a repetition rate up to 300 Hz and at an average current of up to 0.3 mA. The higher energy linacs for radiation therapy employ high power klystron as RF source. The demand of dual mode and multiple energies is high from medical community especially for radiation therapy applications [9]. At SAMEER we have developed a linac test facility to operate Klystron to its rated values and determine the RF power required to produce dual energy x-ray i.e., 9 MV and 15 MV. Further, the Klystron operating points are determined for achieving these energies. The challenges involved in achieving dual energy operation namely variation of HV bias applied to Klystron, low-level RF input power and gun-injection voltage are overcome by modifying the existing units. Further, the Beam Flatteners have been developed for both energies using the image processing tools. Also, a test facility control unit along with Graphical User Interface (GUI) is developed for day-to-day operation. Based on the operating points, experiments have been carried out and two energies have been successfully demonstrated. This paper presents the High-Power RF power measurement setup with modulator, control unit with GUI, Variation of RF power with respect to bias voltage, Modifications in the existing unit for addressing the challenges, unflatten beam profile using image processing tools, Beam Flattener design and flatten beam profile and x-ray attenuation curves for energy confirmation.

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Present Status report of 30MeV Medical cyclotron Facility at VECC, Kolkata

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Medical cyclotron is a device which generates radioisotope for cancer detection and therapy. 30 MeV, high intensity (500μA) proton beam generates from the Medical cyclotron. Medical cyclotron facility is a unique facility under the aegis of department of atomic energy which facilitates production of various radioisotopes and basis research simultaneously. The heart of this facility is a 30 MeV H-cyclotron called CYCLONE-30. This cyclotron is a negative hydrogen ion accelerator. This cyclotron is a fixed magnetic field, fixed RF frequency, variable energy and dual-beam cyclotron. There are two RF cavities, called dee, to accelerate the negative hydrogen ions. At the extraction radius, two carbon stripper foils are placed at diametrically opposite ports. All the systems such as various contactors of distribution cabinet for pumps etc., power supplies, RF system, gate valves are operated and different field interlocks, limit switch positions, vacuum gauge readings etc are monitored from a centralized PLC based control system. Signal cables were accordingly laid for connection between those systems and were terminated. Cables for current monitoring and video monitoring were also laid and terminated. Current measurements are important for sensing the beam current at various points such as faraday cups, pop-up probe, stripper extraction, beamline collimators, target etc. Video monitoring is required to monitor the radioactivity at vault and the beam profile at the beam viewer inside hot cell from the control room. Three beamlines are dedicated for medical isotope production from liquid and solid targets and two beam lines for material science research and target window study for Lead-Bismuth target assembly. There are nine hot cells (two for positron emission tomography, seven for single-photon emission computer tomography) for radioisotopes production in clean room area. During this period the machine availability was satisfactorily and it has delivered beam for irradiation of O18 to produce F18 and FDG (Fluorodeoxyglocose) is produced supplied to various hospitals. Production was carried out everyday morning for 5 days a week without any major interruption. Two hot cells were used in automatic process for regular production FDG from medical cyclotron. In addition to the regular production beam of different energy were developed and transferred to the target at beamline#1.1 . Using this facility Ga68 was produced and supplied to local hospitals. Beams of energies from 15.5 MeV to 30 MeV (up to 50 mA) were developed and transported to the end of beam line faraday cup in the low current and high current beamlines of the Materials Science Cave. target facility for carrying out irradiation of solid targets in the low current beam line has been developed and tested at 16 MeV and 10 mA beam current. Beam is transported up to the target station and various interlocks have been integrated and tested. During the irradiation the required radiation data have also been recorded.

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Development of Hydrogels and Dose Indicators Using Indigenously Developed Electron Beam Accelerator

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Hydrogels are three-dimensional structures of polymers containing significant amount of water. Based on their chemical structure different types of gels can be produced. Depending upon application, gel formulations can be modified to achieve appropriate results. For medical dressing, formulation based on PVA and PVP were used along with gelling polysaccharides like agar and carrageenan. These ingredients are mixed in hot water and autoclaved to give homogenous solution. The hot solution is cooled to 55 ^{0}C and poured in plastic trays. The trays are then irradiated using indigenous electron beam accelerator at Kharghar. The formulation was optimized to form the gel at 25 kGy. With this dose hydrogel is formed and sterilized simultaneously. We have optimized different concentration of polymers, polysaccharides to form usable gels. These gels can absorb tincture of iodine to become antibacterial gels. Issues like bubble formation during electron beam irradiation was studied. In another development we have tried poly acrylic acid and carrageenan hydrogels to form superabsorbent. The gels are formed in the same way as above, dried and crushed to powder form. These gels can absorb 400-500 times of water to their weight.

PVA based dose indicators were prepared using dimethyl yellow dye and methanol. These were prepared at different compositions and tested using 1 MeV electron beam accelerator. These indicators can be used for industrial applications to ensure the product gets irradiated.

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Thermal Characterisation of Indirectly Heated 40kV Solid Cathode Electron Beam Emitter Assembly for Linac

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Abstract: *Electron Beam emitter assembly is indigenously designed and developed for use in linear accelerator as particle source. This is an indirectly heated solid cathode emitter assembly. It consists of primary filament which is made up of tungsten wire of diameter of 0.5mm and spiral in shape. This filament is heated up to the temperature of 2800K by passing direct current through it. When the primary filament is at this high temperature it heats up the solid cathode by direct radiation heating. Solid cathode is made of lanthanum hexaboride (laB6). By direct radiation heating from the primary filament its reaches to its emission temperature of 1500K. Solid cathode is button type cathode having diameter of 10mm and thickness 1mm. Thermal simulation and characterisation of emitter assembly has been carried out to find the power required to achieve the emission temperature of the solid cathode and validate it with the experiment. The thermal simulation of the gun has been done using the commercially available analysis package. On the basis of the simulation analysis design has been finalised and the gun has been fabricated. Experiments have been done on the fabricated gun to find the actual temperature distribution. Thermocouple and two colour pyrometer have been used to measure the temperature at different points in the electron gun. The temperature distribution obtained by simulation and experimentation is in tandem. This paper presents thermal analysis of the electron gun and its characterisation.*

Initial Investigations on distribution of absorbed dose in waste water treatment using electron beam

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Irradiation of waste water using high energy electron beam has been found to be capable of removing various organic compounds, which are otherwise difficult to be removed using conventional treatment methods. An industrial demonstration system (EBWWT - Electron Beam Waste Water Treatment) using 1MeV electron accelerator has been designed at BARC. In this system, the accelerated electron beam pass through a 50 µm thick Titanium (Ti) window. The transmitted electrons and the bremsstrahlung photons produced in Ti foil, travel towards waste water flowing below in the form of a film of 1500 x 100 x 4 mm dimension. The electron beam scans across the length and breadth of the Ti foil. In order to assess the uniformity of irradiation of the water flowing beneath the Ti foil, a set of monte carlo simulations were carried out using FLUKA [1, 2] code. The electron beam is assumed to be along z-direction. FLUKA simulations were carried out for 5 cycles (500000 particles in each cycle). The absorbed dose distribution in the waste water film due to a Gaussian electron beam (having 50 mm FWHM along x and y - axes) incident at the center of the Ti foil in (XY plane) is shown in Fig. 1. The dose shown in this figure corresponds to one electron. A parametric study of absorbed dose distribution due to electron beam incidence at different position of the Ti foil was subsequently carried out. Further the effect of distance between the Ti and waste water film on the dose distribution was also studied. These simulations generated valuable data for optimization of the EBWWT accelerator parameters. The absorbed dose was found to be mostly concentrated around the path of incident electron beam. The peak value of absorbed dose per electron was approximately. 2.5E-5 GeV/g. As the FWHM of the beam is reduced to 10 mm, the peak absorbed dose per incident electron increases to 4.5E-5 GeV/g.

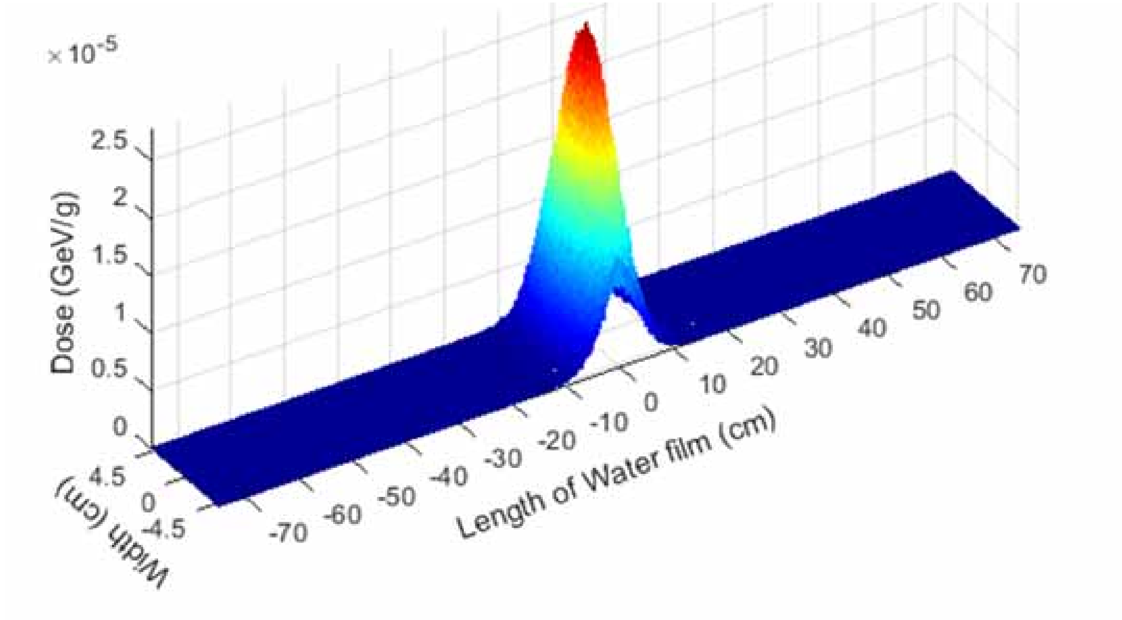

Fig. 1: Dose distribution in waste water film irradiated by 1 MeV electron beam

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Development of a versatile low temperature irradiation system for radiation damage studies

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The most profound effects of irradiation in materials occur in the core of nuclear power reactors, where atoms comprising the structural components are displaced numerous times throughout engineering lifetimes. Essential irradiation effects: low-temperature radiation hardening and embrittlement; irradiation-induced precipitation; phase stability; irradiation-induced creep; and void swelling affect the performance of structural materials in nuclear energy systems. Hence there is a considerable thrust in understanding the radiation effects of materials. In this context, the concept of "ion simulation of neutron damage" using ion irradiation has grown in popularity [1]. The simulation vests on the similarity in the type of primary damage state, i.e., the collision cascade and average primary recoil energy between neutron and heavy-ion irradiations, are comparable. Low-temperature irradiation is one of the most important experimental methods for fundamental research in radiation damage because the primary damage state at the end of the thermal-spike quench process can be observed without the effects of thermal diffusion.

A versatile, low-temperature ion-irradiation system that is usable at the end stations of the 1.7 MV tandetron and 150 kV accelerators at MSG, IGCAR, is developed. The irradiation system comprises the following components (in an order down-stream to the beam from the accelerator): 1. beam-defining slits, with the capability to ensure beam uniformity while using raster scanned (50 × 50 mm^2) and defocussed beams 2. an indigenously developed insertable water-cooled Faraday cup for beam current measurements and 3. a low-temperature sample holder. The sample holder is cooled with the help of a closed-cycle refrigerator (CCR). The control of sample temperature is achieved through a temperature sensor (DT470) and temperature controller. The temperature stability during ion irradiation was maintained with an accuracy of + 0.5K.

A tilt table design of the system enables quick change of samples. The tilt table holds the CCR and sample holder in a horizontal orientation during irradiation. The setup has rails to retrieve the chamber and facilitates rotation (on the hinge point) to vertical orientation with safety locking, providing easy sample changing operation. Viewports are provided to facilitate light collection during in-situ luminescence experiments at low temperatures. The temperature on the sample holder is measured using a silicon diode temperature sensor, the minimum temperature attained on the sample holder is 7K. A 1.4 MeV Ni^+ beam with a current of 200 nA was incident on the sample holder for 6 hours; the sample temperature remained invariant at 10K, variation within ±10%. The vacuum in the low-temperature ion irradiation system was in the 10^{-9} mbar range. Rutherford Backscattering Spectrometry was used to estimate the carbon buildup in samples. The carbon concentration is slightly higher than in samples where irradiation to the same dose was conducted at ambient temperature. Although the vacuum in the chamber prior to low-temperature cooling was ~ 2×10^{-8} mbar, the gettering of impurities on the cooled samples is a potential source of carbon contamination. A secondary liquid nitrogen trap in the chamber is a solution to this problem.

Several irradiation experiments in bulk Ni and nanocrystalline Ni have been undertaken using this system. This presentation will also encompass the indigenous development of beam diagnostic devices, vacuum systems for ion irradiation experiments, and in-house refurbishment of turbo-molecular pumps.

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The ion beam induced target heating phenomena

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The Variable Energy Cyclotron Centre is a cyclotron-based premier accelerator centre in India. A low-energy ion beam facility up to 20 keV is available from the ECR ion source, and a high-energy ion beam from 7 MeV/u to 12 MeV /u is available from the K130 cyclotron. We have accelerated light ions 7–12 MeV proton and 28–60 MeV alpha beam. At the same time, 100 MeV N^{+5} was also accelerated in the VEC K130 cyclotron. An irradiation experiment is a well-known technique for characterizing materials, modifying target surfaces, and so on. Electron emission is an obvious phenomenon during target ion collision. During collision, the ions slowed down and entered the target, all the kinetic energy of the ions was converted into heat, and thereby thermionic electron emission occurred. By detecting thermionic emission, we find out the beam spot temperature. At the same time, we measure the dynamics of temperature rise at the Si target utilizing 28 MeV alpha and 7 MeV proton beam which will be helpful to get an idea of the maximum global target temperature rise during irradiation. Our experimental results differ from the earlier model. Material constant (Λ) is an important parameter. Many models on ion induced electron emission phenomena incorporate the material constant (Λ) to quantify the secondary electron yield of a target, and this idea can be extended for the accurate measurement of beam current. Therefore, we experimentally find out the value of (Λ) of Si with different energies of alpha projectiles. The value of (Λ) decreases with the projectile energy. There is limited experimental evidence of the value of (Λ) with this energy range of an alpha projectile. In this experimental set-up, we also measure the energy distribution of ion induced emitted electrons. The shape of the energy distribution of emitted electrons and the value of energy matched the theoretical simulation.

Radiation based ethylene oxidation studies and impact of radiation products on pressure tubes

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During investigation of events at Kakrapar Unit-I & II and impurity species of ethylene was found in carbon dioxide cylinders employed in reactor AGMS. The radiolytic processes which ethylene will undergo needed to be explored to understand it's impact on pressure tubes (PT).

Short burst experiments were carried out at 7MeV Electron accelerator of LINAC facility and the reaction route, mechanism and kinetics were evaluated The experiments brought out the fast kinetics of the reaction with almost 75% ethylene undergoing radiolysis within 160 seconds as compared to only 20% degradation in 2 hours for thermal reaction in absence of radiation. The reaction products were analyzed and reaction route through ozonolysis of ethylene was disseminated. The study provided evidence for formation of both reducing species like formic acid and hydrogen and strongly oxidizing species like peroxy radicals and peroxides etc.

Based on these data further experiments were carried out at 10MeV accelerator at EBC, Kharghar. The PT coupons were exposed to gas mix in presence of radiation and it's impact was observed on PT surfaces.

Both the studies provided experimental evidence for the involved processes and along with time scale of events evolved the explanation towards root cause for KAPs events.

Surface structuring of PMMA polymer by 30 keV argon beam erosion

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State-of-the-art experimental facility 200 kV Ion Accelerator, with energy range of 30-200 kV has been running successfully at Ion Beam Centre, KUK. This facility offers single charge state, switching magnet with five exit ports and large area irradiation/implantation using hollow cathode ion source.

Ion beam induced patterning and structuring of polymeric surfaces has drawn strong interest due to latent applications in photonics, magnetic devices, optical devices, photovoltaics, and surface-wetting tailoring etc. In this work, we report the controlled surface modifications and structuring of Poly(methyl methacrylate) (PMMA) polymer using 30 keV Ar^+ ion beam for different oblique incidences of 15º, 30º, 40º, 50º, 75º, 90º at constant argon ion flux. Morphological and optical analysis has been performed by ex situ atomic force microscopy and UV-Vis-NIR spectroscopy. The effect of oblique incidences on argon sputtered films was evaluated by various surface topography and texture parameters, such as Fast Fourier Transforms, surface roughness, skewness, kurtosis. One dimensional cross section scans of surface profiles are determined and morphological features are investigated. AFM study demonstrates prominent changes in surface morphology of argon sputtered surfaces showing distinct dependence on argon ion incidences. The formation of surface structures is attributed to the different degree of sputtering yield at different off-normal incidences and preferential sputtering of hydrogen in comparison to carbon in ion sputtered surfaces. An increase in the optical absorption and a shifting of absorption edge towards longer wavelengths were observed. Concomitantly, a pronounced decrease in the optical band gap was recorded. A possible correlation between surface topographical evolution and band gap is discussed.

Simulation of low energy positron bunching in 150 MHz quarter wave resonator

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A 150 MHz quarter wave resonator is used to bunch nano second positron pulses into picosecond pulses which are subsequently used in positron annihilation lifetime spectrometer [1,2]. Roughly 100 W power is fed to the cavity using loop coupler. A copper tuner is used to adjust the thermal load induced frequency shift. We have used CST microwave studio [3] to design the loop and the tuner. The resultant electrical field distribution is recorded and exported to SIMION [4] software to track the trajectory of the low energy positrons (250 eV). Effect of various parameters such as- particle energy spread, deviation from axis and stray magnetic fields - on the final timing of the positron bunches are studied. We have also simulated the accepted drift in the various components of the RF circuit such as – amplifier and phase shifter which is needed to achieve a sub 300 psec positron pulses on the sample.

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Alloying effect of gold nitride by applying MeV-proton ionization

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Gold nitride (GN), a recently developed advanced material, is useful for the electronic industry. Several attempts have been made over the last twenty years to synthesize gold nitride. Very recently researchers at the University of Newcastle upon Tyne, UK, have been successful in synthesizing GN material [1-3].In the present report, alloying of gold nitride has been studied using AuL_{α}-to-AuL_{β} intensity ratio from PIXE experiments, performed using MeV-proton ionization technique at the 3 MV tandem Pelletron facility at the Institute of Physics (IOP), Bhubaneswar. The GN material used for the above study was synthesized by applying a novel technique [4]. The corrected intensity ratio [5] of AuL_{α}-to-AuL_{β} can be a sensitive probe for studying the charge-transfer effect in noble metal nitrides.

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Electron LINAC as photo-neutron source for neutron radiography application

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'Neutron Radiography' has been successfully demonstrated using 9 MeV RF Electron LINAC at ECIL, Hyderabad [1] by the collaborative efforts of Pulsed Power & Electromagnetics Division (BARC, Visakhapatnam), Technical Physics Division (BARC, Mumbai), Control & Automation Division (ECIL, Hyderabad) and Accelerator and Pulsed Power Division (BARC, Mumbai). The entire LINAC system is inside radiation shielded room and it is remotely operated through a PC in control room. At full rating, the X-ray dose rate of ~24 Gy/min is produced at 1m distance from Tantalum target [2]. The photo-neutron target assembly for neutron radiography has overall dimensions of 700mm (L) × 855mm (W) × 700mm (H) and collimation ratio (L/D) of 28. For producing neutrons 'ϒ-n' neutron production scheme has been implemented in this setup [3-5]. To obtain maximum thermal neutron fluence rate, two beryllium cylinders of 63mm diameter having lengths of 44mm and 84mm have been used along with 60mm HDPE moderator in between. Collimator is placed after HDPE in between two Beryllium targets in +Y direction. To minimize the gamma content at image plane, neutron collimator has been designed in perpendicular direction to the incident beam and also the Beryllium target is cylindrically covered with lead shielding. Collimator has 500mm length, 10mm aperture and 150mm image plane diameter. Thermal neutron flux measured at image plane was ~6×10^3 neutrons/cm^2/second/kW e-beam. The entire photo-neutron target assembly was covered with 100mm thick lead shielding for reducing the gamma background. Neutron radiographs of various objects with adequate resolution were successfully imaged using gated ICCD camera. This paper will cover details on design, installation and testing of photo-neutron target assembly for neutron radiography application along with highlights on contrast imaging intricacies in such setup.

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Low Flux Heavy Ion irradiation Set up at BARC-TIFR Pelletron Accelerator

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Low flux of heavy ions is required for calibration of various detectors besides other potential irradiation applications. Ease of irradiation of multiple samples necessitates a sample changing mechanism compatible with ultra-high vacuum environment. In order to obtain a fluence of ~10^6 particles/cm^2, the particles need to be counted using detector and associated electronics. An amplifier coupled with pulse shaper and counter are employed for counting particles. A set up has been designed and developed in-house accordingly, to ensure irradiation of multiple samples as per the user requirements. Details of the set-up, sample changer, particle flux and fluence measurements along with its effective utilization shall be presented in this paper.

The samples were mounted in the irradiation chamber and changed remotely using a Rotary Vacuum feedthrough in combination with a video camera & monitor. Heavy ions from Pelletron Accelerator were scattered using gold foil and the scattered beam at +/-45^o ports was used for irradiation and monitoring, respectively. In the present work, scattered Lithium beam at 44 MeV from Pelletron was used for irradiation. Flux and fluence measurements were carried out at 45° mirror symmetry using PIN Diode detector and an Amplifier developed by Electronic Division, BARC. Six no. of samples can be loaded and changed remotely using a rotary vacuum feed-through without breaking vacuum.

Optically Stimulated Luminance Detectors (OSLDs) developed by RP&AD, BARC for dose measurements, to be utilised in space-based applications, were irradiated for various doses using this set up, successfully.

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