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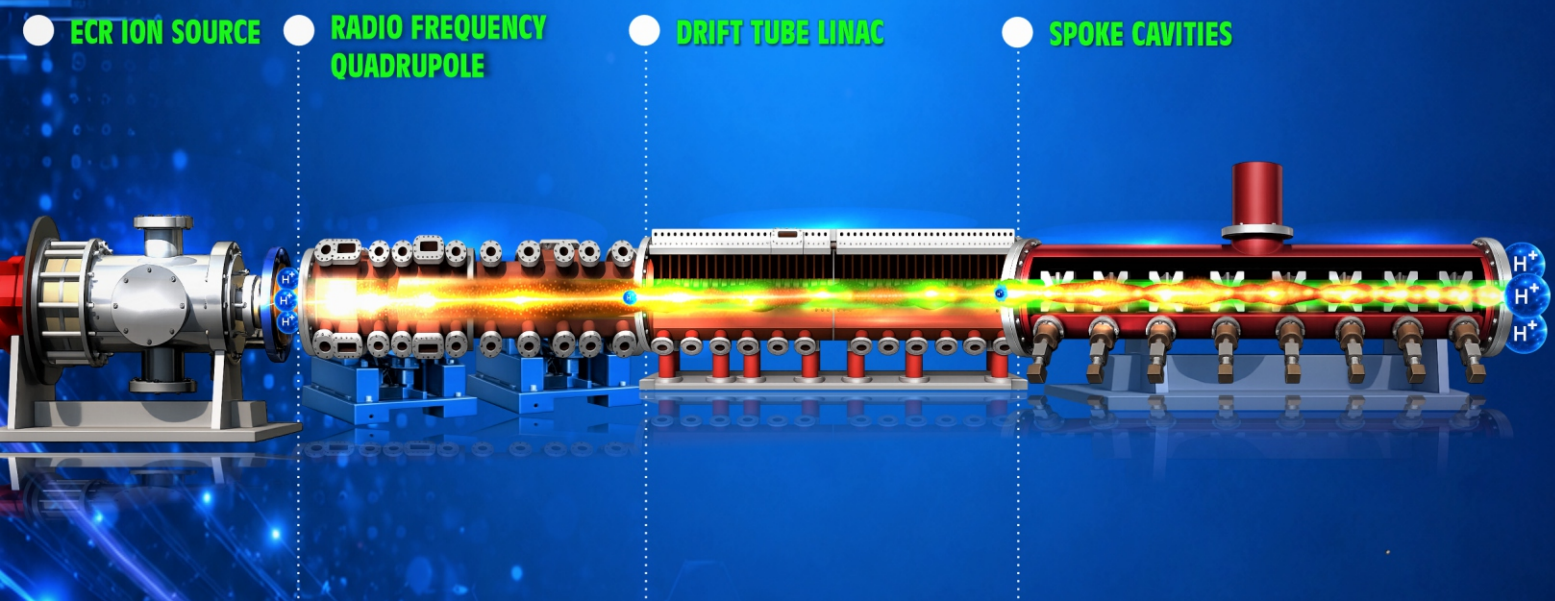
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● Development for MEHIPA ● Proton Accelerators ● Beam Diagnostics ● Women in STEM



PROTON ACCELERATION: ENERGY GAIN ALONG THE LINAC



उच्च तीव्रता वाले प्रोटॉन लीनॉक HIGH INTENSITY PROTON LINAC

वर्तमान स्थिति एवं भावी योजनाएं...
Current Status and Way Forward...

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मुख्य विस्तार को प्रशस्त करता प्रोटॉन त्वरक कार्यक्रम

लेहिपा से मेहिपा संक्रमण एवं प्रोटॉन लिनाॅक आत्मनिर्भरता हेतु एक प्रमुख प्रवर्तक से आगे

उच्च-तीव्रता वाले प्रोटॉन त्वरकों में, नाभिकीय ऊर्जा, पदार्थ विज्ञान एवं प्रगत स्वास्थ्य सेवा अनुप्रयोगों के संबंध में भारत के दीर्घकालिक केंद्रीय दृष्टिकोण बनने की क्षमता है।

मिली एम्पीयर-श्रेणी के प्रोटॉन किरणपुंज के साथ 20 MeV की अपनी अभिकल्पित ऊर्जा हेतु सामान्य प्रचालन निम्न ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (लेहिपा) का प्रदर्शन इस यात्रा में एक निर्धारित मील का पत्थर है। लेहिपा के विकास, कमीशनन एवं प्रचालन ने न केवल प्रोटॉन त्वरक की उच्च-वर्तमान अग्रांत प्रौद्योगिकियों के विषय में आवश्यक अंतर्दृष्टि विकसित की है, जिसमें आयन स्रोत, निम्न-ऊर्जा किरणपुंज परिवहन, रेडियो आवृत्ति (आरएफ) चतुर्ध्रुव और संवहन-नलिका लीनाॅक संरचनाएं, कुशल आरएफ ऊर्जा संचरण, प्रभावी नियंत्रण एवं सुरक्षा के साथ-साथ किरणपुंज की गुणवत्ता एवं निरंतर संचालन की मांग की आवश्यकताएं शामिल हैं, बल्कि समान रूप से महत्वपूर्ण पारिस्थितिकी तंत्र भी है, जहां भारतीय प्रयोगशालाओं ने घरेलु उद्योग तथा एमएसएमई के साथ मिलकर कार्य किया है ताकि जटिल त्वरक उप-प्रणालियों को स्वदेशी रूप से साकार किया जा सके।

अनुभव का यह आधार अब एडीएस एवं समुत्खंडन स्रोतों जैसे अनुप्रयोगों हेतु आवश्यक युक्तियुक्त उपलब्धता और कार्य-निष्पादन लक्ष्यों को बनाए रखते हुए दसियों MeV से सैकड़ों MeV तक स्केलिंग के लिए एक ठोस प्लेटफॉर्म बनाता है। इसके अलावा, संयुक्त राज्य ऊर्जा विभाग के प्रोटॉन सुधार योजना-II कार्यक्रम के एक भाग के रूप में फर्मी राष्ट्रीय त्वरक प्रयोगशाला (एफएनएल) में उच्च ऊर्जा प्रोटॉन त्वरक स्थापित करने के लिए भारतीय संस्थानों एवं फर्मीलैब सहयोग (आईआईएफसी) में भागीदारी ने अत्याधुनिक अति-चालक(एससी) आरएफ प्रौद्योगिकियों जैसे क्रायो-प्लांट, क्रायो-मॉड्यूल, ठोस अवस्था आरएफ ऊर्जा प्रवर्धक, एससी गुहिकाओं, आरएफ ऊर्जा संचरण घटकों एवं प्रणालियों आदि के संविरचन, प्रसंस्करण एवं परीक्षण हेतु आरएफ कपलर से संबंधित संरचनात्मक ढांचे को विकसित करने में अनुभव प्राप्त करने हेतु सक्षम बनाया है।

लेहिपा के विकास और आईआईएफसी में भागीदारी से प्राप्त अनुभव के आधार पर, अब चरणबद्ध तरीके से दसियों MeV से सैकड़ों MeV तक वृद्धि हेतु एक ठोस प्लेटफॉर्म बनाता है-मध्यम ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (मेहिपा) के प्रथम चरण की स्थापना के रूप में पहला कदम 40 MeV, 10 mA प्रोटॉन रैखिक त्वरक के रूप में परिकल्पित है। मेहिपा के चरण-1 का साकार होना रिएक्टरों हेतु त्वरक संचालित प्रणालियों (एडीएस) के लिए उच्च ऊर्जा उच्च तीव्रता वाले प्रोटॉन त्वरक के विकास, नाभिकीय पदार्थ के रूपांतरण और अपशिष्ट भस्मीकरण की दिशा में अगले महत्वपूर्ण उपलब्धियों को प्राप्त करने में सहायक होगा। पूर्ण होने पर, मेहिपा में एक प्रमुख राष्ट्रीय संपदा बनने की क्षमता है, जो समुत्खंडन न्यूट्रॉन विज्ञान, एडीएस-आधारित नाभिकीय अपशिष्ट भस्मीकरण, नाभिकीय पदार्थ के तत्वांतरण एवं उच्च-परिशुद्धता वाले प्रोटॉन किरणपुंज अनुप्रयोगों में अनुसंधान को समर्थ बनाता है।

उच्च-तीव्रता वाले प्रोटॉन त्वरकों हेतु प्रणालियों के विकास के लिए समर्पित इस समाचार पत्र का उद्देश्य लेहिपा से मेहिपा चरण-1 तक की निरंतरता का रेखांकन और भारतीय त्वरक समुदाय के लिए आगे की प्रगति, चुनौतियों एवं अवसरों को साझा करना है।

श्री. यू. डी. मालशे

प्रतिष्ठित वैज्ञानिक एवं निदेशक
बहु-विषयक अनुसंधान वर्ग
भाभा परमाणु अनुसंधान केंद्र

Proton Accelerator Programme enroute Major Expansion

LEHIPA to MEHIPA transition and beyond a key enabler for Aatmanirbharta in Proton Linac

A High-intensity proton accelerators has a potential to be central to India's long-term vision with respect to nuclear energy, materials science and advanced healthcare applications.

The demonstration of the Normal conducting Low Energy High Intensity Proton Accelerator (LEHIPA) to its design energy of 20 MeV with milli ampere-class proton beams marks a defining milestone on this journey. The development, commissioning and operation of LEHIPA have evolved not only necessary insight about high-current front-end technologies of proton accelerator, including Ion sources, low-energy beam transport, Radio Frequency (RF) Quadupole and drift-tube linac structures, efficient RF power transmission, effective control and protection as along with the demanding requirements of beam quality and continuous operation, but also equally important ecosystem, where Indian laboratories worked closely with domestic industry and MSMEs to realise complex accelerator subsystems indigenously.

This experience base now forms a solid platform for scaling from tens of MeV to hundreds of MeV while maintaining stringent availability and performance targets needed for applications such as ADS and spallation sources. In addition, participation in the Indian Institutions and Fermilab Collaboration (IIFC) for establishing high energy proton accelerator at Fermi National Accelerator Laboratory (FNAL) as a part of Proton Improvement Plan-II programme of United States Department of Energy has enabled to gain experience in developing the state-of-the-art superconducting (SC) RF technologies viz. cryo-plant, cryo-modules, solid state RF power amplifiers, RF couplers associated infrastructure for fabrication, processing and testing of SC cavities, RF power transmission components and systems etc.

The experience base, generated from LEHIPA development and participation in IIFC, now forms a solid platform for scaling from tens of MeV to hundreds of MeV in a phased manner - with the first step in the form of establishing first phase of Medium Energy High Intensity Proton Accelerator (MEHIPA) envisaged as a 40 MeV, 10 mA proton linear accelerator. The realization of Phase-1 of MEHIPA would represents the next significant milestone towards development of High Energy High Intensity Proton accelerator for Accelerator Driven Systems (ADS) for reactors, transmutation of nuclear materials and waste incineration. When completed, MEHIPA has potential of becoming a key national asset, enabling research in spallation neutron science, ADS-based nuclear waste incineration, nuclear material transmutation and high-precision proton beam applications.

This newsletter, dedicated to development of systems for high-intensity proton accelerators, aims to capture that continuum from LEHIPA to MEHIPA Phase-1 and to share the progress, challenges and opportunities that lie ahead for the Indian accelerator community.

Mr. U. D. Malshe

Distinguished Scientist and Director
Multidisciplinary Research Group
Bhabha Atomic Research Centre

उच्च तीव्रता वाले प्रोटॉन त्वरकों का अग्रणी क्षेत्र

स्वदेशी विकास, प्रचालनगत लक्ष्य एवं भावी पथ

उच्च-तीव्रता वाले प्रोटॉन त्वरकों पर आधारित इस न्यूज़लेटर का यह अंक कार्यनीतिक रूप से महत्वपूर्ण इस क्षेत्र में, भारत की तेज़ी से विकसित होने वाली क्षमताओं की समयबद्ध समीक्षा करता है।

पिछले कुछ वर्षों में, भापअ केंद्र में निम्न ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (लेहिपा) को एक विकासात्मक परियोजना से संकरित करने का निरंतर प्रयास जारी रहा है, जिसने प्रोटॉन त्वरक से संबंधित कई प्रौद्योगिकियों को मेगावाट-श्रेणी की मशीनों में मान्यता दी है।

यह संक्रमण फेज़ न केवल विभिन्न उप-प्रणाली मापदंडों को इष्टतम कर, न्यूनतम नुकसान के साथ उच्च-धारा किरणपुंज को ट्यून करके और चौबीसों घंटे प्रचालन के दौरान वास्तविक समय मशीन डेटा को संचित करके किरणपुंज की उच्च उपलब्धता एवं स्थिरता प्राप्त करने पर केंद्रित है, बल्कि अतिचालक रेडियो आवृत्ति (एसआरएफ) गुहिकाओं, चुंबक, उच्च शक्ति वाले आरएफ कपलर, क्रायोमॉड्यूल्स, निम्न स्तर की आरएफ प्रणाली (एलएलआरएफ) और ठोस अवस्था प्रवर्धक आदि जैसी स्वदेशी तकनीकों को विकसित करने पर भी केंद्रित है जो कि मेगावाट-श्रेणी की मशीनों के विश्वसनीय निरंतर प्रचालन हेतु आवश्यक हैं।

इसका मूल्यांकन एवं स्वदेशी विकास भारतीय फर्मिलैब सहयोग संस्थान (आईआईएफसी) के माध्यम से पीआईपी-II कार्यक्रम में भारतीय भागीदारी द्वारा उत्प्रेरित है।

आईआईएफसी-संचालित एसआरएफ क्षमता निर्माण के साथ लेहिपा के अभिकल्पन एवं प्रचालन के दौरान प्राप्त अनुभव का लाभ मध्यम ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (मेहिपा) के विकास के अगले चरण में उठाया जा रहा है, जो उच्च ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक के अंतिम लक्ष्य की ओर बढ़ता एक कदम है।

न्यूज़लेटर के इस अंक में उन लेखों को समेकित किया गया है जो-अवधारणा से लेकर कमीशनन तक, सामान्य-प्रचालन अग्रांत से लेकर अति-चालन मध्यम-ऊर्जा सेक्शन तक, और एकल परीक्षण से लेकर एकीकृत राष्ट्रीय सुविधाओं तक की निरंतरता को दर्शाते हैं। मैं आशा करता हूँ कि इसमें दिया गया योगदान उन शोधकर्ताओं, अभियंताओं और छात्रों को जानकारी प्रदान करेगा, प्रेरित करेगा और संलग्न करेगा जो भारतीय उच्च तीव्रता वाले प्रोटॉन त्वरकों की अगली पीढ़ी के अभिकल्पन, विकास एवं उपयोग को आकार देंगे।

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डॉ. सिस्ता वी.एल.एस. राव
आईएडीडी

सह-संपादक
का संदेश

Advancing Frontiers of High Intensity Proton Accelerators

Indigenous Developments, Operational Milestones and Road Ahead

This newsletter issue on high-intensity proton accelerators provides a timely overview of India's rapidly evolving capabilities in this strategically important domain. Over the past years, a sustained effort is going on at BARC for transitioning the Low Energy High Intensity Proton Accelerator (LEHIPA) from a developmental project that validated many of the proton accelerator related technologies to megawatt-class machines.

ASSOCIATE
EDITORS'
message

This transition phase focuses not only on achieving high availability and stability of beam by optimizing the various sub-system parameters, tuning the high-current beams with minimal losses and accumulating real time machine data during round-the-clock operation but also evolving indigenous technologies like Superconducting Radio Frequency (SRF) cavities, magnets, high power RF couplers, cryomodules, low level RF system (LLRF) and solid-state amplifiers etc. that are essential for reliable continuous operation of megawatt-class machines.

The evolution and indigenous development of is catalyzed by Indian participation in the PIP-II programme through the Indian Institutes Fermilab Collaboration (IIFC).

The experience gained during design and operation of LEHIPA along with IIFC-driven SRF competence building is being leveraged for next phase of developing Medium Energy High Intensity Proton Accelerator (MEHIPA), a stepping stone of end goal of High Energy High Intensity Proton Accelerator.

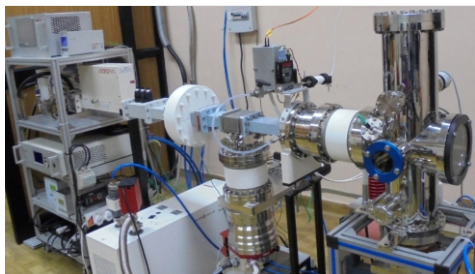
This newsletter issue brings together articles that reflect this continuum - from concept to commissioning, from normal-conducting front ends to superconducting medium-energy sections, and from standalone test stands to integrated national facilities. I hope the contributions herein will inform, inspire and connect researchers, engineers and students who will shape the design, development and utilization of next generation of Indian High Intensity Proton Accelerators.

Dr. Rajesh Kumar
Head

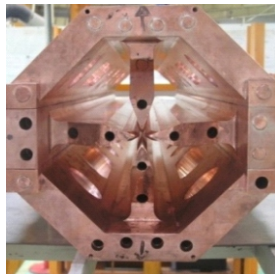
Ion Accelerator Development Division (IADD)

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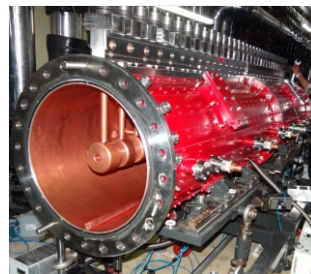
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ECR ion source with tetrode extraction system



Radio frequency quadrupole



LEHIPA Drift Tube Linac

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Mr. U. D. Malshe, Director, Multidisciplinary Research Group

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Advancing Frontiers of High Intensity Proton Accelerators: Indigenous Developments, Operational Milestones and Road Ahead

*Dr. Rajesh Kumar, Head, Ion Accelerator Development Division (IADD) &
Dr. Sista V. L. S. Rao, IADD*



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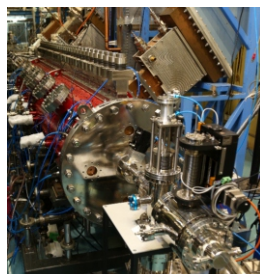
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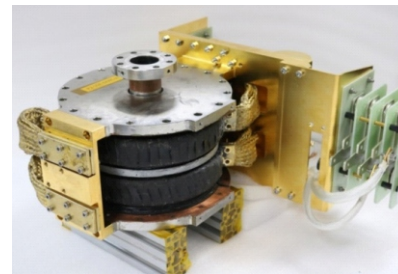
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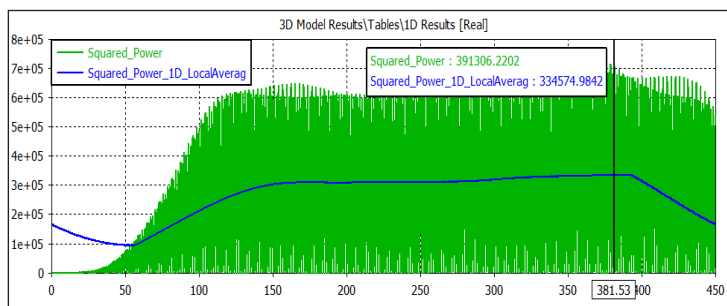
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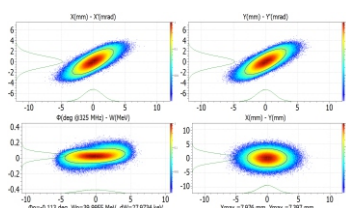
भारत में उच्च तीव्रता वाले प्रोटॉन त्वरकों का अभिकल्पन

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सारांश



मेहिपा-1 निर्गम पर कणपुंज वितरण

त्वरक संचालित प्रणालियों (एडीएस) को संधारणीय नाभिकीय ऊर्जा, अपशिष्ट रूपांतरण और थोरियम के उपयोग जैसे अनुप्रयोगों के लिए अत्यंत कम कणपुंज हानि के साथ अत्यधिक विश्वसनीय उच्च तीव्र निरंतर तरंग (सीडब्ल्यू) प्रोटॉन लीनॉक की आवश्यकता होती है। भारत ने, इस प्रौद्योगिकी को साकार करने के लिए 20 MeV, 200 MeV और अंततः 1 GeV के त्वरक परिक्षेत्तों के साथ एक चरणबद्ध विकास का दृष्टिकोण अपनाया है। भापअ केंद्र, मुंबई में पहला चरण, निम्न ऊर्जा उच्च तीव्रता (लो एनर्जी हाई इंटेन्सिटी) प्रोटॉन त्वरक (लेहिपा), 20 MeV तक प्रोटॉन को गति देता है और प्रमुख निम्न-ऊर्जा कणपुंज गतिकी के मामलों को निष्पादित करता है। अगले चरण में, 200 MeV तक मध्यम ऊर्जा उच्च तीव्रता वाले प्रोटॉन त्वरक (मेहिपा) का विकास शामिल है, जिसमें महत्वपूर्ण प्रौद्योगिकियों को अधिमन्य करने के लिए भापअ केंद्र, वैज़ाग में मेहिपा-1 (40 MeV) विकसित किया जा रहा है। ये प्रयास भारत में एडीएस अनुप्रयोगों के लिए उच्च तीव्रता वाले त्वरकों को साकार करने की दिशा में महत्वपूर्ण प्रगति को दर्शाता है।

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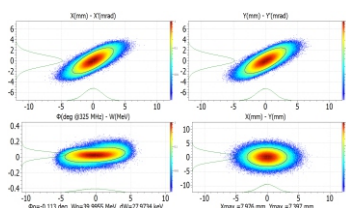
Design of High Intensity Proton Accelerators in India

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ABSTRACT



Beam distribution at MEHIPA-1 output.

Accelerator Driven Systems (ADS) require highly reliable high intensity Continuous Wave (CW) proton linacs with extremely low beam loss for applications such as sustainable nuclear energy, waste transmutation, and thorium utilization. To realize this technology, India has adopted a staged development approach with accelerator sections of 20 MeV, 200 MeV, and ultimately 1 GeV. The first stage, Low Energy High Intensity Proton Accelerator (LEHIPA) at BARC, Mumbai, accelerates protons up to 20 MeV and addresses key low-energy beam dynamics issues. The next stage involves the development of Medium Energy High Intensity Proton Accelerator (MEHIPA) up to 200 MeV, with MEHIPA-1 (40 MeV) being developed at BARC, Vizag to validate critical technologies. These efforts mark significant progress toward realizing high intensity accelerators for ADS applications in India.

KEYWORDS: LEHIPA, MEHIPA, Proton accelerator

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Introduction

ADS is being developed for sustainable nuclear energy generation, transmutation of long lived radioactive waste, and efficient utilization of India's abundant thorium resources. A key component of ADS is a highly reliable high current CW proton linac operating with extremely low beam losses. The design of such accelerators is challenging due to strong space charge effects at low energies, beam halo formation, RF power dissipation and stringent reliability requirements. To address these challenges, India has adopted a phased development approach [1]. The first stage, LEHIPA [2] at BARC, accelerates protons up to 20 MeV and serves as a platform for studying low energy beam dynamics and space charge effects. The next phase involves the development of MEHIPA, which will accelerate the beam up to 200 MeV [3]. The superconducting section of this linac employs three families of single spoke resonator cavities, SSR-A, SSR-B, and SSR-C, each optimized for different velocity regimes of the proton beam to enable efficient acceleration with controlled beam losses. As an intermediate step toward this goal, the 40 MeV MEHIPA-1 [4] accelerator under development at BARC, Vizag, will serve as both a technology demonstrator and a user facility for applications such as the Stable and Unstable Isotopic Beams for Heavy Ion Research (SUBHIR) facility and other accelerator-based research. The final stage of the ADS accelerator aims to reach a beam energy of about 1 GeV. In this energy range, the accelerator design transitions to superconducting elliptical cavities [5] that are well suited for high-energy CW operation. The 1 GeV linac incorporates two families of five-cell elliptical cavities optimized for different beta ranges of the beam. A schematic layout of the complete 1 GeV accelerator is shown in Fig.1.

Through this phased development from LEHIPA to MEHIPA and ultimately to the 1 GeV linac, it is planned to build the technological capability required for high intensity, high reliability proton accelerators, forming an important step toward the realization of ADS.

MEHIPA-1

MEHIPA-1 is a proposed 40 MeV proton linac that will serve as an injector for the 1 GeV ADS accelerator and as a multipurpose facility for research and applications. The MEHIPA-1 linac consists of an Electron Cyclotron Resonance (ECR) ion source producing a 30 keV proton beam, followed by a Low Energy Beam Transport (LEBT) system for beam focusing and matching into a Radio-Frequency Quadrupole (RFQ) that accelerates the beam to 3 MeV. The beam is then transported through a Medium Energy Beam Transport (MEBT) section and

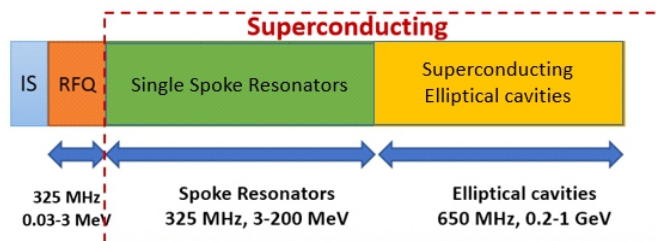


Fig.1: Schematic Layout of 1 GeV linac for ADS.

Table 1: Parameters of LEBT.

Parameters	Values
Solenoid 1 integrated field (Tm)	0.31
Solenoid 2 integrated field (Tm)	0.19
Solenoid 3 integrated field (Tm)	0.32
Solenoid effective length (cm)	15.2
Solenoid aperture radius (cm)	8.3
Beam tube radius (cm)	6
Total Length (m)	2.42

further accelerated in a two tank Drift Tube Linac (DTL) up to 10 MeV. A High Energy Beam Transport (HEBT) section matches the beam into the superconducting linac, where a Single Spoke Resonator-B (SSR-B) cavity section accelerates the beam to approximately 40 MeV. The overall layout of the linac is shown in Fig.2 and the design is discussed in the following subsections.

Design of MEHIPA-1

An ECR ion source will deliver a 10 mA, 30 keV proton beam with an rms emittance of 0.3π mm mrad. The beam will be matched to the RFQ using a three solenoid LEBT for focussing the beam. The LEBT also includes a 30 degrees bending magnet to filter out the unwanted species like H_2^+ and H_3^+ from the ion source. The parameters of the LEBT are listed in Table 1.

The 325 MHz RFQ accelerates this beam from 30 keV to 3 MeV [6] while simultaneously bunching and focusing it. Designed using the TOUTATIS code with a conventional four section structure (Radial matching section, Shaper, Gentle Buncher and Accelerator), the 4 m long RFQ achieves ~99.9% transmission with negligible transverse emittance growth. A dedicated 60 cell section with synchronous phase fixed at -90° was introduced before the Shaper to reduce longitudinal emittance from ~ 0.45 to $\sim 0.18 \pi$ -mm-mrad. Beam loss is primarily observed near the end of the Gentle Buncher section, where the beam energy remains below 1 MeV. The parameters of the RFQ are listed in Table 2. To address mechanical and fabrication considerations, the RFQ is divided into four segments of ~ 1 m each, assembled into two sections coupled via a coupling cell.

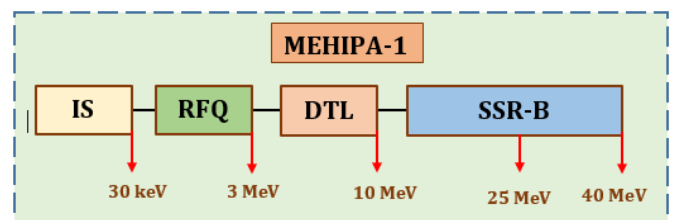


Fig.2: Layout of MEHIPA-1.

Table 2: Parameters of the RFQ.

Parameters	Values
Species	H ⁺
Input/output energy (MeV)	0.03/3.00
Modulation	1-2.05
Average bore radius r ₀ (cm)	0.3014
Transverse radius of curvature (cm)	0.2682
Length (m)	4
Transmission/Accelerated (%)	99.98/99.94
Output RMS Emittance (π-mm-mrad)	0.299/0.302
Longitudinal Emittance (deg.MeV/mm-mrad)	0.068/0.18
Kilpatrick	1.7
Dissipated RF power (considering 70% of simulated Q) (kW)	292
Beam Power (kW)	30

The 3 MeV RFQ output beam is matched to the DTL through an MEBT comprising five quadrupoles and two buncher cavities which focus the beam in the transverse and longitudinal directions respectively. The maximum gradient requirement for the quadrupoles is 25 T/m. Two gap buncher cavities with gap voltage of up to 120 kV will be required. The MEBT buncher power requirement is 14 kW. Total length of MEBT is 1.85 m.

For the DTL, several transverse focusing lattices were investigated. The final design adopts a Focusing-Focussing-Defocusing-Defocussing (FFDD) based focusing scheme with the transverse phase advance maintained nearly constant along the structure. Quadrupoles are grouped with gradually decreasing gradients (48 T/m to 44.5 T/m) to ensure smooth

Table 3: Parameters of the Drift Tube Linac.

Parameters	Values	Values
Input/output Energy (MeV)	3-6.332	6.332-10
No. of cells	28	22
Effective length of quadrupoles (cm)	3.7	3.7
Quadrupole Gradient (T/m)	48-46.5	46.5-44.5
Aperture (cm)	2.4	2.4
Synchronous Phase (deg)	-30	-30
Accelerating Field Gradient (MV/m)	2.1	2.1
Dissipated RF power (considering 70% of simulated Q) (kW)	236	233
Beam Power (kW)	33.32	36.68
Quality Factor	54157	57059
Tank Length (m)	2.51	2.65

beam transport. To match the strong focusing of the DTL to the weaker solenoid focusing in the downstream Single Spoke Resonator cavities, the phase advance per unit length is tapered from ~240°/m at the DTL entrance to ~150°/m at the exit, ensuring a smooth transition. Tune footprint analysis using the Hofmann chart confirms that the operating point avoids major space charge resonances, thereby minimizing emittance exchange and beam halo formation. TRACEWIN simulations using 5 million macroparticles show stable beam transport with negligible halo formation and emittance growth of ~0.7% transversely and ~3% longitudinally. The DTL will be fabricated in two tanks of nearly equal lengths. The parameters of the two DTL tanks are summarized in Table 3.

The 10 MeV beam from the DTL is matched to the superconducting section through an HEBT consisting of six quadrupoles and three buncher cavities. The maximum

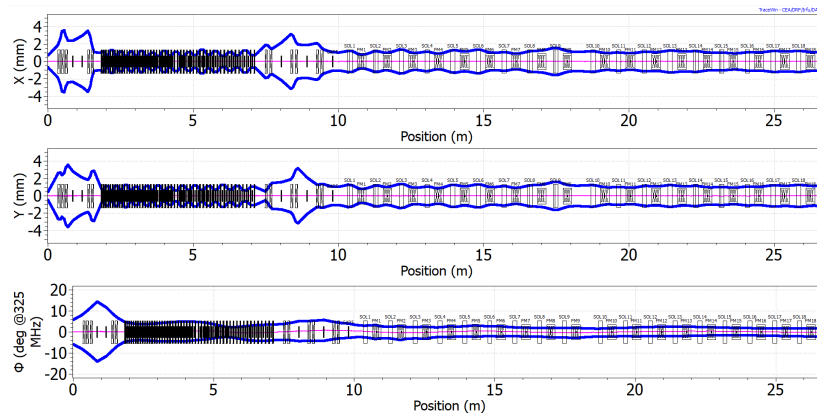


Fig.3: Beam envelope along the 40 MeV MEHIPA-1 linac.

Table 4: Parameters of SSR-B linac.

Parameters	Values
Input/output Energy (MeV)	10-40
No. of Cryomodules	2
No. of Solenoids	18
No. of SSR Cavities	18
Cryomodule length (m)	7.965
Period Length (m)	0.885
Solenoid Field (T)	3.2-4.1
Accelerating Gradient (MV/m)	5-8.8
RMS Beam Size (mm)	1.67
Transverse Emittance Growth (%)	0.7
Longitudinal Emittance Growth (%)	4.9

quadrupole gradient required in the HEBT is 25 T/m. Three gap buncher cavities will be used to obtain the effective voltage of up to 350 kV, required for beam matching. Buncher power requirement is 7 kW. The total length of HEBT is 3.12 m.

Beyond 10 MeV, acceleration is provided by an SSR-B superconducting linac, a suitable choice for CW operation due to its low RF power dissipation. The superconducting lattice employs a periodic solenoid-SSR structure arranged in two equal length cryomodules separated by a 400 mm drift. The lattice was optimized [7] to ensure stable beam transport while maintaining transverse and longitudinal phase advances below 90° , avoiding major resonance crossings, and keeping the aperture-to-beam size ratio above 7 to minimize beam loss. A total of 18 SSR-B cavities accelerate the beam from 10 MeV to 40 MeV, with gradients gradually increased from ~ 5 MV/m to ~ 8.8 MV/m and synchronous phase varied from -30° to -25° . The RF power requirement varies from 10 kW in the first SSR-B cavity to 19 kW in the last cavity. Hofmann chart analysis confirmed operation away from resonance regions, preventing emittance exchange. Simulations showed that the beam

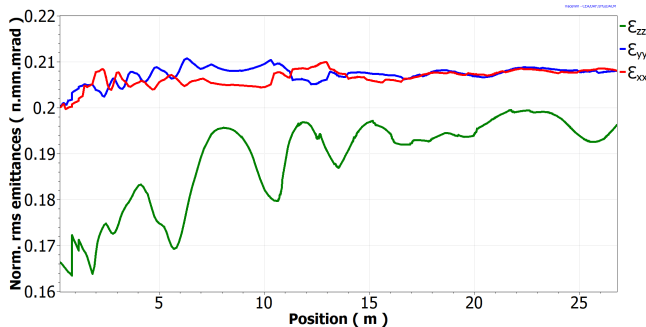


Fig.4: Beam emittance evolution along the 40 MeV MEHIPA-1 linac.

remains well confined within the aperture with negligible halo formation, while emittance growth is limited to $<2\%$ transversely and $\sim 5\%$ longitudinally, demonstrating stable and efficient acceleration up to 40 MeV. The parameters of the superconducting linac are summarized in Table 4.

End-to-end beam dynamics simulation was done through the entire linac starting with ion source output beam distribution. The beam envelope and beam emittance evolution along the linac are shown in Fig.3 and 4. The beam distribution at the end of the linac is shown in Fig.5.

MEHIPA-1 is envisioned not only as a technology demonstrator for the ADS program but also as a multipurpose user facility delivering 40 MeV proton beams for various applications such as radioactive ion beam (RIB) production, neutron production, material irradiation studies, and nuclear physics experiments. To support these activities, the facility includes two general-purpose experimental beamlines and a dedicated beamline for the SUBHIR RIB facility. Beam transport and delivery will be achieved using appropriate focusing and steering elements, with quadrupole magnets employed to maintain the required beam quality and spot size at experimental targets.

International Collaboration

In parallel with the indigenous ADS accelerator development programme, India is also participating in the Proton Improvement Plan-II (PIP-II) programme at the Fermi National Accelerator Laboratory through the Indian Institutions Fermilab Collaboration (IIFC). This collaboration is playing a significant role in the development, testing, and validation of key High Intensity Superconducting Proton Accelerator (HISPA) technologies relevant to future high power accelerator facilities. As part of the Indian contribution to PIP-II, the Department of Atomic Energy (DAE), India is involved in the design, fabrication, qualification, and delivery of several critical accelerator subsystems, including single spoke resonator and elliptical superconducting RF cavities, tuners, power couplers, cryomodules, solid-state power amplifiers (SSPA), accelerator magnets and cryogenic plant. Participation in this large scale international programme has enabled the development of substantial indigenous expertise and infrastructure in superconducting radio-frequency (SRF) technology, cryogenics, RF power systems, precision fabrication, surface

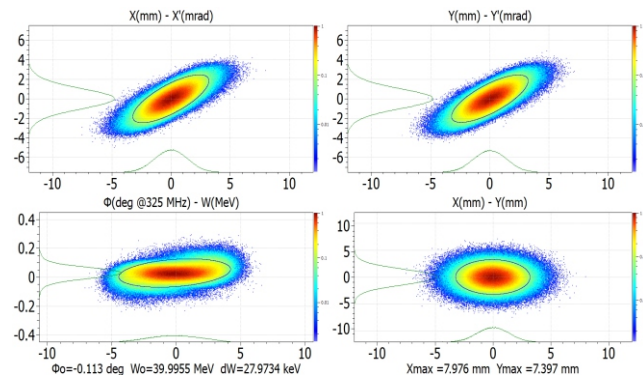


Fig.5: Beam distribution at MEHIPA-1 output.

processing and accelerator integration. The experience gained through PIP-II is expected to play a crucial role in advancing India's capabilities toward the realization of future high-current superconducting proton linacs for Accelerator Driven Systems and other accelerator applications.

Since India is contributing to the development of PIP-II SSR-1 superconducting cavities through IIFC, feasibility and beam dynamics studies for MEHIPA-1 have also been carried out using PIP-II SSR-1 cavities as an alternative to the earlier BARC designed SSR-B cavities. The existing MEHIPA-1 lattice geometry, cryomodule layout, and focusing configuration were retained, while the cavity accelerating gradients and synchronous phases were re-optimized for the SSR-1 configuration. Compared to SSR-B cavities, SSR-1 cavities exhibit higher E_{pl}/E_{acc} , resulting in operation closer to the peak electric field design limit of 40 MV/m, whereas SSR-B cavities provide larger operational margin and improved fault tolerance. However, SSR-1 cavities possess lower B_{pl}/E_{acc} , ensuring peak magnetic fields remain well below superconducting limits. RF studies further show that SSR-B cavities do not exhibit multipacting barriers beyond 6.5 MV/m, whereas SSR-1 cavities show multipacting activity up to approximately 10 MV/m. The cavity RF power requirement for SSR-1 cavities varies between 13 kW to 18 kW. Detailed beam dynamics studies indicate that both cavity configurations provide comparable beam quality, beam size and emittance growth, demonstrating the feasibility of employing SSR-1 cavities in the MEHIPA-1 superconducting linac.

Conclusion

The proposed 40 MeV MEHIPA-1 facility represents an important milestone in India's phased development of high-intensity proton accelerators for ADS. The accelerator design incorporates a 325 MHz RFQ, a two tank DTL, and an SSR-based superconducting linac to accelerate a 10 mA proton beam to 40 MeV while maintaining low emittance growth and controlled beam losses. Detailed beam dynamics studies and

end-to-end simulations demonstrate stable beam transport, smooth lattice matching, and operation away from major space charge resonances throughout the linac. Feasibility studies using both indigenously designed SSR-B cavities and PIP-II SSR-1 cavities further establish the flexibility and robustness of the superconducting linac design. In addition to serving as a technology demonstrator for the ADS programme, MEHIPA-1 is envisioned as a multipurpose user facility for applications such as radioactive ion beam production, neutron generation, material irradiation, and nuclear physics experiments. Together with India's participation in the PIP-II programme at Fermilab, these efforts contribute significantly to the development of reliable high power superconducting proton accelerator technologies in India.

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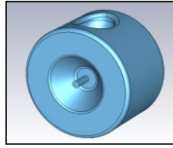
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मेहिपा-I लीनॉक हेतु त्वरक संरचनाओं का विद्युत चुम्बकीय अभिकल्पन

श्वेता रॉय^{1*}, मानस आर. मिश्रा¹, श्री राम जी.¹, अभिषेक पाढ़ी¹, पीजुष दास¹, आलोक कुमार घोष^{1,2}, रजनी पांडे¹, एस.वी.एल एस. राव^{1,2} और राजेश कुमार^{1,2}

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एसएसआर-बी गुहिका का 3डी मॉडल

सारांश

मेहिपा-1 चिकित्सा एवं अनुसंधान अनुप्रयोगों के लिए रेडियोसक्रिय आयन कणपुंज उत्पादन हेतु एक प्रस्तावित 40 MeV, 10 mA प्रोटॉन लीनॉक है, जिसमें 3 MeV RFQ, एक 3-10 MeV DTL और 10-40 MeV से अति-चालक एसएसआर-बी गुहिकाएं शामिल हैं। इस लेख में, इन त्वरक संरचनाओं का एक विस्तृत विद्युत चुम्बकीय अभिकल्पन प्रस्तुत किया गया है।

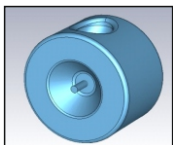
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Electromagnetic Design of Accelerating Structures for MEHIPA-1 linac

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3D model of a SSR-B cavity

ABSTRACT

MEHIPA-1 is a proposed 40 MeV, 10 mA proton linac for radioactive ion beam production for medical and research applications, comprising a 3 MeV RFQ, a 3-10 MeV DTL, and superconducting SSR-B cavities from 10-40 MeV. A detailed electromagnetic design of these accelerating structures is presented in this article.

KEYWORDS: MEHIPA, Proton linac, Radioactive ion

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Introduction

The layout of MEHIPA-1 linac [1] is shown in Fig.1. All the accelerating structures will operate at a frequency of 325 MHz. The electromagnetic design details of the individual accelerating structures are presented in the following sections.

Radio Frequency Quadrupole (RFQ)

RFQs are widely used in the front end of linear accelerators for simultaneous beam focusing, bunching, and acceleration [2]. The cavity design and optimization of the MEHIPA-1 RFQ were carried out to achieve TE_{210} like operating mode at 325 MHz with low RF losses, accepted peak surface electric field and practical fabrication feasibility.

Electromagnetic Design

First, the transverse cross-section of the RFQ was optimized using SUPERFISH (SF) [3]. The optimized geometry was then modelled in CST MWS [4] to study the effects of asymmetric structures such as tuners, vacuum ports, end cells, coupling cells, and DSRs. Initially, a comparative study between 2D and 3D simulations was performed using a single quadrant 3D model of the RFQ with a length of 25 cm without any asymmetric structures. The parameters obtained from the 2D and 3D simulations show good agreement, as summarized in Table 1. International experience indicates that the achieved RFQ cavity Q is typically about 70-80% of the simulated value. With 70% of the simulated Q, the cavity RF power dissipation is estimated to be 292 kW.

Tuners: Adjustable cylindrical tuners (Fig.2 (a)) are installed along the cavity walls to fine-tune the resonant frequency and field distribution. A total of 64 tuners of radius 2.25 cm will be used in the 4-meter-long RFQ, providing an overall tuning range

Table 1: RF Parameters from 2D and 3D simulations.

Parameters	SF	MWS	Unit
Quadrupole Mode Frequency (f_o)	322.99	322.98	MHz
Dipole Mode Frequency(f_d)	313.19	313.17	MHz
Q Value	11326	11338	
Power Dissipation (P)	204	203.5	kW
Max Electric Field E_{max}	29.43	29.48	MV/m

of 0.31 MHz/mm. To achieve a resonant frequency of 325 MHz, each tuner has to be inserted by 6.4 mm.

Beginning / End Cell and Coupling Cell: The TE_{210} -like mode cannot be sustained in an RFQ terminated by conducting end walls because the longitudinal magnetic field must vanish at the boundaries. Vane undercuts (Fig.2(b)) are therefore introduced to support the required field configuration, forming the beginning cell (BC) and end cell (EC), whose geometries were optimized using CST simulations.

Dipole and higher-order quadrupole modes close to the TE_{210} operating mode can degrade beam dynamics and longitudinal uniformity of TE_{210} mode. To suppress these effects, the RFQ is divided into shorter segments and resonantly coupled using an optimized coupling cell designed in CST MWS (Fig.2(c)).

Dipole Stabilizer Rods (DSRs): The operating field in the RFQ is stabilized against nearby dipole modes using DSRs [5], which are cylindrical rods mounted on the end flanges and

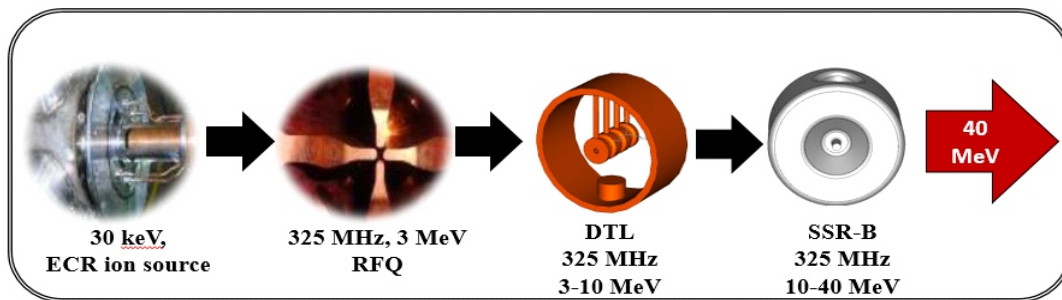


Fig.1: Layout of MEHIPA-1 linac.

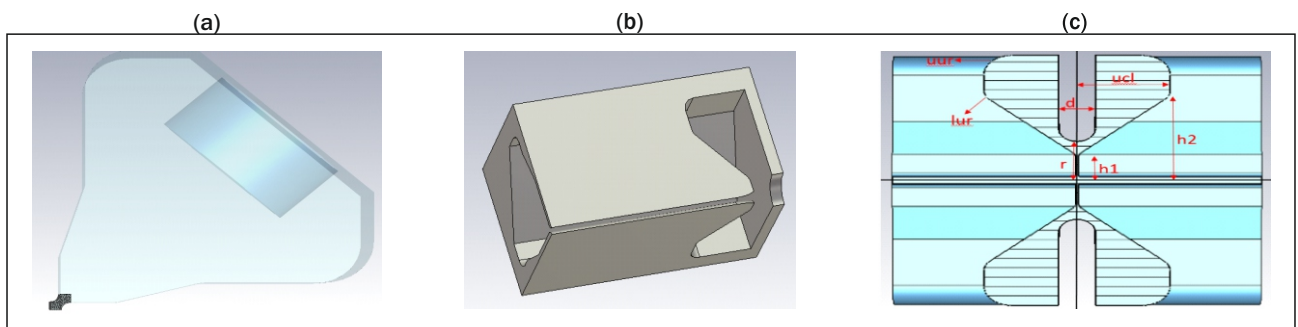


Fig.2: CST MWS model of RFQ with (a) Tuner (b) End cell (c) Coupling cell.

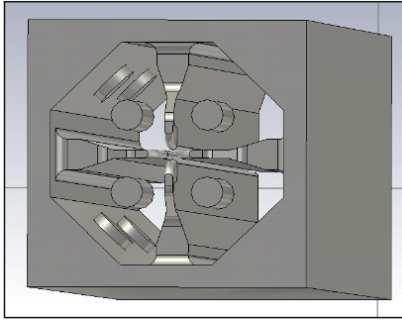


Fig.3: 3D CST model of RFQ with DSRs.

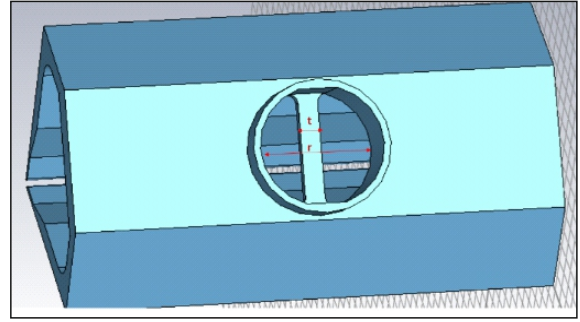


Fig.4: RFQ model with vacuum port.

either side of the coupling plate at suitable locations in all four quadrants of the RFQ. A 3D CST model of the RFQ, including vane undercuts and DSRs is shown in Fig.3. The optimized DSR diameter is 15 mm and length is 120 mm.

Vacuum ports: The RFQ is designed to operate at a vacuum level of approximately 10^{-7} Torr using circular pumping ports distributed across the cavity walls. A conducting bar is provided across each port aperture (Fig.4) to maintain surface current continuity and minimize degradation of the quality factor. An optimized port diameter of 6 cm ensures reasonable vacuum conductance while maintaining a 3.83 GHz cutoff frequency for rapid electromagnetic field decay.

Drift Tube Linac (DTL)

The DTL will be used to accelerate 10 mA proton beam from 3 MeV to 10 MeV. The DTL will be fabricated in two tanks of approximately 2.5 m length. Permanent magnet quadrupoles will be installed in the drift tubes for transverse focusing of the beam.

Electromagnetic Design

The program DTLFISH in the Poisson SUPERFISH [3] code distribution is used to design the cavity shape and compute fields, RF power losses, transit time factor and shunt impedance. The Quality Factor (Q) listed in Table 2 corresponds to 2D simulations performed using SF. Based on internationally reported results and experience from the LEHIPA project, the achieved Q is typically about 30% lower than the simulated value. Accordingly, the estimated power dissipation for the two tanks is 236 kW and 233 kW, respectively.

Table 2: Parameters of MEHIPA-1 DTL.

Parameters	Tank 1	Tank 2
Frequency (MHz)	325	325
Energy Range (MeV)	3-6.33	6.33-10
Tank Diameter (cm)	58.207	58.166
Quality factor	54157	57059
Bore Radius (cm)	1.2	1.2
Dissipated Power (kW)	165	163

DTL Cavity 3D design

In order to include features that break the 2D symmetry, a 3D design of the DTL tank was done using CST MWS. A 4-cell simulation model was used for computational ease with high number of mesh cells.

Stems and Tuners: The drift tubes are supported by stems attached to the tank surface, which introduce a shift in the cavity resonant frequency. In the CST MWS model (Fig.5) of the four-cell DTL, inclusion of 2.5 cm diameter stems shifted the TM_{010} mode frequency by 0.84 MHz for tank 1 and 0.71 MHz for tank 2, which was compensated by increasing the tank diameter.

Six tuners of 12 cm diameter will be installed uniformly along the length of each tank to provide frequency tuning. The total tuning range is ± 1.1 MHz for tank 1 and ± 1 MHz for tank 2, with maximum tuner depths of 13 cm and 12 cm, respectively. CST model of tuner is shown in Fig.6.

Postcoupler: Postcouplers are employed for field stabilization of the DTL. A total of 9 and 11 postcouplers will be used in tanks 1 and 2, respectively, with confluence achieved at postcoupler lengths of 18 cm and 17.8 cm. CST model of DTL tank 1 is shown in Fig.7.

Single Spoke Resonator (SSR)

For CW structures a lot of RF power is dissipated on the structures and removing this dissipated heat is a major challenge, besides being wasteful. Use of superconducting technology will make the linac compact and cost effective [6]. For the MEHIPA-1 project, after evaluating all options, we have decided to go ahead with superconducting single spoke resonators in the medium energy region from 10-40 MeV.

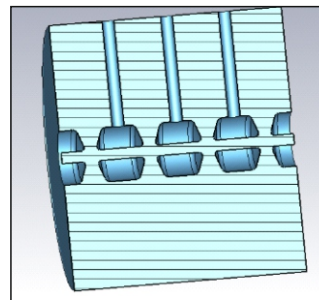


Fig.5: Four cell model of DTL.

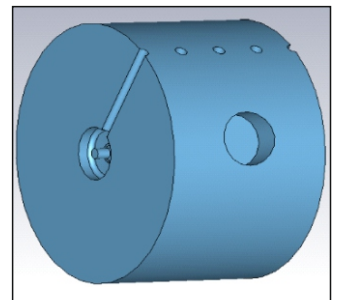


Fig.6: DTL model with tuner.

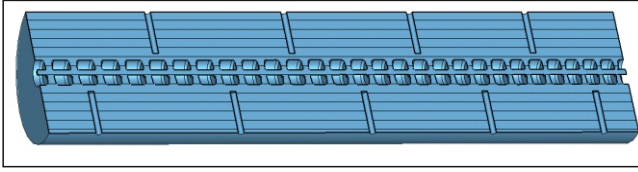


Fig.7: DTL model showing postcoupler location in tank 1.

Table 3: RF Parameters of SSR-B.

Parameters	Values
Frequency (MHz)	325
Beam Tube Radius (cm)	1.5
Cavity Length (cm)	30
Cavity Diameter (cm)	49.62
Average accelerating gradient, E_{acc} (MV/m)	10
Peak surface electric field, E_{peak} (MV/m)	37.6
Peak surface magnetic field, B_{peak} (mT)	66.5
(R/Q) (Ω)	227.2
G (Ω)	98.9

Cavity Design

The geometry optimization for the SSR-B cavity ($\beta_g = 0.21$) was performed using CST MWS. Fig.8 shows the vacuum model of a SSR-B cavity. One of the primary objectives of the RF design is to minimize the peak surface electric and magnetic fields through optimization of the cavity geometry in order to avoid field emission and prevent loss of superconductivity in the niobium spoke cavities. Secondly, the optimization aims at maximizing the R/Q and G ($=R_g Q$) of the cavity. The optimized parameters of the SSR-B cavity are listed in Table 3. Fig.9 shows the Transit Time Factor as a function of particle velocity, which is maximum for $\beta_{opt} = 0.2557$.

Higher order mode

The calculated R/Q values for the dominant monopole, dipole, and quadrupole HOMs of the SSR-B cavity are negligibly

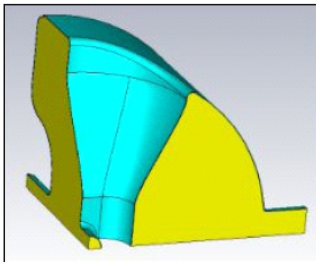


Fig.10: One-eighth cavity model.

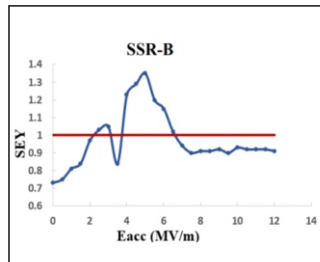


Fig.11: SEY vs accelerating gradient for SSR-B.

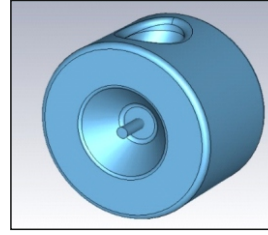


Fig.8: 3D model of a SSR-B cavity.

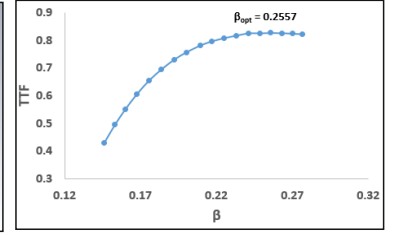


Fig.9: Transit Time Factor as a function of β .

small, indicating no significant risk of beam instability or additional cryogenic load.

Multipacting

Resonant amplification of secondary electron emission can cause RF power loss and localized heating, limiting accelerating fields and potentially causing quenching in superconducting cavities. Multipacting studies of the SSR-B cavity were therefore carried out using a one-eighth model (Fig.10) for computational efficiency. The variation of SEY with accelerating gradient is shown in Fig.11, revealing a pronounced multipacting barrier in the 4–6.5 MV/m range and no multipacting activity beyond 6.5 MV/m.

Conclusion

The electromagnetic design of the RFQ, DTL, and SSR structures for the MEHIPA-1 proton linac has been carried out using integrated 2D and 3D simulations. The optimized structures satisfy the required RF and operational constraints while maintaining fabrication feasibility. Studies of field stabilization, tuning, HOMs, and multipacting demonstrate the suitability of the proposed designs for reliable accelerator operation.

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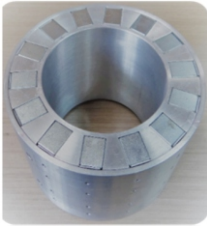
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ईसीआर आयन स्रोत

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कणपुंज उत्सर्जकता को कम करने के लिए एक नया
14-ध्रुवीय बहु-शिखर

सारांश

इलेक्ट्रॉन साइक्लोट्रॉन अनुनाद आयन स्रोत (ईसीआरआईएसएस) आज के उच्च-तीव्रता वाले प्रोटॉन त्वरकों के पीछे की प्रेरक शक्ति हैं। मौलिक प्लाज्मा भौतिकी पर प्रचालन करते हुए, ये अत्यधिक विश्वसनीय प्रणालियाँ 2.45 GHz माइक्रोवेव ऊर्जा को एक सावधानीपूर्वक गढ़े गए चुंबकीय क्षेत्र में निमज्जित हाइड्रोजन से भरे कक्ष में इंजेक्ट करती हैं। जब माइक्रोवेव आवृत्ति इलेक्ट्रॉन साइक्लोट्रॉन आवृत्ति से मेल खाती है, तो इलेक्ट्रॉन हाइड्रोजन गैस को प्रतिध्वनित करते हैं और कुशलतापूर्वक आयनित करते हैं, जिससे एक घना, स्थिर प्लाज्मा बनता है। चूंकि वे उपभोग्य तंतुओं पर निर्भर नहीं हैं, 2.45 GHz ईसीआर स्रोत असाधारण दीर्घायु और निरंतर-तरंग प्रचालन प्रदान करते हैं, जिससे वे प्रगत नाभिकीय भौतिकी के लिए आवश्यक विशाल कणपुंज धाराओं को वितरित करने के लिए पूरी तरह से उपयुक्त हैं।

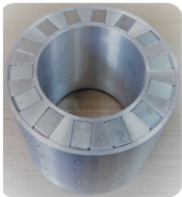
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ECR Ion Sources

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Picture of 14 pole multi-cusp

ABSTRACT

This article presents an overview of the 2.45 GHz Electron Cyclotron Resonance Ion Sources (ECRIS) developed for high-intensity proton accelerators, specifically detailing the operational three-electrode (3E-ECRIS) systems designed for LEHIPA and MEHIPA. Furthermore, it highlights advanced R&D frontiers, including a 14-pole multi-cusp geometry with a tetrode extraction system designed to minimize beam emittance, utilize permanent magnets, and enhance microwave power coupling. Finally, the paper outlines an international DAE-STFC collaboration focused on developing a tunable hexapole assembly to modulate ECR resonance and optimize plasma density distributions.

KEYWORDS: Plasma physics, Microwave plasmas, Proton Ion Sources

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Introduction

Electron Cyclotron Resonance Ion Sources (ECRISs) are the driving force behind today's high-intensity proton accelerators. Operating on fundamental plasma physics, these highly reliable systems inject 2.45GHz microwave energy into a hydrogen-filled chamber immersed in a carefully shaped magnetic field. When the microwave frequency matches the electron cyclotron frequency, the electrons resonate and efficiently ionize the hydrogen gas, creating a dense, stable plasma. Because they do not rely on consumable filaments, 2.45GHz ECR sources offer exceptional longevity and continuous-wave operation, making them perfectly suited to deliver the massive beam currents required for advanced nuclear physics.

The Three-Electrode ECR Ion Source

Currently, a 50keV, three-electrode ECRIS (3E-ECRIS) serves as the proton injector for the 20 MeV Low Energy High Intensity Proton Accelerator (LEHIPA) [1]. Building on this foundation, a 30keV, three-electrode ECR-IS has been developed for the 40 MeV Medium Energy High Intensity Proton Accelerator (MEHIPA) (Fig.1(a)) [2]. The system architecture and beam characterization details of the MEHIPA ECRIS are discussed below.

System Architecture: Microwaves, Magnets, and Extraction

The 3E-ECRIS system is engineered for precise plasma generation using a 2.45GHz magnetron and a WR284/340 waveguide line. To achieve ECR resonance and optimal confinement, two electromagnetic coils provide a tunable magnetic field around the nominal 875 Gauss at the chamber's central axis. Protons are then extracted through a streamlined three-electrode geometry, beginning with a 30kV plasma electrode with an 8mm aperture (Fig1(b)). The beam subsequently passes through a suppressor electrode (-2 to -5kV, 13mm aperture) to block back-streaming electrons, before exiting through a ground electrode. Finally, precise spacing; a 17mm gap between the plasma and suppressor

electrodes, followed by a 2mm gap to the ground, ensures optimal beam dynamics.

Beam Characterization

To ensure the ion source meets the stringent demands of accelerators like LEHIPA and MEHIPA, the extracted beam undergoes rigorous testing using in-house developed diagnostic tools. We focus heavily on two critical metrics:

Beam Emittance

Minimizing beam emittance, a measure of the beam's phase space area, is critical to prevent beam spreading, halo formation, and downstream radio activation. Using an Allison-type scanner, the un-separated beam (H^+ , H_2^+ , H_3^+) emittance of the 3E-ECRIS was measured at $0.27 \pi\text{-mm-mrad}$ rms normalized for a 30keV, 15mA beam (Fig.3(a)). After isolating pure H^+ ions with a focusing solenoid, the usable beam emittance drops to $0.12 \pi\text{-mm-mrad}$ rms normalized (at 30keV, 10mA), demonstrating excellent beam quality (Fig.3 (b)) [2].

Proton Fraction

An ECR plasma generated from hydrogen gas naturally produces a mix of ions, primarily protons (H^+) alongside molecular (H_2^+ and H_3^+) ions. As LEHIPA and MEHIPA are strictly proton accelerators, the presence of heavier hydrogen isotopes reduces overall beam efficiency and contributes to space-charge degradation. The proton efficiency was characterised using a Wien filter, which applies orthogonal electric and magnetic fields to act as a precision velocity selector (Fig.4(a)). This is the destructive type of Wien filter, 1st aperture of 0.4 mm to intercept the main beam, allowing only a small beamlet to pass. The species are filtered by scanning the electric field against a fixed magnetic field. Measurements taken immediately downstream of the vacuum chamber confirm a proton fraction of 60%. (Fig.4(b)) [3].

New Frontiers in ECR-IS Research

While the operational 3E-ECRIS provides a highly dependable beam, the demand for superior beam quality and system efficiency has driven the development of a novel

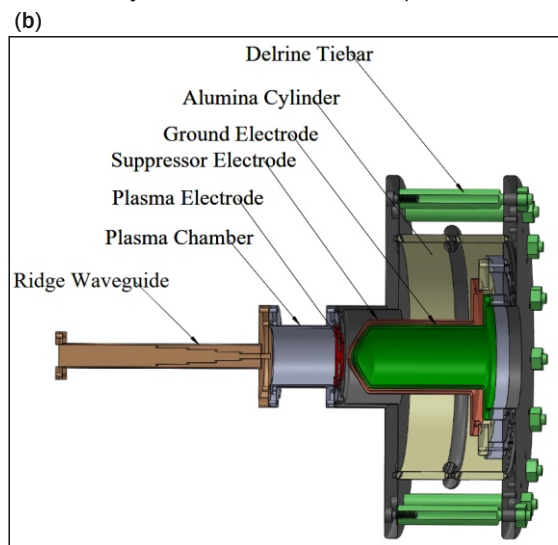
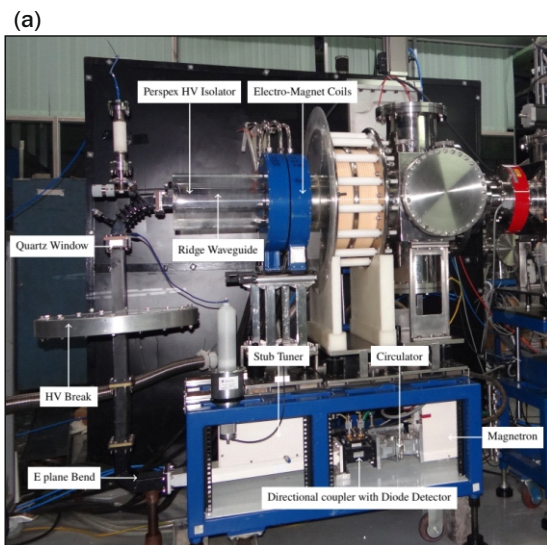


Fig.1: (a) The MEHIPA 3E-ECR ion source at VDG, (b) 3E Extraction geometry.

उच्च तीव्रता वाले प्रोटॉन लीनॉक: वर्तमान स्थिति एवं भावी योजनाएं

HIGH INTENSITY PROTON LINAC : CURRENT STATUS AND WAY FORWARD

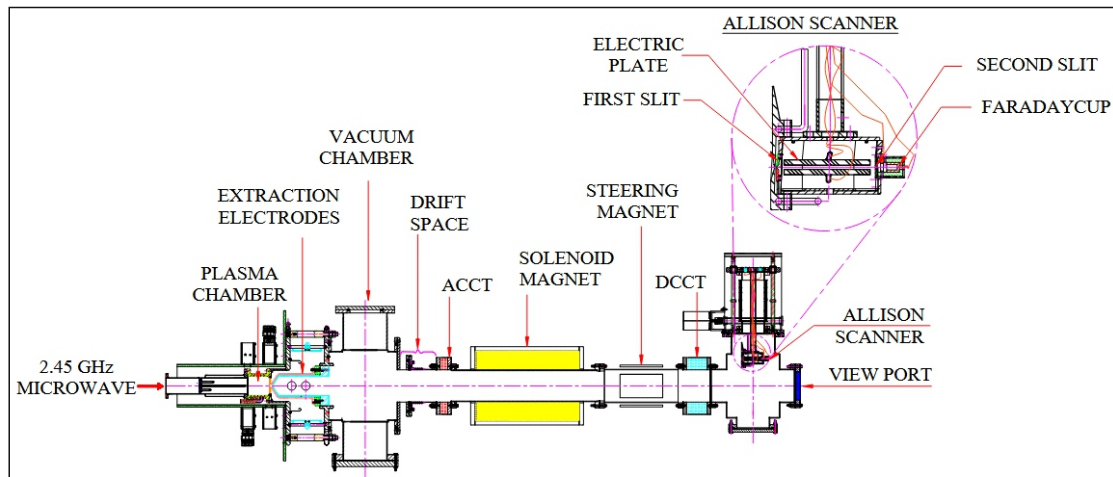


Fig.2: Experimental beam line of 3E-ECRIS.

2.45GHz multi-cusp ECR proton source to serve as a parallel injector for MEHIPA [4]. This design is driven by three core objectives:

- Minimizing Beam Emittance:** Achieving the lowest possible emittance remains a primary goal in modern ion source design. Because axial magnetic fields in the extraction region can account for nearly 50% of total emittance [5], this new 14-pole multi-cusp geometry completely eliminates the on-axis magnetic field (Fig.5) [4, 6]. By expanding the zero-field region at the chamber's core, beam emittance becomes solely dependent on ion temperature, drastically reducing the overall emittance footprint compared to traditional axial systems.

- Improving Microwave Power Coupling:** Another vital area of exploration is the optimization of microwave power launching schemes to maximize electron heating efficiency within the plasma chamber. By developing a novel single-step quarter-wavelength ridge coupler, the electric field amplitude can be amplified to at least five times that of conventional ridge waveguides [4]. This enhanced coupling allows for comparable plasma densities even at much lower input microwave powers, significantly boosting overall system efficiency.

- Embracing Green Technology:** Unlike traditional systems that rely on power-intensive electromagnetic coils, this new multi-cusp geometry utilizes permanent magnets. This

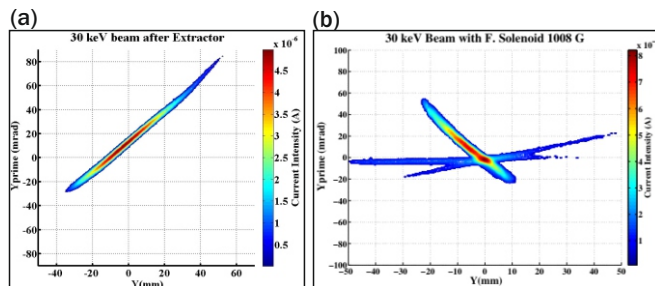


Fig.3: Beam phase space plot (a) just after the 3E-ECRIS and (b) after focusing solenoid.

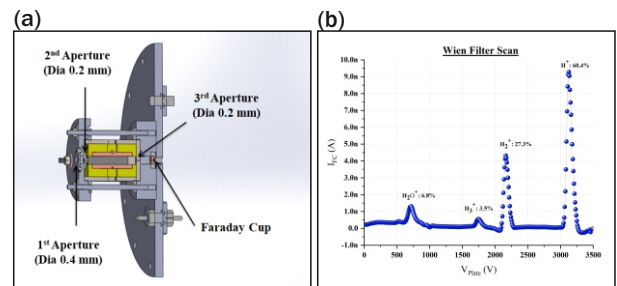


Fig.4: (a) 3D cross-section view of Wien Filter and (b) Wien filter scan spectrum.

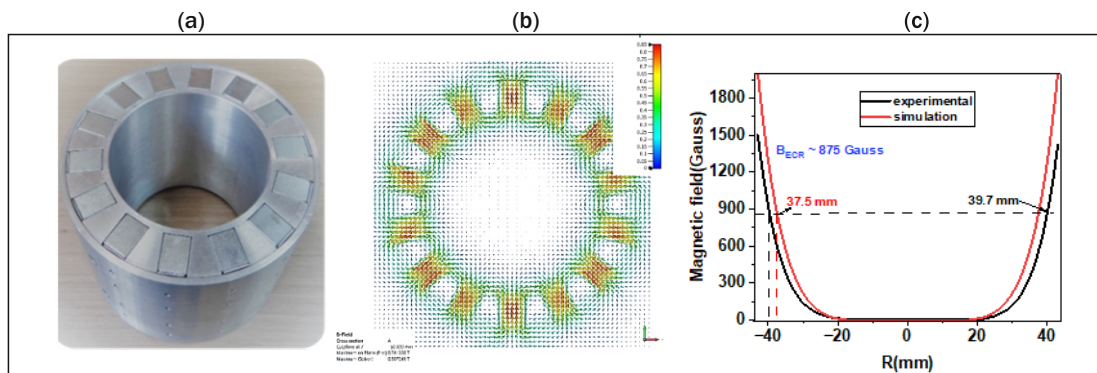


Fig.5: (a) Picture of 14 pole multi-cusp assembly and (b) its transverse magnetic field distribution using CST, (c) Radial magnetic field plot.

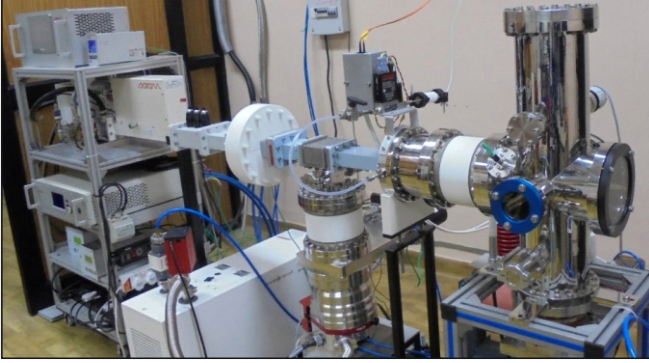


Fig.6: 14 pole Multi-cusp ECR ion source with the compact tetrode extraction system shown in inset.

strategic shift eliminates the need for massive power supplies and cooling systems for the magnets, drastically reducing the overall energy footprint of the injector [4, 6].

To maximize beam quality and offer greater tuning capabilities, this new multicusp source employs a tetrode-based extraction design. Building on the familiar Plasma, Suppressor, and Ground electrodes, this configuration introduces an Extractor/Puller Electrode (EE) to precisely control the initial beam convergence and prevent emittance growth.

Following rigorous geometric and angular optimizations, this four-electrode assembly has been successfully fabricated (Fig.6). Preliminary beam trials have commenced, with detailed characterization of the source currently in progress(Fig.6).

International Synergy: The DAE-STFC Collaboration

The exploration of the intricate dynamics of beam formation and phase-space emittance within this novel multicusp geometry constitutes a key collaborative endeavour under the collaboration between DAE (BARC) and the UK's Science and Technology Facilities Council (STFC). Through this partnership, an innovative tunable hexapole multicusp assembly was conceptualized and subsequently fabricated and tested at BARC. This advanced assembly introduces several capabilities like:

- **Dynamic Tuning:** The key innovation of this assembly is the

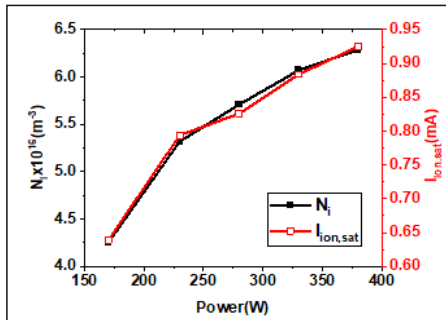


Fig.7: (b) Plasma ion density, N_i data for MW power variation, for 0° magnet orientation.

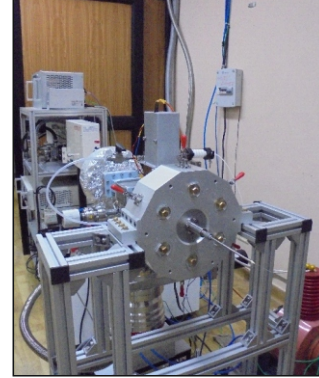


Fig.7: (a) Tunable multicusp assembly integrated with BARC test stand.

ability to modulate the ECR resonance geometry by adjusting the angular orientation of the permanent magnets.

- **Optimized Output:** By varying the rotation of the magnetic cusps, the plasma density distribution and subsequent beam current densities can be optimized.

The mechanical integration of this tunable system onto the BARC test stand is now complete (Fig.7(a)). Currently, active plasma measurements are underway, utilizing optical emission spectroscopy alongside an in-house developed Langmuir probe (Fig.7(b)).

Conclusion

The operational 3E-ECRIS successfully meets the demanding proton beam requirements for both LEHIPA and MEHIPA, demonstrating excellent beam quality with a measured 60% proton fraction and highly refined emittance. To push the boundaries of accelerator capabilities, the ongoing development of multi-cusp sources utilizing permanent magnets and a novel tetrode extraction system promises to significantly reduce emittance while improving overall energy efficiency. With mechanical integration complete, ongoing active plasma measurements on the tunable hexapole assembly will continue to refine beam dynamics, establishing these green, high-efficiency technologies as the standard for next-generation high-intensity proton injectors.

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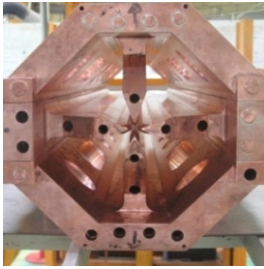
4

मेहिपा हेतु त्वरक संरचना अभियांत्रिकी अभिकल्पन एवं संबंधित विकास

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चतुर्ध्रुवीय रेडियो आवृत्ति (आरएफक्यू)

सारांश

यह शोध पत्र, मध्यम ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (मेहिपा) के लिए सामान्य प्रचालन एवं अति-चालकता आरएफ त्वरण गुहिकाओं के लिए किए गए ताप-संरचनात्मक, बहु-भौतिकी तथा गुहिका विकास से संबंधित अध्ययन प्रस्तुत करता है। उच्च ताप अभिवाह स्थितियों में आरएफ तापन, ताप विरूपण, शीतलन प्रदर्शन एवं आवृत्ति पृथक्करण का मूल्यांकन करने के लिए रेडियो आवृत्ति चतुर्ध्रुव (आरएफक्यू) एवं ड्रिफ्ट ट्यूब लीनाक (डीटीएल) गुहिकाओं का ताप-यांत्रिक विश्लेषण किया गया है। अति-चालक एसएसआर-बी गुहिकाओं के लिए, लोरेण्ट्ज़ फोर्स डिट्यूनिंग (एलएफडी) और पतली उच्च-शुद्धता वाली नायोबियम संरचनाओं की यांत्रिक स्थिरता का मूल्यांकन करने के लिए युग्मित विद्युत चुम्बकीय-संरचनात्मक विश्लेषण किए गए हैं। विनिर्माण क्षमता, आयामी सटीकता एवं दोष नियंत्रण में सुधार के लिए नायोबियम घटकों के गठन हेतु गहन रेखाचित्रण प्रक्रिया अनुकरण भी किए गए हैं। शोध पत्र में, फर्मीलैब पीआईपी-II परियोजना हेतु विकसित गुहिका विकास, संविरचन पद्धति एवं एसएसआर-2 गुहिकाओं के प्रमुख निर्माण पहलुओं पर भी चर्चा की गई है।

4

Engineering Design and Related Development for MEHIPA Accelerating Structures

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ABSTRACT

The MEHIPA Phase-I (40 MeV) accelerator comprises type of three accelerating structures: Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL), and Superconducting Single-Spoke Resonator (SSR-B). Multiple finite element method (FEM)-based analyses are required to finalize their engineering design. The RFQ and DTL require detailed thermo-structural analyses to optimize cooling schemes and evaluate water-cooling-based RF control. The RFQ exhibits high thermal sensitivity, where $\pm 1^\circ\text{C}$ variation in inlet water temperature results in $\pm 100\text{ kHz}$ de-tuning. A gradual water-flow increment scheme has been developed to support high-duty-cycle continuous-wave (CW) operation. For the DTL, three-dimensional computational fluid dynamics (CFD) analyses with conjugate heat transfer have been performed to assess drift tube cooling, while two-dimensional thermal analyses have been carried out for the DTL tank. The thin-walled SSR-B cavity requires coupled structural and electromagnetic optimization to determine material thickness and stiffener geometry while ensuring ASME Section VIII, Division 2 compliance. This paper outlines deep-drawing simulations and forming limit diagram (FLD) characterization for the novel spherical SSR-B design developed at BARC. It further discusses the cavity development, fabrication methodology, and key manufacturing aspects of SSR-2 cavities developed for the Fermilab PIP-II project.

KEYWORDS: Medium Energy High Intensity Proton Accelerator (MEHIPA), Drift tube linac (DTL), Radio frequency quadrupole (RFQ), Lorentz Force Detuning (LFD)

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Introduction

Proton beam acceleration in MEHIPA phase-I will be carried out using Normal Conducting RFQ (3 MeV), Alvarez-type DTL (10 MeV), and superconducting SSR-B cavities (40 MeV), operating at 325 MHz (3-D model shown in Fig.1).

RF power dissipation on cavity surfaces causes heating, thermal deformation, and RF detuning. Hence, thermo-structural design of RFQ and DTL cavities focuses on minimizing frequency shifts. Since RF losses are confined within the skin depth region (few microns), the heat load is treated as a surface phenomenon with peak value around 90 kW/m².

Single spoke resonators (SSR-B) for MEHIPA are dumbbell shaped cavities made up of thin sheet of high RRR Niobium. They are positioned subsequent to DTL (11MeV beam energy onwards) and operate at cryogenic temperature. Thin sheet construction enables compression based tuning; however makes cavity prone to deformation due to vacuum and Helium pressure and also to RF based (Lorentz force) detuning, which are addressed by multi-physics and structural analysis. Manufacturing of SSR cavities are done by deep drawing of niobium sheet, followed by electron beam welding of formed parts.

CDM, BARC has fabricated SSR-2 cavities for the Fermi lab PIP-II project as part of Indian institute and Fermilab collaboration (IIFC), which are discussed in later sections⁵.

RFQ Thermal Design and RF Detuning

Thermal analysis of 2-D element of RFQ cross section (1/8th symmetry model, Fig.2) has been done using FEM solver based on heat flux data obtained from RF heat dissipation simulation which is limited to skin depth of inner surface exposed to RF. Considering simplicity of calculation and conservative approach, heat generation is taken as surface phenomenon (heat flux). Thermal analysis assumes heat transfer coefficient obtained through correlation: $Nu=0.023Re^{0.8}Pr^{0.4}$. Temperature, obtained as result, is used to obtain thermal deformation. Complete details are available in Ref.1.

Thermal deformations in term of Δx and Δy are used in relation to get RF detuning

$\Delta f = \sum_{i=1}^{12} (\partial f / \partial x \Delta x + \partial f / \partial y \Delta y)$ where $\partial f / \partial x$ and $\partial f / \partial y$ are the RF sensitivity constants.

Detuning Control by LCW Temperature Variation

Baseline LCW inlet temperature for coolant channel H1/H2 is 16°C and for H3/H4, it is 20°C. Due to very high RF sensitivity, minor variation of 0.1°C alone is sufficient to detune

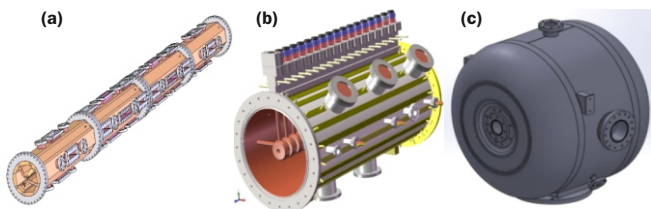


Fig.1: (a) Vane-type RFQ. (b) Alvarez Type DTL Segment. (c) Single Spoke Resonator.

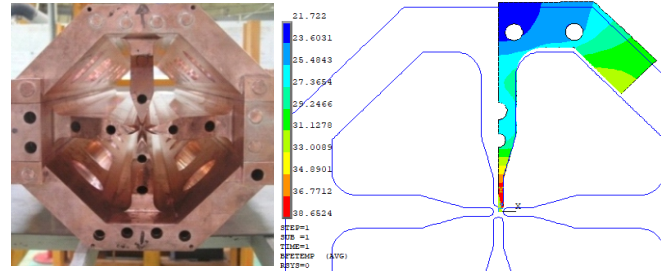


Fig.2: (a) RFQ (b) Temperature profile of 1/8th symmetry RFQ segment (°C).

the RFQ. Considering Q_L (loaded quality factor) around 3500, uncompensated small detuning of ± 25 kHz can result into RF power reduction by around ~20% in the RFQ. Table-1 summarizes individual and combined effect of all coolant channels on RF detuning.

Detuning Control by LCW Flow Variation

When RFQ is operating at lower RF Duty Level (%SF), coolant channels can be supplied with the lower LCW flow instead of baseline 3.5 m/s. A possible regime (Fig.3) of flows was worked out. H1 being closest to the proton beam, it is better to initiate the cooling at the lowest possible SF. However, up to 0.1% SF, H1 channel supply results into appreciable detuning therefore cannot be switched ON. H4 having lower impact on detuning can be switched ON, however needs to have higher inlet temperature at 21°C. 1% SF onwards, full 3.5 m/s supply in H4 can be turned on and also very low supply in H1 can be initiated here. Up to 60% SF, there is hardly any need of any other coolant channel supply, while H1 supply is gradually ramped up. At 60% SF, H2 supply needs to be switched ON. At 150% SF, H3 supply becomes necessary to reduce the temperature.

DTL Thermal design and RF Detuning

Thermal analysis of DTs and the DTL tank was performed to ensure effective cooling. DTs are usually analyzed using computational fluid dynamics (CFD) technique with conjugate heat transfer (Navier-Stokes equation, energy equation and turbulent model equation), while the DTL tank can be conveniently evaluated using 2D correlations (dittus-bolter equation).

Cooling scheme: The cooling scheme provides directional flow in drift tubes (DTs), where water enters through the outer 0 annular passage in the stem (Fig.4), circulates to achieve 360 cooling of RF-exposed surfaces, and exits through an inner return pipe. For the DTL tank, cooling is achieved using straight, open rectangular channels running longitudinally from one end to the other.

Table 1: Inlet Water (LCW) temperature vs RF

RFQ Channels (Ø10mm)	dF/dT _{inlet} (kHz/±1°C)	dF/dT _{inlet} (kHz/±0.1°C)
H1	-55.5	-5.55
H2	-46.4	-4.64
H3	14.14	1.41
H4	84.57	8.45
RF Detuning dF for in-phase temperature variation →		-0.31 kHz/±0.1°C
RF Detuning dF, Worst case scenario →		-20.06 kHz/±0.1°C
Total available water tuning range →		-101 to 98 kHz/±0.1°C

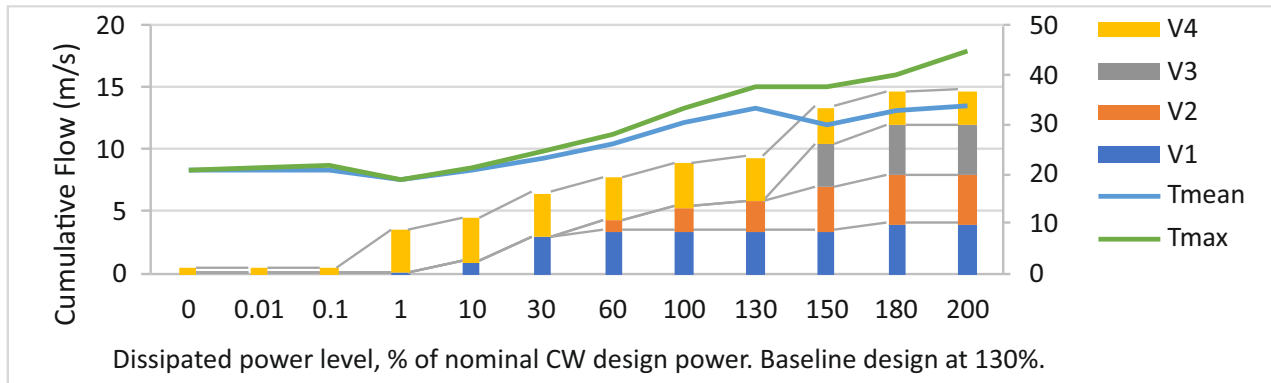


Fig.3: RFQ LCWflow (H1-H4) & T_{mean}/T_{max} (°C) for Various RF power level.

In MEHIPA DTL, DTs see peak heat flux $\sim 91 \text{ kW/m}^2$ (2.4–3.9 kW per DT), and the tank $\sim 32 \text{ kW/m}^2$. The cooling estimation assumes LCW inlet temperature of 20°C , and inlet velocity of 2m/s for DT and 3m/s for DTL tank (to avoid material erosion). The cooling design maintains temperatures well below 100°C to avoid boiling and limit thermal deformation (complete details in Table-2), with PMQ casing temperature restricted much below 60°C (to avoid demagnetization). Total RF-induced detuning estimates guide tuner range and mechanical offset requirements which, in terms of RF detuning, should be within few 10s of kHz.

Dynamic control of RF detuning: Inlet fluctuation within $\pm 0.2^\circ\text{C}$ with DTL tank sensitivity of around $-8\text{kHz}/^\circ\text{C}$ keeps frequency variation within bandwidth. Complete details are available in Ref.2

Table 2: Cooling requirement of DTL for RF detuning

Design parameters/Constraints	Requirements/Permissible Range
1. Maximum temperature	a. $<100^\circ\text{C}$, to avoid boiling of cooling water b. To be minimized for better electrical conductivity and lower RF detuning
2. Maximum temperature (Magnet)	$<60^\circ\text{C}$, to avoid de-magnetization of PMQ
3. Maximum temperature variation	$<10^\circ\text{C}$, to avoid differential thermal deflection of DTs
4. Thermal deflection (DT center)	a. $<50 \mu\text{m}$ w.r.t. tank centerline b. $<50 \mu\text{m}$ w.r.t. mean DT center position c. To be minimized to check RF detuning
5. Pressure drop	a. $<$ differential static head available b. Should satisfy velocity constraint
6. Water flow velocity	a. $<2.5\text{m/s}$ (copper) b. $<6\text{m/s}$ (steel)
7. Inlet water temperature range	$19\text{--}22.5^\circ\text{C}$

Fig.5 illustrates maximum and average temperature of a DT with variation in water inlet velocity and variation of LCW inlet flow velocity to maintain constant RF detuning at varying duty factor.

SSR Structural, Multi-physics and Process/Deep Drawing Design

The structural, multi-physics, and process design of the SSR cavity plays a crucial role in achieving stable RF performance and manufacturability. Detailed analyses were carried out to optimize cavity stiffness, thermal behavior, RF characteristics, and deep drawing feasibility while ensuring compliance with stringent accelerator requirements.

SSR Structural Design

A set of analyses towards ensuring structural integrity were done and qualified as ASME, VIII-2. This included MAWP, local plastic failure, buckling, weld joint safety, and von-mises qualification are shown below in Fig.7, Table-4 & Table-5. Among the evaluated cases, the condition corresponding to 2bar external pressure at room temperature is identified as the more critical.

Stress-linearization

Maximum von-Mises stress at maximum stress locations breaches allowable stress (42.5MPa). Stress linearization technique is utilized to qualify those locations. The breakup of membrane, bending and peak stress along stress concentration line (SCLs) at maximum equivalent stress

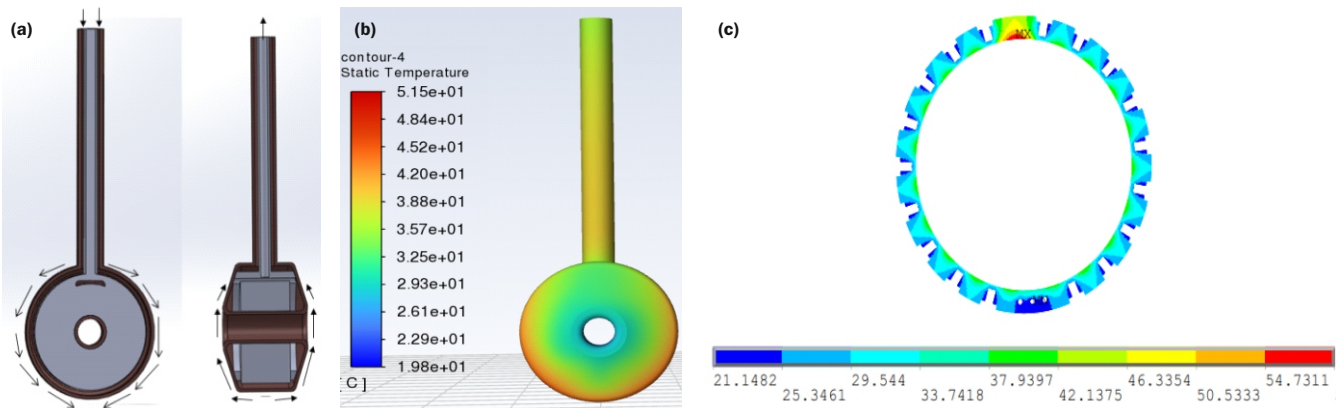


Fig.4: (a) DT LCW Flow (b) DT Temperature (c) DTL Tank Temperature.

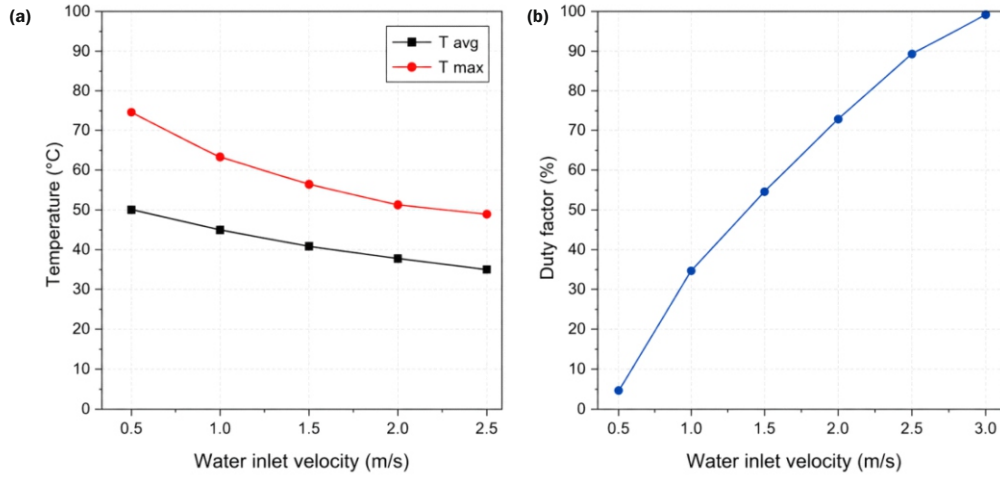


Fig.5: (a) DT Temperature vs LCW Inlet flow. (b) DT LCW flow change required to maintain the RF Detuning.

Table 3: Summary SSR-B design.

	Design Parameter	Target Value	Achieved
Operational Requirements	1 Stiffness of Cavity (kN/mm)	<35	10
	2 LFD No., Hz/(MV/m) ²	<-4.5	-4.38
	3 Course Frequency Tuning Range (kHz)	>135	~200
	4 Tuning Sensitivity (kHz/mm)	> 250	472.4
	5 Max von-Mises Stress (MPa)	<42.5(S)	>42.5*
	6 RF Detuning vsCryogenic Pressure Variations, - (Hz/mbar)	<25	6.5
Safety Requirements. Qualification:ASME SectionVIII, Div-2	7 Maximum Allowable Working Pressure, MAWP (bar)	2.05 (RT)/4.1	4.93/21
	8 Buckling Pressure (bar)	> 4.1	24
	9 Protection against Local plastic failure	-	Safe
	10 Weld joint safety	$\sigma_{eq} < S.E$	Qualified
Process/ Forming Analysis	11 Thinning	<15%	25%
	12 Tearing	None	None
	13 No. of forming stages	≤3	2

location has been shown in Fig.8. The results confirm that the selected wall thickness of 3.25 mm provides an optimal structural integrity.

SSR Multi-physics Studies

In normal conducting DTL/RFQ structures, RF behavior is primarily governed by geometry, with negligible feedback from electromagnetic forces due to high structural stiffness, resulting in essentially one-way coupling (structure → RF). In contrast, SSR cavities exhibit strong two-way RF-structural coupling, where Lorentz forces, along with Helium pressure, can deform the thin-walled niobium structure and significantly shift the resonance frequency. Therefore, multi-physics analysis is required for SSR to accurately capture this interaction and predict detuning behavior, ensuring stable RF performance and reliable operation. The LFD coefficient (k) is

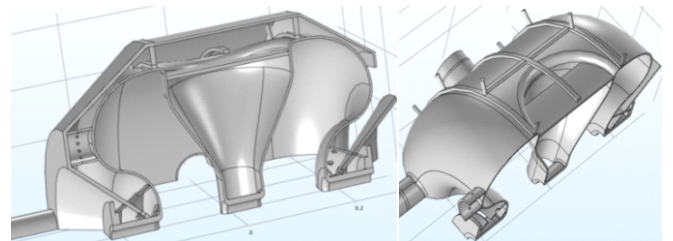


Fig.6: SSR jacketed cavity and Bare Cavity (1/4th symmetry)

given by $\Delta f = k E_{acc}^2$ where E_{acc} is accelerating gradient field and Δf is frequency shift (derived from relation $\frac{\Delta f}{f} = \frac{\int_{\Delta V} (\mu_0 \vec{H}^2 - \epsilon_0 \vec{E}^2) dV}{\int_V (\mu_0 \vec{H}^2 - \epsilon_0 \vec{E}^2) dV}$). V represents the complete volume of the cavity and ΔV represents the volume inside the cavity where the deformation

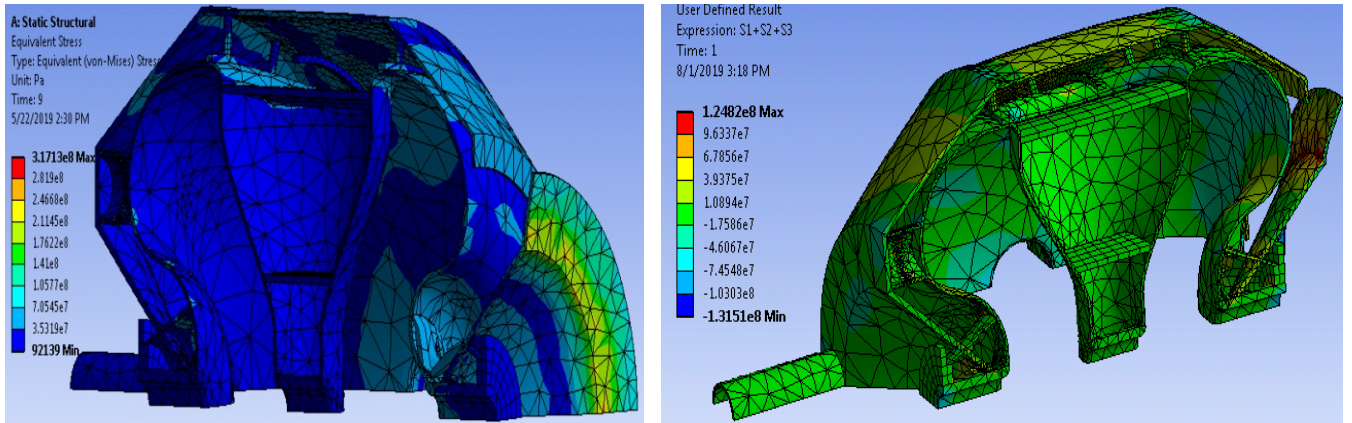


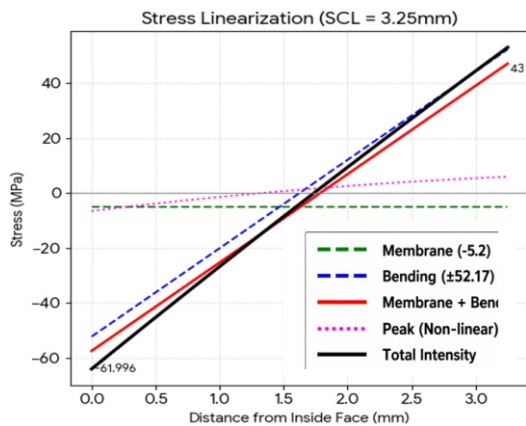
Fig. 7: Von-Mises eq. stress at Critical Pressure-MAWP. Sum of principle stress (S1+S2+S3) plot for local plastic failure.

Table 4: MAWP, ASME Qualification.

Load Case->	1	2	3	4
Loads->	P+D	P+D+T1	P+D+T2	P+D+T1+T2
Temperature (K)	293	293	2	2
Pr _c (Collapse Pr in bar)	7.4	10.3	28	28
MAWP = Pr _c /1.5 for RT and Pr _c /1.3 for 2K	4.93	6.8	21	21
Min MAWP Required	2.05	2.05	4.1	4.1
Safe on ASME Criterion?	Safe	Safe	Safe	Safe

Table 5: Local Plastic Failure, ASME Qualification.

Load Case->	1	2	3	4
Loads->	P+D	P+D+T1	P+D	P+D+T1
Temperature (K)	293	293	2	2
P (bar)	2.05	2.05	4.1	4.1
S1+S2+S3 (MPa, Max, including Peak Stress) at RT/2K	96.31/124.78	96.33/124.8	192.63/249.5	192.67/249
4S	170/392	170/392	682/1274	682/1274
Safe on ASME Criterion?	Safe	Safe	Safe	Safe



Stress type	Allowable limit	Value achieved
Membrane stress, σ_m	$\leq S$ (42.5MPa)	-5.2MPa
Bending stress, σ_b	$\leq 1.5S$ (64MPa)	± 52.1 MPa
$\sigma_m + \sigma_b$	$\leq 1.5S$	-55MPa, 48MPa
$\sigma_m + \sigma_b + \sigma_p$ $\sigma_p = \text{Peak stress}$	$\leq 2S$ (85MPa)	-61MPa, 43MPa

S* : Allowable Stress.

Fig.8: Linearized stress intensity plot over stress concentration line (SCL) at maximum stress value location and linearized max stress intensity values.

(Fig.9) has occurred. Detailed multi-physics analysis has been carried out to quantify both Lorentz Force Detuning (LFD) coefficient k and helium pressure sensitivity $\partial f/\partial p$ which are critical parameters governing frequency stability in superconducting RF operation. For the finalized geometry with a niobium wall thickness of 3.25 mm, an optimized stiffener

configuration has been implemented to enhance structural rigidity. This design achieves a Lorentz force detuning coefficient of $-4.38 \text{ Hz}/(\text{MV}/\text{m})^2$ and a helium pressure sensitivity of $-6.5 \text{ Hz}/\text{mbar}$, indicating controlled frequency shifts under field and pressure variations (Ref.3).

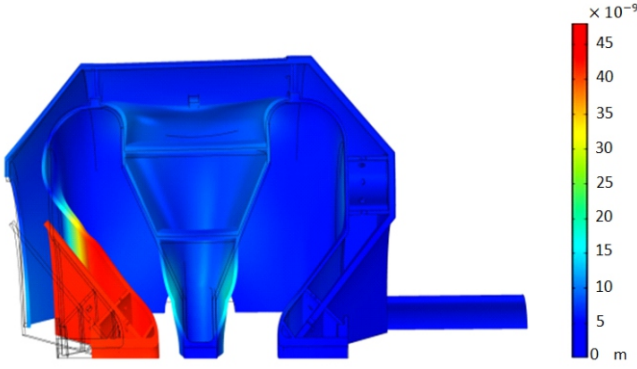


Fig.9: Displacement profile of SSR-B cavity due to Lorentz.

Deep Drawing Structural Studies for SSR end-wall

SSR cavity design emphasizes manufacturability and mechanical stability, particularly in niobium sheet metal forming and structural performance under vacuum and helium pressure loads. Process optimization is essential to control thinning and ensure consistent quality. Thinning in SSR cavity forming must be minimized to maintain structural stiffness, ensuring resistance to vacuum and helium pressure loads while reducing detuning effects. It also improves manufacturing quality, weld integrity, surface finish, and optimizes costly niobium material utilization. Most important part of SSR is end-wall in which quality control over deep drawing process is challenging. To minimize wastage in high RRR Nb consumption for projects such as MEHIPA, it is essential to minimize thinning.

FLD (Forming Limit Diagram) is used to predict failure or excessive thinning and was obtained through the Nakajima Test (test sample in Fig.10). As a prototype study, the FLD for ETP copper has been generated and used for the FEM analysis of the cavity end-wall. Fig.11 shows the FLD for both single-stage and double stage deep drawing analysis.

Lankford coefficients, given by $r = \frac{\epsilon_{width}}{\epsilon_{thickness}}$, are required to know anisotropic behaviour of material obtained through tensile test. r_0 , r_{45} , and r_{90} are different 'r' values at 0° , 45° and 90° to the rolling directions. For high RRR niobium, $r_0 \sim 1.66$; $r_{45} \sim 1$; $r_{90} \sim 2.3$ Ref.4

a. Planar anisotropy, $\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2}$, ~ 0.98 for high RRR Nb

b. Normal anisotropy, $\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4}$, ~ 1.49 for high RRR Nb

Optimization of deep-drawing parameters and multi-staging of forming process are employed to get the desired

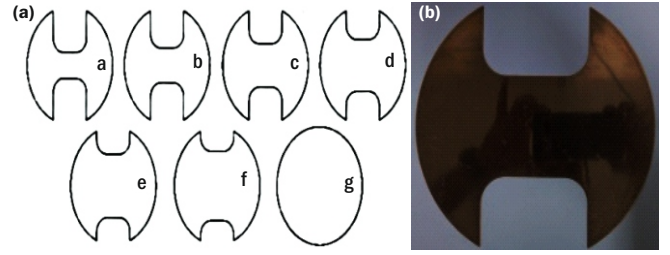


Fig.10: (a) Different test specimen used for Nakajima test. (b) Typical Nakajima Test Sample.

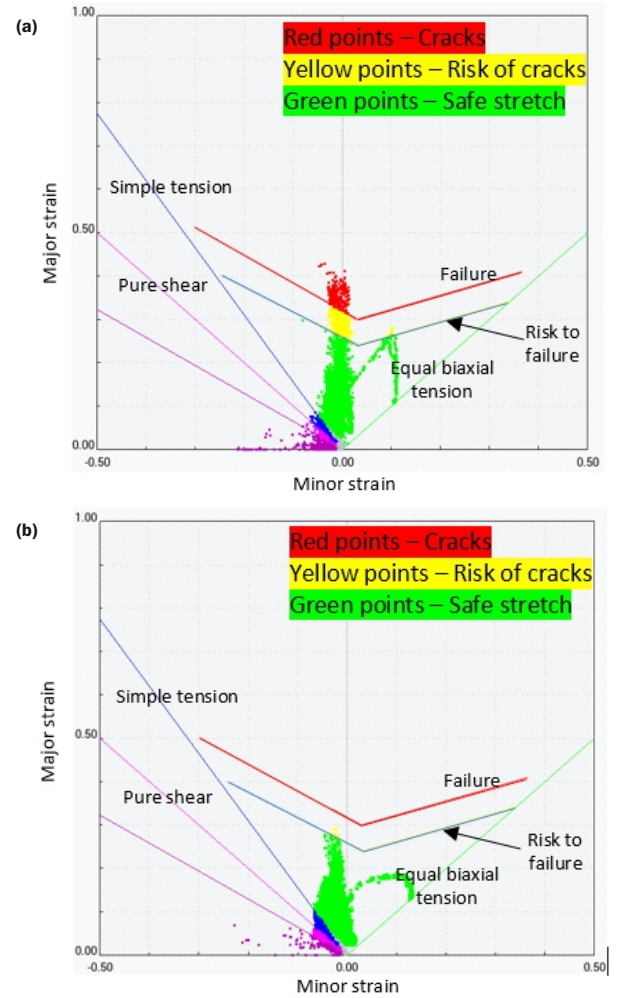


Fig.11: SSR end-wall FLD plot for (a) single-stage (b) 2-stage

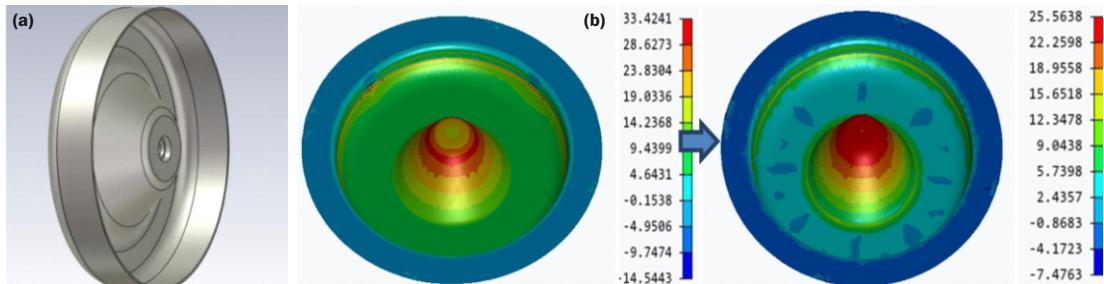


Fig.12: (a) SSR end-wall. (b) Its thinning %, Single stage vs Two-stage deep



Fig.13: (a) Spoke Collar. (b) End-wall.

outcome. Reduction in maximum thinning from 33% to 25%, achieved by increasing the number of forming stages from one to two, is illustrated in Fig.12. Further, it can be reduced up to 10-15% range by further optimization of parameters such as blank size, friction etc.

Fabrication of SSR Cavities

As part of the Indian Institutes and FermiLab Collaboration (IIFC), the Department of Atomic Energy (DAE) is fabricating Spoke cavities designated as SSR-2 as an in-kind contribution for the PIP-II accelerator at Fermilab, USA. The fabrication expertise and process knowledge gained through this collaboration is being leveraged for the indigenous development of SSR cavities for Indian accelerator programs, including MEHIPA Phase-1. The key fabrication methodologies and processes involved in the development of SSR-2 cavities are detailed in this section.

Overview

The SSR2 bare cavity is a superconducting radio-frequency (SRF) accelerating structure developed for the PIP-II project. Operating at 325 MHz, these high-purity niobium cavities are designed to accelerate ions across the 35–185 MeV energy range within seven cryomodules. The cavity is optimized for a velocity factor of $\beta_{opt} = 0.472$ and operates in Continuous Wave (CW) mode at 2.0 K in super fluid helium. The mechanical design emphasizes stability against microphonics and helium pressure fluctuations, with specified longitudinal stiffness below 16 kN/mm and tuning sensitivity below 250 kHz/mm. Comprehensive manufacturing, assembly, and quality assurance procedures for the SSR2 cavities were developed at the Centre for Design and Manufacturing (CDM), BARC. Owing to the stringent performance requirements of superconducting linear accelerators, the cavities demand extremely high precision during forming, machining, cleaning, and electron beam welding. The fabrication process is carried out in two stages: development of the ultra-high-purity niobium bare cavity, followed by integration with the helium vessel to form the jacketed cavity assembly.

The Bare Cavity Fabrication

The performance of the SSR-2 cavity critically depends on the integrity of its raw material and fabrication processes. The cavity is manufactured from high-purity niobium (RRR > 300), which is highly sensitive to contamination and mechanical damage. Accordingly, stringent handling procedures are implemented throughout fabrication to prevent surface defects and cross-contamination. The complex spoke and end-wall geometries (Fig.13) are produced through precision deep drawing using specially developed tooling. Subsequently, all formed components are finish-machined on advanced CNC systems to achieve tight dimensional tolerances and precise fit-up for the Electron Beam Welding (EBW) process.

The bare cavity represents the electromagnetic heart of the system. Niobium readily reacts with oxygen, nitrogen, and hydrogen at elevated temperatures, all primary structural and RF-surface welds is performed in a high-vacuum EBW chamber. Components undergo chemical etching i.e., Buffered Chemical Polishing (BCP) and ultrasonic cleaning before entering the vacuum chamber. The welding parameters (beam current, focus, speed, etc) are developed to ensure full penetration while explicitly preventing anomalies on RF side of welds, which can trap chemical residues and degrade RF performance. The assembly progresses from rolled components seam weld, sub-components weld to form the sub-assemblies & final welds of the sub-assemblies to close the bare cavity (Fig.14).

During the manufacturing of the bare cavity (Fig.15), Visual, Dimensional & CMM inspection are carried out. Radiographic and Ultrasonic Testing are done wherever required. Final bare cavity is qualified to ensure helium leak rate of 1×10^{-10} mbar. l/s. Room temperature RF measurements are conducted which also involves controlled mechanical deformations (inelastic tuning) of the cavity to ensure the cavity meets the required frequency profile.

Helium Vessel Jacketing (Dressing) of Cavity

The SSR-2 niobium cavity operates in a superconducting state by immersion in liquid helium. For this, the bare cavity is enclosed within a titanium Grade-2 helium jacket. The jacket assembly and cavity integration are carried out using precision TIG welding of formed and machined titanium components. During welding, RF pickups, oxygen monitors, and temperature sensors are used to continuously monitor cavity health and avoid RF degradation. The completed jacketed cavity is qualified through pressure and leak testing of the annular

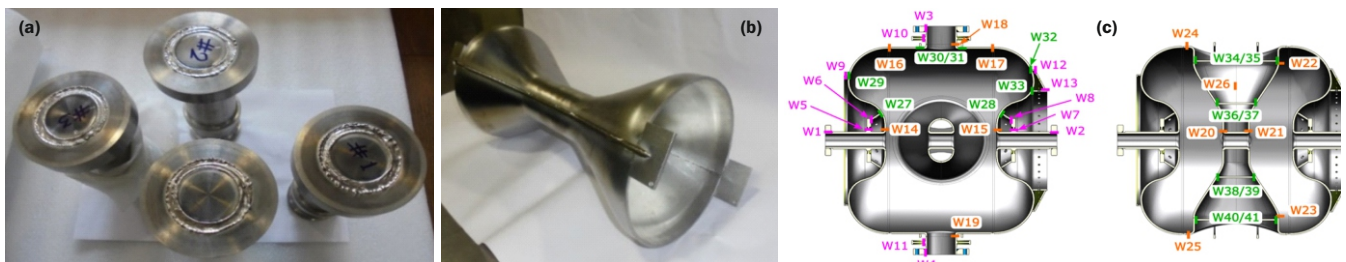


Fig.14: (a) Beam Pipe Sub-assembly. (b) Spoke Sub-assembly. (c) Cross Section View of 3-D CAD Showing All EB Welds.

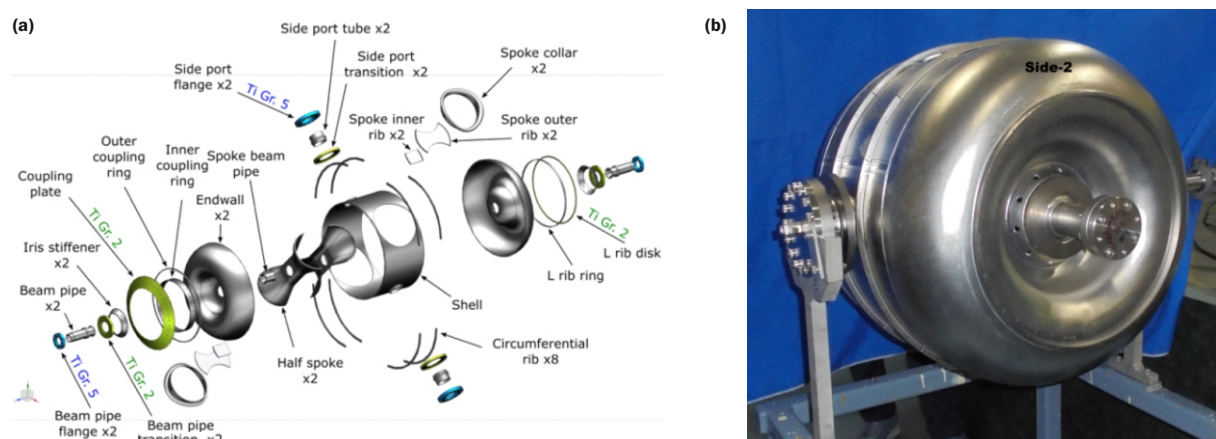


Fig.15: (a) SSR2 Bare Cavity Exploded View. (b) SSR2 Bare Cavity.



Fig.16: Bare Cavity preparation for Jacketing and Jacketing of Bare Cavity.

space (Fig.16). Comprehensive fabrication, weld, and inspection records are maintained to ensure traceability and manufacturing compliance.

Conclusions

This paper presents comprehensive thermo-structural, multi-physics, and cavity development studies carried out for the MEHIPA-Phase1 accelerator program. Thermal and RF detuning analyses of the RFQ and DTL established that precise control of LCW inlet temperature and flow rates is key to maintaining frequency stability. For SSR-B cavities, coupled electromagnetic-structural analyses achieved a Lorentz Force Detuning coefficient of $-4.38 \text{ Hz}/(\text{MV}/\text{m})^2$ and helium pressure sensitivity of $-6.5 \text{ Hz}/\text{mbar}$, both within target specifications, with full structural qualification under ASME Section VIII, Div-2. Deep drawing process simulations demonstrated that two-stage forming significantly reduces niobium thinning, improving material utilization. The fabrication experience gained through the IIFC collaboration on

SSR-2 cavities for Fermilab's PIP-II project has proven immensely valuable, directly strengthening India's indigenous capability in accelerator cavity development.

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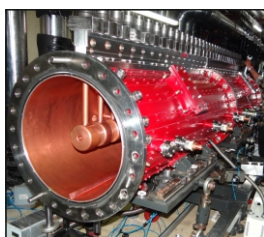
उच्च-तीव्रता वाले प्रोटॉन लीनॉक हेतु स्थायी चुंबक चतुर्ध्रुव में नवाचार

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सारांश



संवहन नलिकाएं जिनके भीतर पीएमक्यू रखे जाते हैं, को प्रदर्शित करता, लेहिपा डीटीएल

निम्न ऊर्जा उच्च तीव्रता वाले प्रोटॉन त्वरक (लेहिपा) हेतु असाधारण अनुप्रस्थ किरणपुंज फोकस की आवश्यकता होती है, जिसे इसके संवहन नलिका लीनॉक (डीटीएल) गुहिकाओं की अत्यधिक सीमित मात्रा के भीतर विशेष स्थायी चुंबक चतुर्ध्रुव (पीएमक्यू) को जड़ित करके प्राप्त किया जाता है। आरंभिक डीटीएल टैंकों की अत्यधिक स्थानिक बाधाओं एवं उच्च-प्रणता आवश्यकताओं को पूरा करने हेतु, क्षेत्र सांद्रता को अधिकतम करने और स्वाभाविक रूप से बहुध्रुवीय लुटियों को निरुद्ध करने के लिए एक 16-खंडीय शुद्ध स्थायी चुंबक वास्तुकला की अभिपूरति की गई। बाद के टैंकों के लिए, जहां स्थानिक बाधाएं कम होती हैं, स्थायी चुंबक एवं सटीक रूप से समोच्च नर्म लोहे के पोलों का उपयोग करते हुए एक 8-ब्लॉक वाले संकर अभिकल्पन का नवाचार विकसित किया गया। यह संकर वास्तुकला एक नई पोल-लेंथ शिमिंग तकनीक का परिचय देती है जो फ्रिजिंग क्षेत्रों को नियंत्रित करने के लिए चुंबकीय प्रतिष्ठम्भ को बदलकर एकीकृत ढाल को बारीकी से ट्यून करने की अनुमति देती है। त्वरक के कठोर वातावरण का सामना करने के लिए, दोनों अभिकल्पन विशेष रूप से समेरियम कोबाल्ट ($\text{Sm}_2\text{Co}_{17}$) चुंबक का उपयोग करते हैं, जो चरम चुंबकीय शक्ति पर विकिरण कठोरता एवं तापीय स्थिरता को प्राथमिकता देते हैं। अंततः, ये दो पूरक पीएमक्यू वास्तुकला लीनॉक की विकसित किरणपुंज गतिशीलता के अनुरूप एक इष्टतम अनुकूलित केंद्रित जाली बनाने के लिए तालमेल में काम करते हैं।

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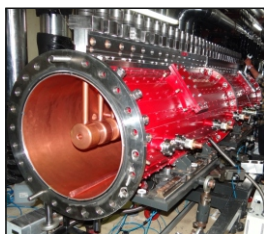
Innovations in Permanent Magnet Quadrupoles for High-Intensity Proton Linacs

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ABSTRACT



Picture of LEHIPA DTL, displaying drift tubes within which the PMQs are housed

The Low Energy High Intensity Proton Accelerator (LEHIPA) requires exceptional transverse beam focusing, achieved by embedding specialized Permanent Magnet Quadrupoles (PMQs) within the highly constrained volume of its Drift Tube Linac (DTL) cavities. To address the extreme spatial constraints and high-gradient requirements of the initial DTL tanks, a 16-segment pure permanent magnet architecture was implemented to maximize field concentration and naturally suppress multipole errors. For the subsequent tanks, where spatial constraints relax, an innovative 8-segment hybrid design utilizing permanent magnets and precisely contoured soft iron poles was developed. This hybrid architecture introduces a novel pole-length shimming technique that allows to finely tune the integrated gradient by altering the magnetic reluctance to control fringing fields. To withstand the accelerator's harsh environment, both designs exclusively utilize Samarium Cobalt ($\text{Sm}_2\text{Co}_{17}$) magnets, prioritizing radiation hardness and thermal stability over peak magnetic strength. Ultimately, these two complementary PMQ architectures work in synergy to form a highly optimized focusing lattice tailored to the evolving beam dynamics of the linac.

KEYWORDS: LEHIPA, Permanent Magnet Quadrupoles (PMQs), Drift Tube Linac (DTL)

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Introduction

The Low Energy High Intensity Proton Accelerator (LEHIPA) project at the Bhabha Atomic Research Centre (BARC) represents a significant leap forward in accelerator technology. As a pre-injector to the 1 GeV proton accelerator for the Accelerator Driven Sub-critical reactor System (ADSS), the demands on beam quality and stability are paramount. Following initial acceleration by a Radio frequency Quadrupole (RFQ), the proton beam enters the Drift Tube Linac (DTL), which is configured to accelerate the 10 mA beam from 3 MeV to its final energy of 20 MeV utilizing four consecutive DTL tanks, each approximately 3 meters in length [1].

At the relatively low initial beam energies of the Drift Tube Linac (DTL), space-charge forces dominate the beam dynamics. If left unmitigated, these forces lead to resonance trapping and beam halo formation, causing unacceptable particle losses and radioactivation of the accelerator structures. To counteract this, exceptional transverse focusing is required throughout the accelerator lattice.

To provide this focusing, Permanent Magnet Quadrupoles (PMQs) are embedded directly inside the concentric hollow copper conductors (drift tubes) of the DTL as shown in Fig.1. The use of permanent magnets is necessitated by the extremely limited volume inside the drift tubes, which also must accommodate cooling channels to dissipate the intense RF heat generated on the tube surfaces.

Because beam dynamics and physical constraints evolve significantly as the protons accelerate from tank to tank, a “one-size-fits-all” magnetic design is physically impossible. To solve this, two highly specialized, complementary PMQ architectures have been developed: a pure 16-segment design for the extreme constraints of the initial tanks [3], and an 8-segment hybrid design for the subsequent tanks [4, 5].

The Spatial-Gradient Paradox of DTL 1 & 2

The focusing strength of a quadrupole is determined by its Integrated Gradient (IG), rigorously defined as the longitudinal integral of the magnetic field gradient. In practical terms, this is expressed as $IG = G(0) \times L_{eff}$, where $G(0)$ is the central peak gradient and L_{eff} is the effective magnetic length.

The Challenge of Low-Energy Drift Tubes

Because the required focusing kick (IG) must remain constant to maintain beam stability, any reduction in the physical space available for the quadrupole necessitates a

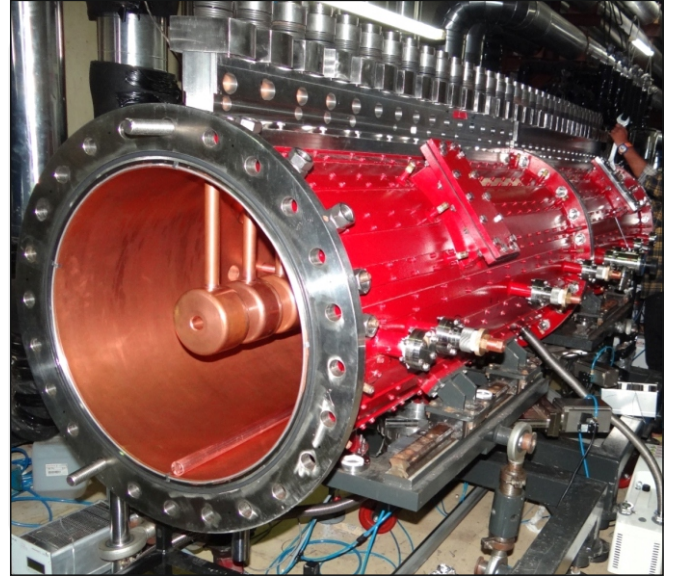


Fig.1: Picture of LEHIPA DTL, displaying drift tubes within which the PMQs are housed.

proportional, sometimes substantial, increase in the peak gradient.

At the low-energy entrance of the DTL (Tanks 1 & 2), the proton velocity is at its lowest. Consequently, the drift tubes that enclose the magnets are exceptionally short. In DTL-1, after accounting for the drift tube wall thickness (3 mm) and vital cooling channels, the maximum allowable length for a PMQ is restricted to just 37 mm. To achieve the required integrated gradient of ~ 2.19 T in such a constrained space, the internal magnetic gradient must reach a highly aggressive 60 T/m.

The 16-Segment Architecture (DTL 1 & 2)

To overcome the extreme gradient requirements in the tightly constrained initial tanks, a specialized 16-segment pure permanent magnet architecture was implemented as shown in Fig.2 (a) [3].

Physics and Field Linearity

Conventional quadrupoles struggle to reach a 60 T/m gradient within these dimensional constraints while maintaining a sufficiently large aperture for the beam. By dividing the magnetic cylinder into 16 discrete segments, the

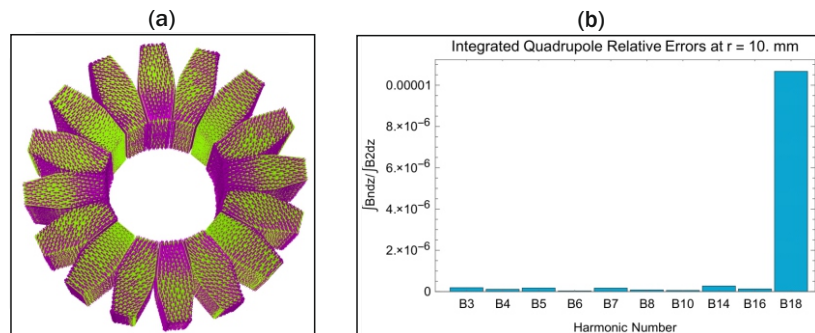


Fig.2: (a) 16 segment rectangular PMQ and (b) Simulated multipole field components.

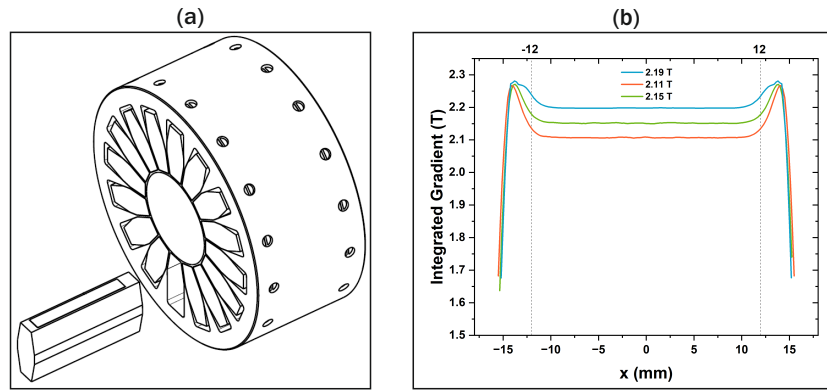


Fig.3: (a) CAD drawing of the PMQ assembly and (b) Integrated gradient tuning of the PMQ within the drift tube aperture, $x=\pm 12\text{mm}$ shown by the dashed lines.

design approximates an ideal $\cos(2\theta)$ magnetization distribution much more closely. This refined geometry efficiently concentrates the magnetic flux within the central bore, maximizing the achievable field gradient.

Beyond achieving higher gradients, the finer segmentation provides a much cleaner linear focusing lattice. It naturally suppresses higher-order magnetic multipole errors, specifically the disruptive dodecapole harmonic (Fig.2 (b)). Minimizing these non-linear error fields leads to a larger “good field region” (GFR), which is vital for minimizing resonance trapping and preventing halo formation in the delicate early stages of acceleration.

Mechanical Design and Precision Tuning

The 16-segment design utilizes a highly modular, removable mechanical architecture with a baseline outer diameter (OD) of 80 mm as shown in Fig.3 (a). Because the external drift tube housing has an OD of 120 mm, this compact magnet footprint creates a critical annular space, essential for routing cooling channels to maintain the thermal stability of the assembly.

Beam dynamics optimization often requires slight variations in focusing strength along the initial tanks. The 16-segment design accommodates this through a practical mechanical solution. By making precise transverse adjustments to the individual magnets within transverse gaps

in the holder, the assemblies were fine-tuned to meet multiple strict Integrated Gradient targets (e.g., 2.19 T, 2.15 T, and 2.11 T shown in Fig.3 (b)).

The Spatial-Gradient Paradox of DTL 1 & 2

As the proton beam accelerates through the linac, its velocity increases. By the time the beam reaches DTL Tanks 3 and 4, the physical length of the drift tubes naturally extends to match the higher particle velocity. With drift tubes in these later sections extending to lengths of 105 mm or more, the maximum allowable length for the embedded PMQs relaxes significantly (e.g., to 70 mm).

According to the spatial-gradient principle, as the available length L_{eff} increases, the peak gradient $G(0)$ required to maintain the ~ 2.05 T Integrated Gradient drops significantly (down to ~ 30 T/m). This relaxation in physical constraints opens the door for a different, highly advantageous engineering approach.

The 8-Segment Hybrid Architecture (DTL 3 & 4)

To capitalize on the increased spatial envelope in the later DTL tanks, an innovative 8-segment hybrid PMQ architecture was developed [4,5]. Instead of a pure permanent magnet Halbach array, this design integrates eight permanent magnet blocks with precisely contoured soft iron magnetic poles as shown in Fig.4 (a) and the design multipole components are shown in Fig.4 (b).

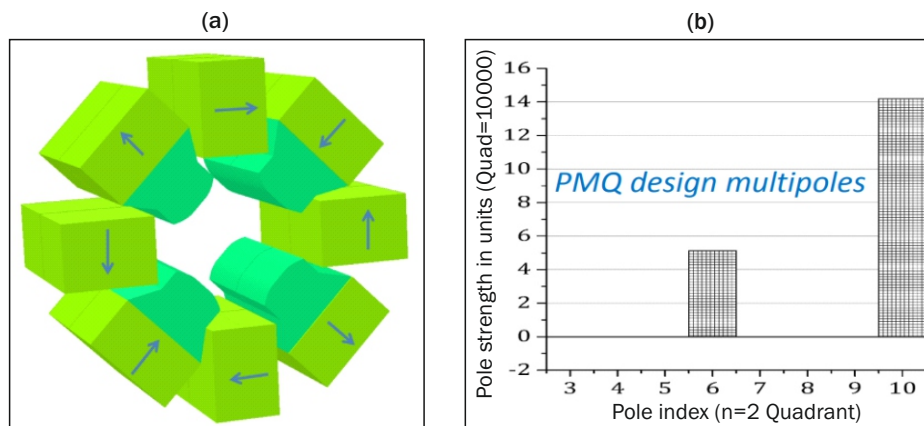


Fig.4: (a) The 8-Segment Hybrid PMQ Assembly and (b) multipole field components.

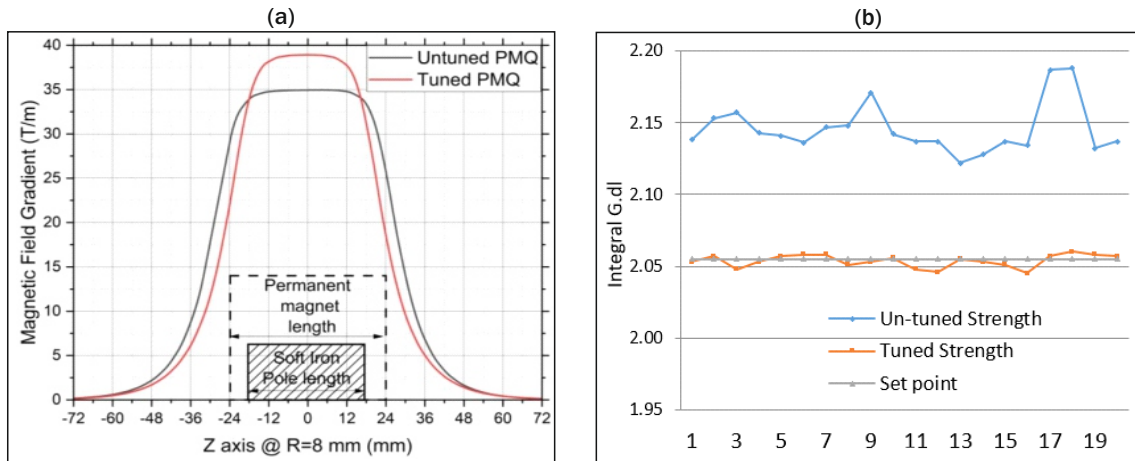


Fig.5: Hybrid PMQ Tuning Performance (a) Axial magnetic field plot and (b) IG plot for 20 number of PMQs before and after tuning.

Soft Iron Poles and Field Linearity

In this hybrid configuration, the permanent magnets act as the “engine” providing the required magneto-motive force (MMF), while the soft iron poles serve to concentrate and shape the magnetic field within the beam aperture.

Because the field quality in this design is governed by the geometry of the iron pole tips rather than the discrete magnetization angles of the permanent magnet blocks, the shape of the focusing field can be highly optimized. Second-order spline curves were utilized to precisely contour the pole faces. This iron-dominated central region allows the design to achieve an exceptionally linear magnetic field, with a theoretical uniformity of better than 0.2% in the good field region, leaving a sufficient budget for minor fabrication tolerances.

Innovative Pole-Length Tunability

The defining feature of this design is its novel approach to tuning the Integrated Gradient (IG). Traditionally, tuning permanent magnet quadrupoles involves altering the radial distance of the magnets or introducing magnetic shunts. Instead, this design uniquely leverages the longitudinal length of the soft iron poles for strength control.

By adjusting the length of the soft iron poles relative to the permanent magnets, engineers can intentionally alter the reluctance of the magnetic circuit to control fringing fields. Specifically, shortening the poles allows magnetic flux to escape the aperture to reduce the Integrated Gradient, while extending them captures this fringe flux to increase focusing strength. This pole-length shimming technique provides a highly precise and mechanically stable mechanism to tune the integrated gradient as shown in Fig.5. By deriving a transfer function that relates normalized pole length to field strength, a production series of 36 PMQs was successfully tuned. The assemblies effortlessly achieved the strict beam dynamics requirement of 2.05 T with an integrated gradient uniformity better than $\pm 0.5\%$, all without the need to manipulate the permanent magnet blocks.

Material Selection: A Shared Foundation

While the 16-segment and 8-segment hybrid designs utilize entirely different architectures and tuning mechanisms to solve their specific spatial challenges, they share a critical, unifying engineering choice: the permanent magnet material.

When selecting magnetic materials, the fundamental trade-off between peak magnetic strength and operational survivability arises. Neodymium Iron Boron (NdFeB) offers a

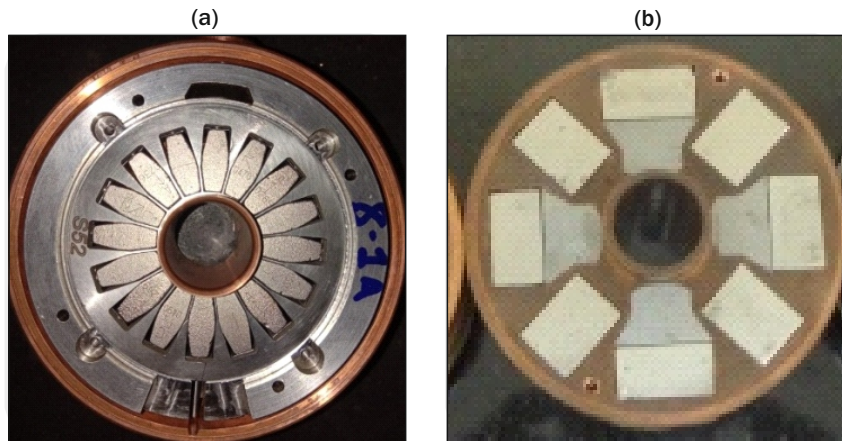


Fig.6: Final Fabricated Assemblies (a) 16-segment PMQ and (b) The 8-segment hybrid PMQ.

higher remanent magnetic field (Br) of ~1.4 T, making it an attractive choice for maximizing gradients. However, Samarium Cobalt ($\text{Sm}_2\text{Co}_{17}$), despite a lower remanent field of ~1.1 T, was selected exclusively for both LEHIPA PMQ designs.

In the high-radiation environment of a high-intensity proton accelerator, neutron irradiation can rapidly demagnetize permanent magnets. $\text{Sm}_2\text{Co}_{17}$ exhibits vastly superior radiation resistance and thermal stability compared to NdFeB. By prioritizing radiation hardness, both PMQ architectures ensure long-term gradient stability, preventing beam degradation and minimizing the need for costly accelerator downtime and maintenance.

Conclusion: A Synergistic Lattice

The successful operation of a complex, high-intensity linac like LEHIPA relies on engineering solutions that adapt to the evolving physics of the particle beam. By deploying the 16-segment pure PMQ design in the highly constrained, extreme-gradient environment of the initial tanks, and transitioning to the self-shielding, highly tunable 8-segment hybrid PMQ design in the later tanks, a highly optimized focusing lattice has been created.

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उच्च शक्ति वाले आर. एफ. युग्मकों का डिजाइन और विकास और प्रोटॉन त्वरकों के लिए परीक्षण व्यवस्था

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सारांश



उच्च-शक्ति 325 MHz अनुनाद वलय परीक्षण स्टैंड जिसमें से दो एकीकृत प्रोटोटाइप युग्मक परीक्षण के दौर से गुजर रहे हैं

उच्च-शक्ति वाले रेडियो-आवृत्ति (आरएफ) युग्मक रेखिक त्वरक (लीनॉक) में महत्वपूर्ण इंटरफेस घटकों के रूप में कार्य करते हैं, जो निर्वात विलगन और तापीय भार का प्रबंधन करते हुए बाह्य आरएफ स्रोतों से विद्युत चुम्बकीय ऊर्जा को गति देने वाली गुहिकाओं में स्थानांतरित करते हैं। यह पांडुलिपि भापअ केंद्र में लेहिपा और मेहिपा कार्यक्रमों के सामान्य प्रचालन और अति-चालकता संरचनाओं हेतु विकसित विभिन्न आरएफ युग्मकों के अभिकल्पन, अनुकरण और उच्च शक्ति अभिलक्षणन को प्रस्तुत करती है। रेडियो आवृत्ति चतुर्भुजी (आरएफक्यू) और अपवाह नलिका लीनॉक (डीटीएल) गुहिकाओं के लिए सुयोजित वेवगाइड-आधारित युग्मक 325 MHz पर 300 kW निरंतर-तरंग (सीडब्ल्यू) शक्ति के प्रहस्तन हेतु सुयोजित किए गए हैं, जबकि समाक्षीय लूप युग्मक का उपयोग एमईबीटी/एचईबीटी गुच्छक गुहिकाओं के लिए किया जाता है। अति-चालक संरचनाओं के लिए, भारतीय संस्थान एवं फर्मीलैब सहयोग (आईआईएफसी) तथा स्वदेशी कार्यक्रमों दोनों के तहत 325 MHz और 650 MHz समाक्षीय युग्मक विकसित किए गए हैं। इन युग्मकों का लागत प्रभावी ढंग से परीक्षण एवं सत्यापन हेतु, समर्पित उच्च-शक्ति परीक्षण स्टैंड स्थापित किए गए हैं, जिनमें 325 MHz अनुनाद वलय सुविधा शामिल है जो >12 dB शक्ति लाभ प्रदान करती है और 650 MHz स्थायी तरंग परीक्षण सुविधा हेतु सफलतापूर्वक प्रचालित की गई है।

6

Design and Development of High Power RF Couplers and Test Setup for Proton Accelerators

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ABSTRACT



The high-power 325 MHz resonant ring test stand with two integrated prototype couplers undergoing testing

High-power radio-frequency (RF) couplers serve as critical interface components in linear accelerators (linacs), transferring electromagnetic energy from external RF sources into accelerating cavities while managing vacuum isolation and thermal loads. This manuscript presents the design, simulation, and high-power characterization of various RF couplers developed for the normal conducting and superconducting structures of the LEHIPA and MEHIPA programs at BARC. Waveguide-based couplers designed for Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) cavities are engineered to handle up to 300 kW continuous-wave (CW) power at 325 MHz, while coaxial loop couplers are utilized for MEHT/HEBT buncher cavities. For superconducting structures, 325 MHz and 650 MHz coaxial couplers have been developed under both the Indian Institute and Fermilab Collaboration (IIFC) and domestic programs. To test and validate these couplers cost-effectively, dedicated high-power test stands, including a 325 MHz resonant ring facility providing a power gain of >12 dB and a 650 MHz standing wave test facility, have been established and successfully operated.

KEYWORDS: LEHIPA, MEHIPA, Radio Frequency Quadrupole (RFQ), Proton accelerators, Drift Tube Linac (DTL), Radio-frequency (RF).

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Introduction

In a linear accelerator (linac), high-power radio-frequency (RF) couplers serve as critical interface components that transfer electromagnetic energy from an external source, such as a klystron or solid-state amplifier, into accelerating cavities. These couplers perform several essential functions simultaneously, including efficient power transfer, vacuum isolation, and thermal management across different regions of the system [1, 2]. The primary role of an RF coupler is to ensure efficient delivery of power from the generator to the load, which consists of the accelerating cavity and the beam. From this standpoint, a coupler can be viewed as a carefully engineered transition within an otherwise perfectly matched transmission line, enabling the precise amount of power required for beam acceleration to be delivered with minimal reflection and loss.

Typically, a linear accelerator consists of an initial section of normal conducting accelerating cavities followed by superconducting accelerating cavities. Since normal conducting cavities require significantly higher RF power compared to superconducting cavities, the design and operational requirements of RF couplers differ for these two sections. This article presents the detailed design and development of various high-power RF couplers, along with their associated test setups [1,3,4], for the linear accelerators LEHIPA and MEHIPA of BARC.

Design Methodology

RF Couplers for Warm Accelerating Structures of LEHIPA and MEHIPA

The RF couplers for the Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) cavities of LEHIPA and MEHIPA are waveguide-based [2, 5, 6]. The RFQ features two input ports requiring two couplers. For the LEHIPA DTL1 and DTL2, four ports are configured each, requiring a total of eight waveguide RF couplers. In contrast, the MEHIPA DTL up to 10 MeV requires only four waveguide couplers. Each DTL waveguide coupler is engineered to handle 250 kW to 300 kW of continuous-wave (CW) power.

Because the dimensions of the input waveguide transmission lines (WR2300 Half-Height) are significantly larger than the cavity dimensions, a narrow cross-section transition with an iris of suitable dimensions is required at the coupler interface to establish sufficient coupling with minimal frequency perturbation. A separate waveguide window provides the necessary vacuum barrier separating the air-filled

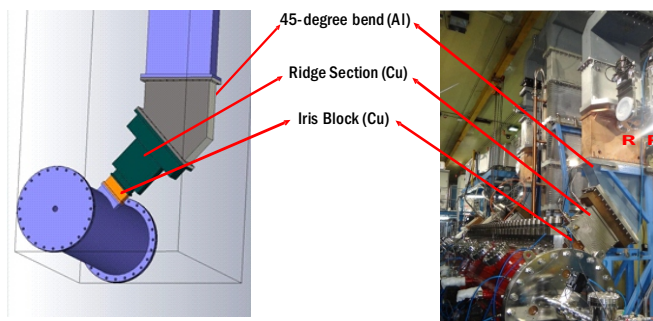


Fig.1: Schematic of the waveguide couplers designed for DTL cavities, highlighting the RF window, ridge section, and iris block.

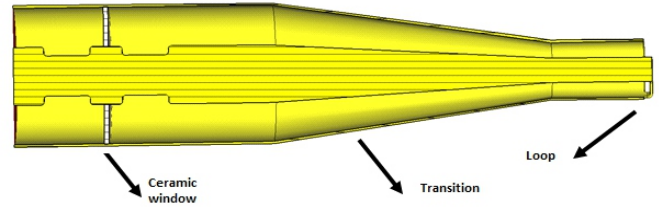


Fig.2: Cross-sectional design model of the 50 kW CW coaxial loop coupler optimized for MEBT and HEBT buncher cavities.

waveguide from the vacuum-driven cavity structure. The electromagnetic design progresses through three stages: a waveguide transition at 325 MHz matching the WR2300HH interface to a smaller ridge waveguide, an optimized iris configuration, and mechanical interfaces facilitating ease of manufacture, vacuum sealing, and thermal management, as illustrated in the schematic layout in Fig.1.

For the Medium Energy Beam Transport (MEBT) and High Energy Beam Transport (HEBT) buncher cavities of MEHIPA, coaxial couplers are employed [7]. Five coaxial couplers are planned in total: two for the MEBT bunchers and three for the HEBT bunchers. This coaxial design incorporates an RF window, a coaxial transition from a 6-inch line to a 70 mm outer diameter coaxial line, and a rotatable loop coupler that allows tunability of the coupling coefficient (as shown in Fig.2). The loop is water-cooled through its inner conductor to fulfill a 50 kW CW power rating while the structure is optimized to suppress multipacting probabilities.

RF Couplers for Superconducting Cavities

Under the Indian Institute and Fermilab Collaboration (IIFC), BARC has developed coaxial RF couplers to deliver high RF power to Single Spoke Resonators (SSR, 325 MHz) and elliptical (650 MHz) superconducting cavities [8]. Prototype units—consisting of two 650 MHz and three 325 MHz couplers—have been successfully built (Fig.3), with an additional 19 production-phase couplers under development for Fermilab.

For the superconducting spoke resonator cavities (SSR-B) of MEHIPA-1, 18 coaxial couplers operating at 325 MHz are being developed [9]. Waveguide structures at 325 MHz would be prohibitively bulky and impose unsustainable thermal loads on the cryogenic system, making coaxial lines the ideal choice. The domestic design builds upon the Fermilab configuration but implements geometric changes to accommodate a significantly higher power requirement of 50 kW CW, which is 2.5 times greater than Fermilab's 20 kW rating.

The coupler utilizes a 105 Ω coaxial geometry featuring a single 7 mm thick alumina ceramic disk acting as a room-temperature vacuum RF window between the warm and cold

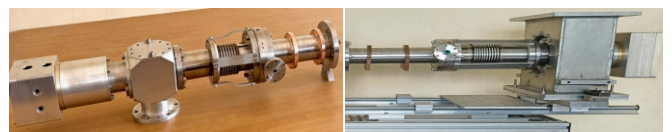


Fig.3: Fabricated prototype IIFC coaxial RF couplers operating at 325 MHz and 650 MHz for superconducting cavities.

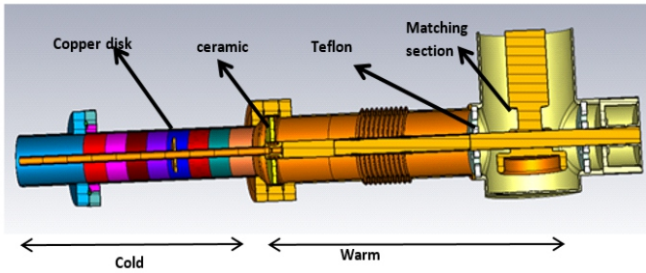


Fig.4: Structural (cutaway) view of the 325 MHz SSR-B coaxial coupler, detailing the warm and cold parts, ceramic RF window, and matching section.

regions. It employs an air-cooled inner antenna for capacitive coupling to the SSR-B cavity, converting from a 6-1/8" rigid coaxial line on the air side to a 4" coaxial line at the cavity interface. The structural arrangement and detailed cutaway view of this assembly are depicted in Fig.4. It has an integrated provision to apply a high-voltage (HV) DC bias to suppress multipacting, and specialized mechanical bellows to accommodate thermal contraction.

Result & Discussion

RF, Thermal, and Stress Simulation Performance

Electromagnetic and multi-physics simulations for the MEHIPA superconducting couplers were conducted using CST Microwave Studio and COMSOL [10]. RF simulation results demonstrate excellent impedance matching, achieving a return loss better than 34 dB at the input port. Evaluation of the electric field monitors indicates a maximum RF field strength of 27 kV/cm on the vacuum side, which remains well below critical breakdown thresholds, as shown in the electric field distribution profile in Fig.5.

Thermal simulations were directly coupled with the RF field profiles to calculate temperature distribution and heat loads. Managing the thermal gradient of the cold section is essential to minimize the cryogenic load, as the temperature transitions from 293 K on the warm side to 2 K at the cavity interface. Two thermal intercepts, positioned at 5 K and 50 K respectively, are integrated to actively cool the outer conductor. Under the worst-case operating envelope of 50 kW full reflection, the maximum antenna temperature reaches 341 K, while the residual heat leakage into the 2 K cryogenic environment is tightly restricted to 0.68 W (Fig.6). Structural stress analyses under atmospheric pressure combined with thermal expansion (50 kW, 20% reflection case) indicate a maximum stress of less than 70 MPa at the critical outer

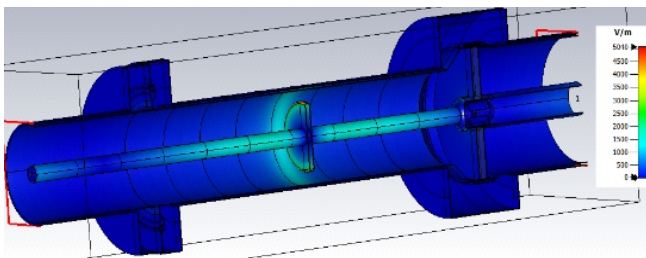


Fig.5: Electromagnetic simulation identifying the maximum electric field distribution (27 kV/cm) within the vacuum side of the SSR-B coupler.

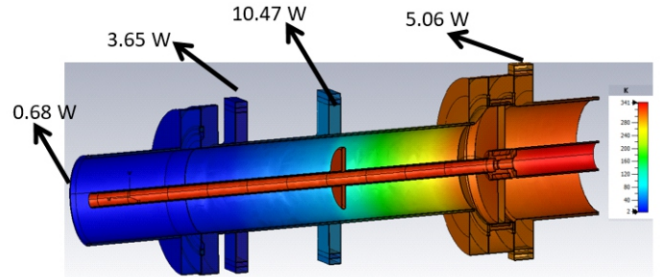


Fig.6: Multi-physics thermal profile of the coupler's cold section during the worst-case scenario (50 kW, full reflection), showing a maximum heat flow of 0.68 W towards the cavity.

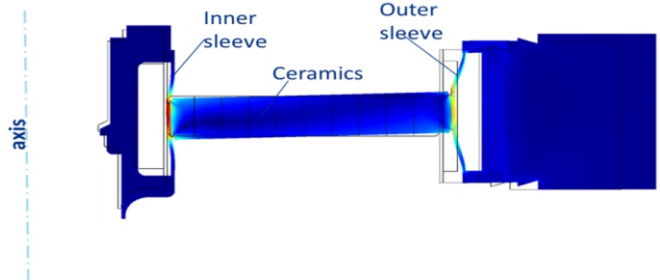


Fig.7: 2D analysis displaying mechanical deformation and stress distribution at the alumina ceramic joint due to atmospheric pressure and thermal expansion.

sleeve-to-alumina ceramic brazed joint, ensuring a highly reliable mechanical safety margin, as shown in the deformation analysis in Fig.7.

High-Power Characterization and Test Setups

To validate and qualify the engineered couplers before accelerator integration, cost-effective high-power test stands have been developed [1, 3,4]. Two primary test facilities have been established:

325 MHz Test Facility: A high-power resonant ring-based test stand was developed where two couplers can be tested simultaneously under either traveling wave (TW) or standing wave (SW) regimes [1,3]. When the electrical length of the ring is tuned to an integral multiple of the guided wavelength, resonance is established, leading to an optimal power multiplication gain. Initial bare-ring testing reached up to 130 kW CW power with a 4.5 kW input, achieving a power gain of 14.4 dB. Recently, two fabricated 325 MHz couplers were integrated into the ring assembly, pre-tuned with the help of Vector Network Analyzer (VNA) measurements. The couplers were tested upto 25 kW in pulsed traveling wave mode, yielding a measured gain of 12.4 to 12.83 dB with respect to the input RF Amplifier output. The fully assembled physical setup is shown in Fig.8. The critical experimental parameters from this evaluation run are outlined in table 1, and the corresponding transient high-power data is illustrated in Fig.9.

650 MHz Test Facility: Based on a Fermilab layout, a high-power test stand configured around a central tuning cavity positioned between two prototype 650 MHz couplers has been established, as shown in Fig.10. Low-power tuning and S-parameter optimization were verified using a VNA, showing an achieved power multiplication gain of approximately 6 dB

Table 1: High-power testing parameters of 325 MHz couplers in the resonant ring facility.

Sr. No.	Parameter	Measured Value
1	Input Power	1.3 kW
2	Output Power (Circulating / Ring)	25 kW
3	Frequency of Operation	325.37 MHz
4	Measured Ring Gain	12.83 dB
5	Pulse Width	500 μ s
6	Pulse Repetition Rate (PRR)	1 Hz



Fig.8: The high-power 325 MHz resonant ring test stand with two integrated prototype couplers undergoing testing.

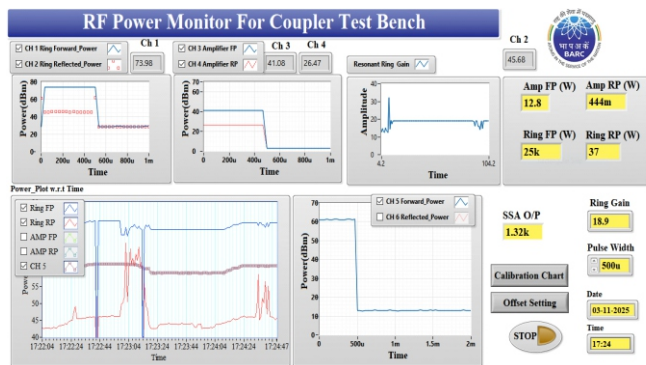


Fig.9: High power test results of the 325 MHz couplers characterized in the resonant ring facility.

[4]. This setup allows high-power testing exclusively in the standing wave (SW) mode when the electrical length is configured to match an integral multiple of the operating wavelength.

Conclusions

A comprehensive suite of high-power waveguide and coaxial RF couplers has been engineered, fabricated, and simulated to support the normal conducting and superconducting linac infrastructure of BARC's LEHIPA and MEHIPA programs. Multi-physics analyses validate that the specialized 325 MHz 50 kW coaxial couplers operate within safe breakdown (27 kV/cm) and structural stress (< 70 MPa) bounds while minimizing cryogenic heat leakage down to 0.68 W. Furthermore, operational implementation of the 325 MHz resonant ring and 650 MHz test stands demonstrates reliable power gains (>12 dB and 6 dB respectively), establishing an efficient methodology for full-scale high-power verification of accelerator-grade RF window and coupler systems.



Fig.10: The 650 MHz high-power test facility setup, featuring a central cavity positioned between two prototype couplers for standing wave mode evaluation.

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7

लेहिपा और मेहिपा हेतु ठोस अवस्था शक्ति प्रवर्धक तथा निर्वात इलेक्ट्रॉनिक उपकरणों का स्वदेशी अभिकल्पन एवं विकास

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सारांश



एकीकृत प्रोटोटाइप – आईओटी एवं 64:1 पावर कॉम्बाइनर

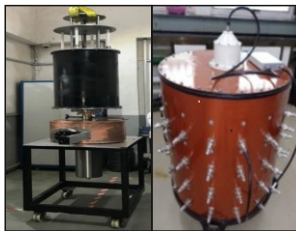
भापअ केंद्र ने त्वरकों के लिए स्वदेशी रूप से अभिकल्पित ठोस अवस्था शक्ति प्रवर्धक (एसएसपीए) तैयार एवं विकसित किया है। फर्मिलैब के पीआईपी-II अंतःक्षेपण परीक्षण (पीआईपी2आईटी) सुविधा में नौ 7 kW SSPAs का कमीशनन किया गया। एसएसपीए के 25 kW, 50 kW और 300 kW का एक समूह मेहिपा और लेहिपा हेतु विकास के अधीन है। ये एसएसपीए क्रमशः लेहिपा और मेहिपा के आरएफ त्वरकों के अति-चालकता और कमरे के तापमान वाले गुहिकाओं को शक्ति प्रदान करते हैं। इन उच्च लाभ एवं उच्च दक्षता वाले एसएसपीए की महत्वपूर्ण उप-प्रणालियाँ हैं: 2 kW शक्ति प्रवर्धक (पीए) मॉड्यूल, मॉड्यूलर एवं हॉट स्विपेबल डीसी विद्युत आपूर्ति, विद्युत विभाजक एवं संयोजक, एसी विद्युत वितरण प्रणाली, अंतर्बंध संरक्षण एवं निगरानी प्रणाली (आईपीएमएस) और आवासीय उप-प्रणालियों के लिए एक संहत एवं स्थिर यांत्रिक संरचना। वैकल्पिक रूप से उच्च दक्षता (एचई) प्रेरक उत्पादन नली (आईओटी) और एचई 400 kW क्लाइस्ट्रॉन का अभिकल्पन एवं विकास आरंभ किया गया है। इस लेख में, भापअ केंद्र में इन अभिकल्पन एवं विकास प्रयासों का विवरण दिया गया है।

7

Indigenous Design and Development of Solid State Power Amplifiers and Vacuum Electronic Devices for LEHIPA and MEHIPA

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Integrated prototype IOT and 64:1 power combiner

ABSTRACT

BARC has indigenously designed and developed Solid State Power Amplifiers (SSPA) for accelerators. Nine 7 kW SSPAs were commissioned at Fermilab's PIP-II Injector Test (PIP2IT) facility. A family of SSPAs 25 kW, 50 kW, and 300 kW are under development for MEHIPA and LEHIPA. These SSPAs power the super-conducting and room temperature cavities of RF accelerators of LEHIPA and MEHIPA respectively. The important subsystems of these high gain and high efficiency SSPAs are: 2 kW power amplifier (PA) module, modular and hot swappable DC power supplies, power divider and combiner, AC power distribution system, interlock protection and monitoring system (IPMS) and a compact & stable mechanical structure for housing the subsystems. Alternatively design and development of high efficiency (HE) inductive output tube (IOT) and high Efficiency 400 kW klystron has been initiated. This article gives details of these design and development efforts at BARC.

KEYWORDS: IOT, Klystron, Radio Frequency, solid state Power amplifiers, IPMS

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Introduction

Bhabha Atomic Research Centre has envisaged development of an Accelerator Driven subcritical reactor System (ADS). A 1 GeV high-intensity proton accelerator is being developed in a phased manner for the Indian ADS program. These are Low Energy High Intensity Proton Accelerator (LEHIPA), Medium Energy High Intensity Proton Accelerator (MEHIPA) and High Energy High Intensity Proton Accelerator (HEHIPA). As envisioned in the Amrit kaal document [1] of DAE, all the accelerators of the 1 GeV proton linac shall be powered by Solid State Power Amplifiers (SSPA) [2,3,4,5] in radio frequency (RF) range. As a part of roadmap for indigenous RF power technology development, research and development (R&D) of RF power devices and /or systems is focused on three distinct technologies viz., inductive output tube (IOT), high efficiency klystron and solid state power amplifier (SSPA) in ultra-high frequency (UHF) range.

In modern RF accelerators worldwide, a gradual shift towards solid state power amplifier (SSPA) technologies has been observed. This is attributed to the advantages offered by solid state RF over conventional vacuum tubes such as a) use of low voltage DC power supplies (DCPS), b) low power circulators, c) increased efficiency d) increased MTBF, e) simple on and off sequence, f) modularity and redundancy, and g) graceful degradation of RF power. As a complimentary technology development, design and development of kW level high efficiency (HE) inductive output tube (IOT) and HE klystrons has started.

SSPA System Architecture

Fig.1 shows the modular architecture and the interconnections of all sub-systems of SSPA. A Low Power RF amplifier (LPRF) amplifies a 325/352 MHz input signal. An n -way input divider splits it equally. This $1/n$ output is fed to each identical 2 kW PA modules. These amplified outputs are combined by an $n:1$ power combiner and measured by a

directional coupler. The value of n scales with the SSPA rating. It is 14, 28, and 160 for the 25, 50 and 300 kW SSPAs respectively.

SSPA System: 25 kW @ 325 Mhz

In 25 kW SSPA, a LPRF system amplifies 325 MHz signal input from signal generator. The amplified power is split equally by a 14-way divider and fed to each identical 2 kW power amplifier (PA) module. A 14:1 power combiner combines these amplified outputs. An output directional coupler measures the forward and reflected power output. A circulator rated at 28 kW protects the SSPA system against RF reflection from the SC cavities. The amplifier can operate in both pulse and CW mode. Power factor is greater than 0.9 and THD is below 30%. Table 1 lists its principal RF specifications.

SSPA System: 50 kW @ 325 Mhz

A 50 kW, 325 MHz SSPA is RF power amplifier designed using 28 power modules, which are combined using a 28-way cavity combiner. An external signal is amplified by a LPRF system rated at 600 W. This RF power drives the 28 modules rated at 2 kW each. The combined power output is taken on EIA 6-1/8" line. A CW directional coupler rated at >60 kW is used to measure and have circulator for protection of SSPA against the reflected power. The main specifications of the 50 kW SSPA are shown in Table 1.

SSPA system: 300 kW at 325/352 MHz

The configuration of the 300 kW SSPA is shown in Fig.1. A small signal input is amplified to a power level of 3 to 4 kW at 325/352 MHz by a LPRF system. The LPRF output is divided into 160 outputs each rated at 18 to 25 W by a 160-way power divider. It drives each PA module rated at 2 kW, 352 MHz and biased by a respective DCPS. The outputs of such 160 power modules (PA) biased by 160 numbers of DC power supplies (DCPS), are combined by a 160-way power combiner to produce the net RF power output of 300 kW. The main

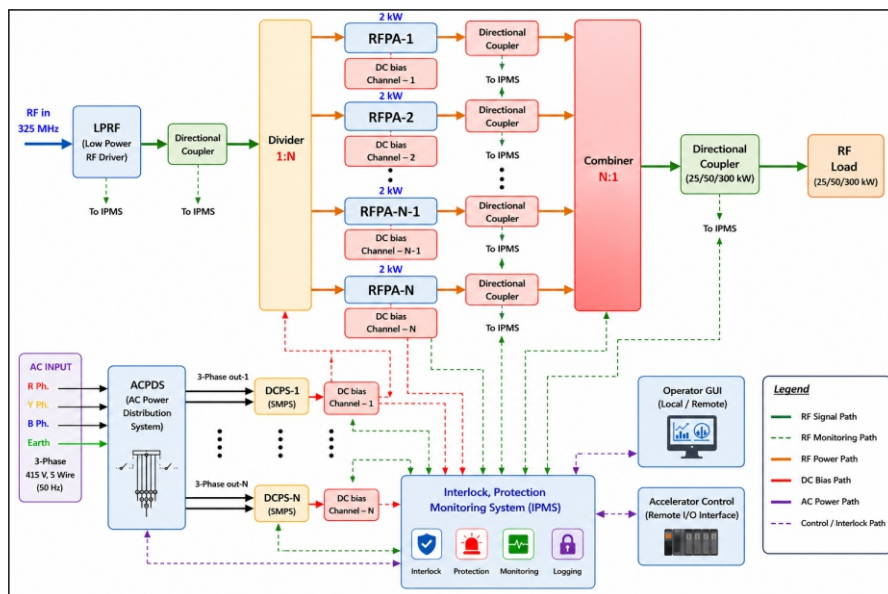


Fig.1: Modular architectural block diagram of SSPA systems.

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Table 1: Technical Parameters of designed SSPAs.

Sr. No.	Parameters	25 kW SSPA	50 kW SSPA	300 kW SSPA
1.	Centre frequency	325 MHz	325 MHz	352;325 MHz
2.	Mode of operation	Pulse&CW	Pulse&CW	Pulse; pulse&CW
3.	RF output power @ 1dB compression	≥ 25 kW	≥ 50 kW	≥ 300 kW
4.	Bandwidth @ 3 dB	≥ 4 MHz	≥ 4 MHz	≥ 4 MHz
5.	Power gain	≥ 68 dB	≥ 71 dB	≥ 71 dB
6.	Gain variation (30%–90% output power)	≤ 2 dB	≤ 2 dB	≤ 2 dB
7.	Phase variation over power band	$\leq 15^\circ$	$\leq 15^\circ$	$\leq 15^\circ$
8.	Harmonic power (half & full power)	Better than –25 dBc	Better than –25 dBc	Better than –25 dBc
9.	Spurious power (half & full power)	Better than –50 dBc	Better than –50 dBc	Better than –50 dBc
10.	VSWR handling (half to full power)	≤ 1.4	≤ 1.4	≤ 1.4
11.	AC to RF efficiency at peak power	$\geq 45\%$	$\geq 42\%$	$\geq 42\%$

technical specifications of the 300 kW SSPA are shown in Table 1. SSPA rated at 300 kW, 325 MHz is designed to operate in both pulse and CW mode whereas 300 kW, 352 MHz amplifier is designed to operate at 10% duty factor with pulse length of 50 us to 2 ms only.

Description of Sub-systems of SSPAs

AC Power Distribution System

AC Power Distribution System (ACPDS) implements the distribution, routing and monitoring of AC mains power from high power transformer to the resp. DC power supplies (DCPS). It distributes the incoming 3- ϕ main power line into multiple 1- ϕ lines to power DCPS modules.

DC Power Supply (DCPS) with hot swapping scheme

The DC biasing system (Fig.2) of the SSPA uses multiple high-efficiency Switched Mode Power Supply (SMPS) units as DCPS (Fig.2) powered through the ACPDS. It operates from a

415 V, 3-phase AC supply and integrates protection and monitoring through the IPMS. These supplies are optimized for stable output under dynamic load conditions. They use a compact water-cooled design with high power density and efficient thermal management suitable for high-channel-count SSPA systems. Remote ON/OFF control, enable/disable functions and health-status monitoring are provided for integration with the central IPMS system.

Stable Mechanical Structure

A stable mechanical structure shall house SSPA sub-systems viz., LPRF, power divider and combiner, ACPDS, DCPS, PA modules, cables, water cooling hardware and circuit.

Low Power Radio Frequency (LPRF) system

A LPRF system is the front-end RF amplifier stage of the all the SSPAs. It feeds required power at 325/352 MHz to the input of the 1: n -way power divider. LPRF have a limited no. of

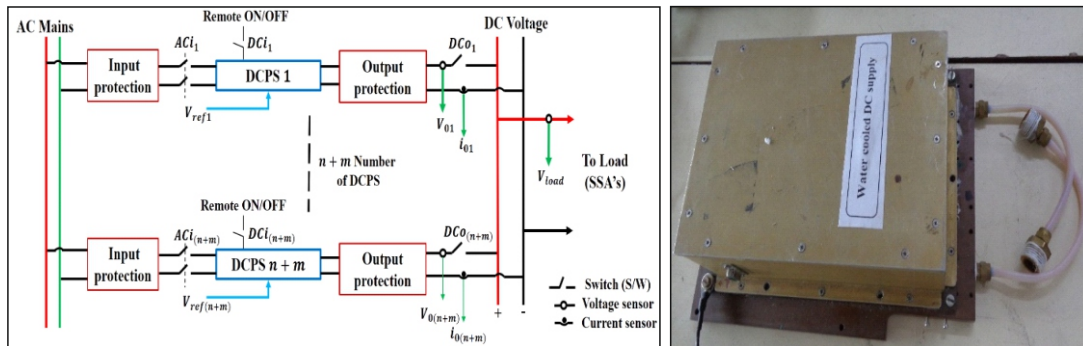


Fig.2: DC power supply system architecture with hot swapping scheme and tested DCPS.

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Table 2: LPRF Specifications.

Sr. No.	Parameters	Values
1.	Power rating (peak)	≥ 3 kW
2.	Gain @ 3 kW peak power	57 dB
3.	3 dB bandwidth	7 MHz
4.	Harmonics	<-30 dBc
5.	Input VSWR	≤ 1.2

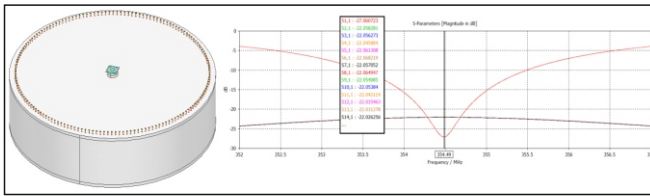


Fig.3: Fabrication model of divider and its Transmission and return loss.

series of amplifiers along with protections. Table 2 lists the salient specifications of LPRF for 300 kW SSPA. The LPRF for 25 and 50 kW SSPAs are scaled down version of LPRF used in 300 kW SSPA.

Power divider

All the SSPA systems use either a cavity divider or planar PCB based power divider. Power divider derives respective number of RF power outputs to drive the PA modules. A 160-way RF power divider has been designed and simulated for the 300 kW, 352 MHz SSPA. It consists of a cylindrical cavity, 160 numbers of RF outputs on SMA connectors and a 1-5/8" RF input. Fig.3 shows the fabrication model of the 1:160-way divider and its simulation results.

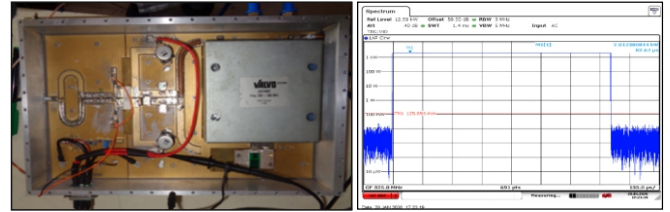


Fig.4: Developed 2 kW PA module and its measured power waveform.

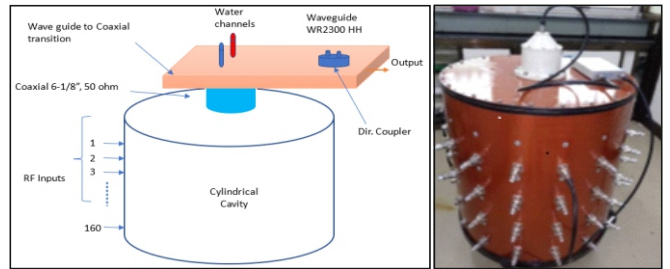


Fig.5: Sketch of 160-way combiner and fabricated 64 way cavity combiner.

PA Module

The Power Amplifier (PA) module is the fundamental building block of all the SSPA systems mentioned above. Each PA module is capable of delivering approximately 2 kW RF output power at 325/352 MHz. Since the reliability of the PA module is critical for the overall performance of the SSPA system, the design utilizes high-reliability RF components with Mean Time Between Failures (MTBF) greater than 200,000 hours. The developed RF PA module and its test results shown in Fig.4.

Power combiner

The power combiner [5] is a multi-input and single output device used to combine the output from multiple PA modules.

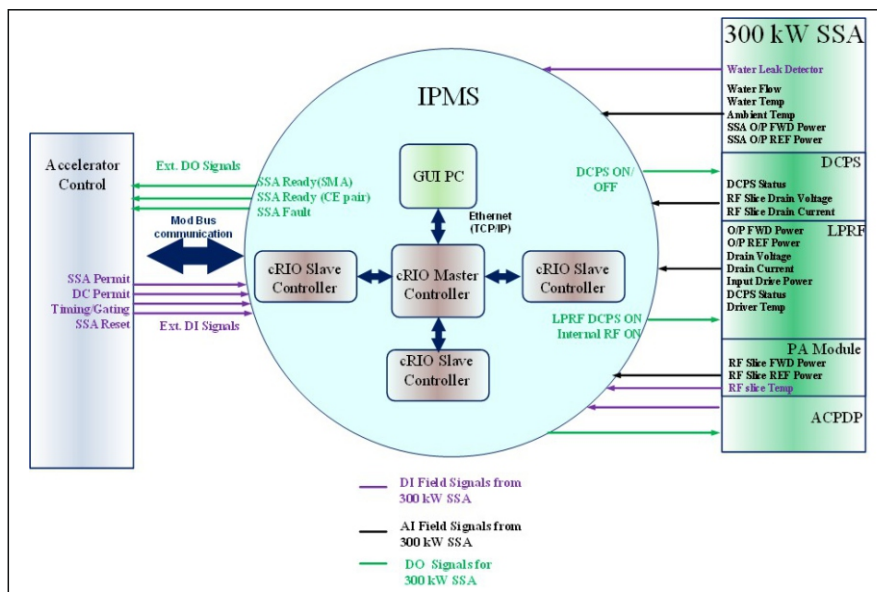


Fig.6: Scheme of IPMS.

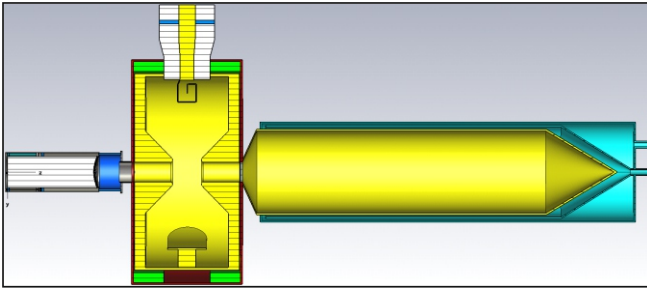


Fig.7: Integrated model of IOT.

Fig.5 shows the 160-way cavity type power combiner comprising of a cylindrical cavity, 160 numbers of RF inputs, a coaxial to waveguide transition, an output WR2300 half-height waveguide (CW case) etc. For CW operation, it has provision for water-cooling. All the SSPAs use the similar type of power combiner with scaled number of inputs.

Interlock, Protection and Monitoring system (IPMS)

IPMS is used for the safe and reliable operation of SSPA. It protects the SSPA in case certain parameters of signals exceed the specified trip limit. The IPMS can accept the commands from Local GUI display as well as the Remote-control system. Main functions of IPMS are a) To ensure interlock among internal/External signals, b) Sequential ON/OFF of various subsystems of SSPA, c) Acquiring and processing of signals d) Data logging and real time display e) Trip generation and protection of SSPA system f) Trip annunciation to the operator in case of abnormal signal conditions g) Calibration and setting of trip parameters h) Protect the SSPA against faulty operating conditions i) Communication of SSPA parameters to remote system. Fig.6 shows the scheme of the IPMS system.

HE Inductive Output Tube

Efficiency of high power RF system is mainly governed by its power generation device. High efficiency (HE) vacuum electronic devices (VEDs) operating in UHF range (300 MHz to 3 GHz) are specialized vacuum tubes intended for generation of high RF power with high efficiency. The simulated design of one such inductive output tube (IOT) is shown in Fig 7.

IOT design at 325 MHz

An IOT [6] has been simulated and designed for operation at 325 MHz, 100 kW and at an efficiency of approximately 70%. The design simulation of all the sub-

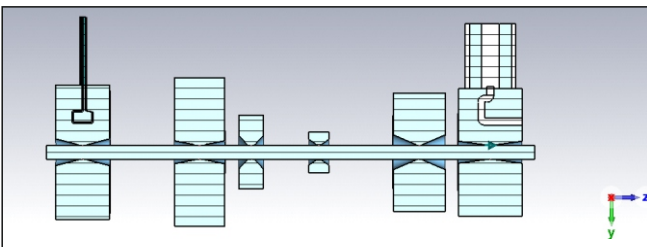


Fig.9: Simulated model of HE klystron at 352 MHz.

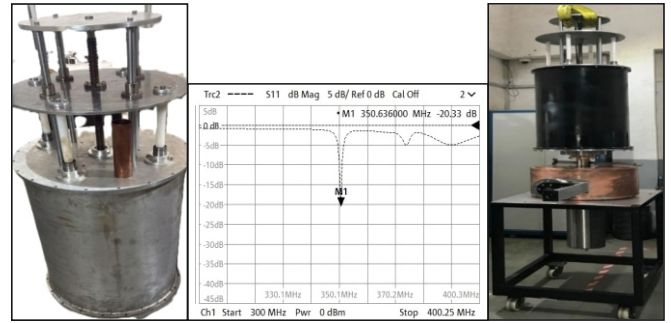


Fig.8: Input Cavity of IOT and its input matching graph and integrated prototype IOT.

components of the IOT, viz. the gridded electron gun, drift space, the input and output cavities, the magnetic circuit, and water cooled collector are completed. The input cavity ($3\lambda/4$) is a TM^{01} mode coaxial cavity, while the output cavity ($\lambda/4$) is a TM^{01} mode re-entrant cavity.

The magnetic circuit is designed to provide a brillouin focusing to the electron beam. The simulation of the integrated model (Fig.7), along with studies on the effect of the output gap and the R/Q of the output cavity on the efficiency and output power level is completed.

Prototype IOT development

Based on the design, a prototype IOT (Fig.8) was developed. Its input cavity with insulator arrangements for electron gun was fabricated. It has variable input tuner for tuning the cavity. Its variable input coupler matches the cavity impedance to 50-ohm. The fabricated input cavity and its RF characterisation is shown in Fig.8. Its further optimization is in progress. The fabricated output cavity has variable tuner for achieving the resonance at 325 MHz and an output loop coupler for extracting RF power via output Teflon window. The integrated IOT assembled together and RF characterised with both input and output cavities and water cooled collector with stainless steel water jacket is shown in Fig.8. Design of electron gun has been initiated.

High Efficiency Klystron at 352 Mhz

Though vacuum devices excel in high power, achieving high efficiency in smaller and compact footprint remains a primary research challenge. HE klystron [7] with efficiency

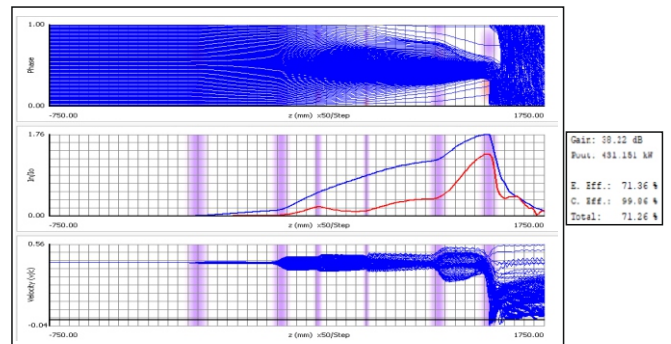


Fig.10: Initial 1-D Model 352 MHz Klystron Design-simulation and its parameters.

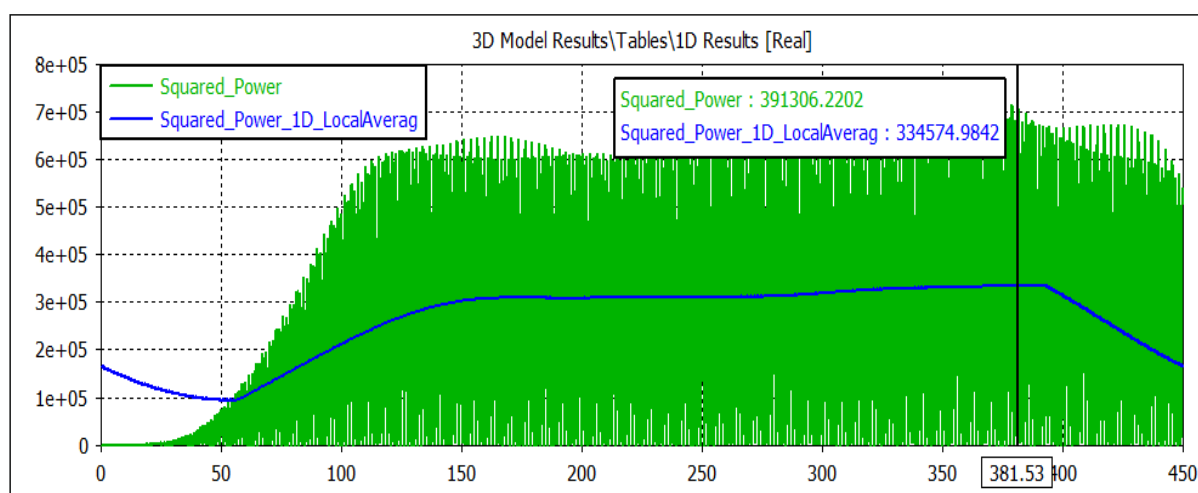


Fig.11: RF power Output received from simulation of HE UHF klystron at 352 MHz.

more than 75% is strongest candidate among all. This technology development initiated is HE, vertically mounted klystron of RF power 400 kW at 352 MHz. The initial simulated model is shown in Fig.9. Figure 10 gives 1D model of HE klystron, its initial beam parameters and efficiency achieved via simulation. RF power obtained from simulated HE klystron is shown in Fig.11. Further design is in progress.

Management of electron scattering, secondary electron emission in insulators, cavities and collector remains crucial, as they degrade their performance.

Conclusion

IOT has been successfully designed and its prototype has been developed except electron gun. HE UHF klystron design has been initiated. BARC has developed solid-state amplifiers for indigenous accelerator programs. SSPA development [2, 3, 4, 5] progress is well continuing. Major subsystems of 352/325 MHz and 25 kW, 50 kW 300 kW SSPAs have been designed and their development is underway. All these technologies are completely indigenous and are in line with the Atmanirbhar Bharat mission.

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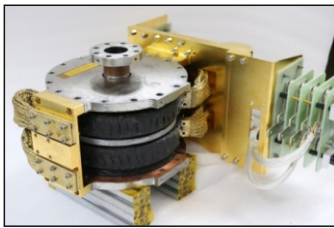
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उच्च तीव्र प्रोटॉन त्वरकों हेतु चालन शीतित अति-चालक चुंबक का बहु-भौतिक अभिकल्पन, विकास एवं कार्य-निष्पादन

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सारांश



ऊष्मा अभिगम एवं शीत डायोड के साथ प्रसाधित चुंबक समाहार

उच्च तीव्रता रेखिक प्रोटॉन त्वरकों को मध्यम और उच्च ऊर्जा व्यवस्था में अति-चालक त्वरण संरचनाओं के कार्यान्वयन की आवश्यकता होती है ताकि एकल-स्पोक अनुनादकों और दीर्घवृत्ताकार गुहिकाओं के संयोजन का उपयोग किया जा सके जो उच्च ऊर्जा के लिए प्रोटॉन कणपुंज के कुशल त्वरण को समर्थ बनाता है। लीनॉक के मध्यम ऊर्जा खंड में दो प्रकार के अतिचालक एकल स्पोक अनुनादक (एसएसआर) रेडियो आवृत्ति गुहिकाएँ (एसएसआर1 और एसएसआर2) होती हैं, जो उच्च-क्षेत्र सोलनॉइड फ़ोकसिंग लेंस के साथ अंतरित होती हैं [1]। त्वरक नियंत्रण प्रभाग, भापअ केंद्र में अति-चालक सोलनॉइड का एक एकीकृत बहु-भौतिकी अभिकल्पन विकसित किया गया है, जो एसएसआर 1 और एसएसआर 2 क्रायोमॉड्यूल अभिकल्पनों दोनों का ध्यान केंद्रित करते हुए आवश्यकताओं की पूरा करता है। उच्च ऊर्जा त्वरकों हेतु मध्यम ऊर्जा क्रायोमॉड्यूल के लिए पारंपरिक अभिकल्पित एससीआरएफ गुहिकाओं के समान अति-चालक सोलनॉइड्स के लिए संवहन-शीतित तापन-पात्र शीतित अभिकल्पन अपनाते हैं। वर्तमान अभिकल्पन चुंबक एवं गुहिका शीतलन को काफी हद तक वियुग्मन करके क्रायोमॉड्यूल प्रचालन हेतु एक अद्वितीय और तकनीकी रूप से बेहतर समाधान का अन्वेषण करता है। लीनॉक कणपुंज-रेखा में चुंबक के एकीकरण के बाद समान अभिकल्पन आवश्यकताओं [2,3] के साथ अंतरराष्ट्रीय सहयोग कार्यक्रमों के अंतर्गत क्रायोमॉड्यूल प्रचालन में प्रायोगिक रूप से विश्वसनीयता स्थापित की जाएगी।

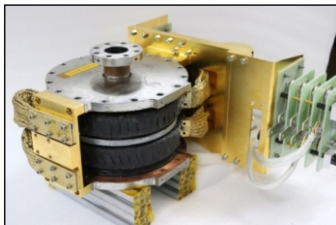
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Multi-physics Design, Development and Performance of Conduction Cooled Superconducting Magnets for High Intensity Proton Accelerators

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ABSTRACT



Dressed magnet assembly with heat sinks and cold diodes

High Intensity Linear proton accelerators necessitate implementation of superconducting accelerating structures at the medium and high energy regime to utilize combination of single-spoke resonators and elliptical cavities enabling proficient acceleration of proton beam to higher energies. The medium energy section of the linac contains two types of superconducting Single Spoke Resonator (SSR) radio frequency cavities (SSR1 and SSR2), interspersed with high-field solenoid focusing lenses [1]. A unified Multi-physics design of the superconducting solenoid has been developed at the Accelerator Control Division, BARC, satisfying the focusing requirements of both the SSR1 and SSR2 cryomodule designs. Conventional designs for medium energy cryomodules for high energy accelerators adopt convection-cooled bath cooled design for superconducting solenoids similar to that of the SCRF cavities. The present design explores a unique and technically superior solution for the cryomodule operation by decoupling the magnet and cavity cooling to a large extent. Reliability in cryomodule operations shall be experimentally established after integration of magnets in the Linac beamline under International collaboration programs with similar design requirements [2,3].

KEYWORDS: Single spoke resonator, Cryomodule operation, Linac beamline

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Introduction

Functional requirement of the SSR focusing lens envisages a primary focusing solenoidal field along with horizontal and vertical correction fields for the beam centroid. Furthermore, it is imperative to minimize the fringe magnetic field at the cavity surface to prevent field dependent escalation in the cavity surface resistance. To meet these requirements, the magnet assembly has been designed to consist of one main coil, two active shielding coils and four steering coils. The design has been optimized to maximize the strength of the focusing field in the aperture, limiting the peak fields on the superconductor surface and minimizing the fringe magnetic field at the cavity surface, all within the specific spatial and electrical constraints. Fig.1. shows the cross-section of the focusing lens assembly inside the cryomodule.

Electromagnetic Design

The arrangement of elements in the SSR cryomodules has been meticulously selected to minimize optics perturbations at the cryomodule-to-cryomodule transitions. Aperture limitations in the superconducting (SC) cavities constrain the SSR1 and SSR2 modules, setting the apertures at 30 mm and 40 mm, respectively [3]. Notably, the SSR1 and SSR2 cavities lack axial symmetry, causing the compensation of their quadrupole components challenging across the entire beam velocity range. The quadrupole field strength is proportional to the strength of axially symmetric cavity defocusing. The cavity quadrupole and skew-quadrupole fields exert a minor yet discernible impact on beam dynamics, compensatory measures become necessary. Hence, it is imperative that the SSR1 and SSR2 cryomodule are equipped with skew-quadrupole correction coils positioned within the focusing solenoids. The creation of the skew-quadrupole field will entail an intentional imbalance in the currents of independently powered x and y dipole correctors. Functional requirements for focusing lenses in the SSR cryomodule are summarized in Table1.

The necessity for fringe field requirements arise from the operational context of the lenses housed within the cryomodule alongside adjacent superconducting Spoke cavities made of pure Niobium (Nb). In the event of a quench occurring in one of the cavities, the energy stored in the electro-

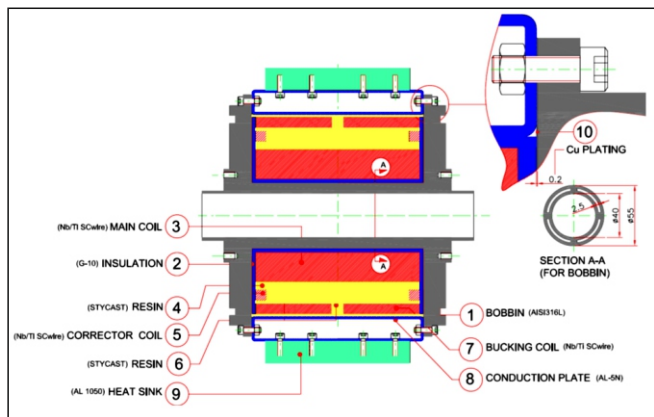


Fig.1: Cross-section of the proposed conduction cooled SSR lens in the cryomodule.

Table 1: Design Specifications.

Sr. No.	Parameters	Values
1.	Focusing strength $\int B_z^2 dl$	4.5 T ² m
2.	Nominal current	< 100 A
3.	Bmax at cavity Surface	<10 G
4.	Bending strength	5mT.m
5.	Effective length of solenoid (FWHM)	≤ 150 mm
6.	Maximum current in the dipole correctors	< 50 A

magnetic field is discharged onto the RF surface surrounding the point of initiation [4]. This elevated temperature causes a portion of the cavity wall to transition into a normally conducting state, thereby allowing the external magnetic field to penetrate inside the cavity.

Fig.2 shows the magnetic field (Bmod) plot with only main coil powering configuration & with Main coil and Bucking coils powering configuration. It shows the level of reduction in the fringe field at the cavity location, thereby justifying the need for an active bucking coil.

Tolerance studies on bucking coil dimensions

The electromagnetic analysis of the SSR Focusing lens indicated the critical requirement for precise tolerances concerning the dimension and positioning of the bucking coil relative to the main coil. Any positional inaccuracy of the bucking coil can significantly impact the fringe magnetic field on the cavity surface [1].

The analysis results shown in Fig.3. Indicates the anticipated level of accuracy necessary in the bucking coil dimensions, estimated to be in the order of 0.5 mm. This precision is crucial to optimize the fringe field level at the maximum energy deposition surface on the cavity. These studies were utilized to specify the manufacturing tolerances for the bucking coil during coil winding. Bucking coil inside and outside diameter were varied for a fixed dimension of main coil and effect on the Peak field on the cavity surface as well as surface integral was seen at the cavity location of maximum energy deposition.

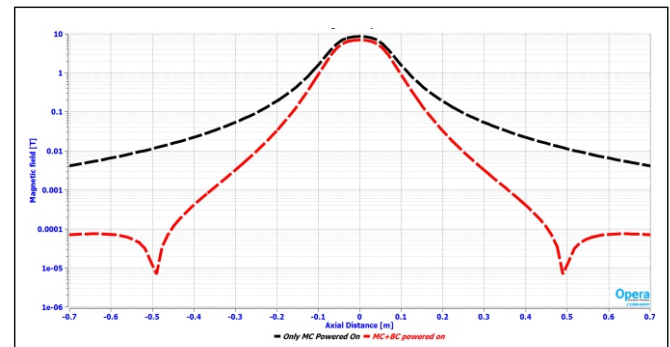


Fig.2: Bmod field profile of the SSR2 Focusing lens.

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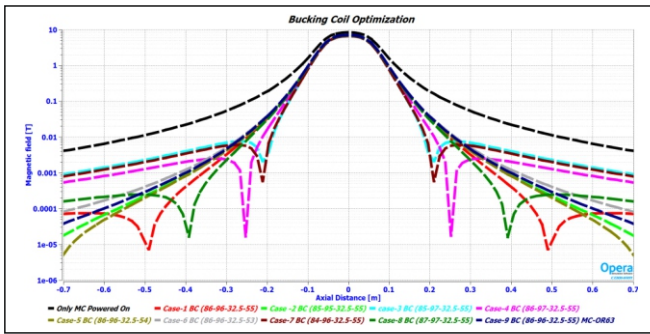


Fig.3: Effect on Fringe Field level for different configuration of Bucking Coil Design.

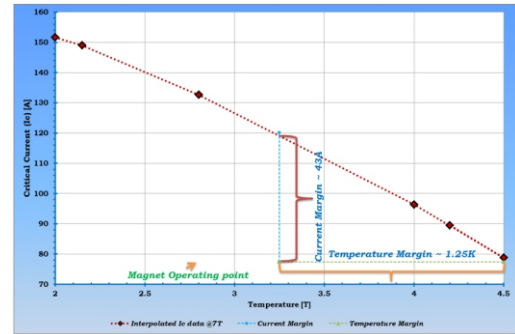


Fig.4: Design Margin for the SSR magnet.

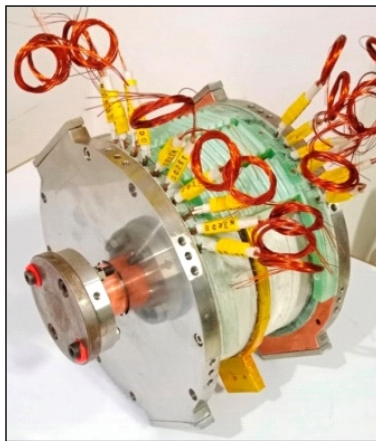


Fig.5: Bare SSR magnet assembly.

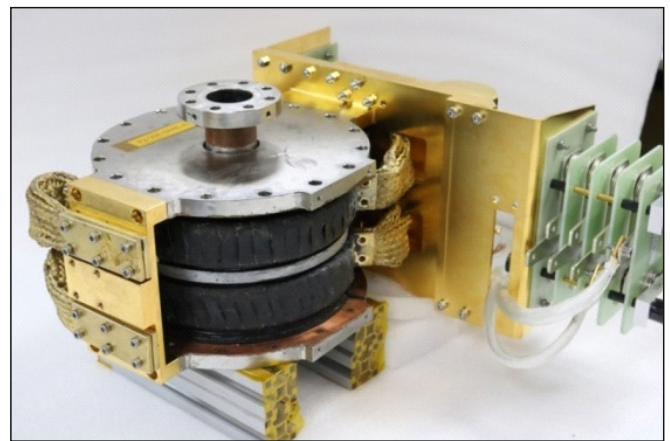


Fig.6: Dressed magnet assembly with heat sinks and cold diodes.

Operating Region and design margins

The SSR focusing lens design parameters are chosen in the way so as to operate with sufficient safety margin that is well below the Quench limit. Nominal operating current for the magnet is 75 A with a peak field level of 7.135 T on wire strand shown with yellow marker in the graph. Steady state operating temperature of the magnet inside cryomodule is ~3.2K. Fig.4. Shows the current margin and temperature margin of the designed lens.

Development of the Magnet assemblies

Maintaining tight tolerances during the winding of the coil is imperative due to the high sensitivity associated with the dimension of bucking coil. Moreover, variations in the fringe

field level from magnet to magnet might occur based on the dimensions achieved during winding. Manufacturing of the magnet assemblies were carried out with tight tolerance during winding. Additional positional tolerances were specified on the coil former and coil spacers used during manufacturing. Fig.5-6 shows the photograph of the developed magnet assemblies.

Results

Developed magnet assemblies were tested in a cryocooler based test stand developed indigenously at Accelerator control Division, BARC. Axial field mapping and detailed thermal tests were carried out during cryogenic testing of the magnet assemblies. Quench data was acquired

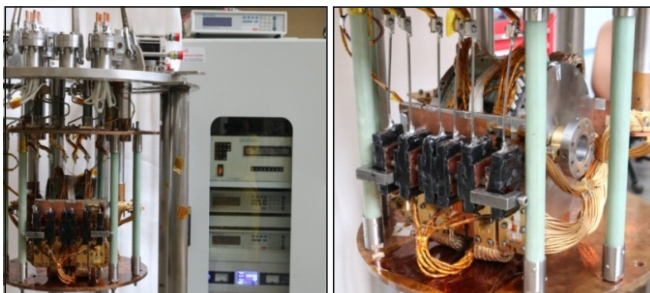


Fig.7: Magnet assembly integrated with indigenous cryo-cooler based magnet test stand.



Fig.8: Cryostat housing the conduction cooled magnet assembly during cryogenics tests & the measured magnetic field in the aperture @ 43.5A.

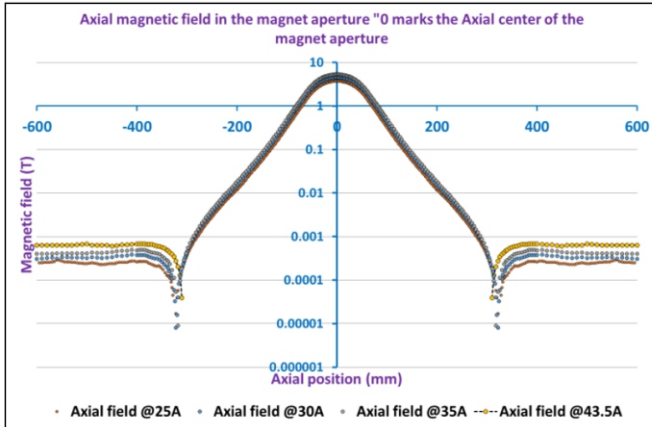


Fig.9: Measured axial field profile of the magnet assembly.

using with voltage tap data acquisition and thermal sensors data. Fig.7-8 shows the magnet assemblies integrated with the test stand during cryogenic testing of magnets.

Axial field mapping and detailed thermal tests were carried out during cryogenic testing of the magnet assembly. Passive quench protection cold diodes were used during testing of the magnet in the test stand. Fig.9. shows the measured axial field map.

Conclusion

Conduction-cooled superconducting solenoid consisting of the main coil, the bucking coils and the corrector coils has been designed for a medium beta cryomodule for a high intensity proton accelerator. Four magnet assemblies were constructed and successfully tested in indigenously developed Vertical and horizontal magnet test stands. The measurement results, enhanced insight into the thermal analysis, leading to improvement in the thermal design, thereby enhancing the

efficiency of conduction cooling inside the cryomodule. Electromagnetic parameters have been experimentally assessed and validated with the design estimates in terms of integral focusing strength, fringe fields present on the cavity surface, and evaluating the nominal operating currents. The upcoming stages of testing are expected to encompass comprehensive quench characterization and ramp rate dependence studies. These tests are crucial as they help testing the magnets under simulated machine operation cycle and contribute significantly to the thermal design validation.

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9

मेहिपा चरण-I के लिए निम्नतापिकी

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सारांश



एसएचपी 50 शीत कोष्ठ और ऊष्ण पंपन प्रणाली के साथ एसएचपी 20 शीत कोष्ठ स्थापना का एक दृश्य

इस शोध-पत्र में, पऊवि के 1 GeV प्रोटॉन त्वरक कार्यक्रम के प्रारंभिक चरण, मेहिपा चरण-1 को समर्थ बनाने के लिए अभिकल्पित उप-वायुमंडलीय हीलियम निम्नतापिकी संयंत्रों (एसएचपी) के विकास का वर्णन किया गया है। मेहिपा चरण-1, प्रोटॉन कणपुंज को 40 MeV तक तीव्र करने के लिए एकल स्पोक अनुनाद (एसएसआर-बी.) क्रायोमॉड्यूल के भीतर रखे गए अति-चालक त्वरण गुहिकाओं का उपयोग करता है। 2 K प्रशीतन के लिए त्वरक की प्रचालन आवश्यकताओं को बड़े पैमाने पर निम्नतापिकी प्रौद्योगिकियों अर्थात् उप-वायुमंडलीय हीलियम निम्नतापिकी संयंत्रों (एसएचपी) हेतु एक चरणबद्ध निम्नतापिकी कार्यक्रम द्वारा समर्थित किया जाता है। इस ढांचे के भीतर, यह लेख एसएचपी 20 के विकास को प्रस्तुत करता है, जो 2 K निम्नतापिकी प्रशीतन पर 20 W है, जो प्रारंभिक अति-चालक (एससी) त्वरक घटक (एससी गुहिका) विकास एवं स्वदेशी 2 के निम्नतापिकी क्षमताओं की स्थापना के लिए अभियंत्रित है। इसके अलावा, मेहिपा चरण-1 की प्राथमिक निम्नतापिकी मांगों को पूरा करने के लिए अभिकल्पित 2K संयंत्र पर 500 W के एसएचपी 500 की एक रूपरेखा भी प्रस्तुत की गई है। विशेष रूप से, एसएचपी 500 में पऊवि प्रोटॉन त्वरक विकास कार्यक्रम के बाद के चरणों (मेहिपा चरण-1 की आवश्यकताओं से परे) में प्रत्याशित बड़े हुए निम्नतापिकी भार को कम करने में समर्थ एक उन्नयन योग्य संरचना है।

9

Cryogenics for MEHIPA Phase-I

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ABSTRACT



A view of the SHP20 cold box installation along with LHP50 cold box and warm pumping system

This article presents the development of sub-atmospheric helium cryogenic plants (SHPs) designed to support MEHIPA Phase-1, the initial phase of 1 GeV proton accelerator program of DAE. To accelerate the proton beam to 40 MeV, MEHIPA Phase-1 utilizes superconducting accelerating cavities housed within single spoke resonator (SSR-B) cryomodules. The operational requirements of the accelerator are supported by a phased cryogenic program for large-scale cryogenic technologies namely sub-atmospheric helium cryogenic plants (SHP) for 2 K refrigeration. Within this framework, this article presents development of the SHP20, a 20 W at 2 K cryogenic refrigerator, engineered for initial superconducting (SC) accelerator component (SC cavity) development and the establishment of indigenous 2 K cryogenic capabilities. Furthermore, an outline of the SHP500, a 500 W at 2 K plant, designed to meet the primary cryogenic demands of MEHIPA Phase-1, is also presented. Notably, the SHP500 features an upgradable architecture capable of mitigating enhanced cryogenic loads anticipated in subsequent phases (beyond requirements of MEHIPA Phase-1) of DAE proton accelerator development program.

KEYWORDS: MEHIPA, Proton linac, Radioactive ion

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Introduction

The cryogenic requirements for the MEHIPA Phase-1 system are fulfilled by SHP cryogenic plants, which are connected to the MEHIPA cryomodules (CMs) via a Cryogenic Distribution System (CDS). Fig.1 presents a schematic of the cryogenic infrastructure required for MEHIPA Phase-1. The warm accessories such as helium compressors, warm pumping system and helium buffers are not shown in the figure although they are important components of helium infrastructure required to operate the cryogenic systems. The refrigeration requirements for the MEHIPA cryogenics are detailed in [1, 2]. The SHP cold box provides the supercritical helium stream required for 2 K refrigeration and for the cooling of low temperature thermal shield/thermal intercepts and 35 K helium stream for cooling of high temperature thermal shield. Moreover, the sub-atmospheric (VLP) return stream, required to maintain sub atmospheric pressure and 2 K bath temperature in the cryomodules using Cold Compressors (CC) or Warm Pumping System (WPS), is directed back to the SHP cold box. The cold box is connected to the application cryomodules through cryogenic transfer lines, a distribution box, various bayonet cans, a turnaround box and U-tubes as shown schematically in Fig.1.

The Cryogenic Distribution Box (CDS-DB), operating in tandem with the turnaround box, manages the routing of helium streams during system cooldown and warmup procedures. Specifically, the CDS-DB serves as the interface between the cold box and the CMs, with the multiple cryogenic transfer lines originating from the cold boxes routed to the CMs through it. It also accommodates future system upgrades by offering the flexibility to integrate multiple cold boxes and distribute flow via dedicated valve operations. Furthermore, the turnaround box enables independent cool down and warm-up of individual CMs while adjacent CMs remain operational at their targeted cryogenic temperatures. To support future

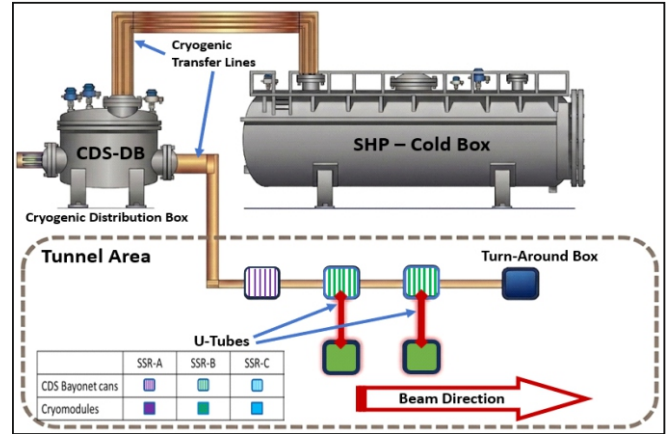


Fig.1: Schematic of cryogenic infrastructure for MEHIPA phase-1.

expansions, the cryogenic infrastructure is also equipped with specialized bayonet cans configured for SSR-A CMs.

SHP20: 2 K Refrigeration System

SHP20 is the first in the series of sub-atmospheric cryogenic refrigeration plants conceived and developed by BARC with a rated refrigeration capacity of 20 W at 2 K. The SHP20 is developed with the intention of mitigating anticipated cryogenic load requirements during initial SC accelerator/cavity development activities and to establish and demonstrate 2 K cryogenic capabilities at BARC. SHP20 is not a standalone refrigeration system, rather, it works only in tandem with BARC developed helium liquefaction/refrigeration plants, namely, the LHP100 or LHP50. Important components of the SHP20 coldbox, along with internal construction, are shown in the process flow diagram (Fig.2).

The SHP20 cold box components are engineered for stringent thermal and structural performance [3]. Its process

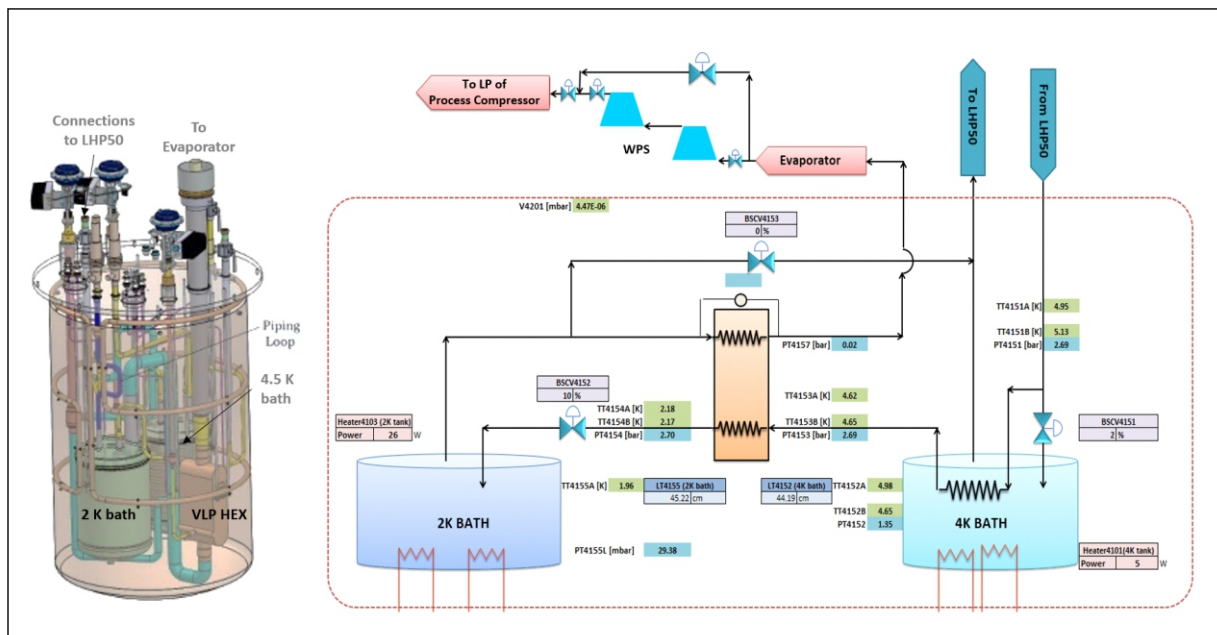


Fig.2: Schematic of SHP20 cold box internals and process flow.



Fig.3: Bird's-eye view of the SHP20 cold box installation along with LHP50 cold box and warm pumping system (WPS).

pipings are constructed from SS 304L/316L as per ASME B31.3, utilizing strategic physical routing, rather than flexible joints, to absorb thermal stresses down to 2 K. A liquid nitrogen (LN₂) cooled, 1 mm thick ETP copper thermal shield intercepts radiant heat from the vacuum vessel to protect the low-temperature core. Internal inventory is managed by two 45 L liquid helium (LHe) vessels equipped with cartridge heaters (to simulate heat load) and individual superconducting wire level sensors. One of these vessels is a 4.5 K pre-cooler with an immersed copper coil for supercritical helium stream, while the other is a sub-atmospheric 2 K reservoir. To maximize the post-expansion liquid fraction and refrigeration capacity, a brazed aluminum plate-fin heat exchanger (VLP HEX), designed for high-throughput PIP-II cryomodules [4], is integrated. This custom heat exchanger utilizes 3 mm offset strip fins in both channels, specifically optimized for minimal very low-pressure (VLP) stream pressure drop to maintain downstream pumping efficiency and stable 2 K bath temperatures. For process monitoring and control, about 20 nos. temperature sensors (carbon ceramic, silicon diode, and PT-100 types) are deployed via direct-fluid, thermo-well, and surface-mounting configurations. At critical nodes such as the VLP HEX cold stream exit, redundant sensors (primary and spare) are installed via thermowells with their lead wires thermally anchored to the process piping using cryogenic tape, grease and nylon rope. Fig.3 presents a bird's-eye view of the SHP20 cold box installation along with LHP50 cold box and warm pumping system (2 K helium vacuum pumping system).

Fig.4 presents key operational parameters during a long duration operational trial of the SHP20 refrigeration system. The objectives achieved through operating SHP20 cold box in multiple runs include the following:

- Establishing concurrent operation of SHP20 cold box with helium liquefier and warm pumping system.
- Achieving operational efficacy of the indigenously developed VLP heat exchanger essential for large capacity 2 K refrigeration systems.
- Establishing reliable instrumentation and control

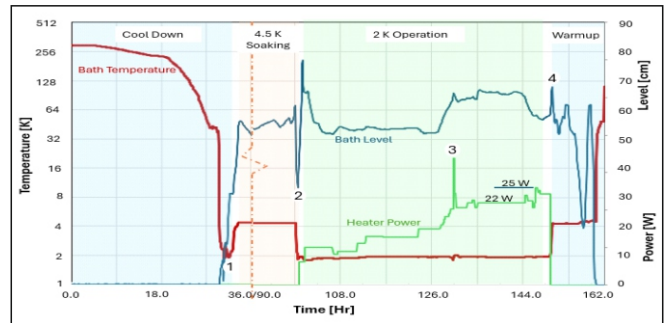


Fig.4: Transient profiles of the 2 K bath temperature, liquid level & applied refrigeration load during the SHP20 long-duration operational trial.

strategies for maintaining 2 K temperature (with metered heat load) over longer duration.

As illustrated in Fig.4, the cooldown of the SHP20 cold box was conducted gradually over a 30-hour period in conjunction with the LHP50 helium liquefier. The sub-atmospheric cycle was initiated, through operation of the WPS, during this cool down phase, successfully establishing a 2 K bath temperature at the conclusion of the cycle (designated as Point 1 in Fig.4). Thereafter, to ensure steady-state operation and accurate refrigeration capacity measurements, the WPS was disengaged and a prolonged thermal soak of the entire system was performed at 4.5 K. This soaking period was necessary to mitigate transient parasitic heat loads originating from the high-thermal-mass radiation shields integrated into the system. Following the completion of the thermal soak, the warm pumping system (WPS) was again operated to depressurize the helium bath and decrease its operating temperature. Transient liquid level fluctuations occurred during this pump-down phase (Point 2). The system was subsequently maintained at 2 K for the ensuing 50 hours. During this interval, the system's refrigeration capacity, which is bounded by the throughput limits of the installed WPS, was evaluated by systematically ramping the internal electric heaters. This operational phase also verified the efficacy of the active level control loop via heater modulation (Point 3), where a rapid surge in the 2 K liquid level was successfully stabilized by increasing the heater power output. Thereafter, a steady-state refrigeration capacity of 22 W was continuously maintained at a constant liquid (2 K) level for 9 hours. By maximizing the volumetric capacity of the WPS, it was possible to demonstrate a peak system refrigeration capacity in excess of 25 W. The experimental run concluded with the disengagement of the WPS, marked by an abrupt rise in the liquid level (Point 4), and followed by a controlled warm-up of the cold box to ambient temperature using a warm helium gas stream from the LHP50.

2 K Refrigeration System SHP500

The SHP500 is a 500 W at 2 K cryogenic plant engineered to meet the primary cryogenic requirements of the MEHIPA Phase-1 SC accelerator. Notably, the plant incorporates a scalable architecture designed to accommodate the enhanced cryogenic loads anticipated in subsequent phase of MEHIPA. Table 1 outlines the primary

Table 1: Client process requirements [1, 2].

Parameters Descriptions	MEHIPA Phase-I	MEHIPA
Maximum total CMs heat load at 2 K	225 W	900 W
CDS load to the supercritical lines	30 W	70 W
Supercritical supply temperature	5 K	5 K
Maximum total LTTS load to cryomodules	100 W	200 W
Maximum LTTS return Temperature	9 K	9 K
Maximum total HTTS heat load in CMs	1200 W	1700 W
CDS heat load for the HTTS lines	60 W	220 W
HTTS supply temperature	35-37 K	35-37 K
Maximum HTTS return temperature	45 K	45 K
Minimum supercritical supply pressure	2.6 bar(a)	2.6 bar(a)
Minimum HTTS supply pressure	10 bar(a)	10 bar(a)

process requirements established for the design of the SHP500 cryoplant. These client-side cryomodule refrigeration requirements [1, 2], paired with the projected heat loads from the cryogenic distribution systems (CDS), are detailed in Table 1 for both the MEHIPA Phase-1 and MEHIPA configurations. The thermodynamic process of the SHP500 is designed with operational flexibility - Mode 2 represents a reduced-capacity mode tailored to sustain baseline MEHIPA Phase-1 operations, whereas, two identical SHP500 plants operating in Mode 1 (the full-capacity mode) can seamlessly meet the anticipated enhanced MEHIPA refrigeration requirements in the future. Furthermore, the cryogenic distribution box (CDS-DB) detailed in Section 1 and Fig.1 serves a dual purpose: it guarantees the seamless integration of future plant upgrades and provides the necessary operational latitude for intermediate capacity adjustments, mitigating risks associated with potential heat load calculation uncertainties in the MEHIPA Phase-1 SC accelerator.

As shown in Fig.5, the SHP500 refrigeration architecture utilizes a three-stage thermodynamic cycle to simultaneously sustain the High-Temperature Thermal Shield (HTTS: 37-45 K), the Low-Temperature Thermal Shield/Intercepts (LTTS: 4.5 K to 9 K), the sub-atmospheric 2 K cryomodule bath, and the Cryogenic Distribution System (CDS) heat loads. In the first stage, a HP1 compressor (25 bara discharge, 3.5 bara suction) drives a 10 K Brayton cycle with two turboexpanders (expansion stages) in series. The HTTS stream is extracted from downstream of the first turbine at 37 K. In the second stage, a HP2 compressor (13 bara discharge, 1.01 bara suction) powers a Claude cycle, generating 4.5 K liquid helium via sequential expansion through a turboexpander (TEX3) and a Joule-Thompson valve (JT1, state point 7 in Fig.5) expansion stages; a pre-JT1 bypass stream feeds a sub-cooler to deliver supercritical helium to the cryomodules and LTTS. Finally, a

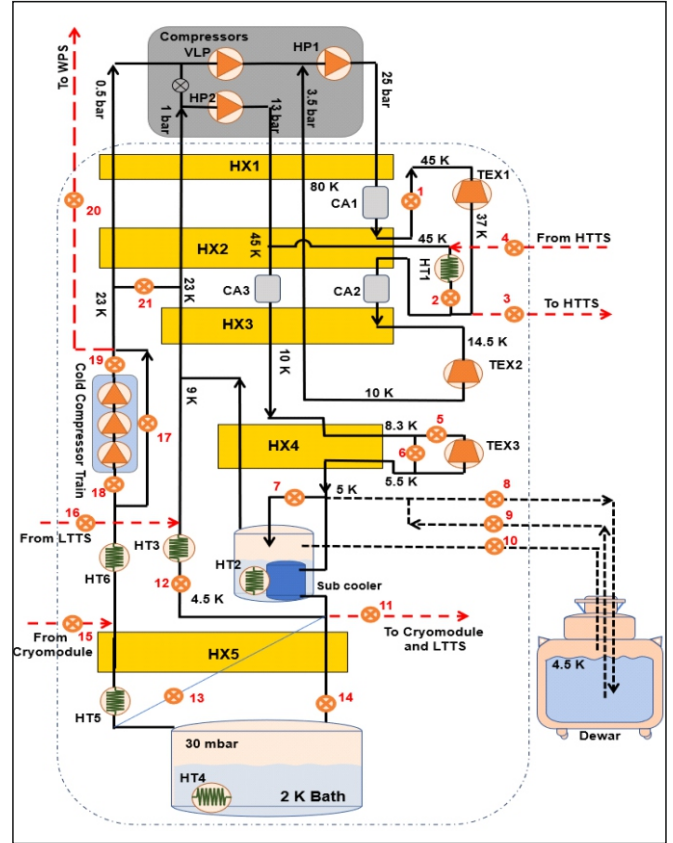


Fig.5: SHP500 process schematic.

combined cold compressor (CC) train and VLP compressor (sub-atmospheric suction pressure) regulates the cryomodule bath sub-atmospheric pressure to maintain the required ~ 2 K target temperature. For lower 2 K refrigeration load requirements, CC train and VLP compressor may be bypassed in favour of the WPS.

Recuperative cold recovery across the cold box is executed via compact plate-fin heat exchangers (PFHEs: HX1-3), a Joule-Thomson heat exchanger (HX4), and a VLP heat exchanger (HX5). For process stability and fast cool down operations, an external large-capacity liquid helium Dewar is integrated with the internal 4.5 K bath to provide thermal damping. Process regulation is managed by 21 cryogenic control valves, while three charcoal adsorbers (CA-1-3) positioned downstream of HX1 and 2 remove residual oxygen, nitrogen and neon impurities. In isolated standalone mode, a dedicated test loop, comprising HX5, two heaters (HT-4 and HT-5), and control valve CV-14, acts as a 2 K load and hydraulic resistance simulator to independently verify thermal efficiency and control automation. Similarly, heater HT2 serves as a 4.5 K bath load simulator for standalone, client-free 4.5 K refrigeration testing while damping user-side thermal and pressure transients.

Conclusion

To conclude, this article reports successful development and subsequent operational validation of the SHP20 2 K helium refrigeration system, which features a rated

refrigeration capacity of 20 W at 2 K. During extended operational trials, it was possible to maintain a 2 K steady bath temperature and constant liquid level with a 22 W refrigeration (heater) load for over 9 hours. The peak refrigeration capacity, successfully demonstrated over a shorter duration, exceeded 25 W. This campaign successfully verified the concurrent, integrated operation of an indigenously developed helium liquefier, the 2 K refrigeration cold box, and the downstream warm pumping system. Furthermore, the trials validated the hydrodynamic and thermal performance of the custom-developed, very low-pressure (VLP) plate-fin heat exchanger, which serves as a critical milestone for high-capacity sub-atmospheric cryogenic infrastructure. Finally, the engineering and operational strategies detailed herein establish a robust development pathway for mitigating the primary cryogenic heat loads of the MEHIPA Phase-I accelerator utilizing the SHP500 cryogenic plant.

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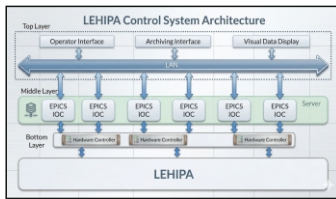
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उच्च तीव्रता वाले प्रोटॉन लीनॉक हेतु नियंत्रण प्रणाली का अभिकल्पन एवं विकास

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लेहिपा की नियंत्रण प्रणाली का वास्तुकला

सारांश

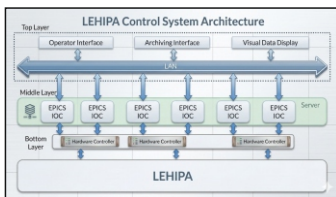
यह लेख भाभा परमाणु अनुसंधान केंद्र में भारत के त्वरक प्रचालित प्रणाली (एडीएस) कार्यक्रम के तहत निम्न ऊर्जा उच्च तीव्रता वाले प्रोटॉन त्वरक (एलईएचआईपीए) हेतु विकसित नियंत्रण प्रणाली के अभिकल्पन, वास्तुकला एवं प्रचालन अनुभव को प्रस्तुत करता है। ईपीआईएस-आधारित वितरित नियंत्रण प्रणाली त्वरक उप-प्रणालियों के विश्वसनीय प्रचालन, संरक्षण एवं निगरानी को समर्थ बनाती है। प्रमुख घटकों में एलएलआरएफ, समय प्रणाली, पर्यवेक्षी नियंत्रण, डाटा संग्रह और मशीन संरक्षण प्रणाली शामिल हैं। लेहिपा नियंत्रण प्रणाली के स्वदेशी विकास और एक दशक में त्वरक प्रचालन अनुभव प्रस्तुत किए गए हैं। लेख में आगामी अति-चालक मेहिपा चरण-1 त्वरक के लिए भविष्य की चुनौतियों एवं नियंत्रण आवश्यकताओं पर भी चर्चा की गई है।

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Design and Development of Control System for High Intensity Proton LINACs

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Control System Architecture of LEHIPA

ABSTRACT

This article presents the design, architecture, and operational experience of the control system developed for the Low Energy High Intensity Proton Accelerator (LEHIPA) under India's Accelerator Driven System (ADS) program at Bhabha Atomic Research Centre. The EPICS-based distributed control system enables reliable operation, protection, and monitoring of accelerator subsystems. Major components include LLRF, timing system, supervisory control, data archiving, and machine protection systems. Indigenous developments of the LEHIPA control system and accelerator operational experiences over a decade is presented. The article also discusses future challenges and control requirements for the upcoming superconducting MEHIPA Phase-1 accelerator.

KEYWORDS: Control systems, Machine Protection System, EPICS

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Introduction

Long term goal of the Indian nuclear program is to be self-reliant in nuclear fuel by utilizing vast thorium reserves of India. Accelerator Driven System (ADS) has emerged as one of the promising route for Thorium utilization. At the heart of the Accelerator Driven System lies High Intensity Proton Accelerator (HIPA) which delivers CW proton beam to carry out spallation reaction to generate external neutrons required for ADS [1].

Low Energy High Intensity Proton Accelerator (LEHIPA) is a flagship accelerator project of BARC. LEHIPA is the front end of the ADS program. LEHIPA accelerates proton beam to 20 MeV and is capable of delivering beam of 10 mA maximum. LEHIPA is commissioned in August 2023 in pulsed mode. Time of flight method is used for the final beam energy measurement in LEHIPA [2].

LEHIPA consists of many subsystems such as Ion Source, Vacuum System, Low Conductivity Water System, High Power Amplifiers, RF distribution and coupling system, Beam Diagnostics System to name a few. Reliable long term availability of proton beam at target depends on the fine balance of optimal operation of these subsystems.

Control System is one of the most important subsystem of the LEHIPA [3]. Control system ensures safe and efficient

operation of the accelerator via proper signal, data and command exchange between various subsystems and with the operator running the machine. To ensure safe and efficient operation of high power accelerator like LEHIPA control system must carry out following responsibilities:

- Maintaining stable electric field in the cavity. (LLRF System)
- Ensure unified timing reference to synchronize various activities/events distributed in space for beam acceleration efficiently and safely. (Timing System)
- Data acquisition and presentation of field data to operators, users/experimenters and Implementation of operator actions on field devices.
- Generation of alarm for operator.
- Acquiring and presenting beam diagnostic data to operator.
- Protection and Interlock System
- Archiving of machine data during operation and retrieval of historic data.
- Operational logbook of accelerator operation.

Technical Specification of Control System

Details on typical hardware, software and signals that are used in the linac control system are as given in Table 1.

Table 1: Specifications of linac control system.

Sr. No.	Parameters	Values
1.	Type of control system	Distributed Control System (DCS)
2.	Software Platform	RTEMS, Linux, EPICS SCADA system
3.	Software Layers	3 Layers (Layer-1: Machine interface running on RTEMS, Layer-2: Middle layer Running on Linux/RTEMS, Layer-3: Operator interface running on Linux)
4.	Programming Language	C/C++, Qt C++ API
5.	Redundancy level	Machine protection System in layer-2
6.	Communication protocols	MODBUS over TCP/IP , EPICS Channel Access protocol
7.	Time Server	Centralized time server and event trigger
8.	Type of signals	Voltage signals, 4-20 mA and contacts
9.	No of signals	Approximately 5000
10.	Signal levels	variable analog signals max span -10 to +10 Volts , ADC /DAC 16 bit precision, optical signals (0-10 kHz, 0-100 kHz , 0 to 300 kHz)
11.	Response Time (min, max)	Control system - 50 milliseconds, fast interlock protection system-10 microseconds
12.	Control hardware (standard)	cPCI, VME and VME based Trombay PLC, standalone Modbus-based control modules
13.	Control hardware (custom made)	cPCI , VME
14.	PLC hardware	Trombay PLC

Control System Architecture

LEHIPA is a three layered distributed control system (Fig.1). Bottom most layer is the hardware that ensures the functional requirements of the accelerator. The top level is the presentation layer. In this layer operator interface and other graphical representation of the accelerator parameters and field data assist operators to operate the accelerator to deliver accelerated beam. In between top and bottom layer, Experimental Physics and Industrial Control System (EPICS) exists as the middle layer which acts the 'glue' between the operator interface and field hardware.

The middle layer, EPICS Input Output Controllers (IOC), acquire field data from the hardware controllers such as vacuum gauge controller, magnet power supply etc. and make that data available in the network so that every EPICS compliant system can get that data seamlessly. IOCs also receive the operator commands and soft interlock I/O signals and send them to the particular hardware controller to carry out the I/O operation in the field.

In LEHIPA all EPICS IO controllers are developed in house, using C programming language and are working satisfactorily for the last ten years.

Brief overview of control system

The control system of any high power accelerator and that of LEHIPA is a distributed control system as accelerator and its supporting subsystems are spread over a considerable area both inside the tunnel and in the ground level. Each subsystem has its own local control station/controller, often placed in the field. Control station/controller implements subsystem's data acquisition and control requirements. These subsystems are interconnected via a high speed redundant Local Area Network (LAN) to the control room servers and Operator Work Stations (OWS) as shown in the Fig.2. Each subsystem has three types of connection, LAN for data, command and slow interlocks, hard wired signal lines for the fast interlocks and timing signal for maintaining common

uniform timing across all the components of the accelerator. All subsystems provide the required global control to the Integrated Control System (ICS) of LEHIPA to carry out LEHIPA operation by operator at control room in a cohesive manner.

The ICS is responsible to carry out communication with each of the Local Control Stations (LCS) of various subsystem and synchronize the various operations to start the accelerator, provide synchronization requirements for various subsystem during operation, tune the beam for required characteristics and shutdown the accelerator under normal condition and emergency condition. ICS also provides overall machine protection and interface with various subsystems to the operator in a homogeneous manner for comprehensive operations, troubleshooting and maintenance. Another important responsibility of ICS is to keep archiving data from different subsystems for future reference/provision of historical operational and event data. The front end of the ICS is operator Interface, which is the application that present the data, information and command panels to the operator. ICS presents important operational data to the wall mounted large displays. The control system works on Linux operating system and uses EPICS-based SCADA frame work for LCS and Qt-EPICS based GUI panels for operator workstation.

The timing pulses for the pulsed subsystems (like ion source, HV for klystrons, RF for cavities and data acquisition) is generated by the LEHIPA Timing System (LTS) using cPCI-based programmable timer cards.

Protection system

Protection system is the crucial aspect of the control system. It has two parts , Personnel Protection System (PPS) and Machine Protection System (MPS). PPS is used to protect human from any danger. Search and Secure system for LINAC tunnel is the part of personnel protection system, implemented using Trombay PLC.

The Machine Protection System (MPS) in LEHIPA is designed to protect the accelerator and its components from

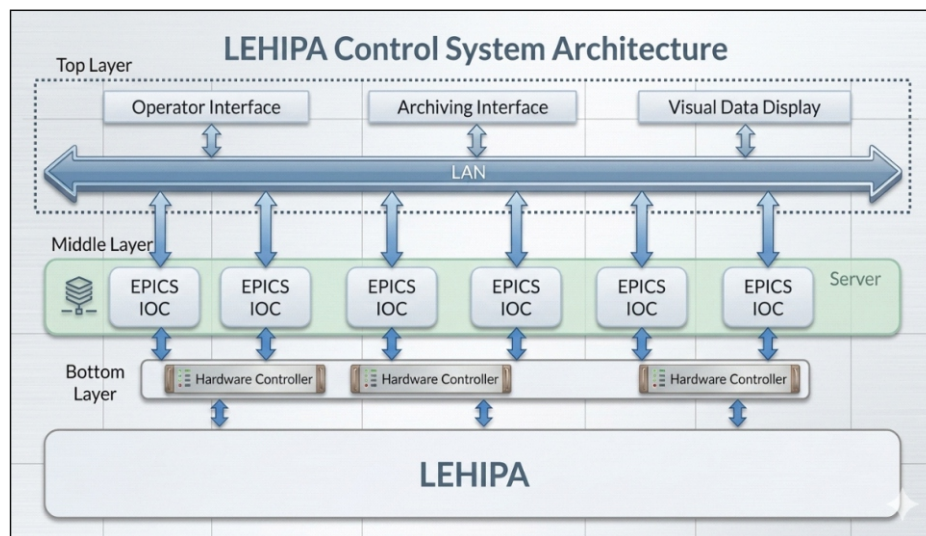


Fig.1: Control System Architecture

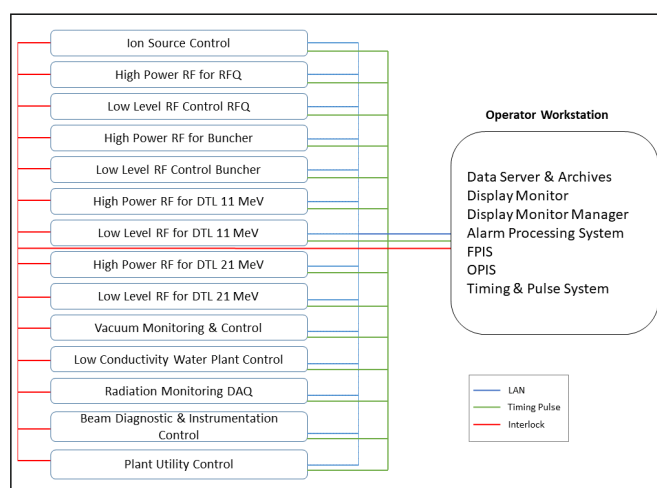


Fig.2: LEHIPA Control System.

damage during abnormal operating conditions. It continuously monitors parameters such as beam current, vacuum, RF systems, magnet status, and cooling systems. When a fault is detected, the MPS quickly generates an interlock signal to stop or inhibit the RF and beam. The system ensures safe and reliable operation of the accelerator by minimizing the risk of equipment failure and beam-induced damage. Fast response and high reliability are essential features of the LEHIPA MPS.

Control System of MEHIPA

The next stage of ADS program is 40 MeV MEHIPA Phase-1, planned to be commissioned in Vizag. MEHIPA Phase-1 is very similar to the LEHIPA till 10 MeV and design of the control system for that will be the refinement of the control system design of LEHIPA. Use of latest hardware platforms like MicroTCA and other emerging technologies will be explored for achieving better performance and reliability.

However, MEHIPA is different from LEHIPA in a significant way: from 10 MeV to 40 MeV it will have superconducting accelerating structures which brings new challenges for their very high quality factor. LLRF system needs to be designed considering the low bandwidth of the superconducting cavities requiring sophisticated algorithms for feedback and feed-forward control. Also due to the presence of cryogenics

subsystem, requirement of machine protection system for MEHIPA phase-1 will be significantly more challenging than the LEHIPA. Quench protection system will be an important additional control requirement for the superconducting cavities to protect the cavities from becoming normal conducting one and completely dissipating the stored energy. Compensation of cavity de-tuning due to various factors will also be a significant challenge of the MEHIPA control system and will be addressed by a resonance control system.

In the design of MEHIPA control system, integration of emerging new areas of technology such as machine learning and artificial intelligence are also in consideration.

Currently, IADD is carrying out the design of the MEHIPA phase-1 control system incorporating the learning from the decade-long experience of round the clock operation of the LEHIPA control system.

Conclusion

LEHIPA control system is working satisfactorily round the clock as per design requirements. It was designed as modular and scalable system and this helped to expand the control system organically as the LEHIPA commissioning was taking place starting with the RFQ commissioning in the year 2017 to full beam acceleration through DTL in 2023. A wealth of operational knowledge and experience gathered during LEHIPA operation is guiding the design of upgraded LEHIPA control system. Challenges arising out of superconducting cavities is being taken care in the design of MEHIPA control and machine protection system.

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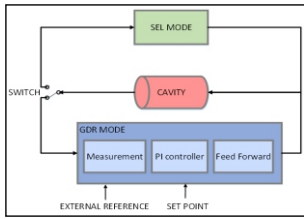
प्रोटॉन त्वरकों हेतु निम्न स्तरीय आरएफ नियंत्रण एवं सुरक्षा प्रणालियाँ

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सारांश



जीडीआर वास्तुकला का मूल ब्लॉक आरेख

आधुनिक आरएफ त्वरकों में, निम्न-स्तरीय आरएफ नियंत्रण और सुरक्षा प्रणाली महत्वपूर्ण उप-प्रणालियों, नामतः एलएलआरएफ नियंत्रक, अनुनाद नियंत्रक, आरएफ सुरक्षा एवं समय नियंत्रक का एक निर्बाध एकीकरण है। इस प्रणाली के प्रदर्शन का किरणपुंज की गुणवत्ता, प्रचालन स्थिरता, मशीन की उपलब्धता और समय त्वरक प्रदर्शन पर सीधा प्रभाव पड़ता है। एलएलआरएफ नियंत्रक किरणपुंज भरण, माइक्रोफोनिक्स, लॉरेंट्ज़ बल डिट्यूनिंग और घटक संवहन जैसी विसंगति की उपस्थिति में सटीक आरएफ क्षेप आयाम और चरण स्थिरता बनाए रखता है। अनुनाद नियंत्रक यांत्रिक एवं तापीय प्रभावों से उत्पन्न होने वाले गुहिका अनुनाद में गतिशील भिन्नताओं को पाटने का कार्य करता है, जिससे प्रचालन के दौरान इष्टतम गुहिका ट्यूनिंग सुनिश्चित होती है। आरएफ सुरक्षा उप-प्रणाली असामान्य प्रचालन परिस्थितियों और दोष की घटनाओं के विरुद्ध गुहिकाओं, आरएफ युग्मकों, आरएफ विंडो और उच्च-शक्ति प्रवर्धकों सहित महत्वपूर्ण आरएफ घटकों की सुरक्षा करता है। इसके अलावा, एक उपयुक्त समय नियंत्रक विश्वसनीय मशीन प्रदर्शन हेतु सभी त्वरक उप-प्रणाली के तुल्यकालिक प्रचालन को सुनिश्चित करता है। यह लेख संक्षेप में इन उप-प्रणालियों का एक अवलोकन प्रस्तुत करता है जिसमें महत्व, कार्यप्रणाली और हार्डवेयर वास्तुकला को भी शामिल किया गया है।

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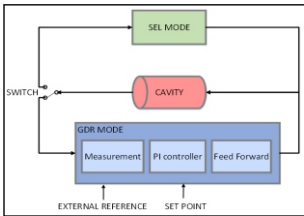
Low Level RF Control and Protection Systems for Proton Accelerators

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ABSTRACT



Basic block diagram of GDR architecture

In modern RF accelerators, the Low-Level RF Control and Protection System is a seamless integration of the critical sub-systems, namely, LLRF Controller, Resonance Controller, RF Protection, and Timing Controller. The performance of this system has a direct impact on beam quality, operational stability, machine availability, and overall accelerator performance. The LLRF Controller maintains precise RF field amplitude and phase stability in the presence of disturbances such as beam loading, microphonics, Lorentz force detuning, and component drifts. The Resonance Controller compensates for dynamic variations in cavity resonance arising from mechanical and thermal effects, thereby ensuring optimal cavity tuning during operation. The RF Protection subsystem safeguards critical RF components, including cavities, RF couplers, RF windows, and high-power amplifiers, against abnormal operating conditions and fault events. In addition, an appropriate Timing Controller ensures synchronized operation of all accelerator subsystems for reliable machine performance. This article briefly presents an overview of these sub-systems dwelling a little bit into their importance, functioning and hardware architecture.

KEYWORDS: Generator Driven Resonance (GDR), RF Control, Proton Accelerators

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Introduction

Particle accelerators rely on precisely controlled electromagnetic fields to transfer energy to the charged particle beam, making stability and accuracy of Radio-Frequency (RF) systems the fundamental requirements for their operation. Low Level RF (LLRF) Controller serves as the core control layer responsible for regulating the amplitude and phase of RF field inside accelerating cavities. Even small deviations in these parameters can lead to beam energy spread, emittance growth, and overall degradation of accelerator performance, particularly in high-intensity accelerators. The LLRF system is designed to operate in either or both operating modes namely; Self Excited Loop (SEL) and Generator Driven Resonance (GDR). It is also operated in open-loop for cavity conditioning. Cavity detuning caused due to mechanical, thermal, and electromagnetic perturbations can significantly impact RF performance in Superconducting and Normal-conducting particle accelerators. The primary objective of Resonance Controller or the Resonance Control System – (RCS) is to maintain the cavity's resonant frequency at the desired operating frequency, while countering the detuning effects. The high power RF subsystems, responsible for transfer of RF energy from RF source to beam being accelerated, must be protected and in the event of an unacceptable scenario quick response needs to be generated. The RF Protection and Interlock (RFPI) System is suited for this. It is fast, scalable, expandable, multi-channel and reliable.

A simplified block diagram of Low Level RF Control and Protection System is shown in Fig.1

LLRF Control System

An RF cavity needs to be driven with different signals for testing and conditioning purpose. For successful operation of a particle accelerator, finding and correcting the resonance frequency of a cavity is essential. Also, modern accelerators operate under a wide range of conditions, including continuous

wave (CW) and pulsed modes, each introducing distinct challenges in RF control. Effects such as beam loading, microphonics, thermal drift, Lorentz force detuning etc. continuously perturb the cavity fields, requiring fast and accurate compensation mechanisms. LLRF systems address these challenges through a combination of open-loop, feedback [1] and feedforward control techniques, enabling real-time correction of disturbances and ensuring stable operation.

A typical LLRF system has broadly two modes of operation

- SEL mode
- GDR mode

SEL Mode

The SEL is a control technique used in RF cavity systems to operate the cavity at its natural resonant frequency. In this mode, the system does not rely on any external reference signal; instead, it forms a closed feedback loop using the cavity's own pickup signal. The loop starts oscillating from inherent noise present in the system, and the oscillation naturally builds up at the frequency where the loop satisfies the required conditions for sustained oscillation. As a result, the SEL inherently locks onto the cavity's instantaneous resonant frequency, ensuring that the cavity is always driven at its natural frequency, even in the presence of detuning effects. The operation of SEL is fundamentally governed by the Barkhausen criterion, which states that sustained oscillations occur when the total loop gain is equal to unity and the total phase shift around the loop is zero or an integer multiple of 2π . In this state, the cavity behaves like a part of an oscillator, and the loop continuously adjusts itself so that the oscillation frequency follows the cavity resonance. It is important to clearly distinguish the role of SEL from that of the resonance controller. The SEL does not force the cavity to operate at a predefined or desired frequency. Instead, it simply ensures

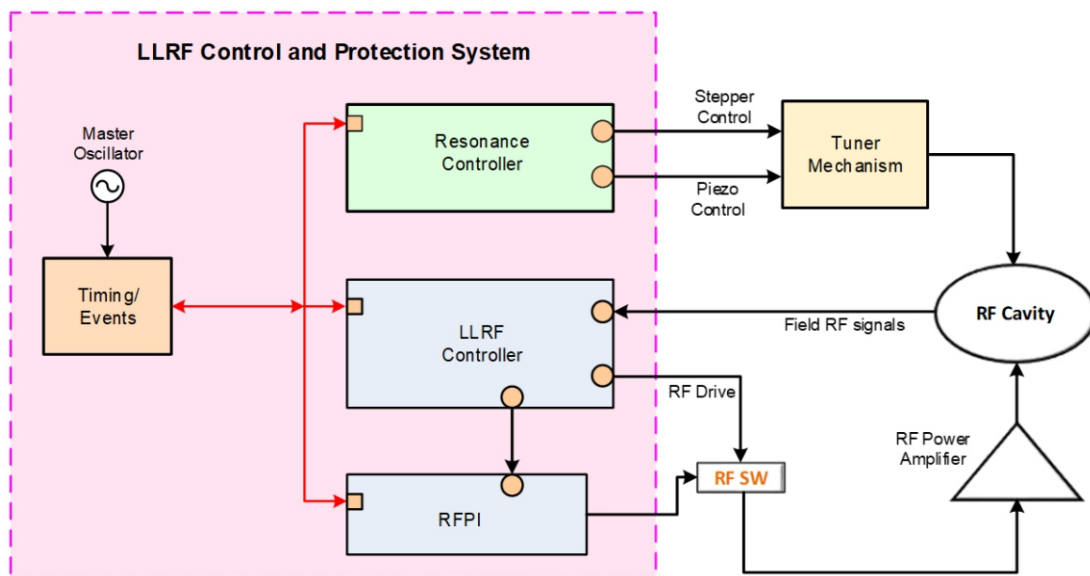


Fig. 1: Simplified block diagram of a Low Level RF Control and Protection System.

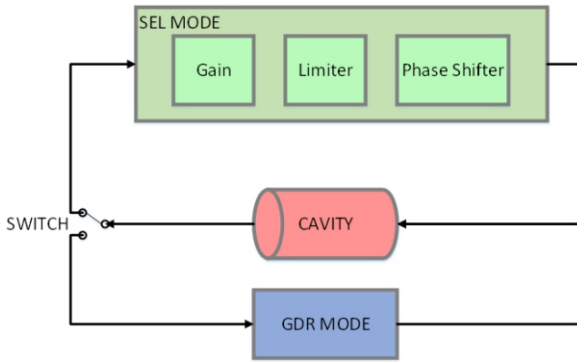


Fig.2: Basic block diagram of SEL architecture.

that the cavity is driven at whatever its current natural resonant frequency is. If this natural frequency deviates from the desired operating frequency, the SEL will still faithfully track this shifted resonance. The task of bringing the cavity resonance back to the desired frequency is performed by the resonance controller, which typically uses electro-mechanical tuners and piezoelectric actuators to physically adjust the cavity parameters. The SEL loop typically consists of three main components: a phase shifter, a gain block, and a limiter. The block diagram of SEL architecture is shown in Fig. 2. The phase shifter ensures that the overall loop phase satisfies the oscillation condition by compensating for delays introduced by system components such as cables and digital processing blocks. The gain block provides sufficient amplification so that the loop gain meets the requirement for oscillation startup and sustainment. The limiter introduces nonlinearity into the loop to stabilize the amplitude of oscillations; without it, the signal amplitude would continue to grow once the loop gain exceeds unity. Together, these components ensure that the loop achieves stable, self-sustained oscillations at the cavity's resonant frequency.

GDR Mode

The GDR mode is a method of operating an RF cavity in which the system is driven by an external RF source at a fixed reference frequency. Unlike the SEL mode, where the oscillation frequency is determined by the cavity itself, GDR mode enforces a predefined frequency, and the cavity is required to follow this reference. The primary purpose of GDR is to achieve accurate control over cavity field amplitude and phase with respect to a global reference, such as a master oscillator. This is particularly important in particle accelerators, where multiple cavities must operate synchronously to ensure proper beam acceleration. In GDR mode, the LLRF control system maintains the desired field by continuously adjusting the drive signal based on feedback from the cavity pickup. GDR mode is typically used after the cavity has been properly tuned, often with the help of SEL. Once the resonance controller aligns the cavity's natural frequency with the desired operating frequency, the system can safely switch to GDR mode. At this point, the detuning is minimal, and the cavity can efficiently accept power from the generator with low reflection. Operating directly in GDR without prior tuning is generally not preferred, as any initial mismatch between the cavity resonance and the

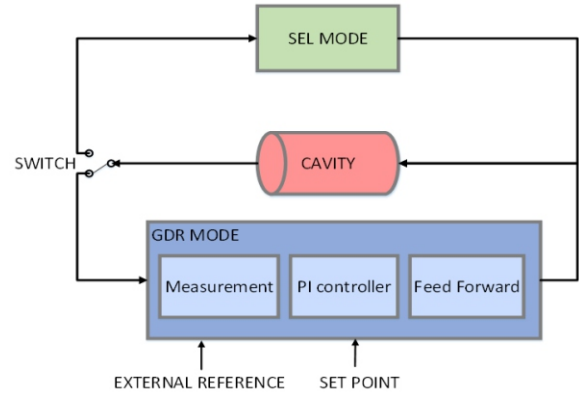


Fig.3: Basic block diagram of GDR architecture.

drive frequency can lead to high reflected power. In terms of operation, GDR relies on a closed-loop feedback system within the LLRF framework. The cavity pickup signal is compared with the reference signal to generate amplitude and phase error signals. These errors are processed through controllers, typically PI-based, to adjust the drive signal such that the cavity field matches the desired set points. This enables tight regulation of field parameters, which is critical for maintaining beam quality and accelerator performance. The block diagram of GDR architecture is shown in Fig. 3.

Performance of an LLRF System

The performance of an LLRF system is qualified based on its ability to maintain precise control over the amplitude, phase, and frequency of the accelerating RF field under varying operating conditions. Since beam quality and accelerator stability are highly dependent on RF field stability, the LLRF system must demonstrate reliable and repeatable operation within stringent specifications. The qualification of an LLRF system may involve verifying its functionality in SEL and GDR operating modes and its behavior while switching [2] from one mode to another. The performance is quantified using several measurable parameters. The most important among these are amplitude and phase stability, typically specified in terms of RMS or peak deviation over a defined bandwidth. Other important matrices include loop bandwidth, latency, noise floor, dynamic range, cavity field settling time, frequency tracking capability, and suppression of disturbances such as power supply ripple or microphonics. In superconducting accelerators, cavity detuning compensation and field regulation during pulsed operation are also key performance indicators.

Achieving very stringent amplitude and phase stability in an LLRF system requires careful optimization of the complete RF control chain, including hardware design, signal processing architecture, feedback algorithms, synchronization systems, and environmental control. Modern particle accelerators and specifically superconducting RF accelerators often demand amplitude stability in the order of 0.01% and phase stability at 0.01 degrees, making the suppression of even small disturbances critically important. One of the primary methods for ensuring high stability of field is the implementation of a high-bandwidth closed-loop feedback system. Although, high bandwidth helps in correcting wide range of disturbances, it

amplifies the inherent noise introduced by different components in the RF loop. Therefore, selection of adequate closed loop bandwidth is important to correct disturbances, suppress unwanted noise and maintain closed loop stability.

The quality of the reference clock and synchronization system plays a major role in phase stability. Ultra-low phase noise master oscillators and low-jitter clock distribution networks are essential to minimize phase fluctuations throughout the RF chain. Careful clock tree design further helps to reduce timing-induced errors. High-performance RF hardware is equally important. Low-noise mixers and RF amplifiers with excellent linearity and thermal stability are required to minimize gain variation and measurement noise. Furthermore, temperature-controlled electronics racks, stable and low ripple power supplies, proper grounding & shielding techniques reduce drift and electromagnetic interference.

With the advancements in digital electronics and with the availability of high-speed, high resolution ADC - DAC, LLRF implementation has increasingly transitioned toward System-on-Chip (SoC) based FPGA and DSP-based architectures, allowing high-speed signal processing, flexibility in control algorithms, and improved system integration.

Digitization Schemes

The process of digitization of the RF signal is the first important block in a signal processing chain of a digital LLRF system. Digitization of incoming signal essentially implies conversion of RF to digital quadrature IQ signals. Depending on the application a number of digitization schemes are used for the LLRF with each having its own pros and cons. Selection of the digitization scheme depends upon a number of requirements such as the control precision, control loop bandwidth, system configurability, remote control & data transfer requirements etc. and factors such as development cost, implementation efforts etc. Some of the popular schemes are discussed below.

Baseband Sampling

In this scheme the incoming RF or cavity probe signal is first demodulated using quadrature analog demodulator with the RF Reference. The resultant In-phase and Quadrature (IQ) components are baseband signals which after low pass filtering are digitized using two moderate speed ADCs. The digital and clocking requirements are very simple. This scheme however suffers from I/Q imbalance which needs to be compensated from time to time for good accuracy. Fig.4 shows the baseband sampling scheme.

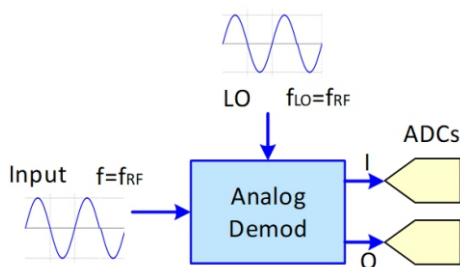


Fig.4: Baseband Sampling scheme.

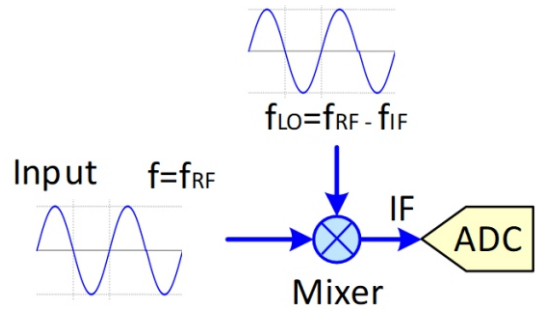


Fig.5: IF Sampling scheme.

IF Sampling

This sampling scheme is suited in applications where the accelerator reference frequency is above several hundreds of MHz and high precision control of RF field is required.

The RF frequency is down converted using a mixer to IF which is generally a few tens of MHz and this IF signal is digitized using IQ sampling or non-IQ sampling scheme. Digitized data is processed and up-converted to the accelerator RF frequency using IQ modulator. This scheme requires additional hardware in the form of down and up-converters but offers very high precision. The scheme is depicted in Fig.5.

The LLRF system designed and developed for HTS, RRCAT employs this sampling scheme whereby 650MHz RF is down-converted to an intermediate Frequency of 20MHz for processing and subsequently up-converted back to 650MHz for driving Superconducting RF cavities. The system has been commissioned at HTS, RRCAT and successfully evaluated with Spoke Test Cryostat (STC) at Fermilab, USA. The system tested at STC is depicted in Fig.6.

RF Sampling

In this scheme the RF input signal is directly digitized by high bandwidth ADC using under-sampling technique by carefully selecting the ADC sampling clock. This scheme can be used for improved measurement bandwidth and reduction in



Fig.6: Testing of LLRF system at STC, Fermilab.

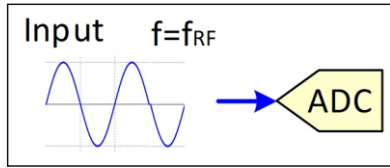


Fig.7: RF Sampling scheme.

frontend RF hardware requirements which in turn reduces errors due to RF-IF conversion. The scheme however requires extremely low jitter clock for the ADC to reduce the phase noise generated as a process of digitization. Thus the scheme may not achieve very tight precision as achieved with IF sampling. However, it can be very conveniently used where stability requirements are around 0.2% in amplitude and 0.2 degrees. in phase. The scheme is depicted in Fig.7.

LLRF systems based on this sampling scheme have been developed and commissioned to control the RF field in Buncher, RFQ, DTL1 and DTL2 within the LEHIPA lattice. Built on the Compact PCI platform, the systems receive 352MHz RF signals and under sample them to generate an intermediate lower frequency image by the way of sampling process. This image is then processed and digitally modulated back to 352MHz. The ADC sampling frequency is judiciously selected based on a variety of system parameters. Operational results demonstrate a field stability of 1% in amplitude and 1 degree in phase.

Every scheme requires a demodulation loop subsequent to the process of digitization and is carefully designed to reduce the effect of local oscillator and clock jitter [1]. Also, use of appropriate digital filters help in suppressing noise components. Feedforward algorithms are often added to compensate for predictable disturbances such as repetitive beam loading or pulsed cavity transients. RCS is additionally employed to compensate cavity detuning. Mechanical and environmental stability are also critical factors. Variations in cable length, vibration, and ambient temperature can introduce measurable phase shifts. Therefore, phase-stable cables, vibration isolation and thermal regulation are commonly adopted to reduce long-term drift.



Fig.8: Two LLRF controllers in a cPCI chassis for LEHIPA.

Another key aspect of performance of a LLRF system is reducing the transients while switching from SEL to GDR mode. A critical aspect of this transition is the difference in phase behavior between SEL and GDR modes. In SEL mode, while the amplitude of oscillation is stabilized by the limiter, the absolute phase is not defined with respect to any external reference; it is effectively arbitrary. In contrast, GDR operation requires a well-defined phase relationship with an external reference signal. At the instant of switching from SEL to GDR, there may be a large phase difference causing abrupt changes in the cavity field. This typically results in high transient in reflected and forward power, which is undesirable and can stress the RF system. Simulation using known algorithms demonstrates reduction in transients to as much as 60% [2].

Resonance Control System

The RCS is an integral part of modern LLRF systems for particle accelerators, where cavity detuning can significantly impact RF performance. The primary objective of RCS is to maintain the cavity's resonant frequency at the desired operating frequency, counteracting detuning effects. Unlike amplitude and phase control, which manage the properties of the RF field itself, resonance control addresses the dynamic physical behavior of the cavity structure, ensuring that RF power is efficiently transferred and the beam receives the intended energy gain. Effective resonance control is especially critical for achieving high RF cavity gradients and high duty cycles, as detuning at high gradients can lead to increased reflected power, reduced operational efficiency, and even cavity quenching in superconducting systems. By stabilizing the resonant frequency under varying operational conditions, the RCS enables sustained high-gradient operation while supporting reliable, continuous beam delivery.

Sources of Cavity Detuning

Several mechanisms can induce detuning in RF cavities:

- (1) **Thermal Drift:** RF power dissipation heats the cavity structure, causing expansion and frequency drift. Even small temperature changes can shift the resonance frequency.
- (2) **Lorentz Force Detuning (LFD):** High-intensity electromagnetic fields in superconducting RF cavities generate Lorentz forces that physically deform the cavity walls, shifting the resonant frequency. The magnitude of LFD increases with the square of the accelerating field gradient and can lead to frequency shifts of several hundred Hz in high-gradient cavities.
- (3) **Microphonics:** Vibrations from ambient sources—cryogenic pumps, building vibrations, or by acoustic noise—can induce rapid, small fluctuations in cavity frequency. Microphonics may be broadband or concentrated at specific mechanical resonance modes.

Principles of Resonance Control

The RCS maintains the cavity's resonant frequency by compensating for both fast and slow detuning effects.

- (1) **Tuner Control:** Adjusting the physical geometry of the cavity using mechanical and piezoelectric tuners to correct frequency shifts.

(a) Slow Mechanical Tuners: These devices adjust the cavity geometry over seconds to minutes to correct long-term frequency drifts caused by thermal expansion, cooldown effects, or gradual structural deformation. Mechanical tuners typically use stepper motors or screw-based actuators to change the cavity length, ensuring the cavity resonates near the desired operating frequency.

(b) Fast Piezoelectric Tuners: For rapid disturbances such as microphonics or LFD during pulsed operation, piezoelectric actuators make fine adjustments in sub-millisecond timescales. These fast tuners dynamically compensate small frequency shifts, maintaining high RF efficiency and minimizing reflected power.

The designed and developed RCS has been commissioned at HTS, RRCAT and evaluated at Fermilab. A similar system shall be developed for MEHIPA also. The integrated RF control system commissioned at HTS RRCAT is shown in Fig.9.

(2) Temperature (Thermal) Control: Regulation of the cavity temperature is often done using Low Conductivity Water (LCW) based cooling systems in order to counteract detuning caused by thermal expansion or contraction of the cavity walls. Temperature-controlled LCW circulates through channels in the cavity structure to remove heat. The resonance controller monitors water temperature and flow, integrating this data into feedback and feed-forward loops to compensate for thermal drift. Precise regulation minimizes detuning due to thermal expansion. Apart from manual offline tuning of frequency, this principle for control of frequency is used in LEHIPA to avoid excessive reflected power.

Development of EPICS based Application Software

The control system architectures developed and evaluated leverage the Experimental Physics and Industrial Control System (EPICS) framework, tailored precisely to the specific hardware deployments. At the HTS Facility in RRCAT and STC facility in Fermilab, the LLRF and RCS systems were implemented using the legacy EPICS 3 framework, closely integrated with a customized SoC FPGA platform to handle

deterministic and low-latency processing. In this configuration, the LLRF system exhibits high-throughput data handling capabilities, successfully acquiring and processing 40 concurrent waveforms, each with a record size of 1k samples, at a repetition rate of 20Hz. The LLRF system deployed and commissioned at the LEHIPA facility transitions to the modern EPICS 7 framework. This implementation takes full advantage of the high-performance pvAccess (PVA) protocol, which enables structured data types and optimized network streaming to significantly enhance data throughput, multi-variable communication, and overall system scalability. Future developments for MEHIPA will also be planned using EPICS 7 framework.

RF Protection and Interlock System

RFPI System is responsible for safe operation of expensive RF components through rapid fault detection and protective actions. The system accepts outputs from different sensors and monitors their signal levels against pre-defined settable limits. Based on the results, decision through a pre-configured logic matrix is taken to switch off the RF power to the RF cavity in 1-2 μ s. Modern RFPI system, employing state-of-the-art FPGAs, are extensive systems that detect and respond to fast events such as cavity arcs, field emissions and slow events such as water pressure, temperature etc. RFPI system also supports acquisition and storage of these signals. Field signals isolation, fast response, modularity, scalability, flexibility, redundancy, and reliability form key parameters of a good RFPI system.

A typical RFPI system [3] has the capability to process:

- Digital status signals from different subsystems including Machine Protection System (MPS), LLRF, vacuum system, cooling system, personal protection system and RF power source. Interlocks between these systems can be implemented by programming the required logic in the controller.
- Forward, reflected and pickup RF signals to/from the cavity.
- Signals from Photo Multiplier Tube (arc detector).
- Field Emission signals from probes.
- Analog signals (4-20 mA/0-5 V) from plant process parameters like temperature, vacuum and flow.

In the event of a fault detection, typically following output signals are generated from the system:

- (a) RF Inhibit:** This signal can be used to turn off the RF switch placed between the LLRF output and Power amplifier input.
- (b) LLRF Inhibit:** This signal can be used to notify the LLRF that the RF power to the cavity is switched off enabling the LLRF to initiate suitable action.
- (c) PWR Inhibit:** This signal can be used to switch Off driver stage of RF power source
- (d) MPS Inhibit:** This signal can be used to switch off the beam.

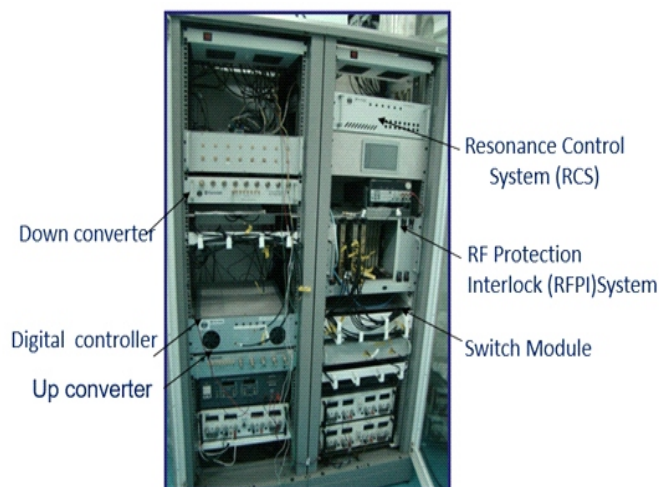


Fig.9: Integrated RF control system commissioned at HTS, RRCAT.



Fig. 10: VME64x based RF Protection Interlock System.

A VME 64x based RFPI system has been installed at LEHIPA and HTS, RRCAT (Fig.10). The functionalities of the RFPI system have also been demonstrated at Fermilab under IIFC.

Initiatives are underway on developing advanced SoC-FPGA architectures leveraging cutting-edge technologies.

Timing Control System

In high-performance accelerator facilities, precise multi-subsystem timing and synchronization are of paramount importance to ensure robust beam control, deterministic measurement accuracy, and deterministic machine protection. At the core of this synchronization architecture is the Event Generator Board (EGB), which serves as the central orchestration node for real-time signal generation across the entire facility network. By driving a specialized distribution topology, the EGB-centric timing system establishes the rigid real-time framework necessary to coordinate heterogeneous subsystems under strict operational constraints. Specifically, it fulfills four critical functions: ultra-low-jitter clock synchronization, deterministic event generation and distribution, distributed nanosecond-scale time-stamping, and synchronous data transmission. This precise temporal framework directly drives the LLRF systems, enabling deterministic phase and amplitude field control, phase-locked loop stabilization, and tightly coupled RF-to-beam synchronization across the accelerating cavities.

Conclusions

In conclusion, the Low-Level RF Control and Protection System form the backbone of modern particle accelerators by ensuring precise regulation, synchronization, resonance control, and protection of RF systems. The LLRF system plays a central role in maintaining stable amplitude and phase of cavity fields under disturbances such as beam loading, microphonics, thermal drift, and LFD. The SEL and GDR modes provide operational flexibility during cavity tuning, conditioning, and stable beam acceleration. Modern FPGA and DSP based implementations enable high-speed digital signal processing, low latency control, and sophisticated feedback and feedforward algorithms required for stringent accelerator performance. The RCS further enhances operational stability by compensating cavity detuning through mechanical tuners, piezoelectric actuators, and thermal regulation techniques. Simultaneously, the RFPI System ensures safe operation of expensive RF components through rapid fault detection and protective actions. High-quality synchronization, low phase-noise clock distribution, careful grounding, shielding, and thermal management are equally critical in achieving the demanding stability requirements of modern accelerator. The timing and synchronization system based on the Event generation architecture is yet another critical subsystem in high performance accelerator facilities for real-time signal generation across the entire facility network.

The integration of all these subsystems and control through a common EPICS platform enables reliable, efficient, and high-performance accelerator operation while supporting future advancements in high-gradient and high-duty-cycle accelerator technologies.

Acknowledgement

We are sincerely thankful to Director, BARC and Director, MRG for encouraging and permitting us to pursue developments in the areas of Accelerator Control.

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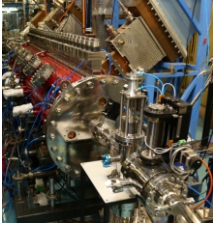
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उच्च-तीव्रता त्वरकों के लिए अगली पीढ़ी के बीम निदान

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लेहिपा में एस-एफएफसी असेंबली

सारांश

यह लेख लेहिपा और मेहिपा जैसे उच्च-तीव्रता वाले प्रोटॉन त्वरकों के प्रभावी संचालन के लिए महत्वपूर्ण बीम नैदानिक उपकरणों में हाल की स्वदेशी प्रगति पर प्रकाश डालता है। जबकि पारंपरिक अवरोधक उपकरण एक मूलभूत माप रीढ़ प्रदान करते हैं, ध्यान तेजी से उच्च-रिज़ॉल्यूशन, गैर-विनाशकारी प्रौद्योगिकियों की ओर स्थानांतरित हो गया है। चर्चा किए गए प्रमुख नवाचारों में उप-नैनोसेकंड वाइड-बैंडविड्थ मॉनिटर, क्रायोजेनिक बीम पोजीशन मॉनिटर, गैर-आक्रामक गैस शीट प्रतिदीप्ति प्रोफाइलर और भौतिकी-सूचित मशीन लर्निंग फ्रेमवर्क शामिल हैं। एक साथ, ये अगली पीढ़ी के उपकरण तेजी से, डेटा-संचालित चरण अंतरिक्ष पुनर्निर्माण और अत्यधिक सटीक ऑनलाइन बीम ट्यूनिंग की सुविधा प्रदान करते हैं।

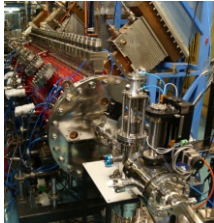
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Next-Generation Beam Diagnostics for High-Intensity Accelerators

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S-FFC assembly in LEHIPA

ABSTRACT

This article highlights the recent indigenous advancements in beam diagnostic instruments critical for the effective operation of high-intensity proton accelerators such as LEHIPA and MEHIPA. While traditional interceptive devices provide a foundational measurement backbone, the focus has rapidly shifted toward high-resolution, non-destructive technologies. Key innovations discussed include sub-nanosecond wide-bandwidth monitors, cryogenic beam position monitors, non-invasive gas sheet fluorescence profilers, and physics-informed machine learning frameworks. Together, these next-generation tools facilitate rapid, data-driven phase space reconstruction and highly precise online beam tuning.

KEYWORDS: Energy High Intensity Proton Accelerator (LEHIPA), Medium Energy High Intensity Proton Accelerator (MEHIPA), High-Intensity Accelerators

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Introduction

The effective commissioning and operation of high-intensity proton accelerators, such as the Low Energy High Intensity Proton Accelerator (LEHIPA) and the Medium Energy High Intensity Proton Accelerator (MEHIPA), rely heavily on robust diagnostic instruments. While conventional tools like Faraday cups, current transformers, and wire profilers form the foundational backbone of beam measurement, new frontiers are rapidly expanding our capabilities. Recent indigenous developments have introduced wide-bandwidth devices for sub-nanosecond longitudinal profiling, specialized warm and cold beam position monitors for precise alignment in extreme environments, and non-invasive gas sheet fluorescence techniques for continuous transverse profiling. Furthermore, the integration of tomographic phase space reconstruction and physics-informed machine learning is revolutionizing the field, transitioning from traditional interceptive measurements to rapid, data-driven, and non-destructive online tuning.

The Foundation: Conventional Beam Diagnostics

Before exploring the new frontiers, it is important to recognize the foundation of conventional beam diagnostics which are deployed in LEHIPA [1]. Precise measurement of the beam current and transverse profile is crucial for optimizing accelerator performance and ensuring overall stability. For beam current measurement, interceptive devices like Faraday Cups (FCs), often utilizing water cooling and high-temperature radiation-resistant materials like tantalum or copper, are designed to safely intercept and measure the entire beam charge. Non-interceptive Current Transformers, such as DCCTs and ACCTs, are also heavily relied upon to accurately measure steady-state and fast macro pulsed beam currents without disrupting the beam path. For mapping spatial distributions, interceptive tools like wire profilers, multiwire profilers, and water-cooled slit profilers remain standard instruments, providing the high-resolution data necessary for essential beam tuning in low-intensity transport lines.

New Frontiers in Beam Diagnostics

As accelerator technologies advance, so too must the diagnostic tools used to measure them. The latest developments push the boundaries of bandwidth, non-invasive measurement, and intelligent data processing.

Wide Bandwidth Devices: Catching the Sub-Nanosecond

Capturing the high-speed dynamics of modern linac beams requires devices with extraordinary temporal resolution.

Strip-line Fast Faraday Cup (S-FFC)

Fast Faraday cups are crucial interceptive diagnostic devices used for measuring the time structure of sub-nanosecond beam bunches. For the Low Energy High Intensity Proton Accelerator (LEHIPA), a novel, wide-bandwidth strip-line fast Faraday cup (S-FFC) was successfully developed, employing a robust 3.5 mm thick strip capable of withstanding larger beam intensities and longer pulse durations [2]. With a broad operational bandwidth of approximately 7 GHz, this device accurately captures the time structure of individual micro-pulses, measuring a full width at half maximum (FWHM) of ~300 ps.

Coaxial Wall Current Monitor (C-WCM)

For continuous, online characterization of high-intensity bunches without disrupting the beam, a Coaxial Wall Current Monitor (C-WCM) was designed for LEHIPA [3]. Devoid of ferrite materials to eliminate high-frequency performance degradation, the C-WCM achieves a substantial measured bandwidth of about 6 GHz. Its eight azimuthally distributed feedthroughs equip it with both longitudinal profiling and high-performance beam position monitoring capabilities.

Warm and Cold Beam Position Monitors

Beam position monitors (BPMs) are essential for precise beam alignment and stability, conventionally utilizing four symmetrically arranged electrodes to detect beam-induced

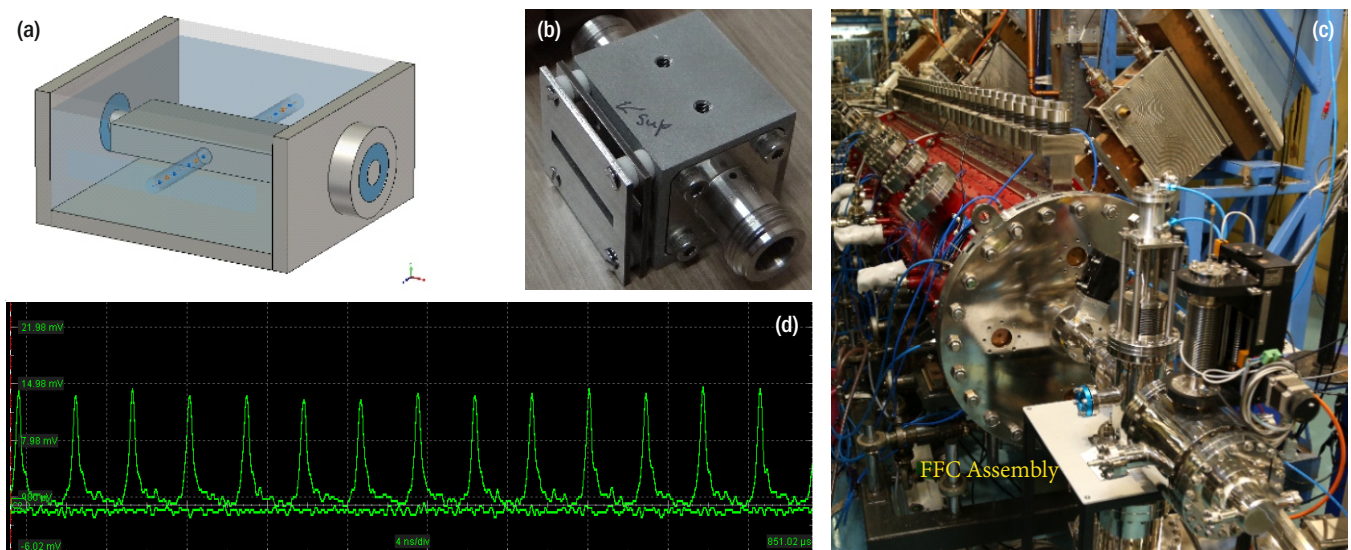


Fig.1: (a) Model and (b) picture of S-FFC; (c) S-FFC assembly in LEHIPA and (d) beam bunch train measured with S-FFC (4 ns/div).

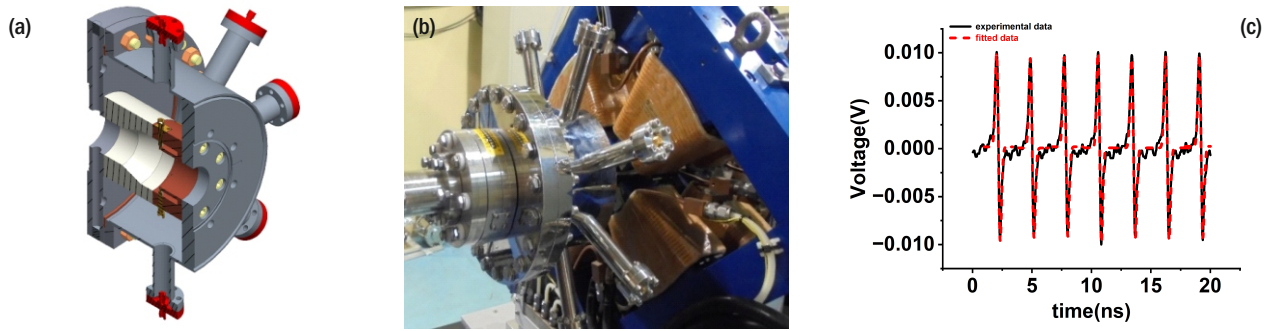


Fig.2: (a) 3D model of C-WCM final assembly, (b) C-WCM in the high energy beam transport line of LEHIPA, (c) Individual beam bunches on C-WCM with a derivative Gaussian fitting.

electric fields. For room-temperature sections of the LEHIPA accelerator, "warm" BPMs are deployed, delivering a sensitivity of 11 %/mm within a linear measurement region of ± 3 mm. As beamlines push into cryogenic environments, such as the 40 MeV MEHIPA, specialized "cold" BPMs have been engineered [4]. These cold variants are fabricated from SS 316 LN stainless steel to withstand severe thermal contraction and feature uniquely curved electrodes to ensure structural integrity under cryogenic stress. Despite the extreme conditions, these cold monitors expand their sensitivity to 11 %/mm and offer a broader linear measurement region of ± 4 mm, securing highly precise diagnostics.

Non-Invasive Gas Sheet Beam Profiling

To overcome the thermal and mechanical limitations of interceptive profilers, a novel dual gas sheet beam profile monitor is being developed for the LEHIPA facility [5]. This non-invasive system works by generating two thin nitrogen gas sheets at a 45-degree angle to the beam axis. When the charged particle beam intersects this gas sheet, it induces molecular excitation and subsequent fluorescence, providing a direct two-dimensional visual representation of the beam's intensity profile. Experimental testing with a 20 keV, 10 mA pulsed proton beam successfully imaged this characteristic fluorescence, making it directly visible to the eye without requiring complex image intensifiers. Crucially, the beam profile measurements obtained using this gas sheet technique showed close agreement with those from conventional solid scintillator screens. This innovative development marks the first time such an intense low-energy proton beam has been used to directly view the beam-induced fluorescence of a gas sheet.

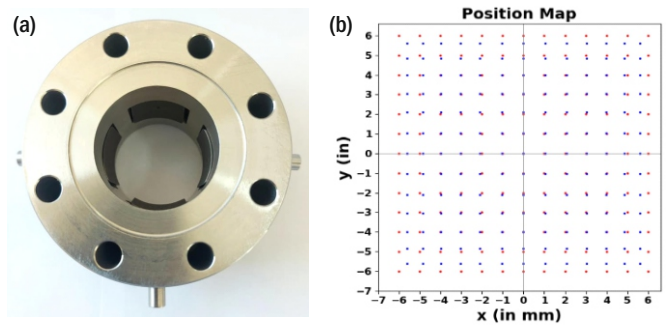


Fig.3: (a) Picture of cold BPM assembly, (b) Position map of the cold BPM with CST simulations.

Tomographic Phase Space Reconstruction

Accurate transverse phase space characterization is vital for matching beams and minimizing emittance growth in facilities like LEHIPA. A minimally interceptive Computed Tomography (CT) approach has been implemented to reconstruct the two-dimensional transverse phase space by utilizing one-dimensional spatial profiles measured across varying solenoid magnetic field strengths [6]. An essential feature of the custom Python-based reconstruction program is its ability to digitally filter out secondary molecular species (like H_{2+} and H_{3+}) from the composite profiles. By choosing the Simultaneous Algebraic Reconstruction Technique (SART) over Filtered Back-Projection, this method provides superior reconstruction accuracy, guiding the successful re-optimization of beamline parameters.

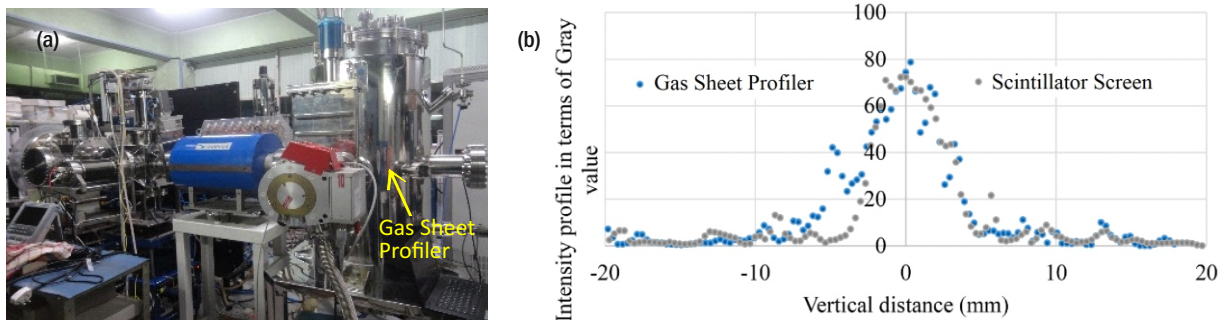


Fig.4: (a) Photograph of the gas sheet generator setup in test bench (b) Beam profile acquired by the gas sheet profiler and scintillator screen.

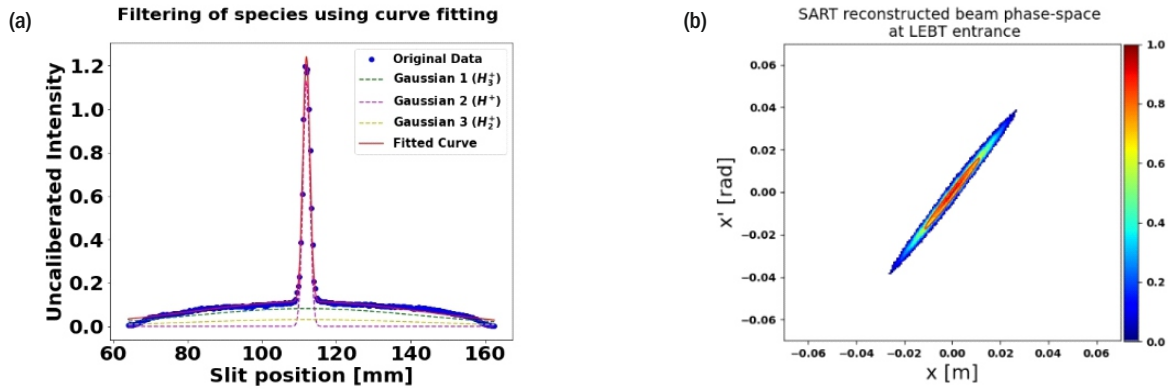


Fig.5: (a) 3-species curve fitting of a measured beam profile. (b) SART reconstructed beam phase space distribution in x - x' .

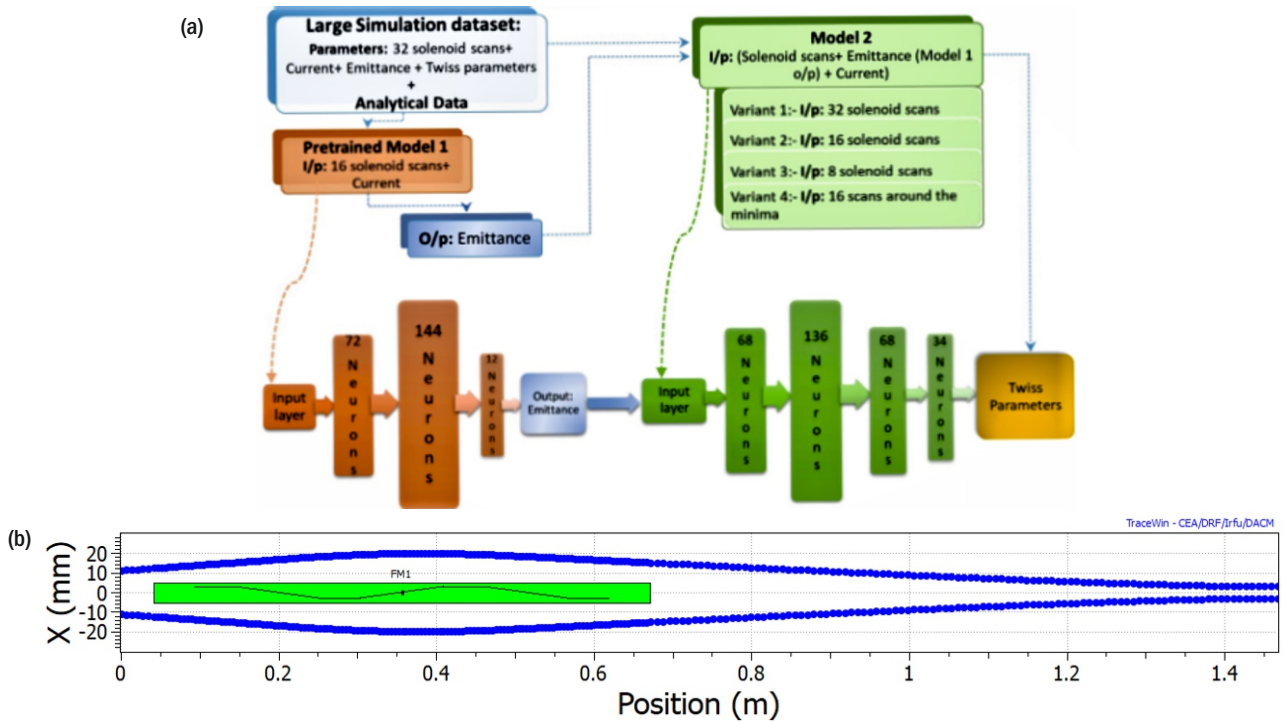


Fig.6: (a) Architecture of the two-stage cascaded neural network framework. (b) PIC beam envelope simulation result for LEHIPA parameters predicted by Two-stage NN model.

The AI Revolution: Machine Learning in Diagnostics

The integration of machine learning (ML) marks a paradigm shift toward rapid, data-driven beam diagnostics, overcoming the computational and noise-sensitivity limitations of traditional methods.

Physics-Informed ML for Phase Space Reconstruction

A novel dual-network machine learning framework has been developed for the LEHIPA facility to effectively overcome the noise sensitivity and computational overhead of traditional solenoid scans [7]. This cascaded architecture features an initial model that predicts transverse beam emittance from RMS beam size data and current, which then feeds into a secondary model alongside additional RMS measurements to accurately deduce the Twiss parameters. By employing

physics-informed pre-training based on analytical envelope equations and subsequent fine-tuning with TraceWin simulations, this approach successfully embeds fundamental beam physics constraints, drastically reducing the reliance on expensive simulation datasets while delivering highly accurate, real-time predictions for automated accelerator tuning.

Transverse Profile Reconstruction

To expand non-invasive diagnostic capabilities, advanced machine learning techniques are now being applied to reconstruct detailed transverse beam profiles from multi-electrode monitors such as the C-WCM. This approach utilizes a newly developed hybrid computational framework that pairs a Neural Network (NN) with Differential Evolution (DE) optimization. Within this architecture, the NN serves as a high-speed predictive surrogate model, instantly mapping

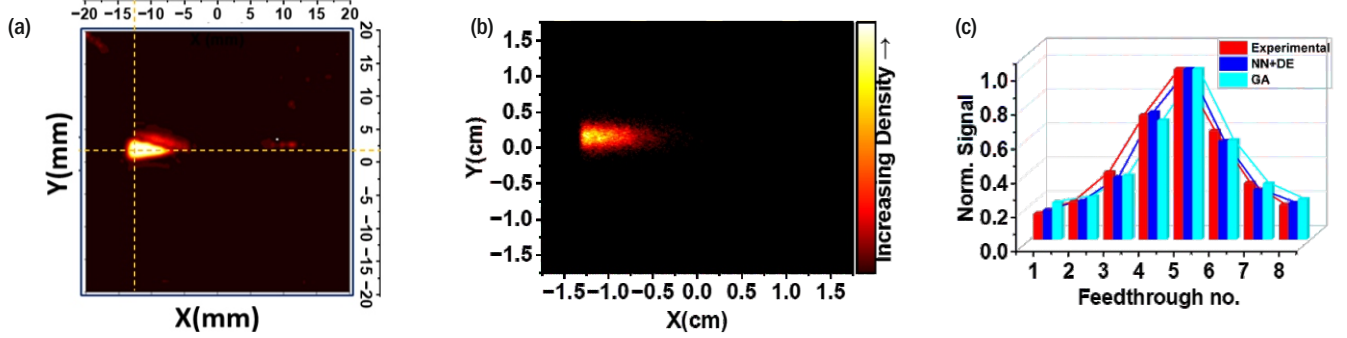


Fig.7: (a) Beam profile recorded at scintillator screen; (b) C-WCM based reconstructed beam profile; (c) comparison of experimental and simulated feedthrough signals.

fundamental beam parameters to corresponding electrode responses. Simultaneously, the DE algorithm efficiently minimizes the discrepancy between these predicted outputs and the actual measured signals, ensuring rapid and highly accurate profile reconstruction.

Conclusions

The continuous evolution of beam diagnostic tools is imperative to safely and efficiently meet the rigorous demands of modern high-intensity particle accelerators. By integrating wide-bandwidth devices and non-invasive profiling techniques like gas sheet fluorescence, the thermal and mechanical limitations of conventional interceptive monitors are effectively mitigated. Moreover, the application of tomographic phase space reconstruction and physics-informed machine learning heralds a new era of rapid, automated, and highly accurate beam characterization. Ultimately, these state-of-the-art indigenous developments secure the operational stability, alignment, and optimized performance of advanced facilities like LEHIPA and MEHIPA.

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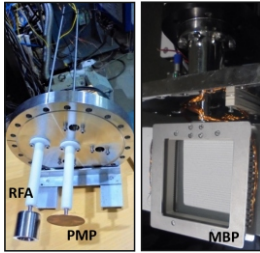
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उच्च-तीव्रता वाले प्रोटॉन त्वरकों के लिए अंतराकाशी आवेश क्षतिपूर्ति अध्ययन

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एल. ई. वी. टी. बीम डायग्नोस्टिक चैम्बर-1 में आर. एफ. ए., पी. एम. पी. और एम. बी. पी. विधानसभाओं को तैनात किया गया है

सारांश

यह लेख उच्च-तीव्रता वाले प्रोटॉन त्वरकों में मजबूत विफोकसन बलों को कम करने के लिए लेहिपा सुविधा में संचालित व्यापक अंतराकाशी आवेश क्षतिपूर्ति (एससीसी) अध्ययन प्रस्तुत करता है। 3डी पार्टिकिल-इन-सेल और मोटे कार्लो टक्कर (पीआईसी-एमसीसी) अनुकरण को एक स्वदेशी रूप से विकसित नैदानिक सुइट के साथ जोड़कर-एक नए, गैर-आक्रामक कण मॉनिटर प्रोब (पीएमपी) द्वारा हाइलाइट किया गया-कणपुंज उदासीनीकरण की क्षणिक और स्थिर-स्थिति गतिशीलता को सफलतापूर्वक चिह्नित किया गया। क्षतिपूर्ति करने वाले गैस मापदंडों के लक्षित अनुकूलन ने लगभग पूर्ण क्षतिपूर्ति ($\eta \sim 0.96$) हासिल की, जिससे सीधे अनुवर्ती आरएफक्यू कणपुंज संचरण में 65 प्रतिशत से 85 प्रतिशत तक सुधार हुआ। अंततः, यह अंतर्दृष्टि अगली पीढ़ी के त्वरक प्रणालियों में निम्न ऊर्जा कणपुंज परिवहन (एलईबीटी) अभिकल्पन एवं प्रचालन का इष्टतमीकृत एक मजबूत, भावी ढांचा प्रदान करता है।

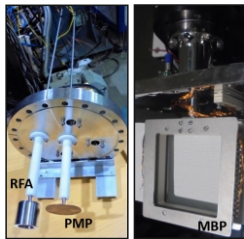
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Space Charge Compensation Studies for High-Intensity Proton Accelerators

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RFA, PMP and MBP assemblies deployed in LEBT Beam Diagnostic Chamber-1

ABSTRACT

This article presents comprehensive Space Charge Compensation (SCC) studies conducted at the LEHIPA facility to mitigate strong defocusing forces in high-intensity proton accelerators. By combining 3D Particle-in-cell & Monte Carlo Collision (PIC-MCC) simulations with an indigenously developed diagnostic suite highlighted by a novel, non-invasive Particle Monitor Probe (PMP) the transient and steady-state dynamics of beam neutralization were successfully characterized. Targeted optimization of compensating gas parameters achieved near-complete compensation ($\eta \sim 0.96$), directly improving downstream RFQ beam transmission from 65% to 85%. Ultimately, these insights offer a robust, predictive framework for optimizing Low Energy Beam Transport (LEBT) design and operation in next-generation accelerator systems.

KEYWORDS: Space Charge Compensation (SCC), Particle Monitor Probe (PMP)

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Introduction

The Front-End Challenge

In high-intensity proton accelerators, one of the most critical regions is the front-end, where the beam energy is low (typically tens of keV) and the current is high. At these non-relativistic velocities, the electrostatic repulsion between particles is not mitigated, allowing strong space charge forces to dominate beam dynamics. Consequently, the beam experiences severe defocusing, leading to rapid transverse expansion, emittance growth, and halo formation.

If these effects are not controlled at the LEBT stage, they propagate downstream and cause significant beam losses and component activation. Therefore, preserving beam quality via SCC is essential. A diagnostic-guided SCC optimization in the Low Energy High Intensity Proton Accelerator (LEHIPA) facility directly improved transmission through the 3 MeV Radio Frequency Quadrupole (RFQ) from 65% to 85%. Crucially, the diagnostics developed for this are completely indigenous, showcasing deep *atma nirbhar* capabilities in advanced accelerator technologies.

The LEHIPA Facility and SCC Physics

At the Bhabha Atomic Research Centre (BARC), the LEHIPA serves as a testbed to study these phenomena. Its compact ~2.7 m dual-solenoid LEBT (Fig.1) transports and matches the high-intensity proton beam from the ECR ion source to the RFQ. To study the dynamics of beam neutralization, the “gas feed” port in LEBT injects controlled amounts of compensating gas (H_2 , N_2 or Ar). This allows systematic variation of gas type and its pressure, enabling detailed parametric studies of SCC.

SCC arises when the primary beam ionizes this residual gas [1]. The produced electrons are rapidly trapped within the beam potential, progressively neutralizing its space charge and reducing transverse defocusing forces. This dynamic process is characterized by two key parameters:

- **Degree of Compensation (η):** Indicates the level of neutralization, where $\eta \rightarrow 1$ means near-complete compensation. $\eta = 1 - \phi_c / \phi_0$, where ϕ_c and ϕ_0 are the

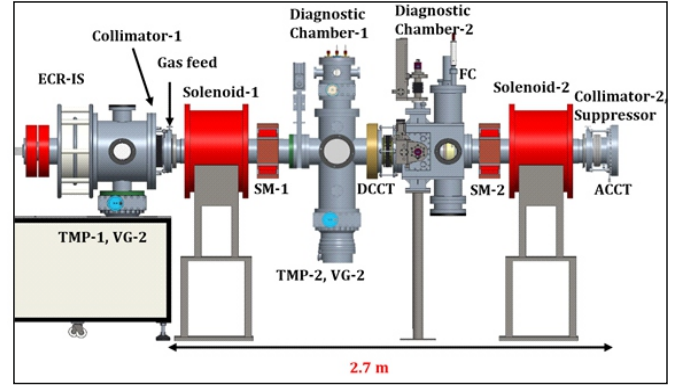


Fig.1: Schematic of LEHIPA LEBT. ECR Ion Source (ECR-IS), Turbo Molecular Pump (TMP), Vacuum Gauge (VG), Steerer Magnet (SM), Faraday Cup (FC), Current Transformer (CT).

compensated and uncompensated on-axis beam potentials.

- **Characteristic Timescale (τ_{SCC}):** The time required for compensation buildup. $\tau_{SCC} = 1/(\sigma(E) \cdot n_g \cdot \beta c)$, where $\sigma(E)$ is the ionization cross-section, n_g the gas density, and βc the beam velocity.

Integrated Modelling: PIC-MCC Simulations

To fundamentally understand these complex beam-plasma interactions, comprehensive 3D Particle-In-Cell Monte Carlo Collision (PIC-MCC) simulations were performed [2,3]. These models track the ionization of the residual gas and the kinematics of generated secondary electrons and slow ions. By resolving the trapping of neutralizing electrons and the radial expulsion of positive ions, the framework captures the transient buildup and steady-state plasma. Fig.2(a) shows the clear reduction in beam potential at 2 μs and 4 μs as SCC progresses. Furthermore, in Fig.2(b), the simulations confirm that τ_{SCC} corresponds directly to electron density saturation and beam size stabilization.

The Space Charge Compensation Diagnostic Suite

Understanding transient SCC is critical, but conventional beam size measurements are intrusive and can perturb the SCC process via secondary electron emission. To overcome

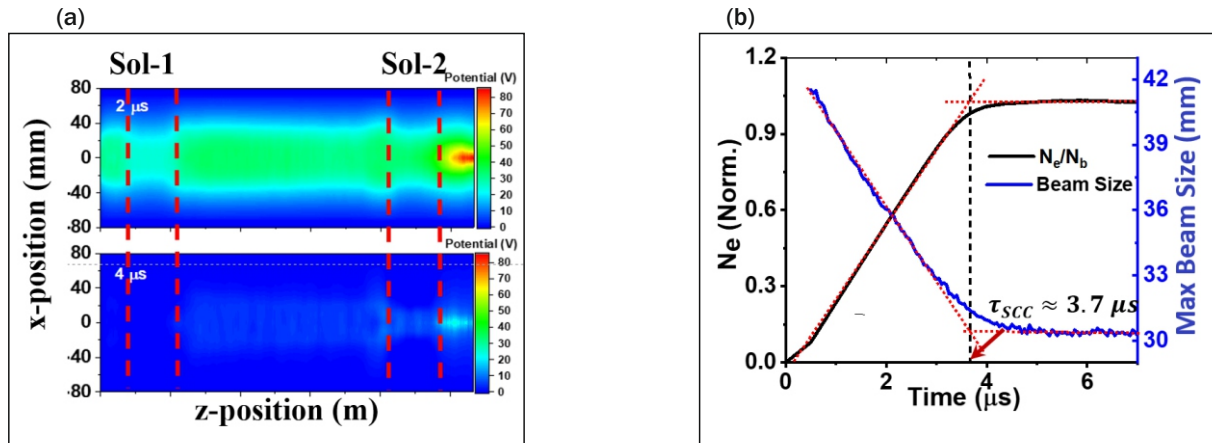


Fig.2: For 5×10^{-5} Torr N_2 : (a) beam potential evolution; (b) temporal evolution of normalized electron density (N_e/N_b , left axis) and maximum beam size (right axis).

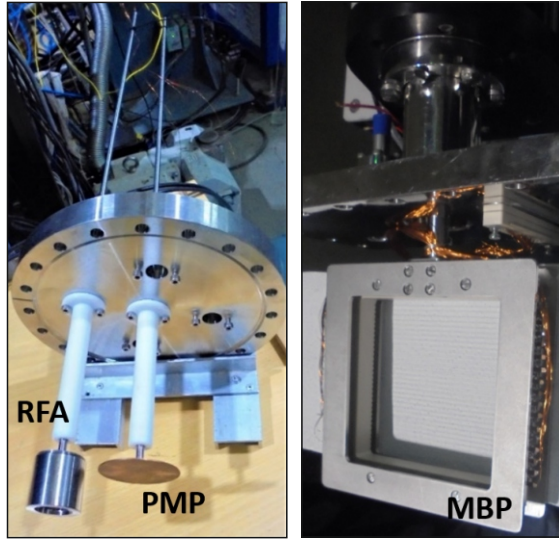


Fig.3: RFA, PMP and MBP assemblies deployed in LEBT Beam Diagnostic Chamber-1.

this, a dedicated, non-invasive diagnostic suite, comprising the PMP [2,3] Retarding Field Analyzer (RFA) [3] and Multiwire Beam Profiler (MBP)[3] was developed and deployed in a diagnostic chamber downstream of the first solenoid (Fig.3).

Particle Monitor Probe (PMP)

The novel PMP operates non-invasively by measuring the radial flux of secondary plasma particles expelled during SCC buildup. Utilizing a specialized cylindrical pick-up electrode, it boasts a fast response time (~ 1.3 ns) for high temporal resolution during initial transient phases [3]. Simulations (Fig.4(a)) predict a distinct rise-peak-decay profile for the transverse electron current, where the subsequent minimum marks steady-state compensation. Experimental measurements with the PMP capture this exact temporal minimum, yielding a direct measurement of τ_{sc} (Fig.4(b)). Benchmarking against a Multi-Pixel Photon Counter (MPPC)

demonstrated a comparable response without beam perturbation, establishing the PMP as a highly robust diagnostic.

Retarding Field Analyzer (RFA)

To complement the PMP's transient data, the RFA quantifies the steady-state degree of space charge compensation [3]. By measuring the energy distribution of secondary ions repelled radially from the beam core, the maximum kinetic energy serves as a direct, experimental proxy for the compensated on-axis beam potential (Fig.5 (a)).

Multiwire Beam Profiler (MBP)

The MBP completes the suite by providing reliable measurements of the transverse beam profile in the steady state [3]. It actively tracks beam size reduction and profile evolution toward a Gaussian distribution during compensation (Fig.5(b)).

Experimental Results

The primary objective of these studies was to systematically identify the optimal compensating gas species and flow rates to maximize downstream RFQ transmission [3].

Initial investigations characterized compensation dynamics across different species. As shown in Fig.6, τ_{sc} decreases with increasing gas pressure, strictly depending on the injected gas's ionization cross-section. While experimental values are marginally higher than ideal simulations due to realistic effects (finite beam rise time, electron losses, localized pressure gradients), the accurately reproduced scaling behavior provided the empirical data needed to select the best gas for rapid neutralization.

Next, optimizing the localized gas flow was critical to balance necessary compensation pressure against beam degradation from scattering. By tracking the transverse profile across various flow rates (Fig.5(b)), MBP data identified the ideal flow regime yielding the most tightly focused, well-matched beam.

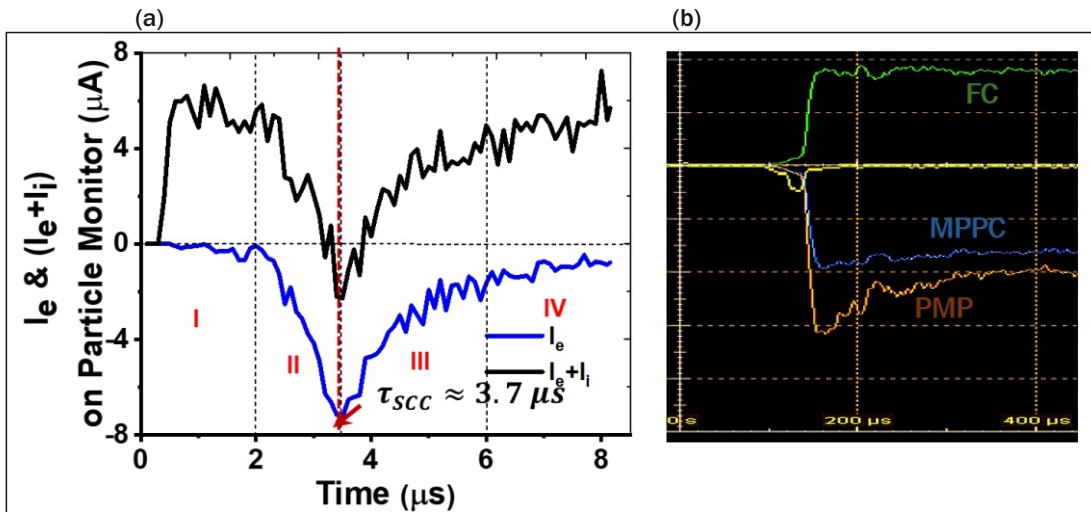


Fig.4: (a) Time evolution of the simulated transverse electron current (I_e) and total current ($I_e + I_i$) on particle monitor; (b) measurement plots of Particle Monitor Probe (PMP), Multi-Pixel Photon Counter (MPPC) and beam current signal on Faraday Cup (FC).

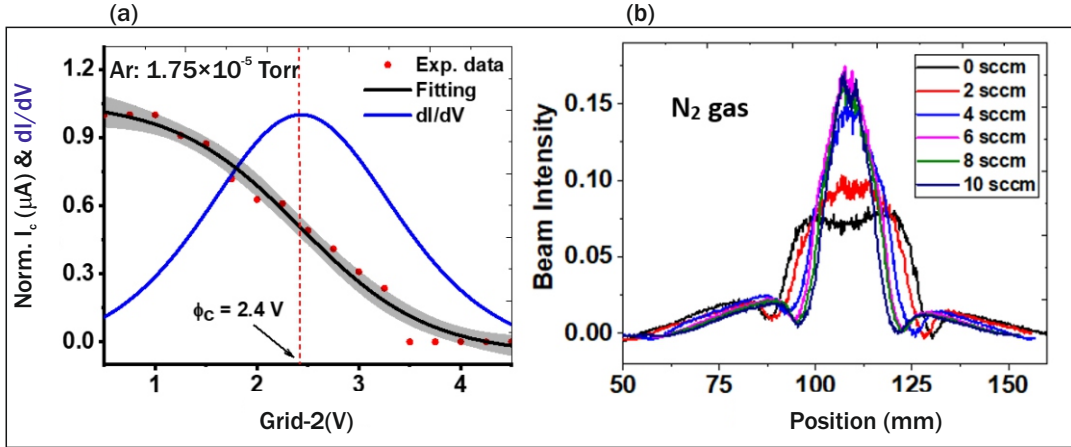


Fig.5: (a) RFA I-V characteristics and corresponding energy distributions for Ar gas. (b) MBP plots for different residual gas flow rates.

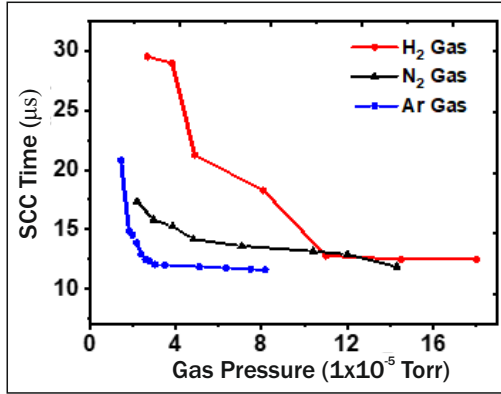


Fig.6: Variation of τ_{scc} with gas pressure for H₂ (red), N₂ (black) and Ar (blue) gases.

Under these optimized conditions, the LEHIPA LEBT achieves near-complete space charge compensation ($\eta \sim 0.96$). The RFA independently verified this highly neutralized state (Fig.5(a)), recording a dramatic beam potential drop from an uncompensated ~ 70 V to just ~ 2 V. This targeted optimization directly facilitated maximum matching efficiency and transmission through LEHIPARFQ.

Conclusion

The LEHIPA studies establish a consistent, predictive understanding of SCC through integrated PIC-MCC simulations and targeted diagnostics. The non-invasive Particle Monitor Probe successfully overcomes the limitations of conventional techniques by enabling direct, fast measurement of SCC time. These practical insights into gas selection, pressure optimization, and diagnostic strategy are directly relevant for designing and operating next-generation high-intensity proton accelerators, ensuring the precise beam control essential for reliable performance.

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Top: Invited dignitaries from the ranks of senior officers of BARC launch the training course booklet during the inaugural session.

Bottom: Training course participants pose for a group photograph.

Training Course on 'Safety in Accelerators'

Dr. Manjiri Pande

BARC Safety Council Secretariat organized a one-day training course on 'Safety in Accelerators' on Feb 14, 2026 in Multipurpose Hall, Training School Hostel, Anushakti Nagar. This training course benefitted the new entrants working in the area of accelerators and the accelerator community as a whole.

It has brought the safety committees, radiological safety officers, designers, operating personnel, etc. on a single platform for sharing their knowledge and experience on safety and regulation of accelerators. It has improved the safety awareness of all personnel involved in design, development and operation of Accelerators.

Training Course topics

Overview of Accelerators

Regulatory Requirements, Framework and Regulation of Accelerator Facilities

Accelerator - Radiological, Occupational Safety & Emergency Response

Industrial Safety and Hazards in Accelerators

Accelerators in Medical Applications

Cryogenic Safety in Accelerators

Industrial Applications of Accelerators - ICS, Medical Sterilisation, Agriculture, Semi-Conductors Operational Safety Management in Accelerators

Sharing Experiences in Regulation and Path Ahead in Proton and Electron Accelerators



Clockwise from top: Inaugural Session of InPAS-2025, Valedictory Session of InPAS-2025 and Group Photo of InPAS-2025 participants.

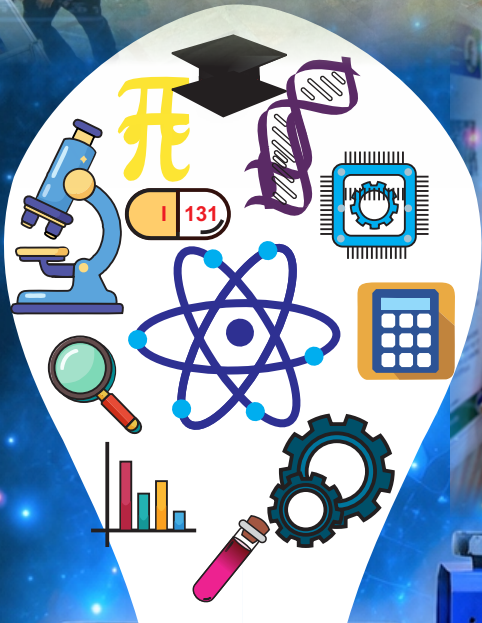
InPAS 2025

The Indian Particle Accelerator School 2025

Dr. Sista V.L.S. Rao and Mr. Manas R. Mishra

The Indian Particle Accelerator School 2025 (InPAS 2025) was organized under the aegis of the Board of Research in Nuclear Sciences (BRNS) and the Indian Society of Particle Accelerators (ISPA) from 15–20 September 2025 at BARC, Mumbai. InPAS-2025 emerged as a significant national initiative, successfully blending academic rigor with experiential learning. A total of 50 participants from DAE labs, universities, and research institutions across India engaged in an intensive week-long program on RF Linear Accelerators, featuring expert lectures, simulation-based sessions, and facility visits. The curriculum covered key aspects of LINAC science and technology, including transverse and longitudinal beam dynamics, space-charge effects and mitigation, beam diagnostics, accelerator controls, machine protection, RF systems (Couplers and power supplies etc), magnet designs, ion sources, electron guns, and heavy-ion accelerators. Specialized sessions on superconducting RF (SCRF) technology addressed cavity design, processing, and associated mechanical challenges, providing participants with exposure to both normal-conducting and superconducting accelerator systems.

A major highlight was the seamless integration of theory with practical exposure, through hands-on training in simulation tools along with RF measurement exercises and magnet design studies. Participants also gained first-hand insights during field visits to LEHIPA, FOTIA, and the Electron Beam Centre (EBC), Kharghar, where they observed operational accelerator systems in action. The special evening lectures by senior scientists on emerging areas in accelerator science and technology provided valuable insights into current research frontiers. The inaugural ceremony, graced by Prof. Avinash Chandra Pandey, Director IUAC (Chief Guest), Dr. Pitamber Singh, Ex-Head, IADD (Guest of Honour), Shri U. D. Malshe, Director, MRG, BARC and the valedictory function led by Shri Martin Mascarenhas, Director, BTGD, BARC added distinction to the event. InPAS-2025 was widely appreciated for its well-structured curriculum, exceptional faculty, and effective organization, making it an enriching platform for young scientists and engineers to advance their understanding of accelerator science.



NUCLEAR R&D Tech Spin-offs

Bhabha Atomic Research Centre (BARC) continues to foster industry collaboration by transferring emerging nuclear spin-off technologies and associated know-how besides stimulating rural entrepreneurship. The Centre is also accelerating efforts to incubate deep-tech startups in high-priority domains critical to sustained economic growth.



Technology Streamlining & Transfer

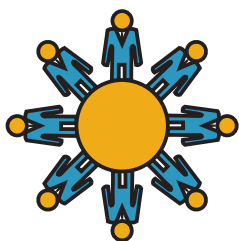


Multiple indigenous technologies for public and industrial applications were streamlined during January–April this year. These include:

Preservative-free Ready-to-Eat Mint Coriander Spice Dip (AB66FTD)
D/H Mass Spectrometer (AI42TPD)
Radiation Processing of Fresh Leafy Vegetables (AB67FTD)
Hollow Cathode Plasma Torch System (CERPPT-25KW)
Portable Thyroid Monitor (MD34RSSD)
Carbon Nanotube Fiber via CVD (CH50GAMD)
Semi-Automatic OBT & Carbon-14 Extraction System (CH51EMAD)
Absolute Capacitance Diaphragm Gauge (AI43TPD)

BARC signed over 30 agreements with industry partners for the transfer of 27 technologies spanning metallurgy, agriculture, water purification, waste management, food processing, and healthcare diagnostics. These technologies include innovations in e-waste copper recovery and polymer resins, plasma-based fertilizer synthesis, superabsorbent materials for oil removal, waste composting and biodegradable conversion systems, lithium-ion battery material synthesis, and whole-body scanning systems. Key high-impact solutions include the Soil Organic Carbon Detection Kit (SOCDK), biosensor kits for pesticide detection, portable Raman spectroscopy for oral cancer screening, USB-based TeleECG systems, rapid composting solutions for organic waste, rare earth recovery from ores, and mixed-matrix membrane systems for electrochemical applications.

Innovation Ecosystem



An incubation extension agreement was signed with Hyurja Fuels Pvt. Ltd. focusing on plasma pyrolysis of methane for green hydrogen production. A collaborative incubation agreement was also established with IEC Hydrogen Frontiers for scaling up zirconium composite membrane

diaphragms used in alkaline water electrolyzers, strengthening hydrogen and clean energy R&D commercialization.

Deep Tech Summit 2026 organized jointly by AIC Anushakti Foundation and TT&CD, BARC. The program witnessed launch of Deep Tech Cohort 1.0, where 6 startups (showed EoI) were selected from 64 applicants. Formation of the DAE Incubator Alliance, bringing together AIC Anushakti, AIC FAST, AIC PI HUB, and AIC PLASMATECH across Department of Atomic Energy centres. Signing of 12 technology transfer agreements, accelerating lab-to-market translation. Showcasing of policy discussions around deep-tech startups, MSME funding, and ecosystem development. The summit featured a keynote narrative by A. Velumani, sharing his journey from BARC colleague to entrepreneur, inspiring deep-tech founders.

Semiconductor crystal development technology transferred to Raana Semiconductors. A chitosan-based plant regulator startup successfully graduated in collaboration with Vasant Dada Sugar Institute. BARC-DAE medical diagnostics and healthcare technologies were showcased at Odisha Medical Expo 2026 and Medical Kolkata 2026.

Rural Entrepreneurship



AKRUTI Kendras promote rural entrepreneurship and sustainable development through the dissemination, demonstration, and training of DAE-BARC technologies. During the review period, an agreement was signed with Savitribai Phule Pune University for establishing an AKRUTI Kendra,

strengthening institutional collaboration.

Extensive training programmes, workshops, and awareness camps were conducted across villages and academic institutions, including practical exposure to technologies such as Foldable Solar Dryer, Neem Biopesticide, Soil Organic Carbon Detection Kit, and Rapid Bio-Composting. Women self-help groups (Bachat Gat) were trained in food processing and livelihood-oriented tech.

Students, faculty, entrepreneurs, and officials from institutions, including IIT Mumbai, Dandekar College (Palghar), Theem College (Boisar), Pravara Rural Engineering College (Loni), NPCIL, BARC, and others participated in visits, trainings, and knowledge exchange programmes. International engagement included a study visit by a delegation from Kenya and the Rotary Club, Boisar.

AKRUTI Kendra-MGU advanced academic outreach through exposure visits, innovation programmes, and participation in events such as the Kerala Science Congress 2026 and Kerala Higher Education Conclave. Outreach programmes and expert sessions highlighted innovation, preventive healthcare, and women-led entrepreneurship.

BARC-INYAS-IIM Honor Women in STEM

Inclusivity, Empowerment, Leadership take centrestage on International Women's Day 2026

By Dr. Poulami Chakraborty, Dr. Ruma S. Gupta, Dr. Mohit Tyagi, Dr. Supratik Roychowdhury and SIRD Editorial Team

BARC took centre stage on International Women's Day by celebrating the remarkable contributions of women in science, technology, engineering, and mathematics (STEM) across India.

The Women's Cell at BARC led the event, held on 27 March 2026 under the theme "Give to Gain." The Chief Guest, Dr. Reena Dayal Yadav, Founder & CEO of QETCI, delivered a compelling talk titled "Enabling the Quantum Ecosystem in India."

To broaden participation, a digital poster contest on gender equality and sensitivity was held. Winners were recognized at the event. The Scientific Information Resource Division, KMG, compiled stories of women in STEM and their legacies into a concise publication, which dignitaries from HS&EG, BSG, KMG, and the Administrative Group released during the program.

Earlier, BARC partnered with the Indian National Young Academy of Sciences (INYAS) and the Indian Institute

of Metals (IIM) Mumbai Chapter to host discussions, keynote lectures, and interactive sessions emphasizing women's roles in STEM.

Under the "Give to Gain" theme, IIM invited Ms. Koneru Bhavani, Senior Vice President, Heavy Civil Infrastructure, L&T Construction, as Chief Guest for the event at the DAE Convention Centre Auditorium on 6 March, organized by senior scientific officers from the Materials Group.

Indian National Young Academy of Science (INYAS) organized "Beyond the Lab: Women in Science - Careers, Challenges & Choices" at the Multi-Purpose Hall (Training School Hostel) in Anushakti Nagar, featuring lectures by experienced BARC women scientists and coordination by senior officers from the Radiochemistry and Isotope Group.

The programs highlighted career paths beyond traditional lab roles, with presentations on mentorship and institutional support showing how women navigate scientific



Designed by Ms. Jyoti Panda

careers. A panel discussion addressed real-world challenges and opportunities, and testimonials from senior women scientists showcased journeys that break stereotypes and open doors.

By fostering supportive environments, encouraging young women toward leadership, and recognizing achievements in materials science and infrastructure, these events demonstrated a shared commitment to an inclusive scientific ecosystem. Bringing together scientists, students, and industry leaders, it painted a vision of a future where women not only participate in science but lead, inspire, and transform.

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① डॉ. जी. सुगीलाल, निदेशक, नाभिकीय पुनश्चक्रण वर्ग का पुष्पगुच्छ भेंट कर स्वागत करते हुए "भा.प.अ. केंद्र राजभाषा समन्वय समिति" के पदाधिकारीगण। ② डॉ. जी. सुगीलाल, निदेशक, एनआरजी की अध्यक्षता में आयोजित "भा.प.अ. केंद्र राजभाषा समन्वय समिति" की बैठक की कार्यवाही का एक दृश्य। ③ दिनांक 13.03.2026 को आयोजित हिंदी कार्यशाला में उपस्थित प्रतिभागीगण। ④ श्री संतोष झा, अध्यक्ष एवं प्रबंध निदेशक, कोंकण रेलवे के कर-कमलों से पुरस्कार ग्रहण करते हुए श्री हार्दिक वर्मा, प्रवर श्रेणी लिपिक, भा.प.अ. केंद्र।

भा परमाणु अनुसंधान (भा.प.अ.) केंद्र, मुंबई में राजभाषा के प्रभावी कार्यान्वयन के अंतर्गत मार्च-अप्रैल, 2026 के दौरान निम्नवत गतिविधियां आयोजित की गईं :-

आंतरिक राजभाषा निरीक्षण - भा.प.अ. केंद्र के विभिन्न प्रभागों/अनुभागों में, राजभाषा का प्रभावी कार्यान्वयन सुनिश्चित करने के उद्देश्य से, दिनांक 10 से 31 मार्च, 2026 तक की अवधि के दौरान आंतरिक राजभाषा निरीक्षण किया गया। इस प्रयोजन हेतु गठित चार (04) आंतरिक राजभाषा निरीक्षण समितियों ने प्रशासन, लेखा एवं सुरक्षा प्रभागों के कुल 67 अनुभागों का सफल निरीक्षण किया। निरीक्षण के बाद, उपर्युक्त समितियों ने अपनी समेकित रिपोर्ट श्री सैयद इरफान अली, उप निदेशक (राजभाषा) के माध्यम से श्री मनोज सिंह, अध्यक्ष, एसआईआरडी एवं अध्यक्ष, आंतरिक राजभाषा निरीक्षण समिति, भा.प.अ. केंद्र को प्रस्तुत की।

एक-दिवसीय हिंदी कार्यशाला - दिनांक 13 मार्च, 2026 को भा.प.अ. केंद्र, मुंबई में कार्यरत वैज्ञानिक अधिकारियों के लिए एस.सी.एफ. ऑडिटोरियम, कंप्यूटर प्रभाग में एक-दिवसीय हिंदी कार्यशाला का आयोजन किया गया। इस कार्यशाला में भाग लेने वाले 40 वैज्ञानिक अधिकारियों को संघ सरकार की राजभाषा नीति/नियम के अतिरिक्त अभ्यास सहित हिंदी में नोटिंग-ड्राफ्टिंग, कंप्यूटर पर हिंदी टंकण, प.ऊ.वि. की प्रोत्साहन योजना (अटॉलिस) और केंद्रीय कर्मचारियों हेतु आचरण नियमावली आदि विषयों की जानकारी साझा की गई।

राजभाषा कार्यान्वयन समिति की बैठक - दिनांक 27 मार्च, 2026 को निदेशक, भा.प.अ. केंद्र की अध्यक्षता में राजभाषा कार्यान्वयन समिति (OLIC) की बैठक का आयोजन किया गया। इस बैठक में, जनवरी-मार्च, 2026 की तिमाही के दौरान केंद्र में राजभाषा के कार्यान्वयन में हुई प्रगति की समीक्षा की गई, कार्यान्वयन के विभिन्न पहलुओं पर विचार-विमर्श किया गया और तदनुसार, निर्णय लिए गए।

भा.प.अ. केंद्र राजभाषा समन्वय समिति की बैठक - भा.प.अ. केंद्र राजभाषा समन्वय समिति के नव-पदनामित अध्यक्ष डॉ. जी. सुगीलाल, निदेशक, एनआरजी की अध्यक्षता में दिनांक 29.04.2026 को एचआरडी सम्मेलन कक्ष, सी.सी. में बैठक आयोजित की गई। इस बैठक में, समिति द्वारा विगत एक वर्ष के दौरान आयोजित कार्यक्रमों की गहन समीक्षा और भावी कार्यक्रमों के आयोजन पर चर्चा की गई। समिति ने, केंद्र में राजभाषा कार्यान्वयन के उत्तरोत्तर विकास हेतु कई महत्वपूर्ण निर्णय लिए।

परमाणु ऊर्जा विभाग (प.ऊ.वि.) राजभाषा प्रोत्साहन योजना (अटॉलिस) के अंतर्गत वित्तीय प्रोत्साहन - भा.प.अ. केंद्र में, मूल रूप से हिंदी में कार्य करने वाले पदाधिकारियों को प्रोत्साहित करने के उद्देश्य से लागू प.ऊ.वि. राजभाषा प्रोत्साहन योजना (अटॉलिस) के अंतर्गत जनवरी-मार्च, 2026 की तिमाही में कुल 44 पदाधिकारियों को पुरस्कृत किया गया।

भा.प.अ. केंद्र के पदाधिकारी को पुरस्कार - नराकास (बैंक एवं बीमा), बेलगावी के द्वारा अंतरराष्ट्रीय मातृभाषा दिवस, 2026 के अवसर पर आयोजित अखिल भारतीय हिंदी कविता लेखन प्रतियोगिता में, श्री हार्दिक वर्मा, प्रवर श्रेणी लिपिक, भर्ती-I, भा.प.अ. केंद्र, मुंबई को हिंदी भाषा वर्ग में प्रथम पुरस्कार प्राप्त हुआ।

राजभाषा संबंधी विभिन्न रिपोर्टों का प्रेषण - वित्तीय वर्ष 2025-26 के दौरान भा.प.अ. केंद्र में राजभाषा कार्यान्वयन के क्षेत्र में हुई प्रगति संबंधी विभिन्न रिपोर्टें गृह मंत्रालय, राजभाषा विभाग के वेब-पोर्टल; परमाणु ऊर्जा विभाग, मुंबई; परमाणु ऊर्जा विभाग केंद्रीय सचिवालय, नई दिल्ली; नगर राजभाषा कार्यान्वयन समिति, नवी मुंबई; क्षेत्रीय राजभाषा कार्यान्वयन कार्यालय, मुंबई और हिंदी शिक्षण योजना कार्यालय, मुंबई आदि को प्रेषित की गईं।



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