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भारत में उच्च तीव्रता वाले प्रोटॉन त्वरकों का अभिकल्पन

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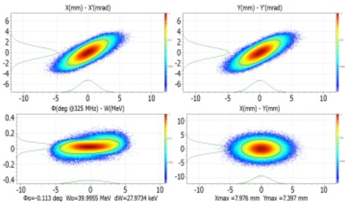

मेहिपा-1 निर्गम पर कणपुंज वितरण

सारांश

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 लिनॉक की आवश्यकता होती है। भारत ने, इस प्रौद्योगिकी को साकार करने के लिए 20 MeV, 200 MeV और अंततः 1 GeV के त्वरक परिक्षेत्रों के साथ एक चरणबद्ध विकास का दृष्टिकोण अपनाया है। भापअ केंद्र, मुंबई में पहला चरण, निम्न ऊर्जा उच्च तीव्रता (लो एनर्जी हाई इंटेंसिटी) 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 अधिमान्य 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।

1

Design of High Intensity Proton Accelerators in India

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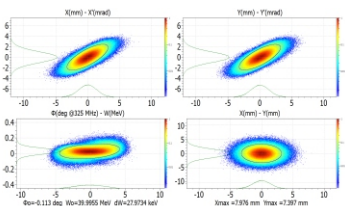

Beam distribution at MEHIPA-1 output.

ABSTRACT

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 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.

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

Design of MEHIPA-1

An ECR ion source will deliver a 10 mA, 30 keV proton beam with an rms emittance of 0.3 π 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 -90^0 was introduced before the Shaper to reduce longitudinal emittance from ~0.45 to ~0.18 π-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.

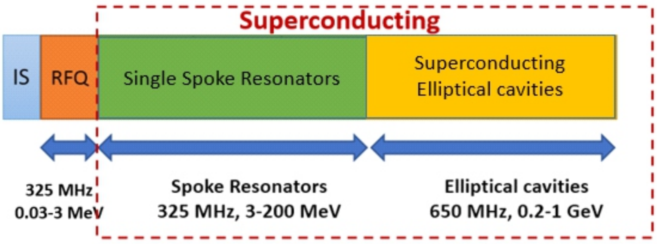

Fig.1: Schematic Layout of 1 GeV linac for ADS.

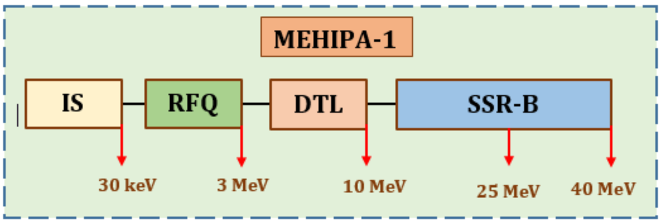

Fig.2: Layout of MEHIPA-1.

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 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.

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

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

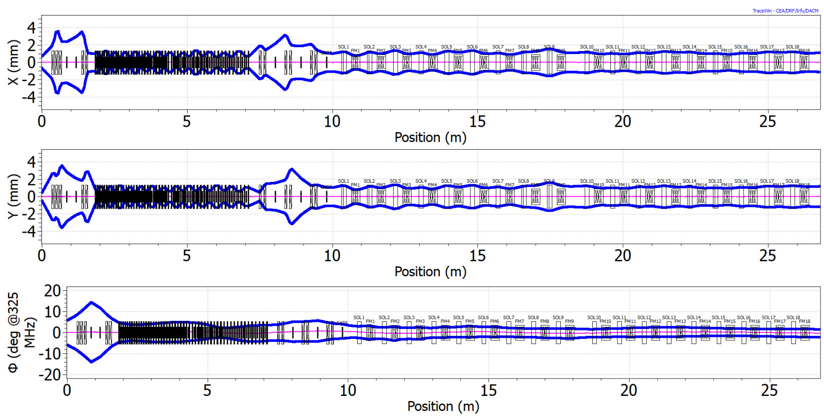

Fig.3: Beam envelope along the 40 MeV MEHIPA-1 linac.

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^{o}, 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^{o} to -25^{o}. 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 remains well confined within the aperture with negligible halo formation, while emittance growth is limited to <2% transversely and ~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

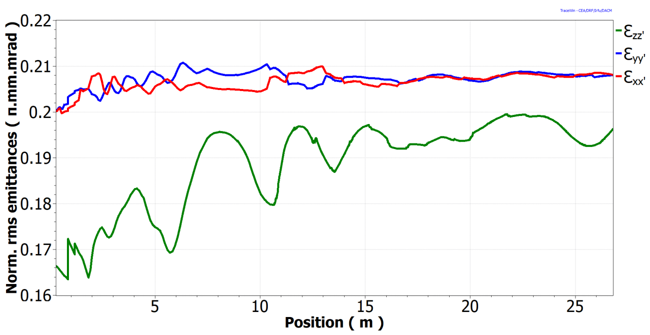

Fig.4: Beam emittance evolution along the 40 MeV MEHIPA-1 linac.

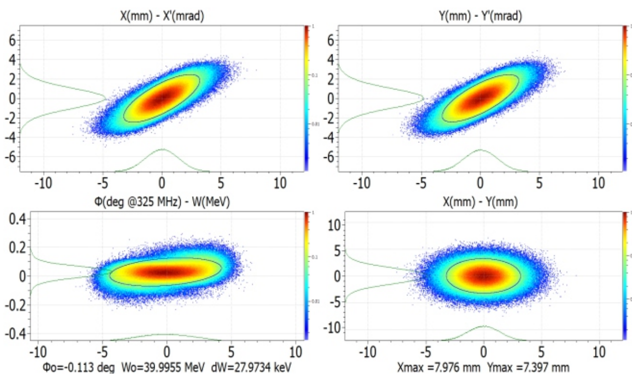

Fig.5: Beam distribution at MEHIPA-1 output.

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_{pk}/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_{pk}/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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