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

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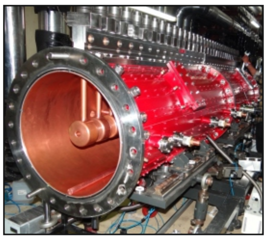

संवहन नलिकाएं जिनके भीतर पीएमक्यू रखे जाते हैं, को प्रदर्शित करता, लेहिपा डीटीएल

सारांश

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 त्रुटियों को निरुद्ध करने के लिए एक 16-खंडीय शुद्ध स्थायी चुंबक वास्तुकला की अभिपूर्ति 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 फ्रिंजिंग क्षेत्रों को नियंत्रित करने के लिए चुंबकीय प्रतिष्टम्भ 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 (Sm_2Co_{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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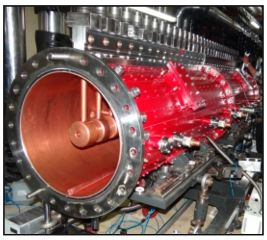

Picture of LEHIPA DTL, displaying drift tubes within which the PMQs are housed

ABSTRACT

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 (Sm_2Co_{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) × Leff, where G(0) is the central peak gradient and Leff 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 proportional, sometimes substantial, increase in the peak gradient.

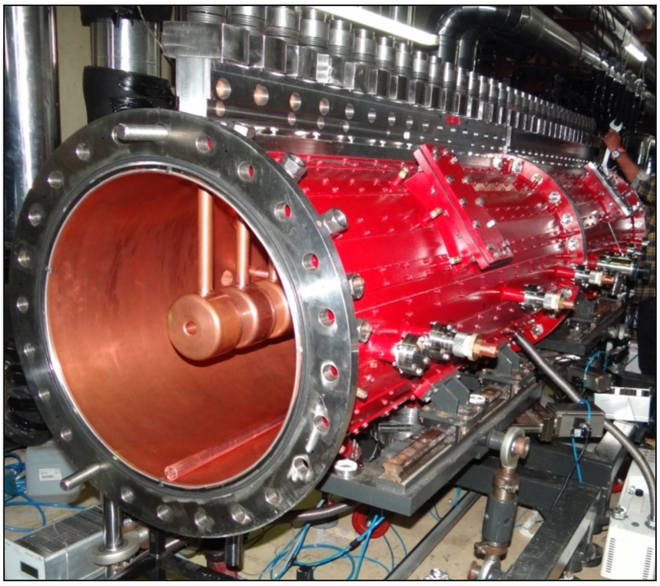


Fig.1: Picture of LEHIPA DTL, displaying drift tubes within which the PMQs are housed.

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.

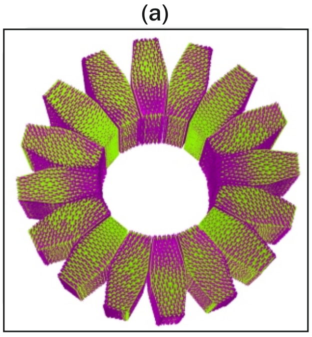
The 16-Segment Architecture (DTL 1 & 2)

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

(a)



(b)

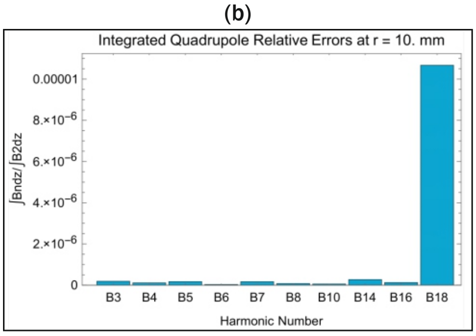


Fig.2: (a) 16 segment rectangular PMQ and (b) Simulated multipole field components.

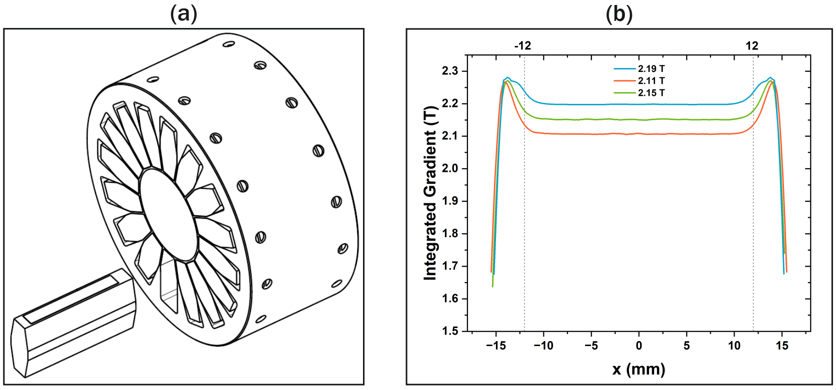


Fig.3: (a) CAD drawing of the PMQ assembly and (b) Integrated gradient tuning of the PMQ within the drift tube aperture, x=±12mm shown by the dashed lines.

design approximates an ideal cos(2θ) 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 Leff 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).

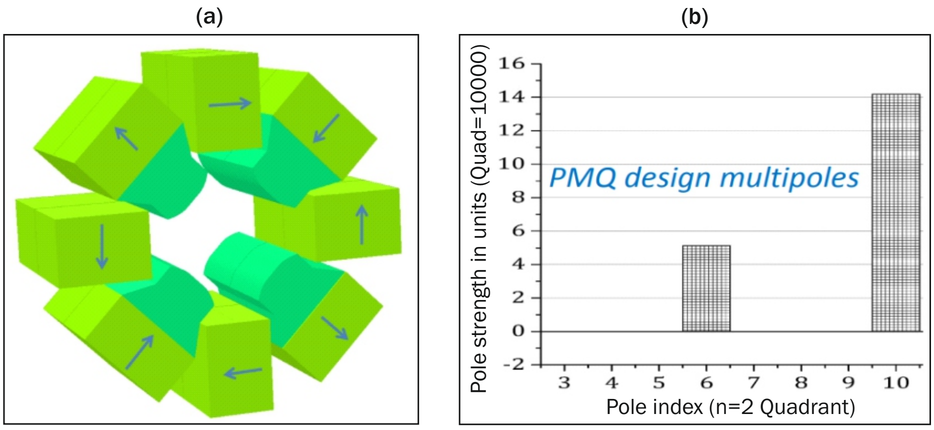


Fig.4: (a) The 8-Segment Hybrid PMQ Assembly and (b) multipole field components.

Pole index (n=2 Quadrant)

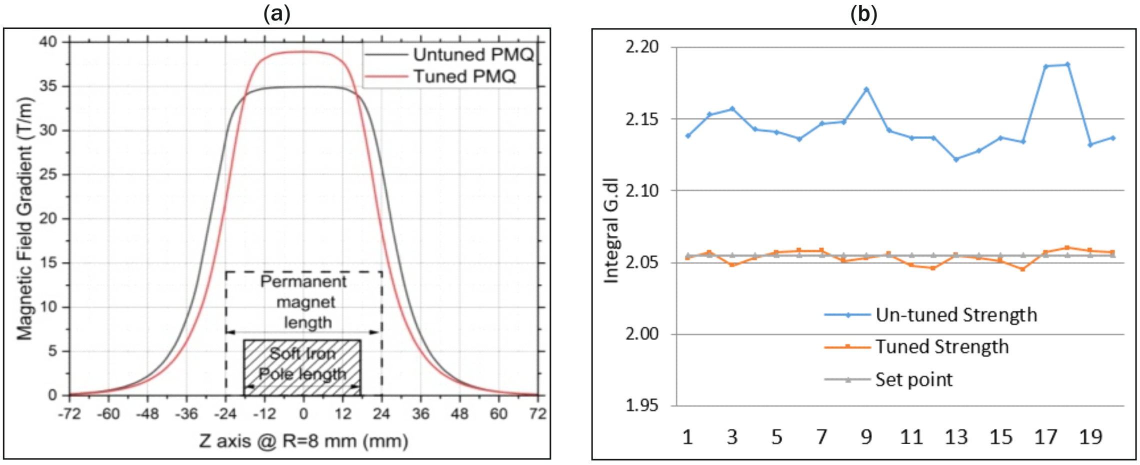


Fig.5: Hybrid PMQ Tuning Performance (a) Axial magnetic field plot and (b) IG plot for 20 number of PMQs before and after tuning.

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 ±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

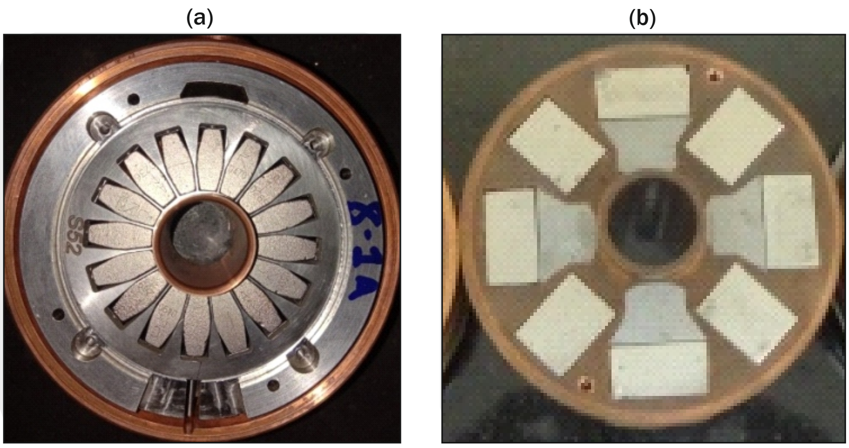


Fig.6: Final Fabricated Assemblies (a) 16-segment PMQ and (b) The 8-segment hybrid PMQ.

higher remanent magnetic field (Br) of ~1.4 T, making it an attractive choice for maximizing gradients. However, Samarium Cobalt (Sm_2Co_{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. Sm_2Co_{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.

References

[1] S. Roy et al, “Electromagnetic and Beam dynamics studies of a high current drift tube Linac for LEHIPA”, Journal of Instrumentation, Volume 9, June 2014.

[2] Klaus Halbach, “Design of Permanent Multipoles Magnets with oriented rare earth cobalt materials” Nuclear Instruments and Methods 169, 1980.

[3] Jose V. Mathew et. al., Nucl. Instr. and Meth. in Phys. Res. A, 727 (2013)

[4] Sanjay Malhotra et al., “Focusing Magnets for Proton Linac of ADS”, International conference on peaceful uses of atomic energy 2009, New Delhi.

[5] Vikas Teotia et al., “Focusing magnets for drift tube Linac”, Proceedings of InPAC-2011, Delhi.