Design and Development of Magnetic lenses for Proton Accelerators

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Abstract
High Energy Proton beams have application in scientific, industrial and Medical fields. High energy proton accelerators mainly consist of an ion source and array of RF accelerating cavities and focusing magnets. Low energy section of accelerator deploys solenoid magnets as they focus the beam simultaneously in both axes, although they are less efficient than quadrupole focusing magnets. The paper discusses design of Electromagnetic Quadrupole for transverse focusing in 200 MeV sections of a High Energy Proton Accelerator and magnetic measurements carried out on Permanent Magnet Quadrupoles for DTL of LEHIPA (Low Energy High Intensity Proton Accelerator). Optimisation techniques to achieve magnetic field uniformity better than 1000 ppm in Good field region is described. Detailed studies carried out on the influence of Magneto motive forces on figure of merit of the magnet, in terms of uniformity and magnetic field gradient is described. Field uniformity, linearity and higher order modes achieved in the design are elaborated. Based on this design, fabrications of the magnets were taken up. Paper also discusses measurement results of Permanent Magnets based quadrupole focusing lenses developed for LEHIPA project of BARC.

Keywords: Accelerators, proton, PMQ, EMQ, Good Field Region, HEPA, emittance

Introduction
Charged particle beams in accelerators tend to defocus due to Columbic repulsions and transverse kicks attributable to fringe E-fields in the cavity, the strength of which depend on the synchronous phase and Electromagnetic design of RF accelerating cavities [1, 5]. The transverse blow-up of beam increases the cross section of the beam which degrades the spatial current density which is undesirable. Electromagnetic forces are required to annul this transverse defocusing. Among the available options of using Electric field or magnetic field for charged particle focusing, magnetic fields are preferred since generation of an equivalent B-field is convenient than generation of equivalent E-field [2]. However, at low particle energy, E-fields are preferred as magnetic Lorentz forces are low owing to low particle velocity. For high energy beams, B-field focusing is natural choice for transverse focusing. Magnetic Quadrupole are used for focusing of charged particle beams. Depending on design, these quadrupoles could be permanent magnet based [3, 4] or electromagnet based (Warm (iron dominated) or Superconducting (coil design)). The latter choice provides the advantage of ease in tuning while former is more efficient in terms of power consumption during operations [5]. Magnetic field strength of quadrupole magnet is given in terms of integrated magnetic field gradient denoted as integral G.dl. The required integral G.dl depends on beam emittance at entry of the magnetic lens; magnetic quadrupoles are therefore operated normally from 50% to 100% of their rated strength. Electromagnetic Quadrupole becomes the obvious choice for such applications. This paper describes design and analysis of an EMQ for 200 MeV section of a proton accelerator, in detail and also describes the results of magnetic measurements on Permanent Magnet Quadrupoles for LEHIPA. Since quadrupoles provides alternate gradient focusing [5], the focusing and de-focusing quadrupoles are always used in pairs, aptly named as “doublet assembly”.

System specifications
Layout
The high energy section of proton accelerator consists of an array of accelerating cavities and focusing elements. Depending on the particle β, the accelerating cavities
could be normal conducting DTL, half wave resonators, Spoke resonators or elliptical cavities. At 200 MeV elliptical cavities are more efficient than other families of resonators. HEPA (High Energy Proton Accelerator) has three five-cell elliptical cavities followed by a doublet assembly. The RF cavities and focussing magnet arrangement is periodic, number of which depends on desired output energy.

![Beam envelope in one section of the HEPA with doublet assembly and RF cavities](image1)

**Fig. 1**: Beam envelope in one section of the HEPA with doublet assembly and RF cavities

![Phase space of beam at entry of Quadrupole Doublet magnet assembly](image2)

**Fig. 2(a)**: Phase space of beam at entry of Quadrupole Doublet magnet assembly

- $X(\text{mm}) - X'(\text{mrad})$
  - $X_{\text{max}} = 4.986 \text{ mm}$
  - $X'_{\text{max}} = 0.898 \text{ mrad}$

- $Y(\text{mm}) - Y'(\text{mrad})$
  - $Y_{\text{max}} = 7.229 \text{ mm}$
  - $Y'_{\text{max}} = 1.598 \text{ mrad}$
Specifications

The beam envelope along one of the sections of the HEPA is shown in figure 1. The input and output phase space of the beam is shown in figure 2. Figure 2(a) and Figure 2(b) shows how quadrupole magnets limit the beam emittance and when quadrupoles are off the beam emittance blow ups as shown Figure 2(c). The integral $G.dl$ in good field region of 24 mm (diameter) with uniformity better than 1000 ppm is a critical requirement. The required value of Integral $G.dl$ is 3 Tesla. The sum of higher order multipoles normalized to fundamental quadrupole component is required to be less than 0.1 %.

Design and Analysis

The magnetic design of EMQ meeting above specifications is carried out using TOSCA/OPERA-3D from Vector Fields [6]. A perfect Quadrupole have hyperbolic pole, however due to engineering constraints, a perfect hyperbola is truncated which results in systematic multipoles which are odd multiples of quadrupole ($n=2$). The errors in mechanical fabrication results in non-systematic multipoles which are even
multipoles of the quadrupole [7]. The hyperbola pole shape is modified to a customized pole shape which gives high integral magnetic field uniformity. The design consists of optimization of the magnetic pole contour to achieve the required uniformity and minimal higher order multipoles. Second order splines are used for magnetic pole design and the coordinates of the constituent points are optimized for high integral G.dl uniformity. The magnetic field distribution in the yoke is shown in figure 3. The primary figure of merit of the EMQ is strength, uniformity and linearity of integral G.dl and also the higher order multipoles in the GFR.

Fig. 3: 3-D model of the magnet with magnetic field profile in the yoke

**Integral Magnetic field gradient**

The strength of integral G.dl determines the focal length of the Electromagnetic Quadrupole (EMQ) and thereby the phase space of the beam along the axis. Ideally the integral G.dl shall remain constant in the entire good field region. Non-uniform integral G.dl cause beam aberrations. This quantity is therefore studied as function of radial and azimuthal axis to determine the points of maxima and minima for evaluation of uniformity in the designed EMQ. Figure-4 shows the variation of integral G.dl as function of azimuthal axis at rated current. The linearity of integral G.dl along the radius is shown in figure 5.

Fig. 4: Integral G.dl as function of azimuthal axis for radius of 12 mm
The uniformity in integral G.dl remains within specified value for the range of operations which is normally 50% to 100%. The magnetic analysis was conducted for different values of input magneto motive force (MMF) and is shown graphically in figure 6.

Fig. 5: Linearity of magnetic field gradient as function of radius

Fig. 6: Relative variation in integral G.dl as function of azimuthal axis for different MMF
**Good field region**

The uniformity of integral G.dl is inverse function of radius in the beam aperture. At low radius, uniformity is high. The required Good field region is decided on basis of the beam size and uniformity affects the output beam emittance. The uniformity of integral G.dl as function of radius is shown in figure 7.

![Good field region](image)

**Fig. 7: Uniformity in integral G.dl as function of radius**

**Higher order multipoles**

The sum of amplitudes of the higher order multipoles (from n=3 to n=8) shall be less than 0.1% of the quadrupole components (n=2). Figure-8 gives spectrum of multipoles in the designed EMQ. The achieved sum of HoMs normalized to quadrupole component is 3.8e-4.

![Spectrum of HoMs](image)

**Fig. 8: Spectrum of HoMs**
Permanent Magnet Quadrupoles

Drift Tube Linac of LEHIPA consists of array of Drift Tubes (DTs) the dimensions and pitch of which are governed by energy of beam. These DTs fulfills the Physics and functional requirements. DTs consist of Permanent Magnet Quadrupoles (PMQ) which provides transverse focusing to the beam. They are OFE copper made hermetically sealed cavities which are subject to large surface heat generation due to high frequency H-field. This heat is removed by water channels cut through these DTs. The CFD design of DTs ensures less than 80um dimension changes and hot spot temperature not exceeding 50° C.

The magnetic design of PMQ ensured large good field region with uniformity of $fG.dl$ to be better than 1%. The optimized magnetic pole shape design ensured high linearity and high uniformity in the GFR. The magnetic design has ensured long term stability of magnetic parameters in the PMQ. Figure 9 shows developed Drift Tube and its technical specifications. Figure 10 shows the set-ups used for carrying out the measurements.

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**Fig 9:** Snap shot of developed Drift Tube with embedded PMQ

**Fig 10(a):** PMQs being measured on Hall Probe Magnetometer at BARC

**Fig 10(b):** PMQs being measured at Harmonic Coil Magnetometer at RRCAT (Measurements & Photo courtesy : AMTD, RRCAT)

- **Magnets**: Sm$_2$Co$_{17}$
- **$fG.dl$**: 2.05 Tesla
- **Uniformity of $G.dl$**: ±0.5%
- **Linearity of Gradient**: Better than 1%
- **Tunability**: -10%, +2%
- **HoMs relative strength**: <0.5%
- **Maximum length**: 80mm
- **Maximum diameter**: 110mm
- **Hydrostatic**: 6 Kg/cm$^2$
- **DM water flow rate**: 10 LPM
- **Stem alignment**: <0.05°
- **Maximum Temp**: 50° C
- **Pole material**: Low C steel
- **Material of Drift Tube**: OFE Copper
- **Vacuum level**: 1e-8 Tor
- **Welding**: Laser
- **Qualification**: Welding, Hydro geometric, Magnetic
The measurements of PMQs were carried out using Hall probe magnetometer and Harmonic Coil Magnetometer. The longitudinal magnetic field profile and Hamonic spectrum of magnetic field in the aperture are shown in figure 11. The PMQs were tuned to 2.05 Tesla and uniformity better than 0.5% was obtained in about 20 PMQs measured till date.

Conclusions

The complete cycle of Accelerator magnet design, development and qualifications is established and implemented. Analytical models and Design codes have been validated on number of developed magnets. Stage is reached when series production can be taken up on basis of design. Local industry in and around Mumbai have catered to all fabrication requirements. In house developed magnetic measurement benches are sufficient to meet the requirements of accelerator magnet qualifications.

References

6. OPERA-3D (TOSCA), Vector Fields