PERMANENT MAGNET QUADRUPOLE FINAL FOCUS SYSTEM FOR THE MUON COLLIDER

F. O'Shea, G. Andonian, J.B. Rosenzweig UCLA, Los Angeles, CA, USA

Abstract

The future muon collider requires a $\beta^\star$ of 10mm at the interaction region. The current focusing strengths of magnetic lenses make this target challenging. One approach to achieving this goal is based on permanent magnet quadrupole techonology to achieve the highest field gradient possible. In this paper, we describe a design for a novel focusing triplet using an alloy of Praseodymium, in a Halbach pure permanent magnet quadrupole configuration to achieve an unprecedented field gradient of ∼1000T/m. Various engineering issues, such as magnetic nesting, tuning and cooling, are also explored.

INTRODUCTION

The design parameters of the muon collider have undergone many iterations over the last decade, eventually producing a parameter list that still pushes the cutting edge of accelerator technology. One challenging parameter is the small beta-function that the beam must achieve at the interaction point (IP), $\beta^\star$, to meet luminosity goals. The current design goal for $\beta^\star$ is 10mm for the 1.5 TeV scenario [1]. There are many interesting and exotic ideas proposed [2, 3] to attain the necessary $\beta^\star$ at the IP, however no definitive consensus has developed around a singular solution.

Beam simulation studies have been carried out to determine the feasibility of using a PMQ triplet as a final focus for the muon collider. The first-pass simulations using ELEGANT [4] demonstrated that, although challenging, $\beta^\star = 10$mm is achievable in principle by means of a quadrupole triplet using a D-2F-2D setup, where the magnet lengths are on the order of 1-2 m and the gradients on the order of 1000T/m.

Recent work by UCLA, the Max-Planck-Institut für Quantenoptik and Helmholtz-Zentrum Berlin, as well as previously published work from RIKEN Lab [5], have demonstrated that Praseodymium (Pr) is a viable candidate for use in undulators, as a replacement for Neodymium (Nd) based magnets. Initial work has shown that using Pr in a permanent magnet quadrupole (PMQ) achieves unprecedented field gradients.

PRASEODYMIUM BASED PERMANENT MAGNET QUADRUPOLE

Since muons have over 200 times the rest mass of electrons, they have an increased magnetic rigidity and thus need higher gradient fields for focusing [8]. The initial step is to design a quadrupole magnet with the highest possible gradient. The highest gradients in a PMQ arise from the Halbach geometry [6], which approximates the ideal quadrupole field as closely as mechanically possible. Simulations show that Pr-based PMQs with apertures on the order of 5-6 beam sigma (∼3mm) are able to reach ∼1000T/m gradient.

Praseodymium is chosen due to promising recent work in the field of magnetization of this element [5]; rare-earth permanent magnets with large fractions (up to complete substitution) of Pr replacing Nd have many desirable properties compared to conventional materials. PrFeB is capable of greater remnant magnetic fields than Samarium Cobalt and has no spin-axis reorientation (unlike Nd-based magnets where the reorientation occurs at ∼135K). As both remnant field and coercivity increase with decreasing temperature, Pr-based magnets are capable of energy products of 520 kJ/m^3 at 85K [9]. Pr-magnets can operate at lower temperature than Nd-magnets and exhibit greater radiation hardness [7], a vital issue for magnets located near the collider IP. Pr cooled to 30 K exhibits a remnant field of 1.7 T and coercivity of 72 kOe. The operating point of 30-80K thermal environment is not available to low temperature superconducting (SC) magnet systems and greatly reduces the cryostat complexity. It also allows for a larger thermal budget compared to SC magnets. Although SC technologies are the current front-runners for muon final focus ideas, they suffer from field quenching, radiation exposure and are extremely sensitive to beam heating effects when placed near the beam axis.

Radiation hardness of high remnant field permanent rare-earth magnet materials has prevented widespread use in high exposure environments [10]. At room temperature there is a trade off between remnant field and coercive strength. The magnets capable of surviving the environment do not have the necessary field strength. According to Ref. [5], cooled materials have a much larger (absolute value) coercive thermal coefficient than remnant field coefficient, so the trade off of higher remnant field for lower coercivity at room temperature is acceptable and limited by safe handling and assembly procedures.

In the design shown in Fig. 1, a circular magnet made of wedges with varying magnetic field orientation, the superposition of the fields from all of the wedges results in a quadrupole field within the aperture. Precise tolerancing is required to minimize higher order multipole components; methods to improve mode purity are discussed below.

The field gradient for the Halbach configuration is

$$B' = a\frac{2B_r}{r_i}\left(\frac{x-1}{x}\right), \tag{1}$$

where r_i is the inner radius, $r_o = xr_i$ is the outer radius, B_r is the remnant field of the wedges, and a is the segmentation factor. Circular colliders require the aperture to be at least 5-6 times the rms beam size (σ). For σ=600μm, 5σ corresponds to $r_i = 3$ mm. Because the gradient is limited by the minimum possible inner radius, beam clearance will dictate the maximum achievable gradient.

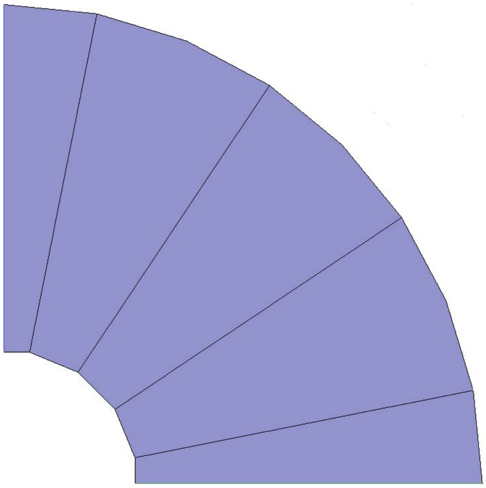

Figure 1: Simulation region of the 16 segment quadrupole. A symmetry plane bisects the vertical and horizontal axes.

Using Eq. 1 and the inner aperture given by 5σ, the maximum gradient is obtained when the geometric factors, a and x, are maximized. This, however, is difficult in practice due to the properties of Pr. Pr-magnets are brittle, and difficult to machine with radii ratios too large, as the wedge would be thin near the inner radius and thick at the outer edge causing an internal torque that would break apart the material. A technique called nesting, where two or more Halbach quadrupoles are aligned concentrically, would mitigate this effect. It is important that the quadrupoles contain only permanent magnets so that the fields of the quadrupoles add linearly.

Nesting can improve the PMQ structural stability as well as provide space for cooling conductors. However, high tolerances may be required to align each corresponding inner and outer piece without compromising the field gradient. The results of MAXWELL 2D simulations using Pr are shown in Table 1.

Table 1: Maxwell 2D simulation results for the Praseodymium magnet quadrupoles. The top row shows the segmentation number while r_o=30 mm.

r_i	16	32
3.0 mm	960 T/m	990 T/m
3.6 mm	780 T/m	810 T/m

SIMULATIONS

The initial studies on Pr-magnets are driven by beam simulations using ELEGANT, to determine the PMQ gradients necessary to achieve a $\beta^\star$ of 10mm. The interaction region of the muon collider must remain optics free to make space for the detector. Therefore, the final focus system must focus in both transverse planes before the beam the enters the detector drift region. Further, conservation of phase space demands that the beam be large in the quadrupoles so that it can be small at the interaction point (Fig. 3). Since large beams require large aperture quadrupoles the field gradent is constrained. The competing demands between the PMQ focusing strength and physical aperture are addressed in simulation optimization algorithms. Simulations using the 990 T/m quadrupoles show that a collimated beam can only be focused to the desired spot size if the emittance of the beam is decreased to 1.7 π mm mrad, an order of magnitude lower than the current design.

Table 2: Muon collider parameters used in simulations.

Parameter	**Value**
Energy	1.5 TeV
Luminosity	$0.8{\times}10^{34}$ cm^2/s
$\beta^\star$	1 cm
Beam Size at IP	6 μm

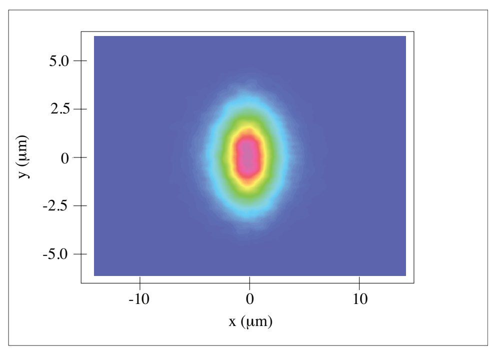

Figure 2: Interaction point spot size of the muon beam whose properties are given in Table 2. The quadrupole gradient is 990 T/m.

The currently accepted methodology to reduce the emittance of the beam involves ionization cooling [11]; the beam passes through many stages of H_2 gas columns to transfer emittance to the gas in all three spatial dimensions, it is then accelerated to restore longitudinal kinetic energy. The currently agreed-upon figures for ionization cooling indicate that the beam emittance will be 20 π mm-mrad. This disparity between simulations and design parameters requires additional effort to address. Continued efforts directed at further cooling (and beam emittance reduction) will mitigate the stresses on the final focus of the collider.

TUNING OPTIONS

The development of Pr-based PMQs necessitates a method for tuning in order to ensure the purity of the pro-

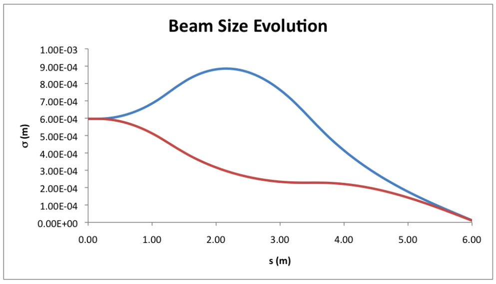

Figure 3: Evolution of the beta function through the D-2F-2D final focus.

duced quadrupole field. The most straight forward way of ensuring good field quality is to sort the magnets according to their measured magnetic moments and then shuffle them such that the field quality is optimum. Further, during assembly, a pin tuning system [12] can be used to correct for defects that cannot be corrected for with sorting and shuffling.

A novel approach to online control of the gradient involves temperature tuning. Because the remnant field of Pr is temperature dependent, precision temperature control leads to precision gradient tuning. The nominal temperature for operations is 30K; however, mild, controlled temperature fluctuations can improve field tuning. An obstacle to this scheme is immediately obvious, even if precise temperature control is maintainable (which should not be difficult at the proposed muon collider), the beam heating effects on the PMQ are still unaddressed. These heating effects have been studied for the International Linear Collider (ILC) [13] and are a major concern as ample cooling power is required. Another approach consists of rotating the outer array of magnets with respect to the inner array in the nested configuration. The superposition of the fields from the two rings can be used to cancel out some higher order modes. One of the technical challenges associated with this approach entails the ability to control the movement of the outer ring with enough granularity to provide the desired field modification resolution.

CONCLUSIONS

Permanent magnet quadrupoles based on Prasedymium alloys in a triplet D-2F-2D configuration are a viable solution if the emittance of the beam can be decreased to 1.7 π mm mrad. In a Halbach configuration, the theoretical gradient reaches 990 T/m.

One drawback of Praseodymium is its low coercivity at room temperature and brittleness, this makes it difficult to machine and handle during assembly. This problem is magnified for long quadrupoles required in this study (1-2m long), because in practice, shorter magnets would have to be stacked to reach the required length also increasing the tolerances of machining. Current studies are being conducted to improve the rigidity of the material, with the use of other alloys or hybrid magnets with Dysprosium concentrators. Dysprosium has similar coercivity at low temperatures, and in recent work has been shown to work well with PrFeB in undulator geometries [5]. Furthermore, other exotic solutions will reduce the constraints on the beam-quadrupole system. For example, if the permanent magnet quadrupoles are seated within a superconducting quadrupole (producing a field gradient of 1350 T/m) the emittance required to reach the desired $\beta^\star$ is increased to 5 π mm mrad.

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