HIGH GRADIENT FINAL FOCUSING QUADRUPOLE FOR A MUON COLLIDER*

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Abstract

To achieve the high luminosity required for a muon collider, strong quadrupole magnets will be needed for the final focus in the interaction region. These magnets will be located in regions with space constraints imposed both by the lattice and the collider detector. There are significant beam related backgrounds from muon decays and synchrotron radiation which create unwanted particles which can deposit significant energy in the magnets of the final focus region of the collider. The energy deposited results in the heating of the magnet which can cause it to quench. To mitigate the effects of heating from the energy deposition, shielding will need to be included within the magnet forcing the aperture to be larger than desired and consequently reducing the gradient. We propose to use exotic high magnetization materials for pole tips to increase the quadrupole gradient.

STATEMENT OF THE PROBLEM

In order to achieve the high luminosity required by a muon collider, high gradient quadrupole magnets will be required in the final focus region near the interaction point. These magnets are located in regions with space constraints imposed by the lattice and the detector. There is also a significant beam background present from muon decay electrons and synchrotron radiation which is deposited into these magnets. The deposited energy results in heating the magnets which can cause them to quench. Typically to achieve the high gradients the magnet coils use a low temperature superconductor such as Nb_3Sn which has a large current capacity at 4.2 K. Shielding is included inside the aperture and in front of the magnet to reduce the effects of heating from the energy deposited by beam background. The shielding requirements increase the aperture size and consequently reduce the gradient of the magnet. High temperature superconductors such as Bi-2212 may be an interesting choice for the magnet coils since they can have a large current density at higher temperature. The use of high magnetization materials as pole pieces can increase the gradient of these magnets. This paper will describe such an approach.

Table 1 shows the parameters of the final focusing quadrupole magnets that are closest to the interaction point [1]. These parameters represent the current lattice which could change as the muon collider design matures.

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Table 1: Parameters of the final focusing quadrupole magnets closest to the IP.

Quad	*Units*	*QLB1*	*QLB2*	*QLB3*
Gradient	T/m	250	187	-131
Center Position	m	6.75	8.65	10.85
Radial Aperture	cm	3.5	5	7.5
Quench Gradient at 4.5°K	T/m	282	209	146

HIGH MAGNETIZATION MATERIALS

Certain rare-earth elements have a high magnetization ferromagnetic phase below the Curie temperature. Figure 1 shows the number of magnet moments per gram of holmium at fixed magnetic field [2]. The magnetization is obtained by dividing by the density. The Curie point temperature for holmium is 20 K. Above the Curie point the material becomes anti-ferromagnetic up to the Néel temperature above which the atomic spins are randomized. Even above the Curie temperature there is significant magnetization particularly when the field is large. For holmium approximately 80% of the maximum magnetization is still present at 40 K for H=16000 Oe. Table 2 shows the magnetization properties for three rare-earth metals that have high magnetization: holmium [1], dysprosium [3] and gadolinium [4]. The nominal magnetization is achieved when the field is aligned with one of the crystal directions. The saturation magnetization is achieved when the magnetic material is driven into saturation by applying a high field. This magnetization value is more relevant for magnet poles.

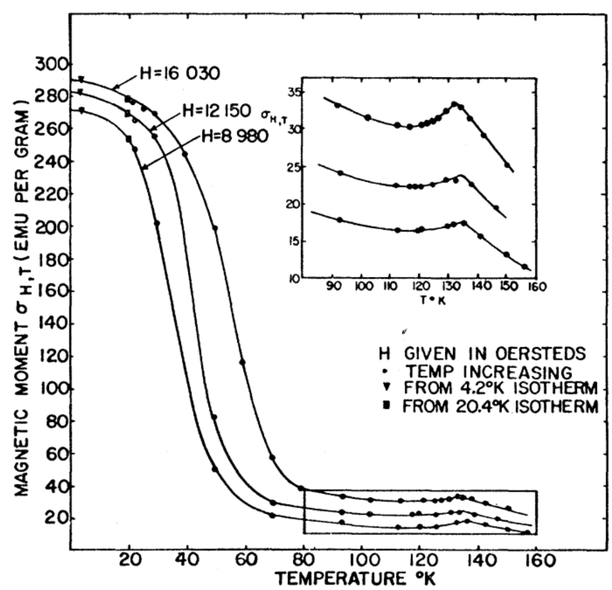

Figure 1: Magnet moment in EMU/g as a function of temperature for holmium at a constant field.

Table 2: Properties of high magnetization metals:

Parameter	Units	Ho	Dy	Gd
Magnitization	Bohr-Magnitons	11.2	10.83	7.98
Nominal Magnetization	Tesla	4.19	4.00	2.81
Saturation Magnetization	Tesla	3.2		2.4
Curie Temperature	Kelvin	20	89	293
Néel Temperature	Kelvin	132	179	

Ref. [2, 3, 4] provide B-H tables for Ho, Dy and Gd respectively. Figure 2 shows the B vs. H relation for increasing field for these metals. These curves will be used in our analysis and will be extrapolated to the higher field region as a linear extension.

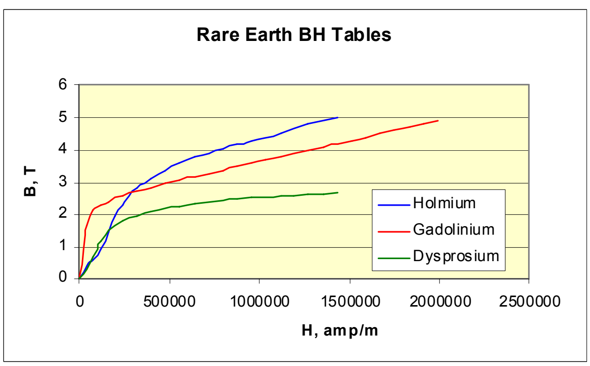

Figure 2: B-H tables for Ho, Dy and Gd at cryogenic temperatures.

MAGNET DESIGN

Quadrupole magnets with holmium pole pieces have previously been built at LANL [5] and ANL [6]. The ANL quadrupole achieved a magnetic gradient of 350 T/m for an aperture of 1.5 cm and a pole field of 5.25 T.

We are looking at a design of a quadrupole using exotic high magnetization materials that would be appropriate for a muon collider IR magnet. Radial space within the aperture must be allowed for shielding of the quadrupole from energy deposition of beam related debris. In our magnet design we have assumed 2 cm of shielding on the inner radius of the magnet. A study of the pattern of energy deposition of beam backgrounds will need to be performed to establish a reasonable thickness for this shield. Allowing the poles to extend into the shielding would significantly increase the quadrupole gradient. Our preliminary study has indicated that the temperature of the shield and the poles could not be maintained at 4.2 K due to the anticipated heat load. We imagine that the inner aperture shielding and extended pole would be at 70-80 K which would rule out the use of holmium for the pole extension. Figure 1 shows a sketch of a magnet concept for this quadrupole. The figure shows a tungsten shield in the aperture with the extended pole into the shielding is made of gadolinium. The main part of the pole which is at 4.3 K is made of holmium and is surrounded by Nb_3Sn coils which subtend 30º. We have not yet looked at a turn-by-turn design of the Nb_3Sn coils, however we have examined the efficiency of the coil thickness to coil inner radius and found that $(R_{outer}-R_{inner})/R_{inner}=2$ gives the most efficient choice for pole field produced with a given current density.

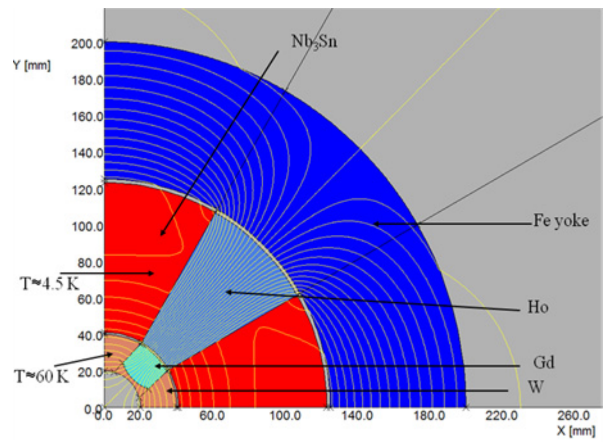

Figure 3: Sketch of a IR quadrupole using exotic high magnetization materials for the poles

Figure 4 shows the field along the 45º axis through the pole. The field peaks in the holmium pole with a field just below 12 T. The field gradient in the aperture is 250 T/m. The field in the coils is shown in figure 5. The figure shows that peak field in the coils is 10 T and is adjacent to the pole. The permeability of the gadolinium and holmium poles is shown in figure 6. The gadolinium pole shows a significant degree of saturation.

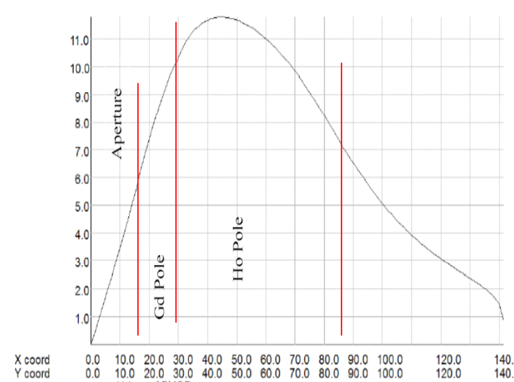

Figure 4: Field in Tesla along 45º pole. The regions associated to the aperture, Gd pole and Ho pole are marked. The x and y dimensions shown are in mm.

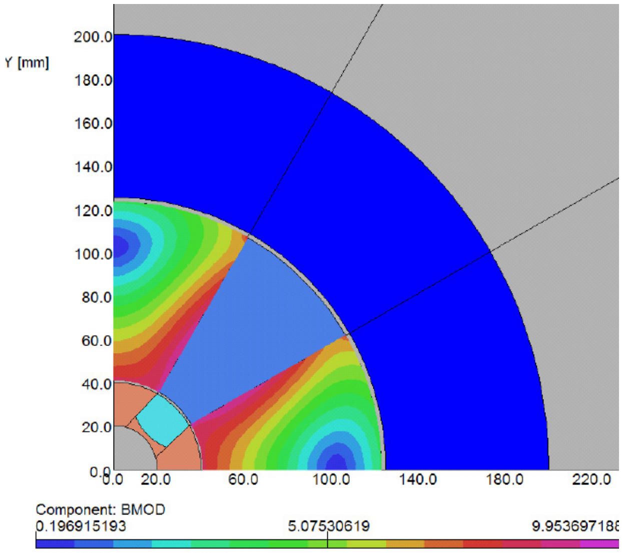

Figure 5: The field in Tesla is shown in the coils.

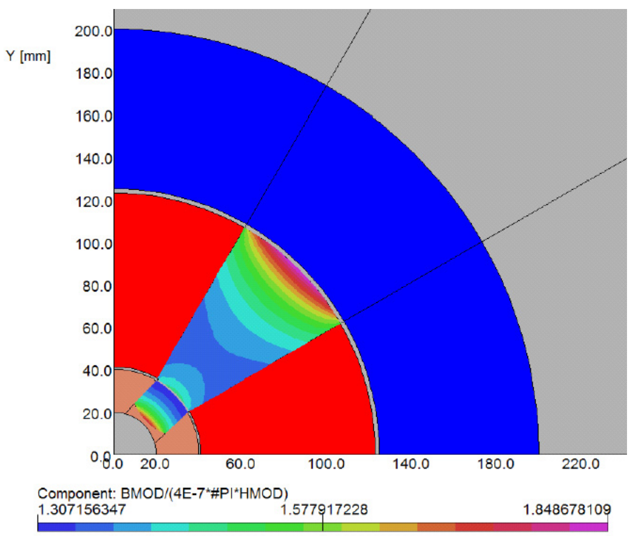

Figure 6: The permeability of the Ho and Gd poles.

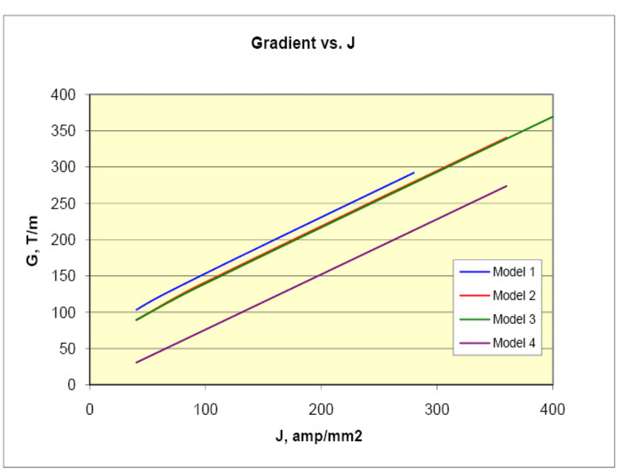

Figure 7: Quadrupole gradient vs. J for (1) exotic pole material with flux return, (2) exotic pole material without a flux return, (3) steel poles with a flux return and (4) no ferromagnetic material.

We have compared the efficiency of using these rare-earth material poles with using accelerator grade steel instead. Figure 7 the quadrupole gradient in the aperture as a function of coil current density for four cases: Case 1 where exotic poles are used with an iron flux return. Case 2 where exotic poles are used, but with no flux return. Case 3 where steel poles are used with a flux return. Case 4 where no ferromagnetic material is used at all. The effect of using exotic pole material instead of steel poles is to enhance the gradient by 10 %.

CONCLUSIONS

Using rare earth metals for pole pieces offers an interesting approach for the final focus magnets near the collider IP where muon decay background deposit considerable energy into these magnets. Using these materials enhances the gradient by 10 %.

REFERENCES

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