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THERMAL-MECHANICAL ANALYSIS OF THE FRIB NUCLEAR FRAGMENT SEPARATOR DIPOLE MAGNET*

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Abstract

Dipole magnets in the Facility for Rare Isotope Beams (FRIB) fragment separator are critical elements used to select the desired isotopes. These magnets are subjected to high radiation and heat loads. High temperature superconductors (HTS), which have been shown to be radiation resistant and can operate at 40 K where heat removal is substantially more efficient than at 4.5 K where conventional superconductors such as NbTi and Nb_3Sn operate, are proposed for the magnet coils. The magnet coils carry large currents and will be subject to large Lorentz forces that must be constrained to avoid deformations of the coils. It is desirable to minimize the use of organic materials in the fabrication of this magnet because of the radiation environment. This paper will describe an approach to support the coils to minimize coil deformation and cryogenic heat loss.

INTRODUCTION

The FRIB facility at MSU will provide intense isotope beams for physics research [1]. Large quantities of various isotopes are produced when a 400 kW linac beam hits the target. A variety of secondary nuclides with various ionic charge states is produced. Following the target are the fragmentation separator magnets which consists of three quadrupole magnets to provide focusing and two dipole magnets to select the desired nuclei. The beam enters the first dipole magnet with a spread of rigidities. The undesired nuclides are removed with a beam dump between the two dipole magnets.

To collect a sufficient sample of the rare isotopes the magnets in the fragment separator will have large apertures and strong. The radiation level in the fragment separator magnets is quite high and these magnets need to be radiation resistant. The radiation dose seen by the first quadrupole after the target is estimated to be 2.5×10^{15} neutrons/cm^2 per year [2] which corresponds to 10 kW/m of deposited power. The deposited power will drop by a factor of 10 when it reaches the bending dipole. The radiation environment influences the choice of materials used. Although NbTi and Nb_3Sn are robust conductors in radiation, they must operate at 4.5 K which is not practical, since the anticipated heat load would be difficult and costly to remove efficiently at that temperature. HTS conductors are reasonably resistant to radiation and can carry a significant current at 40 K where the heat capacity of the refrigerant is much larger and the Carnot efficiency is greater making heat removal and refrigeration easier. Also we would like to minimize the use of organic materials, both for conductor insulation and for coil support as these materials can degrade in the radiation environment.

Brookhaven National Laboratory has been involved in an R&D program to develop the quadrupole magnets for fragment separator at FRIB [3-6] using HTS conductor. The design of the fragment separator dipole magnets has relied on the technology learned from the quadrupole project. Previous articles [7-9] describing design aspects of this dipole magnet have been published.

MAGNET DESIGN

A superferric design has been chosen for this magnet where HTS coils are used to magnetize the iron which provides the desired field. The coils surround the iron poles and each coil is enclosed in its individual cryostat. Because of the large bend angle and the desire to avoid winding a coil with negative curvature the coil is wound with a "D" shape [10] with the inner section straight and the outer section curved. The coil and cryostat package is recessed behind the iron pole to protect them from direct exposure from the beam. Most of the radiation and the associated heat deposition will be deposited into the iron pole and flux return which are at room temperature and water cooled. The main source of radiation into the coils comes from neutrons that can penetrate deeply into material. It is estimated that ~700 W will be deposited into the coil cryostats [9]. The design parameters of the fragment separator magnet are shown in Table 1.

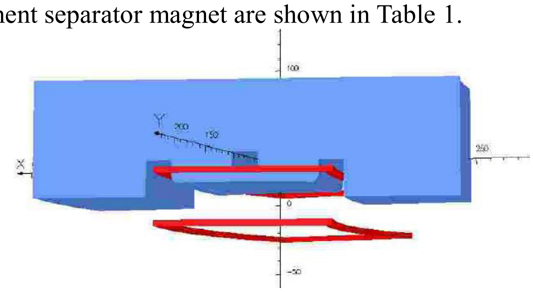

Figure 1: Model of the upper quarter of the magnet geometry.

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Table 1: Design Parameters for the Fragment Separator Dipole Magnet

Parameter	Value
Bending Radius	4 m
Bend Angle	30º
Magnetic Length along Beam Path	2.094 m
Nominal Central Field	2.0 T
Operating Field Range	0 to 2.2 T
Field Non-Uniformity	<0.7 %
Good Field Width in Bend Plane	0.3 m
Good Field Height in Non-Bend Plane	0.2 m
Total Current in Each Coil	256 kA turn
Operating Temperature	40 K

LORENTZ FORCES

The coils will be situated in a region with large fields which will see large forces. The coil forces from a 2D model of the magnet [7] are shown in Table 2. The forces are dependent on the position of the coil relative to the magnetic pole and flux return. Fig 2 shows the radial (red) and vertical (blue) forces as a function of the horizontal distance between the front of the coil and the magnetic pole. As the radial forces grow with distance from the pole, the coils should be situated as close to the pole as practical. The vertical forces are to a lesser extent affected by the vertical distance to the return yoke.

Table 2: Lorentz Forces per Unit Length on the Coil

Field	Coil	F_{radial}/Length	$F_{vertical}$/Length
Tesla		N/m	N/m
2.0	Outer	120735	105252
	Inner	-108828	108512
2.2	Outer	167079	112226
	Inner	-146093	117935

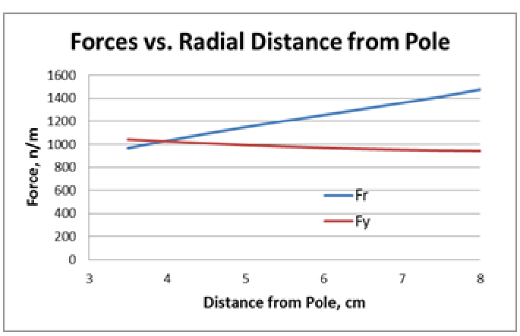

Figure 2: Dependence of F_r (red) and F_y (blue) on the horizontal distance from the pole.

The forces on the coil do vary with position along the coil. Figure 3 shows the radial (red) and vertical (blue) forces in the local coordinate system as a function of position. The forces are reasonably uniform (±20%) except in the transition regions between sections.

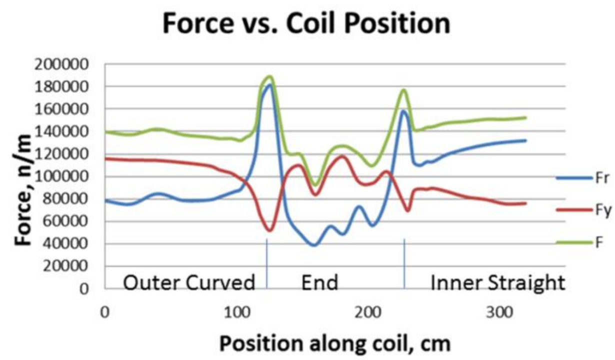

Figure 3: Forces on the coil as a function of position.

MECHANICAL AND THERMAL ISSUES

The large Lorentz forces will need substantial mechanical support to minimize coil movement when the coils are energized.

Internal Support

Constraining these forces with a support structure that is entirely within the cryostat will result in large coil deflections. We have simulated a 2D finite element model of the coil and support structure in the radial plane. The Lorentz force from Table 2 is applied at the location of the coil. The width of the support structure is varied and the maximum deformation of the structure as a function of the width is shown in Fig. 4. Increasing the width of the support is effective in reducing the coil deformation however it increases the material inside the cryostat, which will increase the heat generated in the cold mass. It is desirable to keep the support inside the cryostat at a minimum.

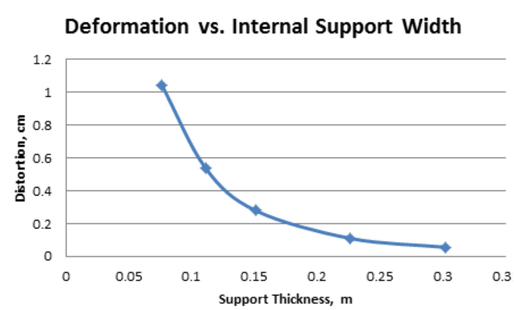

Figure 4: Maximum deformation as a function of the width of the internal support structure.

External Support

A different approach is to have minimal support internally and to use external beams anchored to the massive iron flux return. These beams must have low thermal conductivity however they cannot be made of plastics which cannot withstand the radiation. We have chosen to use titanium grade 5 for these beams as it has exceptionally low thermal conductivity along with very high strength. The finite element model was modified to use beams spaced approximately 10 cm apart that are anchored to the exterior flux return to support the coil

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structure. Figure 5 shows the coil deformation as a function of the cross section width of the support beams. Figure 6 shows the equivalent stress in the support beams for different beam widths. Also shown in the figure are the 40 K and room temperature yield limits of titanium. The support beams can permit heat from outside the cryostat to enter. To determine the fraction of the cooling budget lost to this heat leak a thermal finite element analysis of a 3D segment of the coil and support structure was modelled. All material inside the cryostat was subjected to an energy deposition of 3 kW/m^2. The helium flow passage was held to 40 K and the flux return where the support beams are attached was held at room temperature. Figure 7 shows the dependence of the heat leak fraction as a function of the width of the support beam. Although it is desirable to keep the width of the support beams as small as possible to reduce the refrigeration requirements, the stress in the support beams increases.

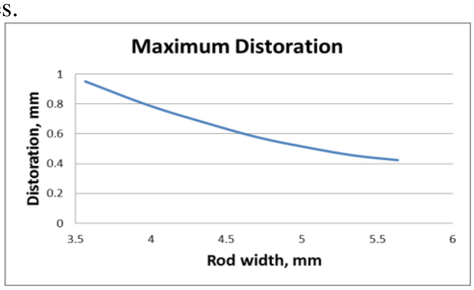

Figure 5: Maximum displacement at the coil as a function of the support beam cross-section width.

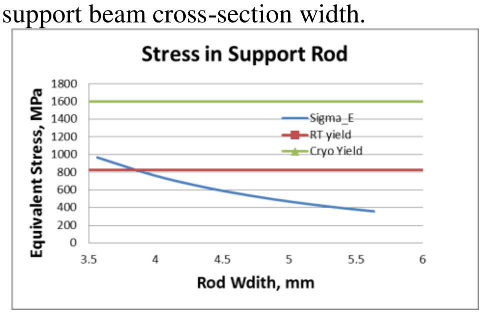

Figure 6: Equivalent stress seen in the support beam.

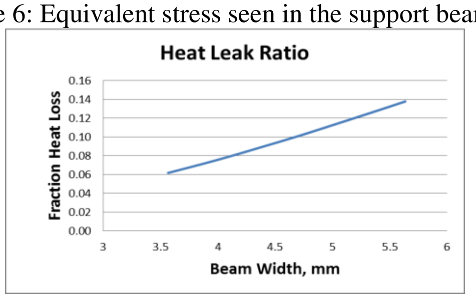

Figure 7: Fraction of the heat leaked into the cryostat by the support beam as a function of the beam cross-section width.

There are concerns about using support beams with small diameters. Although there is sufficient yield stress margin with the titanium support rods to keep the heat loss fraction below 10 %, there is a worry that the narrow support rods could buckle. The Euler buckling formula calculates the critical force where a beam can buckle assuming that there is no alignment or other imperfections. Figure 8 shows the calculated critical force as a function of the heat loss fraction. This suggests that increasing the diameter of the support rods and accepting a heat loss fraction ~20% would provide a safer margin.

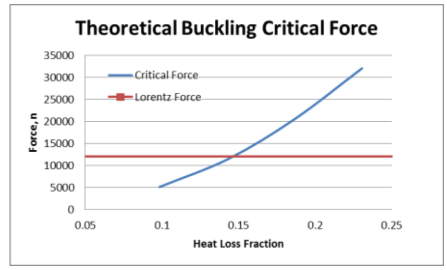

Figure 8: Euler critical force as a function of heat loss.

CONCLUSION

We have examined the structural related to the 30° bend dipole proposed for the FRIB fragment separator. This superferric magnet uses HTS conductor operating at 40 K for efficient heat removal in the high radiation environment. We have examined supporting the coils against the large Lorentz forces present by using titanium rods fixed to iron flux return which is exterior to the coil cryostat. We have analyzed the cryogenic heat loss associated with the support exterior to the cryostat.

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