RADIATION TOLERANT MULTIPOLE CORRECTOR COILS FOR FRIB QUADRUPOLES*

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Abstract

Multipole correction insert coils with significant field strength are required inside the large aperture superconducting quadrupole magnets in the fragment separator section of the Facility for Rare Isotope Beams (FRIB). Corrector coils made with copper can not create the required field and conventional low temperature superconductors are not practical in the fragment separator magnets which will operate at 40-50 K. The corrector coils for this application should be made of HTS as are the main quadrupole coils in this magnet. There is a significant advantage to using HTS in these coils as it can withstand the high radiation and heat load that will be present. This paper will describe the innovative design suitable for coils with the complex end geometry of cylindrical coils. We will look at the forces in the corrector coils from the main quadrupole fields and anticipate possible coil distortions.

INTRODUCTION

The FRIB facility will provide isotope beams for physics research with intensities not available elsewhere. Large quantities of various isotopes will be produced when a high power (400 kW) linac beam from protons to uranium hits the target. The magnets in the fragment separator region, which selects the rare nuclides from the multitude of secondary fragments, would be subject to extremely high radiation and high heat loads [1,2]. Figure 1 shows a sketch of the first part of the FRIB fragment separator. The first quadrupole magnet after the target will see a flux of 2.5×10^{15} neutrons/cm^2 corresponding to 10 MGy/year. Similar high heat loads are faced by other quadrupole and corrector magnets in the fragment separator region. The baseline fragment separator design for the first several quadrupoles is based on HTS magnet operating at 38-50 K as the removal of a heat load of this magnitude would be difficult and expensive for NbTi or Nb_3Sn superconductors since they are operated at 4.2 K. HTS on the other hand have a significant critical current density at 40 K where the Carnot efficiency is greater and the heat capacity of the refrigerants is significantly higher making heat removal easier.

Corrector magnet inserts, which will be placed between the beam tube and quadrupole coils would face the same challenging situation as the other magnets in the fragment separator region. As corrector magnet inserts made with copper coils do not generate enough field strength and because conventional superconductors would not be practical in this environment, HTS wound coils will be necessary for these corrector inserts.

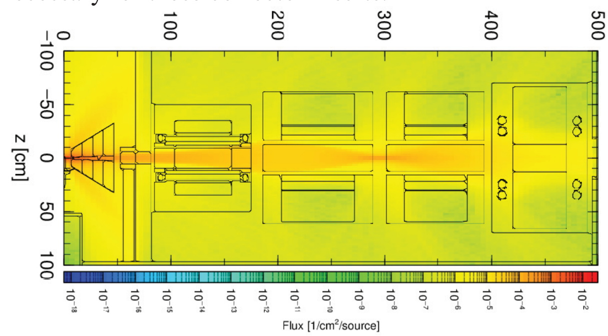

Figure 1: Proton flux seen in the first three quadrupoles of the fragment selector at FRIB. The figure is from ref [2].

CORRECTOR COIL DESCRIPTION

Seven quadrupole magnets in the fragment separator require multipole corrector inserts. Table 1 shows the beam line elements that follow the target. Table 2 shows the quadrupole, sextupole and octopole strengths for the quadrupole magnets that require multipole corrections [3]. The component strengths are evaluated at the reference radius shown in the table.

Table 1: Beam-line Elements in the Fragment Separator

Magnet	Half-gap (mm)	Field or Gradient	Length (m)	Element Position
Quad 1	100	-8,47 T/m	0.55	1.175
Quad 2	120	14.27 T/m	0.65	2.280
Quad 3	160	-11.67T/m	0.65	3.280
Octopole	130	163 T/m^3	0.50	4.570
Quad 4	140	6.53 T/m	0.55	5.350
Dipole 1	100 H, 150 V	2 T	1.75	6.900
Sextupole	100 H, 120 V	-42 T/m^2	0.40	9.320
Dipole 2	100 H, 200 V	-2 T	1.75	10.64
Quad 5	200	10 T/m	0.55	12.24
Quad 6	150	-4.95 T/m	1.357	13.54
Quad 7	160	4.2 T/m	1.357	15.51

The physical length of these inserts range from 0.6 to 0.7 m, with the effective length of the magnet being ~20% shorter. The inner radius of the octopole insert is between 75 and 110 mm adjusted to the various quadrupole apertures and the sextupole insert inner radius will be 5 mm larger than the corresponding octopole insert. The largest quadrupole pole tip field is 2.5 T, so the field at the insert coils is about 2 T. The design will assume that the sextupole and octopole fields at the insert coil radius are 0.25 T. The multipole coils should be shaped on a

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cylinder to take up a minimum of radial space and the mounting tube needs to be radiation resistant and should have a minimum mass.

Table 2: Multipole components needed at the quadrupole elements. The component is shown at the reference radius.

Element	Ref. Radius	Quad. Field, T	Sextupole Field, T	Octopole Field, T
Quad 2	0.15 m	2.14	-0.06	-0.21
Quad 3	0.15 m	-1.75	-0.06	-0.12
Quad 4	0.15 m	0.98	0	0.1
Quad 5	0.20 m	2.00	0.21	0.04
Quad 6	0.20 m	-0.99	-0.12	0.09
Quad 7	0.20 m	0.84	-0.22	-0.13
Quad 8	0.20 m	-1.55	0.015	0.103

The BNL magnet division has made HTS R&D quadrupole magnets for the fragment separator region of FRIB [4, 5, 6]. These quadrupoles were super-ferric magnets where the coils magnetized the iron producing an iron dominated field. The magnet yoke is warm and is thermally isolated from the coils which are at cryogenic temperatures. This design minimizes the space for the coils and cryogenics, while allowing a wider pole region to improve magnetic efficiency. Figure 2 shows an Opera-3D representation the quadrupole magnet illustrating the coils and the upper half of the yoke.

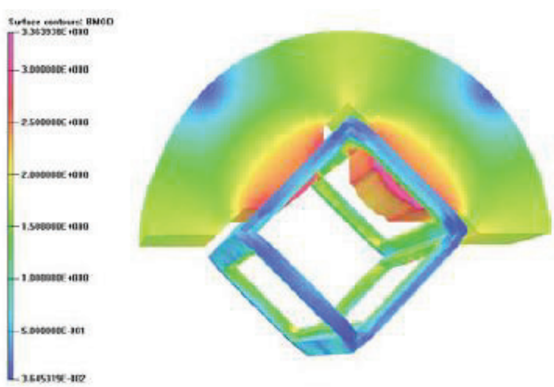

Figure 2: Opera 3D magnetic model of the FRIB fragment separator quadrupole. The sketch shows all of the coils and the upper half of the yoke.

Both YBCO and Bi-2212 are potential candidates to be used for these corrector coils. Both conductors can carry a reasonable current at 38-50 K and are radiation tolerant. In a study at the BLIP facility at BNL, a sample of YBCO conductor was irradiated and shown to withstand the cumulative effects of radiation over the anticipated lifetime of the facility [7]. In that study it was shown that the critical current, I_c, would be reduced by 20% for each dose of 10^{17} protons/cm^2. A similar study with Bi-2212 conductor showed that I_c was relatively unchanged for proton fluences up to 10^{17} protons/cm^2 [8].

The conductor for the corrector coils will be wound on a cylindrical mandrel. The Bi-2212 conductor is available as a round wire which is easier to wind on a cylinder. However Bi-2212 has the disadvantage that it has to be reacted at 890°C in pure oxygen after it has been wound. The YBCO conduct is available in tape form. YBCO conductors are formed by a continuous deposition of conductor and coatings onto a substrate that provides mechanical strength. The I_c of the YBCO conductors is sensitive to the orientation of the conductor in a magnetic field. This is an important consideration for the corrector coils since the dominant quadrupole field can be perpendicular to the conductor plane in various parts of the geometry. As such, YBCO available today, carries sufficient current to meet the requirement.

The end geometry of a coil wound on a cylinder with an YBCO tape conductor is more complicated than wound with a round Bi2212 wire. Since the tape does not want to bend in the "hard" direction, the tape conductor will tilt as it is wound around the ends on the cylindrical mandrel. The tilt angle will be slightly different for each turn. The ends will have to be supported to prevent movement in the small voids between turns caused by the varying tilt angles. Figure 3a and b show two views of the ends of a quadrupole test magnet wound with Nb_3Sn tape as an example.

Figure 3: Photograph of coil ends of a test quadrupole wound with Nb_3Sn tape.

MAGNETIC SIMULATION

We have created an Opera2D [9] electromagnetic finite element model using of the correction coils inside the large aperture R&D quadrupole magnet built at BNL for FRIB. Figure 4 shows the sextupole coils inside the quadrupole magnet. (The quadrupole magnet should be rotated by 45° so that the quadrupole coils are on the x, y axes which is the normal orientation in an accelerator.) A similar model has been made for the octopole coils. Each half coil in each sextant (octant) will subtend 20° (15°) of the available 30° (22.5°). These angles are chosen to zero the contribution of the next largest allowed harmonic above the fundamental one. The allotted radial space for each corrector coil is 5 mm which must include the conductor plus its support structure. If YBCO conductor is used, a 3 mm wide tape such as Superpower SCS030 would be appropriate. Table 3 shows the engineering current density, J_E, in the coils required to produce 0.25 T at the multipole coils. Also shown is the conductor current and the corresponding critical current. The corrector coils carry current in the field of the quadrupole magnet. The radial and azimuthal forces in the central part of the magnet (away from the ends) are shown in

Table 4 for the sextupole corrector coils and in Table 5 for the octopole coils. Since the corrector coils have a different symmetry from the dominant quadrupole coils the forces will be different on each individual coil. The correction coils could be deformed by these forces. The mechanical design of these corrector coils will need to be studied to minimize the effects of these forces.

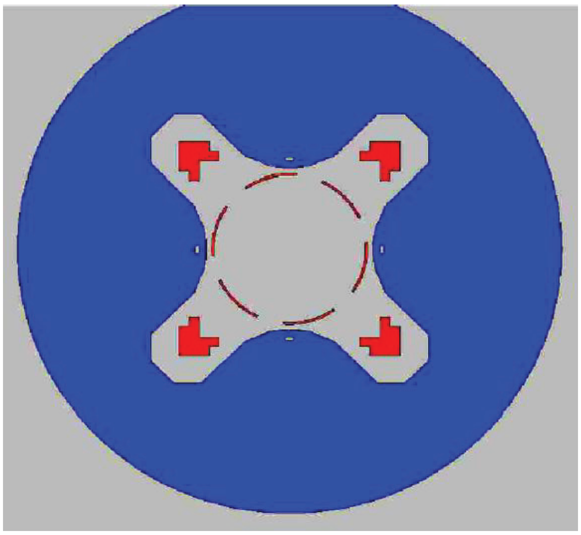

Figure 4: Sketch of the sextupole coils inserted into the BNL R&D quadrupole magnet.

Table 3: Current in the conductor for maximum field seen at the coils is shown along with the critical current of the conductor.

Coils	Field at Coils	J_E, amp/mm^2	I, amp	I_C(40 K)
Sextupole	0.25 T	110	58	96
Octopole	0.25 T	140	74	96
Main Quadrupole	2 T	125	211	400

Table 4: Forces on the sextupole coils from the quadrupole field.

Coil	Center Angle	<B>, T	F_r, nt/mm	F_ϕ, nt/mm
1	45°	1.8892	41.624	0
2	105°	1.9488	23.044	36.332
3	165°	1.6328	-19.272	32.345
4	225°	1.7555	-39.543	0
5	285°	1.8865	-20.073	-36.952
6	345°	2.1442	23.044	-36.332

Table 5: Forces on the octopole coils from the quadrupole field.

Coil	Center Angle	<B>, T	F_r, nt/mm	F_ϕ, nt/mm
1	45°	1.8666	32.696	0
2	90°	1.8770	0	33.068
3	135°	1.7688	-31.562	0
4	180°	2.4780	0	-40.441
5	225°	1.8666	32.696	0
6	270°	1.8770	0	33.068
7	315°	1.7688	-31.562	0
8	360°	2.4780	0	-40.441

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[3] From the FRIB pre-separator optics spread sheet V2b dated 2010-07-15. As the FRIB CDR has not yet been published any numbers quoted are not necessarily reliable and are subject to change.

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[9] Opera2D is an EM finite element program from Cobham Technical Service.

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