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Radiation Hardened Superconducting Mixed Multipole Magnet Designs for FRIB

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Abstract

Higher multipole magnets for FRIB may be either superconducting or conventional. The superconducting multipole magnets can be shorter than the conventional version with the same integrated field. If the magnet is in a region with a small amount of ionizing radiation, the superconducting option is attractive because the multipole magnets can be nested, and they can be installed into cold iron. In regions with large amounts of ionizing radiation, the superconducting option is less attractive because of radiation damage and the heat deposited at low temperatures. High and low radiation designs are compared for an octupole nested within a sextupole that can be used in FRIB.

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1. Introduction

Construction of the Facility for Rare Isotope Beams (FRIB) [1] at Michigan State University (MSU) requires various types of magnet to be built. The FRIB magnets are both conventional water-cooled magnets and superconducting magnets. Many of the superconducting magnets are made with unsaturated iron, because the beam momentum is low [2]. FRIB has a linac that is made using superconducting RF cavities. Most of the new magnets will be dipoles and quadrupoles. There are, however a large number of correction magnets that produce higher multipole fields (for example, sextupole and octupole).

For a number of the FRIB magnets both superconducting and normal magnets are being considered. Superconducting magnet are important when the space is limited and their fields are above the magnetic field limits for the usual-water cooled magnet, where iron saturation is a key factor. The front end of

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FRIB has high levels of neutron radiation exposure. In some regions of FRIB, the radiation level is high enough to cause heating of a superconducting magnet as well as the usual damage to organic insulations.

One of the magnets studied for FRIB is a 200 mm bore a combined sextupole and octupole magnet that is in a high radiation region that is near the FRIB primary beam fragmentation target. Water-cooled conventional copper conductor designs of this magnet have been studied [3], [4], [5]. This paper presents the design results for the superconducting version of the mixed sextupole and octupole for FRIB.

2. Radiation Resistant Superconductors

The type of insulation needed for a magnet is dependent on the intensity of the radiation where the magnet is located. Two types of radiation resistant conductors have been considered by MSU.

The first insulation system is a form of the standard Kapton insulation used for superconducting magnets [6], [7]. Kapton combined with glass B staged with cyanate-ester polymer is thicker than the resins normally used as insulation. The addition of a cyanate-ester-based insulation adds about 100 μm to the dimensions of a conductor with standard Formvar insulation. An un-insulated conductor that is 0.95 mm by 1.60 mm (see Fig. 1a below) would have insulated dimensions of 1.10 mm by 1.75 mm with cyanate-ester-Kapton insulation. This conductor is about 77 percent copper and superconductor, which is less than a standard Formvar insulated conductor with a 100-μm layer-to-layer insulation. The glass around the conductor forms a layer-to-layer and the turn-to-turn insulation. The cyanate-ester-Kapton based insulation withstands about $4 \times 10^{22}$ fast neutrons per m$^2$ (~200 MGy) [8]. This type of insulation can be used with relatively small conductors like the one in Fig 1a. At low fields (<2.5 T), the magnet current with the conductor in Fig. 1a can be 300 A with a temperature margin > 2 K.

![Figure 1. Two types of radiation hardened superconductors. a) This is a standard MRI conductor with Kapton based insulation. The un-insulated dimensions of this conductor are 0.95 by 1.60 mm. The Kapton and glass are not shown. The insulation thickness is about 75 microns. The insulated dimensions of this conductor are about 1.10 mm by 1.75 mm. b) This is a cable in conduit conductor with a 304 stainless-steel sheath, magnesium oxide insulation, a copper or stainless steel tube, and a S/C cable with 30 percent helium. This conductor dimensions are 11 by 11 mm. About 28 percent of the conductor cross-section is niobium titanium in a copper matrix.](image)

The second insulation is also a variation on a MSU insulation that has been developed for a highly radiation resistant conventional conductor [5] [9], [10]. This insulation, used as a MSU radiation resistant superconducting quadrupole [11] employs a layer of magnesium-oxide (MgO) that is between the CICC tube and the outer sheath. The tube contains about 30 percent helium, with rest of the volume occupied by a cable of twisted superconducting stands to form a CCIC conductor. This CCIC conductor is ~60 percent sheath and MgO insulation, ~12 percent helium and ~28 percent copper plus Nb-Ti. This
conductor is about as radiation hard as the superconductor and the copper. Helium flow through the CCIC is needed to remove heating from the neutrons as well as other heat sources. The conductor copper-to-superconductor ratio can be 7 or more. The MSU developed conductor is ~11 by 11 mm. See Fig 1b. This conductor can carry over 9000 A with a temperature margin of > 2 K at 2.5 T.

3. Magnet Designs Considered for the Combined Sextupole and Octupole Magnet

The basic requirements for a conventional combined sextupole and octupole are as follows: 1) The nominal beam stay clear radius is 100 mm in the horizontal and vertical directions. 2) The design sextupole induction at a radius of 100 mm is ~0.28 T, for an iron length of 400 mm. If the magnetic length is decreased to 200mm, the sextupole field at the poles increases to 0.56 T. The design sextupole gradient is 112 T m$^{-2}$. 3) The maximum octupole induction at 100 mm is ~0.15 T, for a magnetic length of 400 mm. If the iron length is reduced to 200 mm, the induction at a radius of 100 mm is ~0.30 T. The design octupole gradient is 1800 T m$^{-3}$. The magnetic length of the magnet is some 70 to 80 mm longer than the physical length of the iron. As result, the magnetic length of the superconducting version of the mixed multipole magnet is limited by saturation at poles in the iron return path and possibly the safe current limit for the superconductor with a temperature margin of >2 K at 4.2 to 4.5 K and 2.5 T. It is desirable to limit the stray field from the combined multipole magnet.

Two designs were considered for a mixed superconducting sextupole and octupole magnet. These are: 1) The first magnet is a modified cos(T$\theta$) magnet with simple block coils (where T=3 is a sextupole and T = 4 is an octupole). This magnet is conductor-dominated where the field is shaped by the coil position. The magnet would have a circular bore iron shield to return the flux. The iron shield thickness is determined by an allowable induction of 1 T. The shield should be unsaturated. There are separate windings for the sextupole and the octupole. 2) The second type of magnet is a standard iron dominated sextupole with added windings to allow octupole to be formed along with the sextupole. The sextupole field is determined by the iron poles. The octupole field is determined by the position of the octupole conductors. This design is used for a water-cooled version of this magnet [5]. The superconducting windings will carry far larger currents than the conventional conductors that the superconductor replaces. The two magnet designs were calculated using the two MSU superconductors shown in Fig. 1.

4. The Conductor Dominated Magnet Designs for a Block Modified Cos(T$\theta$) Multipole Magnet

If a circular coil has an average radius $R_c$ and the current carrying region is bounded by radii $R_c + \Delta R/2$ (the coil thickness is $\Delta R$), and the current in the coil has a current density that varies as $J_o \cos(T\theta)$ where $T$ is the order of the multipole magnet ($T=1$ is a dipole, $T=2$ is a quadrupole, $T=3$ is a sextupole and so on) and $J_o$ is the current density on the mid-plane of the multipole magnet, the multipole magnet of order $T$ will have a perfect field. For a skew multipole magnet of order $T$ the current density will varies as $J_o \sin(T\theta)$. A skew multipole magnet of order $T$ is a normal multipole of order $T$ with the poles rotated by an angle of $\pm \pi/2T$ (depending on the sign of $J_o$).

An iron shell of radius $R_I$ adds to the field generated by the currents because there are image currents in the iron. If $R_I = R_C$ and $\Delta R$ approaches 0 ($J_o$ approaches infinity), the strength of the multipole generated by the iron approaches the strength of the multipole generated by the coil alone as long as the iron has infinite permeability. For real magnets with $\Delta R \neq 0$ and $R_I > R_C$, the iron increases the strength of the multipole $T$ but not by a factor of two. The increase in strength of the higher multipoles (say $T=3$ and $T=4$) is much less than for a dipole term ($T=1$) or a quadrupole term ($T=2$). The extra multipole term generated by the image currents in the iron is perfect like the multipole term generated by the coil. If the circular iron is saturated, the multipole of order $T$ generated by the iron is reduced. The field is no longer perfect because there are symmetric multipoles ($N = T(2P+1)$ $P = 1, 2,$ and so on) are introduced by
saturation in the iron. (For a symmetric dipole the allowed symmetric multipoles are N = 3, 5, 7, and so on. For a symmetric sextupole (T=3) the symmetric multipoles are N = 3, 9, 15, and so on.) Multipoles of order N = 7 and above due to iron saturation can be ignored because they are very small.

For simplicity the normal \( J_0 \cos(T\theta) \) coils can be replaced by symmetric currents \( I \) at a radius of \( R_C \) and an angle \( \theta_C \). The poles for a symmetric multipole are located at \( \theta = \pm \pi/2T, \pm 3\pi/2T, \pm 5\pi/2T, \pm 7\pi/2T \) and so on for \( \theta \) between 0 and \( \pi \). The symmetric skew magnet poles are at \( 0, \pm \pi/T, \pm 2\pi/T, \pm 3\pi/T, \pm 4\pi/T \) and so on for \( \theta \) between 0 and \( \pi \). The symmetric currents can be expanded into power series of the field generated by all of the currents (There are 4T of these currents, where T is the fundamental multipole number. This expression is as follows [12];

\[
H^*(z) = \sum_{N=1}^{N=\infty} C_N R_C^{N-1} z^{N-1}
\]

(1)

where \( H^*(z) \) is the complex conjugate of the field \( H(z) = H_x - iH_y \) as a function of the complex position \( z \) where the absolute value of \( z \) is less than the radius convergence for the series (the radius of the closest current from the origin). For symmetric multipole magnet the complex multipole coefficient \( C_N = A_N + B_N \), where \( A_N \) is the complex multipole coefficient of the current \( I \) at a radius \( R_C \), and \( B_N \) is the complex multipole coefficient for the image currents in the iron with a circular in bore of radius \( R_I \) with its center the same as the magnet center. The \( A_N \) and \( B_N \) coefficients are:

\[
A_N = \left( -\frac{2TI}{\pi} \right) \cos(N\theta_C) R_C^{-N} \quad \text{when } N = T(2P+1), P = 0, 1, 2, \text{ and so on}
\]

(2a)

\[
A_N = 0
\]

\[
B_N = \left( -\frac{2TI}{\pi} \right) \cos(N\theta) \frac{R_C^N}{R_I^{2N}} \quad \text{when } N = T(2P+1), P = 0, 1, 2, \text{ and so on}
\]

(2b)

\[
B_N = 0 \quad \text{when } N \neq T(2P+1), P = 0, 1, 2, \text{ and so on}
\]

The equations above apply for any symmetric multipole magnet with block coils where the center of the block is at \( R_C \) and \( \theta_C \). In a symmetric sextupole the allowed multipoles are N = 3, 9, 15, 21 and so on. In a symmetrical octupole the allowed multipoles are N = 4, 12, 20, and so on. The inner radius of the block coils should be at least thirty percent more than the good field radius for the magnet. The radius of the iron should be thirty percent larger than the radius of the block coil. If the superconducting coils are cold and the iron and the bore are warm, these percentages are easily achieved. The field generated by the images in the iron falls off rapidly with multipole number. One can eliminate one more multipole (the \( N = (2P+1) \) where \( P = 1 \). For the normal magnet \( \theta_C = \pi/6T \). For a dipole, \( \theta_C = \pi/6 \); for a normal quadrupole, \( \theta_C = \pi/12 \); for a normal sextupole, \( \theta_C = \pi/18 \); and for a normal octupole, \( \theta_C = \pi/24 \). The dipole has four blocks (two coils around \( \theta = 0 \) and \( \pi \)); the quadrupole has eight blocks (four coils around \( \theta = 0, \pi/2, \pi, \) and \( 3\pi/2 \) and so on. The normal sextupole has twelve blocks (six coils) symmetrically placed and the octupole has sixteen blocks (eight coils) symmetrically placed. For a skew magnet, rotate the blocks over a \( \theta = \pi/6T \).

From equations 1 and 2a and 2b one can calculate the current needed to produce the desired magnetic induction at the reference radius \( R_{\text{ref}} \) for the multipole magnet. It should be noted that the magnitude of \( \cos(T\theta) \) is always the square root of three divided by two (0.866). Thus the current for each magnet pole is \( 1/0.866 = 1.155 \) times the current needed for each pole in a perfect \( \cos(T\theta) \) magnet. When a magnet is
made with block coils, one must adjust the current radius \( R_C \) so that the block consists of an integral number of turns. The inside of the block coil made with a single large conductor has a width \( w = (R_C - 0.0055)(\pi/3T) \). \( R_C \) must be set so that \( w = 0.011 N_T \), where \( N_T \) is the number of turns per coil. For the octupole coil, \( R_C = 132 \) mm, so there is 3 turns per pole. For the sextupole coil, \( R_C = 163 \) mm, so there is 5 turns per pole. When the large conductor is used, it is assumed that the inner bore radius is 100 mm. The iron \( R_I = 185 \) mm. This is also the boundary of the outside of the cryostat, if the iron is warm.

For the small conductor, we assume the iron is cold and the bore is warm. The physical size per turn is 1.1 mm. The radial thickness of the conductor is 1.7 mm. Thus, in the space of one turn of the large conductor, there will be 60 turns of the small conductor. The octupole magnet would have a total of 180 turns per pole. The sextupole can be brought closer to the octupole windings. In this case \( w = (R_C - 0.0051)(\pi/3T) \). \( R_C \) must be set so that \( w = 0.0011 N_T \). If one sets the minimum radial spacing between the outside of the octupole coil and the inside of the sextupole coil of 10 mm, the minimum value for \( R_C \) for the sextupole is 152.2 mm. To get an integral number of turns \( R_C \) must be moved out to 153.2 mm. Since the iron is cold the iron radius can be moved into a radius of 170 mm. The \( N_I \) per pole for a multipole magnet can be calculated using the following expression [2], [12]:

\[
N_I = \frac{G_T R_C^T 2A_T}{T \mu_0 \sqrt{5C_T}}
\]  

(3)

where \( G_T \) is the multipole gradient and \( \mu_0 \) is the permeability of air (\( \mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1} \)). \( G_T \), for \( T > 1 \), can be calculated using the following expression [2]:

\[
G_T = \frac{(T-1)!B_{ref}}{R_{ref}^{T-1}}
\]

(4)

where \( B_{ref} \) is the induction at the reference radius \( R_{ref} \). In this case \( R_{ref} = 100 \) mm.

Table 1 shows the basic parameters for the block sextupole and octupole using both the small conductor and the large conductor. Note: the sextupole coils eliminate the \( N = 9 \) term plus the other non-symmetric terms; the octupole coils eliminate the \( N=12 \) term plus the other non-symmetric terms. The \( N \) terms from \( N = 15 \) on up can be neglected.

| Parameter                      | Sextupole (T=3) | Octupole (T=4) |
|--------------------------------|-----------------|-----------------|
|                                | Large           | Small           | Large           | Small           |
| Reference Radius \( R_{ref} \) (m) | 0.100           | 0.100           | 0.100           | 0.100           |
| Coil Center Radius \( R_C \) (m) | 0.163           | 0.153           | 0.132           | 0.132           |
| Inner Iron Radius \( R_I \) (m) | 0.185           | 0.170           | 0.185           | 0.185           |
| Multipole Gradient (T m\(^{-2}\)) | 112.0 T m\(^{-2}\) | 112.0 T m\(^{-2}\) | 1800 T m\(^{-3}\) | 1800 T m\(^{-3}\) |
| \( A_N \) Coefficient (A m\(^{-T}\)) | 382 I/i         | 460 I/i         | 7264 I/i        | 7264 I/i        |
| \( C_N \) Coefficient (A m\(^{-T}\)) | 580 I/i         | 706 I/i         | 7753 I/i        | 8225 I           |
| Ampere Turns / pole (A)         | 50037           | 40028           | 19608           | 18468           |
| No. Turns per Block            | 5               | 282             | 3               | 180             |
| Conductor Current (A)          | ~10000          | ~142.0          | ~6536           | ~102.7          |
= 15 and above terms are small at the reference radius of 100 mm.

From Table 1 it is clear that one can make a combined sextupole-octupole magnet with a magnetic length between 230 and 300 mm. The current in the sextupole is large for large conductor. This magnet will operate with the large radiation hard conductor, but the current will be from 4500 to 10000 A. The real problem with large conductor is that a high current power supply is needed to power the magnet. With the small conductor, the currents are in a very reasonable range. With both conductors the temperature margin at 4.2 to 4.5 K should greater than 2 K. For both conductors the copper to superconductor ratio in the strands was assumed to be four. If the large conductor has its inside stainless steel tube replaced with a copper tube the copper to superconductor ratio could be as large as eight.

5. The Iron Dominated Sextupole with the Octupole Field determined by the Winding Position

This magnet is essentially identical to the conventional iron dominated sextupole with added octupole windings [5]. For this case, the iron length as been reduced to about 165 mm, so that the magnetic length is of the order of 235 mm. Each of the large conventional conductors that have effective dimensions of 20 mm by 20 mm can be replaced with 66 superconductors of the type shown in Fig. 1a. Each of the 20 mm by 20 mm conventional superconductors can be replaced by four superconductors of the type shown in Fig 1b. The upper half of the combined function magnet with iron poles for the sextupole is shown in Fig 2. Table 2 shows the parameters of the magnet shown in Fig 2 with the two conductors shown in Fig. 1.

![Figure 2. The upper half of the combined sextupole and octupole where the sextupole field is shaped by the iron. The octupole is generated by separate windings. The sextupole winding with + have a positive current. The sextupole windings with a – have a negative current. The octupole windings that are shaded have a positive current. The un-shaded octupole winding have a negative current.](image-url)
Table 2. The basic parameters of a combined sextupole and octupole with the two superconductors shown in Fig 1. The magnetic length of this magnet is about 200 mm.

| Parameter             | Sextupole (T=3) | Octupole (T=4) |
|-----------------------|-----------------|-----------------|
|                       | Large           | Small           | Large           | Small           |
| Reference Radius $R_{\text{ref}}$ (m) | 0.100           | 0.100           | 0.100           | 0.100           |
| Iron Pole Radius $R_\text{C}$ (m)      | 0.120           | 0.120           | 0.120           | 0.120           |
| Octupole Coil Radius $R_\text{l}$ (m) | 0.10 to 0.18    | 0.10 to 0.18    | 0.10 to 0.18    | 0.10 to 0.18    |
| Multipole Gradient    | 112.0 T m$^{-2}$| 112.0 T m$^{-2}$| 1800 T m$^{-3}$| 1800 T m$^{-3}$|
| Ampere Turns / pole (A)| 25668           | 25668           | 13380           | 13380           |
| No. Turns per Block    | 48              | 792             | 8               | 132             |
| Conductor Current (A)  | ~508            | ~30.8           | ~1673           | ~101.4          |

From Table 2, it is clear that iron pole design requires less current in the windings for both the sextupole and the octupole. The number of turns per pole for the sextupole should be reduced by a factor of three. If one did this the current per turn would be comparable to that of the octupole. The design shown in Fig. 2 applies for the conventional magnet with a magnetic length of 400 mm. Even the conventional sextupole can have fewer turns per pole [5].

6. Some Concluding Comments on a Radiation Hard Combined Sextupole and a Octupole

When comparing the two types of magnets, it is clear that having a sextupole that has iron poles with windings around the poles is a solution that is superior for both sextupole and octupole. The ampere-turns per pole is reduced a factor of about 1.5 to 2.0 for the sextupole depending on the conductor. The ampere-turns per pole for the octupole are reduced by a factor of about 1.5. The iron poles help to reduce the octupole term.

We looked at other designs such as a helical wound octupole inside of a helical wound sextupole [13], [14]. One can fabricate this type of magnet using the less radiation resistant conductor. One problem with this design is the amount of conductor used to produce the sextupole and octupole field. If superconductor radiation heating is a problem, it is far worse with this type of magnet, because there are at least four layers of cancelling solenoid windings. The bulk of the conductor in this magnet is used to produce the canceled solenoid field [15].

It would be difficult to make a combined function magnet that has the coils thermally shielded from the iron, but it is not impossible. It is clear that more work is needed to allow one to have iron at a different temperature than the coils. A possible solution is to have the iron cooled to 77 K while the coils are at 4 K. This may require the iron poles to be moved out radially so shielded octupole coils can be installed. The magnet bore can be at 77 K or 300 K. A solution may be to reduce the number of turns in the octupole coil by a factor of two while reducing the number of turns in the sextupole coils by a factor of six to make room for shielding between the iron and the coils and the octupole coils and the warm bore. Clearly more study is needed. There are other designs that could have been investigated, but they have many of the same problems as the designs that were looked at for this paper. The final design that will be adopted for this magnet will depend on the level of radiation that occurs where this magnet is to be located at FRIB.
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