RHIC Insertion Magnets*

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Abstract

The Relativistic Heavy Ion Collider[1] (RHIC) under construction at Brookhaven National Laboratory (BNL) has six interaction regions for the colliding beam. Each interaction region is part of an insertion region consisting of several magnets. The required aperture of some of the quadrupoles and dipoles in the insertion regions is much larger than the nominal 80 mm aperture of the other magnets in the accelerator. There will be 82 quadrupole magnets having an aperture of 130 mm and a maximum operating field gradient of 59 T/m and 12 dipole magnets having an aperture of 200 mm and an operating central field of 4.3 tesla. In this paper we discuss the magnetic design of the coil and iron cross section for these magnets. The first part will describe the quadrupoles and the second part the dipoles.

1. RHIC Insertion Quadrupoles

A small beam size is required at the point of interaction between the two counter rotating beams to produce a high luminosity in the Relativistic Heavy Ion Collider. An unavoidable consequence of this is the increased aperture of several magnets in the insertion regions if a sufficient space for the experiments is to be provided in the lattice. Therefore, the aperture of many quadrupole magnets must be more than the nominal 80 mm aperture of the arc magnets. Since the maximum requirement of the aperture in any quadrupole is 130 mm, it has been decided that all large aperture quadrupoles in the insertion region will have a coil inner diameter of 130 mm. To minimize the variation in the gradient requirements, two lengths have been chosen for these quadrupoles; 54 quadrupoles will have a magnetic length of 1.44 meters and 28 quadrupoles 2.41 meters. In addition to these 82 large aperture quadrupoles the six insertion regions will also have 134 nominal 80 mm aperture quadrupoles; 66 will have a magnetic length of 1.13 meters (same as in arc quadrupoles) and the rest 1.5 meters. The 80 mm aperture quadrupoles will be constructed as per the design of arc quadrupoles[2].

As in the case of arc quadrupoles, the large aperture quadrupoles will also use a keyed yoke to provide the necessary pre-compression of the coil. In the proposed design a single layer coil will be used with a 10 mm RX630 phenolic spacer between the coil and the yoke. The iron inner radius and hence the thickness of the spacer is a compromise between the need to maximize the transfer function and to minimize the iron saturation.

1.1 Coil Design

A single layer cosine θ coil using the wider cable developed for the outer layer of the SSC 50 mm aperture dipole[3] is proposed for the RHIC insertion quadrupoles. The parameters of this cable, which is used both in insertion dipoles and quadrupoles, are given in Table 1.

Table 1: Properties of the cable to be used in the RHIC insertion dipoles and quadrupoles.

Cable parameters	Value
Filament diameter, μ	6.0
Strand diameter, mm	0.648
No. of strands	36
No. of strands × Strand Area, mm^2 (Approximate cable area)	11.87
Critical Current density, A/mm^2 (in Superconductor)	2750
Copper to Superconductor Ratio	1.8
Cable width, bare, mm	11.68
Cable width, insulated, mm	11.85
Cable mid-thickness, bare, mm	1.156
Cable mid-thickness, insulated, mm	1.331
Keystone, (max-min) thickness, mm	0.206

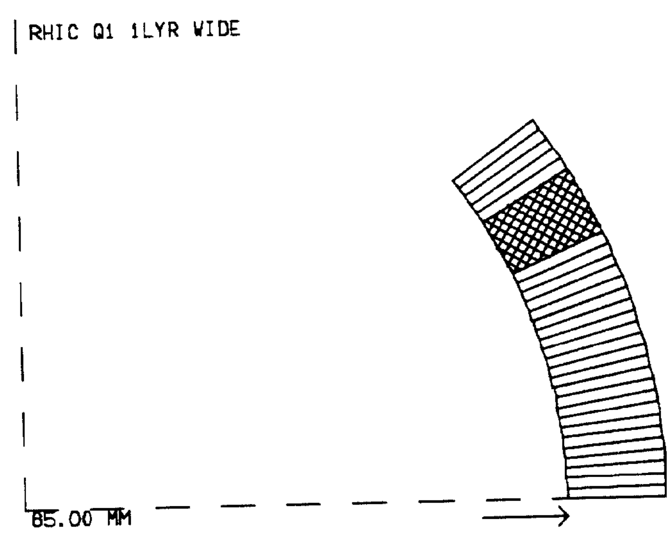

Figure 1: Cross section of the coil for RHIC insertion quadrupoles.

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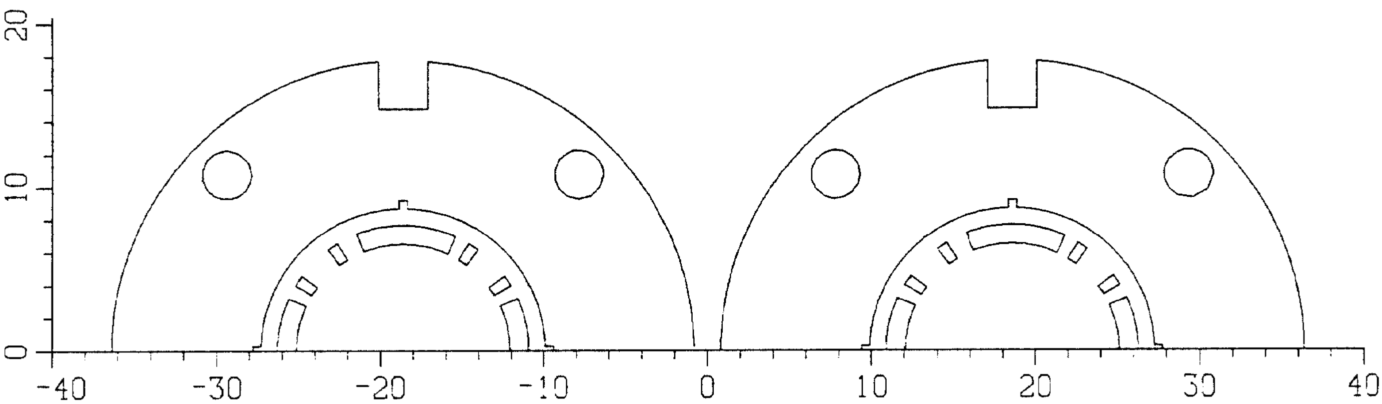

Figure 2: Cross section of the top half of the two side by side 130 mm aperture RHIC insertion quadrupoles as placed in the lattice when the separation between the two is minimum.

The coil cross section is shown in figure 1. It has a pole angle of 36.5 degree. There are 28 turns in each octant of the coil. There are two blocks in each octant with 23 turns in the first block and 5 in the second. The size of the wedge between the two blocks is 6.376 degree. The blocks are almost radial since the cable is almost fully keystoned – actually it is a bit over-keystoned for a 130 mm coil aperture. The coil cross section has been optimized to produce a low value of field harmonics (see appendix for the definition). The allowed harmonics of this cross section are given in Table 2 for infinite μ circular iron aperture. This cross section is also chosen because it has a high value of transfer function and a low value of peak field in the conductor which maximizes the achievable field gradient in a superconducting magnet.

Table 2: Field harmonics for infinite μ circular iron aperture in the RHIC insertion quadrupoles for 40 mm normalization radius.

TF(T/m/kA)	b_5	b_9	b_{13}	b_{17}
10.2	0.3	-1.9	-1.2	0.1

1.2 Yoke Design

The outer diameter of the insertion quadrupoles is limited by the transverse space available in the lattice. The center to center distance between the two counter rotating beams in the inner and outer rings is 372 mm when the beam first enters the insertion quadrupoles which are placed side by side to each other. In order to fit these quadrupoles in this limited cross sectional space, we plan a yoke design with outer diameter of 356.6 mm (14 inch). A stainless steel shell having a thickness of about 5 mm will be put on the yoke outer diameter. A minimum clearance of a few mm will be left between the two insertion quadrupoles of the inner and outer ring of the accelerator. The computer model of the cross section of the two side by side quadrupoles in this case is shown in Fig 2. The direction of the field in these two quadrupoles will be the same because the lattice is basically asymmetric with respect to the crossing point. However, since in general the two colliding beams may have different rigidities, the magnitude of the gradient in the two quadrupoles could be different. In two extreme cases, it is 1:1 for similar beams and 1:0.4 when the two beams have the maximum allowed difference in the rigidities as per the design.

In Table 3 we give the computed variation in field harmonics in 1:1 case. Transfer function, b_0 and b_5 as a function of current are plotted in fig 3. The change in the b_5 harmonic (due to iron saturation) will require an external corrector. An iron inner radius of 87 mm was chosen to keep the b_5 saturation within a modest amount even at a small expense of the transfer function. A non-zero value of b_0, b_2, b_3, etc. at high current is the influence of the field of one quadrupole on the other. This is commonly referred to as "cross-talk" and when the direction of field in the two magnets is same, it is maximum when both run at same current. If they are powered at different currents, then the flux lines leaking out of the high field quadrupole would be contained by the yoke of the low field quadrupole. Since the iron in the low field magnet is not yet saturated, it provides a good shielding against the cross talk. The effect of cross-talk on field harmonics in the design range is within an acceptable limit. The harmonics not listed in table 3 have a variation of ~ 1 unit.

Table 3: Variation of field harmonics as a function of current in the RHIC insertion quadrupoles for 40 mm normalization radius. We require all harmonics to start from zero.

I kA	Grad $\frac{T}{m}$	TF $\frac{T/m}{kA}$	b_0	b_2	b_3	b_5
1	10.19	10.2	0	0.0	0.0	0
4	40.69	10.2	0	0.0	0.0	1
5	50.46	10.1	0	0.0	0.0	6
6	59.58	9.93	0	0.0	0.0	12
7	68.11	9.73	3	0.0	0.8	15
8	76.16	9.52	16	0.8	1.5	15
9	83.87	9.32	45	1.8	1.7	14
10	91.40	9.14	80	2.4	1.9	12

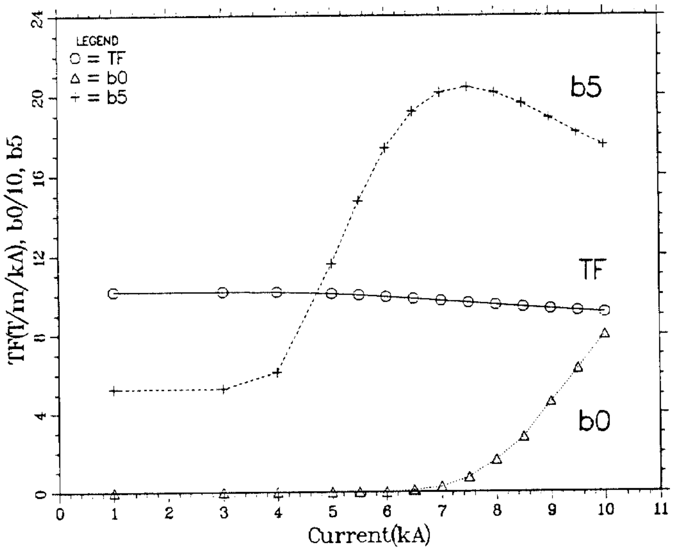

Figure 3: Transfer function, $b_0/10$ and b_5 as a function of current in the RHIC insertion quadrupoles when two of them are placed side by side and are at their minimum distance in the lattice. In this case the two quadrupoles have the same currents.

1.3 Quench Performance

In this section we discuss the expected quench performance and other related parameters for these quadrupoles. We assume a 5% degradation in the cable having a specification of 2750 A/mm^2 for the critical current density (J_c) in the superconductor at 5 tesla field and 4.2 K temperature. We compute a quench gradient of 82 T/m at 4.35 K operating temperature for a copper to superconductor ratio of 1.8. This gives a 38% margin over the design gradient of 59 T/m. The current density in the copper at quench will be 1193 A/mm^2 and at the design gradient 863 A/mm^2.

2. RHIC Insertion Dipoles

The six insertion regions will have 84 dipoles; 72 with 80 mm aperture and 12 with 200 mm. The 80 mm aperture dipoles will have three lengths (magnetic) – 24 will be 9.45 meters long (same as in arc dipoles), 12 will be 5.45 meters long and 36 will be 3.57 meters long. These dipoles will be constructed as per the design of the arc dipoles[4].

The 200 mm aperture dipoles will be the first magnets to be placed in the lattice on either side of the crossing point in the six insertion regions and will be common to the beams going to the inner and the outer ring. The aperture requirement of this dipole is governed by the separation between the two counter rotating beams going through this dipole and the size of the two beams. The design of this dipole, like that of 130 mm aperture quadrupole, is based on a single layer coil configuration using the wider cable described in Table 1. In Table 4 we present the summary of the basic design parameters and the expected performance of these magnets. A detailed cross sectional design of these magnets is still under development.

Table 4: Basic parameters of the 200 mm aperture RHIC insertion dipole.

Coil i.d.	200 mm
Coil o.d.	224 mm
Turns per Quadrant	85
Blocks per Quadrant	4
Iron i.d.	244 mm
Iron o.d.	600 mm
Design Field	4.27 T
I at design field	5.25 kA
Field at Quench	5.6 T
Field Margin	31%
Magnetic Length	3.7 m
Stored Energy	1091 kJ

Appendix

The field harmonics in the prime units are defined by the following relation:

$$B_y + iB_x = C_0 \sum_{n=0}^{\infty} \left[b_n' + i\ a_n'\right] \left[cos\,(n\theta) + i\ \ sin\,(n\theta)\right] \left(\frac{r}{R_0}\right)^n$$

where a_n' are the skew harmonics and b_n' the normal. B_x and B_y are the components of the magnetic field at (r,θ). R_0 is the normalization radius which is 40 mm for the 130 mm aperture quadrupoles and 65 mm for the 200 mm aperture dipoles. C_0 is $G_q \times R_0$ for quadrupoles with G_q being the field gradient at the center of the magnet. C_0 is B_0 for dipoles with B_0 being the magnetic field at the center of the magnet. The field harmonics in prime units are given in units of 10^{-4} throughout this paper.

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