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Interactive Procedure for Rapid Performance Estimates of Accelerator Magnet Designs*

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Abstract:

An interactive procedure to estimate magnetic field harmonics in simple cosθ dipole and quadrupole magnets, with an optional wedge and yoke, is included in a CD-ROM tutorial on superconducting magnets for particle accelerators. Input values define the coil geometry and the current density. Output includes the normalized multipole coefficients, a color-coded graph of the field strength in the conductor region, and the Lorentz forces on the coil. The tutorial also includes interactive procedures that calculate the critical current density of NbTi and NbSn at various operating conditions to support the magnet performance estimates. Sample calculations for current accelerator magnets are presented .

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1. Introduction

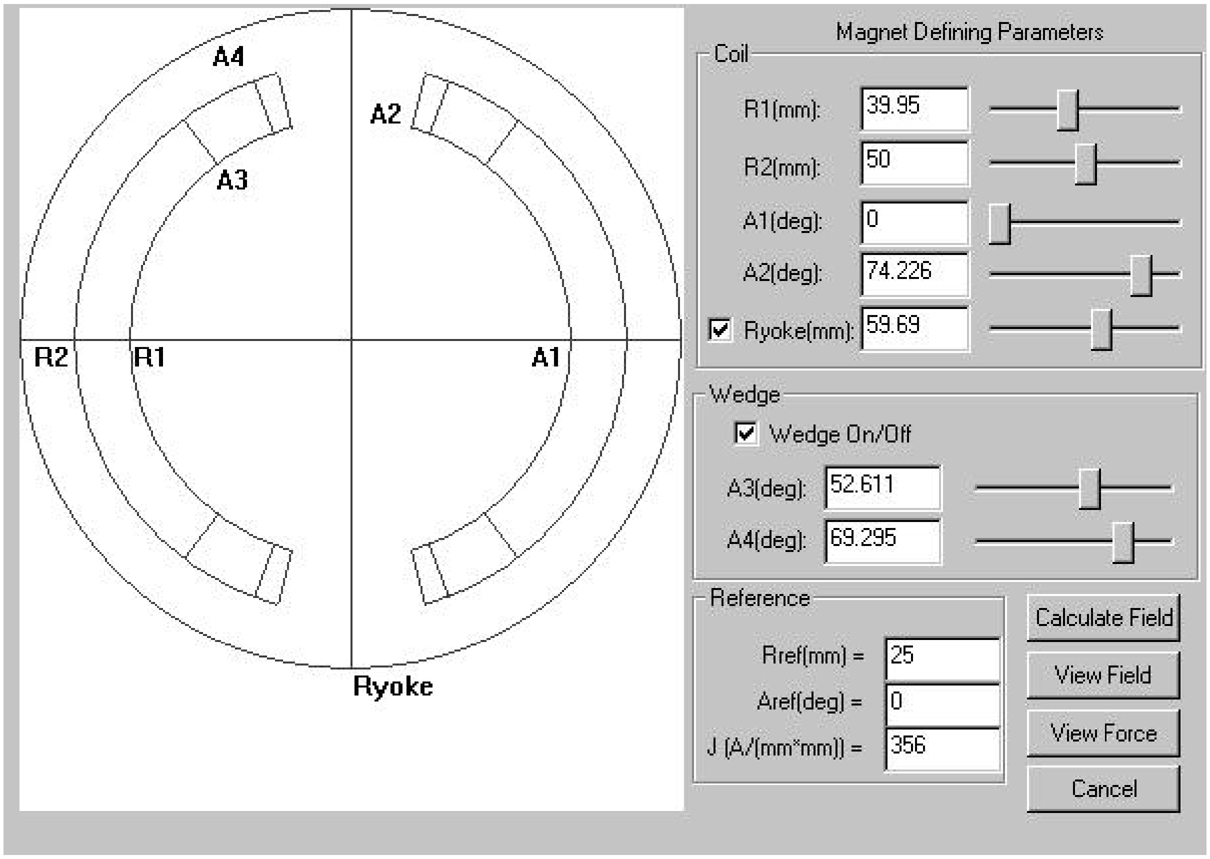
Interactive procedures for rapid performance evaluations of potential cosθ magnetic designs have been implemented. They are included in a CD-ROM tutorial on superconducting accelerator magnets[1].

The field and force calculation procedures for single layer dipole and quadrupole magnets with an optional wedge and iron yoke are based on algorithms developed by DESY during construction of HERA [2]. Multi-layer magnets can be studied by adding the contributions of single layers. The present implementation of the program is limited to one wedge per layer. Calculations of magnetic field harmonics are illustrated on configurations similar to the Tevatron and RHIC dipoles. The coil dimensions and superconductor operating conditions for the Tevatron and RHIC dipoles are also available from the magnet designs reference section of the CD-ROM tutorial. The results are compared with the actual values of these magnets.

The procedure for calculating critical current densities as a function of temperature and field is based on short sample measurements at BNL[3]. Estimates of operating margins are illustrated for the RHIC dipoles.

2. Magnetic Field Estimator

The Input Screen of the interactive magnetic field calculator (IMFC) is illustrated in Figure 1.



R1(mm): 39.95
R2(mm): 50
A1(deg): 0
A2(deg): 74.226
☑ Ryoke(mm): 59.69
☑ Wedge On/Off
A3(deg): 52.611
A4(deg): 69.295
Rref(mm) = 25
Aref(deg) = 0
J (A/(mm*mm)) = 356

Figure 1.

Coil geometry parameters and conductor properties are entered into the Graphical User Interface (GUI) and can be varied by adjusting the adjacent ‘slider controls’. The given geometry is displayed in the cross section diagram of the GUI.

Descriptions of the parameters are available online as 'pop-ups' from an instruction screen.

- R1: Inner coil radius, i.e., coil aperture
- R2: Outer coil Radius
- A1: Start angle of coil near midplane
- A2: Upper angle of coil, i.e., coil pole face angle
- R_{yoke}: Radius of concentric iron yoke with infinite permeability

- A3: Lower wedge angle
- A4: Upper wedge angle

- R_{ref}: Reference radius for field calculations
- A_{ref}: Reference angle for field calculations

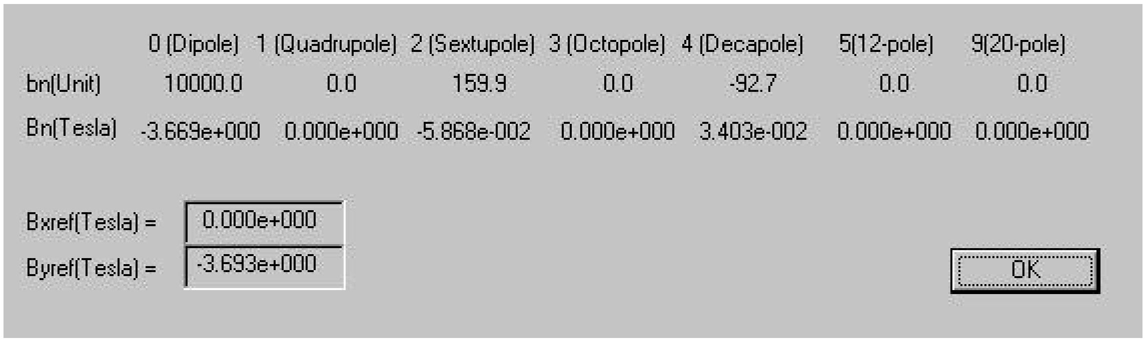
J: Critical current density in coil cross section. For a given magnet the critical current density is calculated from the number of conductor turns, the cable cross section and the operating current of the magnet.

The program automatically checks all values for consistency.

IMFC Calculations

- Calculate Field: Calculate multipole fields of given coil
- View Field: Generate color-coded plot of fields inside the conductor cross section, as well as minimum and maximum fields in this region.
- View Force: Calculate forces on coil integrated over the four coil quadrants

The output window, displaying the calculated multipole fields is shown in Figure 2, the graphical displays of fields and forces are shown in Figures 3a and 3b.



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              0 (Dipole)  1 (Quadrupole)  2 (Sextupole)  3 (Octopole)  4 (Decapole)  5(12-pole)   9(20-pole)
bn(Unit)      10000.0     0.0             159.9          0.0           -92.7         0.0          0.0
Bn(Tesla)     -3.669e+000 0.000e+000      -5.868e-002    0.000e+000    3.403e-002    0.000e+000   0.000e+000

Bxref(Tesla) = 0.000e+000
Byref(Tesla) = -3.693e+000
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Figure 2. Output table for magnetic field calculation. The magnitude of the fundamental field and the first two allowed multipoles are shown. Bx_{ref} and By_{ref} are the horizontal and vertical field components on the reference radius.

Field and Force Display:

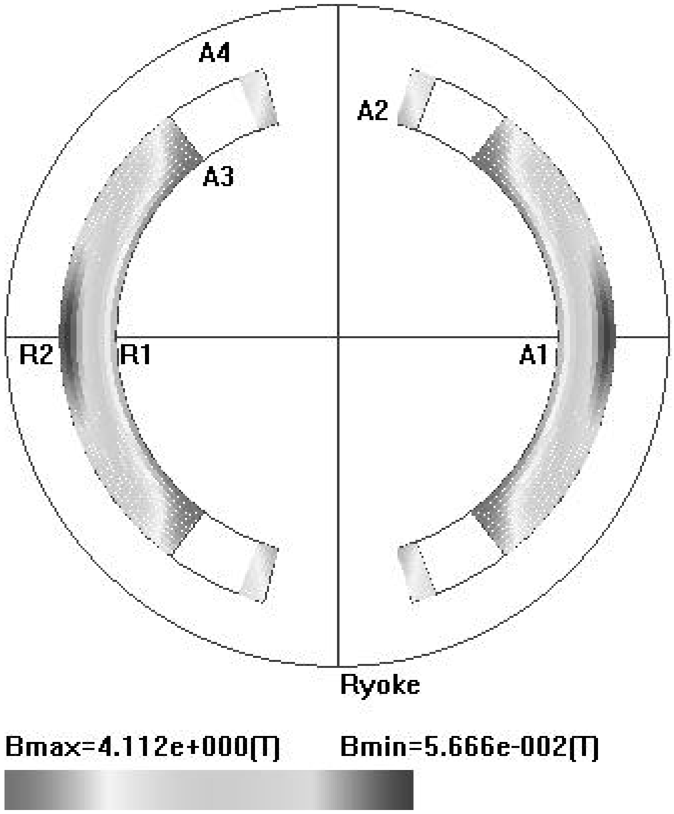


Figure 3a. Color-coded field inside of the coil cross section. Also indicated are the peak field and the minimum field strength in this area

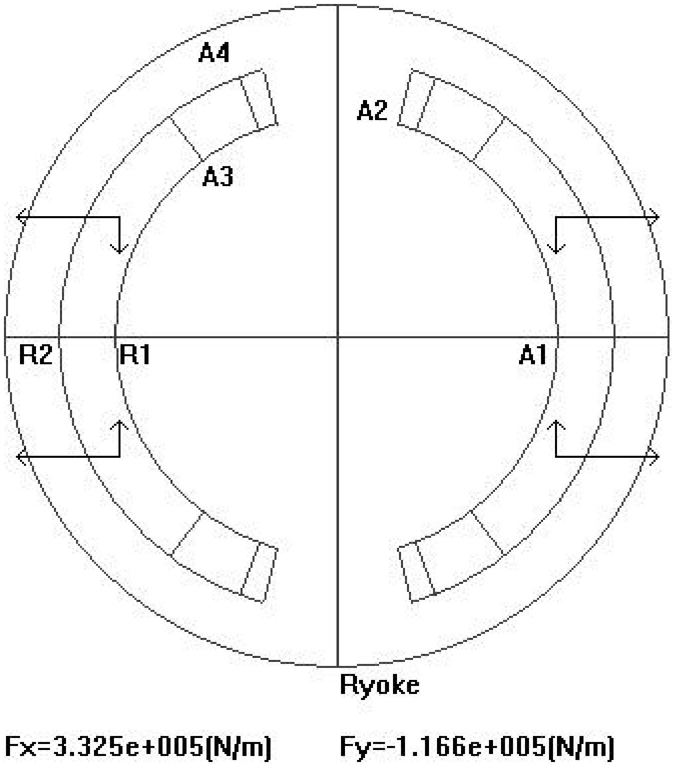


Figure 3b. Horizontal and vertical components of Lorentz force acting on the coil integrated over each quadrant .

3. Sample Applications

The IMFC was used to compute the central field and the higher-order multipoles for two examples of existing magnets:

1. **The Tevatron Dipole**
2. **The RHIC dipole**

Results are compared with the published parameters of these magnets as obtained from measurements and/or sophisticated calculations.

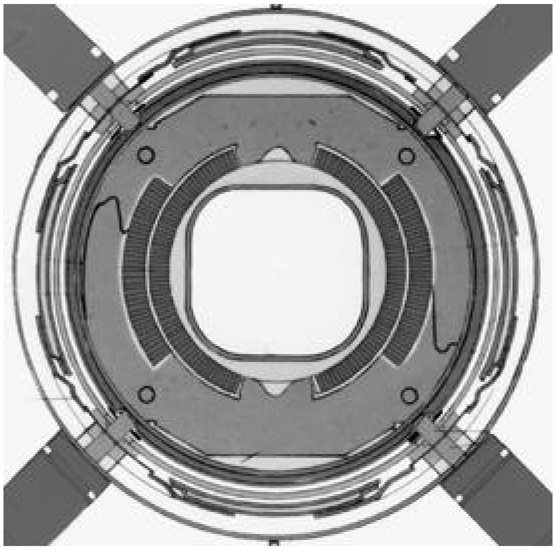


Figure 4a. Tevatron dipole collared

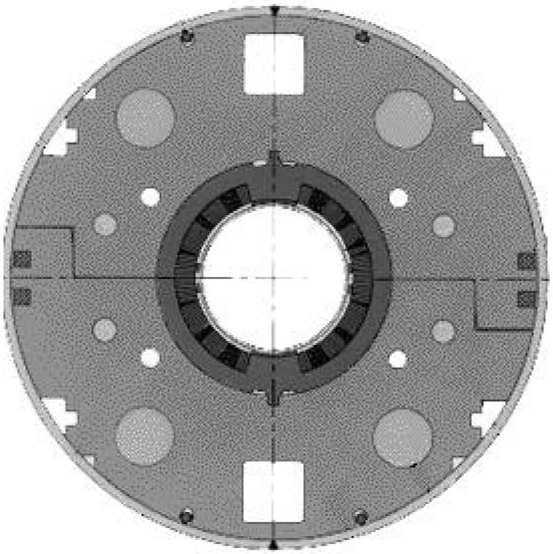
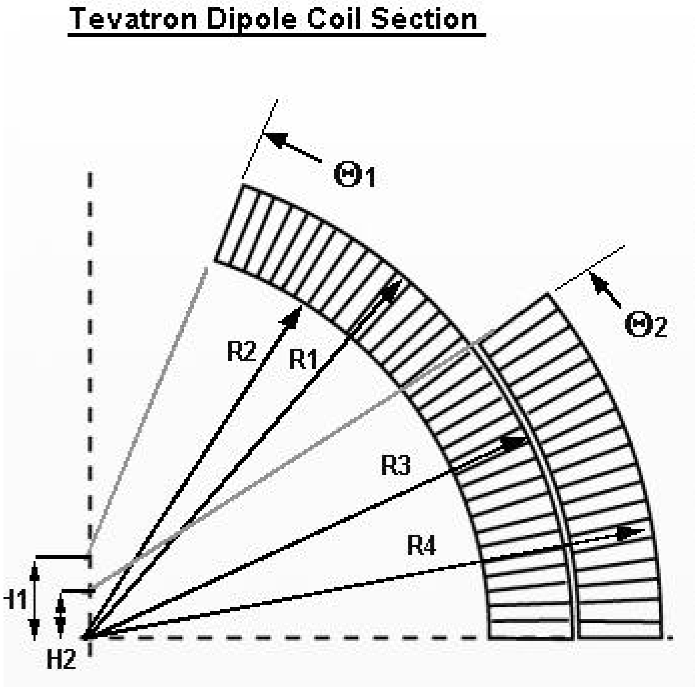
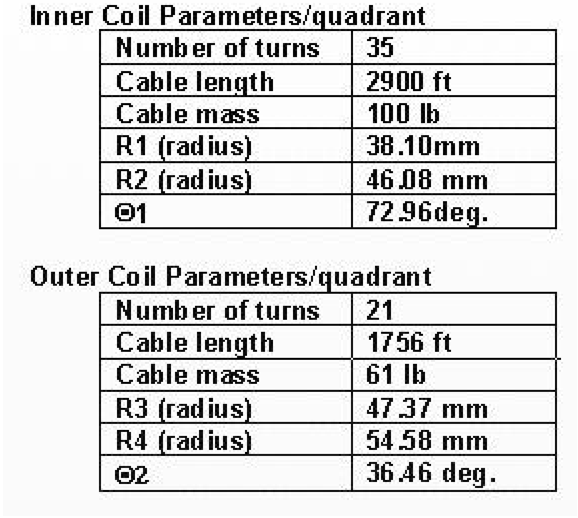


Figure 4b. RHIC dipole coil cross section

Tevatron Dipole Geometry

The coil geometry parameters of the Tevatron dipole, shown in Figure 4a, are detailed in Figure 5. The magnet uses a two layer coil without wedges. The magnetic field generated by each layer is independently calculated and then added to obtain the total field inside of the magnet bore.





Inner Coil Parameters/quadrant

Number of turns	35
Cable length	2900 ft
Cable mass	100 lb
R1 (radius)	38.10mm
R2 (radius)	46.08 mm
Θ1	72.96deg.

Outer Coil Parameters/quadrant

Number of turns	21
Cable length	1756 ft
Cable mass	61 lb
R3 (radius)	47.37 mm
R4 (radius)	54.58 mm
Θ2	36.46 deg.

Figure 5. Tevatron coil geometry

Other parameters of the magnet and its operating conditions are listed in Table I.

Table I

Parameter	Value
Central Field	4.4 T
Operating current	4400 A
Operating current density in inner coil*	360 A/mm^2
Operating current density in outer coil*	395 A/mm^2
Operating temperature	4.6 T
Number of turns/coil (Inner)	35
Number of Turns/coil (Outer)	21
Strands/cable	30
Strand diameter	0.648 mm
Copper:Superconductor	2.25
Inner radius of yoke	59.69 mm

***** The required average current density in the coil is found by dividing the total current through the magnet cross section by the area of the coil as computed from the geometrical parameters in Figure 5.

Comparison between IMFC Results and Published Data

Table II summarizes the results of the IMFC calculation and compares them with the FNAL values [4]. All multipole fields of the inner and outer coil are given in tesla and can be added to obtain the field of the total coil assembly. The comparison shows good agreement. Note that the sign reversal is arbitrary and based on the magnetic field direction convention used.

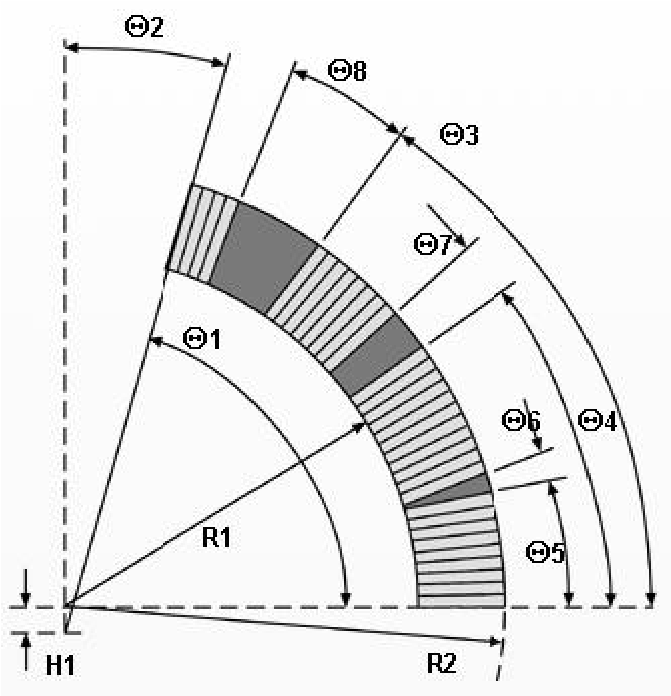
Table II

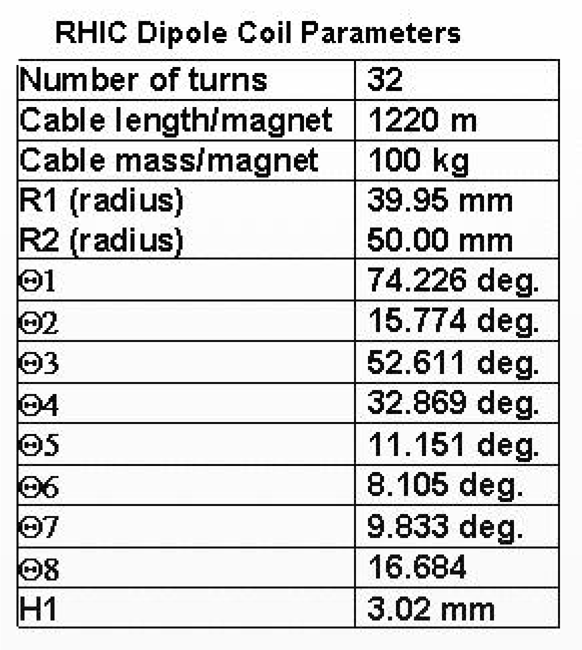
	IMFC Calculation			FNAL Value
Field component	Inner Coil	Outer coil	Total	
Dipole, T	-2.623	-1.74	-4.363	4.5
Sextupole, T	0.1724	-0.1772	-0.0048	0.00351
Decapole, T	-0.004935	0.001078	-0.003857	0.00445
Sextupole (Units)			11.0	7.80
Decapole (Units)			8.8	3.21
Peak field, T (total)	3.235			

RHIC Dipole Magnet

The coil geometry parameters of the RHIC dipole, shown in Figure 4b, are detailed in Figure 6 . The field uniformity of this single layer coil is tuned with 3 wedges, which are inserted into the coil cross section.

For the field calculation the coil is divided into two coils with one wedge each as shown in Figure 7. The total field is obtained by summing the components from the two coil sections.





RHIC Dipole Coil Parameters

Number of turns	32
Cable length/magnet	1220 m
Cable mass/magnet	100 kg
R1 (radius) R2 (radius)	39.95 mm 50.00 mm
Θ1	74.226 deg.
Θ2	15.774 deg.
Θ3	52.611 deg.
Θ4	32.869 deg.
Θ5	11.151 deg.
Θ6	8.105 deg.
Θ7	9.833 deg.
Θ8	16.684
H1	3.02 mm

Figure 6. RHIC coil geometry

RHIC Dipole Coil

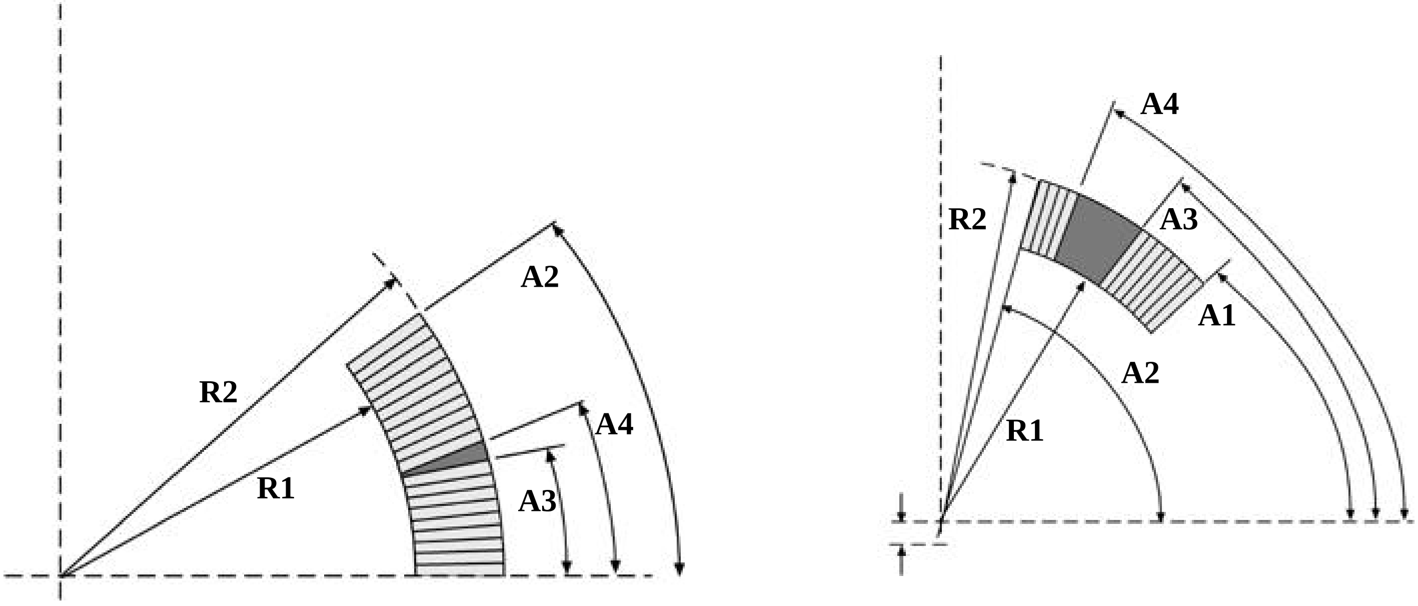


Figure 7. RHIC coil separated into two sections for field calculation with the IMFC.

Other parameters of the magnet and its operating conditions are listed in Table III.

Table III

Parameter	Value
Central Field	3.46 T
Operating current	5050 A
Current density in the coil (1 coil, 1 wedge)*	356 A/mm^2
Current density in the coil (2 separate sections)*	517 A/mm^2
Operating temperature	4.6 K
Number of turns/coil	32
Strands/cable	30
Strand diameter	0.648 mm
Copper:Superconductor	2.25
Inner radius of yoke	59.69 mm

***** The current density is uniformly distributed throughout the coil conductor area and is determined from the dimensions in Figure 6.

Comparison of IMFC Results with Published Data

Table IV summarizes the results of the IMFC calculation and compares them with the published values [5]. Note that the sign reversal is arbitrary and based on the magnetic field direction convention used.

Table IV

	IMFC Calculation 1 coil, 1 wedge	IMFC Calculation 2 separate sections with wedges	BNL Value
Dipole, T	-3.69	-3.57	3.45
Sextupole, T	0.0587	-0.0379	0.00073
Decapole, T	-0.034	-0.007761	0.00077
Sextupole (Units)	153.9	106.2	-2.11
Decapole (Units)	-92.7	21.7	-2.23

While the main dipole field is estimated with acceptable precision, the higher-order multipole fields, in particular the sextupole component are significantly over estimated by IMFC. This is due to the fact that the limiting angles of the wedges do not point radially to the center of the coil as modeled by the IMFC. Also iron saturation effects are not taken into account in this simple model

4. Quench Current and Operating Margin

The IMFC calculates the peak field, B_{max}, on the conductor in the two dimensional cross section of the magnet. From the operating temperature, T_{op}, and the current density in the superconductor, J_{op}, the operating margin of the magnet is estimated by the following relation (neglecting the field enhancement in the coil ends).

$$M \arg in = 1 - \frac{J_{op}}{J_C\ (B_{\max}, T_{op})}$$

The critical current density at a specified field and temperature $J_C(B_{max}, T_{op})$ can be obtained from the interactive Material Properties Library, which is included in the Tutorial [1].

Interactive Retrieval of Critical Surface Data

The Material Properties Library of the tutorial includes parameterizations of the critical surfaces for NbTi and Nb_3Sn, which enable the user to retrieve values of the critical current density as a function of field and temperature.

The NbTi critical surface and the upper critical field can be described by the following parameterization [6, 7]. Parameters fitted to short sample data of the RHIC magnet wire are given in Table V [3].

$$J_c(T,B) = C_1\,[B_{C2}(T)]^m \left[\frac{B}{B_{C2}(T)}\right]^p \frac{\left[1-\frac{B}{B_{C2}(T)}\right]^q}{B}$$

$$B_{C2}(T) = B_{C0}\left[1-\left[\frac{T}{T_C}\right]^e\right]$$

Table V: Fitted parameter values

C1	1046.8
m	1.73
p	0.948
q	1
BC0	14.45
TC	8.66
E	1.61

Estimating the Operating Margin of the RHIC Dipole

An estimate of the operating margin requires the following steps

1) Determine the peak field on the conductor. Using the IMFC and only considering the largest wedge, yields a peak field of 4.1 T.
2) The current density in the superconducting cable at the operating current of 5050 A yields 1680 A/mm^2. This number is obtained by multiplying the current density of 517 A/mm^2, given in Table III, with 3.25, which takes the Cu:SC ratio into account.
3) From the Material Properties Library in the Tutorial one obtains a critical current density for the given peak field and the operational temperature of 4.6 K of J_C = 3067 A/mm^2.
4) Using the above values, one obtains:

$$M\,\mathrm{arg}\,in = 1-\frac{J_{op}}{J_C\ (B_{\max},T_{op})} = 1-\frac{1680}{3067} \approx 45\%$$

Assuming that the peak field in the coil ends is about 5% higher than the maximum field in the straight section, reduces this margin to 43%, which is in good agreement with the measured value.

5. Conclusions

- The IMFC program provides a user friendly interface for evaluation of cosθ type dipole and quadrupole designs.
- A first approximation of a proposed magnet design can be quickly generated.
- Results of the program allow one to estimate the main field, higher-order multipole components, and the operating margin for a given conductor used in the magnet design.
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The program is supported by an interactive Material Properties Library, which contains useful information on superconductors, copper, and other materials.

References:

[1] M. Ball and C. Goodzeit, "Tutorial on Superconducting Accelerator Magnets", Proceedings of the 1997 Particle Accelerator Conference. See also www.mjb-plus.com

[2] R. B. Meinke, private communication.

[3] G. H. Morgan, "A New Critical Surface for RHIC NbTi", Brookhaven National Laboratory Memo 560-1 (RHIC-MD-2611) Jan. 6, 1997

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[6] A. M. Campbell and J. E. Evetts, "Critical Currents in Superconductors", Barnes and Noble Books, N. Y. 1972 p. 159

[7] J. S. Lubell, "Empirical Scaling Formulas for Critical Current and Critical Field for Commercial NbTi", IEEE Trans. on Magn., Vol. MAG-19, No. 3, p. 754 (May 1983)