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Field Calculations and Measurements of a Helical Snake Magnet for RHIC

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Spin Note

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Abstract — **For the Relativistic Heavy Ion Collider (RHIC) Spin Project, superconducting helical dipole magnets are being developed. These magnets will be used in 'Siberian Snakes' and 'Spin Rotators', which manipulate polarized proton beams in RHIC. The dipole field in these magnets rotates 360 degrees and is required to reach a magnetic field strength of approximately 4.0 T. The planned bore radius of the coils and the magnetic length of the magnets are 50 mm and 2400 mm, respectively. To ascertain the performance of the magnets, a half length model has been fabricated. The quench performance, field distribution and field uniformity were investigated. Three dimensional (3D) fields were also calculated using TOSCA. The measured values in the model magnet agreed well with calculations. These results demonstrate adequacy of the fabrication method adopted in the model magnet and the reliability of the 3D calculations by TOSCA.**

I Introduction

We have studied acceleration of polarized proton beams in RHIC as a part of the RHIC-Spin project[1], a joint project between RIKEN and BNL. The development of the superconducting helical dipole magnets is one of the key issues to the success of this project.

Generally, the spin precession frequency of the particles being accelerated in synchrotrons can become resonant with the undesired magnetic fields and this phenomenon leads the beam to depolarization. A device called Siberian Snake[2] controls the axis of spin by magnetic fields and can avoid this resonance in synchrotrons.

The Siberian Snakes adopted by RHIC are of a type called Full Snake, and must flip the spin direction by 180 degree without influencing with the beam orbit. Also Spin Rotators will be installed in RHIC, in order to provide the beams that have several required spin directions, to the two collision points for experiments. Each of the Siberian Snakes and Spin Rotators consists of four superconducting helical dipole magnets. Since the dipole field in these magnets rotates through a full 360 degree, the transverse magnetic fields felt by the accelerated particles are canceled. Furthermore, the symmetric combination of the four helical dipole magnets, altering polarity for the Siberian Snake and altering handedness of the magnet structures for the Spin Rotators, prevents the shift of the beam orbit. The required performance for each helical dipole magnet is to achieve more than 3.9 T with 2.4 m effective length and zero integrated transverse fields. Optimization of the multipole components is also important to avoid a tune shift. In order to test the design and fabrication method, quench tests and field measurements of a half-length model of this magnet were performed. Three dimensional field analysis has also been done using TOSCA. In this paper, the measured performance and the field calculations will be described.

II Features of the Helical Dipole Magnets for RHIC

To maintain polarization of the beams in the two rings and to provide beams of specified spin direction to two experimental halls, a total of four Snakes and eight Rotators, which correspond to forty-eight helical dipoles, are required. From the cryogenic point of view, it is necessary to minimize the heat leak from these independently powered magnets. Therefore, a thin round cable of 1 mm diameter comprised of seven wires is used instead of the Rutherford-type cable used in the regular arc magnets. The Kapton-wrapped cables are wound in precisely machined helical slots in an aluminum cylinder. Thin fiberglass sheets containing b-stage epoxy are inserted between layers. Finally, the wound cables locked in the slots by heating while applying radial pressure. The model magnet was wound by hand, and considerable skill and time were required. An automatic winding process is being developed at BNL.

III Half-Length Model Magnet

As mentioned above, the coil structure of this magnet is very different from conventional designs. In order to test the performance of this magnet, a half-length model magnet[3] was produced at the end of last year. The cross-section of this model magnet and design parameters are shown in Fig. 1 and TABLE I respectively.

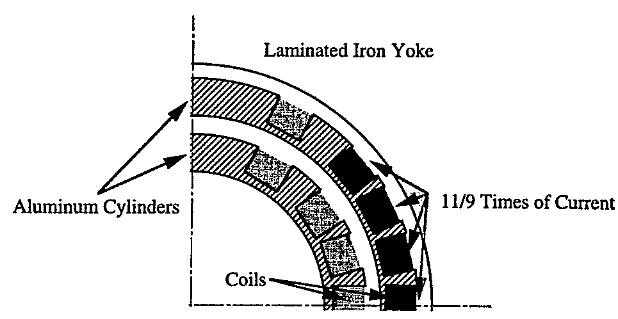

Fig. 1. Cross-sectional view of a quadrant of the model magnet.

The coils are divided into two layers. The separation between the coils and the yoke is only 5.5 mm and the yoke enhances the field from the coils by about 50%. The coils are entirely enclosed by the iron yoke. The inner radius of the yoke is increased at the end regions of the magnet to prevent quenches in the coil ends. This model magnet was designed to be used with two currents in the ratio of 9 to 11. In order to increase the maximum field strength around the axis, the coils in the stronger field have a lower current.

TABLE I
DESIGN PARAMETERS FOR THE MODEL MAGNET

Parameter	Value
Coils	Inner, Outer
No. of current blocks per cylinder	7, 9
No. of cable turns per layer	12,12
No. of layers per current block	9, 9
No. of cable turns per block	108, 108
No. of cable turns per cylinder	756, 972
Total turns	1728
Inner radius (mm)	49.71, 68.63
Outer radius (mm)	60.02, 78.94
Total length (mm)	1371.6
Effective length (mm)	1200
Rotation angle (degree)	180
Helical pitch (degree/mm)	0.15
Yoke	
Outer radius (mm)	177.80
Inner radius in body (mm)	84.46
Inner radius in end (mm)	114.4
Length of lamination for body (mm)	1029.1
Length of lamination for each end (mm)	196.8
Total length (mm)	1422.8

IV THREE DIMENSIONAL MAGNETIC FIELD CALCULATIONS

Helical dipole magnets have a complex structure compared to the usual accelerator magnets and have strong longitudinal fields. The net transverse field seen by the beam, including fringing fields, should be zero. To design a magnet meeting these criteria, 3D field analysis becomes a useful tool. We have analyzed the 3D field in the helical dipole magnets[4] using the computer code TOSCA. Figure 2 shows the model coil illustrated by TOSCA. The coil geometry is described by specifying the location and shape of about 1500 "BR20" blocks.

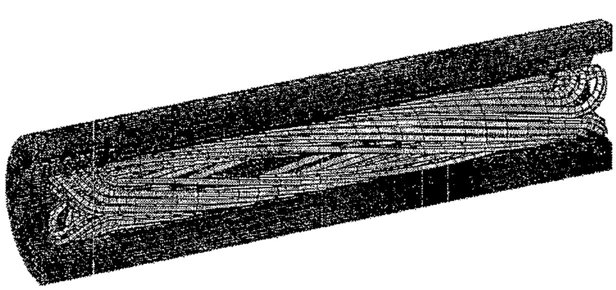

Fig. 2. The model magnet input to the TOSCA

V MEASUREMENT OF THE MODEL MAGNET

Measurements were performed on the model magnet in February and June of 1997 in a vertical dewer at BNL. The results of these measurements are compared here with the 3D calculations from TOSCA.

A. Quench Test

The operating current in the "low-current" slots is expected to be 280 A for 4.0 T. The model magnet quenched at 388 A, and the field strength at the center of the magnet reached 5.0 T. Using TOSCA, peak field strengths in the body and the end regions were estimated. The peaks in the body, which are found at the inner edge of the coils nearest to the poles, are slightly higher than the peaks of the ends which are found at the inside most edge of the curved coils. According to 3D analysis, the coil is expected to quench at 395 A corresponding to a dipole field strength of 5.3 T near the beam axis. This estimate of quench current is based on results from short sample tests of the cable. The comparison is summarized in TABLE II.

TABLE II
QUENCH PERFORMANCE

	Experiment	Calculation
Max. current at high field slots (A)	388	395
Max. current at low field slots (A)	474	483
Max. field at the center of the model (T)	5.0	5.3

The experiment was performed with the magnet at 4.35 K.

B. Field Distribution

To measure field distribution in the model magnet, Hall probes attached to a cylinder were used as shown in Fig. 3. Rotating coils are normally used to measure magnets for synchrotrons. However, this method only measures the average field over the length of the coil. On the other hand, Hall generators usually have a small sensing area, a few mm^2, and can measure local magnetic fields.

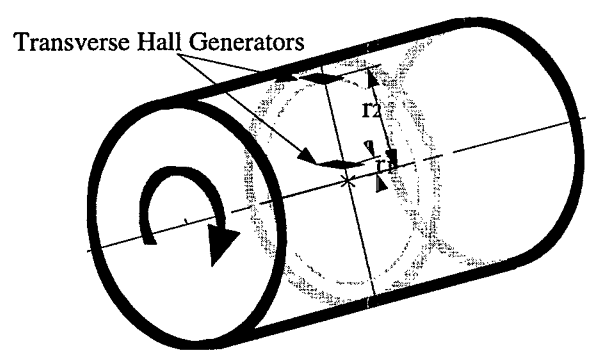

Fig. 3. Hall probe system for measuring the filed distribution

The head shown in Fig 3 was attached to a long aluminum shaft and rotated by a stepping motor. The field was sampled at 64 points per revolution. This number is sufficient to estimate the sextupole and the decapole components. This head was also moved axially by another stepping motor to measure the field distribution along the beam axis. The transverse Hall generator closer to the axis was used for "bucking". We assumed the following expression[5,6] for the field measured by the transverse Hall generators:

$$B_r = B_0 \sum_{n=0}^{\infty} \frac{f_n}{k(n+1)} I'_{n+1}((n+1)kr) \times [a_n \cos((n+1)\theta) + b_n \sin((n+1)\theta)] \quad (1)$$

$$f_n = \frac{2^{n+1}(n+1)!}{(n+1)^{n+1}} \frac{1}{r_0^n k^n} \quad (2)$$

Here, I'_{n+1}, r_0 and k are the derivative of the modified Bessel function, the reference radius of the multipole coefficient, and 2π divided by the length of helical-pitch respectively. r is the distance from the beam axis, and corresponds to r_1 and r_2 in Fig. 3.

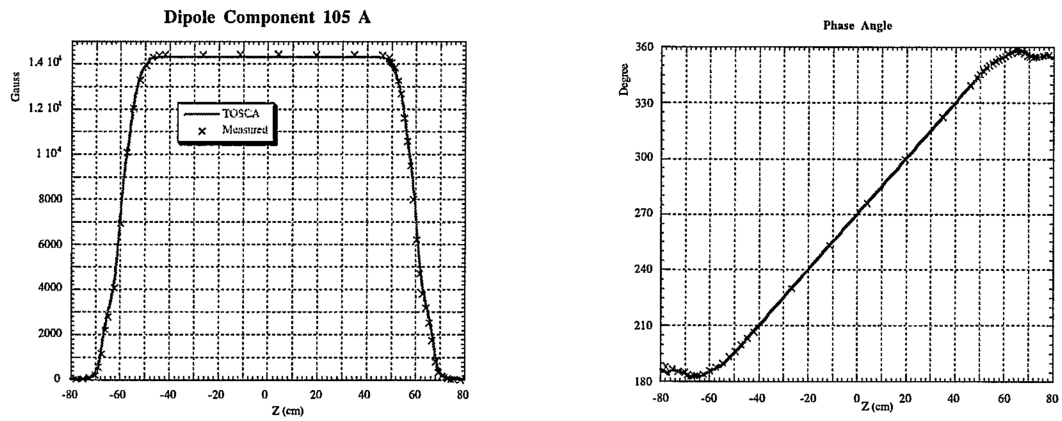

Fig. 4. Dipole component at 105A/Cable

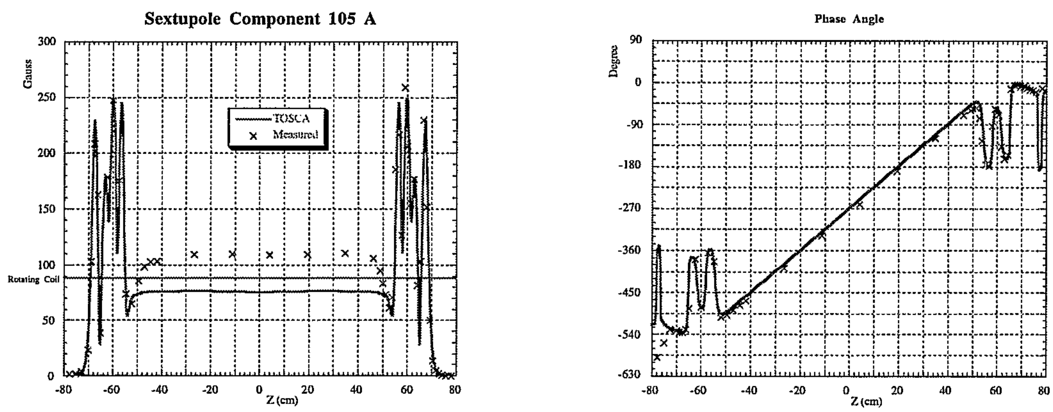

Fig. 5. Sextupole component at 105A/Cable

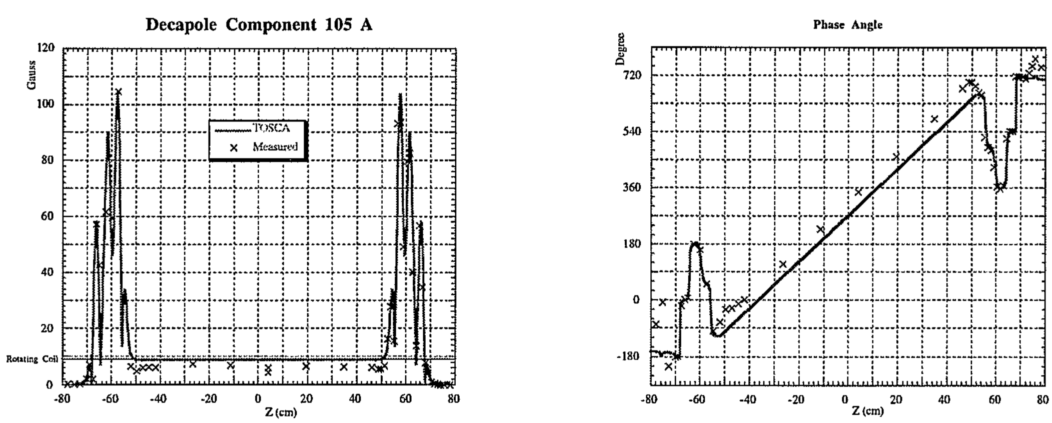

Fig. 6. Decapole component at 105A/Cable

The dipole component was obtained from the outer Hall probe alone. To obtain other multipole components, the values obtained by subtracting the inner generator data from the outer data were analyzed. This subtraction can eliminate noise due to imperfections in rotational motion. The reference radius of the multipole components was set to 31 mm.

The model magnet was excited using the same current for all the cables instead of the 9 to 11 ratio. Comparisons of measurements with calculations for the dipole, sextupole and decapole, are shown in Figs. 4 to 6. In the dipole case, agreement in both the field strength and the phase angle are very good. In the sextupole and the decapole cases, agreement in the end regions, where there are relatively strong multipole fields, is excellent. However, some discrepancies in the body section are observed. It is possible that some spurious multipole components may be observed due to the planar Hall effect. In these figures, the results from the tangential rotating coil measurement are also indicated.

C. Field Uniformity

To specify the field quality at the center of the model magnet, we used a tangential rotating coil which has been used for other RHIC magnets. The length and opening angle of this rotating coil are 230 mm and 15 degrees respectively. In the case of the helical dipole magnets, there is some reduction in signal due to rotation of the field over the length of the measuring coil. For example, the sensitivity of the rotating coil for the decapole component of this helical magnet decreases to about 67 % of the sensitivity for a normal straight magnet. The measured harmonics were corrected for this reduction in sensitivity.

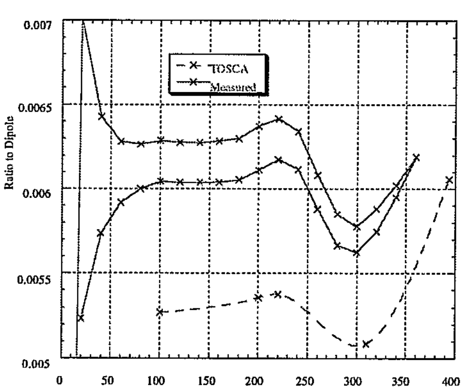

Fig. 7. Current dependence of the sextupole component at the center of the magnet

The measured data and the prediction from TOSCA are shown in Figs. 7 and 8. The calculated ratios of the sextupole and decapole components to the dipole component are smaller than the measured values by about 1×10^{-3} and 2×10^{-4} respectively. The current dependence of the sextupole component (due to iron saturation) agrees with 3D calculation. In this measurement, again, a uniform operating current was used for all current blocks, and the multipole components are larger than the design values which assume the use of two currents.

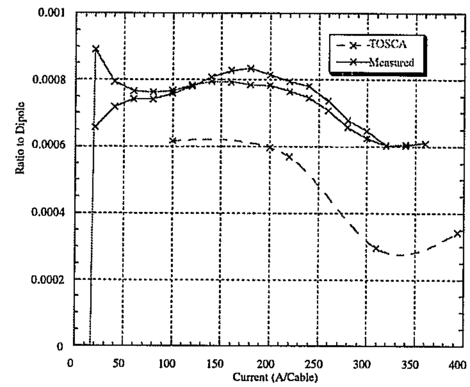

Fig. 8. Current dependence of the decapole component at the center of the magnet

VI CONCLUSION

The fabricated model magnet showed good performance. The measured results of the model tests agree quite well with the 3D calculations except for small discrepancies in the field uniformity. Thus, we can rely on the field calculations and have validated the mechanical design and fabrication method. Acording to the 3D calculations, the integrated transverse field in the full length helical dipole magnets can be optimized, considering the effect of the iron yoke saturation, to within ±0.0032 T.m, which is well within the requirements from beam optics considerations. At present, we are in the process of finalizing the design of the helical dipole magnets for RHIC.

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