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Construction Details and Test Results from RHIC Sextupoles*

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***Abstract*—Four 8 cm aperture sextupoles have been built at BNL to verify the magnetic performance of this magnet in the RHIC installation. Two significantly different mechanical configurations have been designed, and two magnets of each design have been built, and successfully tested, and have exceeded the required minimum quench current by a substantial margin. This report describes the assembly details of the second configuration, which is the final production configuration. In addition the first industry built production sextupole has been delivered and tested. This report presents the results of quench tests on all 5 magnets and field measurements on the first production sextupole.**

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) will be a colliding beam facility with design energy of 100 X 100 GeV/u for ions as heavy as Au. The two accelerator/storage rings are divided into "regular arcs" and intersection regions. A set of 288 sextupole elements are necessary to reduce the natural chromaticity ($\chi \sim -42$) and correct sextupole field imperfections in the dipole magnets. These are positioned at every quadrupole in the regular arcs, and have a design strength of 550 Tesla/meter with an inner bore of 80 mm and length of 750 mm. These superconducting magnets are constructed with the same overall diameter as the arc quadrupoles, and are assembled in one cryogenic cold mass with the arc quadrupoles and correctors.

II. DESIGN

Table 1 lists the basic parameters of these sextupoles. The basic machine requirement is for sextupoles with 80 mm bore and design strength of 550 T/m (bi-polar). The power leads are brought out of the cryostat for each individual unit. Hence, to minimise the cryogenic load the excitation current must be kept small – this forces a wire (as opposed to cable) coil with many turns. The overall length is also specified by the machine lattice. The aperture and the outer physical diameter are chosen to match the other arc components.

Table 1: Parameters of RHIC ARC SEXTUPOLES

Parameter	Value
Wire Diameter	0.50 mm
Copper to SuperConductor	3:1
Ic(2.0 Tesla)	230 A
Turns per layer	20
Layers per coil	10
Number of turns per pole	200
Coils per magnet	6
Clear Bore	80 mm
Length	750 mm
Design Current	100 Amp
Design Integral Strength	554 Tesla/meter
Quench Current	195 Amp
Quench Integral Strength	780 Tesla/meter
Integral Strength for Dipole b2 swing	140 Tesla/meter
Integral Strength for Chromaticity	160 Tesla/meter
Inductance at 0 Amp	815 mH
Inductance at 100 Amp	530 mH
Number for RHIC	288

A. Magnetic Design

For maximum simplicity, a layer wound racetrack coil was chosen. This fits over the shaped iron pole tip. At low field, the pole tip dominates the field, reducing the sensitivity to coil location errors. Because of mechanical limitations, the actual pole tip is narrower than optimum. This results in very noticeable saturation. The neck of the pole tip (see Fig. 1) saturates at about 50 Amps. It also produces a noticeable $\cos 9\theta$ term (within accelerator tolerances). For mechanical compatibility, the yoke is much larger than it needs to be to provide an adequate return path. The iron pole tip in these magnets combined with the magnetisation currents in the superconductors produce hysteresis and residual fields. However, though bipolar in general, individual sextupoles usually will have fixed polarity in the accelerator.

B. Mechanical Design

For the RHIC arc magnets, the philosophy is to use as much as possible of the dipole technology for the rest of the components. Hence, the sextupole yoke differs only in detail from that of the dipole. The 8 cm sextupole is constructed as a modular subassembly, joined at final assembly with the quadrupole and corrector units.

1) Magnet Design: The magnets are built in two yoke halves(Fig. 1, which are almost identical in detail. In order to obtain the desired sextupole field, the magnet halves each contain three superconducting wire-wound coils. These coils are connected to provide the magnetic polarity required for the magnet.

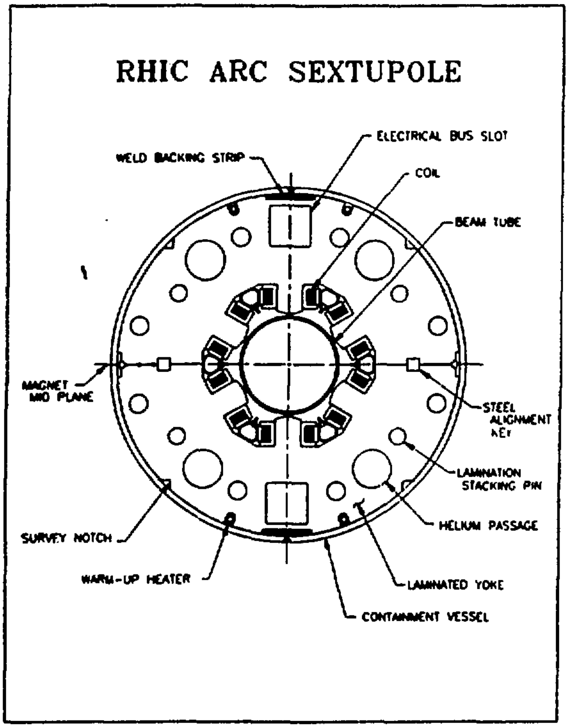

Figure 1: Cross section of RHIC arc sextupole.

2) Iron Mass: The iron mass of the yoke half is divided into modules, made up of stacks of sheet steel laminations 1.6 mm thick. These stacks are carefully controlled to keep the iron quantities (weights) uniform, for consistent performance, and are held together by means of low carbon steel pins, staked at the ends. The laminations contain all the necessary contours and details to provide for pole pieces, coil seats, helium by-pass holes, assembly holes and reference flats for assembly and survey. A number of these modules are placed on accurately machined rails for assembly. End modules, which have no pole pieces but are otherwise identical in shape to the middle modules, are placed at the ends of the yoke half stack. Tooling rods and plates are employed to keep the entire yoke half stack together for subsequent assembly operations. To this point, the upper and lower yoke halves are identical.

3) Coils: The wire is wrapped with Kapton insulation and then fiberglass tape. The coils are layer wound on machined epoxy fiberglass (G-10CR or G-11CR) coil forms, carefully controlled to prevent wire crossovers. Each layer of wire is covered with a layer of fiberglass tape, which is impregnated with liquid epoxy immediately before installation, to provide a stable base for the next layer of wire. Ten such layers are built-up, for a total of 200 turns of wire per coil. Coil closure is effected by means of flat strips of epoxy fiberglass inserted into the coil wire space and compressed to form the wires and fiberglass tapes into a dense mass. To this point, all the coils are identical as to winding direction, number of turns and size. After the epoxy has hardened, the wires are brought out to a terminal board where the connections determine whether the coil is an "A" or "B" coil, "A" and "B" designating coil polarity. The coils are then individually tested for resistance, and inductance. The ends of these coils are unsupported, the Lorentz forces are hoop stress in nature, and the quench performance of the coil is determined by the center section.

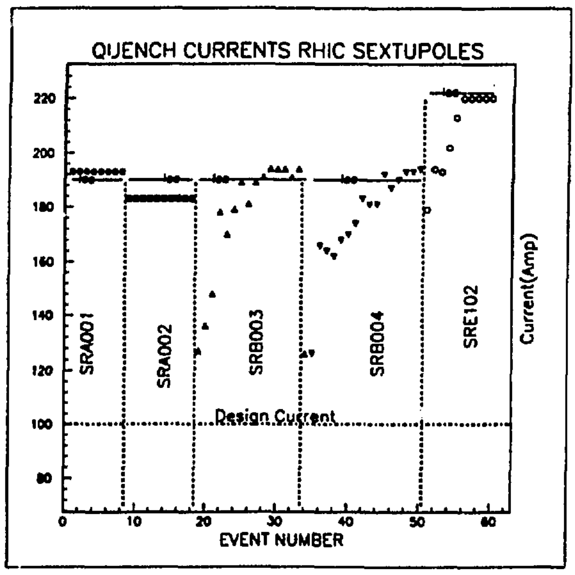

Figure 2: Quench currents for RHIC sextupoles. Design current allows 50% margin above normal operation. Note the suppressed zero.

4) Yoke Half Assembly: The yoke half stacks are placed on assembly rails, and coils are installed on the pole pieces. Depending on whether the half stack is "upper" or "lower", the coil complement is 2 "A" coils and 1 "B" coil for the upper, and 1 "A" coil and 2 "B"

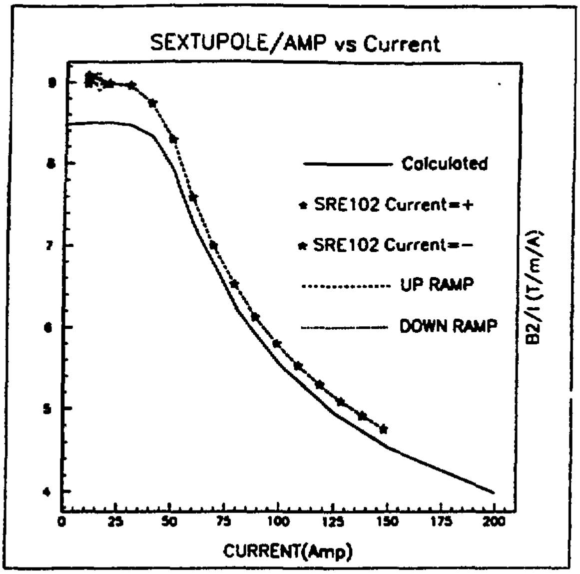

Figure 3: Calculated and measured integral sextupole strength. Note the small hysteresis.

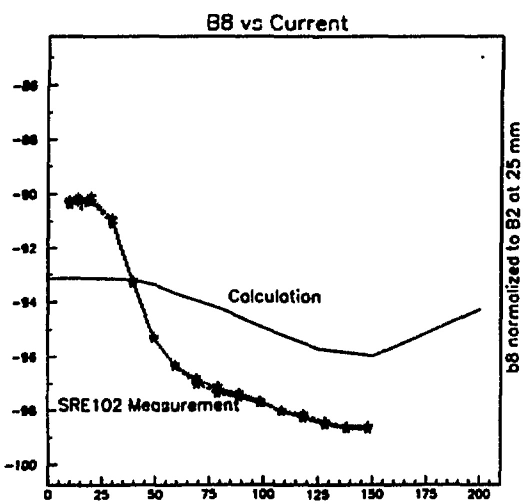

Figure 4: Comparison of measured and calculated first (b8) allowed harmonic. The calculation is for the center of the magnet, the measurement includes the effects of the ends.

coils for the lower half. End fillers are installed at this point to keep the coils from shifting axially. These fillers are machined epoxy fiberglass, and are cemented in place with an epoxy containing an inorganic filler.

Due to the flexibility of the long sides of the wound coil, the coil is restrained with an elastic member that resists the Lorentz forces generated during operation of the magnet. At quench these forces are 80 kN/m at 45° from radial. After some developmental studies, the restraint that evolved was a simple spring shape that slides into place in an axial direction, and is retained by a carefully shaped wedge which is held in place by having the apex angle below the angle of repose. The wedge needs only to be pushed into place by a ball-ended tool, and remains there until forced out by deliberate action. The spring, which develops some 35 kN/m to resist the Lorentz force, is fabricated from beryllium copper, then heat treated. The wedge is precision extruded aluminum alloy. This retainer design allows the replacement of any sextupole coil without complete disassembly of the magnet.

Since both yoke halves are assembled with the mid-plane open, it is necessary to invert the upper half for assembly. The tooling provided to support the upper half module assemblies incorporates stub shafts to allow the upper half to be lifted off the assembly rails, rotated about its longitudinal axis, and then lowered into place on the lower half. After alignment, the two halves are joined by small fillet welds, spring coil retainers that bridge the mid-plane are installed, and end plates are welded into place. Installation of a fiberglass terminal board, and wiring of the coils, are all that remain for completion of the sextupole magnet assembly.

III. Quench Results

The results of quench testing are summarized in Fig. 2. In this figure I_{ss} denotes the calculated limiting current based on the measured wire short sample Ic_2. Numerous(~ 100) quenchs on the plateaux have been omitted for clarity. SRA001 and SRA002 were built with the earlier restraint system and the coils were either built in house or re-worked in house, they have excellent quench behavior. SRB003 and SRB004 were built as pre-production prototypes. In these magnets, the outer surface of the coil was not compressed during cure: the looseness is reflected in the rather extensive training. Note that the lowest quench is still 125% of design. SRE102 is the first sextupole made wholly by industry (Everson Electric). Its first quench at 180% of design is outstanding.

IV. Magnetic Field Results

The five sextupoles have been measured with rotating coils both at room temperature and at 4.2 K, with good agreement between the two measurements. Only the data for SRE102 is presented (the fields for the earlier magnets are similar).

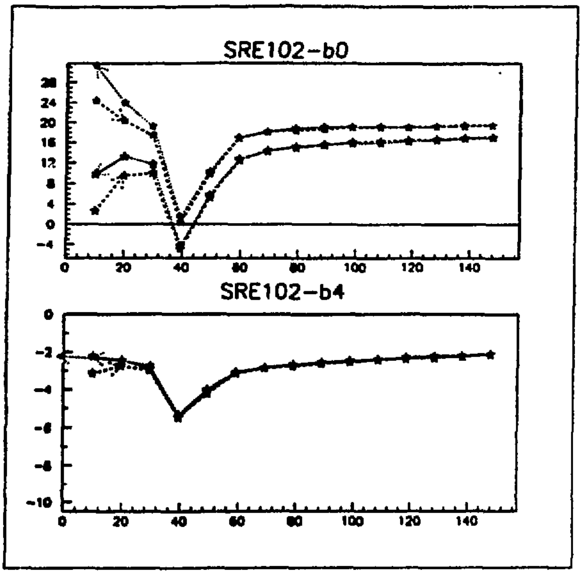

Figure 5: Dipole and Decapole components. The origin of the sharp dip at 40 Amps is unexplained.

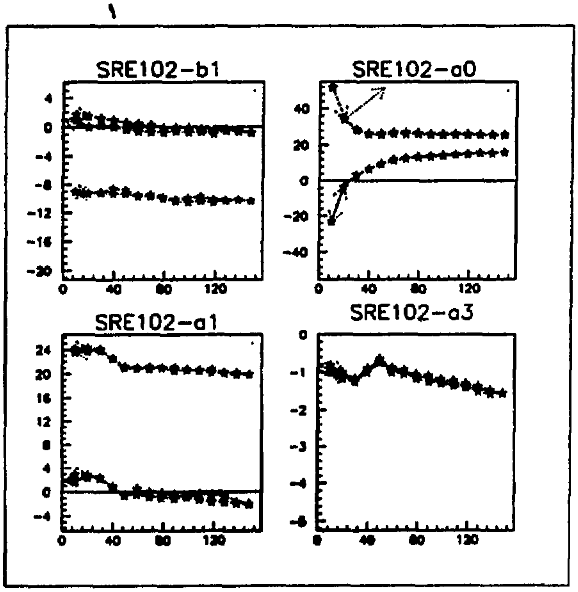

Figure 6: Interesting non-allowed Harmonics. Note the absence of any dip at 40 Amps.

1) Sextupole Term: The transfer function is plotted in Fig. 3. In this and subsequent figures, the data are integral(ie. integrated with a measuring coil significantly longer than the magnet). The units of sextupole are thus T/m. The calculations are only done for the straight section, hence it is to be expected that the measured fundamental is a few percent larger. The strong saturation arises from the "neck" of the pole tip which is narrower than optimum. The measurements cover both up and down sweeps and negative and positive currents. The residual fields are barely apparent at 10 Amps.

2)b8-First Allowed Harmonic: Another result of the narrow pole tip is the large B8 term even at low field. The iron saturation is apparent. The difference between calculation and measurement is due to the ends which have a large positive b8.

3)Other Harmonics: The most interesting forbidden harmonics are bo and b4 shown in Fig. 5. In these figures, the open symbols are the data for positive current, and the dashed lines are for the up ramps. The dipole(bo) term is unexpectedly large. There is no understood source for this. The sharp dip at 40 Amps was seen in SRB003 and SRB004. It is not understood. A dip also appears in the decapole (b4) data at the same current. These interesting effects are well within the accelerator tolerances.

Fig. 6 shows additional non-sero harmonics. These are all forbidden by symmetry. The tails at low currents in the a0 data are either residual fields or superconductor magnetisation. In either case they imply an up-down asymmetry.

V. CONCLUSIONS

A successful design for 550 T/m sextupole has been developed. The 288 of these magnets needed for the accelerator are now in routine production. The first production magnet reached 180% of design right "out of the box". Some of the harmonics are not yet explained but they are well within accelerator tolerances

APPENDIX

The field on the midplane of a sextupole can be expressed as:

$$B_y = B2\ b_n' \times 10^{-4}(x/Rref)^n$$

(the cos(n+1)θ term)

$$B_x = -B2\ a_n' \times 10^{-4}(x/Rref)^n$$

(the sin(n+1)θ term)

B2 = Sextupole strength at Rref = 25 mm.

With this definition, the "primed units" represent the field deviation measured at a radius of 25 mm as parts in 10^4 of the Sextupole field at 25 mm.

NOTE: B2 = 1/2 B".

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