Exotic Magnets for Accelerators

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December 16, 2005

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Abstract—**Over the last few years, several novel magnet designs have been introduced to meet the requirements of new, high performance accelerators and beam lines. For example, the FAIR project at GSI requires superconducting magnets ramped at high rates (~ 4 T/s) in order to achieve the design intensity. Magnets for the RIA and FAIR projects and for the next generation of LHC interaction regions will need to withstand high doses of radiation. Helical magnets are required to maintain and control the polarization of high energy protons at RHIC. In other cases, novel magnets have been designed in response to limited budgets and space. For example, it is planned to use combined function superconducting magnets for the 50 GeV proton transport line at J-PARC to satisfy both budget and performance requirements. Novel coil winding methods have been developed for short, large aperture magnets such as those used in the insertion region upgrade at BEPC. This paper will highlight the novel features of these exotic magnets.**

Index Terms—**Accelerator magnets, combined function magnets, HTS magnets, superconducting magnets.**

I. INTRODUCTION

IN selecting the magnets to include in this paper, the focus was on those which have an "exotic" feature, are superconducting, and have test results available. Beam line magnets have also been included. Resistive magnets are reviewed elsewhere [1].

II. SUPERFERRIC, HTS QUAD FOR RIA

The Rare Isotope Facility (RIA) has been proposed as the next new large accelerator facility to be built for the nuclear physics community in the United States [2]. Protons and heavy ions will be accelerated in a superconducting linac. The protons will be accelerated to 900 MeV. The linac power will be at least 100 kW. Isotopes produced when the accelerator beam strikes a target are collected in a set of magnets called the fragment separator. The first magnet in the fragment separator is a large-aperture quadrupole. The present beam line design calls for a quad with 300 mm aperture, 10 T/m gradient, and 1 m length. The gradient is a factor of two higher than that of the resistive quads of the same aperture built for the Spallation Neutron Source, pointing to the use of superconductor. The RIA quadrupole

also sees high loads of heat and radiation. High Temperature Superconductor (HTS) is now available commercially, so an R&D program has been started to investigate their use in the difficult operating environment of RIA. The R&D program for the magnet is being carried out at Brookhaven National Lab (BNL) [3]. Investigation of the radiation resistance of HTS is being carried out at Michigan State University. This magnet is exotic because it uses HTS.

The RIA beam heating load on a typical superconducting magnet with cold iron would be about 15 kW. To reduce the load on the cryogenics plant, a superferric, warm iron design was chosen. The use of a superferric design allows the coils to be placed at a larger radius, an advantage since the amount of radiation decreases significantly as the radius increases.

The ends of the quadrupole coils which face the target receive particularly large amounts of radiation. It was realized that a quadrupole field could be generated by two coils (as opposed to the usual four) and that two coils in cryostats would have less material to maintain at cryogenic temperatures than four coils in cryostats. (The total number of turns, of course, would be the same, but the amount of cold support structure would be less.) The use of a two-coil design also simplifies construction. The magnetic fields in the end region can be made acceptable for a beam line. Fig. 1 is an end view of the quadrupole. With a tungsten shield placed between the target and the quadrupole, the estimated heat load due to radiation is reduced to 130 W. The planned operating temperature is 30 K.

Fig. 1. End view of the RIA HTS quadrupole, with the coil (placed around the lowest pole) and the cryostat (around the highest pole).

BSCCO 2223 tape, nominally 4.2 mm wide and 0.31 mm thick, was purchased from American Superconductor in

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lengths of 220 m. The HTS had good piece-to-piece uniformity. HTS is brittle, so the coils must be wound in a two-dimensional pattern, such as a racetrack. The minimum bend radius of the coils was 50.8 mm. The coils were cowound with stainless steel tape, slightly wider than the HTS tape and 37 μm thick. In RIA, the quadrupole will be set to a constant current, so current will not flow between turns during operation. The use of stainless steel also allows a more compact coil to be wound without applying tension directly to the HTS tape. After winding, each racetrack coil was painted with epoxy, to make handling convenient. Coils were connected into "double pancake" pairs by splicing their innermost turns together.

With RIA R&D funding limited, it was decided to build a magnetic mirror quad, 0.3 m long. The mirror quadrupole has three double pancakes (i.e., six coils), ¼ the number needed for a full quad. The pole tip field and Lorentz forces are similar to those in a full quad. The completed mirror quad is shown in Fig. 2. The operating current is 125 A.

Fig. 2. Photo of the mirror quadrupole showing the fixture for the coils, the pole tip, and the mirror yoke.

The "short sample limit" was defined as 0.1 μV/cm, a value consistent with a reasonable load on the cryogenics system. At 4.5 K, the mirror quad carried 260A (Fig. 3), the current expected from tests of individual coils in self-field, without training. At 30 K, it carried 165 A, so that $I_{op} = 0.75\ I_c$. At 44 K, $I_c = I_{op}$, giving a thermal margin of 14 K.

III. SERPENTINE QUADRUPOLES FOR THE ILC IR

Serpentine magnets are made by winding continuously around a cylinder, an exotic and useful feature [4]. (Solenoids are excluded). The concept arose as a result of an effort to increase the field strength in regions with tight radial and axial constraints, such as insertion regions. The harmonics of the two ends of serpentine coils nearly cancel, allowing for a quick interplay between magnet and IR design, since optimization of a two-dimensional design is much faster than optimizing a three-dimensional design.

Fig. 4 shows a simple serpentine dipole. Coil winding begins on the lower layer, with the pole near 60º. It continues, wrapping around the support tube, finishing at the pole near

330º. The coil pattern of the upper layer is the same as that of the lower layer, but rotated 90°. Winding continues with the upper layer, finishing with the pole turn near 40°. Winding in this fashion (as opposed to winding each pole of each layer separately) gives excellent registration of all the poles, a key ingredient of field quality. G10 pieces are used to fill the pole regions. Coil construction is completed by bringing the lead of the lower layer up to the radius of the upper layer and then out to the end of the coil. In this way, no extra radial space is devoted to bringing out leads from pole regions. Because the two layers are wound in opposite directions, the longitudinal components of the field cancel. Also, the simple design of the coil ends speeds up production.
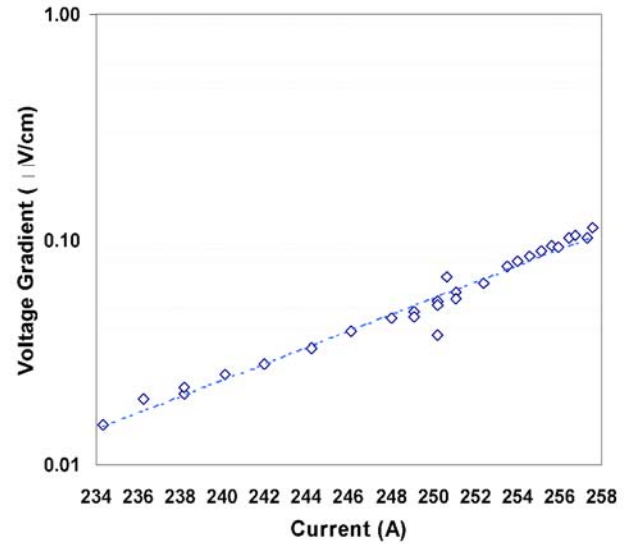

Fig. 3. Resistance versus current in the RIA HTS mirror quadrupole, illustrating the gradual onset of resistance.

Fig. 4. Serpentine dipole coil. The coils cannot be drawn in two dimensions without lifting a pencil.

A design using serpentine coils has been developed for the quadrupoles nearest the beam crossing in the 20 mrad IR of the International Linear Collider (ILC) [5]. The design (Fig. 5) calls for a quadrupole (QD0) with G = 144 T/m, r_{inner} = 10 mm, and length ~ 2m. The quadrupole is wound with six layers of 1 mm-diameter, seven-strand Nb-Ti cable. Dipole, skew dipole, and skew quad correction layers are wound over the quadrupole using 0.33 mm-diameter strand. The magnet will operate in 1.9 K He II and in a 3 T background solenoid field. Serpentine coils will also be used for the IR quadrupoles (QEX) first seen by the extracted beam.

A short (0.38 m) model quadrupole (QT) with the same cross section as QD0 has been made (Fig. 6) and tested. Quench testing was carried out in a vertical dewar that also had a solenoid. Quench testing was carried out at helium temperatures between 4.3 K and 3.0 K, and in background solenoid fields between 0 T and 6 T. In a 3 T background field and at 4.3 K, QT reached 158 T/m, 13% above the operating gradient, with only two training quenches. The performance was almost as good in background fields of 4 T, 5 T, and 6 T. These results extrapolate to I_q of 1100 A at 3 T background field and 1.9 K. The operating current, 664 A, is 60% of I_q.
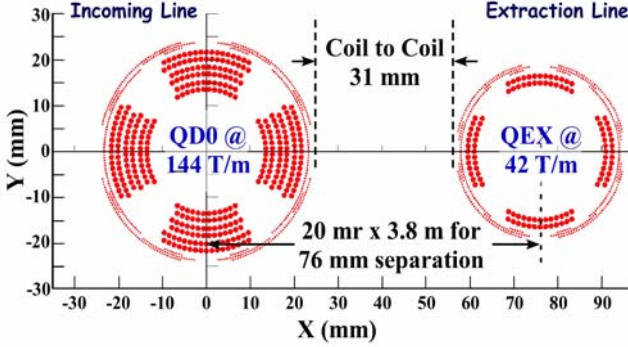

Fig. 5. Cross section of ILC final focus quads for the incoming and extracted beams 3.8 m from the crossing point in the 20 mrad IR.

Fig. 6. Photo of the 0.38 m set of coils, designated QT, made with the same cross section as the ILC QD0 quads for the ILC.

Integral field quality measurements were made at room temperature. Seven of the eight low-order harmonics (normal and skew, n = 3, 4, 5, 6, and 10) were less than 0.5 x 10^{-4} of the main field. (The reference radius was 5 mm, and n=3 denotes the sextupole.) The skew octupole was 1.5 x 10^{-4}.

The ILC requires vertical control of the beams at the nanometer level, an unprecedented challenge. Measurement of the vibration of an available magnet in a cryostat, warm and cold, is just getting underway. Another obvious challenge is controlling the beam power, 10 MW.

IV. COMBINED FUNCTION MAGNET FOR J-PARC

The KEK magnet group is building combined function magnets to transport the 50 GeV high-intensity proton beam at J-PARC to a target station that is the first stage of a neutrino beam. The magnets, which generate dipole with a small amount of quadrupole, are the result of a bold decision forced by the need to significantly cut the cost of the magnets in the beam line. A standard, separated-function, beam line, using dipole and quadrupoles, would have had two magnet types instead of one and approximately twice as many magnets.

The orientation of the J-PARC facility was largely determined by the modest size of the site. Given the site orientation relative to the existing Super Kamiokande neutrino experiment, only superconducting magnets could generate the field needed to bend 50 GeV protons on a radius of 105 m.

In order to further reduce costs, the KEK team incorporated into the design of the combined function magnet several components that it was familiar with from other projects. These included Nb-Ti cable with the same specifications as the cable used in the outer coil of the LHC arc dipole, combining the functions of collar and yoke into a single piece as was done at RHIC, and using a phenolic spacer instead of kapton as ground plane insulation, also as at RHIC.

The resulting design (Fig. 7) is for a magnet with 2.6 T dipole field and 19 T/m quadrupole field. The magnets are 3.3 m long, have a peak field of 4.7 T, and an operating current of 7345 A. The coil inner diameter is 173 mm. The aperture was primarily set by beam loss considerations. In the J-PARC ring, the beam emittance is 80π mm mrad. The magnets were sized for an acceptance of 200π mm mrad, to provide a margin against quenching during off-normal beam conditions. A part of the aperture takes account of the beam sagitta of about 20 mm in these straight magnets. The design field quality is at the level typical for beam lines, dB/B ~ 10^{-3}. The beam line will contain 28 magnets.
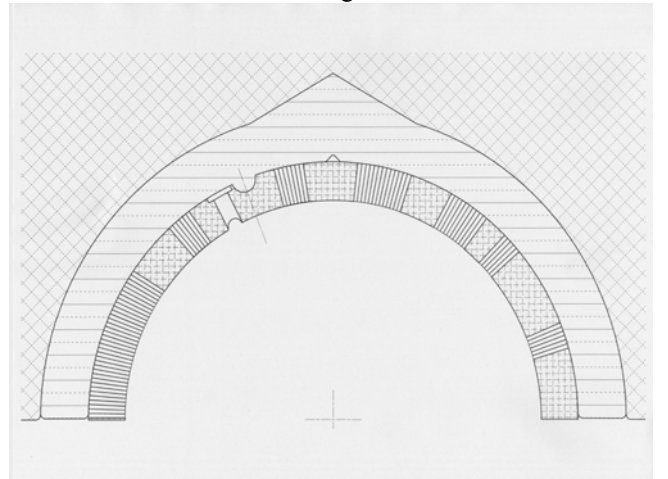

Fig. 7. Cross section of the coil and phenolic spacer of the J-PARC combined function magnet.

The desired field shape is achieved by a very asymmetric distribution of turns (Fig. 7). The coil is locked to the phenolic spacer by the half-round key on the inner surface of

the spacer. The spacer also isolates the coil from ground. The spacer, in turn, is locked to the yoke by the triangular key on the outer surface of the spacer. The two sides of the coil have somewhat different Young's moduli, so it is not possible to have zero net azimuthal force on the two keys during assembly and operation. To partly compensate for the lower Young's modulus of the right side of the coil, it is molded to be 0.2 mm larger than the left side. This was calculated to produce the minimum value of local shear stress, 40 MPa. Good control of the coil size was essential, since a coil size imbalance of 0.1 mm will produce a 10 MPa change in stress.

Fig. 8 shows a cross section of the cold mass. The yoke laminations are thick (~ 6 mm), making it possible to lock in the preload achieved during assembly with keys. The cold mass outer diameter, 570 mm, was chosen to be the same as that of the LHC arc dipole magnets, so that the cryostat design could begin with the LHC cryostat.
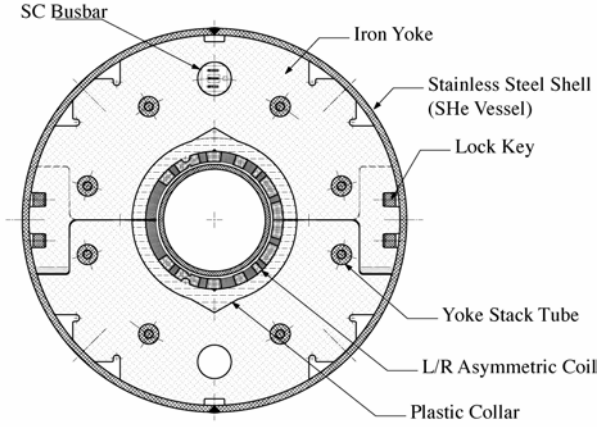

Fig. 8. Cross section of the cold mass of the combined function magnet.
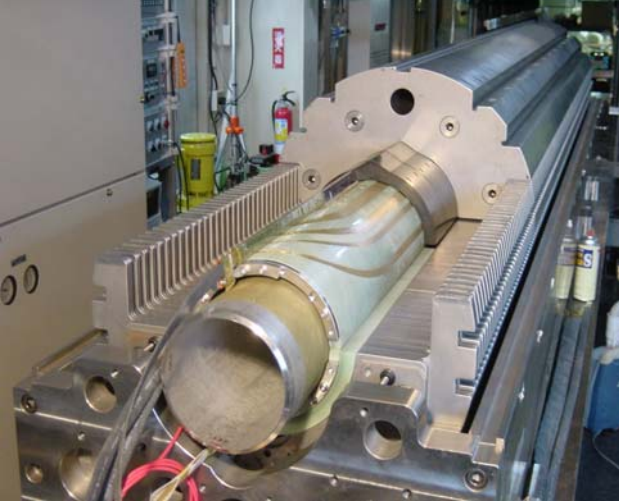

Fig. 9. Photo of the second prototype J-PARC combined function magnet.

Fig. 9 shows a photo of the first prototype magnet. Two full-length prototypes have been made and tested, with good results. Both magnets reached 7700 A, about 5% above I_{op}, without a training quench. The strengths of the dipole and quadrupole fields were in agreement with calculation at both 40 GeV (the initial proton energy at J-PARC) and 50 GeV. Field harmonics were reported with respect to the dipole field, at a reference radius of 50 mm. The coil ends generate a large normal sextupole, 0.25% of the integral dipole field. Other harmonics are smaller. All are in general agreement with calculations, and the field quality met specifications. Several reports of test results have been made [7], [8].

V. CRYOGENIC HELICAL DIPOLE FOR THE AGS

Helical dipoles were built to control the spin of polarized protons in RHIC [9]. They are used for two purposes. "Snakes" rotate the spins of the protons in order to reduce the sensitivity of the beam polarization to spin resonances that occur during acceleration and storage. Rotators flip the vertical spins of the protons so that experiments can study collisions between beams with polarization along the beam direction. In both cases, the helical dipoles are designed so that the net effect on the beam orbit (both position and angle) is zero, an exotic specification. This year, a superconducting helical dipole Snake was also installed in the Alternating Gradient Synchroton (AGS) at BNL [10].

Helical magnets have the exotic property that the design value of their integral field transverse to the magnet axis is zero (Fig. 10). The Snake installed this year has the additional exotic property that the dipole field angle rotates ~ 520° between the two ends of the magnet, as does the field angle of the resistive Snake previously installed in the AGS [11]. (The RHIC helical dipoles rotate the field angle 360°.)

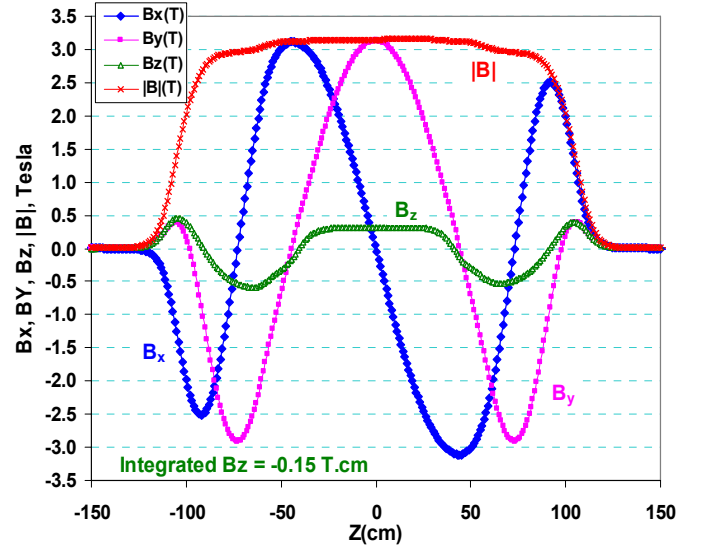Fig. 10. Calculated values of |B|, B_x B_y, and B_z versus z for the AGS cryogenic helical snake magnet.

The construction of the superconducting AGS Snake is based on the construction methods used for the RHIC helical dipoles. The Nb-Ti conductor is a round cable of seven strands, six strands wrapped around the center strand. The strand diameter is 0.33 mm, and the cable diameter is ~ 1 mm.

The insulated cable in wound into rectangular slots milled into thick-walled aluminum cylinders, typically with 12 turns per layer and 9 layers per block. Space limits in the AGS led to the novel suggestion that the magnet be built with different pitch lengths in the center and ends. The central portion of the magnet has a pitch of 0.20°/mm of length. The two end portions have a pitch of 0.39°/mm. The axial position at which the transition was made was set after numerous iterations that brought together the accelerator physics simulation and the magnetic and mechanical models of the magnet. Fig. 11 shows one of the coils.
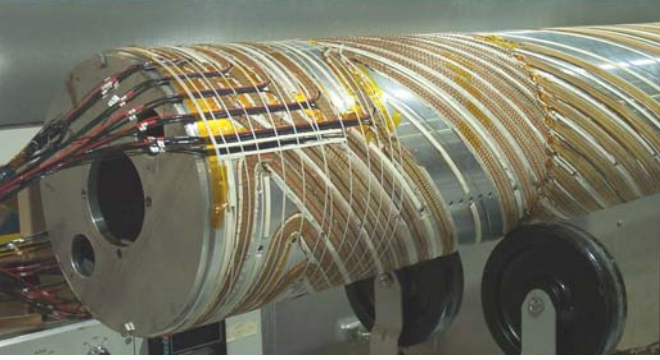

Fig. 11. Photo of the inner coil of the AGS superconducting helical magnet.

Conductor blocks in two close-fitting aluminum cylinders generate a dipole field of 3 T at 350A. At 3 T, the magnet rotates the proton spins 60° over its effective length of 1940 mm at injection energy (γ=2.5). The radius of the innermost conductor is 100 mm. Antisolenoid and short dipole [12] correctors have been wound on the beam tube of the magnet.
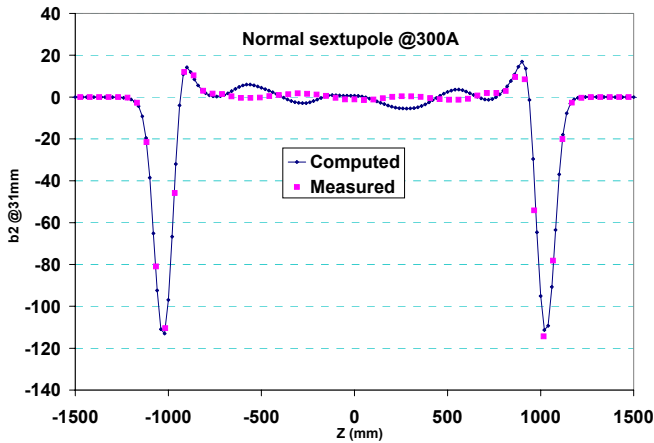

Fig. 12. Calculated and measured values of the sextupole as a function of axial position in the AGS superconducting helical dipole.

Magnetic field measurements were made with both integral and short rotating coils. The calculated and measured values of the dipole and sextupole as a function of axial position agreed well. Results for the sextupole are shown in Fig. 12. The integral of the two-dimensional dipole field was less than 0.01 T•m, within the tolerance. The magnet was operated in the AGS during a several-week period of beam studies this

past spring. Prior to its installation, depolarizing resonances during the AGS acceleration cycle reduced the polarization from ~ 70% at injection to <50% at extraction. Based on beam studies, it is anticipated that the superconducting AGS Snake should be able to maintain the 70% polarization during the full acceleration cycle.

VI. FAST-RAMPED MAGNETS FOR FAIR

The Facility for Antiproton and Ion Research (FAIR) at GSI (Darmstadt) will have two rings of fast-ramped magnets in a single tunnel: SIS100 and SIS300. SIS100 will be built with 2T superferric dipoles, and SIS300 will be built with 6T conductor-dominated cosθ dipoles. For a recent summary and overview of this work, see [13], [14].

A. SIS100

The basis for SIS100 magnets is the Nuclotron, which has been in operation in Dubna since 1993. The Nuclotron dipoles (Fig. 13) easily meet the SIS100 ramp-rate requirements: dB/dt = 4 T/s to 2 T, with a period close to 1 Hz. The key feature that enables the fast ramp rate is the conductor, a cable-around-conduit with helium flowing inside the conduit (Fig. 13 inset). The SIS100 dipole length is 2.6 m. The aperture of the oval beam tube is 55 mm vertical and 110 mm horizontal.
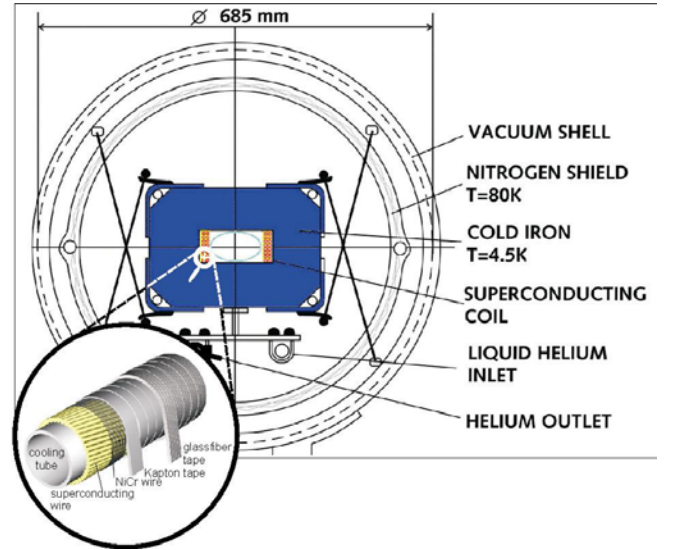

Fig. 13. Cross section of the Nuclotron dipole. The inset shows the cable-around-conduit conductor.

The exotic feature of the SIS100 magnets is the requirement that the magnets have a lifetime of 2×10^8 cycles, to allow operation for 20 years. The lifetime of the Cu-Ni conduit is predicted to be at least 1×10^9 cycles. The coil of the Nuclotron dipole was not designed for long lifetimes, and has been redesigned for SIS100. An extensive fatigue calculation of the 2D cross section of the SIS100 coil indicates that it will sustain at least 10^8 full loading cycles [15].

Other changes to the Nuclotron design have been made to

meet SIS100 operating needs. Cryogenic losses were reduced and good agreement between the calculated and measured energy loss was reached. A key element of this was calculation and measurement of the fields at the end of the yoke, and changes to the yoke to reduce them. The saturation of the DC harmonics has been reduced by careful redesign of the yoke ("negative shim"). Also, measurements of the sum of the sextupole and decapole have shown no difference between DC and fast-ramp conditions. For recent reports of this work, see [16] and [17]. For related papers see [18] and [19].

B. SIS300

Work toward a 6 T dipole began as a program with 4 T magnets, for a lower-energy machine. The goal was to redesign the RHIC dipoles (which ramp to 3.45 T at 0.07 T/s) to ramp to 4 T at 1 T/s, an exotic requirement. To accomplish this, several changes were made to the Nb-Ti Rutherford cable: the twist of the strand was increased, the strand was coated with Sn-Ag solder, and a stainless steel foil was placed between the layers of the cable. Also, about 25% of the Kapton turn-to-turn insulation on the inner edge of the cable was opened to helium. Other magnet components were changed to reduce energy loss. For example, the thickness of the yoke laminations was reduced from 6.35 mm to 0.51 mm, and the material changed to Si steel. A cross section of the 1 m model that was built and tested is shown in Fig. 14.
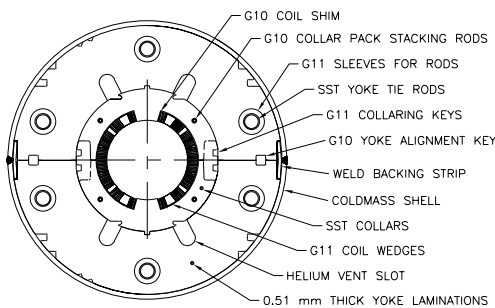

Fig. 14. Cross section of the 1 m model built to test concepts for fast ramps of coil-dominated, Rutherford cable magnets at FAIR.

The model magnet can be ramped to 4 T at rates as high as 4 T/s. The energy loss in the coil and in the yoke, as a function of maximum field and ramp rate, is understood. (The test program includes measurements of the collared coil without the yoke.) Measurement of the sextupole and decapole at 1 T/s shows that of the effect of eddy currents is small [20]. The results of the calculations for and tests of the 4T magnet, plus other R&D underway (e.g., reduction of the Nb-Ti filament diameter) are being used in the design of the 6T dipoles. Two recent papers describe SIS300 R&D work [21], [22].

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