Status of Superconducting Magnet Development (SSC, RHIC, LHC)*

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Abstract

This paper summarizes recent superconducting accelerator magnet construction and test activities at the Superconducting Super Collider Laboratory (SSC), the Large Hardon Collider at CERN (LHC), and the Relativistic Heavy Ion Collider at Brookhaven (RHIC). Future plans are also presented.

I. INTRODUCTION

This paper reviews the status of the superconducting magnet programs for the RHIC, SSC, and LHC accelerator projects. Most of the focus is on dipole magnets, because of their cost and technical difficulty. Critical technical issues include the quench performance, geometric field quality, and time variation of the fields. Conductor development for these magnets was reviewed last year[1].

The dipoles in these programs embody the same concepts: NbTi superconducting strand in a Rutherford-style partially-keystoned cable, cos θ winding with wedges designed for minimum values of the allowed harmonics, cold iron yoke which helps support the coil against motion, aperture in the range 50 - 80 mm, and length in the range 10 - 15 m. RHIC, with the lowest field requirement, uses only a single layer coil. LHC, with the highest field requirement, will operate at 1.8 K.

II. SUPERCONDUCTING SUPER COLLIDER

A. Collider Dipoles

ASST Dipoles. Following a difficult but ultimately successful R&D program with 40 mm-aperture, 17 m-long dipoles[2], the aperture was increased to 50 mm. The current lattice has 7964 dipoles of 15 m length and 496 of 13 m length. At 4.35 K, the quench current is typically 7.4 kA (6.7 kA corresponds to 6.7 T central field and 20 TeV).

The task of the R&D program for the 50 mm aperture dipole was to provide magnets built by staff from industry for an Accelerator Systems String Test (ASST) with a half cell of magnets (five dipoles, one quadrupole, one spool piece). At Fermilab, ASST magnets were built by staff from General Dymanics Space Systems (GDSS). At Brookhaven (BNL), ASST magnets were made by Westinghouse Electric Corp. (WEC). A cross section of the Fermilab/GDSS cold mass is shown in Fig. 1; the BNL design is slightly different. The ASST was operated successfully last summer[3].

The quench performance of both Fermilab/GDSS and BNL/WEC magnets at 4.35 K and 3.85 K was excellent [4]. Measurements of the azimuthal and axial force during cooldown and excitation indicated that the effects of the Lorentz forces were generally as expected[5].

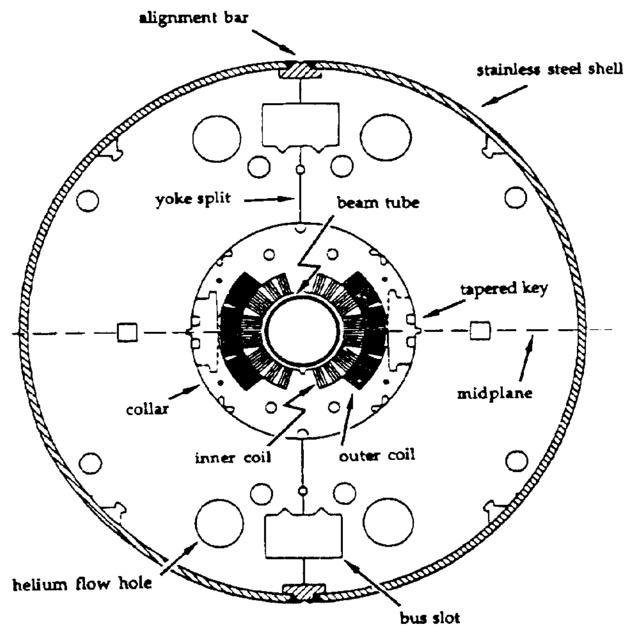

Figure 1. Cross section of SSC Collider dipole cold mass.

The part of the magnetic field that is determined by conductor placement and the saturation properties of iron was well understood in terms of calculations, measurements, and the sizes of the magnet components, within the limitations imposed by low statistics[6,7]. There was good correlation between the "cold" measurements and those at room temperature.

At injection, the expected harmonics due to magnetization were in agreement with calculations for the 6 μm-diameter NbTi filaments[8]. Also at injection, the magnetic field was measured for an hour, the length of time needed for filling both rings of the collider. The drift of the sextupole was within tolerance. The drift of the skew quadrupole needs to be controlled through the basic mechanism underlying this effect, which is not yet

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understood.

Magnet quench performance was studied as a function of ramp rate up to 300 A/sec. Harmonics were measured up to 64 A/sec. For the Collider ramp, 4 A/sec, some magnets had acceptable eddy current effects but some did not. All magnets exhibited significant eddy current effects at the High Energy Booster (HEB) ramp rate, 62 A/sec. The effects were strongly correlated with cable vendor. The most obvious source of such effects, for both quench currents and harmonics, is eddy currents, which in turn are a function of the interstrand resistance R_I of the cable. Studies of the factors which determine R_I are being carried out as part of the HEB dipole R&D.

Recent Activity [9]: At Fermilab, four 15 m R&D dipoles were made by Fermilab staff after the completion of the ASST work. One of these magnets was tested at 1.8 K, where it reached a quench current of 9990A (9.5 T) with little training.

Much of the testing at BNL the past year has focussed on eddy current measurements. Good quench localization information has been provided by a "quench antenna" system, similar to the one first used at the LHC. The ramp rate-induced quenches were found to be located in turns near the midplane, where eddy current effects are largest.

Harmonic measurements were made at the axial location of the eddy current quenches. Current distributions calculated from these harmonics were largest near the midplane. Thus, the recent tests reinforced the conclusion that the ramp rate effects are due to eddy currents in the cable and can be limited by controlling R_I.

Future Activity: As the "leader", GDSS has completed a magnet design taking into account the ASST results and SSC requirements. The first 15 m practice coils magnet have been wound and cured at the GDSS plant. Completion of this magnet is expected in August.

Two 15 m dipoles made at the SSC Magnet Development Lab are scheduled to be tested at BNL this summer. The SSC Magnet Test Facility will be commissioned late in the summer.

B. Collider Quadrupole

Collider quadrupoles will have a central gradient 220 T/m at 6.7 kA, with a 5.2 m magnetic length. Six full-length quadrupoles with 40 mm aperture have been made at Lawrence Berkeley Lab (LBL) by staff from LBL and a Babcock & Wilcox - Siemens collaboration (BW). Initial quenching was in the range 6.6 - 7.2 kA [10]. Typically the magnets trained to about 8 kA and then retrained from 7 kA after thermal cycling. Harmonics were better than the specifications [9]. Correlation between warm and cold harmonics was found at the level of 0.5 units.

The BW quadrupole collared coils are manufactured in Germany and the rest of the magnet in the U.S. Three 1 m models have been quench-tested thus far. The initial quenches in each were at currents near 7.5 kA, with the magnets reaching the conductor limit near 8.4 kA in a few quenches. Retraining after a thermal cycle began about 8.2 kA. Ramp rates up to 200 A/sec have had negligible effect on the quench currents. Full-length magnets are due this fall.

C. High Energy Booster (HEB) Dipoles

To take advantage of previous R&D, the design requirements are as close as possible to those of the Collider dipoles. The HEB dipoles will have a much larger sagitta than the Collider dipoles. Also, there are two important operational differences: 62 A/sec ramp rate and bipolar operation. Tests at BNL this year confirmed that the magnet quench performance was unaffected by the current polarity, as expected.

The R&D contract for developing the HEB dipole is held by WEC. Based on information from the ASST magnets and other experience, WEC is making magnets with cable of different interstrand resistances (untreated cable, oxide-coated cable, and a third, undesignated, choice that could be alternate untreated and oxide-coated strands). Tests of short models have begun and will run through the end of the year. Production of the first prototype is planned for a year from now.

D. Other Superconducting Magnets

The HEB quadrupoles will operate on the same bus as the HEB dipoles and have design central gradient 190 T/m, length 1.23m, and aperture 50 mm. The industrial design is being developed at Saclay. The first test is expected next year.

Two 1 m models of the insertion quadrupoles have been made and quench tested at the SSC. They trained from an initial quench current of about 7.3 kA to the conductor limit, about 8.4 kA, in a few quenches.

III. LARGE HARDON COLLIDER

A. Dipole Design Parameters

To make the most effective use of the existing 27 km LEP tunnel at CERN, magnet R&D has been directed toward reaching the highest possible field level. The target range has been 8 T to 10 T. The options include NbTi operated at 1.8 K and Nb_3Sn at 4.35K. At present, NbTi is forseen for the magnets, although work continues with Nb_3Sn high-field models. Space limitations in the tunnel cross section point toward a single cryostat and cold mass, but with two apertures [11] so that the flux passing through one aperture is returned through the other (Fig. 2). With 1300 twin aperture dipoles, each 13.5 m long, a 9.5 T central field yields a beam energy of 7.7 TeV. More detailed information on the lattice and magnets can be found in recent reviews [12,13,14].

Initially, cables for a two-layer magnet capable of 10 T operation were designed. The subsequent R&D program has explored several options for the remainder of the magnet design, as follows: The collars supporting the coils could encompass both coils in a single stamping or just a single coil. The collars could be aluminum or nonmagnetic stainless steel. The support of the collars by the yoke could be acomplished at room temperture or during cooldown by yokes of several different geometries. For the most part, this work has been carried out by contract with different companies.

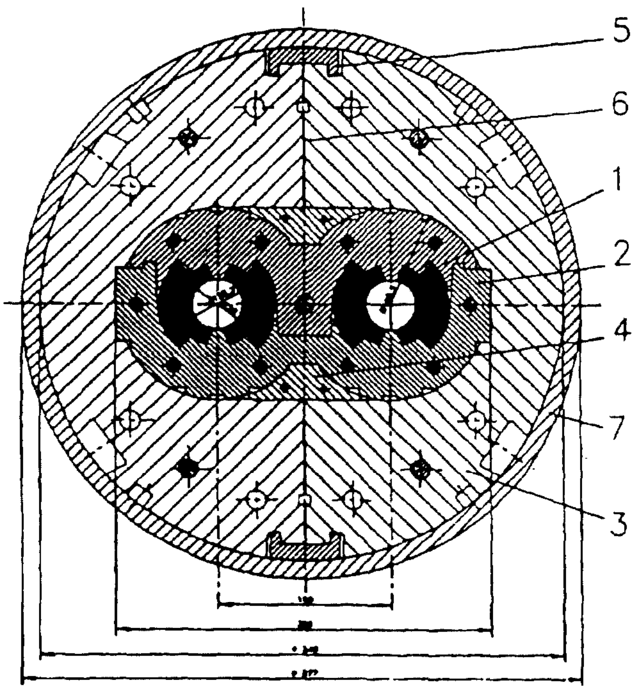

Figure 2. Cross section of LHC twin aperture dipole cold mass, type MTA1. 1. Coils, 2. Collars, 3. Yoke, 4. Iron insert, 5. Clamp, 6. Gap, 7. Outer shrinking cylinder.

B. Dipole R&D Results

Short, single aperture models: Initially, two models with 50 mm aperture were made with HERA-diameter NbTi strand, for speed. At 1.8 K they trained quickly to 9.3 T, the conductor limit. A model with Nb_3Sn strand was also successfully tested.

A KEK model with fully-keystoned cable and other novel features trained well at 4.35 K but did not reach the conductor limit at 1.8 K.

Short, twin aperture models: Using LHC-design cables, four 50 mm aperture models (designated MTA1) have been made by different firms. For each magnet, choices were made among some of the construction features (soldered, partially soldered, and unsoldered cable; common and separate collars; etc.), but all used the same design for the yoke. The quench results of the magnets were quite similar. At 4.35 K they reached 7.9 T within a few quenches. However, at 1.8 K, they trained slowly above 9 T. One reached the conductor limit, 10.02 T, after about 55 quenches [15]. The magnets retrained after a thermal cycle.

It was concluded that the training was due to a common feature of the magnets. To localize the quenches, the CERN group devised a clever analysis for the field disturbance which occurs during a quench. It was detected by small coils in the bore of the magnet [13]. The analysis was confirmed by voltage tap data from the KEK single aperture magnet [16].

It was found that most of the quenches originated in the ends of the inner layer turns close to the pole, where cable winding is most difficult. Some of the quenches originated in the magnet straight section, also near the pole.

Given the need for rapid turnaround and detailed investigation, a magnet R&D facility was started at CERN about a year and a half ago. Recently, new coils of the MTA1 design were made in industry and assembled at CERN in a three-part yoke. At 4.2 K, this magnet reached the limit of the conductor, 8.1 T, after one quench. At 2 K, the magnet had its first quench above 9 T and subsequently trained to a record central field of 10.5 T. After thermal cycle to room temperature the first quench was at 9.74 T [17].

In twin aperture magnets, the normal quadrupole is an allowed harmonic because left-right symmetry is not preserved in the yoke design. In one magnet, measurements at fixed currents were made to 10 T. The value of the normal quadrupole varied from low to high field in agreement with calculation. The normal sextupole was similarly well behaved. Measurements of the relative dipole angle between the two apertures await completion of the horizontal test facility.

A twin aperture version of the KEK design has been recently tested at 4.35 K [18]. The magnet has separately-collared coils basically similar to the one in the single aperture model. It reached 8.12 T central field after six training quenches. The magnet will be tested in superfluid at CERN.

10m, twin aperture model: HERA-type coils were used to construct a twin-aperture prototype (TAP) to gain operational experience with full scale two-aperture magnets. The magnet was tested at CEN, Saclay. At 4.5 K it reached the limit of the conductor, 5.8 T, on the first quench. At 1.8 K, it reached the conductor limit of 8.3 T after five quenches.

C. Future Dipole Program

50 mm aperture: Ten 10 m long twin aperture dipoles have been ordered from four vendors. The magnets will be highly instrumented and four will eventually be assembled into a half cell test. Five of the magnets will have the MTA1 design. One will have the three-part-yoke design recently tested, with additional variants for the other four. The initial magnet is due for delivery soon; the others will follow at two-month intervals.

To explore further the Nb_3Sn route, a 11.5 T twin aperture model is being built in the Netherlands by a FOM-UT-NIKHEF-CERN collaboration.

56 mm aperture: Accelerator studies made following the increase of the design beam intensity indicated the need for a larger physical aperture, so the LHC aperture

has been increased from 50 mm to 56 mm. As a bonus, this also improves field quality. Tooling in the CERN magnet facility is being built for this aperture. A short twin aperture model is being built there by a Finnish-Swedish-CERN collaboration for an operating field of 9.5 T. After a first version with NbTi, this magnet will be equipped with ternary alloy, NbTiTa, coils.

Reduced field option: Last fall, a decision was made to design a magnet using cable of the dimensions developed for the SSC. The SSC strands and cables are significantly smaller than those used for the 10 T LHC design (e.g., 0.81 mm vs. 1.29 mm for the inner layer strand). By applying the experience in the construction of the 40 mm and 50 mm SSC magnets to a 56 mm aperture, the effort at CERN could be concentrated on design issues unique to twin aperture magnets. A short twin aperture model built with cable supplied by the SSC is underway. Its operating field is 8.6 T. The high-field version magnet and the SSC-cable magnet will be completed about the end of the year. Details of this program are given by G. Brianti [17].

D. Other LHC Magnets

The arc quadrupoles have been designed and built by a CEA, Saclay team in collaboration with CERN. They will be powered in series with the dipoles and have an operating gradient of 250 T/m. Two twin aperture, 3 m prototypes, with 56 mm aperture, are due to be completed in mid-'93. One will be tested at the end of the month.

Prototypes of the correctors have been tested in the UK at Rutherford Lab. Prototypes of tuning magnets are underway in Spain, with testing expected soon.

IV. RELATIVISTIC HEAVY ION COLLIDER (RHIC)

RHIC magnets stand exactly at the threshold of mass production. Contracts for the 80 mm aperture arc magnets -- about 270 dipoles, quadrupoles, and sextupoles -- have been let, with the first magnets due this year. Production of the arc correctors and the 130 mm aperture insertion quadrupoles at Brookhaven is scheduled to start within the month.

The production cable run of 567 km of 30-strand cable for the arc dipoles and quadrupoles is well underway at Oxford Superconducting Technology (OST) and is due to be completed by the end of the year. The production of 83 km of 36-strand cable for the insertion magnets has begun at OST and Furukawa and will be completed next spring.

A full cell (two dipoles, quadrupoles, sextupoles, correctors) using production designs is scheduled for operation this fall.

A. Arc Dipoles

The 9.7 m-long dipoles generate a central field of 3.45 T with a current of 5 kA in the single-layer coil, for 100 GeV/u nuclei (Fig. 3). A total of twelve full-length R&D magnets have been made, with the last two scheduled for test in the next month. These two magnets were used for technology transfer to Grumman Aircraft Corporation (GAC).

None of the 9.7 m magnets has quenched below 3.85 T. Ramp rate effects have been insignificant up to twice the design of 83 A/sec. This insensitivity has been confirmed for the production cable in a short model. With cable production underway, the emphasis is on minimal change.

The time drift of the harmonics is much less of an issue with RHIC than SSC because the filling time is only 1 minute instead of 1 hour. Measurements made on this time scale confirm that drifts are negligible. As a further precaution against magnets with different drift times, the cable will have no cold welds.

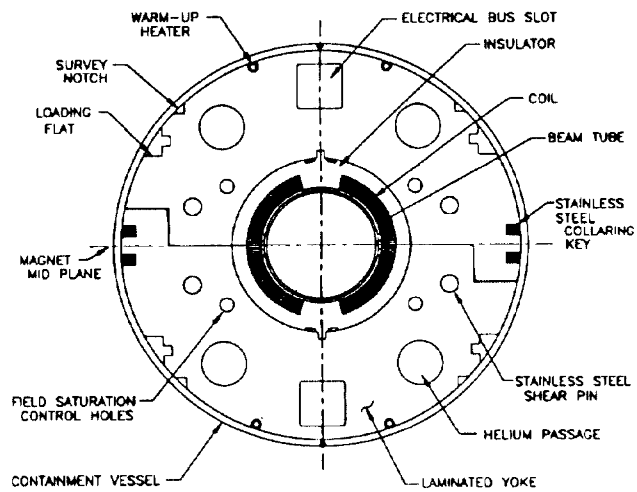

Figure 3. Cross section of RHIC dipole cold mass.

B. Arc Quadrupole/Sextupole/Correctors (QSC).

In each half cell, the quadrupole, sextupole, and corrector are assembled into a single cold mass with 80 mm aperture. The arc quadrupoles have a central gradient of 71 T/m at their operating current of 5 kA and a 1.1 m effective length. A series of eight magnets made at BNL is nearly complete. Systematic harmonics have been identified and reduced to acceptable levels. Production will be at GAC.

The arc sextupoles have an integral field of 550 T/m at $\pm$100A, with 0.75 m effective length. Four R&D magnets, built at BNL, have been used to debug the design. Everson Electric Corporation is scheduled to delived the first of the production models in July.

Four coaxial layers 0.6 m long make up the arc corrector package, providing decapole, octupole, quadrupole, and dipole harmonics. Four R&D models of these have been made using an industral process for making circuit boards ("Multiwire"). Tooling now set up at BNL will be used for the production run.

C. Insertion Quadrupoles

The lattice calls for three lengths (1.44, 2.1, 3.4 m) of insertion quadrupoles, but all with the same cross section for economy of tooling. The central gradient is 48 T/m at 5 kA. Two 1.44 models have been successfully tested. The production run of each length is 26 magnets.

V. GENERAL VIEW OF TRAINING

An interesesting parameterization of the quench performance of "well-built" magnets in terms of conductor properties was developed last year [19]. The parameterization quantifies the ability of the copper in the superconducting strands to carry the current during a local heat pulse in terms of an "instability factor", α, which is proportional to the square of the current density in the copper. Well-built magnets fall on or near a straight line in a log-log plot of α versus the number of training quenches. For example, the improved quench performance of the most recent MTA1 LHC model at 4.35 K falls on this line.

Thus far, rather few magnets have been tested in superfluid. The 10 T LBL model [15] falls near the line. The LHC TAP dipole and the SSC 50 mm magnet fall directly on the line. The LHC MTA1 magnets lie above the line, possibly indicating that the limitations in 1.8 K quench performance lie in magnet construction rather than in the superfluid helium. It will be interesting to see how well the parameterization stands up when the LHC dipoles made with SSC cable are tested at 1.8 K.

VI. ACKNOWLEDGEMENTS

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