Particle Accelerators, 1990, Vol. 28, pp. 207–212
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DESIGN FEATURES OF THE SSC DIPOLE MAGNET

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Abstract The main ring dipole for the SSC is specified as a high performance magnet that is required to provide a uniform, 6.6 T field in a 4 cm aperture at minimum cost. These design requirements have been addressed in an R&D program in which the coil design, coil mechanical support, yoke and shell structure, trim coil and beam tube design, and a variety of new instrumentation, have been developed. The design of the magnet resulting from this intensive R&D program, including various measurements from both 1.8 m and 17 m long models, is reviewed.

INTRODUCTION

This paper describes the principle design features of the dipole magnet that has been developed for the Superconducting Super Collider (SSC). The magnet is a collaborative effort between the SSC Laboratory, Brookhaven National Laboratory, Lawrence Berkeley Laboratory and Fermi National Accelerator Laboratory.[1] The design is based on a high field (6.6 T) over a small aperture (40 mm coil ID) and long (16.6 m) effective length. Numerous short and long models have been constructed and tested with results that meet performance expectations in all respects. The short models have been used to develop features that are part of the current design of the magnet; test results from these models have been reported elsewhere.[2] Figure 1 shows a cross section of the collared coil and Fig. 2, a cross section of the cold mass.

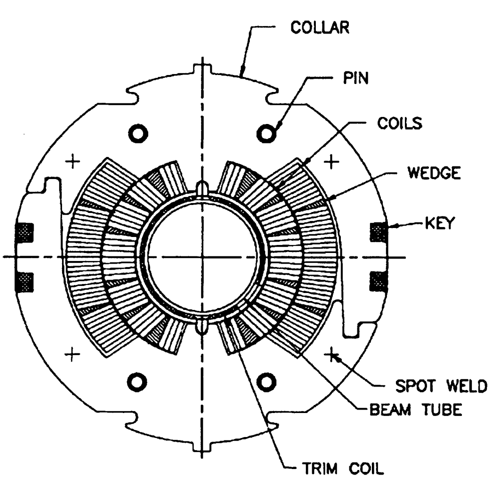

Figure 1 A cross section of the collared coil assembly.

COIL DESIGN AND CONSTRUCTION

The coil design[3], known as C358D, includes three copper wedges in the inner coil and one copper wedge in the outer coil. Both coils are wound from a partially keystoned, high homogeneity NbTi cable of the Rutherford type. The wedges compensate for the partial keystone angle of the cable and furnish additional and required degrees of freedom in the

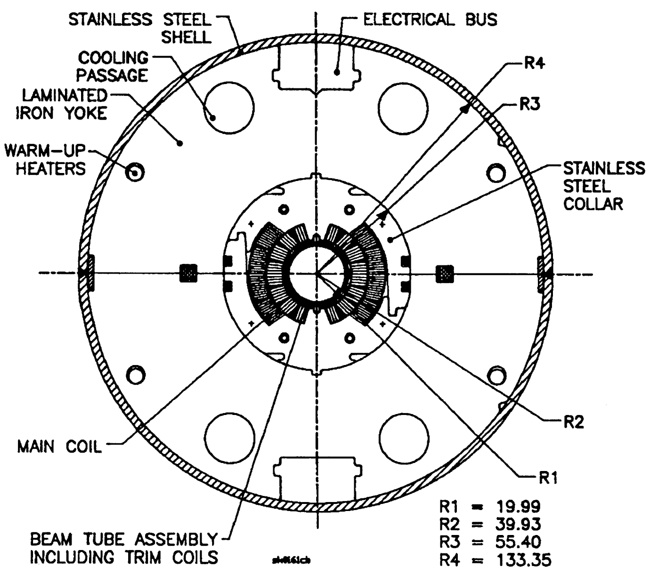

Figure 2 A cross section of the cold mass assembly.

field shaping optimization procedure. To ensure cost-effective superconductor utilization, the inner coil (16 turns) is wound from a 23-strand (wire size 0.0318") cable of Cu:SC ratio 1.3:1 and the outer layer (20 turns) from a 30-strand (wire size 0.0255") cable of ratio 1.8:1. The filament size is 6μm. The cable thickness is controlled at the specified value with a variation of less than 6.25μ. Cable insulation consists of a double layer of 25μ Kapton followed by a layer of epoxy-impregnated (23%) fiberglass. The coil ends maintain the same radial dimensions as in the straight section and are wound in a constant-perimeter configuration. Spacers between groups of turns in the ends shape the field for low multipole content and, between individual turns, protect against electrical shorts. Fiberglass cloth, knife-coated with mineral-filled epoxy, is used on the radial surfaces of the ends to add strength and to give a constant radial thickness throughout. Coils are cured under pressure (~7 kpsi) and temperature (~140 C) in a precision mold to give a rigid structure that can be easily handled and that has precise dimensions. The variation in azimuthal dimension of the coils is less than ±50μ peak-to-peak and less than 35μ RMS. These rigorous tolerances are required to ensure a constant collaring stress as well as acceptable multipole variation.

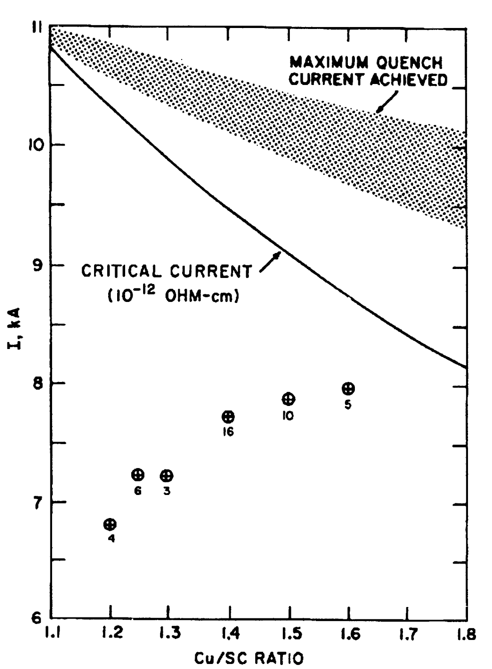

Figure 3 Average cable current for the first quench in a standard fixture as a function of Cu:SC ratio. The number of cable samples is given below the data points.

The coil design is such that the inner layer will quench first with increasing current. The specified current density for the wire of the inner coil is 2750 A/mm^2 at

4.35 K and 5 T. Allowing 10% current degradation in cable manufacture, the C358D design central field is expected to reach 6.86 T before quench. Thus, there is a 4% field margin in the design of the magnet (with 5% cable degradation, the quench field would be 6.96 T, a 5.5% field margin). In practice, short model magnets have generally reached fields a little higher than expected from short sample measurements on the cable, indicating that the superconductor can, under some conditions, operate somewhat into the resistive region before quenching. Many of the model magnets built to date have utilized the higher Cu:SC ratio of 1.5:1 for the inner cable because of concerns about magnet stability with the specified 1.3:1 value. Short sample measurements of cable under standard conditions simulating those in the magnet have shown that more stable performance and less training is obtained in material with more copper. These data[4], taken in BNL's short-sample test facility over several years, are summarized in Fig. 3. The plot shows that quenches for higher Cu:SC ratio material are closer to the critical current on the first quench and have a significantly smaller separation between initial and maximum quench current.

COLLARS AND COIL PRESTRESS

The coils are compressed with 15 mm wide collars of fully austenitic, nonmagnetic stainless steel. The collars supply a compressive pressure of ~8 kpsi, sufficient to restrain coil motion under the action of the Lorentz force at high field. The collars are spot-welded in pairs for greater stiffness and, being asymmetric in shape, are alternated between left and right shapes as they are assembled into packs (15 cm long) in order to avoid the introduction of twist into the collared structure. Brass shims are applied to the collar packs at the poles to adjust for varying coil sizes in the R&D program. The compression of the collars is done in a hydraulic press in which, after sufficient vertical force is applied, a horizontal force pushes the full-hard phosphor bronze tapered keys (3° taper) into position. To reduce the required horizontal force and to reduce scoring of the keys, a film of lead-based lubricant is applied to the keys before installation. Upon release from the press, there is typically a loss of 2 kpsi in the inner coil stress from the maximum experienced during the keying operation. The diameter of the collared assembly typically grows by 0.25 mm vertically from the unstressed state; the horizontal diameter remains nearly unchanged.

In order to determine the azimuthal stress on the coils, not only during the collaring operation but also during cooldown and during excitation of the magnet, a strain gauge system has been developed[5] that is capable of giving accurate readings of the stress under these varying conditions. It consists of precision EDM-cut stainless steel bars that respond to force by bending as beams with supported ends and to which are attached strain gauges that measure the tensile longitudinal strain on the beam surface. These transducers are mounted in a special collar pack with one at the pole of each coil section for a total of eight transducers in one pack. An electronic system using an accurate current source and a high-precision integrating voltmeter is utilized for individual readout of each transducer, thereby avoiding the difficulties of bridge circuits frequently utilized for this purpose. Compensating gauges free of stress are included in each package to adjust for thermal and magnetic field effects. Figure 4 shows a measurement[6] of coil stress vs. current made with this strain effects. Figure 4 shows a measurement[6] of coil stress vs. current made with this strain gauge system. These data show the expected stress variation with the square of the current and the desired residual stress in the coils at high current.

The coils and collars are assembled around a copper-plated beam tube with multipole trim coils mounted on the surface[7]. Notches in the collars at top and bottom engage tabs mounted on the beam tube to provide precision alignment.

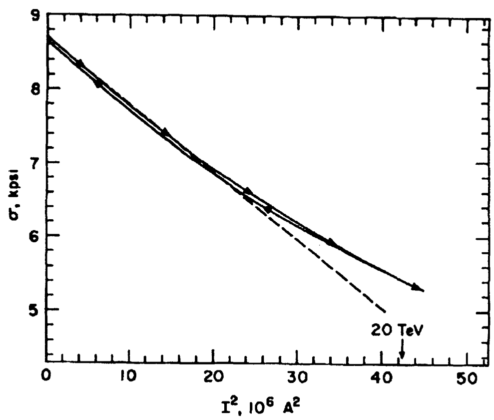

Figure 4 A measurement of coil stress vs. current in 17 m magnet DD0017. The data are the lines with arrows.

IRON YOKE

The yoke laminations (Fig. 2), punched from low-carbon steel of thickness 1-1/2 mm and assembled into blocks 15 cm long, are designed to support the collared coil around the circumference (future models will use steel of thickness 6 mm). This added restraint of the Lorentz force was not a feature of the original design of the SSC magnet. The collared coil is oriented inside the iron yoke with tabs at the top and bottom. The top/bottom yoke halves are aligned via keys on the horizontal midplane. The two large rectangular slots carry bus work for a magnet string and the four large round holes are passages to carry helium through the magnet system. Holes are provided in the yoke for heaters, required in the machine to warm-up a sector of magnets in the specified 24 hours. Upon assembly, the yoke midplane gap is no more than 0.05-0.075 mm; this gap is closed when the outer stainless steel shell that captures the yoke and provides the helium containment is welded in place. Flats are provided on the perimeter of some yoke laminations for alignment of the cold mass structure. Heavy end plates (3.8 cm thick) coupled to the shell prevent significant end motion under the axial Lorentz force. A strain gauge system monitors these forces.

The iron contributes ~1.7 T to the 6.6 T central field of the magnet. With the 15 mm separation of the coil from the yoke provided by the collars, saturation effects are quite small: the transfer function decreases by ~3% and the sextupole component changes by $<0.4 \times 10^{-4}$ (at 1 cm) due to iron saturation.

ELECTRICAL INSULATION

The high dielectric strength, polyimide film Kapton is used to insulate the coils of the magnet against turn-to-turn and turn-to-ground voltage breakdown. Such electrical failures can occur because of puncture through the film or by flashover around the edge of the film. Puncture-type failure may occur if the film contains manufacturing defects (pinholes) or damage. Failure due to pinholes is avoided by using multiple layers of material, thereby giving a low probability that pinholes will align to cause failure. The Kapton used to construct magnets is inspected to ensure less than 10 pinholes/m^2. Damage to Kapton is avoided by good construction practice although it can occur if local pressures are excessive. An R&D program is underway to identify filled Kapton material that is less susceptible to the plastic creep that can lead to pressure failures. Flashover is avoided by the design practice of maintaining creep paths of >5 mm from any conductor around film edges to ground. This allows coil testing ("hipotting") in air at the desired value of 5 kV while maintaining the specification of 1 kV/mm common in electrical design work.

Voltages in the magnet coils during quench can reach 1500 V with respect to ground and turn-to-turn voltages can reach 70 V, based on calculation. As standard practice for SSC magnets, ground insulation integrity is checked by hipot testing at twice the expected voltage plus 2000 V, or 5000 V total. This testing is done under normal room conditions. Because of the low breakdown potential of helium, leading to long creep paths, hipot testing in one atm helium cannot give meaningful tests of ground insulation integrity. Turn-to-turn insulation is checked by applying a 2000 V voltage pulse to each coil after collaring and looking for deviations from the expected ringing pattern of the pulse. This results in a per turn test of greater than 70 V but not quite the factor of two test that would be desirable; higher voltage is not used because of the desire to avoid excessive terminal voltage. Several of these tests are carried out repeatedly throughout the construction process to ensure the electrical integrity of the magnet.

MAGNET COOLING

A modification to the original cooling scheme for the magnets has been adopted which forces the specified 100 g/sec of supercritical helium (4 atm pressure) to circulate from the top passages in the iron yoke around the coil and beam tube to the bottom passages. This is accomplished by blocking the top and bottom passages at alternate ends of the magnet, thereby forcing the helium to pass through slotted, stainless steel laminations placed at regular intervals in the yoke, along the flats on the collar perimeter, then between collar packs to the annular space between the bore tube and the coil ID. The helium is forced to flow inward between collar packs by periodic blocks placed in the collar loading slots. The original cooling scheme depended on conduction of heat from the bore tube outward through the magnet components to the passages; only 1 gm/sec circulated in the annular space between beam tube and coil, serving primarily to transfer heat between the two but not in itself able to extract much heat. Heat is deposited inside the beam tube due to synchrotron radiation; at 20 Tev, this amounts to ~2 watts at the design luminosity but would reach higher levels for beam currents exceeding design. In addition, the warm finger required during testing to map the field deposits considerable heat in the bore tube. With the revised cooling scheme, 10 watts of heat deposited along the length of the magnet will result in a temperature rise in the magnet coil of only ~0.07 K; with the original cooling scheme, this temperature rise would be ~0.6 K. The pressure drop across the magnet remains suitably low at ~0.001 atm.

MAGNET PERFORMANCE

The quench history[6] of a recent 17 m dipole magnet, DD0017, is shown in Fig. 5. All quenches occurred in the pole turn of the inner coil (the expected location) and plateau above 6.6 T is reached after two training quenches. This magnet was built with cable of J_c = 2823 A/mm^2 (4.35 K, 5 T), somewhat higher than the SSC wire specification of 2750 A/mm^2. There was one quench below the operating current of 6.5 kA, and at reduced temperature (3.5 K), the magnet reached a current of 7.5 kA, indicating substantial margin in the mechanical structure against the large forces at this high current.

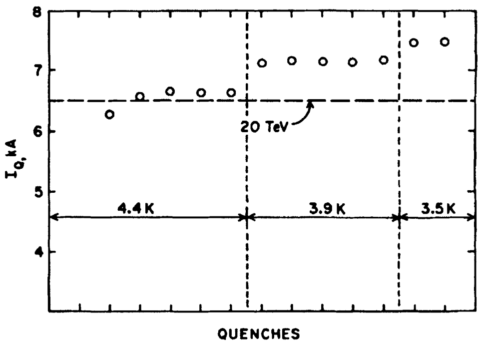

Figure 5 The quench performance of 17m magnet DD0017 at several temperatures.

The maximum temperature reached in the magnet during quench is measured to be on the order of 300 K, occurring in the low field regions of the outer coil. Quench velocities are observed to be between 100 m/s and 250 m/s, higher than expected from analytic models of propagation mechanisms.

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