A HIGH GRADIENT QUADRUPOLE MAGNET FOR THE SSC*

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Abstract

A quadrupole magnet for the SSC has been designed with a gradient of 234 T/m at 6500 A. Coil I.D. is 40 mm. The two-layer windings have 9 inner turns and 13 outer turns per pole with a wedge-shaped spacer in each layer. The 30-strand cable is identical to that used in the outer layer of the SSC dipole magnet. Interlocking aluminum alloy collars are compressed around the coils using a four-way press and are locked with four keys. The collared coil is supported and centered in a cold split iron yoke. A one-meter model was constructed and tested. Design details including quench behavior are presented.

The quadrupole magnets proposed for the main SSC rings have a design gradient of 230 T/m. For one proposed 60 degree lattice cell,[1,2] each 3-m long quad is separated by five 17-m long dipole magnets. About 1356 of these main "arc" quads are required. In addition, there will be numerous similar quads of various lengths for beam collision regions, injection lines, etc. After comparing both single layer and two-layer designs, a high gradient two-layer design was selected to minimize total facility cost. For ease of tracking of the quadrupole field with the dipole field during accelerator operation, the quads and dipoles are powered in series.

Several designs were considered using the computer program PK† with a total of 19 to 23 turns per pole and a single wedge in each layer[3]. All have very low computed multipoles and gradients between 210 T/m and 240 T/m. The cross-section that we adopted, shown in Fig. 1, has 22 turns per pole, reasonable size wedges (e.g., no pointed edges), and a gradient of 236 T/m at 6500 A. Calculations indicate that iron shape and saturation reduce the gradient by 0.85% at full current and harmonic distortion due to iron saturation is negligible (less than 4×10^{-6} at r = 1 cm). The computed design parameters are given in Table I.

†$\mu = \infty$ in iron.

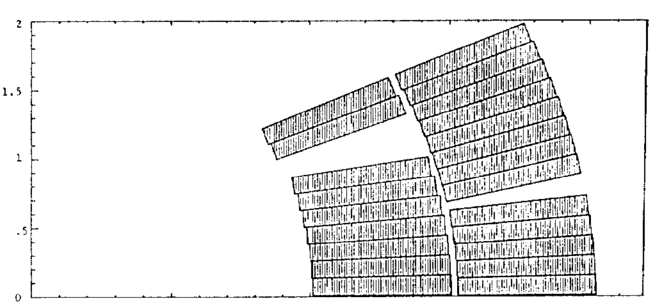

Fig. 1. Cross section of one octant showing the two layer cable layout.

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Table I.

Number of strands	30	
Strand size	25.5 mil	
Mid-thickness (with insulation)	53.0 mil	
Width	.983 cm	
Keystone	8.3 mil	
Cu/SC	1.8:1	
I_0 (A)	6500	
G_0 at I_0 ($\mu=\infty$) (T/m) r=1.0 cm	236.3	
G_0 at I_0 (μ=real) (T/m) r=1.0 cm	233.7	
B_{max} at I_0 (T)	Inner 5.402	Outer 5.228
I_c/I_0 at B_{max}	Inner 1.296	Outer 1.347
$B_c(I_c)/B_{max}(I_0)$	Inner 1.189	Outer 1.228
J_c(A/mm^2), at 4.2 K, 5 T	2750	
J_{NbTi}(A/mm^2) at I_0	1841	
J_{cu}(A/mm^2) at I_0	1023	

The cable has 30 strands of .0255 inch diameter multifilamentary strand with copper-to-superconductor ratio of 1.8 and is identical to the cable used in the outer layer of the 6.6 T main dipole coils; the maximum field at the conductor of both inner and outer coils is close to that in the dipole outer coil and thus the two designs are well matched. Another reason for this choice of a common cable is that economies can be realized in production. The minimum useful cable length (to avoid internal splices is about 75 m for the quad compared to about 700 m for the dipole; thus, lengths too short for the dipoles can be used and scrap cable minimized.

The cable is wrapped with two layers of 2 mil Kapton coated on the outside with B-stage epoxy. Insulation thickness is ~5 mil (metal to metal) in the finished coil. The cable is keystoned with one edge 8.3 mil thicker than the other. The specified minimum current density for the superconductor is 2750 A/mm^2 at 4.2 K and 5 T.

Structural support is provided by interlocking aluminum-alloy collars fastened together by four keys. The collars are identical and are arranged in pairs encasing the windings as shown in Fig. 2. Each pair has a 90 degree orientation to the adjacent pair. This type of collar arrangement was used in the 7.62 cm bore superconducting quads of the Tevatron. An advantage is the inherent four-fold symmetry of the structure to help minimize unwanted field distortions from assembly fits and deformations. At assembly, the collars are individually stacked around the coils and pressed into position using a four-way hydraulic press; the tapered keys are then pressed into place. For the model magnet, maximum azimuthal pressure in the coils during collar assembly was 6250 psi; as the tapered keys were inserted, the pressure on the assembly press was gradually reduced while the tapered keys were inserted. The residual azimuthal pressure in the coils after collar assembly was 5150 psi. The press can be applied successively to short sections of the assembly; a full length press is not needed.

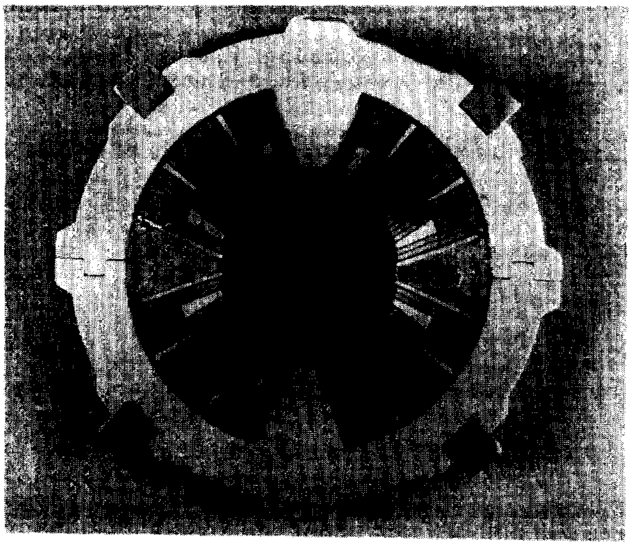

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Fig. 2. Cross section of a short (6 inch long) mechanical model showing collars assembled around the coils.

An alternate collar design is to preassemble collars in packs as shown in Fig. 3. This has the advantage of simplifying the final assembly operation, although additional operations are required to assemble the packs; however, automated assembly techniques can easily be used. Both designs with individual collars and preassembled collar packs were used in the initial one meter model; the packs are used in conjunction with strain gage instrumentation.

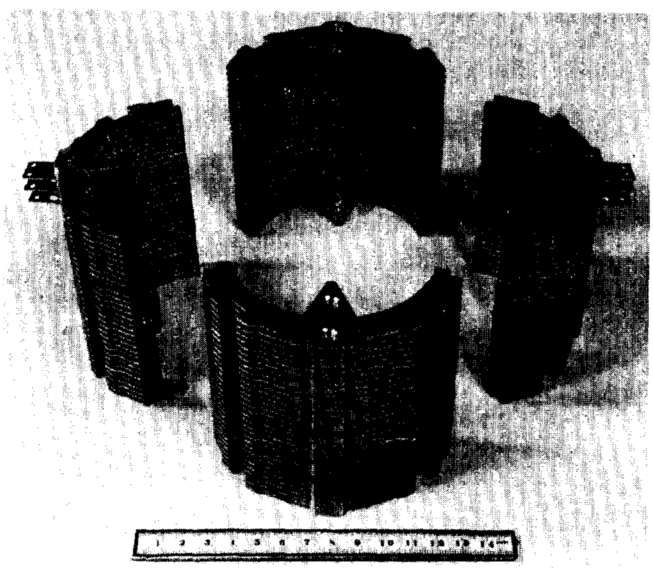

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Fig. 3. A section of preassembled collar packs used to support load cells.

After collaring, the assembly is placed in a split iron yoke and supported at four locations by the protruding keys.

The magnet cross-section is shown in Fig. 4 with a 10.5 inch O.D. iron yoke; the top rectangular groove is to accommodate the main current buss, the lower groove instrumentation wiring and corrector buss, and the symmetrically-placed side grooves are for helium flow. The 10.5 inch O.D. yoke with the same O.D. as the dipole yoke, has excess iron, but simplifies end connections and uses cryostat parts common with dipoles. We have calculated that it is possible to reduce the iron O.D. to 7.5 inches with negligible effect on gradient and quality, if the buss grooves are located at the poles (45 degree rotation).

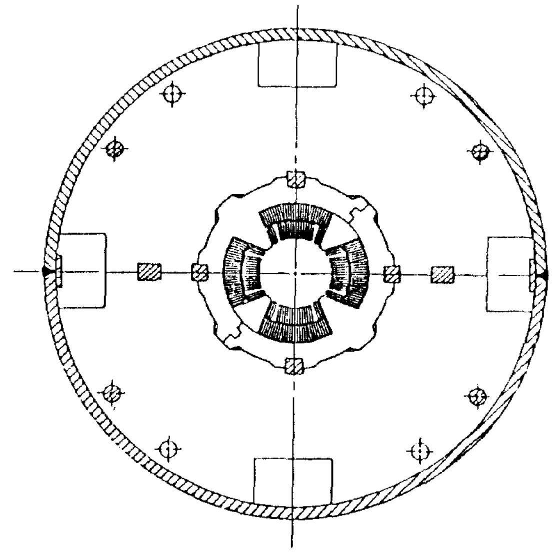

Fig. 4. Cross section of coil in iron yoke.

End Design

Coil ends are designed to minimize the integrated harmonic distortion; also, field at the conductor must not exceed the maximum field in the straight section. Fig. 5 shows the end configuration that has been used in the first 1-m model; the slight azimuthal bulge at the first two pole turns of the inner layer is to make the coil easier to wind by maximizing the bending radius of the cable. There are alternate, more compact designs, now being evaluated that have similar magnetic field properties, but with the azimuthal bulge eliminated.

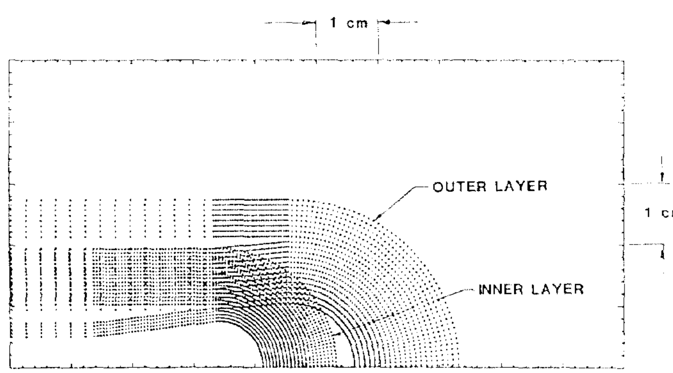

Fig. 5. Developed dimensions show end design used in the model.

Initial Test Results

The magnet showed significant training behavior. The initial quench occurred at 5468 A, the second at 6146 A; the SSC operating current of 6500 A was reached after five quenches. Measured gradient at 6500 A is 240 T/m, slightly above the design value. However, 10 quenches were required to reach 7000 A; the critical computed current, based on magnet performance, was about 7500 A and was reached after the magnet had first been operated to higher currents at 1.8 K and then returned to 4.4 K. This is about 6% above the expected "short sample" current possibly because the S.C. current is defined at an equivalent resistivity of $\rho = 10^{-12}$ ohm-cm, whereas magnet quench current can be higher because of current sharing. Maximum current reached at 1.8 K was 9517 A (345 T/m). However, after cycling to room temperature, there was an initial quench at 6560 A (above operating current of 6500 A) and several additional quenches before stabilizing around 7400 A. Operation at reduced temperature to a current exceeding the design current has been used to eliminate training in several 1-m dipole models[4]; presumably, this technique could also be applied to quadrupoles.

Further work now proceeding includes harmonic measurements and analysis of coil stress measurements. Insulation and mechanical assembly techniques will now be varied to determine effect on training behavior.

References

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