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Author

Taylor, C.E.

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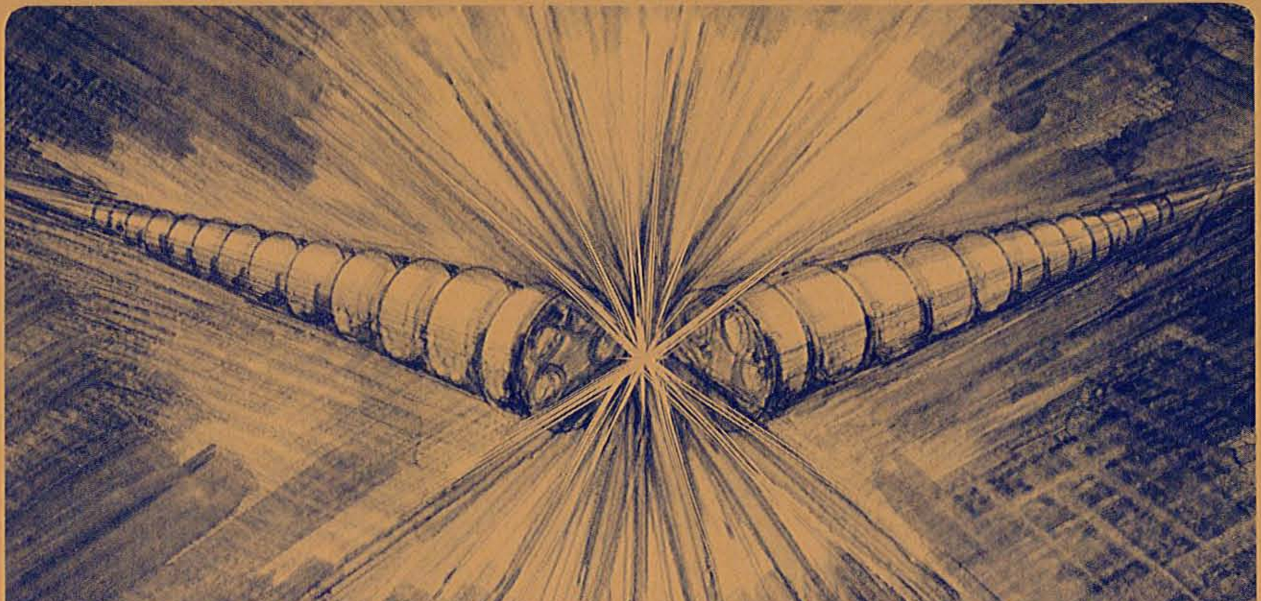

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Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

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A 40 MM BORE QUADRUPOLE MAGNET FOR THE SSC*

C. E. Taylor, P. Barale, S. Caspi, D. Dell'Orco, D. Fritz, W.S. Gilbert, A. Lietzke, C. Peters, and A. Wandesforde
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

A 40 mm bore quadrupole magnet design, called "QC", has been made for the SSC with the following parameters: 208 T/m gradient at 6500A, 2-layer "cos 2 θ" winding arrangement with 30 strand cable and one spacer wedge per coil. Structural support is provided by self-supporting interlocking collars; two types of symmetrical laminations are pre-assembled into collar packs for ease of assembly. This paper will describe the design of a prototype quadrupole magnet for the SSC and preliminary test results on 1 m models.

Introduction

Each of the two 20 TeV proton collider rings of the SSC has 832 quadrupole magnets in the regular beam transport cells; in each cell there are ten 6.6T dipoles, each 15.2 m. long, and two quadrupoles each 5.0 m long.

An earlier design[1] had a higher gradient and thinner collars; however, it was decided recently to pursue a more conservative design with stiffer support structure which is described here.

Design parameters of the prototype quadrupole are given in Table I.

Table I -- Quadrupole Parameters

Coil bore diameter		40 mm
Gradient		211 T/m[+]
Length		5.0 m
Number of quadrupoles		1664 (both rings)
Operating current		6500A
Cable:[++]	No. strands	30
	Strand diameter	0.648 mm
	Width	9.78 mm
	Thickness	1.062/1.268 mm
	Keystone angle	1.2 deg.
	Cu/SC ratio	1.8
	No turns-inner coil	8
	No turns-outer coil	13
Iron I.D.		113.1 mm
Iron O.D.		266.7 mm
Outer shell thickness		4.7 mm

[+]205 T/m is the minimum requirement
[++]without insulation

Cross Section

Fig. 1 shows a cross section cut from a collared coil and figure 2 illustrates a cross-section of the coils as installed in the yoke. The cable is wound in a typical "Cos2θ" pattern around a circular bore with a single spacer wedge in each layer; the copper wedges help maintain a "Roman arch" type of structural support; also, they are located to maximize the uniformity of the gradient.

This type of self-supported coil structure with a free inner bore was first described by Perin[2] and is now nearly universally used in superconducting accelerator magnets.

Cable insulation consists of 2 layers of 25μm Kapton film over-wrapped with fiberglass cloth which is partially impregnated with B-stage epoxy. This insulation system is identical to that used in the SSC model dipoles[3]. After the coil is wound it is placed in a cavity and heated to 130C under about 50 MPa pressure to achieve a precise coil size and to hold the cables rigidly until the structural collars are installed.

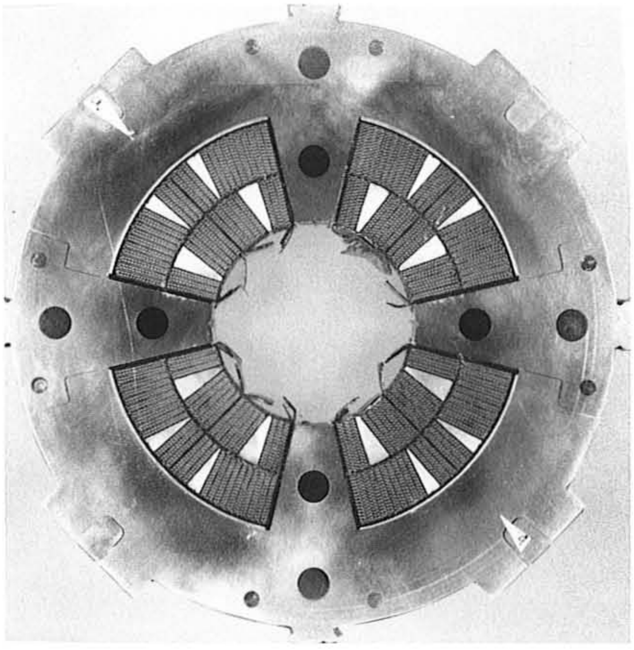

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Figure 1. Cross section of a QC collared coil showing the distribution of turns.

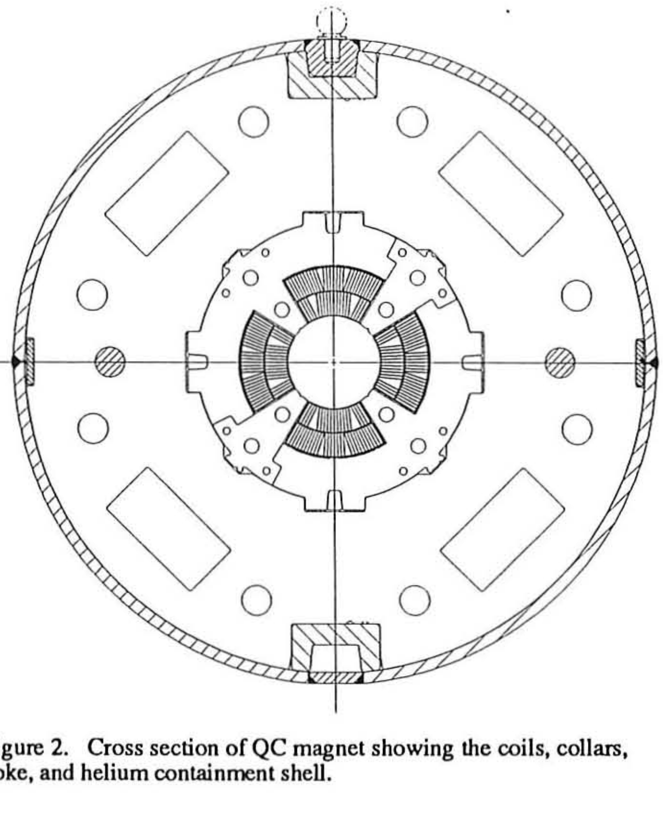

Figure 2. Cross section of QC magnet showing the coils, collars, yoke, and helium containment shell.

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Collars

The coils are enclosed in an interlocking aluminum alloy collar structure that supplies azimuthal precompression, support of the Lorentz forces, and precise coil position. Tabs at four locations engage slots in the yoke to center the coils.

Two types of symmetrical laminations are alternately stacked and pinned together forming 150 mm long packs. The packs are compressed around the coils from four sides as illustrated in Figure 3 and are secured by inserting four tapered keys. There is a small clearance on the sides of the tabs so that collars are centered but not restrained from small motions due to cooldown and operation.

Radial thickness of 18 mm provides a stiff support structure; an analysis of collar stresses and deformations gives acceptable values[4]. Lorentz forces produce a maximum radial deflection of only 10 μm and a stress variation of only 4 percent as the current ramped to 6500A[2].

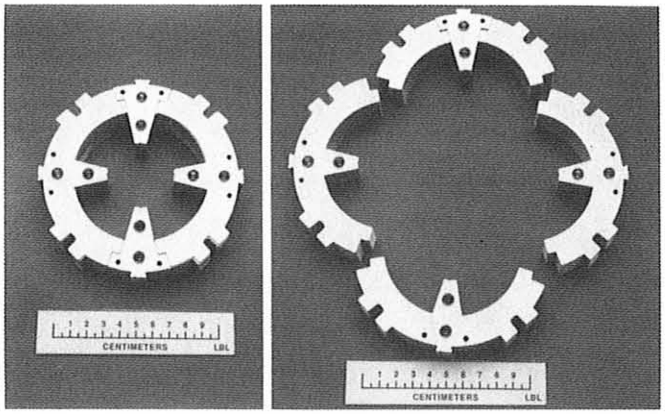

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Figure 3. Photograph of quadrupole collars showing how the preassembled interlocking packs are assembled.

Yoke

The 267 mm OD laminated yoke is split horizontally for ease of assembly. Although a smaller diameter is possible from a magnetic point of view, this diameter ensures enough axial stiffness so that with two cryostat support points the 5 m long cold mass which weighs about 800 kg will sag less than 0.1 mm due to its own weight.

Laminations are pre-assembled in blocks and secured by axial rods. Two pre-assembled yoke halves are placed around the collared coils with a midplane key to insure alignment. A stainless steel shell in two halves is welded to form a rigid support structure as well as a vacuum wall for the helium coolant. Holes in the yoke provide passages for the liquid helium coolant, main buss conductors, and wiring for miscellaneous instrumentation and controls.

An important feature of the yoke is the alignment keys for insuring that the magnet is precisely aligned during welding of the shell. Before the shell is welded, a removable key is inserted periodically along the length between each yoke half, extending through holes in the shell, to engage a rigid beam external to the shell that extends the length of the magnet. The yoke is held in precise alignment by this beam while the shell is squeezed into its final position; it is held in this position during welding. After removal from the welding fixture, plugs are welded in place to seal the holes in the shell.

Test Results

Two 1 m long models called QC–1 and QC–2 were constructed. They both reached nearly 8000 A but required an excessive amount of training; in QC1, the first three quenches were at 6809 amps, 6991A, and 7389A; 7973A was reached on quench 11. However, in QC2 the first three quenches were at 6346A, 6601A, and 6884A; subsequent training was much slower than in QC1 and eventually a plateau of 7914A was reached. All but one of the training quenches occurred in the inner layer pole turns. Each of the eight coils had four voltage taps installed on the pole turn so that the location of quench initiation can be determined by recording voltage vs. time immediately following each quench. This data shows that all of the early quenches in QC2 started in the lead side of the inner pole turn and were predominantly in a poorly supported length of cable where it begins to exit from the winding. We have redesigned the lead configuration and winding procedures to fix this weak spot, and we are building additional 1 m models to evaluate the modified design.

Fig. 4 shows the variation with radius of the field at the pole across the face of the inner and outer cable. At the operating current of 6500A, the maximum field at the conductor is 4.84T and occurs about halfway across the face of the inner layer. However, the maximum field at the outer layer is only 1% less and occurs at the inner edge of the outer cable.

The cable critical current is typically degraded slightly as compared to the same strands before cabling because of filament damage during cable fabrication caused by severe deformation of the strands at the narrow inner edge of the cable.[5] This degradation is reflected by the difference in cable critical current measured with the field maximum at the narrow edge of the cable vs. along the cable face.[6] In the case of the cable in QC1 and QC2, this difference is about 4-5% as measured at BNL. Therefore, the limiting critical current in the magnet should be determined by the outer layer field; this is observed.

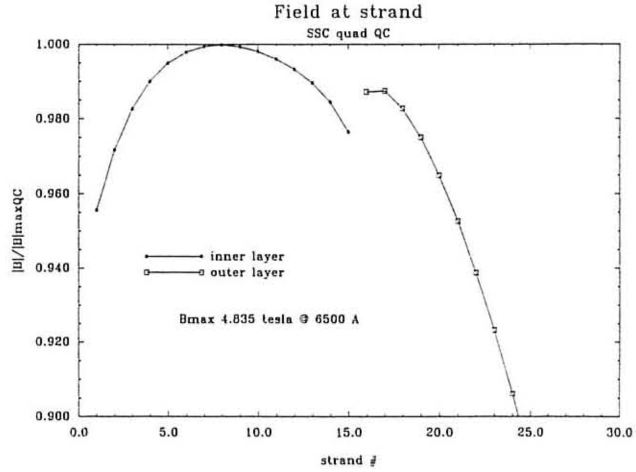

Figure 4. Plot showing how the magnetic field varies with radius at the polt turn of the inner and outer layers.

Magnetic Field

The measured gradient is 208 T/m at 6500A. Iron saturation effects are negligible.

If B is expressed in the usual harmonic expansion:

$$B_x + iB_y = G\,R_0 \sum_{n=0}^{\infty} (a_n + ib_n) \left(\frac{x+iy}{R_0}\right)^n$$

a_n and b_n are the harmonic coefficients, R_0 is a reference radius, G is the quadrupole gradient in T/m and n = 1 for quadrupole, n = 2 for sextupole, etc.; then $b_1 = 1$ by definition and a_n and b_n are in units of 10^{-4}. The allowed harmonics for a symmetric quadrupole are b_5, b_9, . . . and the others represent a distortion of the four-fold symmetry of the windings. Table II shows these harmonics as measured in QC1 and QC2 at I = 3045A. The field was measured using a rotating coil system.[7]

Table II

Harmonic Coefficients in units of 10^{-4} at I = 3054A

	QC–1		QC–2	
n	a_n	b_n	a_n	b_n
2	0.4	1.6	-0.3	-1.2
3	-1.52	0.20	-1.9	-0.55
4	0.06	-0.33	0.74	0.37
5	-0.16	-0.42	-0.22	-0.60
6	0.08	-0.12	-0.12	-0.08
9	0.00	0.11	0.02	0.06

The non-allowed terms indicate some small non-uniformities among the coils of the four quadrants; it is expected that they can be greatly reduced in subsequent models when more uniform coil manufacturing processes are established.

At low fields, magnetization currents induced in the superconducting filaments are an additional source of field distortion. Fig. 5 shows the measured 12-pole (n = 5) and 20-pole (n - 9) harmonics in magnet QC–1 at low fields. QC2 is similar.

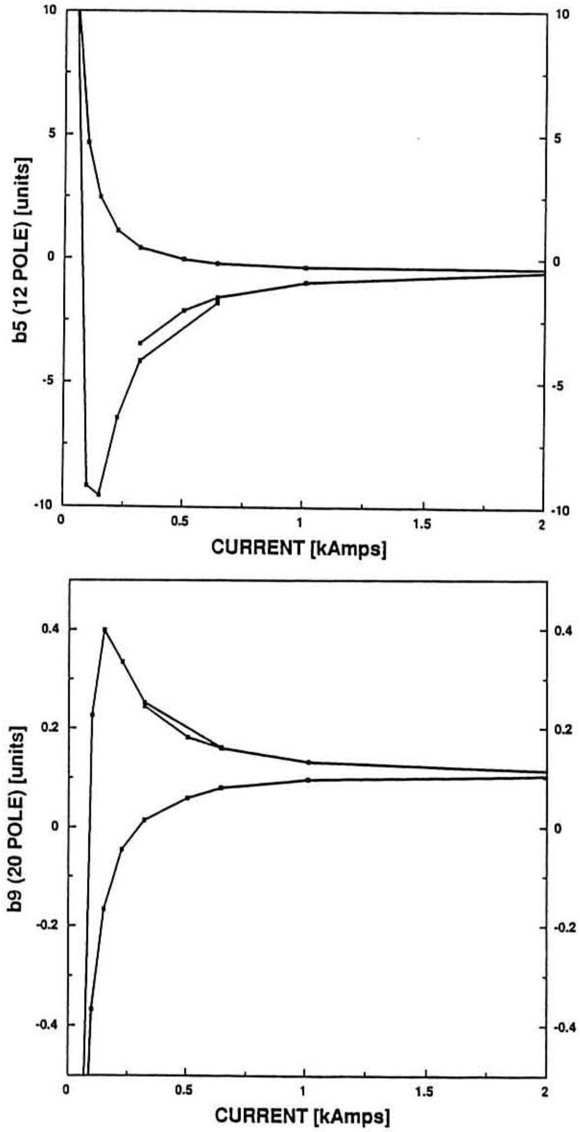

Figure 5. Graph of b_5 (10-pole) and b_9 (20-pole) allowed harmonics vs. current showing magnetization effects caused by persistent currents.

Coil Stress

In QC–2, the Azimuthal stress in the coils after collaring was 37 MPa in both layers, decreasing after several days by about 3% due to creep.

There is little change during cooling because thermal contraction of the aluminum alloy collars is close to that of the coils; after cooldown, the average pressure measured by load cells at the pole was 34 MPa inner and 41 MPa outer. These pressures decreased linearly with I^2 by about 8.5 MPa at the inner pole and 10 MPa at the outer pole as the current increased from 0 to 6,500 A. Measured pole pressures in QC–1 were similar.

Full-Length (5 m) Models

The first 5 m model is now under construction at LBL; the coils are assembled and ready for installation of collars.

Several models will be built. After testing at LBL, it is planned to send the magnets to the SSC Laboratory in Texas for installation into cryostats, which are being designed and built there. Fig. 6 shows a cross section of the complete magnet in its cryostat. The cryostat is similar to that developed at FNAL for the SSC dipoles.

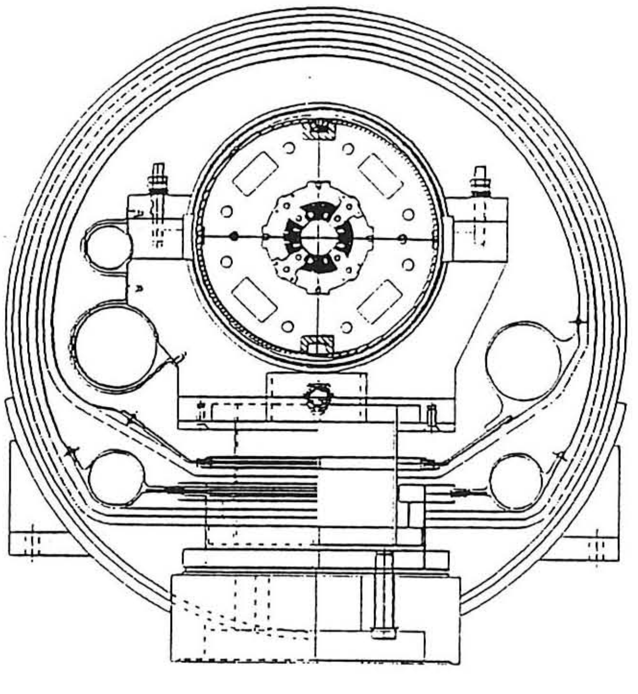

Figure 6. Cross section of complete magnet showing the cold mass mounted in the cryostat.

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