SSCL-Preprint-213

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April 1993
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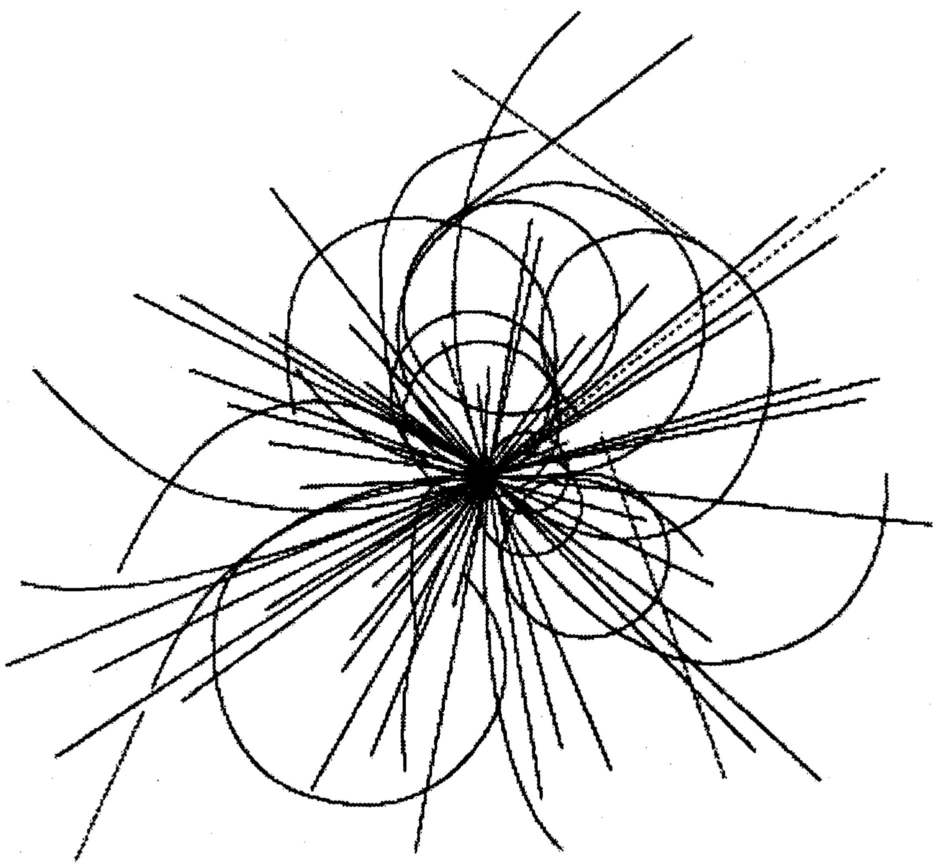

Superconducting Super Collider Laboratory

To be published in *Supercollider 5* SSCL-Preprint-213

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April 1993

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* Presented at the Fifth Annual International Symposium on the Super Collider, May 6–8, 1993 San Francisco, CA.

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† Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

DESIGN AND PERFORMANCE OF A NEW 50 mm QUADRUPOLE MAGNET FOR THE SSC

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INTRODUCTION

A superconducting quadrupole model magnet with a 50 mm aperture and a gradient of 190 T/m, in operation at 4.35 K and 6500 A, has been designed, built and tested at the SSC. This accelerator magnet is expected to have application in the interaction regions of the collider main rings. Its dipole-type stainless steel collars with mated self-aligning pole spacers were a major innovation in design. The model had stringent requirements on field quality and a conservative 21% current margin.[1] The first two articles have now demonstrated satisfactory quench performance over several thermal cycles, reaching plateau at approximately 8660 A with minimal training. This paper is a brief sketch of the design and preliminary results on the first model. Fabrication[2] and testing[3] are described in other papers of this conference.

ORIGINAL SPECIFICATIONS AND REQUIREMENTS

A project began in mid-1990 at the SSC to design and build a 50 mm superconducting quadrupole, soon called the QSE magnet. Central gradient was set at 180±10 T/m at the operating current of collider dipole magnets, then 6500 A. Operating current has since been revised to 6714 A. The magnet was to use an available cable, and the 36-strand outer cable of the CDM was chosen. J_c and other characteristics of this conductor permitted the QSE design to attain its conservative margin. Magnetic field harmonics were specified as in Table 1, in order to permit several possible applications in the machine lattice at the time.

Preliminary requirements on coil and yoke were determined by traditional approximate methods for the critical current[4] and short sample characteristics of NbTi, and infinite iron assumption for the field calculation. Electromagnetic design began from a coil having an inner layer of eleven turns and outer layer of sixteen turns to achieve the gradient transfer. Yoke outer radius was selected to fit the existing CQM cryostat. Rough dimensions of conductor and yoke thus set, stainless steel collars of Nitronic 40 were chosen for their high strength early in the process, and a number of collar and yoke layouts were analyzed with ANSYS[5] programs for (2-d) mechanical structures. While Lorentz forces[1] which these structures counteract are somewhat less than for dipoles, the quadrupole coil assemblies have more parts and are prone to shift under assembly stresses, cooldown and excitation. Therefore great effort was considered necessary to perfect the mechanical "packaging" of this device.

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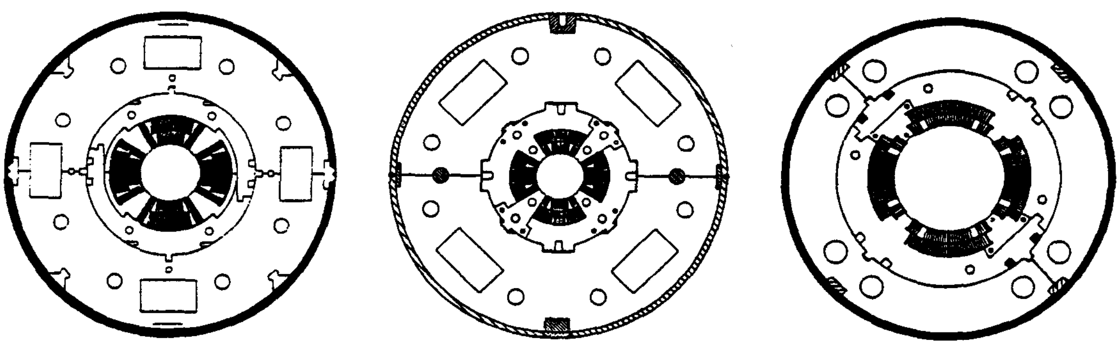
Table 1. Field harmonic specifications in "units". Note 200 units of dipole error is equivalent to 200 μm of centering error in (x,y), and that 5 units of skew quadrupole error is equivalent to a magnet rotation of 0.5 mrad. Allowed terms marked (*).

n	Normal Systematic	Normal Random	Observed Warm Test	Skew Systematic	Skew Random	Observed Warm Test	Multipole
0	20.000	200.000	——	20.000	200.000	——	dipole
1	10000. *	——	10000. ± 0	2.000	4.796	0.0 ± 0	quadrupole
2	0.184	1.765	-2.589 ±.038	0.184	1.765	1.883 ±.038	sextupole
3	0.085	0.812	0.531 ±.013	0.085	0.812	-1.945 ±.013	octupole
4	0.078	0.224	-0.067 ±.011	0.078	0.224	0.013 ±.011	decapole
5	0.573 *	0.103	0.551 ±.011	0.072	0.206	-0.102 ±.011	dodecapole
6	0.033	0.032	-0.022 ±.004	0.033	0.032	0.026 ±.004	quadecapole
7	0.030	0.029	0.006 ±.004	0.030	0.029	-0.005 ±.004	sexadecapole
8	0.028	0.027	0.005 ±.004	0.028	0.027	-0.005 ±.004	octadecapole
9	0.103 *	0.025	0.020±.004	0.026	0.025	-0.009±.003	icosapole

MAGNET DESIGN OVERVIEW

Through a series of reviews from November, 1990 to February, 1991, the conceptual approach to the magnet was refined. Notable was a decision to use dipole-type collars, confining and positioning the quadrants with self-aligning brass pole spacers. This would permit horizontal assembly in an available dipole collaring press and permit extension of the straight section to 15 m length in prototype. First known application of this technique was soon to be announced[6] at MT-12. A dipole structure was thought to increase stiffness and strength of the coil assembly, though that was further enhanced by a line-to-line fit at the collar-yoke interface at the cold operating point. The adopted mechanical cross section design is shown in Fig. 1, with some other quadrupoles for comparison. Yokes, stainless steel collars and brass spacers are all laminated structures, formed into packs of various convenient lengths. Collar laminations are spot welded in alternating left and right pairs, and these weldments are themselves interleaved with left and right hand types to form standard collar packs of 158 mm length. Spacers are assembled in 30 mm packs with roll pins at three points. Finally the iron yokes are pressed into long half-packs held together by flared stacking tubes. Stainless steel collars without spacers extend over coil end sections, and yoke packs are terminated at each end of the magnet by monolithic blocks of stainless steel, cemented with epoxy and baked. This latter feature helps to prevent "chevron" collapse of yoke packs in the yoking press. Laminated structures are confined by a stainless steel shell.



QSE CQM UNK

Figure 1. Cross section of the QSE magnet with comparison to other recent quadrupoles—the SSC (LBL) 40 mm main ring quadrupole CQM, and the IHEP 80 mm UNK quadrupole. Drawings not to scale.

ELECTROMAGNETIC APPROACH

It was stipulated that inner and outer coils would have the same pole angle in order that spacer elements have the simplest shape and to permit easier winding of the layered coil with less chance of damage to pole turns. This also avoids pole wedges which can complicate problems of tolerance and bending. PE2d[7] codes and other special programs were used to optimize the 2-d cross section and obtain an estimate of the allowed harmonics. Unallowed harmonics are essentially constrained only by the very close tolerances on the collared coil and by process control specifications. These harmonics were estimated by simulation of small errors in a coil without symmetry. Experience and simulation runs set the design tolerances. A solution was found to approximate the cos(2θ) current distribution of a perfect quadrupole. It required one asymmetric copper wedge for the inner coil, and another for the outer coil.

Studies of the existing DESY quadrupole, and those in development for LHC and the SSC main ring all used the same cable for both inner and outer coils. Preliminary calculations had shown that an 11.5 mm-wide insulated cable would be suitable here. It was important for production and design scheduling to use an existing cable. The outer CDM conductor was chosen for QSE because of its width and low rigidity. This choice made possible winding the new magnet coil-on-coil without a splice between inner and outer coils. Such technique had been used to advantage in HERA quadrupoles and reduces the number of soldered splice joints from 7 to 3. In some magnet designs, such cable splices had been found to have an adverse effect on quench performance. Salient parameters of the QSE cable are in Table 2.

Table 2. Conductor parameter specifications and *estimates.

Parameter	Bare Cable	Insulated	Final Cured*
Width	11.680 mm	11.982 mm	11.960 mm
Thin Edge	1.054	1.356	1.222
Thick Edge	1.260	1.562	1.426
Keystone Angle	1.05°		
Cable Pitch Length	89 mm with left-hand lay		
Critical Current	9870 A at 5.6 T and 4.2 K		
RRR	> 30 Ratio R_{295}/R_{10} (cold worked condition)		
Cu: SC Ratio	1.8 : 1		
Insulation	50% overlapped Kapton plus fiberglass-epoxy tape		
Twist Pitch	15 mm with right-hand twist		
Strand Diameter	0.648 mm		
Number Strands	36		

Coil design was optimized after basic dimensions—insulation cured thickness, intercoil spacing, ground insulation, collar width, yoke inner radius—were all set and cross-checked. Ground insulation is determined by maximum voltage at quench. Two 125 μm layers of Kapton[8] were judged sufficient, but doubled because they must be cut, and also in order to provide good force transmission during collaring and yoking. Pole-to-pole voltage estimates required two such Kapton layers at the parting planes. Turn-to-turn voltage was estimated at 25-30 V, and a cable insulation composed of a 25 μm thick Kapton layer 50% overlapped, and a 0.10-0.11 mm-thick fiberglass-epoxy tape spaced by 2 mm was judged adequate.

A key dimension to be fixed was the yoke inner radius. Preliminary mechanical calculations were done with the conservative condition that magnet collars had to take the entire Lorentz force at full excitation. It was found that a 20 mm-thick stainless steel collar was suitable for the self-supporting assumption. Hence inner yoke radius was set to 70 mm. With these main parameters, conductor cross section was optimized for the precise position of each turn, and thence the dimensions of all wedges. Thus there were to be four conductor blocks per quadrant, and the QSE cross section is denoted 8-3 and 13-3 by SSC convention. The computed field was within original requirements. The final conductor geometry is input to the PE2d finite element programs, which refine and complete the field calculations, given a hysteresis curve for the iron and precise definition of yoke geometry. PE2d will produce plots of the field, flux and force. The force estimate on conductors is an important input to refine the cross section, in an iterative procedure[9] which aims to guarantee that the final design places every turn at its precise position at cold condition and under full excitation.

Field was optimized in the end region with 3-d modeling by arranging conductor block U-bends of both coil layers along the z-axis, in order to reduce peak field and minimize the integral of allowed harmonics b_5 and b_9. The end parts are called keys, spacers and fillers, and saddles, according to their placement inside a pole turn, between blocks, or outside the final turn. Fig. 2 shows a quadrant coil. Direct numerical specification of these end parts comes out of this optimization process. Design techniques for the coil end parts have been published[10] in a previous conference. Rapid manufacture and cost containment of such small, rigid, and irregularly shaped plastic (G-11CR) parts remains a challenge. Major design issue is to reconcile cured and uncured dimensions for these items.

ITERATIONS TO FINAL MECHANICAL DESIGN

Mechanical analysis was performed by hand and with the finite element code ANSYS. In the calculations plane stress is assumed, creep characteristics of coils are ignored, and coil properties are assumed linear (program limitation). Desired coil prestress after collaring was estimated to be about 43 MPa on average, based on prior experience and preliminary hand calculations. Main objective was to have the coils always in contact with the pole faces of the collars. To limit creep effects in the coils (flow of insulating materials) that mainly occur at room temperature, it is important to have coil prestress as small as possible at warm condition, consistent with cold prestress needs. This prestress was effected in the model by setting a 0.094 mm interference between coils and collars. The finite element calculation predicted that a small yoke gap would exist after the yoking and welding operation (0.021 mm at the inner yoke radius). The yoke tends to force the collars back to their original round shape because of the line-to-line fit between yoke and collars. Like the collaring process, this increases stress in the coils—by an average of about 14 MPa over the inner and outer layers.

Since the Nitronic 40 collars have a higher coefficient of thermal expansion than the iron yoke, cooldown results in a decrease in contact force between the yoke and collars. Also coils have a higher coefficient of thermal expansion than collars, so they shrink away from the collars during cooldown. Combining these effects means that coils lose a substantial amount of prestress on cooldown. These effects aid in closing the yoke midplane gap which remained after welding. As the magnet is energized, Lorentz forces act to separate the coils from the collars at the poles and compress the coils at the parting planes. However model calculations and strain gage data showed the coils still have a safe prestress remaining at full excitation. More complete QSE mechanical analysis will appear in a forthcoming MT-13 paper.

SUMMARY OF MAGNET FEATURES

- Extensive finite element modeling of magnetic field in 2-d and 3-d
- Iterative design achieves mechanical / magnetic specification at cold state
- Conservative 21% current margin for acceptable quench performance
- Outer coils wound on inner coils without a conductor splice
- Strong dipole-type collars with self-aligning pole spacer inserts
- Requires only dipole presses and permits industrialization to 15 m length
- Coil prestress holds at full excitation, aided by collar-yoke interference
- Inter-quadrant splices of doubled cable in copper stabilizer external to shell

CONCLUSIONS FROM THE FIRST TESTS

Production tests and quench performance runs have shown the QSE101 mechanical design to be very satisfactory. Quench data are summarized in Fig. 3 for the first model, which had its first quench at 7120 A, and plateau around 8660 A or slightly above short sample estimate, following 3 or 4 training quenches. Slight improvement was noted in a 2nd thermal cycle. Warm magnetic field tests are summarized by "observed" entries of Table 1. These measurements were made with a 0.25 m rotating coil device (mole) and represent average multipole estimates in the straight section of the magnet, ±0.375 m from the center. Cold measurements so far cannot be directly compared to the warm data, and are continuing. There appears to be a significant amount of sextupole, octupole and decapole in the magnet. This could occur from parts out of tolerance or process variations which alter coil position—100 μm midplane shift in a quadrant can generate ~3 units of sextupole, 1 unit of octupole and 0.5 unit of decapole. The new model may require some tuning of its conductor cross section.

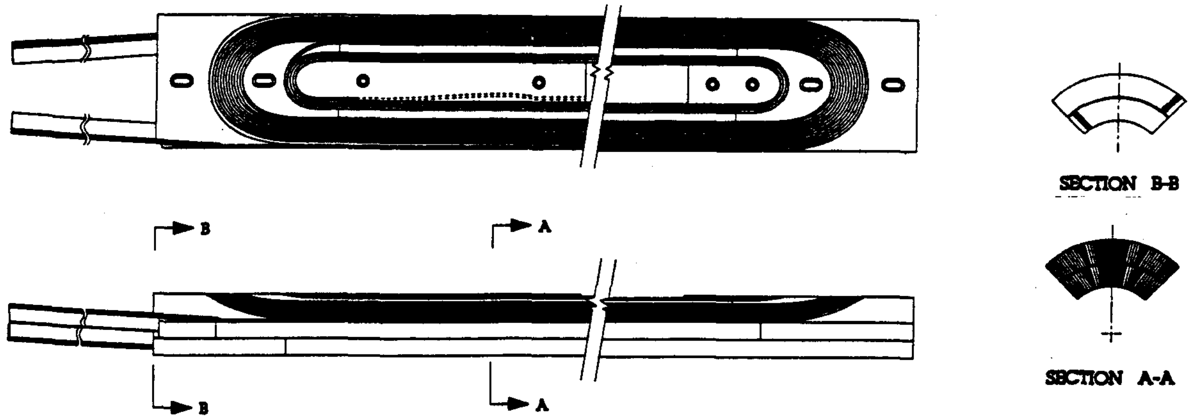


Figure 2. Quadrant coil mechanical design of QSE. Inner and outer coils are wound without a splice.

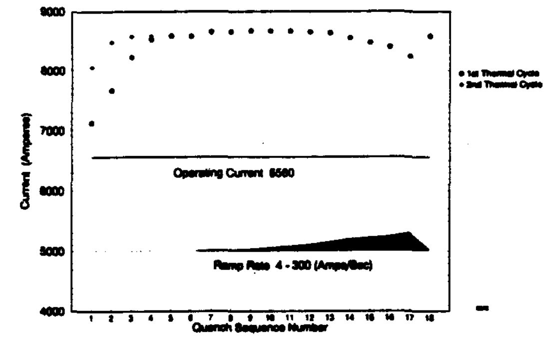


Figure 3. Current at quench for two thermal cycles. First quench occurred at 7120 A, 4.22 K.

ACKNOWLEDGEMENTS

The authors are indebted to many SSC colleagues who have contributed their ideas and experience during the conceptual and detailed design phase, as well as fabrication and final test. Special appreciation is expressed to S. Smith, F. Nobrega, R. Puri, Y. Chen, V. Venkatraman and G. Snitchler of the Cold Mass Design Group; and to N. Hassan who guided the magnet through manufacture; to S. Stromberg, P. Nema, R. Wood, S. Dwyer, E. Cox, D. Bonifert, E. Vrsansky, M. Caracciolo, and W. Stone, who developed all the tooling and production procedures to make the magnet; to D. Albone, A. Fluhmann, D. Covington, D. Block, M. Lewis, A. Jaisle, S. Allen, G. Boswell, R. Williams, L. Brooks, E. McGuire, A. Brown, D. Hart, R. Clerihew, J. Lovell, R. Quick, J. Stephens, R. Rudzinski, L. Thorne, R. Webb, S. Zacharias, A. Leighton and K. Bigert who built the first models with care and diligence; to B. England, R. Lathrop, V. Li and G. McAdams who produced the many detail drawings; to S. Bagwell and F. Ott who found the vendors and made the drawings real; to D. Bailey, R. Fitzgerald, J. Thorne and B. Malnar of the Production Management team for their dedicated leadership and support; to A. Devred, T. Ogitsu, D. Bein, R. Zeigler, J. DiMarco, Z. Wolf and to the entire test laboratory staff, for design and assistance with instrumentation and testing. Without the strong efforts of all these colleagues, the QSE magnet and this paper would not have been possible.

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