SINGLE LAYER QUADRUPOLE DESIGN FOR SSC*

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ABSTRACT

The proposed Superconducting Super Collider (SSC) will require 1360 regular arc quadrupoles. This paper describes a single layer design for these magnets. This design is economically competitive with the more conventional two layer design and appears to be well suited to mass production because of its simplicity. The design uses 9 turns of Cu(NbTi) superconducting cable to produce an 155 Tesla/meter gradient at the 20 TeV peak energy. The systematic field harmonics are all better than the requirements. Detailed results of both magnetic and mechanical analyses are presented.

Introduction

The proposed SSC[1] will contain 1360 quadrupoles in the regular arcs. At the design energy (20 TeV) these will need to generate an integrated gradient of 704 Tesla at the operating current of 6.5 kA. In addition to meeting the neccessary field quality requirements these magnets should be reliable, easy to manufacture and economical. S. Caspi and M. Helm[2] have proposed a quadrupole design with two layers of superconducting cable. The excellent performance and ease of construction of the RHIC prototype magnets[3], which were single layer, has prompted the authors to consider the feasibility of a similar design for the SSC. Because the field in a quadrupole is proportional to the radius, the decrease in gradient for a single layer quadrupole as opposed to a two layer is much less than the loss of central field for equivalent dipoles. (Single Layer dipoles are probably impractical for the SSC). The advantages of such a design are ease of construction and low cost; the disadvantage is that the lower gradient requires longer magnets.

Coil Design

There are practical reasons for designing a quadrupole to use the same superconducting cable as the dipoles. Since the current for the quadrupole is fixed at 6.5 kA and it will be operating well below the superconducting limit, the thinner the cable the higher the gradient. For this reason, the outer cable of the dipole was chosen for this design. The detailed parameters of this 30 wire cable are given in Ref. 1, of note is that the keystone(or taper) of the cable is less than that for a coil strictly radial turns. To minimize the field harmonics, a design with one non-conducting spacer was chosen; in addition, the radius was used as a slightly variable parameter. Because of the quadrupole symmetry, these two parameters are sufficent to suppress all of the low order field harmonics. A cross section of the coil is presented in Figure 1. The effect of partial keystoning is apparent.

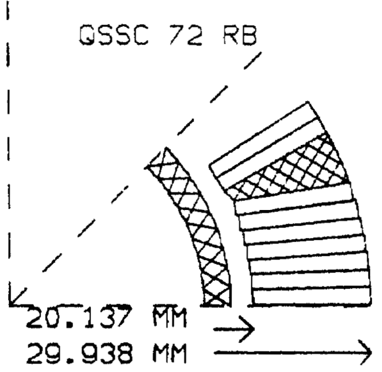

Fig. 1. Octant of Coil Cross Section

Table 1: QSSC 72 RB FIELD PARAMETERS

I =	100	6500	amps
Gradient	2.395	155.5	Tesla/m
Transfer	23.95	23.92	T/m-kA
Saturation	...	-0.09%	
b5′	-0.034	+0.070	10^{-4}
	-0.15	(Magnetization)	
b9′	-0.001	-0.001	10^{-4}
b13′	-0.015	-0.015	10^{-4}
b17′	0.002	0.002	10^{-4}

(QUADRUPOLE UNITS for DIPOLE UNITS MULTIPLY BY 0.24)
(Hence in dipole units max deviation is 0.016 10^{-4}
1.6 ppm)

These field values include the effect of an iron return yoke with circular symmetry and inner/outer radii of 35/75 mm. As can be seen from the above table, the field harmonics are all negligible.

It is neccessary to consider the design of the ends of the coils to minimize the harmonics produced. This is done with two adjustments:

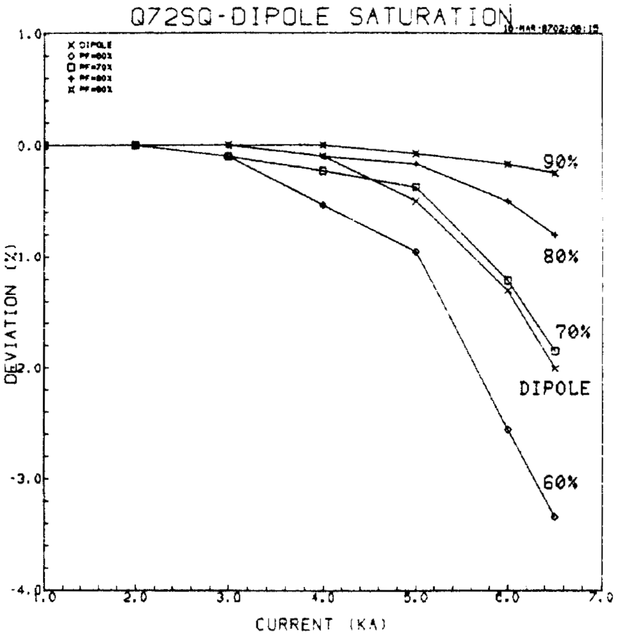

Fig. 2. Saturation and change in b5′ as a function of packing factor for three different iron outside radii.

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1) the spacer between the two current blocks is tapered to zero thickness as the turns go around the ends, and 2) flexible spacers are placed between each turn of the two current blocks. These flexible spacers are 1.48 mm thick in the first block containing 7 turns and 1.73 mm thick in the second block. With these spacers, the calculated fields are less than 0.1 ppm of the central dipole field.

Detailed Iron Design

For the symmetric iron considered above, the saturation (reduction in gradient/amp with increasing current) is negligible. For the SSC dipole magnets the saturation is approximately -2%. It may be desireable to have the quadrupole current track that of the dipole as closely as possible. This minimizes the demands placed upon corrector systems. The goal then is to make the quadrupole saturate more rapidly. Two ways to do this are a) reduce the outside diameter of the iron, and b) reduce the packing factor of the iron. Calculations for finite permeability iron reveal that these changes cause variation in the saturation, but also in the first (b5) harmonic. The variation in b5 has opposite signs for the two changes, hence one can select a combination of packing factor and iron outer radius which will result in the desired -2% saturation and negligible b5 change. Figure 2 shows the interaction of these parameters in the region of interest. From this figure, one can see that an outside radius of 60mm with an iron packing factor of 70% produces the desired -2% decrease in gradient with current with a b5′ shift of only 0.2. It is apparent that the saturation is changing rapidly in this region and will be sensitive to the permeability of the iron. However it will be less sensitive than the dipole. The packing factor could be reduced to the desired 70% by inserting aluminum or other non-ferric laminations between the iron ones. Whether this added complexity in the quadrupole design is worth the savings in the correction systems is unclear.

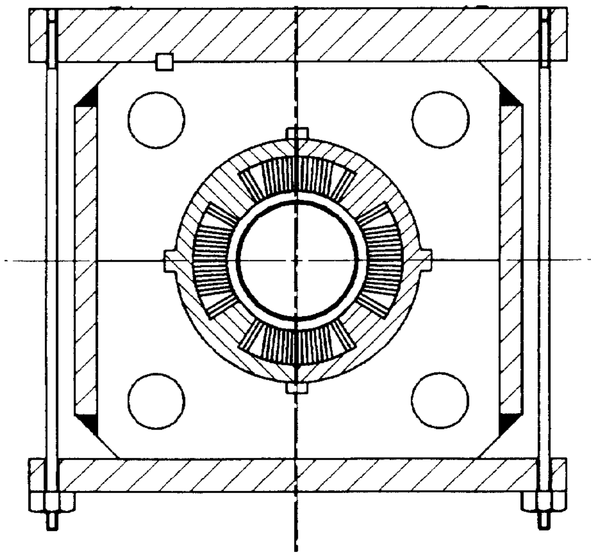

Fig. 3. Cross section of quadrupole in "square" yoke showing welds and support structure.

Square Yoke

The most practical way to assemble production versions of this magnet is to weld the yoke halves together,however the dimensions of the yoke are small enough that the welding is likely to heat the coil components excessively. For this reason, the square design shown in Figure 3 was developed. Magnetically this design is very close to the circularly symmetric designs discussed above. From the data presented in Figure 4, which shows saturation as a function of packing factor, the choice of 70% for the packing factor is obvious. This produces a match to the dipole within 0.1%. Indeed the major deviations will occur at injection where the differing magnetization behaviors of the two magnets will produce proportionately larger effects.

The dominant harmonic in quadrupoles is the first (b5~cos(60)). Except for magnetization effects, this harmonic is less than 0.15 units (0.03 x 10^{-4} x Dipole Field) for the entire current range. This is at the accuracy level of the calculations and within the machine tolerances. Explicit values for all the harmonics are given in the table below.

Table 2: QSSC 72sq Field Coefficents

Current	1.0	5.0	6.0	6.5	kA
Gradient	23.95	119.31	141.97	152.79	T/m
Transfer fun.	23.95	23.86	23.66	23.51	T/m/kA
b1′	10000	10000	10000	10000	10^{-4}
b5′	-0.01	-0.08	0.06	0.15	10^{-4}
b9′	-.002	-.003	-.005	-.006	10^{-4}
b13′	-.015	-.015	-.015	-.015	10^{-4}
b17′	-.002	-.002	-.002	-.002	10^{-4}

(quadrupole units, multiply by 0.2 to get strength relative to dipole central field)

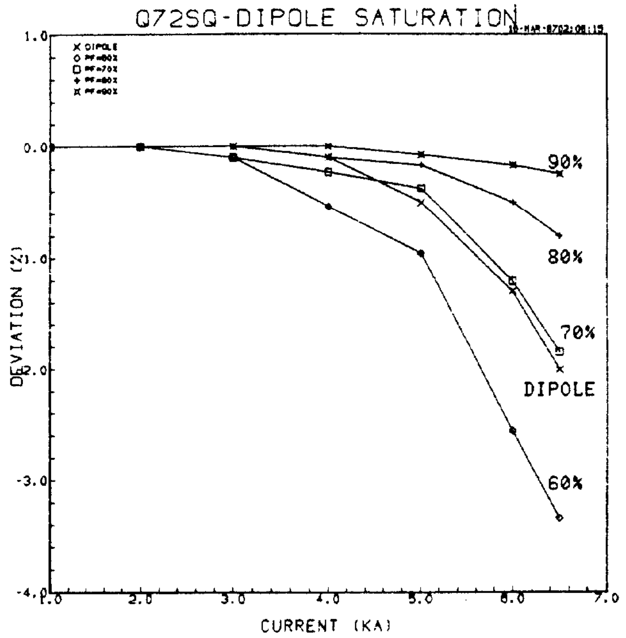

Fig. 4. Saturation at 6.5 kA for "square" yoke quadrupoles with differing packing factors. Also note the dipole saturation plotted on the same scale.

Fringe Fields

Because the iron yoke has been reduced to increase the saturation, the fringe fields are of interest. These fields as calculated by on the midplane (which is where they are largest) are plotted as a function of radius in Figure 5. At the helium containment vessel, the field is 2.5 mT and at the inner surface of the vacuum vessel, it is less than 0.4 mT. The computer code used tends to overestimate such fringe fields by ~2X. Fringe fields of this level are not expected to be significant.

COMPARISON OF DESIGNS

	LBL 2 LAYER	BNL 1-LAYER	
Gradient at 6.5 kA	232	156	T/m
Strand Jc	1.84	1.84	kA/mm^2
Jc/Jo	1.36	2.01	
Length(effective)	3.03	4.56	meter
Length(slot)	4.03	5.56	meter
Cable mass(inner+outer)	32	26	kg
Transfer Function 1 TeV	35.9	23.95	T/m-kA
20 Tev	35.7	23.92	
Saturation	-0.6%	-2.0%	
Magnetization	-0.3	-0.1	10^{-4}
Harmonics			
b5'	0.002	0.034	10^{-4}
b5' 20 TeV	0.017	0.070	10^{-4}
b9'	0.04	0.001	10^{-4}
b13'	0.85	0.015	10^{-4}
b17'	0.23	0.002	10^{-4}

MECHANICAL COMPARISONS

Total # of TURNS	22	9	
Total # of COILS	8	4/2	
Cold Prestress Min.	1.7	1.3	kpsi
Cold Load	1.4	0.5	kp/inch
Collars	yes	no	

COST COMPARISON

Additional Length	---	1.24	meter
Tunnel Cost/m		$1535	
Construction Cost	28.6	23.9	K$/magnet
Total	48.8	41.5	M$
Additional tunnel costs		1.3	M$
TOTAL	48.8	42.8	M$

Conclusions

The magnetic properties of a one-layer quadrupole are equivalent to those of a two-layer design. A rough estimate indicates that the cost of additional tunnel length will be at least offset by the lower cost of the magnet itself. The salient features of the one-layer design are 1)Mechanical simplicity, which should be reflected in ease of construction and reliability, and 2)Very conservative use of the superconducting cable.

In addition to developing the design presented here, several possible extensions of the concept are interesting.

1. Since the superconductor has a very large margin,one could use "scrap" conductor with poorer properties, design a separate cable with a copper to superconductor ratio in excess of 2.5:1, or a 20% thinner cable which would increase the gradient by 20%. Any of these options would decrease the cost of superconductor used.

2. Design a similar magnet with only two separate coils. This saves labor,parts and end splices. The skew harmonics generated can be cancelled with small rotations of the cross section.

References

1. SSC Central Design Group, Conceptual Design of the Superconducting Supercollider, SSC-SR-2020,(1986)

2. S. Caspi and M. Helm, Arc Quad For SSC-First Cut, SSC-MAG-87 (1986)

3. Conceptual Design of the Relativistic Heavy Ion Collider,Brookhaven National Laboratory, BNL 51932 (1986)

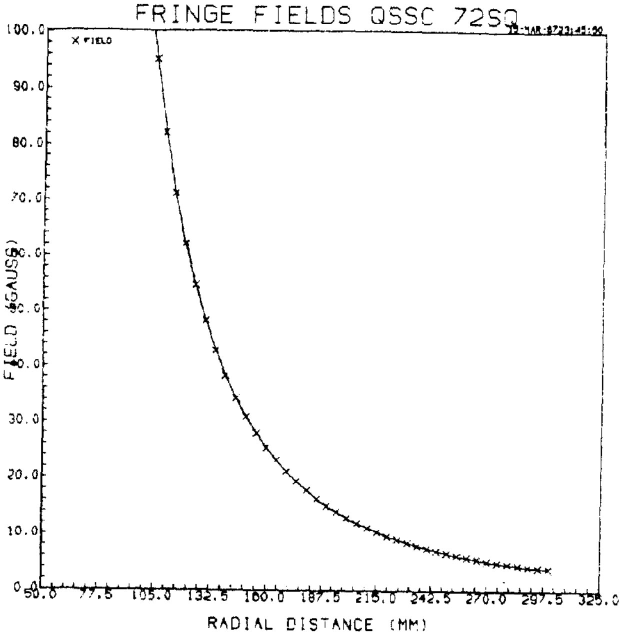

Fig. 5. Fringe Fields in gauss for the "square" yoke quadrupole at full current.