CORRECTION MAGNETS FOR THE SUPERCONDUCTING SUPERCOLLIDER

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ABSTRACT

TAC is designing, building and testing dipole, quadrupole, and sextupole correction magnets for the Superconducting Super Collider. Two approaches were taken, superferric and a new style cosθ. The superferric magnets are three separate packages, while the cosθ magnets are combined into one package. Both types use a ribbon conductor made of parallel superconducting strands on Kapton insulation wired in series to permit use of low current (100A). The superferric design was pursued because of the efficient use of superconductor and iron in shaping the field, minimal training, and the associated cost savings. An alternative to the traditional cosθ design was developed which replaces the annular windings with simpler flat wound coils. The flat winding approach can be applied due to a lenient one percent field accuracy limit for the correction coil package.

INTRODUCTION

The requirements for the correction coil package are:

total length	1.5m
integrated strength of the dipole	3.18Tm
integrated strength of the quadrupole	0.60Tm/cm
integrated strength of the sextupole	0.13Tm/cm^2
maximum current per coil	100A
field quality	$<1\%$ errors
inner radius of beam pipe	16.2mm

The superconducting wire has a copper to superconductor ratio of 1.8/1 with 9.5μm diameter filaments. Each strand of wire has a radius of 8 mils plus 1 mil of Formvar insulation. The maximum current is determined by heat loss considerations and is not a critical parameter. For the prototypes, except the superferric sextupole, the decision was made to wind the coils with cable that consists of several strands of wire laid on Kapton tape with a thickness of 50.8μm, thus making a total thickness of 0.508mm per layer of conductor. The number of strands in the cable varied for each type of coil built. This flat cable allows each conductor in the coil to be accurately placed and held in place against magnetic forces that change and reverse their direction. The technique is expected to provide better superconductor stability than potted coils with random winding.

One complication of using multiwire cable is that it requires several splices per magnet element. For a short magnet, like the superferric sextupole, it is possible to wind each of the six coils with a single strand of wire. For the longer magnets, it is extremely hard to keep the wires aligned in the straight part of the coils over distances of one meter. We measured the resistances of several different types of splices. In the prototype correction magnets, we used both soldered joints, and cold–welded joints, which only welded the copper matrix and not the superconducting filaments. Both methods were very reliable. The solder joints typically had a resistance of about $10^{-9}\Omega$. The cold–welds, which were easier and faster than the solder joints, typically gave a resistance of about $10^{-7}\Omega$.

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SUPERFERRIC CORRECTION MAGNETS

A superferric magnet is a superconducting magnet with an iron yoke and pole pieces. The iron contributes usually 60% or more to the field, thus saving superconductor. The nonlinearity of iron causes no problems because of the lenient 1% requirement of the field quality. The superferric design consists of three independent coils. The cross sections are shown in figures 1, 2, and 3. For each coil, the poles have the exact shape of the equipotential surfaces for the corresponding main harmonic. This is flat for the dipole and given by $\rho^n \sin n\theta =$ constant for a $2n$–pole.

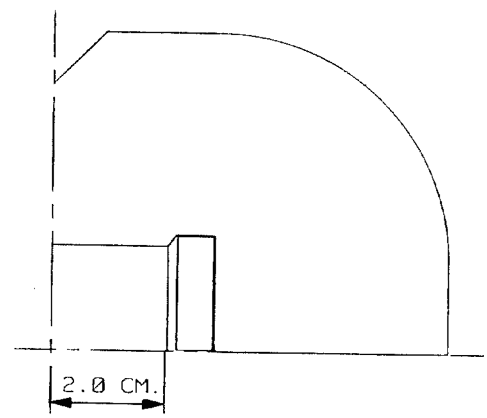

Fig. 1 Quadrant of the superferric dipole cross section.

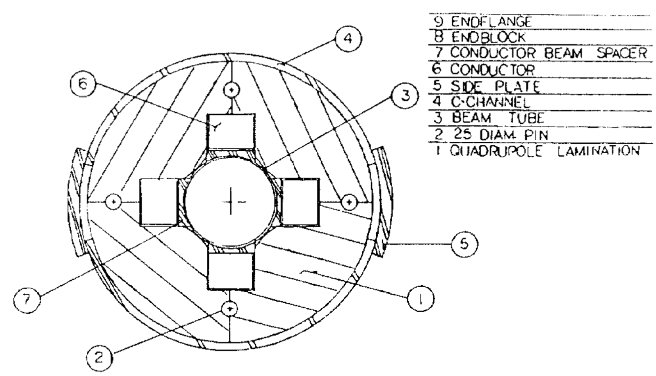

Fig. 2 Cross section of the superferric quadrupole.

The superferric dipole was made with 40 layers of 14–strand cable. Persistent current effects were estimated using the program PERCUR, assuming 684 superconducting filaments with a diameter of 8.7μm per filament and a critical current of 5000$\frac{\mathrm{A}}{\mathrm{mm}^2}$. They were found to be negligible as compared with 1% field accuracy. An equivalent $\cos\theta$ magnet would give $b_2 = 0.4\times10^{-4}\mathrm{cm}^{-2}$. Two model dipoles were built. Table 1 shows the predicted multipoles as calculated by the program POISSON. Measurements of the harmonics are shown in Table 2. At 3 T the sextupole moment is a little bigger than 1%. By making a small gap of 15 mils in the conductor package along the horizontal midplane, the sextupole contribution is decreased as shown in Table 3.

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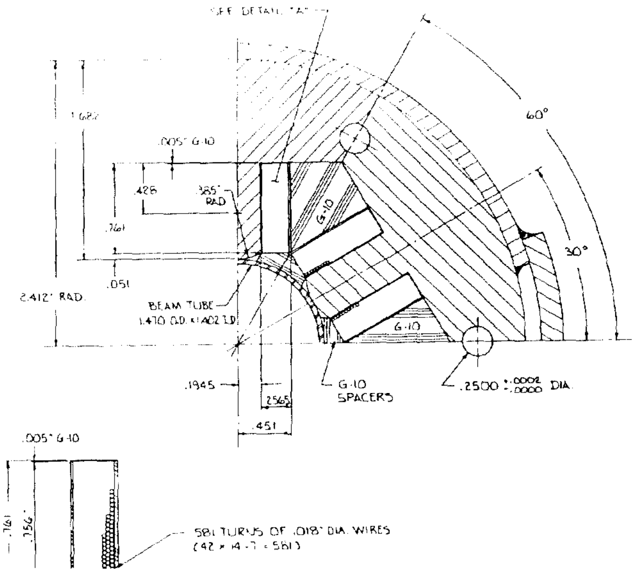

Fig. 3 Quadrant of the superferric sextupole cross section.

I(A)	B_0(T)	$b_2 \times 10^{-2}$	$b_4 \times 10^{-4}$	$b_6 \times 10^{-6}$
10.0	0.3654	-30.0	-7.0	0.4
20.0	0.7310	-28.5	-7.0	0.2
30.0	1.0962	-30.1	-6.7	0.4
40.0	1.4611	-32.7	-7.1	0.4
50.0	1.8196	-34.3	-6.0	0.9
60.0	2.1612	-36.4	-2.4	1.2
70.0	2.4392	-1.1	0.6	1.0
80.0	2.6847	39.4	3.1	0.9
90.0	2.9131	77.8	5.4	0.8
100.0	3.1312	113.5	7.5	0.7

Table 1. Predicted multipoles for the superferric dipole

I(A)	B_0(T)	$b_2 \times 10^{-4}\mathrm{cm}^{-2}$
10.3	0.389	-25
19.5	0.713	-25
28.7	1.043	-26
37.6	1.391	-27
47.4	1.735	-28
59.1	2.143	-27
69.8	2.444	2
79.8	2.696	42
88.4	2.898	77
99.5	3.142	117

Table 2. Measured multipoles for superferric dipole
All other multipoles are less than 1×10^{-3}.

I(A)	B_0(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$	$b_6 \times 10^{-4}$
10.0	0.3771	-83.7	-13.7	1.9
20.0	0.7541	-85.2	-13.4	2.0
30.0	1.1307	-88.2	-12.9	2.2
40.0	1.5052	-93.5	-11.4	2.4
50.0	1.8697	-97.9	-8.3	2.3
60.0	2.1975	-85.4	-3.7	1.6
70.0	2.4722	-44.2	-1.6	1.0
80.0	2.7226	2.4	0.0	0.4
90.0	2.9587	36.7	1.5	0.0
100.0	3.1850	72.9	2.8	0.0

Table 3. Multipoles for final design of superferric dipole

The superferric quadrupole was made up of four identical coils as shown in figure 2. Each coil consisted of 30 layers of 20–strand cable. The 2–D harmonics as calculated by POISSON are given in Table 4. No models of the superferric quadrupole have been built.

I(A)	b_1(T/m)	$\frac{b_5}{b_1} \times 10^{-4}$	$\frac{b_9}{b_1} \times 10^{-4}$	$\frac{b_{13}}{b_1} \times 10^{-4}$
10.0	42.4	-54.5	6.3	-5.0
20.0	83.5	-54.2	6.4	-5.0
30.0	108.1	-44.3	7.6	-5.0
50.0	139.6	-15.1	9.5	-4.8
60.0	152.5	-7.6	10.0	-4.6
70.0	165.1	3.4	7.0	-7.5
80.0	177.3	9.2	8.8	-5.1
90.0	189.5	15.7	8.8	-5.0
100.0	201.6	21.4	8.9	-5.0

Table 4. Predicted multipoles for the superferric quadrupole

The superferric sextupole was made with six identical flat coils, each wound about an iron pole piece. A single coil is comprised of 18 layers with 11 turns in each layer. One model magnet was built. In this case, the coils were wound with a single superconducting wire, since the length of a coil was short. The measurements of the prototype gave no multipoles greater than 1%. The measurements include the ends, since the magnet was shorter than the measurement probe. The program MAGNUS was used to calculate the end effects, and the effective length was found to be 0.89cm longer than the iron at each end of the magnet.

COSINE THETA CORRECTION COILS

This coil package consists of a nested dipole, quadrupole, and sextupole coil inside a cylindrical iron shield, as shown in figure 4. All coils have a flat cross section, rather than an annular one, because this greatly simplifies construction and reduces labor when winding with multistrand cable. Labor is the most important item for cost consideration. In order to define the thickness of the iron shield, the field of the dipole was calculated in several cases. It was found that 3.6cm is the critical value. A thinner shield gives a weaker field of lower quality, while the field is the same for thicker shields. We have examined various combinations of the three coils, and have found that the one shown in figure 4 requires less superconductor. However, since the quadrupole is inside the strong field of the dipole, the quadrupole is built slightly longer so that its ends are at a lower field, reducing the risk of a quench.

The design of the $\cos\theta$ package is described in Table 5. We constructed a modified version of the $\cos\theta$ package which is shorter and does not have the sextupole on the outside. Tables 6 and 7 show the measured harmonics for the dipole and quadrupole in this package. The 3–D program MAGNUS was used to calculate the effective lengths of both the dipole and quadrupole ends. For the dipole, the calculation gave a length of 3.8cm per end, and a measurement of the magnet gave a length of 3.3cm per end. For the quadrupole, a length of 5.8cm per end was calculated, and a length of 5.6cm was measured.

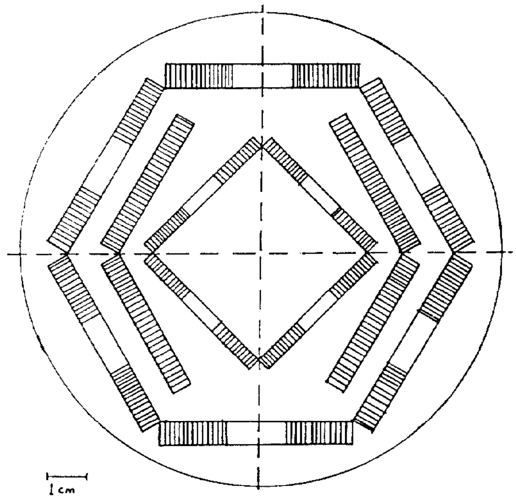

Fig. 4 Cross section of the cos θ package as designed.

Design parameters for the cos θ package			
	Quad	Dipole	Sextupole
Layers per coil	26	75	33
Strands per layer	7	11	13
Turns per coil	182	825	429
Width of coil	0.250cm	0.503cm	0.234cm
Inner Radius of iron	5.84cm	5.84cm	5.84cm
Outer Radius of iron	10.92cm	10.92cm	10.92cm
Field (from POISSON) (at 100A)	$0.428\frac{T}{cm}$	2.075T	$0.099\frac{T}{cm^2}$
higher order multipoles	$< 1\%$	$< 1\%$	$< 1\%$

Table 5.

Harmonic	Dipole Center	Dipole with ends
b_1	$-7 \times 10^{-4} cm^{-1}$	$-7 \times 10^{-4} cm^{-1}$
b_2	$-7 \times 10^{-4} cm^{-2}$	$-17 \times 10^{-4} cm^{-2}$
b_3	$-11 \times 10^{-4} cm^{-3}$	$-11 \times 10^{-4} cm^{-3}$
b_4	$-13 \times 10^{-4} cm^{-4}$	$-13 \times 10^{-4} cm^{-4}$
a_1	$6 \times 10^{-4} cm^{-1}$	$2 \times 10^{-4} cm^{-1}$
a_2	$0 \times 10^{-4} cm^{-2}$	$0 \times 10^{-4} cm^{-2}$
a_3	$-4 \times 10^{-4} cm^{-3}$	$-4 \times 10^{-4} cm^{-3}$
a_4	$0 \times 10^{-4} cm^{-4}$	$0 \times 10^{-4} cm^{-4}$

Table 6. Measured harmonics for the cos θ dipole.
All other higher harmonics are smaller than 1×10^{-4}.

	Central Field		Field with ends	
n	$b_n(cm^{-n})$	$a_n(cm^{-n})$	$b_n(cm^{-n})$	$a_n(cm^{-n})$
2	-0.004	-0.003	-0.001	0.002
3	0.009	-0.004	0.009	-0.004
4	-0.004	-0.014	0.002	-0.012
5	-0.008	-0.002	-0.010	-0.003
6	0.002	0.002	-0.002	-0.000
7	-0.003	-0.004	-0.005	-0.001
8	-0.001	-0.007	0.003	0.005
9	0.002	-0.007	-0.001	-0.006

Table 7. Measured harmonics for the cos θ quadrupole.

QUENCH BEHAVIOR

Tables 8 and 9 give the quench history of each of these magnets. We used the wire described earlier only because it was readily available. Historically[1], Formvar insulated wire has trained badly. We believe this is the only problem with these correction magnets. We would propose to change the insulation and increase the copper to superconductor ratio to a value between 4/1 and 5/1.

Magnet	Currents (Amperes)
Superferric Dipole 1	85,89,100,106,111
Superferric Dipole 2	62,87,101,110
Superferric Sextupole	61,75,80,84,92,90,95,93,105
Cosθ Quadrupole only	133,135,136
Cosθ Dipole only	77,81,83,87

Table 8. Quench Currents for Single Magnets

Coil	Currents (Amperes)										
Quadrupole	10	2	**87**	**90**	**91**	2	2	**76**	**78**	...	**86.6**
Dipole	**92**	**91**	50	50	50	**96**	**100**	74	74	...	86.4

Table 9. Quench Currents for Coupled Cosθ Dipole and Quad. **Bold** faced currents indicate the coil that quenched. The ramp rate was 40 amps/second.

[1] W. Sampson, BNL, Private Communication