LBL--23942

DE88 004573

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ABSTRACT

The SSC colliding beam storage ring requires superconducting magnets capable of producing a magnetic field of 6.6 T which has very high accuracy. For many of the multipoles, that multipole must be reduced (at a radius of 1 centimeter) to the order of 0.2 parts in 10,000. This field accuracy is dictated by the physics of storing very small high-current proton beams at energies ranging from 1 TeV to 20 TeV. Magnetization of the superconductor can cause sextupole field errors of up to 6 parts in 10,000 at an injection field of 0.33 T at a radius of 1 centimeter. Saturation of the magnet iron can induce sextupole field errors of 1 to 2 parts in 10,000 at the full field of 6.6 T. Manufacturing errors can induce other multipole components, both normal and skew. The SSC coil has three wedges separating the superconducting coil blocks on the inner layer of the coil. These wedges must be accurately located. If the wedges have superconductors attached, one can correct all of the magnetic field multipoles (both normal and skew) from N=1 (dipole) to N=6 (12 pole). This paper describes this method of correction as it pertains to the SSC dipole magnet.

Background

The SSC machine requires magnets which produce a good quality magnetic field. The beam in the SSC machine, particularly at injection, is sensitive to magnetic field errors which are less than 1 unit (one unit is defined as one part in 10000.) A partial list of the types of field errors which may be present in the SSC magnets include the following:[1]

1) Errors caused by winding faults in the magnet cause both normal and skew multipoles in the field.

2) Errors introduced by iron saturation or the inverse caused by a designed in error which goes to zero as the iron saturates. This error is predominately a normal sextupole term in the field.

3) Eddy currents in the bore tube, the coils, the collars and the iron will produce predominately normal sextupole and decapole terms in the field.

4) Magnetization of the superconductor will generate a normal sextupole, decapole and N=7 in the field. If the filament diameter and the average superconductor critical current are not the same in the top and bottom coils of the dipole, a skew quadrupole will be generated.[2]

5) Steering errors might be corrected with a normal or skew dipole.

6) Tune errors might be corrected with a normal and or skew quadrupole or sextupole.

Several methods for correcting the field in the SSC magnets has been proposed. Lumped correctors have been used with most accelerators built to date but there is a question as to how far one can go with this technique on the SSC. The SSC design study[3] has proposed continuous correction magnets wound on the dipole magnet bore tube. These correction coils would provide at least normal quadrupole, and normal sextupole. The number of bore tube correction magnets is limited by the radial space inside the dipole coil. The bore tube correction magnet also have an effect on the bore tube surface temperature when synchrotron radiation is present at full energy.[4]. Passive correction of magnetization normal sextupole decapole and 14 pole has been proposed.[5] This method will correct the magnetization field reasonably well provided there is not too much variation in conductor properties between the top and bottom coils.

Correction with Superconductor in the Magnet Wedges

Once one has demonstrated that there is a need for continuous correction along the dipole magnet bore, correction using superconductor located on the magnet wedges should be considered.[6] The advantages of using the superconducting coil wedges as correction elements are as follows:

1) The wedge must be accurately located along with the coil blocks. As a result, the wedge position determines the conductor position with enough accuracy to do a good job of locating the correction windings.

2) The correction occurs along the full straight section length of the dipole magnet. End effects can be compensated for by small changes of current in the wedges. (The dipole magnet length is much shorter than a betatron wave length of the machine.)

3) The bore tube does not have to be machined or formed because it does not carry correction coils.

4) The bore tube can be moved closer to the superconducting coil which permits one to increase the beam clearance somewhat.

5) The outside surface of the bore tube can be helium cooled directly. Hot spots due to synchrotron radiation can be reduced greatly.

6) Wedge correction can be used to correct the first six multipole terms both normal and skew depending on how the wedges are hooked up.

Correction winding on the wedges do present certain problems, which are:

1) The current leads for the wedge corrector might have currents as high as 150 A.

2) The wedges must be extruded in continuous lengths up to 17 meters. This extrusion must be accurate and the placement of the superconductor on the wedge must not affect the wedge cross-section.

3) Additional insulation on the wedges may be required in order to protect the correction circuit during a quench of the dipole magnet.

4) Wedge correction will require from 3 to 12 power supplies per magnet or magnet set depending on the extent of the wedge correction.[7] (Bore tube compensation coils will require at least two power supplies.)

5) Wedge correction may require a large number of gas cooled leads. These leads can significantly increase the refrigeration needed to cool the machine.

Wedge correction in an SSC dipole magnet is illustrated in Figure 1 which shows 3 wedge correction windings on the inside three wedges of the BNL C348A coil cross-section.[8] The largest conductor which can be attached to wedge 1 is about 0.4 mm in diameter; wedge 2 will allow a 0.5 mm diameter superconductor; and wedge 3 will allow a much larger superconductor. The available correction is limited by the current which can be carried in wedges 1 and 2.

If one limits the peak current in each wedge to 90 percent of the superconductor critical current at 4.3 K and 7 T, one finds that wedge 1 can carry up to 90 A and wedge 2 can carry up to 140 A. (This is based on a copper to superconductor ratio of 1 and a superconductor specified J_c= 2750 Amm^{-2} at 4.2 K and 5.0 T.) Table 1 shows the maximum correction available for the first five normal terms using the wedge conductors shown in Figure 1.

Table 1. Maximum Correction at Full Field (6.6 T) for Various Multipoles

Multipole	Correction available (parts in 10000)
1	8.2
2	4.5
3	2.4
4	1.1
5	0.6

*at a radius of 10 mm (see Figure 1)

If the wedges are hooked up in a way which produces normal dipole symmetry (the currents in the second and third quadrants is -1 times the currents in the first quadrant and the currents in the forth quadrant is the same as those at corresponding points in the first quadrant), one can produce correction for normal dipole (N=1), sextupole (N=3) and decapole (N=5). Table 2 shows the values of various normal symmetrical multipoles when the currents are set to produce a dipole of 0.002 T (3 units of correction at full field, a sextupole of 0.00066 T at a radius of 10 mm (1 unit at full field), and a decapole of 0.00033 T at a radius of 10 mm (0.5 units at full field). Table 3 shows the values of the symmetric wedge currents needed to produce the correction field pattern shown in Table 2.

Figure 1.

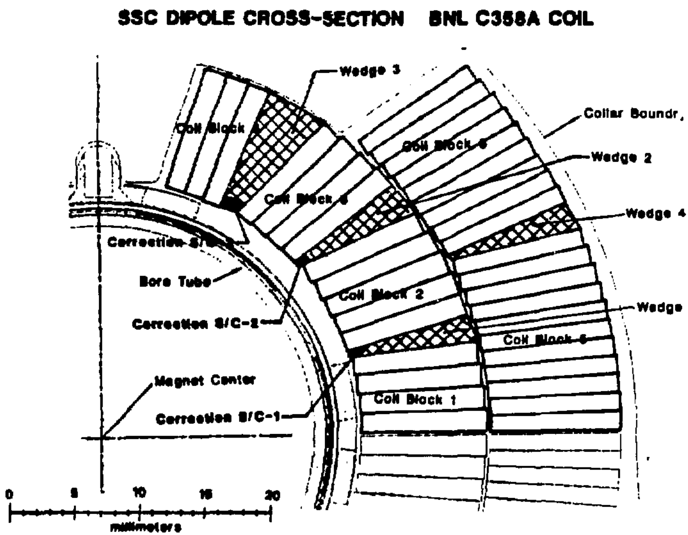


Table 2. The Value of Various Symmetric Normal Multipoles for Various Dipole, Sextupole and Decapole Corrections at Full Field

Multipole Number	Multipole Value (T)* Dipole Correction 3 Units	Sextupole Correction 1 unit	Decapole Correction 0.6 units
1	0.00200	0.00000	0.00000
3	0.00000	0.00066	0.00000
5	0.00000	0.00000	0.00033
7	-0.00001	-0.00002	-0.00001
9	0.00000	0.00000	-0.00003

*at a radius of 10 mm

Table 3. The Current on the Wedges in Figure 1 Needed to Generate the Multipoles Shown in Table 2.

Wedge Number	Wedge Correction Current (A) Dipole Correction 3 Units	Sextupole Correction 1 Unit	Decapole Correction 0.6 Units
1	-32.75	-37.27	-46.62
2	- 8.65	21.80	111.18
3	-14.97	38.10	-83.01

<u>Method for Hooking up the Wedge Correctors and the Lead Refrigeration</u>

Table 2 illustrates correction when one hooks the wedge correction system up to correct only normal N=1, 3 and 5. The circuit diagram for hooking up to correctors to generate the field pattern shown in Table 2 is shown in Figure 2. This circuit is suitable for correcting superconductor magnetization effects, eddy current effects, and iron saturation effects. This circuit does not correct any skew terms or normal quadrupole octupole or N=6. The refrigeration required to cool the leads for the circuit shown in Figure 2 is about 1.5 W (liquifaction equivalent) per magnet or group of six magnets. (The extra refrigeration amounts to 0.09 W per meter for one magnet and 0.015 W per meter for six magnet groups).

The wedge correction system can be hooked up to correct all the normal terms from N=1 through N=6. The circuit diagram for using wedge correction to correct only normal N=1 through 6 is shown in Figure 3. The refrigeration required to cool the leads shown in Figure 3 is about 2.5 W (liquifaction equivalent) per magnet or group of six magnets. (The extra refrigeration amounts to 0.15 W per meter for one magnet and 0.025 W per meter for six magnet groups.)

The correction circuit shown in Figure 3 will correct most of the required terms. The most troublesome term not corrected is the skew quadrupole which is generated by symmetric magnetization of the superconductor on the top and bottom coils of the dipole. Figure 4 shows the magnetization skew quadrupole and normal sextupole generated by an SSC dipole with filament diameter in the upper coil of 5.25 microns and filament diameter in the lower coil of 4.75 microns. A normal sextupole of 6.7 units occurs at injection. The ten percent top-bottom variation of filament diameter will generate first, to first order, just over 1 unit of skew quadrupole at injection. One can reduce this term greatly by superconductor quality control and by shuffling the superconductors in the cables used to build the dipole.[9]

Figure 2.

CIRCUIT DIAGRAM FOR WEDGE CORRECTORS

CORRECTS 1N, 3N, AND 5N

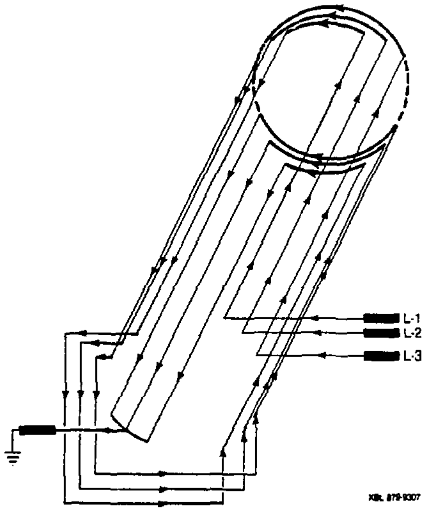


Figure 3.

CIRCUIT DIAGRAM FOR WEDGE CORRECTORS

CORRECTS 1N, 2N, 3N, 4N, 5N AND 6N

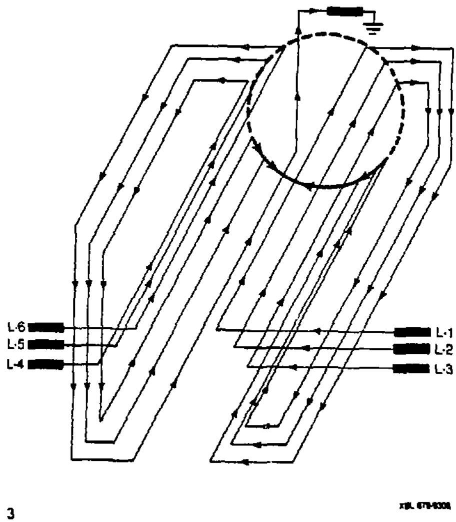


Figure 4.

RATIO OF MAGNETIZATION FIELD TO TRANSPORT CURRENT FIELD WITH A TEN PERCENT TOP BOTTOM ASYMMETRY OF FILAMENT DIAMETER

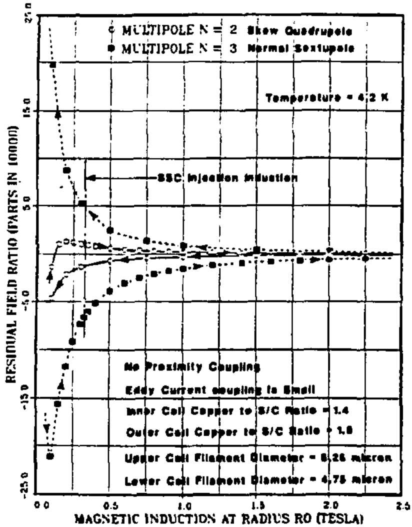
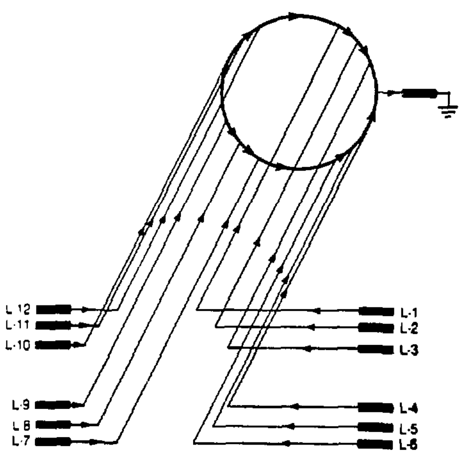


Figure 5.

CIRCUIT DIAGRAM FOR WEDGE CORRECTORS

CORRECTS 1N, 2N, 3N, 4N, 5N AND 6N
CORRECTS 1S, 2S, 3S, 4S, 5S, AND 6S



Wedge correction permits one to correct the first six terms of both the normal and skew fields should that become necessary. The circuit diagram for the correction of all of terms is shown in Figure 5. There are thirteen leads for each set of correction coils. These leads will require about 4.5 W of refrigeration (equivalent liquifaction) per set. (This amounts to add refrigeration of 0.045 W per meter for a set of correction wedges for six magnets in series.)

Concluding Comments

Superconductor mounted on the SSC dipole magnet wedges can be used to correct the magnetic field in the SSC accelerator. Wedge correction can correct more multipoles than either lumped correction coils or continuous bore tube correction coils, which correct two or three terms. The three inner wedges can be used to correct all terms normal and skew from N=1 (dipole) to N=6. The price one pays is additional complication of the dipole magnets and additional helium refrigeration needed to cool the extra magnet leads. (This refrigeration can be reduced by putting the wedges in six dipole magnets in series.) Wedge correction will result in the elimination of continuous bore tube correction coils and it could result in simplication of the SSC lumped correction magnet system.

Acknowledgements

The author thanks J. M. Peterson of the SSC Control Design Group and C. E. Taylor of the Lawrence Berkeley Laboratory for their comments. This work was performed under the Auspices of the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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