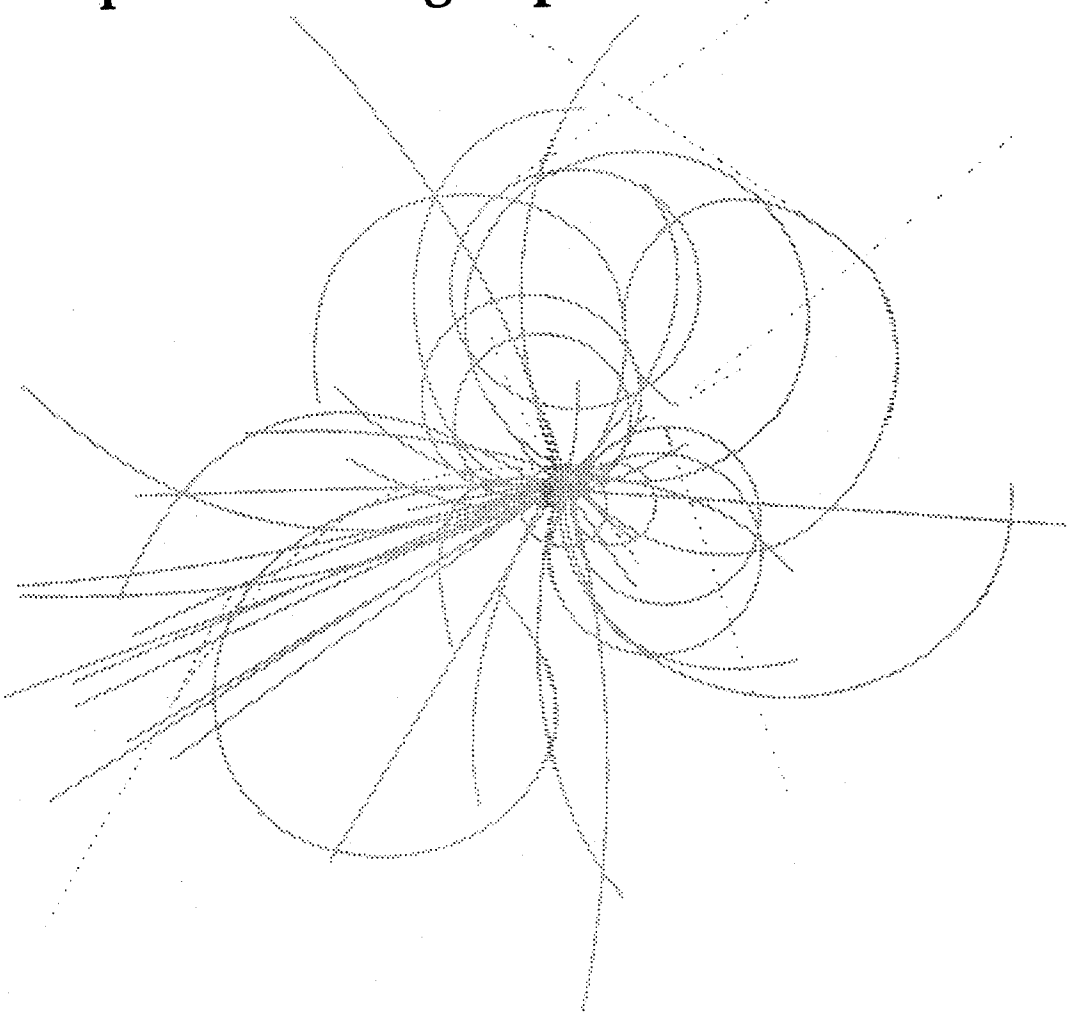
SSCL-489

Superconducting Super Collider Laboratory

SSCL-489



Mechanical and Electromagnetic Design of the SSC QSE101 Quadrupole Ends

D. Orrell, F. Nobrega, J. Lilly, G. Snitchler, J. Jayakumar, V. Venkatraman, and J. Brandt

June 1991

SSCL-489

Mechanical and Electromagnetic Design of the SSC QSE101 Quadrupole Ends*

D. Orrell, F. Nobrega, J. Lilly, G. Snitchler, J. Jayakumar,
V. Venkatraman, J. Brandt

Magnet Division
Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

June 1991

---

*Presented at the MT-12 Conference, Lenningrad, U.S.S.R., June 24–28, 1991.
†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

Mechanical and Electromagnetic Design of the SSC QSE101 Quadrupole Ends

D. Orrell, F. Nobrega, J. Lilly, G. Snitchler, J. Jayakumar, V. Venkatraman
Magnet Division, SSC Laboratory, Dallas, TX 75237

J. S. Brandt, Fermi National AcceleratorLaboratory
Pine & Kirk Roads, Batavia, IL 60510

ABSTRACT

The SSC collider magnets feature grouped ends in which cables of a particular coil remain stacked together as they are bent around the end. Methods have been developed to form the ends in such a way that mechanical stresses are lowered and field quality is optimized. This paper discusses techniques of end turn design and presents calculations of harmonics and peak fields for the SSC quadrupole QSE101.

INTRODUCTION

QSE101 is a 50 mm bore diameter quadrupole magnet intended to operate in the interaction region of the SSC main ring. It has an operating current of 6550 Amps, a central gradient of 189 T/m and an overall length of about 14 m. A cross-section of one octant is shown in Figure 1.

End turn designs range from the individually determined end in which each cable is allowed to follow its own least-stressed path, to the grouped approach in which cables of a particular block remain stacked together. The latter approach is favoured at the SSC chiefly because it lends itself well to high rate production; the end parts can be mass produced at low cost and provide good reproducibility between magnets. A disadvantage of the grouped approach is that it is impossible to have each cable in a coil follow a stress free path, which can lead to damage of insulation or the superconducting filaments. A procedure has therefore been developed that minimizes the stress seen by the cables.

In designing the end it is also necessary to minimize the undesirable harmonics generated by the end turns. Techniques have been developed that accurately model the fields in the end region and can predict the magnet harmonics, peak fields and conductor forces.

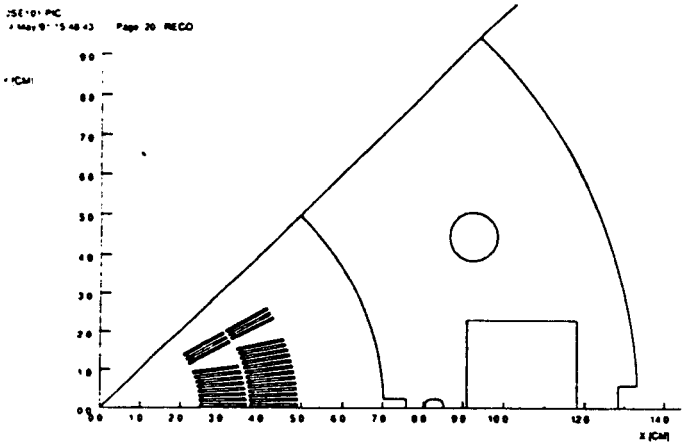


Figure 1. Cross-section of QSE101

MECHANICAL DESIGN

The program BEND[1,2] is used as a design tool to mechanically optimize the coil ends for strain and twist. Group defining data is supplied interactively by the user; the program then constructs the end turn around an infinitely thin strip in space called the "guiding strip". The position of the guiding strip within the group can be varied and the cables adjacent to the strip will follow the least strain surface obtainable with the given constraints. By varying the position of the guiding strip the user iteratively arrives at the solution with a minimum overall strain energy.

Once optimization is complete, BEND outputs six files that contain the X, Y, Z Cartesian coordinates. Three of these files are used to describe the end part surfaces used for manufacturing end parts. Two files, Centroid and Corner, are used to describe the conductor placement for mechanical and magnetic analysis. Output file Centroid provides fifty centroids of each conductor in the group. Output file Corner provides fifty sets of points (trapezoids) that describe each conductor in the group. The remaining file is a Frenet frame file that can be used for automated winding positions.[3] Figure 2 shows a 3-D CAD picture of a saddle piece drawn according to the BEND output.

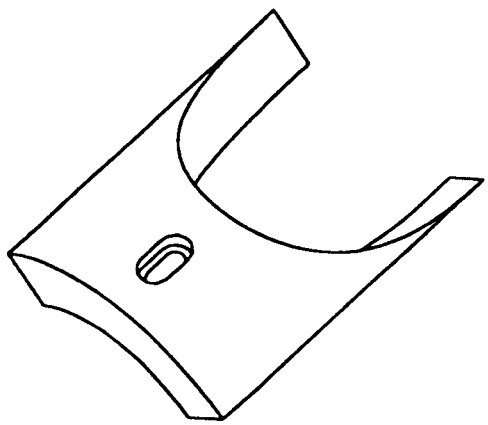


Figure 2. Saddle Piece

MAGNETIC DESIGN

The main goal of the magnetic design for a quadrupole is to adjust the end configuration in such a way as to minimize the integral of b5 through the end (higher harmonics are usually small) while retaining a mechanically feasible design. This is done by adjusting the offsets of the various coils, i.e. the point at which the coil begins its bend. Figure 3 is a schematic diagram of the design sequence. The BEND program Corner output is read by the analytical code ENDS3, which directly calculates the field due to each coil without the presence of iron. The fields are calculated on a number of 20 mm radius circles at various points along the axis of the magnet. A Fourier transform is then performed to yield the harmonics. The integrated harmonics and the harmonics at the center of the magnet are calculated for each coil. It is then straightforward to find what offsets will give zero integrated b5 over all coils, subject to mechanical constraints. This will only be a first estimate since the effect of iron has not yet been taken into account; however the contribution of the iron to b5 is small for a magnet of this sort.

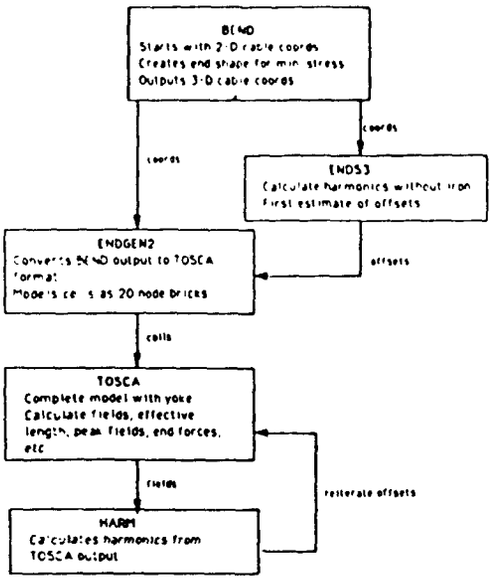


Figure 3. Schematic Diagram of 3-D EM Design

The coils with the new offsets are modelled on TOSCA[4], which is a 3-D finite element program for electromagnetics. An intermediate program ENDGEN2 generates a set of conductor elements from the BEND output in the correct format for TOSCA. Figure 4 shows two coils as modelled by ENDGEN2, on the top, and BEND, on the bottom[5]. Cubic spline fits are made to the four corners, the middle of the four faces and the line running through the center of the conductor. A number of planes are taken at evenly spaced intervals perpendicular to the central line, and the points at which the other lines intersect with the planes are taken. These points are used to generate a number of coil segments which are defined in TOSCA by eight corner points and twelve more points to give the curvature of the faces. Three segments are used across the width of the coil to model the varying current density. The length of the coil is divided into five sections to model the curvature. The number of subdivisions was determined by adjusting them until good agreement was achieved between TOSCA and ENDS3 in the case where no iron is present.

Figure 5 shows the final TOSCA model of the magnet. The finite element model of the iron has been added manually; it uses about 50,000 nodes for one quadrant. Fields are calculated on 2 cm radius circles at various points along the axis of the magnet; the TOSCA output is then read by a program HARM which extracts the fields and performs a Fourier transform to give the harmonics. If necessary the coil offsets can be readjusted at this point to take into account the effect of the iron on b5.

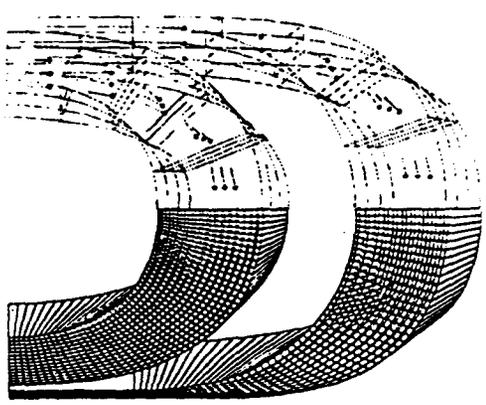


Figure 4. End turns by ENDGEN2 (top) and BEND (bottom)

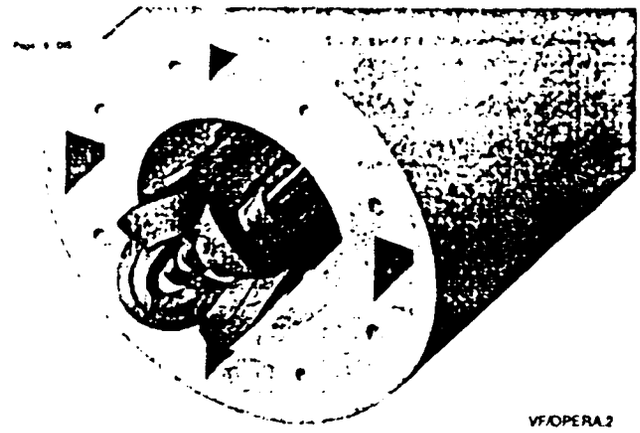


Figure 5. TOSCA model

The gradient and harmonics b5 and b9 for the final design are shown plotted in Figures 6, 7 and 8 as a function of distance z. Here z=0 refers to the point at which the iron yoke laminations end. The integral of the gradient yields the effective magnetic length which for this design is 49 mm past the iron. The harmonics b5 and b9 is expressed in terms of 'units' which are defined as parts in 10000 of the main quadrupole field as evaluated at a 1 cm radius. The integrated b5 due to the ends when averaged over the 14 m length of the magnet is only 0.006 units. Integrated b9 averages to 0.0006 units.

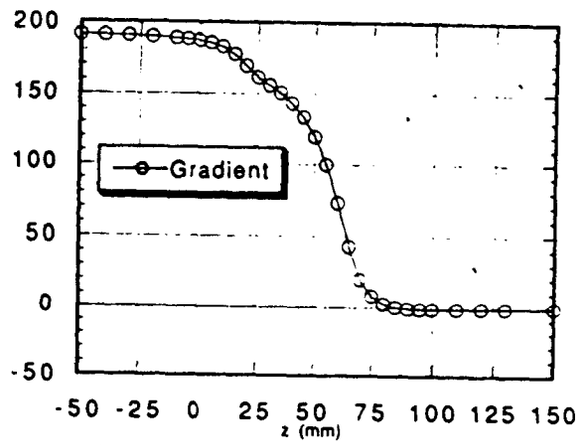


Figure 6. Gradient (T/m) vs z (mm)

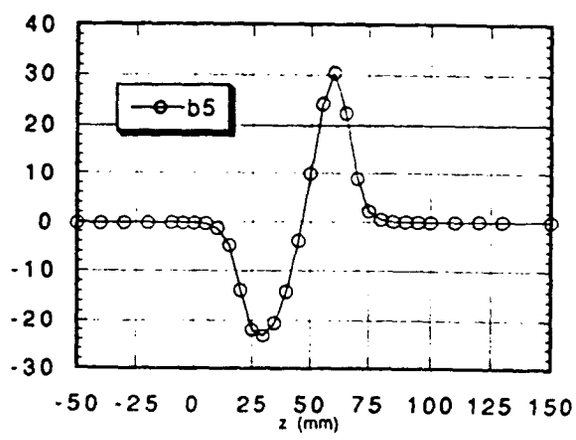


Figure 7. Harmonic b5 (units) vs z (mm)

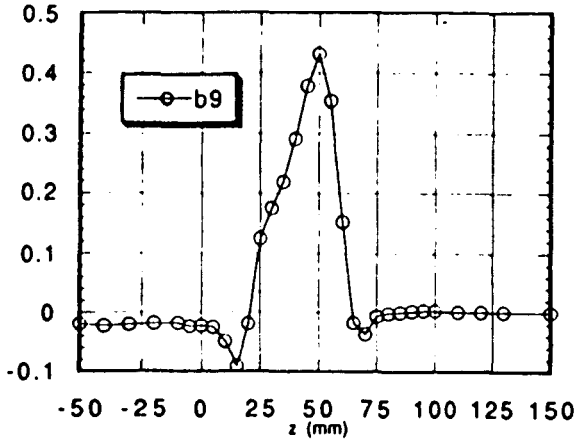


Figure 8. Harmonic b9 (units) vs z (mm)

Figure 9 is a contour plot of the field on the inner pole turn (the contours are not clear in black and white, but indicate the sort of calculation). About 6000 points were sampled on the surface. The peak field occurs at the tip of the end turn and is only 0.3% less than the peak field at the center. This is a matter of concern since the cables are less well supported at the ends than at the center and so the quench behavior of the magnet may be limited by quenches in the ends. Another model was done in which the iron yoke was extended over the ends; this raised the peak field by 3%, an unacceptable amount. The forces on the ends in the axial direction were found to be 16061 N for the inner layer and 28816 N for the outer layer, totalling 44877 N.

SUMMARY

The QSE101 magnet is the first magnet to have been completely designed at the SSC. The end turns have been designed to be mechanically robust and easily produced. By optimizing the end configuration, integrated harmonics through the end have been minimized. Tools are in place for a variety of electromagnetic calculations, such as forces and peak fields.

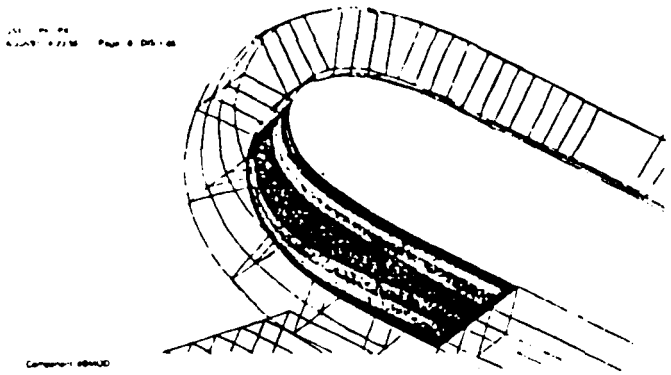


Figure 9. Contour plot of field on inner pole conductor.

REFERENCES

1. J. M. Cook, "An Application of Differential Geometry to SSC Coil End Design," SSC Laboratory SSCL-N-720, 1990.

2. J. M. Cook, "Strain Energy in SSC Magnet Winding," in *IEEE Transactions on Magnetics*, vol. 27, pp.1976-1980, March 1991.

3. J. S. Brandt, N. W. Bartlett, R. C. Bossert, J. A. Carson, J. J. Konc, G. C. Lee, J. M. Cook, S. Caspi, M. A. Gordan, F. Nobrega, "Coil End Design for the SSC Collider Dipole Magnet", 1991.

4. TOSCA, Trademark from Vector Fields Limited, Oxford, England.

5. S. Caspi, private communication.