LBL-21297
SSC-MAG-72
SSC-N-245

DEVELOPMENT OF A 40 mm BORE MAGNET CROSS SECTION WITH HIGH FIELD UNIFORMITY FOR THE 6.6T SSC DIPOLE*

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Presented at the 1986 Applied Superconductivity Conference, Baltimore, MD
September 29-October 3, 1986

*This work is supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

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Abstract

The SSC requires a very uniform dipole field. A 40 mm bore diameter winding cross section has been developed which has computed multipole coefficients less than 1×10^{-6} of the dipole field at 10 mm radius for an operating field of 6.6T at 4.35 K. This cross section has 4 conductor blocks (3 wedges, 16 turns) per quadrant in the inner layer, and two blocks (1 wedge, 20 turns) in the outer layer. "Partially keystoned" cable is used; the inner cable has 23 strands of .0318 inch diameter wire; the outer cable has 30 strands of .0255 inch diameter wire. Model magnets have been constructed and the fields measured at room temperature and at liquid helium temperature up to fields exceeding 6.6T. Measured fields are compared to the predicted field. In addition, the as-built conductor positions in several magnets have been determined after cutting up the magnets. The predictions based on as-built configurations are computed and compared to measurements.

Introduction

A design goal for the SSC, a 20 TeV proton-proton collider, is that the dipole magnetic field be uniform to within $|\Delta B/B|$ of about 10^{-4} at 10 mm radius for random magnet-to-magnet variations. Also, systematic variations must be correctable, using a combination of distributed and lumped trim magnets, to $|\Delta B/B| \sim 10^{-5}$. This requires that the winding cross section have extremely small "built-in" systematic field distortions so that practical trim magnets can be built.

In this paper we describe the design of a SSC dipole cross section that is in accord with the Central Design Group (CDG) specification for field uniformity (comments on the magnet end design and the elimination of training can be found in Ref. 1 and 2). First, we introduce the computational tools used in modeling the magnet cross section. Next, we present the dipole design and report on data and measurements for 9 such models. The difference between the measured and predicted multipoles is then discussed. Finally, we discuss measurements of the conductor positions from an autopsy and compare them with the design.

Computational Tools in Magnet Design

In this section we describe two different computer programs used to model the SSC dipole magnet cross section. These programs have been used cautiously since the requirement for low multipoles demanded accurate modeling. The program PK is a fast, easy to use modeler and optimizer of magnet cross sections, using a simple current distribution and $\mu = \infty$ iron. A design produced by PK is solved by the program POISSON for more realistic iron, and then further refined by PK. This technique was used to develop the SSC magnet cross section.

Program PK

Short for PARTIALKEYSTONE, the program PK is a variation of a computer program developed by R. Fernow and G. Morgan (Brookhaven National Laboratory) for magnet cross section design.[3] This program uses the dimensions of a single conductor turn in a process that stacks them into blocks. The blocks are then stacked into layers, and the layers into a full cross section for which the multipoles are calculated. The block dimensions are regulated by the integer number of turns, whereas the spacing between the blocks (called wedges) can be continuously varied. In order to arrive at a cross section with a predefined set of multipoles (normally they should all be zero), an optimizer is used that varies the number of turns per block and then adjusts the wedge spacing. Of course, the optimization process does not guarantee that a cross section with the exact prespecified multipoles will be found. An acceptable cross section is usually one with multipoles closest to that called for by the design.

Current Density. Due to keystoning, the cable dimensions correspond to a trapezoid. The current density is computed from the area of the rectangle whose base coincides with the smallest base of the trapezoid (as suggested by G. Morgan and R. Meuser). We have verified that such an assumption is sufficiently accurate. Using this current density results in a sextupole which is 1.5 units (parts in 10^4) smaller than that computed by use of the trapezoidal area. The high multipoles are practically unchanged.

Program POISSON

The program POISSON (with special boundary conditions) was used to investigate two types of multipole contributions associated with iron. The first contribution comes from the existing notches along the inner diameter of the iron yoke (the program PK uses only circular iron). The notches yield a systematic offset that can be computed by POISSON. The second contribution is the effect of iron saturation with increasing field. POISSON was also used to compute magnetization effects.[4]

Current Density. The POISSON model does not use individual turns, using instead entire blocks. Each block was cut into two portions (an inner and an outer) along its middle radial width and 50% of that block's current was assigned to each portion, thus assuring some radial dependency of current density.

The Dipole Design

Reference Design D is a 3 wedge (per quadrant) cross section (called C5) for the SSC dipole magnet.[5] This cross section had the following computed multipoles (units): $b_2 = 0.4$, $b_4 = 0$, $b_6 = 0.2$, and $b_8 = 0.8$ (within the values required at that time). As additional tracking studies were made, a new set of multipole tolerances was established[6] (Table I.).

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy under Contract DE-AC03-76SF00098.

Manuscript received September 30, 1986.

Table I.
Dipole Magnet Field Uniformity Requirements at 10 mm

Multipole	Variances (x10^4)	Average (x10^4)
b_1	0.7	0.2
b_2	2.0	1.0
b_3	0.3	0.1
b_4	0.7	0.2
b_5	0.1	0.02
b_6	0.2	0.04
b_7	0.2	0.06
b_8	0.1	0.1

The CDG suggested that we attempt to redesign the dipole magnet cross section so that the higher multipoles -- b_8 (18 pole) and above -- would be less than 0.2 units of the dipole field. Reducing the high multipoles required a major change since small changes usually left them unaffected. We realized that the number of wedges should be increased to 4, and that some of the conductor blocks should depart from their radial orientation in order to improve field quality.

Using the program PK, a cross section with low multipole values (less than 1.0 X 10^{-6}) was found. *This cross section (Fig. 1) had 16 turns and* 3 wedges (per quadrant) in the inner layer, and 20 turns and 1 wedge (per quadrant) in the outer layer. The pole angles could still accommodate the existing collars. This design was called NC515.[7]

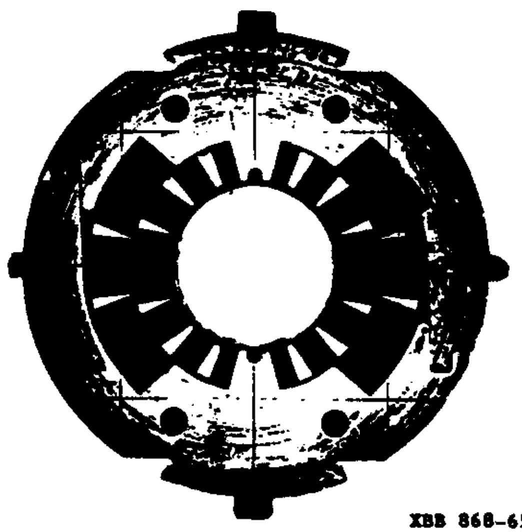
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Fig. 1. A "Radial" Version of an SSC Dipole (NC7 Design)

Once we began building magnets, we built each *cross section* *__precisely__* *according to the conductor* positions in the design. In cases where mechanical difficulties arose, we relaxed requirements of prestress. However, when the need for repositioning of conductor arose (even when very small), our philosophy required a new cross section design. Such changes always resulted in the manufacture of a new set of wedges. Shims along the midplane or any other lumped correctors were not used.

Magnets and Measurements

Three mechanical models of the NC515 design were built, MD-1, MD-2, and MD-3, using stainless steel collars. When our first new model magnet was built (D14-B1), the collars were changed to aluminum, as this modification has economic advantages for the SSC. As more was learned from the model magnets, the design was altered slightly: (NC6), followed by an improved design (NC7) that makes the blocks more radial. Table II is a chronological list of the magnets that were built and tested.

Table II.
LBL 4 Wedge Magnets

Magnet	Design	Collar Type
MD-1	NC515	Stainless Steel
MD-2	NC515	Stainless Steel
MD-3	NC515	Stainless Steel
D14-B1	NC515	Aluminum
D14-B2	NC6	Aluminum
D14-B3	NC6	Stainless Steel
D14-B4	NC7	Aluminum
D14-B5	NC7	Aluminum
D14-B6	NC6	Aluminum

The magnet multipoles were measured at room temperature and during operation at 1.8 K and 4.35 K. In order to compare their values with the design (and requirements), one has to exclude both magnetization and saturation effects. We therefore report here on the measured sextupole component at 3000 A (~ 3 tesla) and at room temperature (~ ±20 A) (Fig. 2.). In both cases these values are an average - between plus and minus current at room temperature, and between the increasing and decreasing sextupole at 3000 A. A difference in collar deformation between aluminum and stainless steel results in an additional ~ 3.0 units of sextupole (cold) for aluminum. This can be seen in Fig. 2 by comparing the sextupole value (cold) for D14-B1 with the values for MD-1, 2, 3, and comparing D14-B3 with D14-B2.

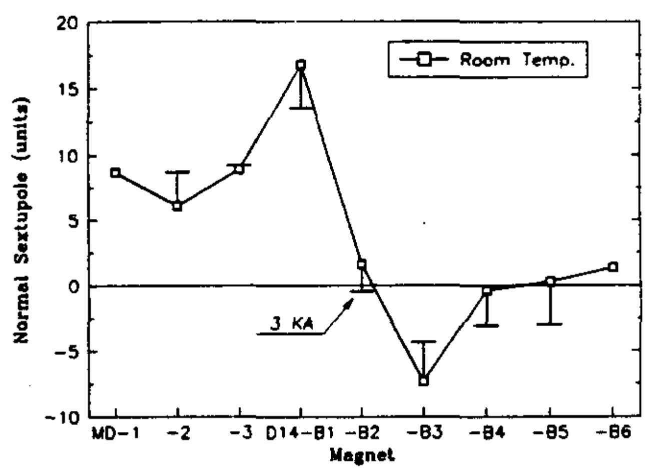

Fig. 2. Measured Sextupole for Configurations Listed in Table II (symbol = warm, bar = cold).

The effect of iron saturation on the sextupole is plotted in Fig. 3. The sextupole data were obtained by averaging values measured during a field increase and during a field decrease, and then subtracting the resulting average from the value measured at 3000 A (~ 3 T). This way we minimized magnetization effects so that data can be compared with predicted values computed by POISSON. The agreement between calculations and measurements (with regard explicitly to saturation) seems reasonable in view of the procedure taken as well as the fact that the maximum saturation effect on b_2 is rather small (~ +2 units). Computations have shown that 50% of the maximum sextupole (+1 unit) is a result of the notch in the iron inner radius across the pole.[8] In a new collar design, thesenotches have been eliminated.[9] Similarly, the notch along the midplane has an inverse effect on the sextupole and its size can be increased (with its current size, its contribution is ~ - 0.3 units).

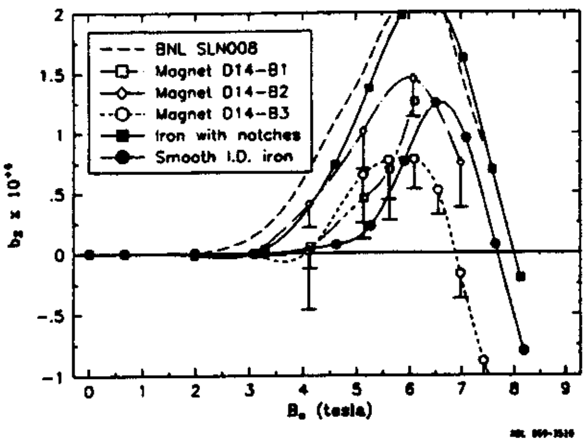

Fig. 3. Computation and Measurements of Saturation Effect on b_2 (dark symbols are computed).

Magnetic Distortions

The values of the measured sextupole (Fig. 2.) were far from what we had expected. We realized, however, that we could account for a part of the sextupole in such factors as manufacturing errors and idealization of current density. These contributions to the sextupole have been calculated and subtracted from the measurements, leaving a net difference between the predicted sextupole and its measured value. We assume that this unexplained "distortion" is a result of real dimension distortions that occur during the collaring process. Figure 4 plots the sextupole "distortion" as a function of the peak collaring pressure in the inner layer.

Although the required prestress in this type of magnet is about 5 kpsi (warm), assembly pressure is usually much higher. (See Fig. 5.) A momentarily high pressure exceeding ~ 17 kpsi, which is due to the existing collar and key system, is enough to cause irreversible distortions in both the conductor and insulation. This kind of distortion directly affects the multipoles. Even though such "damage" might be reproducible and its multipole distortion compensated magnetically, it is uncontrolled, and therefore a possible source of random errors. In order to find such areas of mechanical distortions, we have performed autopsies on a number of our magnets.

Mechanical Distortions (Quality Control)

It was the purpose of the autopsies to provide answers to the following two questions: 1) can the conductor be measured accurately enough to provide a cross check between multipoles calculated from as-built geometry and multipoles from magnetic measurements, and 2) can systematic distortions of the design be identified, and if so, is there evidence that they are responsible for the magnetic distortions?

Positive answers to these questions should provide confidence in our modeling and uncover areas that might be affected by high stress.

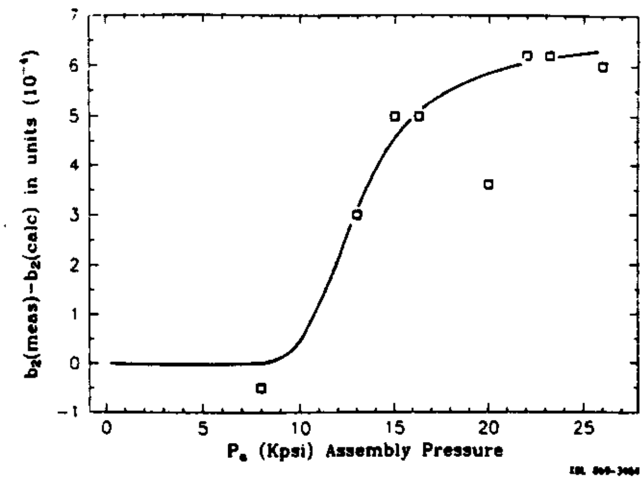

Fig. 4. The Difference Between The Measured and Predicted Sextupole as a Function of the Inner Layer Peak Assembly Pressure.

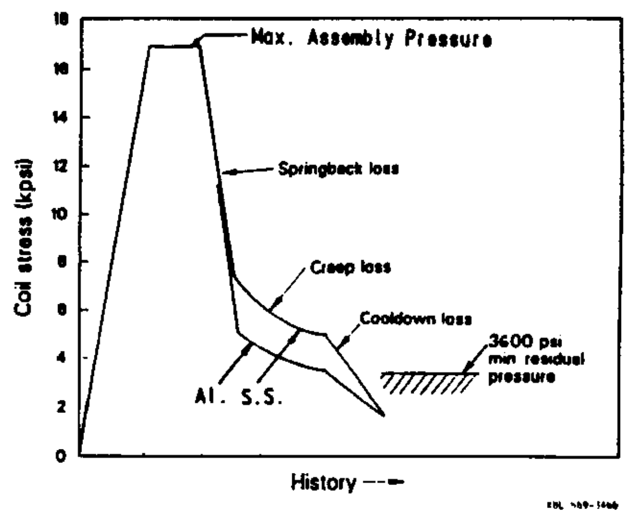

Fig. 5. Coil Assembly Pressure History

The Digitizer

Since we hoped to use the measuring technique more than once, we focussed on a measuring system that delivers high accuracy, convenience, and speed. We have found and used a system, called Sigma-Scan, (Jandel Scientific, Sausalito, CA, USA) which is a digitizer connected to an IBM PC that is fully integrated with a software package that can measure x,y coordinates.

The magnet cross section was digitized from a photographic enlargement (X5). Using fiducial marks on the sample that have been accurately measured, the photograph was calibrated and then measured (digitized). Two sets of measurements were normally taken; one was the "4 corners" of each of the trapezoids around each turn (576 in all), and the other consisted of every strand in every turn (3872 in all). Typically, this process required less than a day's work.

Once the measurements were done, the magnetic multipoles were computed. Such calculations were done separately for the strands and trapezoids, and then compared with the magnet measurements. (See Fig. 6.)

Good agreement between these methods confirmed at the same time the quality of the magnetic

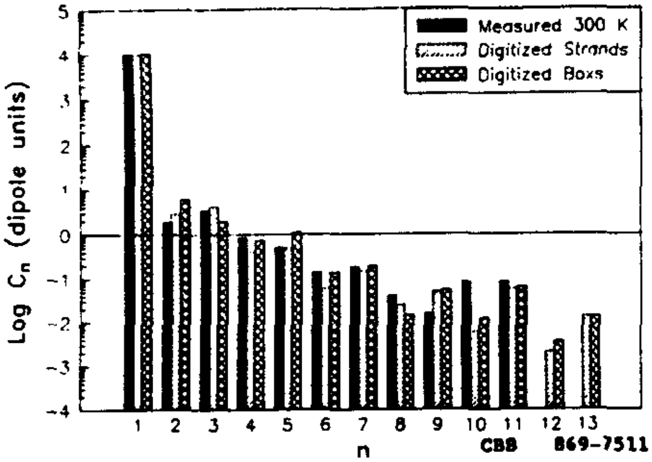

Fig. 6. Comparison of the Measured Multipoles with Those Calculated From the Digitized Autopsy of Magnet D14-B4.

measurements and the adequate accuracy of the photo-digitization process. It also confirmed the sufficient accuracy of using trapezoids in the cable modeling of the program PK.

Figure 7 is a superposition of the digitized strands and the digitized turns of magnet D14-B4. In order to have a direct comparison between the PK design and the digitized geometry, we have superimposed the two and plotted them in Fig. 8. Distorted areas can easily be seen, especially around the midplane blocks of the inner conductor layer. The effect of these distortions on the sextupole was computed and ~ 90% of the total was found to arise from such midplane distortions.

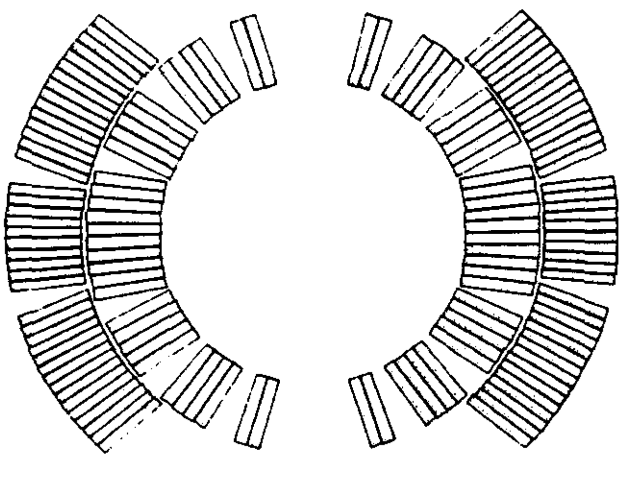

Fig. 7. Superposition of the Measured Strands and Turns

Conclusions

The program PK can accurately model high uniformity dipole cross sections.

The program POISSON satisfactorily predicts the influence of iron on the sextupole.

The predicted and measured sextupole is the same during low prestress operation, but the difference begins climbing sharply at around 10 kpsi to +6 units at approximately 20 kpsi.

Most of the magnetic distortions associated with high prestress operation are the result of permanent deformation of the midplane block of the inner layer.

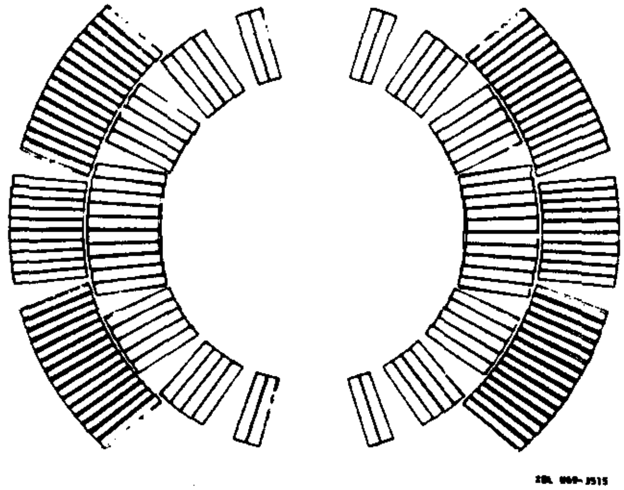

Fig. 8. Superposition of the Measured Turns and Their Computed Design Location

Acknowledgment

We would like to acknowledge the assistance and cooperation of Craig Peters for his engineering effort; James O'Neill and his crew for magnet construction and autopsies; Michael I. Green and his group for magnet measurements; and Robert Benjegerdes for digitizing the autopsied magnets.

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