Design of the Dipole Magnet for the ' 'C' ' version of the Superconducting Supercolilder 20 TeV Twin-Beam Proton Accelerator(SSC)
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The ' $C$ '" version of the SSC dipole is a superconducting superferric magnet with a 1 by 1.4 in. bore. Injection is at 0.15 T and storage at 3.0 Tesla. The length of the ring is 140 km , and it contains 1,000 dipoles 140 m long each. Each dipole is an over-under double-C magnet built of steel laminations, flooded with liquid helium, and with 8 turns of superconducting wire and one elliptic bearn tube per section. A total of 6 bores have been built so far. They all showed excellent quench stability, and the field uniformity was good and in reasonable agreement with predictions.

A detailed analysis of construction errors for dipoles has also been performed. Effects on field harmonics from as many as 9 different sources of error have been taken into account, including mechanical errors and errors in magnetic properties and excitation current. Studies and measurements of errors due to persistent currents and remanent fields have also been conducted. We report the results of the measurements and the error analysis.

## Introduction

Superferric magnets are constructed out of 0.060 inch thick laminations of soft (1008) steel and powered by eight turns of superconducting wire with two additional turns at the pole face for the correction of the decapole. The eight turns are divided into two separate circuits of four turns each with each circuit carrying a different current.

The design has undergone three stages of evolution. The various stages differ in the number and placement of independent currents and in the width of the pole face. The earliest model had a narrow pole face and two currents and is designated by NF2C. The second had a wider pole face and two currents and is designated by WF2C. Two currents proved to be sufficient to control the sextupole component of the field, however, the decapole component proved to be troublesome. The current design has a wide pole face with a small third current added to the pole face along with a Magnetic Shunt which together control the decapole. This is designated as WF3CMS. The WF3CMS model uses the same lamination as the WF2C model with the addition of a coil and a magnetic shunt. The geometry of WF3CMS is shown in Figure 1.

## Predictions

The field and multipoles were calculated using the well know magnetic modeling program POISSON and are shown in Table 1 . The multipoles were calculated at a radius of 1.0 cm ( 0.394 inches) and are defined by

$$
B_{Y}=B_{0} \quad b_{n} x^{n} ; b_{0} \equiv 1
$$

Because the model was perfectly symmetric the predicted skew multipoles are zero as are the odd b's. The currents are in amperes, BO in Tesla and the other B 's are in parts in 10 to the fourth.


FIGURE 1. WF3CMS GEOMETRY

Table I. Predicted Multipoles

| Model | Iin/Iout | Ic | BO | b2 | b4 | b6 | b8 |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| NF2C | $560 / 200$ | na | 0.15 |  |  |  |  |
| NF2C | $4400 / 1550$ | na | 1.18 | -.66 | .50 | .01 |  |
| NF2C | $7350 / 2350$ | na | 1.90 | -.53 | -.41 | -.01 |  |
| NF2C | $10150 / 4250$ | na | 2.59 | -.82 | -.04 | .07 |  |
| WF2C | $560 / 200$ | na | 0.15 | -.17 | 12.20 | 3.33 |  |
| WF2C | $4400 / 1550$ | na | 1.18 | -.47 | 2.97 | 3.24 | .01 |
| WF2C | $7350 / 2350$ | na | 1.90 | -1.7 | 2.53 | 3.17 | .05 |
| WF2C | $9100 / 4000$ | na | 2.41 | -1.2 | 5.63 | 4.46 | .23 |
| WF2C | $8950 / 10200$ | na | 3.01 | -1.2 | 5.17 | 4.90 | .09 |
| WF3CMS | $685 / 0$ | 175 | 0.15 | -0.2 | -21.3 | -.45 | -.49 |
| WF3CMS | $4575 / 425$ | 800 | 1.06 | .53 | -0.07 | 0.76 | .13 |
| WF3CMS | $9420 / 425$ | 2100 | 2.04 | -.43 | -0.25 | 0.59 | .15 |
| WF3CMS | $10900 / 1300$ | 2300 | 2.42 | -.33 | 1.70 | 1.15 | .20 |
| WF3CMS | $11275 / 10225$ | -2400 | 2.98 | -.07 | 0.87 | 1.12 | $.36 C$ |
|  |  |  |  | 1.24 | -1.90 | 2.01 | .16 |

Table II. Measured and Predicted Multipoles

| Model | Iin | Iout | If | B0(P) | BD |
| :---: | :---: | :---: | :---: | :---: | :---: |
| NF 2 C | 584.8 | 143.8 | na | 0.1440 | 0.1453 |
| NE 2 C | 4001.3 | 1220.5 | na | 1.0316 | 1.0332 |
| NF 2 C | 7002.2 | 1996.1 | na | 1.7696 | 1.7740 |
| NF 2 C | 9521.0 | 4523.0 | na | 2.5251 | 2.5360 |
| NF 2 C | 9317.7 | 9307.9 | na | 2.9749 | 2.9880 |
| WE2C | 2405.0 | 2405.0 | na | 0.9454 | 0.9419 |
| WF2C | 4802.0 | 4802.0 | na | 1.8648 | 1.8505 |
| WF2C | 7200.0 | 7200.0 | na | 2.4805 | 2.4737 |
| WE2C | 10003.0 | 10003.0 | na | 3.0126 | 2.9915 |
| WF3CMS | 1926.0 | 1926.0 | 0.0 | 0.7543 | 0.7560 |
| WF 3CMS | 3840.0 | 3840.0 | 0.0 | 1.4982 | 1.4982 |
| WF 3CMS | 6722.0 | 6722.0 | 0.0 | 2.3486 | 2.3486 |
| WF 3CMS | 10202.0 | 10202.0 | 0.0 | 3.0076 | 2.9812 |
| WF3CMS | 4586.0 | 376.0 | 801.0 | 1.0549 | 1.0510 |

## Couparisun belween Measurements and Predictions

Table II shows the measured harmonics and a comparison with predictions. The currents that were predicted to produce zero b2 and b4 were ususally not available due to power supply limitations. Therefore, the table does not show those multipoles as zero. The fields and multipoles were measured using a standard rotating coil arrangement. [4] Currents are in Amperes, B 0 is in Tesla, and the other b'x are in parts per 10 to the fourth. A (p) indicates a predicted value, the others are measured values.

## Magnet Construction Errors

Large scale production of magnets requires that strict tolerances be specified to the manufacturer. Several sources of construction errors have been identified and analyzed. The most important ones for the wr2c model are the following:

HMC - Horizontal misplacement of Conductors ( $1 \mathrm{mil} ; 4$ )
VMC - Vertical misplacement of conductors ( 3.8 mil total; 1)
CS -. See 1 Gap spacing (. 2 mil; $\sqrt{2}$ for bn, $\sqrt{\prime} 4$ for bo)
CR - current ratio (. $01 \% ; \sqrt{2}$ )
MV - $\mu$ variations ( $2 \%$ at $.15 \mathrm{~T}, .13 \%$ at $3 \mathrm{~T} ; 1$ )
MM - Up-down $\mu$ mismatch ( $2 \%$ at . $15 \mathrm{~T}, .18 \%$ at $3 \mathrm{~T} ; 1$ )
SFV - Stacking factor variations (.1\%; 1)
SFM - Up-down stacking factor mismatch (.1\%; 1)
The numbers in brackets are the accuracies with which we believe that the corresponding error can be controlled, and the RMS number of occurrences. The calculated sensitivities of the harmonic components to each error for the WF2C model are as follow:

> | B 0 | b 2 | b 4 | b 6 | al | a 3 |
| :--- | :--- | :--- | :--- | :--- | :--- |

$\begin{array}{llllllllllll}T e s l a & .15 & 3 & .15 & 3 & .15 & 3 & .15 & 3 & .15 & 3 & .15\end{array}$ $\begin{array}{llllllllllllll}\text { HMC } & 0 & .25 & .02 & .007 & .005 & .004 & .002 & .004 & 0 & 0 & 0 & 0 \\ \text { VMC } & 0 & 0 & .08 & 3 & & & & & 28 & 18 & 08 & 03\end{array}$



Units in this table are gauss and mils. b2, b4, b6, al and a3 are evaluated at 1 cm and multiplied by 10,000 , and sensitivities to CR, MV, MM, SFV and SFM are given for a $1 \%$ variation of the corresponding error source. Work is in progress to compute the numbers

| $\mathrm{b} 2(\mathrm{P})$ | b 2 | $\mathrm{~b} 4(\mathrm{P})$ | b 4 | $\mathrm{~b} 6(\mathrm{P})$ | b 6 | $\mathrm{~b} 8(\mathrm{P})$ | b 8 |
| ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| 14.6 | -0.1 | 9.7 | 6.2 | 3.8 | 1.4 | -0.3 | -0.5 |
| 2.4 | -0.4 | 3.7 | 5.1 | 2.8 | 2.1 | 1.2 | 1.0 |
| 3.5 | -0.2 | 5.5 | 7.4 | 3.5 | 2.5 | -0.3 | -0.2 |
| 2.3 | -0.1 | 1.3 | 2.2 | 3.4 | 2.8 | 1.2 | 0.9 |
| 3.8 | 0.3 | -17.2 | -16.7 | -2.5 | -0.5 | -0.6 | 0.7 |
| -64.0 | -70.5 | -31.9 | -33.3 | -5.4 | -4.7 | -0.2 | 1.3 |
| $-94.6-101.0$ | -37.8 | -38.2 | -4.1 | -2.7 | 0.4 | 2.2 |  |
| $-95.8-106.6$ | -24.3 | -25.7 | -1.7 | -0.2 | 0.1 | 1.0 |  |
| -19.2 | -27.2 | -16.2 | -17.7 | -0.9 | -0.1 | 0.1 | 3.7 |
| -59.5 | -58.2 | -30.5 | -28.4 | -5.6 | -3.8 | -0.6 | 2.5 |
| -88.3 | -89.7 | -38.4 | -37.5 | -5.3 | -4.0 | -0.2 | -1.0 |
| $-131 .-135.8$ | -25.2 | -25.8 | -1.0 | -1.2 | 0.5 | 1.3 |  |
| -35.2 | -35.2 | -16.0 | -14.9 | -0.6 | 0.4 | 0.1 | -0.5 |
| 1.5 | -0.7 | 0.0 | 0.9 | 0.2 | 1.2 | -0.1 | 0.0 |

that are missing in the table, and in any case the entire table must be recalculated for the WF3CMS design. We believe, however, that these values are representative also for the WF3CMS case.

By multiplying the accuracy by the number of occurrences of each error source, and by the sensitivity of each harmonic, we obtain the induced random errors, as follows:

|  | B0 |  | b2 | b4 | 4 | b6 |  | al | a3 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Tesla | . 15 | 3 | . 15 | . 15 | 3 | . 15 | 3. | 15 | .153 |
| HMC | 0 | 1 | . 08.03 | . 02 | . 004 | . 01 | . 004 | 0 | 0 |
| VMC | 0 | 0 | .31 .14 |  |  |  |  | 1.1.68 | . 3.11 |
| GS | . 4 | 3.7 | . 76.05 | . 008 | . 02 | . 09 | . 003 | 0 | 00 |
| CR | 0 | 0 | . 005.015 | . 003 | . 004 | 0 | . 001 | 00 | 0 |
| MV | . 02 | 5.1 | . 04 |  | . 022 |  |  |  |  |
| MM | 0 | 2.2 | . 02.07 | . 02 | . 13 | . 01 | . 4 |  |  |
| SHV | 0 | 16 | 0.24 |  | . 07 |  | . 013 |  |  |
| SFM | 0 | 7.1 | 0.63 | 0 | . 36 | 0 | . 22 |  |  |
| error | . 4 | 19 | . 81.1 | . 03 | . 4 | . 09 | . 5 | 1.1 .7 | . 3.1 |

Errors in $B O$ are in gauss and error in the remaining harmonics are dimensionless and multiplied by 10,000 . The last row of the table gives the RMS final error for each harmonic, which is partial in those cases where not all contributions are available. The final errors are small and acceptable in all cases. The table also shows which contributions to the final random error are the most important, and which tolerances must be tighter.

The effect of the persistent currents at injection is very small 3. If filaments of $25 \mu \mathrm{~m}$ are used, the contribution will be -0.583 gauss with 0.264 gauss of sextupole at 0.4' ', while for $20 \mu \mathrm{~m}$ filaments the two numbers are -0.407 and 0.187 gauss, respectively. The remanent field 2 is 6.9 gauss for the WF2C model if 1010 steel is used and is expected to be even smaller for the WF3CMS model because the shunt will short-circuit the remanent flux.

## References

[1] S. Pissanetzky, 'Conductor Misplacenent''. Report TAC 1218/84 (Dec. 1984)
[2] S. Pissanetzky, 'Remanent Fields in the Cold Iron Superferric Magnet'' Report TAC 1084/01 (October 1984)
[3] F. R. Huson and S. Pissanetzky, ''Persistent Currents in Superferric Magnet' Report TAC 384/21 (March 1984).
[4] W. MacKay, Private Cormunication

