Preliminary Analysis of Coil Wedge Dimensional Variation In SSC Prototype Dipole Magnets

D. Pollock, G. Brown, S. Dwyer, R. Gattu, D. Warner
Superconducting Super Collider Laboratory *
2550 Beckleymeade Avenue, MS-1004
Dallas, Texas 75237 USA

Abstract

The wedges used in SSC Prototype Dipole Magnets determine the relative position of conductor blocks within magnet coils. They serve to compensate partially for the less than full keystoning of the superconductor cable and to adjust current distribution with azimuth to determine the magnetic field shape. The ability to control the size and uniformity of wedges therefore is an important factor influencing magnet *field quality*. This paper presents preliminary results of a Statistical Quality Control study of wedge dimensional variation and predicted field quality. Dimensions of samples from outer wedges for magnet DCA102 have been measured using a programmable optical comparator. The data is used to evaluate wedge manufacturing *process capability*, wedge uniformity, and to predict changes in conductor block position due to wedge deviation. Expected multipole variation attributable to observed wedge variation is discussed. This work focuses on a Prototype Dipole Magnet being built at the SSCL Magnet Development Laboratory (SSCL MDL) in Waxahachie, Texas. The magnet is of the same design as the DCA3xx series magnets built at Fermi National Accelerator Laboratory (FNAL) in 1991-92 and later used in the 1992 Accelerator Systems String Test (ASST).

I. INTRODUCTION

The SSCL Magnet Systems Division Quality Assurance department (MSD QA) is currently investigating several sources of manufacturing variation in SSC Prototype Dipole Magnets. The work focuses on features of the cold mass production process which are believed to influence magnet field quality including coil azimuthal size and modulus, as well as wedge, collar, and yoke dimensional variation. In this paper we present preliminary results of a study of outer wedge data from wedges made for the DCA3xx and DCA1xx magnets (DSX201B/W6733B cross section) [1, 2]. The method of wedge measurement is described. Measurement error is quantified. A comparison between drawing tolerances and observed results is provided. The relationship between dimensional variation and manufacturing process capability is discussed. Finally, the expected influence of wedge variation on multipoles is described, using the normal sextupole (b_2) as an example.

II. OUTER WEDGE DESCRIPTION

The symmetric outer coil wedge 2D cross section is described in Figure 1 [3]. The features of the wedge are: (A) Top Width; (B) Delta Width; (C) Large End Height; (D) Bottom Width; (E) Small End Height. The copper wedges are produced using rolling-mill technology in approximately 18 m (60 ft.) lengths. They are cut to intermediate length for shipping and later cut to 1.8 m lengths (6 ft.) for wrapping with kapton insulation. The wedges are installed in the magnet during coil winding.

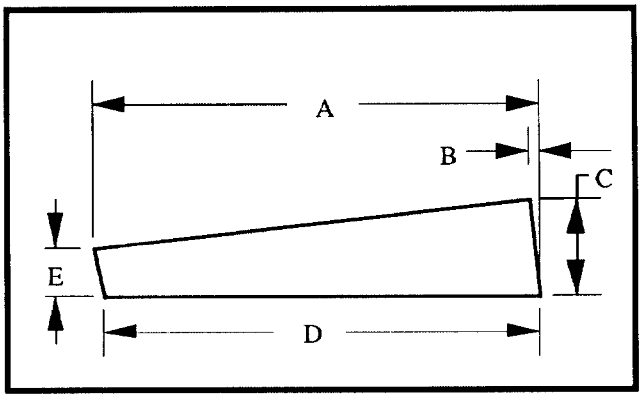

Figure 1. Outer Wedge (2D Cross Section).

III. WEDGE SAMPLING AND MEASUREMENT

A. Measurement Method

Several methods are available for verifying wedge dimensions. Two methods have been studied by MSD QA one using a Coordinate Measurement Machine (CMM) and the other using an Optical Comparator (OGP). Due to programming difficulties and schedule limitations only the OGP technique is described at this time.

Sixteen bare outer wedges (each 1.8 m long) were selected at random from SSCL MDL inventory. Small slices were cut from each end of each wedge and mounted on glass microscope slides for measurement. Each feature of the wedge was measured ten times using the automatic mode on the OGP. Details of the measurement method will be distributed in a future MSD *QA Note* .

B. Measurement Error

The OGP machine certified accuracy and repeatability are both 0.00254 mm (0.0001"), for individual observations. Calibration accuracy and repeatability have been verified using a NIST traceable certified pin and ten repeat measurements. Measurement capability has been compared to wedge tolerance using the Standard Error of the Mean (SEM)

* Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

of the ten repeat measurements on the certified pin. According to this method, the OGP capability is approximately 3.5% of the nominal outer wedge tolerance, as described in Table 1.

Table 1 Optical Comparator Measurement Error

Calibration Accuracy and Repeatability Accuracy (deviation from pin) = 0.00127 mm (0.00005") 1 σ Repeatability = 0.00147 mm (0.000058") SEM = σ / sqrt. (n) = 0.00046 mm (0.000018")
Machine Capability vs. Wedge Tolerance Nominal Tolerance = +/- 0.013 mm SEM/Wedge Tolerance = 0.035 (3.5%)

C. Sampling Error

Each feature has been measured 10 times for each of 31 wedge samples (16 from start ends, 15 from finish ends). The average standard error of the slice measurements is typically less than 12 % of the part tolerance, as listed in Table 2.

Table 2 Sample Standard Error (for 10 repeats)

Figure 1 Feature	Average SEM of 31 Samples	SEM / 0.013
A	0.001566 mm	0.1197
B	0.001188 mm	0.0914
C	0.000491 mm	0.0378
D	0.001414 mm	0.1087
E	0.000533 mm	0.0410

Based on One Way Analysis of Variance (ANOVA), "Between" sample (slice-to-slice) variation explains 98.4% of the observed wedge feature variation, on average. "Within" sample variation (sampling error) accounts for only 1.6% of the observed variation. Figure 2 describes the relationship between measurement error and outer wedge variation for the Bottom Width. Each point on Figure 2 shows the wedge slice mean (+ symbol) and standard deviation (error bars) for the start-end of each of the 16 wedges in the study, (tolerance limits are shown as well, 11.66 mm, +/- 0.013 mm).

IV. ESTIMATE OF PROCESS CAPABILITY

A. $\overline{X}$ *Process Limit Calculation*

Using the Shewhart $\overline{X}$ Control Chart for variables [4, 5], $\pm 3\sigma$ *process limits* have been calculated for the outer wedge features. The sample size is 16 (wedges in the study) and the subgroup size is 2 (slices measured from the ends of each wedge). The average of 10 repeat observations from each slice is used as the feature value. To demonstrate, Figure 3 shows the Bottom Width for start and finish end of each wedge with the tolerance band, while Figure 4 shows $\overline{X}$ (the mean of the 2 slices) for each wedge with estimated $\pm 3\sigma$ process limits.

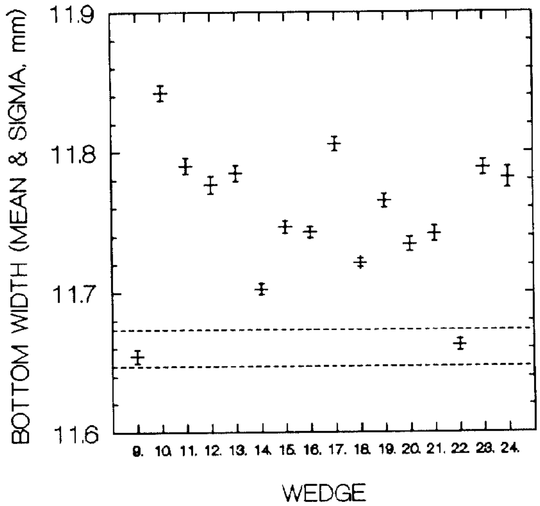

Figure 2. Outer Wedge Bottom Width: Start End Mean and 1 σ Error Bars for 10 repeats.

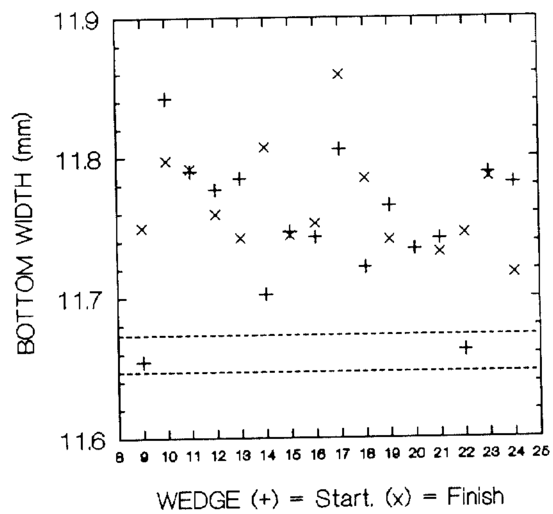

Figure 3. Outer Wedge Bottom Width: Start (+) and Finish End (x) for each Wedge Sample.

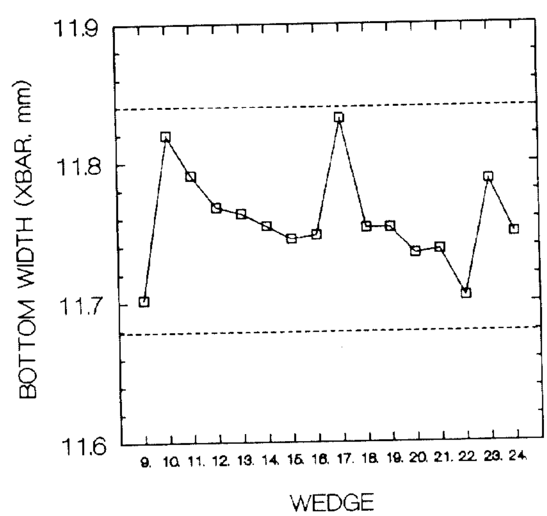

Figure 4. Outer Wedge Bottom Width: $\overline{X}$ Chart of wedge sample means (subgroup size = 2).

B. Process Capability Calculation

The Upper and Lower Process Limits calculated for each feature describe the 3σ range within which similar samples from the source manufacturing process may be expected to occur 99.73% of the time, if the sample is a fair representative of the process. Typically one would not draw firm conclusions from as small a sample as has been studied so far. But for demonstration purposes and to draw preliminary conclusions we feel the reported results are important. Process Capability (C_p) is defined as the ratio of the Tolerance Range (max – min) to the process $\pm 3\sigma$ range. If this ratio is less than 1, the process is not statistically capable of holding the specification tolerance. Under such conditions, causes for the variation in the process should be investigated and (if possible) eliminated. Table 3 shows the Process Capability estimate for the outer wedge data studied.

Table 3 Outer Wedge Process Capability Estimate

Fig. 1 Feature	$\pm 3\sigma$ Range	Process Capability
A	0.078 mm (0.0031")	0.333
B	0.141 mm (0.0056")	0.184
C	0.054 mm (0.0021")	0.481
D	0.161 mm (0.0063")	0.161
E	0.070 mm (0.0028")	0.371

V. WEDGE INFLUENCE ON FIELD QUALITY

A. Estimated Change in b_2 Due to Wedge Average Deviation

The wedge angle described by the outer wedge small end height and the outer coil inside radius (to the center of the magnet) is one of the dimensions used to determine normal multipoles (b_{even}) for the design cross section [6, 7]. The influence of the average deviation from design nominal for the outer wedge has been estimated for the normal sextupole (b_2) multipole harmonic. If the pole angle is fixed (i.e., no pole shims are used, as is the case for the DCA3xx magnets [1]) the change in b_2 has been predicted to be –0.11 units per 0.05 mm change in the outer wedge small end height [2]. For the wedge data in this study, the average deviation of the small end height from the drawing nominal is –0.036 mm. Therefore, the estimated influence of the observed deviation on b_2 is:

$$(-0.036/0.05)\times(-0.11) = 0.079 \times 10^{-4} \text{ units.}$$

B. Outer Wedge Deviation and Observed Field Quality

Based on the assumption that the wedges studied fairly represent the wedges used in the four outer quadrants of the DCA3xx ASST Prototype Dipole magnets, the fraction of observed b_2 deviation from design nominal attributable to measured outer wedge average deviation has been estimated to be 6.1%, (see Table 4). When results from the three inner wedges are added to the study, the cumulative influence of wedge deviation is expected to be significantly larger.

Table 4. Outer Wedge Deviation vs. Observed b_2.

Data Source:	DCA311 - DCA319, Z-Scan data
Average b_2 (at 2 kA):	1.463 units [8]
Design b_2 (at injection):	0.165 units [2]
Average Deviation from Design:	1.298 units
Estimated Outer Wedge influence:	0.079 units
Fraction Attributable to Outer Wedge:	6.1%

C. Outer Wedge Deviation and Systematic Tolerance

The Systematic tolerance for b_2 at high field is +/– 0.8 units [9]. The influence estimated from outer wedge average deviation (0.079 units) alone represents approximately 10% of the normal sextupole high field systematic tolerance.

VI. CONCLUSION

Using an approach similar to the one described in this paper, we plan to expand this study to include inner wedges. We plan to estimate the combined influence of variation in all wedges on observed normal multipoles for DCA3xx and DCA1xx Prototype Dipole Magnets. Working with Production Engineering and our wedge suppliers we will also investigate possibilites for improving wedge process capability.

VII. ACKNOWLEDGMENTS

Ramesh Gupta, Brookhaven National Laboratory, Upton, Long Island, New York.

VIII. REFERENCES

[1] SSCL document: MD-MKA-A-93-001, "Requirements and Specifications for SSC 50mm Collider Dipole Magnet (DCA311 - 319, ASST Dipole Magnet Baseline Design)," August 8, 1991.

[2] R. C. Gupta, S. A. Kahn and G. H. Morgan, "SSC 50 mm Dipole Cross Section," *Supercollider 3*, Plenum Press, New York, 1991.

[3] FNAL drawing number 0102-MB-292038.

[4] D. C. Montgomery, "Introduction to Statistical Quality Control, Second Edition," John Wiley & Sons, New York, 1991, pp. 201 ff.

[5] H. Stenson, "QC STAT: A Supplementary Module for SYSTAT," version 1.1, SYSTAT, Inc., Evanston, IL, 1990.

[6] R. C. Gupta, "Correcting Field Harmonics After Design In Superconducting Magnets," *Supercollider 4*, Plenum Press, New York, 1992, pp. 773 - 780.

[7] R. C. Gupta, private conversations, February 1993.

[8] SSCL document: MD-TA-233, J. DiMarco, "Summary of Axial Multipole Data from 50 mm Dipole Magnet Prototypes DCA311-322," October 7, 1992.

[9] SSCL document: M80-000001, Revision A, "15 Meter Collider Dipole Manget, Magnet System Specification," January 10, 1992, p. 14.