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"Integral Fields of Magnet Ends For DSS2, DSS5, DSS6"

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INTEGRAL FIELDS OF MAGNET ENDS FOR DSS2, DSS5, DSS6

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SUMMARY. The magnetic fields at the ends of three 1.8m SSC magnets have been measured. They are compared with a preliminary version of SSC end-field tolerances. All the multipoles satisfy the tolerances, most by a wide margin.

MEASUREMENT AND ANALYSIS. This is the first report of end field measurements of SSC magnets, so it contains a qualitative overview of the measurement method and details of the analysis as well as the results. Measuring coils for 1.8m magnets contain three sets of windings. One set is long enough (95") to measure the integral field, the second measures a 30"-long region longitudinally centered in the magnet, and the third (also 30" long) is longitudinally centered on the non-lead end of the magnet. Each set of windings contains a "tangential" winding and two dipole bucking windings[1].

The magnet end is only a few inches long, so the end windings measure the sum of the field at the coil end and the field over about 10" of the magnet straight section. The integral over the magnet end is obtained by subtracting the contribution of the straight-section from the measurement made with the end windings. The straight-section contribution is

the measurement of the central 30" winding normalized by the length of the end winding in the magnet straight-section. The method is shown schematically in Fig. 1. The length of the straight-section of the magnet is taken as the length of the straight-section of the inner coil (56.723"). This is the definition used by Morgan in the design program [7].

The principal source of uncertainty in the measurement is the portion of the end winding which is in the magnet straight-section [2]. Several measurements, each accurate to 1/32", and a correction for the thermal contraction of the magnet and suspension system (0.3") enter the calculation. The error is estimated to be +/- 0.25". This uncertainty affects the end multipoles only slightly because of the small size of the straight-section terms. For example, changing the straight-section length 3" changed the end multipoles by at most 0.1 unit*meters, except for the normal sextupole, which changed 0.5, 0.2, and 0.1 unit*meters for the three magnets reported here.

A special winding was provided for the magnet return end but not for the lead end because the lead arrangements of the 1.8m and 17m magnets are not the same. Nonetheless, a measurement of the lead end of the magnet can be obtained by subtracting both the straight-section field (the central 30" field taken to extend over the effective length of the magnet) and the return end field from the integral field. This is also shown schematically in Fig. 1. The random measuring errors are larger for the lead end measurement than for the non-lead

end since the fields involved in the subtractions are generally comparable in size.

One section of the analysis is not shown in Fig. 1. It is necessary because the standard analysis program uses the direction of the dipole as the reference axis for the higher-order multipoles. (I.e., the skew dipole is set to zero by this process.) The dipole angles of the end and of the straight-section are both measured relative to the encoder, so any difference can be determined. Typically, they differ by a few degrees. This changes the relative magnitudes of the normal and skew terms of a given multipole, although the magnitude of the multipole remains unchanged. The effect goes as sin((n+1)*theta). For the 12-pole term, which is the most sensitive on the list of tolerances, a difference of two degrees rotates about 20% of the normal term into the skew term.

The point-to-point measurement variation was estimated by comparing three consecutive measurements (1.8kA, 2kA, 2.2kA). Two different measuring coils were used for these magnets, and they have quite different short-term reproducibility. DSS2 and DSS5 were measured with coil 31, DSS6 was measured with coil 34. The short-term reproducibility of coil 34 was much better than that of coil 31, as can be seen from the results in Table I. In this table, the difference between the maximum and minimum measured values (intended to be a conservative estimate of the reproducibility) is given in parentheses. For DSS2 and DSS5, the larger of the two numbers is given.

The nominal geometries of the two measuring coils were the same. The included angle of the central and integral tangential windings is 12 degrees. This choice of angle allows sensitivity to high-order terms. The included angle of the end tangential winding is 60 degrees. This provides maximum sensitivity for the sextupole in the end, so that high-quality room-temperature measurements can be made. However, it sacrifices sensitivity at higher order and, in particular, a 60 degree winding has no sensitivity to 12-pole fields. To obtain results for the 12-pole, a different method of analysis was used. The central field (measured over 30" and taken to extend over the effective length of the magnet) was subtracted from the integral field. The difference equals the sum of the lead and return end fields. (This analysis also allows a check that the separate calculations for the lead and non-lead ends sum correctly.)

No correction has been made for the effect of magnetization currents on the sextupole. The difference between the up-ramp sextupole and the average of the up-ramp and down-ramp data is 0.2 units at this field, which translates to a correction of less than 0.1 unit*meter.

MAGNET CONSTRUCTION DETAILS. The length of the laminations which make up the yoke in DSS magnets is 65.5". Typically there is 3/4" of material between the longest turn of the longer (inner) coil and the end of the yoke and collar

laminations. Magnets DSS2 and DSS5 had iron yoke modules extending over the full lamination length, but for the last 6.3" at each end the iron i.d. was increased to reduce the peak field at the conductor (6.4" i.d., compared to the straight-section iron i.d. of 4.4")[3]. For DSS6, stainless steel yoke laminations were used for the last 6.8" of both ends of the yoke so that no magnetic iron is over the ends [4].

The magnet coil is both left-right and top-bottom symmetric at the non-lead end, so the only allowed multipoles are the sextupole b2, the decapole b4, etc. The presence of other terms is the result of construction tolerances. This is not the case at the lead end where there are several places having conductors which violate both LR and TB symmetry: the splice between the inner coil and the outer coil, the leads, and the block-to-block transitions in each of the four coils. These will generate even-n skew terms (a2, a4). The splice from the upper coil to the lower coil will be LR symmetric but violates TB symmetry, producing odd normal terms (b1, b3, b5).

<u>RESULTS AND COMPARISON WITH TOLERANCES.</u> Table I (on two pages) gives the results and a comparison with the draft set of end-field tolerances[5]. The entries in the Table are in "unit-meters," the same as those of ref. [5]. The measurements for the lead and return ends are presented separately except for the 12-pole, where the sum is given. The estimated short-term measurement variation is given in

parentheses. As discussed above, the variation at the non-lead end is smaller than at the lead end, and the variation for DSS6 is much less than for the other two magnets.

All the multipoles meet the proposed tolerance, most by a wide margin. This is true even for the lead end data, indicating that the effect of the asymmetries in the coil end design is small. The difference between the DSS2 and DSS5 sextupole and the DSS6 sextupole is presumably due to removing the iron from the end of DSS6 [6]. Also, the design of the magnet ends has not yet been iterated, and subsequent designs should have lower sextupole. The random variation of the skew sextupole at the lead end is close to the tolerance, although it is unclear whether this is due to the leads and could be less in the 17m dipoles.

Footnotes and References

1. The measuring system is described in: J. Herrera, H. Kirk, A. Prodell, and E. Willen, Proceedings of the 12th International Conference on High Energy Accelerators (Fermilab, 1983), p. 563.

2. The error in the axial position of the end windings is thought to be the dominant error, since the measuring coils are typically made to an accuracy of 0.1% in dipole field and calibrated to a still higher degree of accuracy.

3. BNL dwg. 22-354.02-2. The shells of these magnets were 1" longer than shown in the drawing. The standard assembly

procedure is to locate the magnet axially symmetric in the shell.

4. BNL dwg. 22-359.02-2 rev. B (This drawing is for 17m magnets, but it also describes the iron at the ends of DSS6.) Measurements made on DSS6 rebuilt with shims between the yoke and collars gave 71.5" for the shell length, as for the other DSS magnets, and showed that the yoke had been placed axially symmetric in the shell. The multipoles in this note are from the original DSS6. The same shell was used for both the original and the rebuilt DSS6.

5. Chao and Tigner 11/30/87 draft memo

6. The next three magnets in the DSS series, to be tested soon, will have iron-free ends like DSS6.

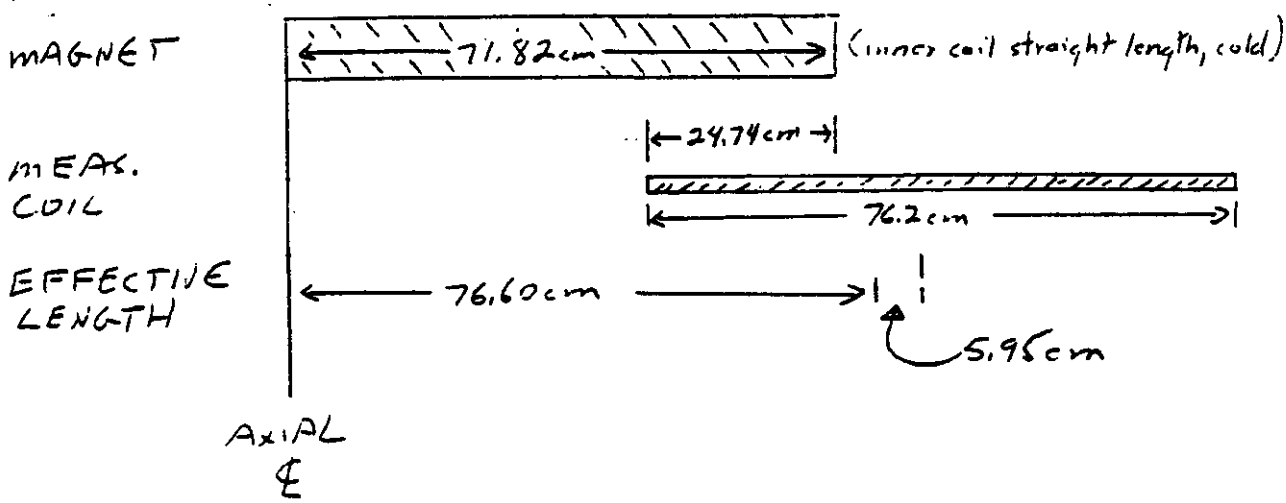
7. An alternative definition of the straight-length would be the effective length, which is the integral dipole field divided by the dipole field in the center of the magnet. The effective length of the magnets in this note ranged from 59.8" to 60.4". As is noted in the error discussion, the results are only slightly sensitive to the definition chosen.

ends.txt

END FIELDS OF 1.8m MAGNETS

P.W. 2/15/88

Nominal lengths:



Length of end winding in straight section (defined by inner coil s.s. length) = 24.74cm

(A) $\begin{pmatrix}\text{Return end}\\ \text{Integral field}\end{pmatrix} = \begin{pmatrix}\text{End meas.}\\ \text{coeff.}\end{pmatrix} \times L_{coil} - \begin{pmatrix}\text{Straight-section}\\ \text{coeff.}\end{pmatrix} \times L$

$$L_{coil} = 30'' = 76.2\text{ cm}$$

(B) $\begin{pmatrix}\text{Level end}\\ \text{Integral field}\end{pmatrix} = \begin{pmatrix}\text{Integral}\\ \text{meas.}\end{pmatrix} \times L_s - \begin{pmatrix}\text{Straight-section}\\ \text{meas.}\end{pmatrix} \times L_{eff} - \begin{pmatrix}\text{Return end}\\ \text{Integral field}\end{pmatrix}$

Note: Must use C_i, α_i to be independent of $\langle B_0 \rangle$ in regions outside the straight-section.

$$L_s = 2.413\text{m} \qquad L_{eff} = \frac{B_0^s \times L_s}{B_0^{central}} = 1.53\text{m} \quad (\text{DSSS})$$

FIG. 1

ENDS DATA COMPILATION @ 2 kA - skew terms

n	feed/return	DSS2	DSS5	meas scatter	DSS6	meas scatter	Random (each end)	Systematic (each end)	Conclusion
1	R	-2.3	-1.3	(.6)	-.9	(.01)	1.9	3	DSS6 ok
	L	-4.8	-3.4	(1.)	-.3	(.03)			
2	R	1.5	.3	(.1)	.6	(<.01)	1.7	6.	ok
	L	1.1	-1.2	(.4)	-1.1	(.02)			
3	R	.3	-.3	(.3)	-.1	(.01)	1.9	1.	ok
	L	.2	-.8	(.2)	-.5	(<.01)			
4	R	-.5	-.1	(.7)	-.3	(.01)	0.6	1.4	ok
	L	1.0	.4	(.6)	.4	(.01)			
5 (RK)		-.1	-.2	(.1)	-.1	(.001)	0.6	2.	ok

Chaos Tigner 11/30/87

Results stated in "unit-meters" $\equiv \left(\int_{end} A_i \, dl\right) / (10^{-4} \times B_0)$

where B_0 is the central field of the magnet straight-section,

and A_i is the skew magnetic field at 1cm radius.

TABLE I (p 1 of 2)

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ENDS DATA COMPILATION @ 2kA – normal terms

n	Lead/return	DSS2	DSS5	meas. scatter	DSS6	meas scatter	Random (each end)	Systematic (each end)	Conclusion
1	R	.1	0	(.1)	-1.5	(.03)	1.9	3.	OK
	L	1.9	1.0	(1.0)	-.2	(.07)			
2	R	-8.3	-7.5	(.06)	-9.3	(.01)	1.1	14.	MAY BE OK
	L	-3.5	-2.7	(.3)	-3.9	(.01)			
3	R	.2	.3	(.15)	.2	(<.01)	0.8	5.	OK
	L	.5	.3	(.3)	-.2	(.02)			
4	R	-.4	-.9	(.5)	-.8	(<.01)	1.9	6.	OK
	L	-.2	-.7	(.5)	-.9	(.01)			
5 (RL)		.1	<.1	(.05)	<.1	(.01)	0.3	0.2	OK

Chao + Tigner
11/30/87

TABLE I (p 2 of 2)

PW 2/12/88