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# COMPARISON OF WARM AND COLD MULTIPOLES IN DSS MAGNETS

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SUMMARY. A group of six 1.8m DSS magnets had good correlation between room temperature and 4.5K measurments of the four lowest order multipoles. In standard 10**-4 units, the mean and standard deviations of the cold - warm differences are:

| | normal | skew |
|---|---|---|
| quadrupole | -0.1 +- 0.6 | 1.0 +- 1.7 |
| sextupole | -0.6 +- 0.2 | -0.1 +- 0.05 |
| octupole | -0.1 +- 0.2 | 0.02+- 0.14 |
| decapole | 0.14+- 0.08 | 0.07+- 0.10 |

(The data have not been corrected for feeddown.) Similar results are found for a DSS magnet with a NC9 cross section.

WARM MEASUREMENTS. Measurements at room temperature are made at currents of +10A and -10A in order to be able to remove the effects of any yoke magnetization remaining from previous excitation to high fields. Five measurements are made at each current, alternating positive and negative. This note looks at multipoles from the central 30" of the magnets.

The multipole analysis program finds the average direction of the dipole field for positive currents and calculates the remaining multipoles with respect to this direction. As a result, all multipoles which are determined by conductor placement will reverse signs when the current is reversed. Terms due to the remnant field of the iron will not reverse sign. Thus, the remnant fields are removed from the data by calculating:

[ai(positive current) - ai(negative current)]/2.

It has not been possible to correct the data for feeddown due to miscentering of the measuring coil. Typically, the radial error in the measuring coil position is 0.1 to 0.2 cm. The magnitude of the apparent quadrupole is twice the radial offset times the sextupole. Octupole terms are four times the radial offset times the decapole.

As a test of the magnitude and variation of the remnant terms, the sum of the positive and negative current multipoles is given for the low-order terms in Table I. The sum corresponds to twice remnant field, in "units" at 100G central field. Two yokes were made for the DSS magnets. Both yokes were at high field before these warm measurements were taken.

The largest remnant terms are the skew quadrupoles of DSS6 and DSS7.

COLD MEASUREMENTS. Magnetization effects are removed by averaging the up-ramp and down-ramp data. To gain some estimate of the measurement-to-measurement scatter, and to reduce it, the results are an average of six measurements made at 200A steps from 2kA through 3kA, where the effects of magnetization and saturation are at a minimum. As with the warm measurements, the data have not been corrected for feeddown.

To check consistency of the data, the differences between the up-ramp and down-ramp results are given in Table II. Excluding the normal sextupole, each term has a difference consistent with zero, the variations being ascribed to measurement fluctuations. Excluding b2, the differences are less than 0.2 units. DSS6 was measured with the most recent coil and shows smaller differences than the data from the other magnets.

The normal sextupole difference is about the same for these magnets, 0.4 to 0.6 units. This difference is due to magnetization effects. The magnets have 5 micron filaments for both inner and outer cables. DSS1 and DSS2 have inner cable from IGC and outer cable from Oxford, with the same billets in the two magnets. DSS4, DSS5, and DSS6 came from the same inner and outer cable reels, all from Oxford. The average difference between the up-ramp and down-ramp measurements is larger for DSS1 and DSS2 than for DSS4, DSS5, and DSS6, but it would be hard to prove that the difference between these groups of magnets is outside measurement uncertainties. DSS7 had 5 micron IGC inner cable, Oxford outer cable [1].

COMPARISON OF WARM AND COLD MULTIPOLES. The comparison is made in Table III. Table III is summarized in the table given at the start of this note. Except for an average offset of 0.6 units, the b2 measurements are highly correlated--the distribution of differences has a sigma of 0.2 units. Similar results hold for b4, with an average difference of 0.14 units and a sigma of 0.08 units. Due to the different materials used in the magnet, some change of shape is expected during cooldown so the offsets are not unexpected. The skew sextupole has an average 0.1 unit offset, with the differences having a sigma of 0.05 unit. The skew decapole is similar.

There is less correlation in the quadrupole terms. This may be due to warm-cold differences in the measuring coil offset. For the normal quadrupole, the cold-warm difference

has a mean of -0.1 unit with a sigma of 0.6 unit. The difference between the cold and warm skew quadrupoles has a mean of 1.0 unit with a sigma of 1.7 units. The difference between warm and cold quadrupole measurements is largest for DSS1 and DSS2. DSS1 had an unsatisfactory assembly which may be a contributor to the problem. Also, the normal sextupole is larger for these two magnets than for the later four magnets and thus any feeddown problems will be worse. The best agreement between warm and cold measurments occurs for DSS6, which was measured with a new measuring coil which has much less point-to-point measurement error than its predecessor.

Differences between the warm and cold measurements of the octupole terms are consistent with zero. The distributions of the differences have sigmas of 0.2 units or less.

FOOTNOTES.

[1] Down-ramp data were not taken for DSS7. To correct for this, 0.27 units have been added to the up-ramp measurement. The correction was determined from magnets having similar cable.

cp warm cold.txt

# Table I

Compare +10A + -10A Multipoles (Warm) for DSS Magnets.

**Quadrupole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | +10A | -10A | (+)+(-) | +10A | -10A | (+)+(-) |
| 1 | -.59 | .36 | -.23 | -5.68 | 4.96 | -.72 |
| 2 | -.89 | -.40 | 1.24 | -1.11 | 1.51 | .40 |
| 7 | -.30 | -.33 | -.63 | -8.24 | -11.54 | -19.18 |
| 4 | .71 | 2.13 | 2.84 | 2.13 | -.71 | 1.42 |
| 5 | -.59 | -.48 | -1.07 | 1.19 | -.89 | .30 |
| 6 | .02 | 1.67 | 1.69 | 19.95 | 17.69 | 37.64 |
| (NC9)9 | -3.43 | -3.39 | | -.90 | .64 | |

**Sextupole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | +10A | -10A | (+)+(-) | +10A | -10A | (+)+(-) |
| 1 | -7.40 | 11.42 | 4.02 | - .28 | .29 | .01 |
| 2 | -7.30 | 4.60 | -2.70 | - .01 | .21 | .20 |
| 7 | -1.57 | 2.27 | .70 | .64 | -.12 | .52 |
| 4 | 4.03 | -2.65 | 1.38 | .02 | .11 | .13 |
| 5 | 4.31 | -.82 | 3.49 | .02 | .13 | .15 |
| 6 | 1.44 | -2.38 | -.94 | .84 | -.21 | .63 |
| (NC9)9 | .88 | -1.12 | | -.34 | .29 | |

Compare +10A and -10A Warm Multipoles for DSS Magnets

**Octupole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | +10A | -10A | (+)+(-) | +10A | -10A | (+)+(-) |
| 1 | .32 | -.32 | 0 | .49 | -.65 | -.16 |
| 2 | .29 | -.29 | 0 | -.01 | .13 | .12 |
| 7 | -.23 | .11 | -.12 | -.72 | .72 | 0 |
| 4 | .15 | .05 | .20 | -.11 | -.05 | -.16 |
| 5 | -.12 | .11 | -.02 | .17 | -.06 | .11 |
| 6 | -.14 | .21 | .07 | .33 | -.38 | -.05 |
| (NC9)9 | -.06 | .04 | -.02 | -.56 | .55 | -.01 |

**Decapole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | +10A | -10A | (+)+(-) | +10A | -10A | (+)+(-) |
| 1 | .10 | .22 | .32 | -.07 | -.07 | -.14 |
| 2 | -.30 | -.13 | .43 | .21 | -.12 | .09 |
| 7 | -.02 | -.04 | -.06 | -.14 | .20 | .06 |
| 4 | .51 | -.24 | .27 | -.10 | .06 | -.04 |
| 5 | .53 | -.26 | .27 | -.09 | .08 | -.01 |
| 6 | .71 | .13 | .84 | -.67 | -.15 | -.82 |
| (NC9)9 | .06 | .02 | .08 | -.03 | -.01 | -.04 |

# Table II

Compare Up-Ramp & Down-Ramp Multipoles - DSS Magnets
(Cold) Avg. 2kA ≤ J ≤ 3kA (6 points)

**Quadrupole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Up-Ramp | Dn-Ramp | U-D | Up-Ramp | Dn-Ramp | U-D |
| 1 | -1.56 | -1.51 | -.05 | -1.45 | -1.60 | .15 |
| 2 | .48 | .64 | -.16 | 1.21 | 1.03 | .18 |
| 7 | -.37 | no data | - | 1.73 | no data | - |
| 4 | -.26 | -.38 | .12 | 1.15 | 1.05 | .10 |
| 5 | -.13 | -.29 | .16 | 1.22 | 1.25 | -.03 |
| 6 | -.97 | -.90 | -.07 | 1.01 | 1.02 | -.01 |
| (NC9)9 | .29 | .24 | .05 | -.46 | -.40 | -.06 |

**Sextupole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Up-Ramp | Dn-Ramp | U-D | Up-Ramp | Dn-Ramp | U-D |
| 1 | -10.44 | -9.84 | -.60 | -.33 | -.38 | .05 |
| 2 | -6.42 | -5.93 | -.49 | -.17 | -.16 | -.01 |
| 7 | -2.75 | no data | - | .20 | no data | - |
| 4 | 2.32 | 2.74 | -.42 | -.18 | -.19 | .01 |
| 5 | 1.79 | 2.20 | -.41 | -.14 | -.18 | .04 |
| 6 | 1.02 | 1.45 | -.43 | .44 | .42 | .02 |
| (NC9)9 | -.09 | .27 | -.36 | -.37 | -.38 | .01 |

Compare Up-Ramp & Down-Ramp Multipoles - DSS Magnets
(Cold) Avg. 2kA ≤ I ≤ 3kA (6 points)

**Octupole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Up-Ramp | Dn-Ramp | U-D | Up-Ramp | Dn-Ramp | U-D |
| 1 | .27 | .32 | -.05 | .45 | .47 | -.02 |
| 2 | -.22 | -.22 | 0 | .11 | .14 | -.03 |
| 7 | -.05 | no data | - | -.52 | no data | - |
| 4 | -.03 | -.08 | -.05 | -.07 | -.15 | +.08 |
| 5 | -.07 | -.15 | -.05 | .03 | .09 | -.06 |
| 6 | -.16 | -.16 | 0 | .35 | .34 | .01 |
| (NC9)9 | -.06 | -.06 | 0 | -.56 | -.55 | -.01 |

**Decapole**

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Up-Ramp | Dn-Ramp | U-D | Up-Ramp | Dn-Ramp | U-D |
| 1 | .14 | .13 | .01 | .21 | .24 | -.03 |
| 2 | .12 | .15 | -.03 | .21 | .16 | .05 |
| 7 | .13 | no data | - | -.02 | no data | - |
| 4 | .51 | .56 | -.05 | -.08 | -.10 | .02 |
| 5 | .41 | .41 | 0 | -.08 | -.10 | .02 |
| 6 | .82 | .80 | .02 | .15 | .14 | .01 |
| (NC9)9 | .02 | .02 | 0 | -.02 | -.02 | 0 |

# Table III

**Warm vs. Cold Multipoles Partial Summary - DSS Magnets**
**(#'s in parentheses are sigmas)**

Quadrupole

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Cold | Warm | C-W | Cold | Warm | C-W |
| 1 | -1.53(.2) | -.48(.5) | -1.06 | -1.52(.5) | -5.32(.4) | 3.79 |
| 2 | .56(.2) | -.22(.3) | .78 | 1.12(.2) | -1.31(.4) | 2.43 |
| 7 | -.37(.2) | .02(.8) | -.39 | 1.73(.2) | 1.65(.6) | .08 |
| 4 | -.32(.5) | -.71(.5) | .39 | 1.10(.5) | 1.42(.5) | -.32 |
| 5 | -.21(.5) | -.05(.4) | -.15 | 1.23(.6) | 1.04(.5) | .20 |
| 6 | -.93(.03) | -.82(.3) | -.11 | 1.02(.22) | 1.13(.2) | -.11 |
| (NC9)9 | .26 | -.02 | .29 | -.43 | -.77 | .34 |

Sextupole

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Cold | Warm | C-W | Cold | Warm | C-W |
| 1 | -10.14(.2) | -9.41(.2) | -.73 | -.36(.2) | -.28(.1) | -.07 |
| 2 | -6.17(.2) | -5.95(.2) | -.23 | -.16(.1) | -.11(.2) | -.05 |
| 7 | -2.47(.3)[1] | -1.92(.2) | -.55 | .20(.1) | .38(.4) | -.18 |
| 4 | 2.53(.3) | 3.34(.2) | -.82 | -.19(.4) | -.05(.2) | -.14 |
| 5 | 1.99(.1) | 2.56(.1) | -.57 | -.16(.2) | -.05(.2) | -.10 |
| 6 | 1.23(.1) | 1.91(.1) | -.68 | .43(.02) | .52(.1) | -.10 |
| (NC9)9 | .09 | 1.00 | -.91 | -.38 | -.31 | -.06 |

[1] 0.27 units added to up-ramp data to compensate for lack of down-ramp data.

**Warm vs. Cold Multipoles Partial Summary - DSS Magnets**
**(#s in parentheses are sigmas)**

Octupole

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Cold | Warm | C-W | Cold | Warm | C-W |
| 1 | .30(.1) | .32(.08) | -.02 | .46(.05) | .57(.1) | -.11 |
| 2 | .22(.04) | .29(.05) | -.51 | .12(.04) | -.07(.07) | .20 |
| 7 | -.05(.04) | -.17(.05) | .12 | -.52(.04) | -.72(.10) | .20 |
| 4 | -.06(.09) | .05(.05) | -.11 | -.11(.10) | -.03(.10) | -.08 |
| 5 | -.11(.12) | -.12(.08) | .01 | .06(.13) | .12(.11) | -.06 |
| 6 | -.16(.00) | -.17(.07) | .01 | .34(.01) | .35(.08) | -.01 |
| (NC9)9 | -.06(.00) | 0.05(.06) | -.01 | -.55(.01) | -.56(.05) | 0.01 |

Decapole

| | Normal | | | Skew | | |
|---|---|---|---|---|---|---|
| Magnet | Cold | Warm | C-W | Cold | Warm | C-W |
| 1 | .13(.05) | -.06(.14) | .20 | .22(.08) | .00(.05) | .23 |
| 2 | .13(.02) | -.08(.03) | .22 | .19(.02) | .17(.02) | .02 |
| 7 | .13(.04) | .01(.10) | .12 | -.02(.04) | -.17(.05) | .15 |
| 4 | .54(.05) | .38(.04) | .16 | -.09(.06) | -.08(.05) | -.01 |
| 5 | .41(.10) | .39(.08) | .01 | -.09(.10) | -.08(.04) | -.01 |
| 6 | .81(.01) | .09(.05) | .11 | .15(.01) | .14(.06) | .01 |
| (NC9)9 | .02(.00) | .02(.02) | .00 | -.02(.00) | -.01(.04) | -.02 |

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