BROOKHAVEN NATIONAL LABORATORY

MAGNET DIVISION NOTES

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Variation in a_1 Saturation in SSC Dipoles

Ramesh Gupta and Animesh Jain

1. Introduction

A large amount of variation has been observed in the value of a_1 as a function of current between magnet to magnet and also at several positions in any particular magnet. The variation with current is commonly referred to as a_1 saturation since the major source of this variation is the off-centered placement of the iron yoke in the magnetic cryostat vessel. However, in practice this variation may also include several other sources, e.g., the effect of an uneven deformation of the coil as a function of current. In this note we try to explain the cause of the measured variations in a_1 saturation and come up with a single formula which can be used to predict a_1 saturation in any BNL built horizontally split long 50 mm aperture SSC dipole magnet.

2. Sources of a_1 variation as a function of current

In this section we list some of the sources responsible for the variation in a_1 as a function of current. For each of these sources, we also give estimates of the magnitude of the change, δa_1, between 6600 amperes and 2000 amperes, i.e.,

$$\delta a_1 = [a_1\,(@6600\mathrm{A}) - a_1\,(@2000\mathrm{A})]\,.$$

Given below is an itemized and brief discussion of some of the sources which may be responsible for the observed δa_1 :

(a) **Off-centered cryostat :** At high current when the flux lines can not be contained in the iron cross section, they start leaking outside the yoke. At this stage the magnetic iron in cryostat vessel provides the additional magnetic path to return the flux lines. However, since the center of cryostat does not coincide with the center of yoke, an up-down asymmetry is noticed in the field. The calculations show a noticeable a_1 current dependence beyond 6.0 tesla and the computed δa_1 is ~ -0.2 unit.

(b) **Difference in the packing factor between the upper and lower yoke halves :** The packing factor is basically the yoke density and consists of the following two factors : (a) Iron weight (b) Iron volume. Though, the overall difference in the packing factor between the top and bottom yoke halves is well controlled, there may be some local variations across the length of the magnet as these have not been controlled. The iron weight is measured for each $3''$ block for top or bottom yoke and a 16 GA lamination is added at the end of each $3''$ block. Since the length of the measuring coil is 1 meter ($39.4''$), a top bottom weight difference in the yoke in a 1 meter region (the region of field measurements) would be seen in the field harmonics. Our 2-d calculations show that a 0.1% higher packing factor in the upper yoke half would give ~ -0.1 unit of δa_1 (the effect is seen after 3000 amperes). The 2-d calculations, however, may be over-estimating this effect because in reality the field lines would not only move from bottom to top (as reflected in the calculations) but they may also move in the axial direction (if the iron density in the neighbouring pack is higher), giving a lesser δa_1. We would discuss this item in more detail later in the note.

(c) **Off-centered coil in the yoke :** If the coil center does not match the yoke center, an additional δa_1 would be seen. This will also give a geometric a_1. Our calculations show that for a +1 mil off-centered coil (1 mil above center, to be particular) there would be an additional $\delta a_1 \sim +0.1$ unit and the geometric a_1 would be ~ -0.12 unit.

(d) **Difference in the top-bottom coil size – Iron Saturation and Geometric a_1 :** It is well known that a difference between the top and bottom coil sizes gives a geometric a_1. The calculations show that if the upper coil half is 1 mil larger in size (which means that the midplane is shifted down by half of this amount, i.e., $\delta y = -0.5$ mil), the geometric a_1 would be $\sim +0.7$ unit. It also gives a small additional contribution to the saturation induced δa_1, which is about 1% of the geometric a_1.

(e) **Difference in the top-bottom coil size – Coil Motion induced δa_1 :** There is an interaction between the initial mechanical forces (during the pre-compression phase) and the Lorentz forces (which are basically I^2 dependent). It is possible that when there is an initial difference in the size between the top and bottom coil halves, the already displaced coil midplane may shift more as a result of the interaction between the initial mechanical forces and the dynamic (current dependent) Lorentz forces.

We have not done the mechanical calculations to compute the amount of this displacement. However, it may be pointed out that merely a 0.1 mil additional displacement in coil center would give a contribution of about 0.14 unit to the observed δa_1.

(f) **Special purpose holes in one yoke pack :** At about 200 inch from the lead end, the strain gauges are installed in all the long magnets. In order to bring the wiring out, two $3/8''$ diameter holes are drilled in one yoke pack from iron inner radius to the two He bypass holes. This is done only in the bottom half of the magnet. This gives a large local a_1 saturation. Our 2-d estimates suggest that in a 1 meter long measuring coil, an additional δa_1 of ~ -0.15 unit would be observed.

(g) **Persistent Currents :** If an up-down asymmetry is present either in the coil geometry (which also gives geometric a_1) or in the coil cables used in the top and bottom coil halves (for example, the cables may have a different J_c), an a_1 due to persistent currents would be present. Depending on the amount of asymmetry, the value may be significant at 2000A. The value, which of course depends on the current, would be very small at 6600 amperes. This would also contribute towards the observed δa_1. We have not done any detailed calculations here, but δa_1 due to persistent currents may be as much as 0.05 unit, based on the measured values of a_1 at 2000A during the up and the down ramps in magnets DCA209-213.

3. δa_1 variation with position within a magnet

High current z-scans have been made in the magnets DCA209 thru DCA213 at 2000A and 6600A. These data provide information on the variation of the a_1-saturation (δa_1), along with the geometric a_1, as a function of position within a magnet. It has been found that δa_1 varies significantly along the length of a magnet. Amongst the various mechanisms proposed in the previous section, the off-centered yoke in the cryostat and the persistent currents [(a) and (f) in Sec.2] can not account for the variation with position. Out of the remaining mechanisms, a difference in the packing factor between the upper and lower yoke halves can be examined most readily from the data on individual yoke block weights. As pointed out earlier, a difference in upper and lower yokes could affect δa_1.

Fig.1 shows the local asymmetry in the top and bottom yoke block weights as a function of block number (position along the magnet) for the magnet DCA213. The asymmetry is defined as

$$\text{asymmetry} = \frac{\text{wt. of bottom block} - \text{wt. of top block}}{\text{average of top and bottom wts.}} \times 100\%$$

As can be seen from the figure, although the average asymmetry for the magnet is nearly zero, there could be a local asymmetry of upto $\pm 0.4\%$. In actual field measurements, the measuring coil is 1m long, and average asymmetry over this length, rather than for each block, should be considered. Fig.2 shows (open boxes) the calculated asymmetry over 1m length as a function of the position of the measuring coil in the magnet. The asymmetry is most prominent when the measuring coil center is located around block numbers 60 and 90. Fig.2 also shows the variation of δa_1 with position (filled boxes, dashed line). A very good correlation between the yoke asymmetry and δa_1 is seen. A similar correlation has been obtained for the magnet DCA212 also. This shows that the major cause of δa_1 variation along the length of the magnet is a local top-bottom asymmetry in the packing factor. It is interesting to note that a similar variation in b_1 saturation is seen in the vertically split Fermilab magnets, which may have a left-right asymmetry in the packing factor.

An examination of the a_1 saturation profiles for all the magnets (see Fig.3) revealed an interesting fact. The maximum saturation is seen at about 200 inches in all the magnets. It appears unlikely that the yokes in all the magnets have maximum asymmetry at the same z-position. Thus, the maximum saturation at about $200''$ position, though correlated with the yoke packing asymmetry in DCA212 and DCA213, should have its origin in the radial hole [see Sec.2(*f*)], rather than the weight asymmetry alone. As mentioned earlier, the 2-d calculations predict an additional δa_1 of ~ -0.15 unit due to these holes.

4. Magnet to magnet variations of integral δa_1

Since the total yoke weight in the top and bottom halves is well controlled, we should not see magnet to magnet variations if the integral (or the average) δa_1 over the entire magnet length is considered. Table 1 lists the average values and RMS variations in a_1(@2000A), a_1(@6600A) and δa_1 for the straight sections in magnets DCA209-213. The last column gives the range of variation of δa_1 within the magnet.

The geometric a_1(2000A) varies over the range -0.229 unit to $+1.758$ units from magnet to magnet. The RMS variation within a magnet ranges from 0.2 unit to 0.623 unit. The value of δa_1 averaged over *all magnets* is -0.163 ± 0.085 unit. Contrary to the expectations,

Table 1: Integral Skew Quadrupole in DCA209-213

Magnet	a_1(2000A)*	a_1(6600A)*	δa_1*	δa_1(max-min)
DCA209	0.261 ± 0.408	0.086 ± 0.420	-0.175 ± 0.115	0.43
DCA210	-0.229 ± 0.227	-0.474 ± 0.211	-0.245 ± 0.118	0.45
DCA211	1.758 ± 0.623	1.724 ± 0.706	-0.034 ± 0.115	0.46
DCA212	-0.187 ± 0.200	-0.417 ± 0.220	-0.230 ± 0.070	0.24
DCA213	0.607 ± 0.335	0.477 ± 0.351	-0.130 ± 0.139	0.52
Average	0.442 ± 0.812**	0.279 ± 0.897**	-0.163 ± 0.085**	0.42 ± 0.11

* Error bars refer to RMS variations along the axial position.

** Error bars refer to magnet to magnet variation.

the integral δa_1 *does* show magnet to magnet variations. Thus, the observed δa_1 averaged over a magnet depends on other factors also. Some of these factors are listed earlier in Section 2. Most of these factors involve a geometrical asymmetry of some kind or the other. If these factors are playing a role, then we will also see a geometric a_1. Indeed, there is a wide range of geometric a_1 in these magnets (see Table 1). One would intuitively expect a correlation between the geometric a_1 and δa_1 due to the Lorentz force enhancing(or reducing) the asymmetry in the coil. Fig.4 shows the integral δa_1 as a function of geometric a_1 in magnets DCA209-213. A linear dependence of δa_1 on a_1 is seen, which may be parameterized as

$$\delta a_1 = -0.209 \quad + \quad 0.104 \times \; a_1(2000\mathrm{A})$$

The constant term agrees with the value of -0.2 unit calculated from the effect of off-centered yoke in the cryostat in the absence of any other asymmetry [See Sec.2(a)]. The second term gives the dependence on the geometric a_1. Using the above equation, one can predict the saturation δa_1 for any BNL built, horizontally split, 50mm SSC dipole magnet.

5. Conclusions

We have examined the possible mechanisms for variation of δa_1 in different magnets, and at different locations in a given magnet. Although there are large variations within a magnet (correlated to the yoke density variations and position of special purpose holes), the integral δa_1 shows a smaller variation. These variations do not call for any change in the present manufacturing process. However, the overall weight of the iron between the top and the bottom halves should be continued to be matched to a level of a few parts in 10,000 in each magnet. There is no need to match it *locally* since it is not important for the accelerator.

A good correlation is also found between the geometric a_1 and the saturation induced a_1 in the magnets built so far. Since the systematic value of the geometric a_1 is expected to be zero, this variation would add only to the random a_1 at high field. The enhancement in the RMS a_1 at the maximum design field will be $\sim 10\%$.

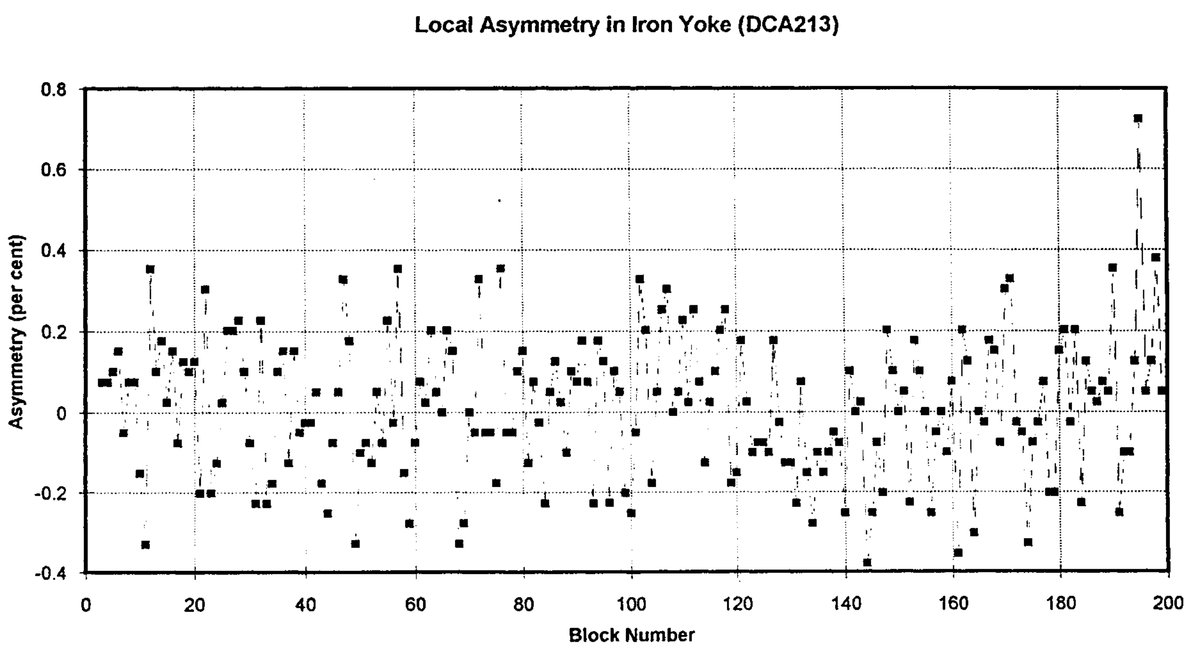
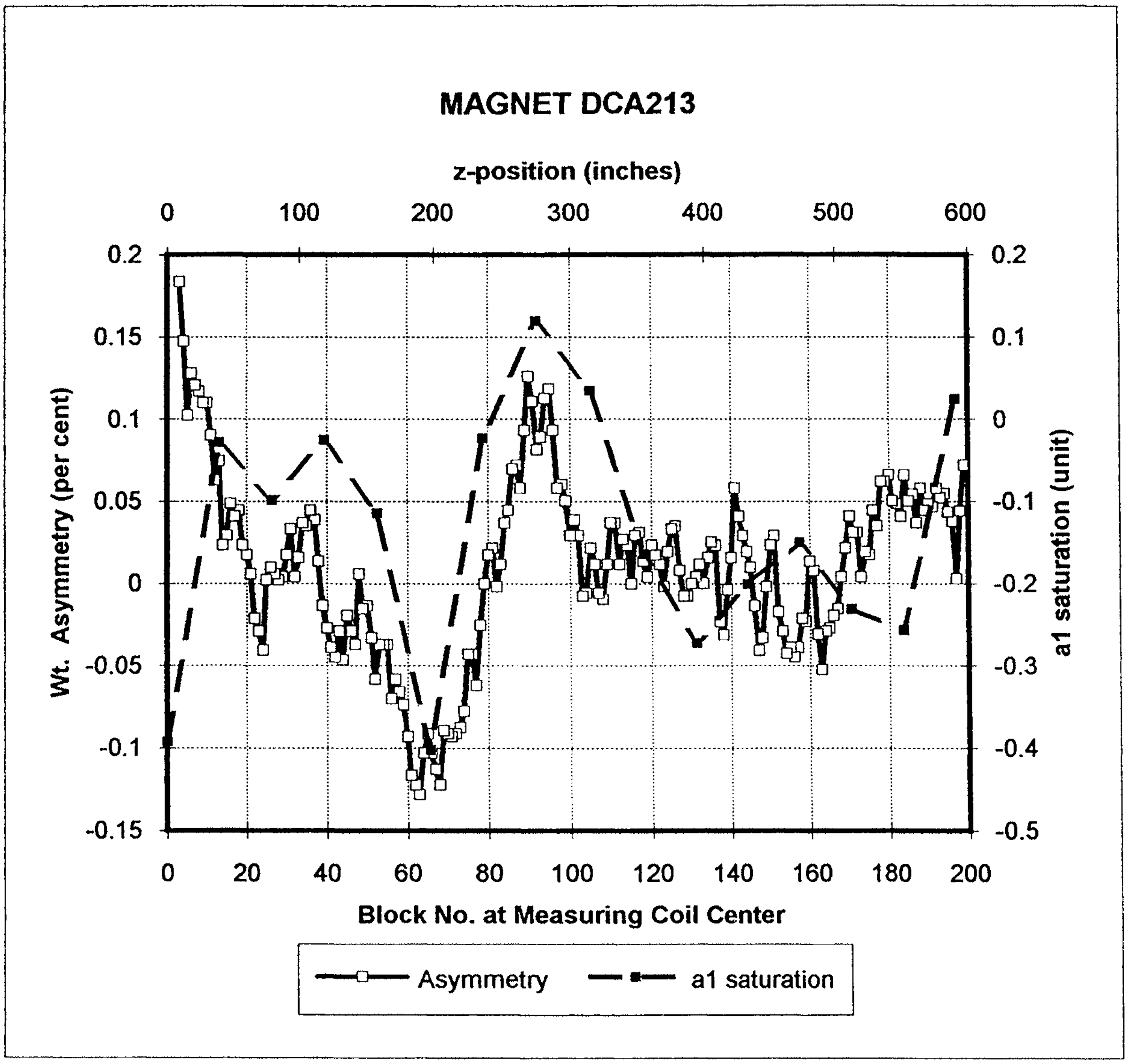


Fig. 1



MAGNET DCA213
z-position (inches)
0
100
200
300
400
500
600
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Wt. Asymmetry (per cent)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
a1 saturation (unit)
0
20
40
60
80
100
120
140
160
180
200
Block No. at Measuring Coil Center
Asymmetry
a1 saturation

Fig. 2

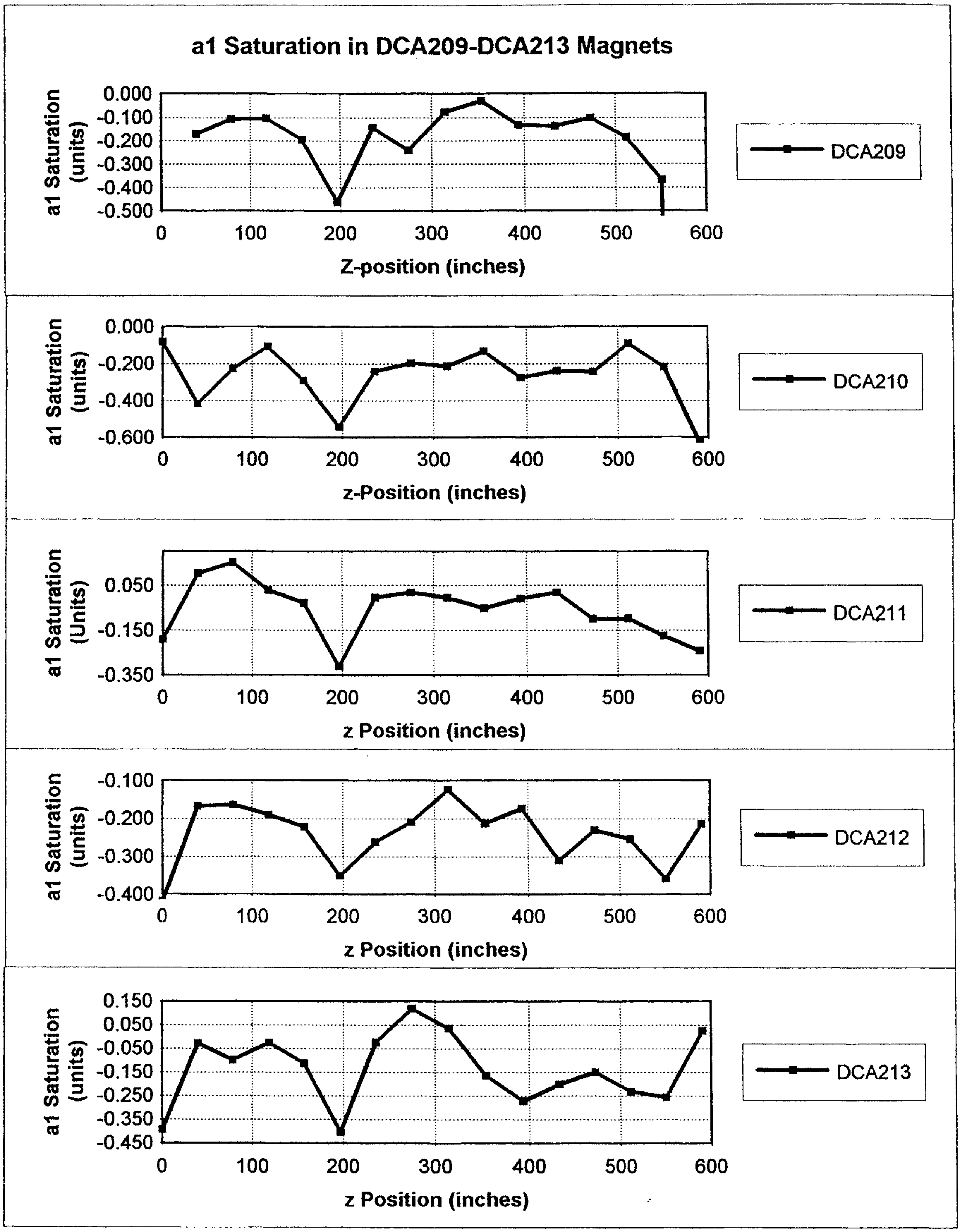

a1 Saturation in DCA209-DCA213 Magnets
a1 Saturation (units)
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
0 100 200 300 400 500 600
Z-position (inches)
DCA209
a1 Saturation (units)
0.000
-0.200
-0.400
-0.600
0 100 200 300 400 500 600
z-Position (inches)
DCA210
a1 Saturation (Units)
0.050
-0.150
-0.350
0 100 200 300 400 500 600
z Position (inches)
DCA211
a1 Saturation (units)
-0.100
-0.200
-0.300
-0.400
0 100 200 300 400 500 600
z Position (inches)
DCA212
a1 Saturation (units)
0.150
0.050
-0.050
-0.150
-0.250
-0.350
-0.450
0 100 200 300 400 500 600
z Position (inches)
DCA213

Fig. 3

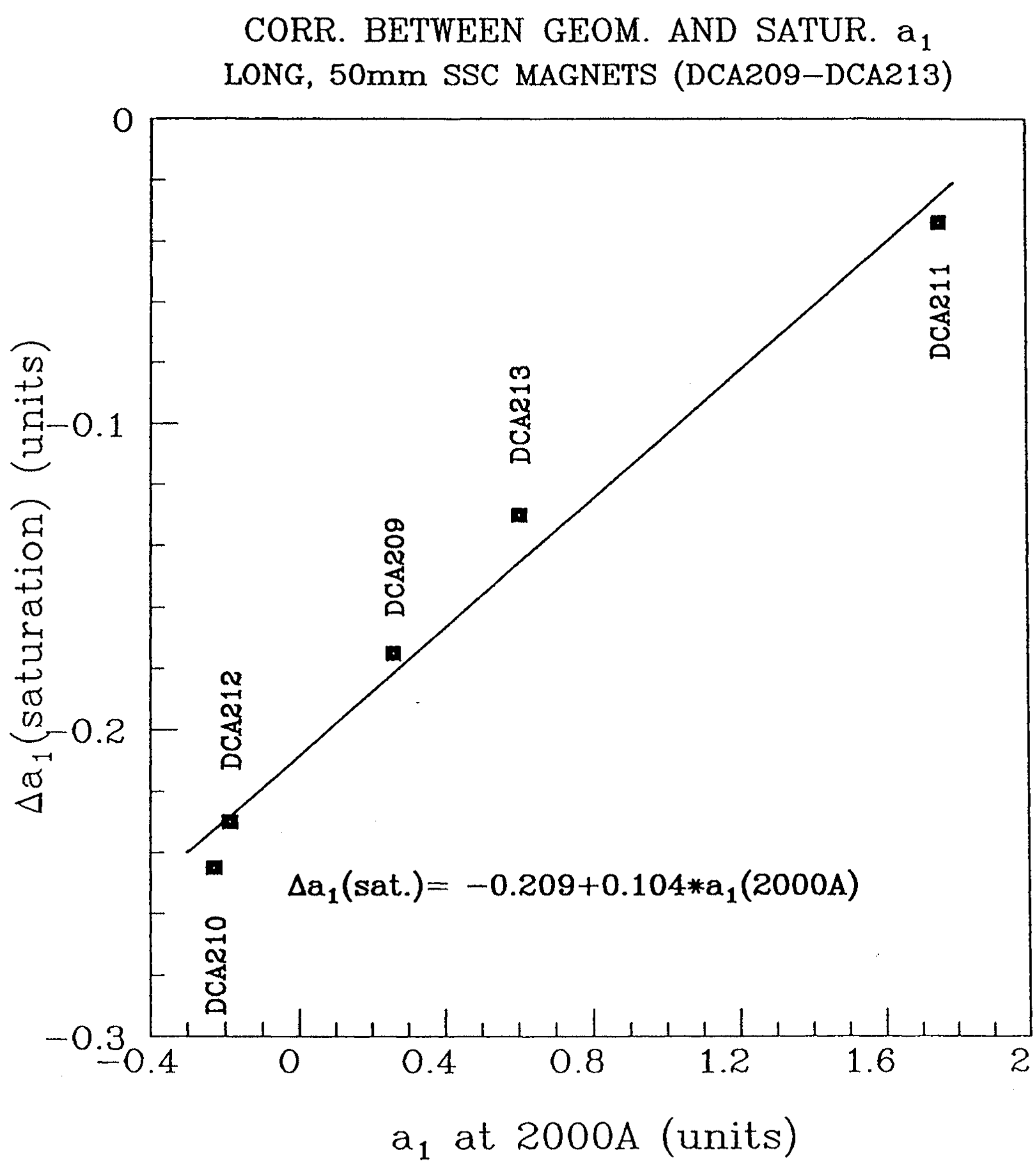

CORR. BETWEEN GEOM. AND SATUR. a1
LONG, 50mm SSC MAGNETS (DCA209–DCA213)
Δa1(saturation) (units)
a1 at 2000A (units)
0
−0.1
−0.2
−0.3
−0.4
0
0.4
0.8
1.2
1.6
2
DCA210
DCA212
DCA209
DCA213
DCA211
Δa1(sat.)= −0.209+0.104*a1(2000A)

Fig.4