Variation in a_1 Saturation in SSC Collider Dipoles*

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Abstract

Analysis of the variation in the saturation of the skew quadrupole (a_1) is presented for the 15m long, 50mm aperture SSC collider dipole magnet prototypes built at BNL. The variations within a magnet are shown to be correlated with *local* top-bottom asymmetry in the iron yoke weight. On the other hand, magnet to magnet variations in the saturation of integral skew quadrupole are shown to be correlated with the geometric a_1.

I. INTRODUCTION

Magnets DCA209-DCA213 are a set of 50mm aperture, 15m long SSC collider dipole models built at BNL[1]. The field quality in these magnets is expressed in terms of the normal and skew harmonic coefficients b_n and a_n in dimensionless "units" defined by the multipole expansion

$$B_y + iB_x = 10^4 \cdot B_0 \sum_{n=0}^{\infty} (b_n + ia_n)[(x+iy)/R]^n$$

where x and y are the horizontal and vertical coordinates, B_0 is the dipole field strength and R is a "reference radius", chosen as 1cm for these dipoles. A large amount of variation has been observed in the value of the skew quadrupole field coefficient a_1 as a function of current at different axial positions in a single magnet and also from magnet to magnet. As an example, Fig.1 shows the current dependence of a_1 measured with a one meter long measuring coil in magnets DCA209-DCA213. To facilitate comparison, the curves are offset along the y-axis such that the value of a_1 is zero at 2kA for all magnets. 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. In this paper we explain the cause of the measured variations in a_1 saturation and present a simple formula which can be used to predict a_1 saturation in long 50 mm aperture SSC dipole magnets with horizontally split yokes.

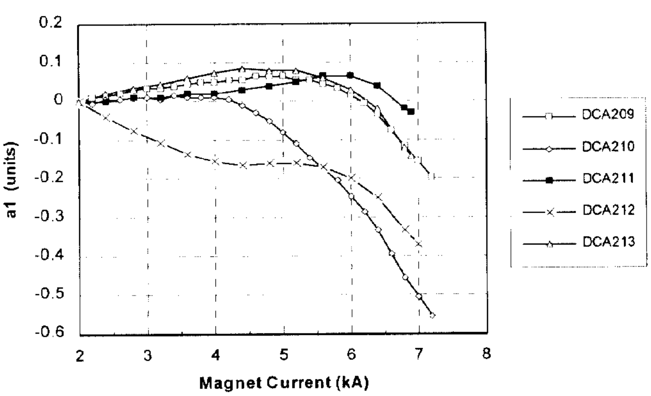

Fig.1 *Current dependence of skew quadrupole (a_1) in magnets DCA209 to DCA213. The curves are offset such that a_1 at 2kA is zero for all magnets.*

II. SOURCES OF a_1 VARIATION

In this section we list some of the sources which may be 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 6600A and 2000A (referred to as "saturation a_1"). Given below is a brief discussion of some of the sources which may be responsible for the observed δa_1:

(a) Off-centered yoke in the cryostat :

At high currents the flux lines are not contained in the iron cross section and start leaking outside the yoke. At this stage the magnetic iron in the 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 would be generated in the field at the center of the dipole. The calculations show a noticeable current dependence in a_1 above a primary field of 6.0 Tesla ($I \sim$ 6kA) and the computed δa_1 is ~ -0.2 unit.

(b) Difference in the packing factors of the yoke halves :

The packing factor is basically the ratio of the amount of yoke material actually present to the maximum amount of yoke material possible in the design volume. Though the overall difference in the packing factor between the top and bottom yoke halves is well controlled (typicaly within ~0.01% in DCA209-213), there may be some local variations along the length of the magnet. The iron weight is measured for each 7.6cm (3") block in the top or bottom yoke. Since the length of the measuring coil is one meter, a top bottom weight difference in the yoke in a one meter region 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 about -0.1 unit of δa_1. This effect is noticeable above 3000A. However, the difference in packing factors is likely to have

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opposite sign in neighboring packs to maintain a low overall difference in the packing factor. This implies that 2-d calculations may be over-estimating the effect because in reality the field lines would not only move from bottom to top, but may also move in the axial direction. We will discuss this item in more detail later in Sec.III.

(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 coil placed 25μm (0.001") above center, there would be an additional $\delta a_1 \sim +0.1$ unit and the geometric a_1 would be approximately -0.12 unit.

(d) Difference in the top and the bottom coil sizes :

A difference between the top and the bottom coil sizes gives a geometric a_1. The calculations show that if the upper coil half is 25μm larger (which means that the midplane is shifted down by half this amount), the geometric a_1 would be $\sim +0.7$ unit. It also gives a small additional contribution to the saturation related δa_1, which is about 1% of the geometric a_1.

There is also a second effect of the coil size difference. 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 (I^2 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 2.5μm additional displacement of the midplane would give a contribution of about 0.14 unit to the observed δa_1.

(e) Special purpose holes in one yoke pack :

At about 5m (200 inches) 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 the 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 $\sim$ -0.15 unit should be observed.

(f) 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 noticeable at 2000A and negligible at 6600A. This would also contribute towards the observed δa_1. We have not done any detailed calculations here, but δa_1 due to persistent currents is expected to be within 0.05 unit, based on the measured values of a_1 at 2000A during the up and the down ramps in magnets DCA209-213.

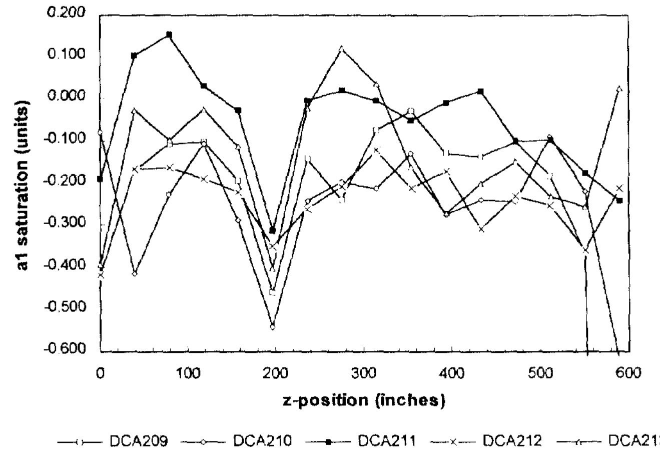

Fig.2 *a_1 saturation (δa_1) in DCA209-DCA213 Magnets*

III. δa_1 VARIATION WITH POSITION

Axial scans have been made in the magnets DCA209 through DCA213 at 2000A and 6600A. It has been found that δa_1 varies significantly along the length of a magnet (Fig.2). 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.II] can not account for the variation with position. 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. Fig.3 (open boxes) shows the local asymmetry in the top and bottom yoke block weights averaged over the length of the field measuring coil (one meter), as a function of block number (position along the magnet) for the magnet DCA213. The asymmetry is defined as

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

As can be seen from the figure, although the average asymmetry for the entire magnet is nearly zero, there could be a local asymmetry of up to $\pm$0.1%, when average values over one meter length are considered. The asymmetry is most prominent when the measuring coil center is located around

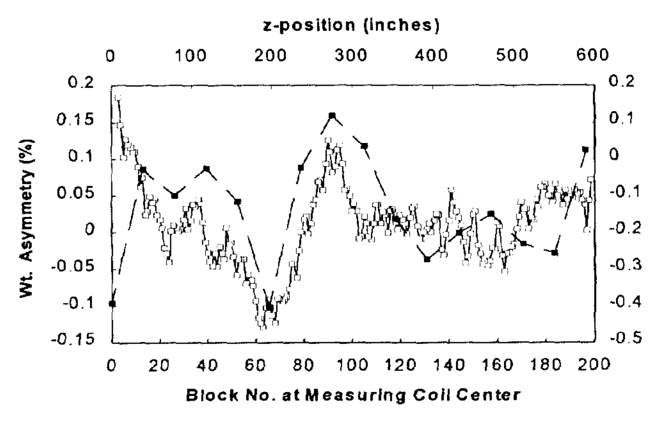

Fig.3 *Variation of Top-bottom weight asymmetry and δa_1 along the length of the magnet DCA213*

block numbers 60 and 90. Fig.3 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 axial variation in b_1 saturation is seen in the Fermilab magnets, which may have a left-right asymmetry in the packing factor because of the vertically split yoke design.

An examination of the a_1 saturation profiles for all the magnets (Fig.2) reveals that the maximum a_1 saturation is seen at about 200 inches in all the magnets, which is also the location of special purpose holes [Sec.II*(e)*]. The location and the magnitude of the dips in δa_1 in Fig.2 suggest that the holes are contributing to δa_1 at about 200 inches. It should be noted that these holes will not be present in the production magnets.

V. MAGNET TO MAGNET VARIATIONS OF INTEGRAL δa_1

Since the total weight in the top and bottom yoke halves is well controlled (within ~0.01%) in these magnets, we should not see any appreciable magnet to magnet variations in the integral (or the average) δa_1. Table I lists the average values and RMS variations (along length) in a_1(2000A), a_1(6600A) and δa_1 for the magnets DCA209-213. Only the straight section data are considered for the averaging.

Table I shows that contrary to expectations, the integral δa_1 does show some magnet to magnet variation (σ = 0.085 units). In fact, there is a strong correlation between the integral values of geometric a_1 and δa_1. We suggest the following mechanism as the possible cause for this correlation. A geometric a_1 implies a mechanical difference between the top and the bottom halves of the coil as seen from the midplane. At high current, the asymmetric Lorentz force due to asymmetric coils could modify this coil asymmetry [Sec.II(d)]. The experimental data are examined in Fig.4 which shows the integral δa_1 as a function of integral geometric a_1 in magnets DCA209-213. A linear dependence of δa_1 on a_1 is seen, which may be parameterized as

$$\delta a_1 = -0.209 + 0.104 \times a_1(2000A)$$

Table I. Integral a_1 and δa_1 in magnets DCA209-DCA213

Magnet	Integral* a_1(2000A)	Integral* a_1(6600A)	Integral δa_1
DCA209	0.26 ± 0.41	0.09 ± 0.42	-0.175
DCA210	-0.23 ± 0.23	-0.47 ± 0.21	-0.245
DCA211	1.76 ± 0.62	1.72 ± 0.71	-0.034
DCA212	-0.19 ± 0.20	-0.42 ± 0.22	-0.230
DCA213	0.61 ± 0.34	0.48 ± 0.35	-0.130

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

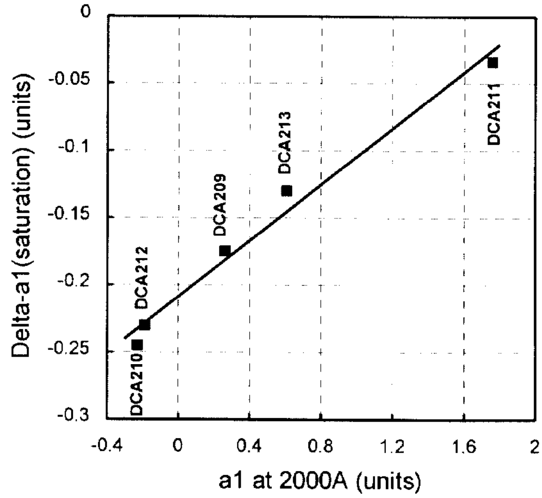

Fig. 4 *Correlation between geometric and saturation a_1.*

The constant term in the above equation 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.II(*a*)]. The second term gives the dependence of the integral δa_1 on the geometric integral a_1. A coefficient of 0.104 implies that there is a ~10% enhancement in coil asymmetry at 6600A due to Lorentz forces. A similar expression, perhaps with a somewhat different coefficient, is expected for magnets built elsewhere.

V. CONCLUSIONS

We have examined the possible mechanisms for variation of δa_1 in different magnets, and at different locations in a given magnet. There are large variations within a magnet which are correlated to the yoke density variations and position of special purpose holes. A good correlation is also found between the integral values of the geometric a_1 and the saturation induced δa_1 in the magnets built so far. Since the systematic value of the geometric a_1 is expected to be zero for the production magnets, this variation would only add slightly (~10%) to the random a_1 at high field. The variation of integral δa_1 in these magnets has σ = 0.085 units, which is small compared to the axial variations and is much smaller than the SSC tolerance of σ = 1.25 units for a_1. This is achieved because the total weights of the upper and the lower yoke halves are very well controlled.

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VI. REFERENCE

[1] P. Wanderer et al., "Magnetic design and field quality measurements for full length 50mm aperture SSC model dipoles built at BNL", *Proc. XVth International Conference on High Energy Accelerators*, Hamburg, Germany, July 20-24, 1992 in Int. J. Mod. Phys. A (Proc. Suppl.) 2B, pp.641-3 (World Scientific, Singapore, 1993).