AD/SSC/TechNo.86

Accelerator Development Department

BROOKHAVEN NATIONAL LABORATORY

Associated Universities, Inc.

Upton, New York 11973

SSC Technical Note No. 86

SSC-N-668

SENSITIVITY OF SSC DIPOLES TO VARIATIONS IN YOKE IRON PROPERTIES

G.H. Morgan, S. Kahn

October 9, 1989

Sensitivity of SSC dipoles to variations in yoke iron properties

G.H. Morgan and S. Kahn

A variation in the properties of the yoke iron, specifically in the coercive force H_c, the saturation magnetization M_s, or in μ at any value of H, will affect the field in the magnet center. The sensitivity of CBA dipoles to iron properties was examined by Tannenbaum[1], and the present note mostly follows his treatment. Because the central field in SSC dipoles is higher, and because the iron is farther from the coils than in the CBA dipoles, the central field is less affected by variations in iron properties than was the case for the CBA dipoles.

The field shape in the aperture of the SSC dipole is specified by it's magnitude B_0 at the center and by Taylor expansion coefficients b_i along the x axis. These are subject to specified limitations both as to nominal value and as to variations from magnet to magnet about the nominal value. We are concerned here only with how variations in iron properties affect B_0; it turns out that the expansion coefficients are much less sensitive to variations in iron properties. The allowed variation in B_0 in the SSC dipoles is 0.03% rms; it is assumed here that no single source should cause a variation greater than 0.02% rms.

The field at injection

The central field is determined, at a given coil current, by the yoke reluctance and by residual yoke magnetization. It was shown by Tannenbaum that at the lowest operational field (at which the protons are injected), the central field is much more affected by residual magnetization than by reluctance. The residual field has been shown by measurements of model dipoles to have low harmonic content b_i, and Tannenbaum derived a simple expression for B_0 in terms of the iron coercive force, H_c: $B_g = H_c\,(l_i/l_g)$, where l_i and l_g are average lengths in the iron and gap, resp., of a closed path through the yoke and gap on one side, enclosing the coils.

Tannenbaum's treatment is inadequate in one respect; it was based on a symmetric hysteresis loop, whereas in magnet use, the hysteresis loop is from zero to + H_{max}, rather than from - H_{max} to + H_{max}, and the demagnetizing line at injection is offset by the amount NI/l_g, so that it passes through the bottom end of the asymmetric loop where it is narrower. This probably means that H_c has less effect, although the difference may not be large. Figure 1 is a sketch of two hysteresis loops with different H_c's, with an attempt to show what they might look like if single ended. Also shown are the two demagnetization lines, one without current, the other with current equal to the value at injection. The difference in injection field, ΔH_g due to the different H_c, is shown for the two demagnetization lines.

Real asymmetric loop data are not available, but there are some magnet data which indicate that the effect of H_c is somewhat less at injection current than in the absence of excitation. Measurements on magnet DSS016 give a difference in B_0 of 16.4 G at the same current (325A), increasing and decreasing. Part of this is due to superconductor magnetization, calculated to be 11.0 G at 325 A with 6 μm filaments, the size in this magnet. The magnet cannot be excited to injection field unless the coils are superconducting. Half the difference is 2.7 G, whereas Tannenbaum's formula gives 3.0 G for H_c = 1.1 Oe. Being based on a difference between similar numbers, the 2.7 value is not very reliable, so to be conservative, we will use Tannenbaum's method.

In the CBA dipole, l_i/l_g had the value of 3.0; in the SSC dipole, it is presently about 2.8. At injection, the central field is 3300 G (0.33 T), of which 0.02 % is 0.66 G (66 μT);

using Tannenbaum's formula, this gives H_c = 0.24 Oe (19 A/m) rms, or equivalently, 95% of the values should lie in the interval ±0.47 Oe (37 A/m). This is about what was observed in the Armco Special steel bought for the CBA, ± 0.4 with 95% confidence. The magnitude of H_c is not so important, but probably the spread in H_c is proportional to it's magnitude, which suggests an H_c of about 1.4 Oe (110 A/m), compared to 1.2 for the CBA steel; a larger value might be acceptable.

The iron at saturation

The approach to saturation is approximated by the empirical equation

$$M = M_s(1 + a/H + b/H^2 + c/H^3 + \bullet\bullet\bullet) + k_0 H \qquad (1)$$

where M_s is the saturation magnetization and a,b,c are signed constants. The term proportional to H, perhaps due to paramagnetism of impurities, is hereafter assumed negligible, and since the terms in H^{-n}, n > 2 are important only well below saturation, we will also ignore them. M_s and the remaining constants a and b are found by fitting high field data to this expression using a non-linear least-squares fitting routine. It is found that, as noted by Bozorth[2], the fit is good only for M = B - H within 99% of M_s, which occurs for H above about 500 Oe (40 kA/m). Data for H from 500 to 3000 Oe (40 to 240 kA/m), for the Armco Special iron at room temperature, bought for the CBA magnets, give a value of M_s = 21.23 kOe (1.689 MA/m) when fitted to this expression and 21.78 kOe (1.733 MA/m) for iron at 4.2 K.

The change in central field due to a change in M_s is given by $\Delta B_0/B_0 = \alpha\, \Delta M_s/M_s$, where α was found by Tannenbaum to be 0.25 for the CBA magnets. The method he used for determining α was to calculate B_0 with a saturable-iron computer program, using a B,H curve based on the Frolich-Kennelly relation in which M_s is a parameter. This could also be done using eq. (1). However, a routine (NUBHTBL) for changing the Armco Special B,H table in a systematic way to reflect changes in packing factor was already available. A comparison of $\Delta\mu/\mu$ obtained using eq. (1) and NUBHTBL shows that they are the same within 5 to 10% above H = 1 kOe (80 kA/m), and $\Delta\mu/\mu$ obtained using NUBHTBL is larger by about a factor of 2 for H = 400 Oe (32 kA/m). Thus they should give about the same results, NUBHTBL being slightly more conservative, with iron close to saturation.

NUBHTBL was used with a saturable-iron program (MDP) with B_0 = 6.6 T and the current SSC iron design, and a value for α of 0.12 was obtained. For α = 0.12 and $\Delta B_0/B_0$ = 0.0002 rms, $\Delta M_s/M_s$ = 0.0016 rms or ± 0.0032 with 95% confidence.

Intermediate field values

At fields between injection and saturation, B_0 is affected by changes in μ due to such factors as extent of annealing, cold working, and alloying ingredients, especially silicon and aluminum. Tannenbaum used an analytic expression for B_0 for the case of a circular iron annulus, with μ constant in the iron, and determined the variation in B_0 due to variations in μ. We do essentially the same thing using a saturable iron program (PE2D), which has a constant μ mode of operation. The differences between Tannenbaum's results and ours are presumably due entirely to the differences in iron configuration. The results are shown in Table 1, which gives the change in constant μ necessary to give a $\Delta B_0/B_0$ of 0.0002 at 3 values of current.

Table 1

I, A	B_0, G	μ_i	H, Oe	B_{fe}, G	μ_r
660	6928	4190	0.62	2617	1810
1650	17320	4300	2.38	10240	1840
3300	34637	2850	4.59	13090	1520

In Table 1, μ_i is that value of constant μ needed to give B_0 with the current equal to I, B_{fe} is the field in the iron, and μ_r is the value of μ necessary to reduce B_0 by 0.02%. Thus, for example a $\Delta\mu$ of - 2380 at 660 A is necessary to reduce B_0 by 0.02%; an increase in μ much greater than this would be necessary to increase B_0 by 0.02% owing to the non-linearity of the effect over such a large range.

References

1) Michael J. Tannenbaum, "Sensitivity of Isabelle Dipoles to the Magnetic Properties of the Lamination Iron", Isabelle Project Tech. Note 382, August 9, 1982

2) Richard M. Bozorth, "Ferromagnetism", D. Van Nostrand Co., 1951, p. 486

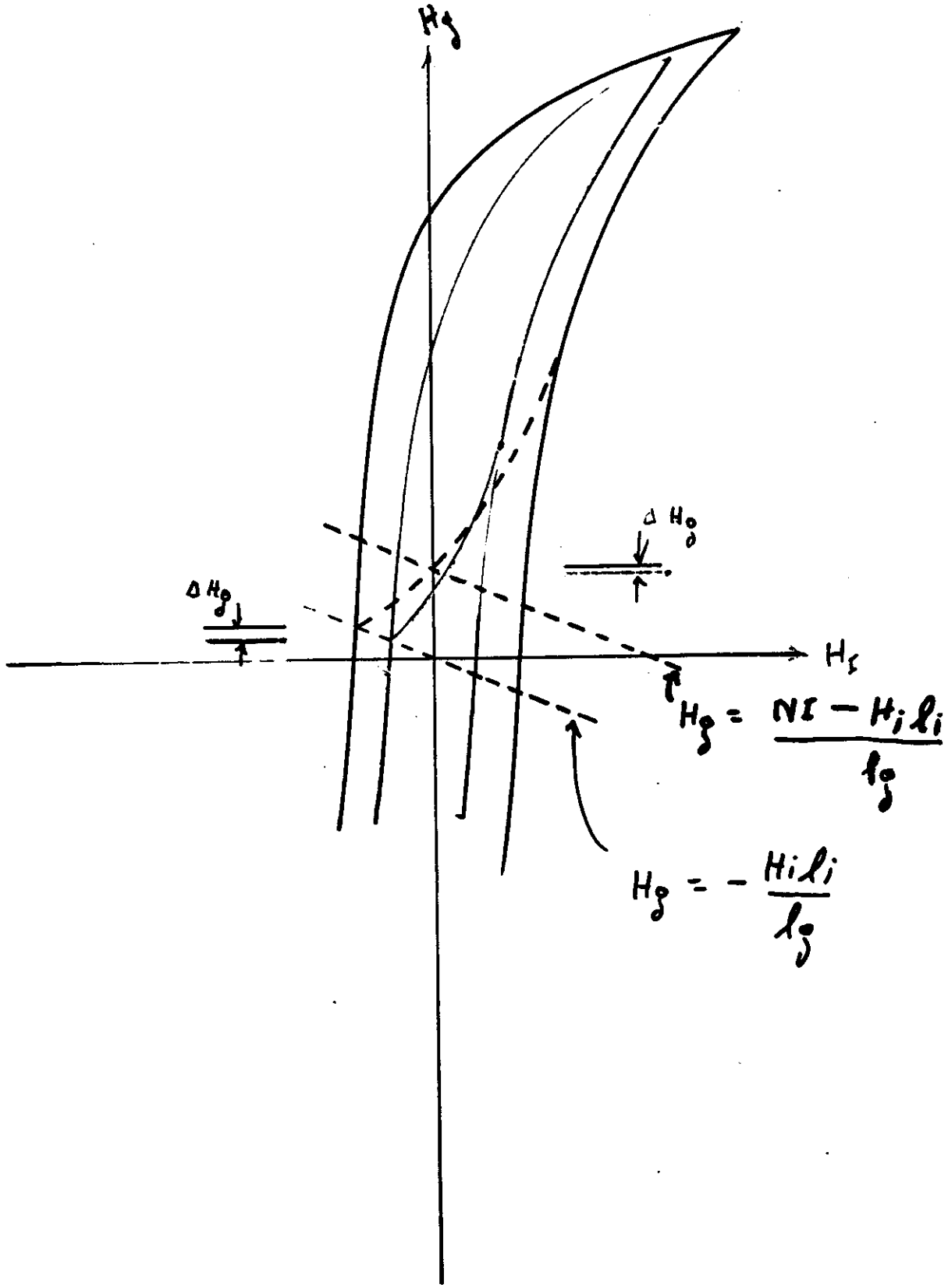

Figure 1