Magnetic Properties of Iron Yoke Laminations for SSC Dipole Magnets*

S.A. Kahn and G.H. Morgan

Accelerator Development Department
Brookhaven National Laboratory, Upton, NY 11973

ABSTRACT

We examine the magnetic properties for the iron used in the SSC yoke laminations so that the accelerator tolerances can be met. The accelerator requirements for field quality specify a tolerance on the variation in the central field. At machine injection the variation in field is attributed to coercivity, H_c. Requirements on the magnitude and the variation of H_c are presented. At the 6.65 tesla operating field the variation in the saturation magnetization dominates the magnetic tolerance for the iron.

1. INTRODUCTION

A high degree of central field uniformity is required for the SSC main ring dipoles. This requirement is specified by a RMS tolerance in $\frac{\Delta B_0}{B_0} < 0.001$. It is assumed that a tolerance half of this value can be safely assigned to variations in the iron properties of the yoke. Since iron properties are independent of magnet construction errors, these tolerances can be added in quadrature. Tolerances for Fourier harmonics higher than the fundamental, B_0, are not significantly influenced by variations in iron properties.

In this study iron properties are examined at low field corresponding to beam injection, at medium fields with rapid changes in permeability, and at the high operating fields. At low field the variation is expected to be dominated by H_c or effects correlated to H_c such as the low field permeability. Low field properties tend to be related to grain size, work hardening, etc. The final processing that is done to the steel has a large effect on H_c as it also has on other properties such as the yield strength of the material. In this report we only consider the magnetic properties of the yoke material, however mechanical properties are considered so as not to make inappropriate specifications. The magnetic effects at high field are dominated by the iron saturation. The iron saturation is governed by the chemistry of the iron. In this report we describe the calculations that have been done to establish the desired iron properties for the SSC main ring dipole magnets. A similar type of analysis was performed on the yoke steel for ISABELLE magnets.[1]

2. INJECTION FIELD REQUIREMENTS

At machine injection energy, the main ring dipole magnets see a field of 0.66 tesla. At injection current the variation in field is dependent on remnant fields from previous excitations and deviations in the low field permeability of the steel. Both of these effects are dependent on H_c. To estimate the size of the field in the aperture from the remnant field in the iron we can apply Ampere's law to a closed path through the aperture and around the yoke. Figure 1 shows the flux lines for the 5 cm dipole magnet at injection field. Applying Ampere's law assuming that there is no current in the magnet gives:

$$B_o \times l_{gap} + H_{iron} \times l_{iron} = 0$$

The mean ratio of $\frac{l_{iron}}{l_{gap}}$ can be determined by taking the flux average of the lengths. This ratio is

$$\left\langle \frac{l_{iron}}{l_{gap}} \right\rangle = 1.71$$

We would expect the variation, ΔB_o in the aperture region due to variations in H_c to be

$$\Delta H_c = \frac{\Delta B_o}{1.71}$$

where ΔB_o is allowed to be 3.3 gauss by the previously mentioned tolerance. This provides a rather achievable requirement that $\Delta H_c < 1.9$ Oe.

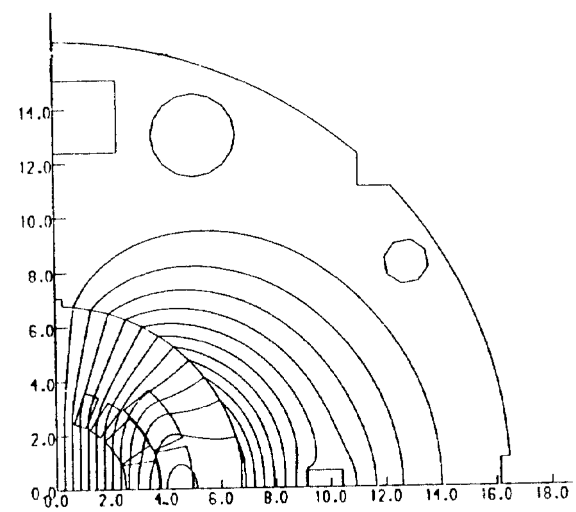

Figure 1: 5 cm SSC dipole with flux plot corresponding to injection field.

A more complete analysis of the low field behavior of this magnet was performed using the finite element program PE2D[2] with normal B-H tables corresponding to $H_c = 0.7$ Oe and 1.8 Oe.[3] To simulate the hysteresis effect on these curves H_c is subtracted (added) to each of these curves corresponding to the descending (ascending) curve.

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Table 1 gives B_o for a current sweep using the 0.7 (1.8) Oe materials. Both the *normal* curve and the *descending* curve are shown. (The *normal* curve is approximately the average of the *ascending* and *descending* curves.) The difference between the *normal* curve and the *descending* curve gives $\Delta B_o = 1.0$ (0.96) gauss for the $H_c = 0.7$ (1.8) Oe. There is an additional contribution from the change in permeablility that is associated to the change in H_c. We see a change in B_o of 1.87 gauss for a change of H_c of 1.1 Oe. As these affects are correlated we add there contributions. Assuming that this difference represents a variation in B_o, the allowable variation in H_c is estimated to be 1.1 Oe. which is quite large. Figure 2 shows the RMS variation in H_c for steels used in and proposed to be used in a number of different accelerators[4] verses H_c. The lower H_c steels are final annealed to various extents. The higher H_c steels are not annealed. Some of the larger ΔH_c is supposedly due to working of the material to make laminations. It is expected that the variation in H_c will not be a problem and that requesting $\Delta H_c < 0.25$ Oe should be attainable.

Table 1: B_o verses I *normal* and *descending* curves corresponding to materials with $H_c = 0.7$ Oe and 1.8 Oe, respectively. The *normal* curve is the average of the *ascending* and *descending* curves.

Current amps	Normal $H_c = 0.7$	Descend $H_c = 0.7$	Normal $H_c = 1.8$	Descend $H_c = 1.8$
660	6883.8	6884.8	6881.9	6882.9
1000	10430.3	10431.3	10428.0	10428.9
2000	20859.7	20860.7	20856.4	20857.4

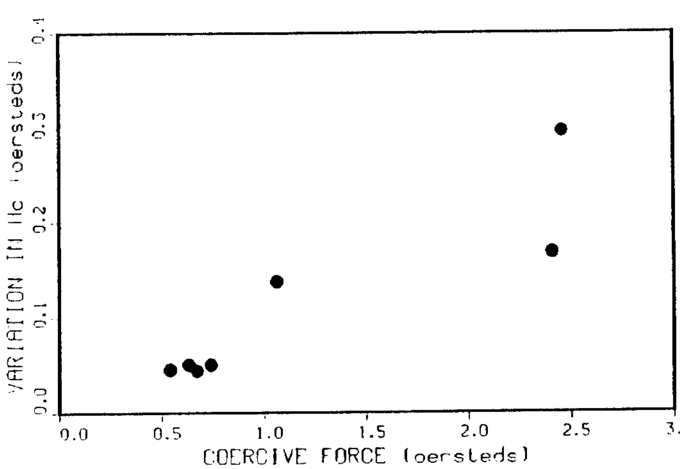

Figure 2: ΔH_c verses H_c for different steels used in existing and proposed accelerators.

The desired mean value of H_c is selected based on the correlation between H_c and the permeability, μ. Figure 3 demonstrates this correlation. H_c is chosen such that μ will be greater than 500 gauss/Oe for essentially all samples. This procedure indicates that $< H_c >$ should be less than 1.8 Oe.

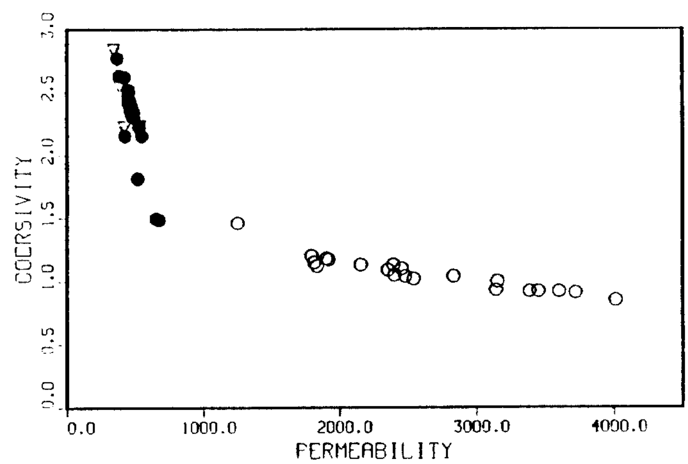

Figure 3: Permeability, μ verses H_c for different steels used in existing and proposed accelerators.

3. OPERATING FIELD REQUIREMENTS

At high field the variation in field is due to variations in the saturation magnetization, M_S. To determine the allowable variation in M_S, different B-H curves are derived corresponding to a known deviation in M_S. These B-H relations are obtained by using the Frohlich-Kennelly formula,

$$\frac{H}{B} = a(H) + \frac{H}{M_S}$$

where a(H) is chosen to be a function of H so that it corresponds to our standard B-H curve and M_S is allowed to vary by a small known amount. Table 2 shows B_o for various currents corresponding to the standard B-H curve and to curves with M_S increased and decreased by 78 Oe. At 6500 amps we find that with

$$\alpha = \left(\frac{\Delta B_o}{B_o}\right)\left(\frac{M_S}{\Delta M_S}\right)$$

$\alpha = 0.187$ where α depends primarily on the geometry of the yoke. The allowable tolerance permits a RMS $\Delta M_S = \pm 57$ Oe.

Measuring ΔM_S to sufficient accuracy to be useful to monitor the production of the steel is not easy. As M_S is primarily dependent on the chemistry of the s-teel, monitoring the steel chemistry may be the practical approach.

4. INTERMEDIATE FIELD

In the intermediate field region the permeability varies substantially across the yoke. The attributes that affect the permeability are the chemistry which determines M_S and the grain size, etc. that affect H_c at low field. The Frohlich-Kennelly relation was originally intended to be a phenomenological expression describing the approach to saturation where *a(H)* is generally chosen to be a constant or a low order polynomial in $\frac{1}{H}$. In this application however we are assuming that the entire H range, which is four orders of magnitude, can be described by the relation where *a(H)* is chosen so that the correct B-H relation holds. Over this range *a(H)* varies by only a factor of 5. Although *a(H)* itself is not a physical quantity, it describes in some sense attributes related to the permeability that are independent of M_S. In a procedure similar to that which was used for M_S we change the B-H curve by varying *a(H)* by a small amount and using the Frohlich-Kennelly relation to reconstruct the curve. Table 3 shows the results for a variation of $\Delta a = \pm 5 \times 10^{-5}$. Although this chosen variation of Δa is considered large it is not unrepresentative (unfortunately) of what one can obtain. (We received a shipment of steel which appeared to be "mechanically worked" to the extent that the variation in *a(H)* was this large.)

Table 3: B_o verses I for curves corresponding to the standard B-H curve and to those with a(H) increased or decrease by 5×10^{-5}.

Current amps	Standard Table	Decreased a(H)	Increased a(H)
660	6884	6885	6883
5000	51858	51871	51846
5500	56702	56717	56687
6000	41340	61358	61323
6500	65799	65816	65781
7000	70118	70134	70101

Table 2 indicates that small effects of the onset of the variation in saturation are present in the intermediate region at 5000 amps. If we assume that the full allowable tolerance in M_S is used at 6500 amps, then ΔM_S at 5000 amps would represent only about 30% of the tolerance. Since M_S and a are presumed uncorrelated, Δa can take 95% of the allowable tolerance implying that $\Delta a < 1.0 \times 10^{-4}$ which we believe can be achieved.

Table 2: B_o verses I for curves corresponding to the standard B-H curve and to those with M_S increased or decrease by 78 Oe.

Current amps	Standard Table	Decreased M_S	Increased M_S
660	6884	6884	6884
5000	51858	51846	51870
5500	56702	56678	56725
6000	41340	61304	61377
6500	65799	65754	65844
7000	70118	70066	70169

5. REFERENCES

1. M.J. Tannenbaum et al., *Magnetic Properties of the Iron Laminations for CBA Magnets*, IEEE Transactions on Nuclear Science 30-NS p3472 (1983), BNL report 32711..
2. PE2D is a computer program for the 2D calculation of Poisson's equation. PE2D Reference Manual, VF088924, Vector Fields Ltd., Oxford, England.
3. Data supplied by Armco Inc., Middletown, Ohio..
4. Data for this figure come from iron samples used for ISABELLE, SSC prototypes, FNAL new mainring project, LEP, and HERA. Published references are
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   - H. Laeger et al, *Production of the Soft Magnetic Steel Laminations for the LEP Dipole Magnets*, CERN LEP-MA/87-52 (1987).
   - Also we would like to thank Armco and LTV for the use of their data.

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