

## Magnetic Properties of Iron Yoke Laminations for SSC Dipole Magnets\*

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### 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 magnetisation 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.<sup>1</sup>

### 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:

$$B_0 \times l_{gap} + H_{iron} \times l_{iron} = 0$$

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,  $\Delta B_0$ , in the aperture region due to variations in  $H_c$  to be

$$\Delta H_c = \frac{\Delta B_0}{1.71}$$

where  $\Delta B_0$  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.

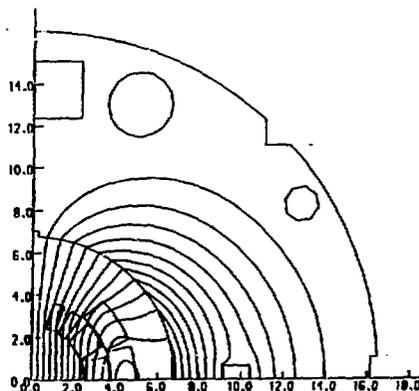


Figure 1: 5 cm SSC dipole with flux plot corresponding to injection field.

A more complete analysis of the low field behavior of this magnet was performed using the finite element program PE2D<sup>2</sup> with normal B-H tables corresponding to  $H_c = 0.7$  Oe and 1.8 Oe.<sup>3</sup> 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 permeability 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 these 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<sup>1</sup> versus  $H_c$ . The lower  $H_c$  steels are final annealed to various extents. The higher  $H_c$  steels are not annealed. Some of the larger  $\Delta H_c$  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:  $B_o$  versus  $I$  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

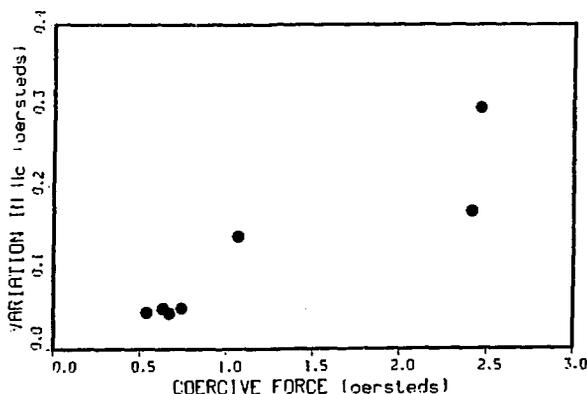


Figure 2:  $\Delta H_c$  versus  $H_c$  for different steels used in existing and proposed accelerators.

The desired mean value of  $H_c$  is selected based on the correlation between  $H_c$  and the permeability,  $\mu$ . Figure

3 demonstrates this correlation.  $H_c$  is chosen such that  $\mu$  will be greater than 500 gauss/Oe for essentially all samples. This procedure indicates that  $\langle H_c \rangle$  should be less than 1.8 Oe.

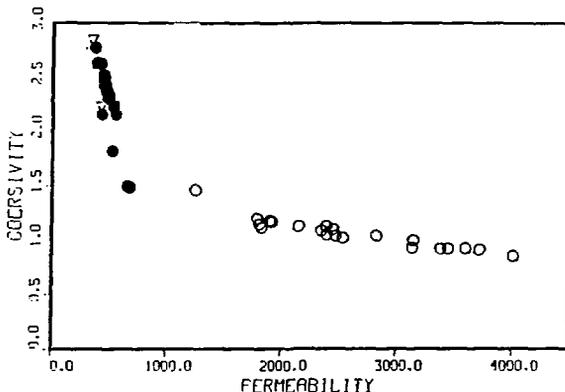


Figure 3: Permeability,  $\mu$  versus  $H_c$  for different steels used in existing and proposed accelerators.

### 3. OPERATING FIELD REQUIREMENTS

At high field the variation in field is due to variations in the saturation magnetisation,  $M_S$ . 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,

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

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

Measuring  $\Delta M_S$  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 steel, 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  $\Delta a$  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:  $B_o$  versus I for curves corresponding to the standard B-H curve and to those with  $a(H)$  increased or decrease by  $5 \times 10^{-5}$ .

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  $\Delta M_S$  at 5000 amps would represent only about 30% of the tolerance. Since  $M_S$  and  $a$  are presumed uncorrelated,  $\Delta a$  can take 95% of the allowable tolerance implying that  $\Delta a < 1.0 \times 10^{-4}$  which we believe can be achieved.

#### 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..

Table 2:  $B_o$  versus 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

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
  - K. Sinram et al, *The Influence of Fine Blanking on the Magnetic Properties of Soft Magnetic Iron*, DESY (1990).
  - 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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