



BNL-105056-2014-TECH

Booster Technical Note No. 8;BNL-105056-2014-IR

Selection of Magnet Lamination Material and Thickness on the Basis of Eddy Currents

G. H. Morgan

February 1986

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

Notice: This technical note has been authored by employees of Brookhaven Science Associates, LLC under Contract No.DE-AC02-76CH00016 with the U.S. Department of Energy. The publisher by accepting the technical note for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this technical note, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Selection of Magnet Lamination Material and Thickness
on the Basis of Eddy Currents

Booster Technical Note

No. 8

by

G. H. Morgan

12 February 1986

*HIGH ENERGY FACILITIES
Brookhaven National Laboratory
Upton, N.Y. 11973*

Booster Technical Note

G. H. Morgan

Selection of Magnet Lamination Material and Thickness on the Basis of Eddy Currents

The procedure used in this study is a solution of the magnetic field diffusion equation for an idealized lamination having constant permeability μ , thickness d , and subject to the same surface field H_s on both sides of the lamination. It is assumed that the field averaged across the thickness has a triangular waveform of frequency f and amplitude (peak to trough) A . The diffusion equation is:

$$\frac{\partial^2 H}{\partial x^2} = \frac{\mu}{\rho} \frac{\partial H}{\partial t} \quad (1)$$

The fourier expansion of the triangular waveform is:

$$\bar{H} = \frac{A}{2} - \sum \frac{4A}{n^2 \pi^2} \cos n\omega t, \quad n \text{ odd} \quad (2)$$

where $\omega = 2\pi f$. The solution to eq. (1) is

$$H = C_n \cosh (K_1 x) e^{in\omega t} + D_n \cosh (K_2 x) e^{-in\omega t} \quad (3)$$

where sinh terms are omitted since they do not satisfy the symmetric boundary condition. Since only cosh $n\omega t$ terms are in the expansion,

$$K_1 = (1 + i)/\delta n \text{ and } K_2 = (-1 + i)/\delta n \quad (4)$$

where $\delta_n = \sqrt{2\rho/n\omega\mu}$

The space average of H is $(1/d) \int_{-d/2}^{d/2} H dx$. If this is matched to the fourier expansion of the time, it is found that

$$C_n = \frac{Ad(1+i)}{n^2 \pi^2 \delta_n^2 \sinh [(1+i)d/2\delta_n]} \quad (5)$$

$$D_n = \frac{Ad(-1+i)}{n^2 \pi^2 \delta_n^2 \sinh [(-1+i)d/2\delta_n]} \quad (6)$$

At the surface, $x = \pm d/2$,

$$H_s = \frac{A}{2} - \frac{Ad}{\pi^2} \sum \frac{1+i}{n^2 \delta_n^2} \frac{e^{in\omega t}}{\tanh [(1+i)d/2\delta_n]} + \frac{(-1+i)}{n^2 \delta_n^2} \frac{e^{-in\omega t}}{\tanh [(-1+i)d/2\delta_n]} \quad (7)$$

n odd

Plots of this equation for two values of d are given in Fig. 1. The figures show that the surface field leads the average field (the dashed line) by an amount which is constant after an initial transient after field reversal. For these calculations, 100 terms are used in (7), i.e., the maximum value of n is 199. The other parameters are $A = 4$, $d = 109$ mil or 50 mil, $\mu = 6.3 \times 10^{-3}$ T/A-m and $\rho = 5 \times 10^{-7}$ μm . Some other cases were run; the lead time δt for them are given in Table 1. The parameters are appropriate to M1-9 (3.75% Si) steel.

Table 1

d, mil	109	50	43.75	37.5	25
gage		18	19	20	24
δt , msec	8.68	1.69	1.30	0.95	0.42

If H_S for the 20 gage case is fitted to an equation of the form

$$H_S = a(t - T_0) + b e^{-t/\tau} + c \quad (8)$$

it is found that τ is about 0.2 msec. On the basis of these results, 20 gage is certainly thin enough and 18 gage might be acceptable.

The loss (watts/cubic meter) has two components, hysteretic and eddy current. The eddy current loss per unit volume W_e is given in PJ^2 , where $J = \partial H / \partial x$. This must be averaged first over one time period and then over the thickness of the lamination. The result is given in Eq. 9.

$$W_e = \frac{8 \rho A^2 d}{\pi^4} \sum \frac{1}{n^4 \delta_n^3} \frac{\sin (d/\delta n) - \sinh (d/\delta n)}{\cos (d/\delta n) - \cosh (d/\delta n)}, \quad n \text{ odd} \quad (9)$$

Data on losses in the various electrical grades of silicon steel are usually given at 60 Hz and for peak fields of 10 and 15 kG. For a sinusoidal field, Eq. 9 reduces to

$$W_e = 8H_{pk}^2 \frac{\rho d}{\delta^3} \frac{\sin d/\delta - \sinh (d/\delta)}{\cos d/\delta - \cosh (d/\delta)} \quad (10)$$

For d/δ less than 1, this can be simplified to the well known expression given in Eq. (11).

$$W_e = \rho H_{pk}^2 d^2 / 6\delta^4 \quad (11)$$

For M-19 steel, 20 gage at 60 Hz and $H_{pk} = 10$ kG, Eq. (6) gives 0.32 W/lb. Data from the Metals Handbook, 8th edition (1961) for three gages, when fitted to a d^2 dependence, extrapolates to 0.36 W/lb at $d = d$. This good agreement gives credence to this approach.

The situation with respect to hysteretic loss is less satisfactory. The Steinmetz formula for an ac field is

$$W_h = \eta B^{1.6} \quad (12)$$

where W_h is the loss per cycle due to hysteresis.

The exponent 1.6 was appropriate to steels in Steinmetz' time (1910). Modern materials have exponents from 1.5 to 2.5. Data for M-22 from the metals Handbook, at 60 Hz and 10 and 15 kg, when extrapolated to zero thickness to eliminate the eddy current portion, give an exponent of 2.3. However, this may not be applicable to the triangular waveform with dc offset. Ignoring this, and assuming a field in the iron varying between 1.5 and 4 kG, one obtains 8.7×10^{-4} W/lb. The field in the iron is assumed equal to the field in the gap. The eddy current loss ($A = 39.7$ amp/m) is 3.75 W/m³ or 2.22×10^{-4} W/lb for a total loss of 1.1×10^{-3} W/lb. The lamination area is 0.312 m² and weighs 16900 lb/m³, so the total loss is 5.8 W/m. This compares to 60 W/m in the beam tube given in Tech Note No. 4.

In summary M-19 or M-22 silicon steel with a gage of 19 or 20 would seem appropriate; the choice between the two might be determined by punchability; M-22 is less brittle. There may be difficulty in obtaining either in gages heavier than 24 (25 mil), but reducing the number of laminations by 1/3 or more is a considerable saving.

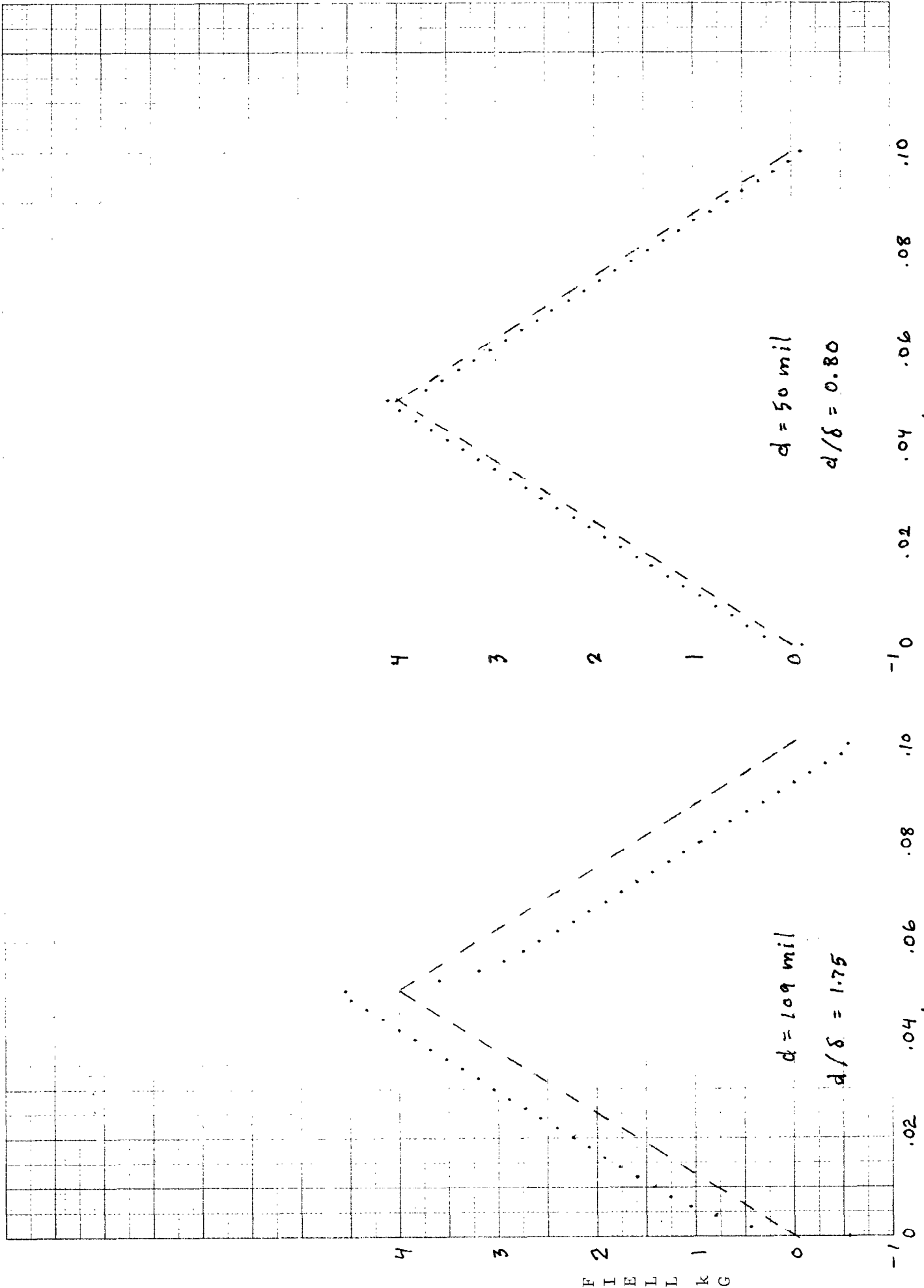


Fig. 1