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A SHORT APPROACH TO THE ELECTRICAL DESIGN OF A MUON SPOILER MAGNET

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1. Abstract

This technical memo describes a simple approach to the electrical design of a muon spoiler magnet (installation #SP712) used in the Proton West beam line. The spoiler is constructed from steel slabs of unknown properties.

Coil operating parameters of 25 A and about 200 V have been chosen, to make it possible to feed the spoiler from an existing D. C. power supply (rated 100 A, 500 V) and cable system.

The coil is watercooled by means of copper tubing wrapped along the outside coil surface.

2. Estimate of the required Ampere turns N.I.

Figure 1 shows that the spoiler steel is built from two 7.5" thick slabs at the bottom and the same at the top. These slabs are separated at the middle by 3 center blocks of 3.5" thickness. An area of about 3.5" x 12" is available for magnetizing windings, and an area of 3.5" x 3" is used for passage of the beam. The field strength in the center blocks is required to be 20 KGauss.

The properties of the steel are not known, but it is reasonable to assume that it is made from hot rolled low carbon steel, such as C-1010 or C-1020. This type of steel is mostly manufactured in plates over .25 inches thick.[1)] The magnetic properties of different types hot rolled low carbon steels at about 16 KG are very similar. However, different annealing temperatures change the magnetic properties substantially at inductions in the order of 8 KGauss. (Fig. 2)

We will assume that the steel used is C-1010 steel, which has not been annealed. The mating surfaces of the steel slabs are machined flat, so that they present a reasonably small air gap (small magnetic reluctance) to the flux passing from one slab to another. We will estimate that the air gap between mating slabs is ∿0.017". The average iron length (l_i) through which the magnetic flux passes may be calculated from Fig. 1 to be l_i = 98". We can also conclude from Fig. 1 that 20 KG in the center blocks results in $\frac{12}{15} \times 20 = 16$ KG in the top and bottom slabs. However, the field strength is more than 16 KG in the area close to the center blocks. We can account for this by assuming, for calculation purposes, that the center blocks are 2" thicker (at 20 KG) than in reality. About half the flux passes two times (Fig. 1) through the air gap between the two top slabs. The same is true for the two bottom slabs. We will therefore count these four gap crossings as two full gaps through which all the flux has to pass. The total flux passes, furthermore, through four air gaps adjacent to the center blocks. Thus the number of gaps through which the total flux passes equals n = 6. We will use a total air gap length $l_g = n \times 0.17 \approx 0.1"$ for further calculations. Now we are ready to calculate the required ampere turns NI for 20 KG in the center blocks. Fig. 2 shows the magnetizing curves for the steel.

In general we can write:

$$\oint H_i \, dl = NI = H_{i20} \, l_{i20} + H_{i16} \, l_{i16} + H_g \, l_g \quad \text{(a)}$$

l_{i20} = iron length at 20 KG = 2 x 3.5 + 4 = 11"

l_{i16} = iron length at 16 KG = 98 - 11 = 87"

l_g = the sum of all air gap length between mating surfaces through which the total flux passes = 0.1"

For (a) we can also write:

$$NI = \frac{B_{i20}}{\mu_0 \ \mu_{r20}} \ l_{i20} + \frac{B_{i16}}{\mu_0 \ \mu_{r16}} + \frac{B_g}{\mu_0} \ l_g \quad \text{Amp. turns (AT)}$$

$B_i = B_g = 20$ KG $= 2$ Wb/m^2

$\mu_0 = 4\pi \times 10^{-7}$

l_g = meters

AT = ampere turns

Iron at 20 KG needs ∿ 400 AT/inch (Fig. 2, curve 1)

Iron at 16 KG needs ∿ 100 AT/inch (Fig. 2, curve 1)

Thus:

$$NI = 11 \times 400 + 87 \times 100 + \frac{2}{4\pi \times 10^{-7}} \times 0.1 \times 2.54 \times 10^{-2} \text{ AT.}$$

$$NI = \underbrace{4400 + 8700}_{\text{NI for iron}} + \underbrace{4023}_{\text{NI for air gaps}}$$

NI = 17,143 AT for 20 KG in center block.

3. Estimate of field strength in beam passage opening

The 3.5" x 3" hole for beam passage will not be field free, especially at higher currents. The spoiler will bend the beam like a dipole would. The field strength in the beam passage hole will increase faster than the spoiler excitation current, due to saturation of the steel.

How much might we expect? Let us look at the 20 KG case. It takes 3.5 x 400 = 1400 AT to drive 20 KG through the 3.5" center blocks around the beam passage hole. This same magneto motive force (AT) tries to push the flux through the beam passage hole.

Thus:

$$1400 = \frac{B}{\mu_0} \times 3.5 \times 2.54 \times 10^{-2}$$

B = field strength in beam passage hole in Wb/m^2 at 20 KG in steel.

$$B = \frac{1400 \times 4\pi \times 10^{-7}}{3.5 \times 2.54 \times 10^{-2}}$$

$$B = 19.5 \times 10^{-3}\ \text{Wb/m}^2 \ \text{(195 Gauss)}$$

For a 118" long spoiler we find:

$$Bdl_{Beam} = 195 \times 118 \times 2.54 \times 10^{-2} \times 10^{-3}\ \text{KGm}$$

$$Bdl_{Beam} = 0.584\ \text{KGm (at 20 KG)}$$

The same exercise can be done for other spoiler excitation currents and is listed in attached Table 1.

4. Estimate of the remanent field in the spoiler steel

There will be a remanent field once a magnetic loop having a total iron length of l_i and a total air gap length of l_g has been magnetized. The strength of the remanent field is greatly influenced by the ratio $\frac{l_i}{l_g}$ and further depends on the value of the coercive magneto motive force H_c of the used steel, and the relative permeability μ_r. H_c for most common electrical types of steel is about -40 to -160 Amp turns/m (-0.5 to -2 Oersted). We can again write the loop integral for this case and find:

$$NI = H_i l_i + H_c l_i + H_g l_g = 0$$

$$\frac{B_i}{\mu_0 \mu_r} l_i + H_c l_i + \frac{B_g}{\mu_0} l_g = 0$$

$$B_i = B_g = B_{r(emanent)}$$

$$B_r\left(\frac{l_i}{\mu_r l_g} + 1\right) = -\mu_0 H_c \frac{l_i}{l_g} \qquad \text{(b)}$$

The relative permeability $\mu_r \approx 1000$ at 10 KG and is different for other values of B. For reasonably large air gaps with a ratio $\frac{l_i}{l_g} < 100$, we find that the value

$$\frac{l_i}{\mu_r l_g} << 1$$

so that we can write:

$$B_r = -\mu_0 \; H_c \frac{l_i}{l_g}$$

or:

$$B_r = -4\pi \times 10^{-7} \; H_c \frac{l_i}{l_g} \times 10^4 \text{ Gauss} \qquad (c)$$

$$H_c = \text{AT/meter}$$

This is an interesting formula because for many electrical steels $H_c \approx -80$ AT/meter. Using this value of H_c in (c) we find:

$$B_r = \frac{l_i}{l_g} \text{ Gauss}$$

Thus, for many air gap magnets, if we want a rough estimate of the remanent field, we might say that:

$$B_r = \frac{\text{average iron length}}{\text{total air gap length}} \text{ Gauss}$$

(for values up to ∿ 100 Gauss)

In our case $H_c = -160$ AT/meter coming from a B_{max} of 10 KG.

$$B_r = 4\pi \times 10^{-7} \times 160 \times \frac{98}{0.1} \left(\frac{\mu_r \times 0.1}{98 + \mu_r \times 0.1} \right) \times 10^4 \text{ Gauss (from b)}$$

$\mu_r \approx 500$ at 600 Gauss

μ_r can be calculated from Fig. 2 via :

$$\mu_r = \frac{B}{4\pi \times 10^{-7} \times H} \quad \text{for B in Wb/m}^2 \text{ and H in AT/m}$$

$B_r = 660$ Gauss

The remanent field might in reality be quite different, due to the fact that we do not know the air gap very precisely at all. The total ampere turns contributed by H_c are $160 \times 98 \times 2.54 \times 10^{-2} =$ 400AT. This equals $\frac{400}{684} = 0.58$ A excitation current and means that 0.58 A less excitation will yield the same induction in the steel, after initial startup (see Table 1).

5. Coil Design

Considerations for the coil design are:

- Available winding space,

- choice of wire size, influenced by quick delivery,
- wire insulation system (radiation and thermal properties of insulation),
- ease of winding the coil,
- coil operating parameters, Volts, Amp.

The coil is built from two identical windings, one around the top blocks and one around the bottom blocks. Both windings are connected in series. Each winding has copper tubing wrapped around the outside for water-cooling.

Choose:

$I = 25$ A

$N = 684$ (342 turns/coil)

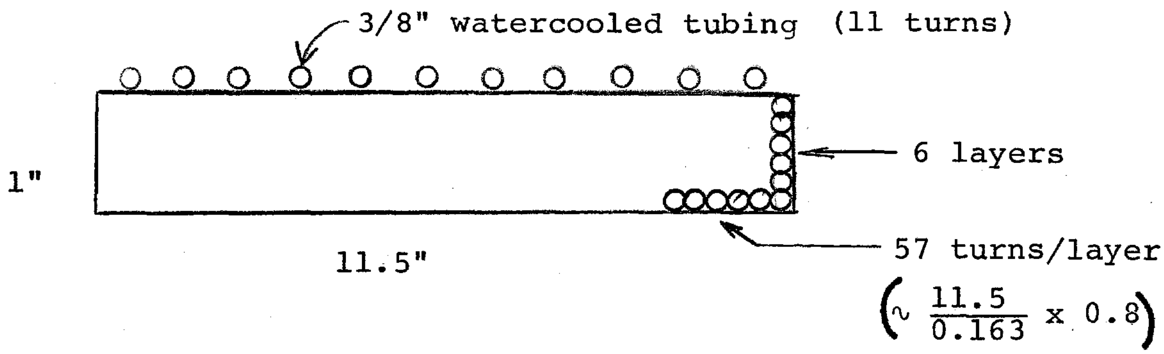
Wire:	AWG #6 copper, O.D. = 0.163", round, 80 lbs/1000 ft, 0.3952 Ω/1000' at 20^0 C.
Insulation:	Film insulated wire, Class H, 180^0 C - 200^0 C, polyester with polyamide - imide overcoat, good heat shock, windability, flexibility. (Note: This wire was readily available.)
Radiation data:	Values indicate beginning of serious damage polyester ∿ 5.5×10^{11} Ergs/gm(c) polyamide ∿ 10^9 Ergs/gm(c) epoxy resins ∿ 9×10^{10} Ergs/gm(c)

The total winding crossection for both coils is estimated to be:

$$2 \text{ coil area} = 684 \times 0.163^2 \times \frac{\pi}{4} \times \frac{1}{0.8} = 18.36 \text{ inch}^2$$

A fill factor of 0.8 is estimated.

Each coil is built as follows:



Average turn length ∿ 274" (from Fig. 1)

Wire length/coil = 274 x 342 x $\frac{1}{12}$ = 7,809 ft/coil

$R_{20°C}$/coil = 7.8 x 0.3952 = 3.08 Ω/coil

$R_{100°C}$/coil = R_{20}(1 + 0.004 x 80) = 4.07 Ω/coil

I^2R/coil = 25^2 x 4.07 ∿ 2550 watt/coil

Coil surface area for cooling ∿ 274 x 11.5 = 3151 $inch^2$

Thus the surface has to dissipate:

$$\frac{2550}{3151} = 0.81 \text{ watt/inch}^2$$

If the coil were mounted in free still air, with no obstructions, we estimate the thermal impedance:

$$\theta_{\text{coil surface to air}} = 100 \quad \frac{^\circ C}{\text{watt/inch}^2}$$

The maximum coil winding temperature would be:

ΔT = 81° C (from .81 watt/$inch^2$)

Ambient = 40° C

Hot spot = 20° C (allowance for hot spot)

Max. coil temp. 141° C

This temperature would be obtained if the coil could cool to free still air without obstructions. This is not the case, especially where the two coils face each other in the winding slot. The horizontal mounting of the coil is also not the best for cooling. As a result, the actual operating temperatures can deviate substantially from the calculated values.

The outer surface of each coil has therefore been provided with 11 turns of 3/8 copper tubing, through which cooling water flows.

Watercooling: 3/8 tubing at ∿ 7/8" center to center

number of cooling turns = 11 turns/coil

Total tubing length = $11 \times 274 \times \frac{1}{12} = 251$ ft/coil

$\Delta P = 80$ PSI available

3/8 tubing I.D. = 0.312"

Flow ∿ 3 GPM/coil (from flow charts)

Cooling water temperature rise may be determined from:

$$\Delta T(^{o}C) = \frac{KW \times 3.2}{GPM}$$

Thus $\Delta T = \frac{2.55 \times 3.2}{3} \sim 3^{o}$ C/coil

Max. water inlet temp 44^{o} C

Max. water outlet temp 47^{o} C

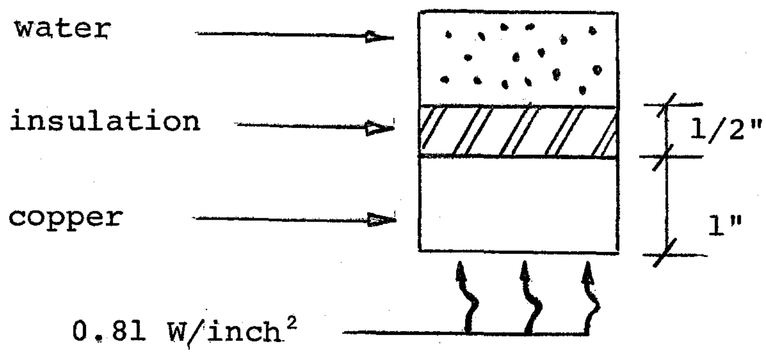
Using cooling water we can estimate the coil temperature rise, assuming that all losses are carried away by the cooling water. The transfer of the heat through the windings to the cooling tubes will be improved by epoxy impregnating the coil.[2)] The coil is therefore wound by means of a wet layup method using room cure epoxy with a filler. A filler improves the thermal conductivity.[2)]

Copper temperature rise estimate:

Coil volume = $274 \times 11.5 \times 1 = 3151$ inch^3

Loss/inch^3 = $\frac{2550}{3151} = 0.81$ watt/inch^3

It is difficult to calculate the thermal impedance from the coil to the cooling water. We will therefore assume that all the heat has to travel through 1" thick copper and 1/2 inch thick insulation before it reaches the cooling water.



Specific thermal conductivity λ_s of materials[2)]:

Cu	= 9.93 watt/inch °C
Epoxy	= 1.4 to 4 x 10^{-3} watt/inch °C
Epoxy with silica mesh	= 19.4 x 10^{-3} watt/inch °C
Alumina epoxy	= 6.24 x 10^{-3} watt/inch °C

For the insulation we will use the specific value for epoxy with silica mesh of $\lambda_s = 19.4 \times 10^{-3}$ watt/inch °C or $\theta_s = \frac{1}{\lambda_s} = 51.5$ °C inch/watt. Thus, 1 watt travelling through a 1-inch thick layer of silica mesh epoxy requires a ΔT of 51.5 °C. In our case we have 0.81 watt dissipation per inch² travelling through ½" thick insulation, which requires $\Delta T = 0.81 \times 51.5 \times \frac{1}{2} \approx 21$ °C. From the above specific values, we can conclude that it reasonable to neglect the thermal impedance $\frac{1}{\lambda}$ of the 1" thick copper.

The coil temperature rise with water cooling is:

Water inlet temp. (max.)	44 °C
Water temp. rise	3 °C
Insulation ΔT	21 °C
Hot spot allowance	20 °C
Max. coil temp.	88 °C

This is well within the temperature range of the wire insulation. A klixon of 145°C is used for overtemperature protection.

6. Coil Cooling Measurements

In Section 5, we had estimated that the thermal impedance from the coil to cooling water equals the thermal impedance a half-inch thick layer of silica mesh epoxy with a $\theta_{ins} = 25.8 \frac{{}^{o}C}{Watt/inch^2}$

It is interesting to find out how close this estimate really is. In order to do this we need to measure the coil losses, the cooling water supply and return temperature, and the coil operating temperature. We found the following:

$I = 25$ A

$V = 170.6$ V

Water temperature = 24.5°C average.

The coil surface was calculated (Section 5) at 3151 inch² so that the losses equal $\frac{25 \times 170.6}{2 \times 3151} = 0.677$ Watt/inch² for two coils. The average coil operating temperature can be determined from the hot and cold resistances of the coils.

It follows that: $R_{hot} = \frac{170.6}{25} = 6.824\ \Omega$*

The coil resistance at 20°C was measured to be $R_{20} = 6.37\Omega$*

We can write:

$$R_{hot} = R_{20}\ (1 + \Delta T \times 0.004)$$

or:

$$\Delta T = \left(\frac{R_{hot}}{R_{20}} - 1\right) 250^{o}C$$

$$\Delta T = 17.7^{o}C$$

The average coil operating temperature T_{ca} was therefore

$T_{ca} = 20^{o} + \Delta T = 37.7^{o}C$ with 24.5°C cooling water and 0.677 Watt/inch² losses.

From this information we can conclude that:

$$\theta_{ins} = \frac{T_{ca} - T_{cooling\ water}}{losses/inch^2}$$

$$\theta_{ins} = 19.5\ ^{o}C/Watt/inch^2$$

This value is about 25% lower than the estimated value of

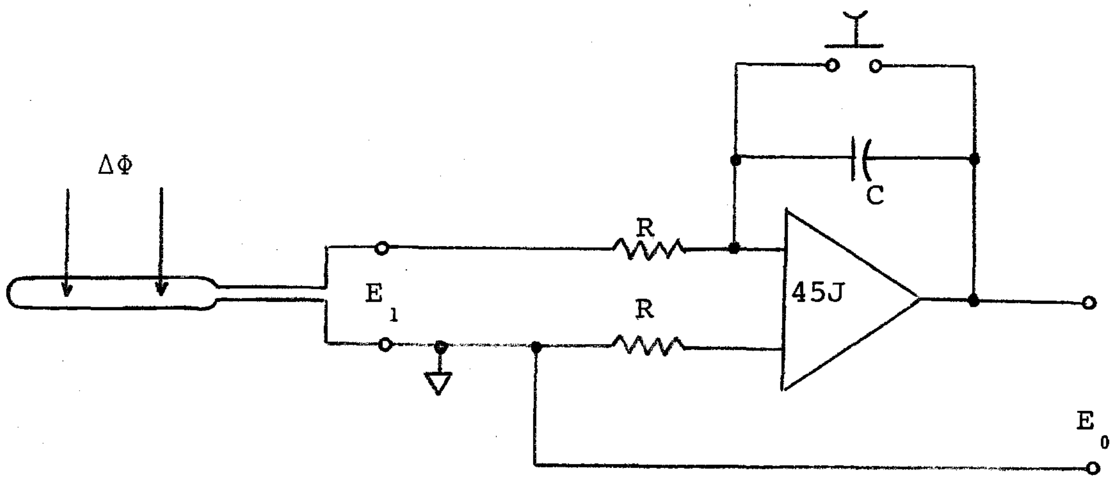
25.8 $^{o}C/Watt/inch^2$

which indicates that the estimate was reasonable.

*Note: All measurements were done at the power supply and include therefore, about 0.2 Ω cable resistance between the supply and the spoiler magnet. The effect of this has been neglected in the calculations, since it does not have a large effect on the check of the thermal impedance.

7. Spoiler Induction Measurement

The spoiler induction can be measured by installing W temporary turns around a center block and changing the magnetizing current in steps. The temporary turns are connected to a voltage input integrator.



$$E_0 = \frac{-1}{RC} \int_0^T E_1 \, dt \qquad \text{(a)}$$

E_1 is the induced voltage at the temporary winding, caused by the change in magnetizing current.

$$E_1 = -W \frac{d\phi}{dt} = K_n \, W \frac{dI}{dt} \qquad \text{(b)}$$

$d\phi$ = change of flux in spoiler

K_n = constant for measuring step n

dI = change in magnetizing current

Dividing $\Delta\phi$ by the area S through which the flux passes will yield the change in induction ΔB.

$$\Delta B = \frac{\Delta\Phi}{S}$$

For (b) we can write:

$$\int_0^T E_1 \, dt = -W \int_0^T d\Phi$$

The output of the voltage integrator is related to the change in flux as follows:

$$E_0 = \frac{W}{RC} \int_0^T d\Phi$$

$$E_0 = \frac{W}{RC} \Delta\Phi$$

$$E_0 = \frac{WS}{RC} \Delta B$$

$$\Delta B = \frac{RC}{WS} E_0 \qquad \text{(c)}$$

Choose: $W = 1$

$R = 10^4 \ \Omega$

$C = 4.14 \times 10^{-6} F$

$S = 0.9136 \ m^2$

($S = 12 \times 118 \times 6.452 \times 10^{-4}$ m^2 for spoiler SP712)

The product of R x C determines the accuracy of the integrator. The individual components were measured as chosen above. The performance of the integrator can also be calibrated by applying a precisely known (time duration and level) pulse to the input and measuring the output. From several calibration measurements it was determined that $RC = 4.1926 \times 10^{-2}$.

For these values we find:

$$\Delta B = \frac{4.1926 \times 10^{-2}}{1 \times 0.9136} \times 10^4 \ E_0 \qquad \text{(c)}$$

$$\Delta B = 459 \ E_0 \ \text{Gauss}$$

ΔB in Gauss

E_0 in Volt

The measurements were made at the outer center block with a calculated crossection of 12" x 118" inch^2. (Note: In reality this block turned out somewhat larger. No correction for this has been made, since the center blocks around the beam hole are 6" x 118" each.) The measurements are listed in table 2 and plotted in fig. 3.

Each quadrant direction was measured in several steps and also in the same direction in one full step. The value of the full step induction change ΔB_F should equal the accumulated value $\Sigma\Delta B_S$ of the small steps. A correction to the small step ΔB_S has been made where there are differences. The correction Δb made at each ΔB_S is:

$$\Delta b = \frac{\Delta B_F - \Sigma\Delta B_S}{n}$$

n = number of steps per quadrant direction

so that:

$B_F = \Sigma\Delta B_{S\ corrected}$. (see table 2)

Anyone who has attempted to make these types of measurements will agree that these measurements are plagued by accumulative errors and a correction is therefore justified. Ideally, the B-H loop should close (accumulated $\Delta B = 0$) when we are back at the starting point. The B-H loop is symmetrical around the 0 point, such that quadrant #1 down has the same curve as quadrant #3 up, and quadrant #3 down equals quadrant #1 up. To construct the B-H loop of fig. 3, we could have gotten sufficient information by measuring quadrant #1 down and quadrant #3 down.

The full step measurement is not very time-consuming and yields the maximum induction and the remanent field. It does not reveal the shape of the B-H loop. From the full step measurement we can conclude:

$$B_{max} = \frac{\Delta B_{F1} + \Delta B_{F3}}{2}$$

and:

$$B_r = \frac{\Delta B_{F3} - \Delta B_{F1}}{2}$$

ΔB_{F1} = full step in quadrant 1

ΔB_{F3} = full step in quadrant 3

Both steps from $+I_{max}$ in the same direction to $-I_{max}$.

Now, let us look at the results shown in fig. 3. The remanent field B_r = 4500 Gauss and is much higher than the 660 Gauss calculated in Section 4. The induction also increases faster than calculated. Both symptoms indicate that the 0.1" airgap estimate may have been too conservative.

From formula (b) in Section 4 we can calculate l_g (assuming that we know the steel) yielding a B_r = 4500 Gauss.

$$\mu_{r\ 4500} = \frac{0.45}{4\pi \times 10^{-7} \times 3.7 \times 80} \quad \text{(see Section 4)}$$

$$\mu_{r\ 4500} = 1240$$

Formula 4(b) yields:

$$0.45 \left(\frac{98}{1240\ l_g} + 1 \right) = 4\pi \times 10^{-7} \times 160\ \frac{98}{l_g}$$

$$l_g = -\ 0.08"$$

which is impossible.

A $\mu_r > 1240$, a $l_g < 0.1"$ and possibly $H_c > |-160|$ AT/m can give a logical result.

We may conclude that steel is better than assumed in curve 1, fig. 2 and that the airgap is smaller than 0.1". The effect of this also agrees with the larger than expected induction in the beam passage hole. The center blocks are very likely made from a different batch of steel than the top and bottom slabs. Although the initial assumption may have been conservative for medium excitations, they are reasonable and offer a good safety factor.

Spoiler Design Data Summary, 2 Coils in Series at 25A

Turns	= 684
$R_{20^\circ C}$	= 6.16 Ω
$R_{100^\circ C}$	= 8.14 Ω
I	= 25 A
$V_{100^\circ C}$	= 204 V
$Loss_{100^\circ C}$	= 5.1 KW
B	= 20 KG
ϕ	= 1.82 Wb
L	= 50 H $(L = \frac{N\phi}{I})$
Cooling	: water
Flow	= 6 GPM (2 coils in parallel)*
ΔP	= 80 PSI
Max. inlet temp	= 44°C
ΔT water	= 3°C (2 coils in parallel)*
Coil operating temp.	= 88°C (calculated at 25A and 44°C water in)*
Insulation temp. rating	= 180°C
Material	: 17,000 ft, #6, (1,350 lbs, $2300, 1/26/80)
	550 ft 3/8 Cu tubing

* Water circuits may be operated in series, resulting in 1.1 GPM flow and 12°C higher coil operating temperatures.

6. Acknowledgements

R. Currier and B. Strickland coordinated and designed the equipment for fabrication of the coil. They also supervised the fabrication and installation of the spoiler. Walt Jaskierny and Bob Innes performed the measurements and designed and calibrated the integrator.

7. References

[1] U.S.S. Electrical Steel Sheets Engineering Manual, 4th Edition. Copyright 1955, United States Steel Corporation, 525 William Penn Place, Pittsburg 30, Pennsylvania, pages 257, 258, 259, 260.

[2] Standard Handbook for Electrical Engineers, 10th Edition. McGraw Hill Book Company, sec. 4-430 to 4-438 (Thermal conductivity of insulation).

Excitation		I for N = 684 in Amp.		B in Center Block		B in Beam Hole	
Amp. Turns for 6 Air Gaps 0.1" Total	Amp. Turn Total	Initial I_1	** With Contribution From Remanent Amp. Turns (H_c) I_2	*Calculated Gauss	Measured Gauss at I_2	Calculated Gauss	Measured Gauss At I_2
4,023	17,143	25	24.42	20×10^3	See Graph Fig. 3	195	See Graph Fig. 4
3,621	10,343	15.12	14.54	18×10^3		90	
3,218	6,534	9.5	8.92	16×10^3		39	
2,822	4,915	7.18	6.6	14×10^3		20	
2,012	3,145	4.6	4.02	10×10^3		9	
1,006	1,605	2.35	1.77	5×10^3		3	

* Used Fig. 2 Curve 1, variations of a factor 3 at lower excitations are possible for different curves.

** Remanent H_c contributes 400 AT or 0.58 Amp. (See Section 4).

TABLE 1

EXCITATION OF SPOILER SP712

CALCULATED VALUES

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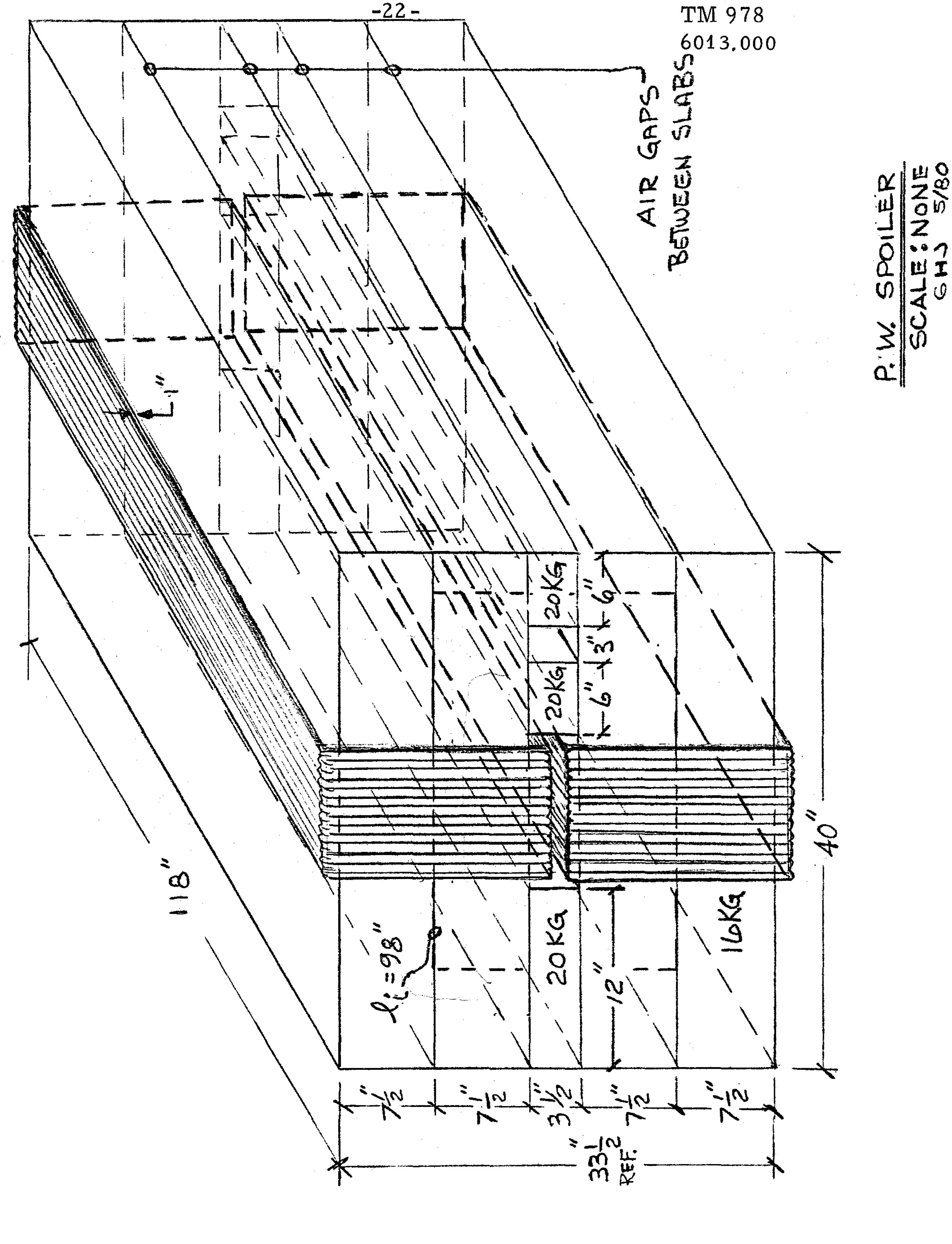
TABLE 2: SPOILER SP712 INDUCTION MEASUREMENT

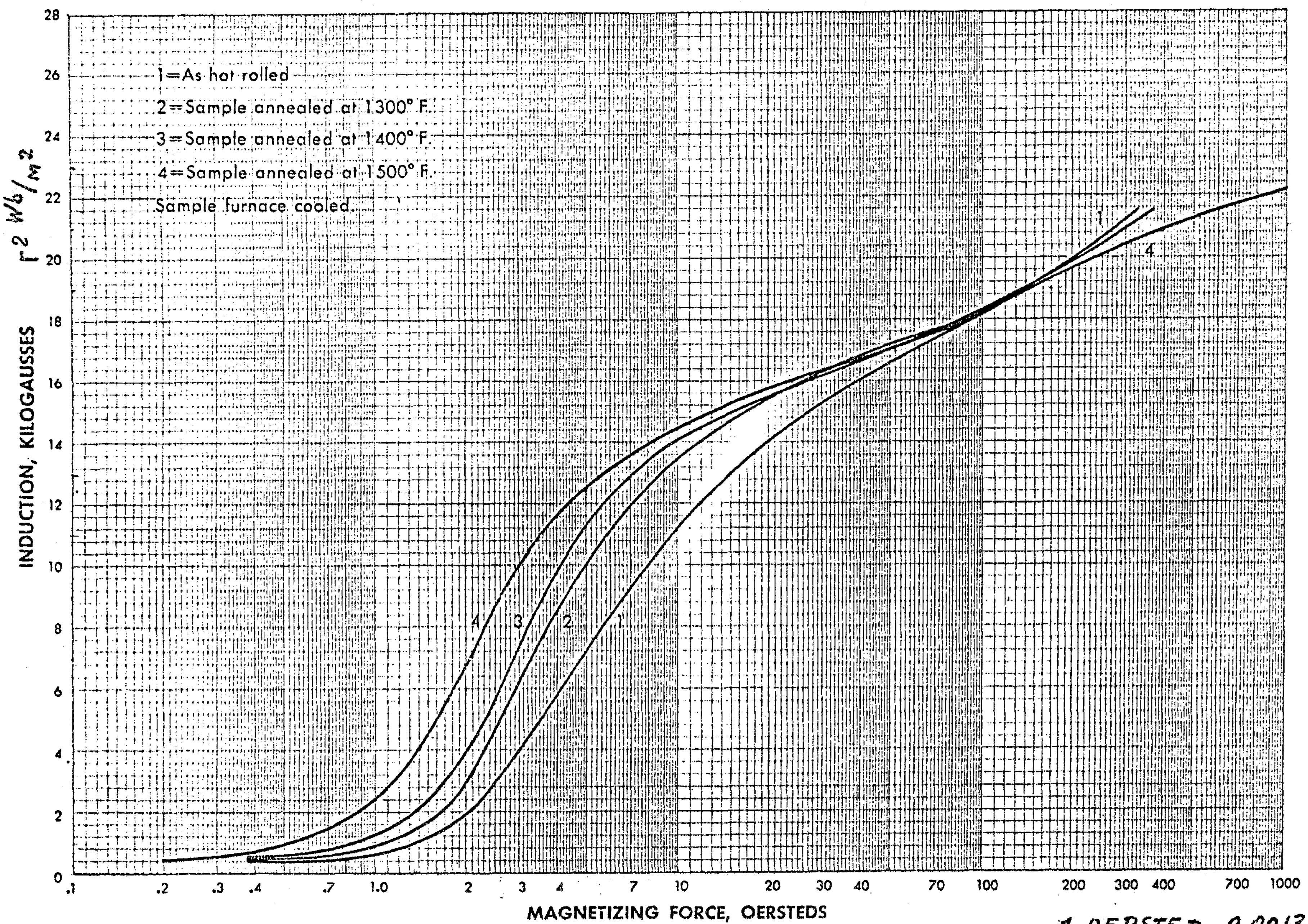
1 Step	2 $I_{spoiler}$ Amp	3 Integrator E_o Volt	4 $\Delta B = 459E_o$ Gauss	5 Accumulated ΔB Per Quadrant Direction From Column 4 Gauss	6 Measured ΔB Per Quadrant in One Step Gauss	7 Step Correction Δb Gauss	8 Corrected ΔB Col. 4 + Col. 7 Gauss	9 Accumulated ΔB from Col. 8 Gauss	10 Plot Value Col. 9 Adjusted for 0 at Symmetry Point Col. 9 + $\frac{39544}{2}$ B Gauss
0	+24.6	0	0			0	0	0	19,772
1	+20	- 1.019	- 468			- 19	- 487	- 487	19,285
2	+15.4	- 1.376	- 632			- 19	- 651	- 1,138	18,634
3	+10.7	- 2.19	-1,005			- 19	-1,024	- 2,162	17,610
4	+ 5.7	- 4.24	-1,946			- 19	-1,965	- 4,127	15,645
5	+ 2.75	- 6.08	-2,791			- 19	-2,810	- 6,937	12,835
6	+ 2	- 2.93	-1,345			- 19	-1,364	- 8,301	11,471
7	+ 1.2	- 4.15	-1,905			- 19	-1,924	-10,225	9,547
8	0	-10.88	-4,994	-15,086	-15,239	- 19	-5,013	-15,238	4,534
9	- 1.3	-19.1	-8,767			- 9	-8,776	-24,014	- 4,242
10	- 2.1	- 7.95	-3,649			- 9	-3,658	-27,672	- 7,900
11	- 5.9	-14.7	-6,747			- 9	-6,756	-34,428	-14,656
12	-10.8	- 5.53	-2,538			- 9	-2,547	-36,975	-17,203
13	-15.6	- 2.61	-1,198			- 9	-1,207	-38,182	-18,410
14	-20.2	- 1.62	- 744			- 9	- 753	-38,935	-19,163
15	-24.8	- 1.22	- 600	-24,243	-24,304	- 9	- 609	-39,544	-19,772
16	-20.1	+ 0.993	+ 456			+142	+ 598	-38,946	-19,174
17	-15.5	+ 1.342	+ 616			+142	+ 758	-38,188	-18,416
18	-10.7	+ 2.15	+ 987			+142	+1,129	-37,059	-17,287
19	- 5.8	+ 4.08	+1,873			+142	+2,015	-35,044	-15,272
20	- 2.8	+ 5.9	+2,708			+142	+2,850	-32,194	-12,422
21	- 2.1	- 2.42	-1,111			+142	+1,253	-30,941	-11,160
22	- 1.3	+ 3.89	+1,786			+142	+1,928	-29,013	- 9,241
23	0	+ 9.34	+4,287	+13,824	+14,963	+142	+4,429	-24,584	- 4,812
24	+ 1.15	+17.13	+7,863			+229	+8,092	-16,492	3,280
25	+ 2.0	+ 7.5	+3,443			+229	+3,672	-12,820	6,952
26	+ 4.8	+11.82	+5,425			+229	+5,654	- 7,166	12,606
27	+10.7	+ 7.29	+3,346			+229	+3,575	- 3,591	16,181
28	+15.5	+ 2.38	+1,092			+229	+1,321	- 2,270	17,502
29	+20.1	+ 1.435	+ 659			+229	+ 888	- 1,382	18,390
30	+24.6	+ 1.032	+ 474	+22,302	+23,905	+229	+ 703	- 679	19,093
0	+24.6	0	0				0	0	
1	0	-33.2	-15,239				-15,239	-15,239	
2	-24.7	-52.95	-24,304				-24,304	-39,543	
3	0	+32.6	+14,963				+14,963	-24,580	
4	+24.4	+52.8	+23,905				+23,905	- 675	



SPOILER SP712

FIGURE 1

USS HOT ROLLED LOW CARBON STEEL PLATES
C1010 — OVER .250 INCHES
DC MAGNETIZATION



Test Conditions: Lengthwise samples tested in Fahy Permeameter.

FIG. 2

1 OERSTED = 2.0213 AMP. TURNS/INCH
= 79.577 AMP. TURNS/METER

TM 978
6013.000

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PROTON			

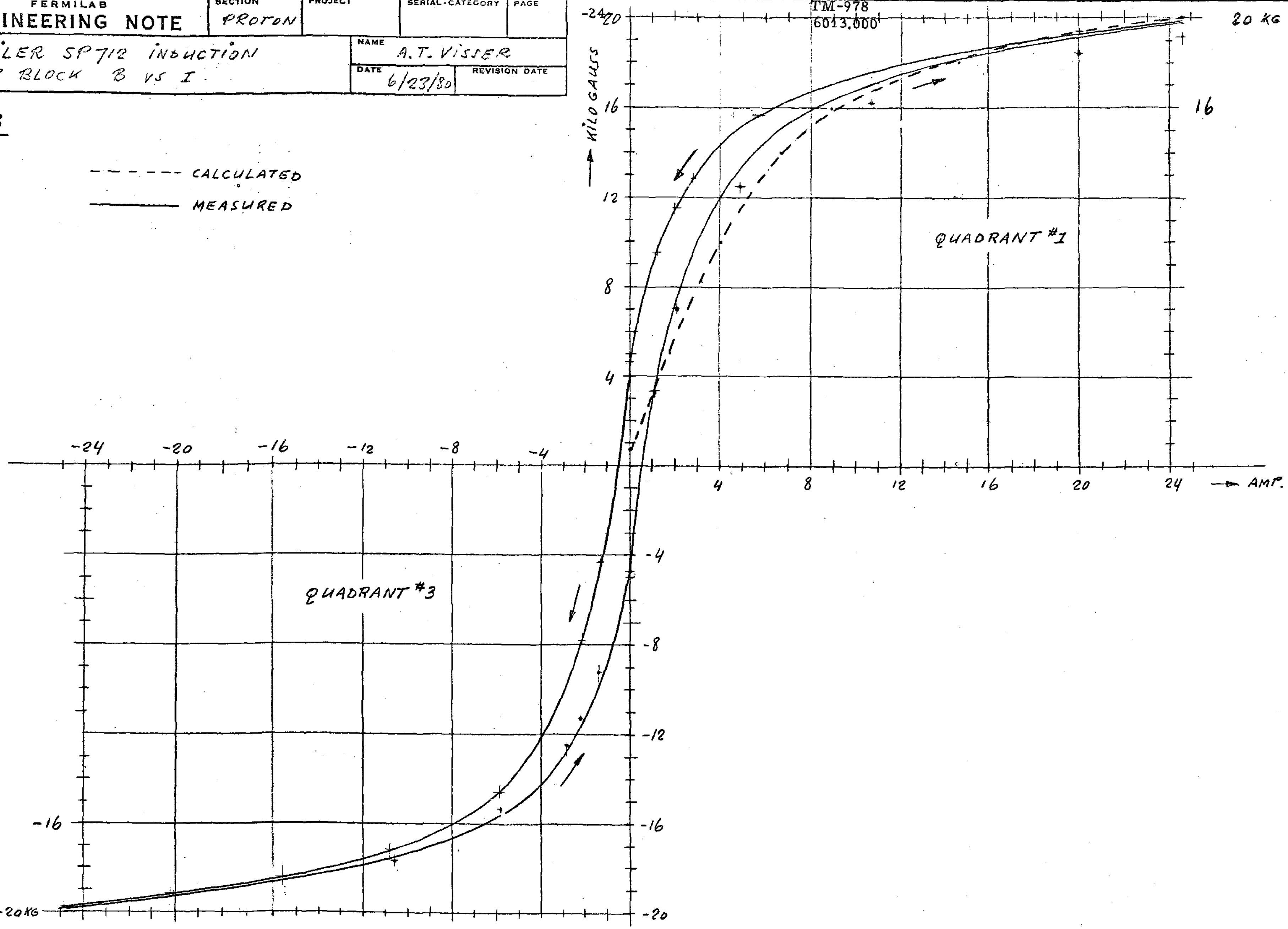
SUBJECT: SPOILER SP712 INDUCTION CENTER BLOCK B VS I

NAME: A.T. VISSER

DATE: 6/23/80

REVISION DATE:

FIG 3



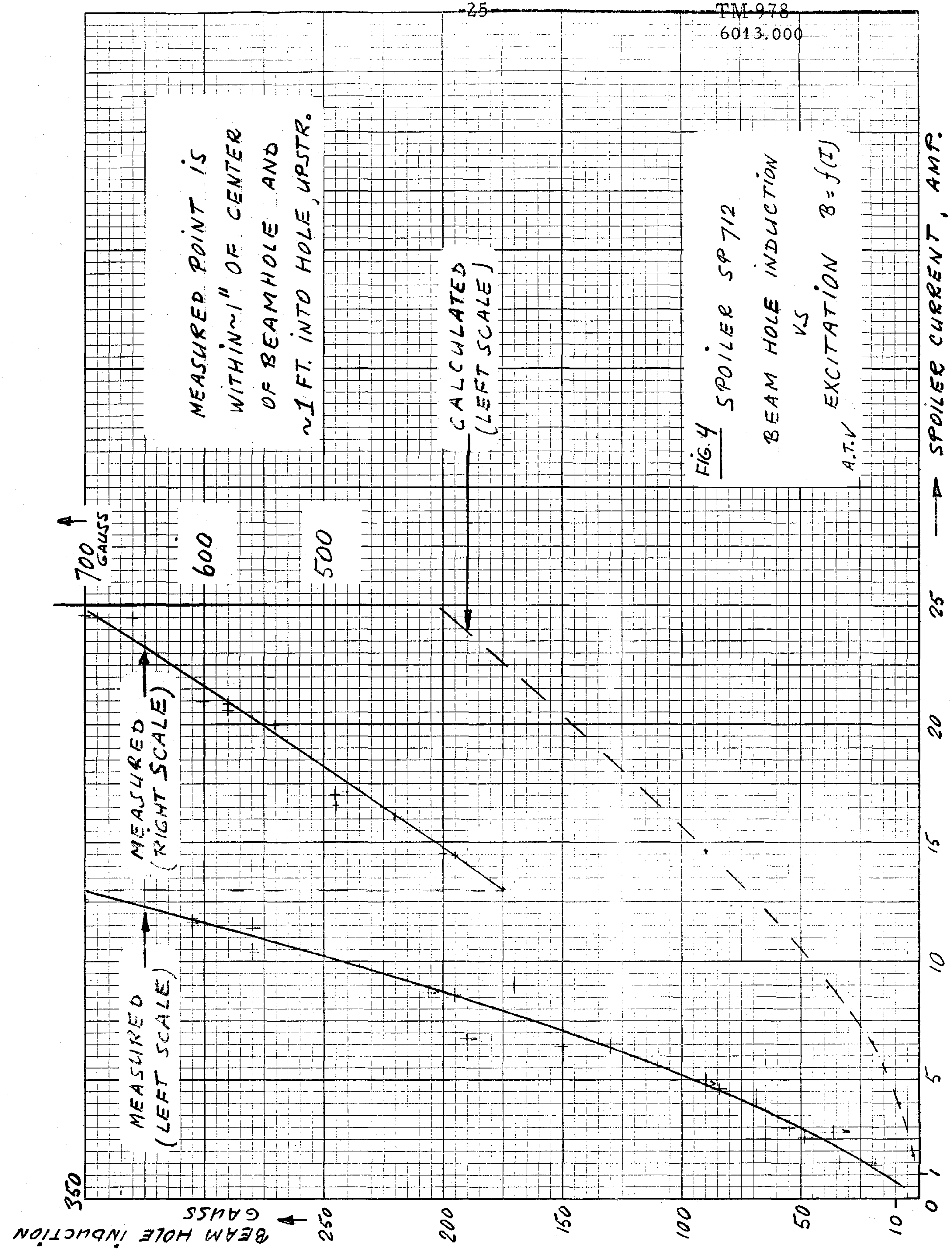


FIG. 4 SPOILER SP 712
BEAM HOLE INDUCTION
VS
EXCITATION B = f(I)
A.T.V
MEASURED POINT IS
WITHIN ~1" OF CENTER
OF BEAMHOLE AND
~1 FT. INTO HOLE, UPSTR.
CALCULATED
(LEFT SCALE)
MEASURED
(RIGHT SCALE)
MEASURED
(LEFT SCALE)
700 GAUSS
600
500
350
250
200
150
100
50
10
BEAM HOLE INDUCTION
GAUSS
0
1
5
10
15
20
25
SPOILER CURRENT, AMP.