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MEASUREMENTS OF THE PULSED FIELD IN THE NEW H-5 KICKER MAGNET

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AGS DIVISION TECHNICAL NOTE

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May 12, 1981

Summary

This note describes some measurements of the spatial distribution and the time-response of the pulsed field in the H-5 kicker magnet and presents a summary of the results obtained.

I. Introduction

The H-5 kicker is a pulsed beam deflection magnet constructed for use in the new AGS fast extraction system(1). The magnet has a C-shaped ferrite core (CMD5005, B_{max} = 3.1 kG, μ_{max} = 4500) and a one-turn coil. One leg of the coil is located inside the magnet gap and the other leg is split into two parts and mounted along the outer edges of the poles as shown in Figure 1. The magnet is divided into two sections, each 43.1 cm long, which are energized in parallel. This arrangement requires a higher output current from the pulse generator but in effect reduces the magnet inductance (L_m), the maximum operating voltage (V) and the propagation delay of the field in the gap.

The pulse generator current is approximately 3.0 kA for a peak gap field of 1.3 kG, and the effective inductance of the magnet including the stray inductance of interconnections (L_{eff}) is in the order of 1.0 μH(2).

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(1) W.T. Weng, BNL 51310, September 15, 1980.

(2) $$L = \frac{\mu_o w\ell}{g} = 0.4\pi\cdot 10^{-6} \cdot \frac{(36.5-1.5)}{14.2} \cdot 0.862 = 3.10\ \mu H \rightarrow L_m = \frac{L}{4} = 0.77\ \mu H$$

$$L_{eff} = L_m + L_{stray} \simeq 1.0\ \mu H$$

$$B/I = \frac{\mu_o}{g} = \frac{0.4\pi\cdot 10^{-2}}{14.2\cdot 10^{-3}} = 0.885\ \text{Gauss/Amp} \rightarrow I = 1.47\ \text{kA for } B = 1.3\ \text{kG}$$

The 0-98% rise-time of the field-strength must be $\simeq 0.15$ μs which in turn requires a peak voltage across the magnet coil terminals of about 30 kV(3). The required width of the magnet excitation pulse (T) is $\simeq 2.6$ μs.

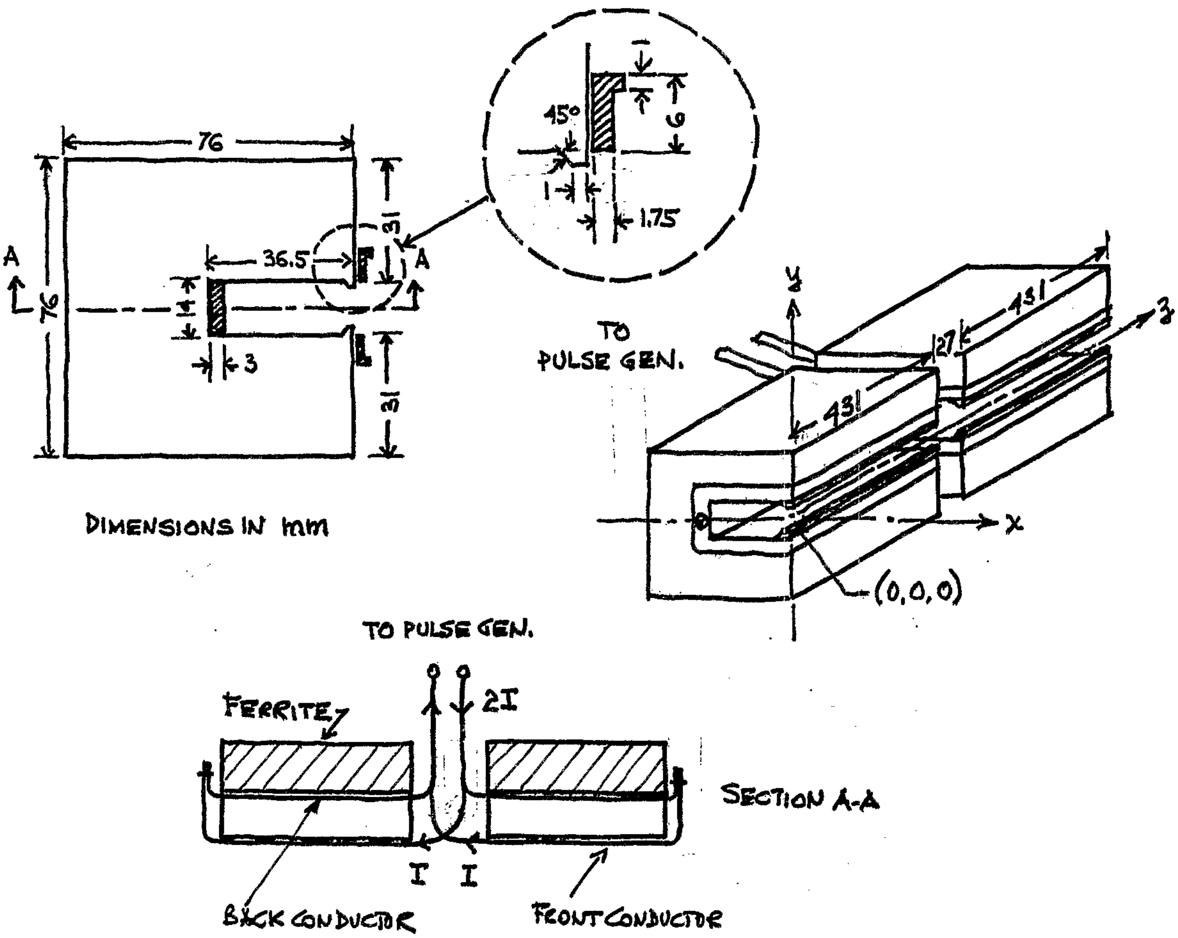

Fig. 1. The H-5 Kicker Magnet

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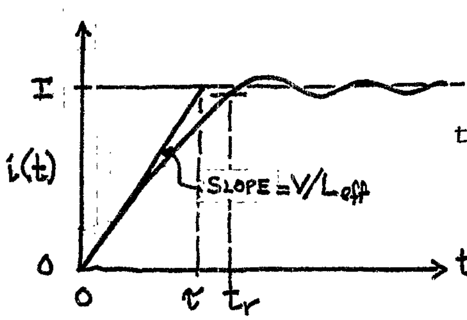
(3)

$$V = L_{eff}\frac{di}{dt} \simeq L_{eff}\frac{I \cdot k}{t_r}$$

$$= \frac{1.0 \cdot 3 \cdot 10^3 \cdot k}{0.15} = 2.0 \cdot 10^4 \cdot k$$

$$= 30 \text{ kV for } k = 1.5.$$



$$t_r = k\tau = k \cdot \frac{L_{eff}}{Z_{gen}}$$

A test system was assembled to measure the time-response of the field integral $\int B_y(x,y,z,t)\cdot dz$ to the pulsed excitation and the distribution of the integral components $\int B_y\cdot dz$ and $\int B_x\cdot dz$ in the transverse plane (i.e., x-y plane defined in Fig. 1). The integral measurements were made with a pair of long orthogonal search coils positioned parallel to the horizontal and vertical surfaces of the magnet gap, respectively. In addition to the integral measurements, "point" measurements of the field were made in the longitudinal (z) direction with two short search coils to determine the variation of the field near the magnet ends. The pulse generator output current was monitored with a precision wide-band current transformer (CT).

II. Experimental Set-up

A block diagram of the test system is shown in Fig. 2. The magnet was placed on a moveable platform which could be positioned in either the x or the y direction with a relative precision of better than 0.1 mm, and the field search coils were mounted on stationary stands. The support fixture of the short coil was mounted on an optical bench parallel to the magnet axis which permitted a precise positioning of the coil in the z-direction. The parameters of the search coils used in the tests are given in Table I.

Table I. Parameters of Field Search Coils

Coil	Length (cm)	Width (cm)	Area (cm^2)	No. Turns	Coil Thick. (cm)	Wire Dia. (mm)
Long x or y	130	0.153	19.89	1	0.03	0.3
Short x	2.66	0.1	0.266	10	0.159	0.076
Short y	2.54	0.1	0.254	10	0.041	0.076

For the measurement of the time-response of the gap field, the magnet was energized with the new H-5 pulse generator ($t_r < 0.2$ μs, T = 2.6 μs) whereas the field distributions were determined using another test generator ($t_r \simeq$ 0.4 μs, T = 6.0 μs) for convenience. As shown in Fig. 2, the voltage induced in the search coil by the time-varying magnetic field was integrated and displayed on a dual-beam oscilloscope together with a signal proportional to the generator output current derived from the CT. The integrator output was also sampled with a fast S/H circuit approximately in the center of the pulse flat-top ($t = t^*$) and then digitized.

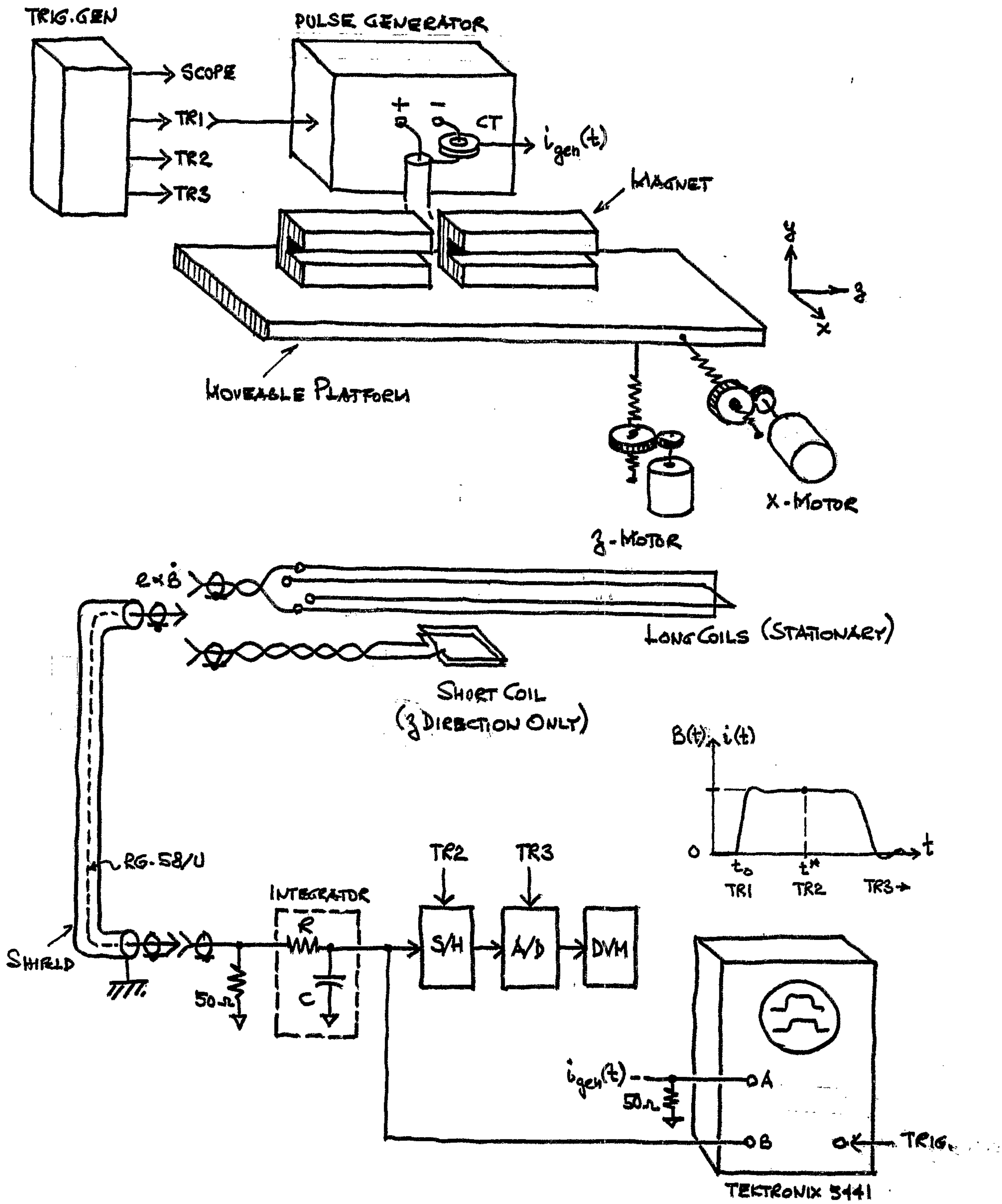


Fig. 2. Block diagram of test system

III. Results

Due to the small clearances between the feed conductors, the magnet (which was tested in air rather than vacuum) was operated only up to 66% of design voltage. When energized with the H-5 pulser, the time response of the gap field (on the median plane at x = −16 mm) was observed to be in good agreement with the waveform of the pulser output current. The pulse generator had not been "tuned" for the test and the current pulse rise-time may not have been optimal. The waveforms at I_{gen} = 1.5 kA are shown in Figs. 3(a) and 3(b).

The measured distributions of the field integrals $\int B_y \cdot dz$ and $\int B_x \cdot dz$ on and off the median plane (y=0) are plotted in Fig. 4. The calibration of a long search coil and of the integrator is described in the Appendix. The data obtained with the x short coil is plotted in Fig. 5 both in the transverse and longitudinal directions. It should be mentioned that the finite length of the short coil tends to broaden the longitudinal field profiles, however, the effect on the areas under the profiles is negligible. The effective length of the magnet, computed from the data in Fig. 5 at two values of x, is given in Table II.

Table II. Effective Length of the Magnet

x-pos'n (mm)	Area	Central Field	ℓ_{eff} (mm)
−16	170.4	9.6	887
0	135.6	9.6	706

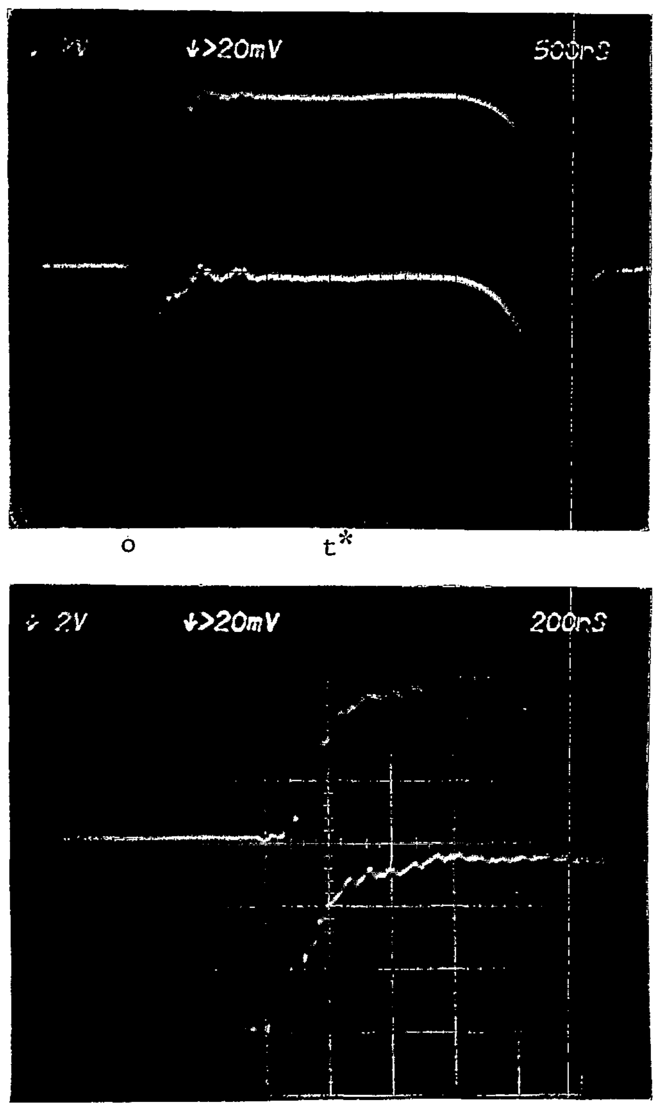
For comparison, Fig. 4 also shows a plot of the predicted field shape[4]. As shown in the Appendix, assuming a $\pm$5% error in the measurement of various parameters, the strength of the field at the center of the gap is calculated to be anywhere from 6% to 30% below that predicted by the relationship $B = \mu_o I/g$. The general layout of the test apparatus is shown in Fig. 6.

(4) J.G. Cottingham, AGS Tech. Note No. 154, May 1979.

Acknowledgments

The test apparatus was assembled by J. Baron with the assistance of W. Cahill and G. Holohan. The field measurements were carried out by J. Baron, S. Ghoshroy and by the author. The author wishes to thank Drs. H.W.J. Foelsche, Y.Y. Lee and W.T. Weng for reading the manuscript.

(a)



i(t)

(~500A/div)

$\int B_y(t) \cdot dz$

o t^*

(b)

i(t)

(~500A/div)

$\int B_y(t) \cdot dz$

Fig. 3. Waveforms of the H-5 generator output current pulse and the induced field $\int B_y(x,y,z,t) \cdot dz$ in the gap at x = −16 mm, y = 0 mm [$i(t^*) \simeq 1.5$ kA].

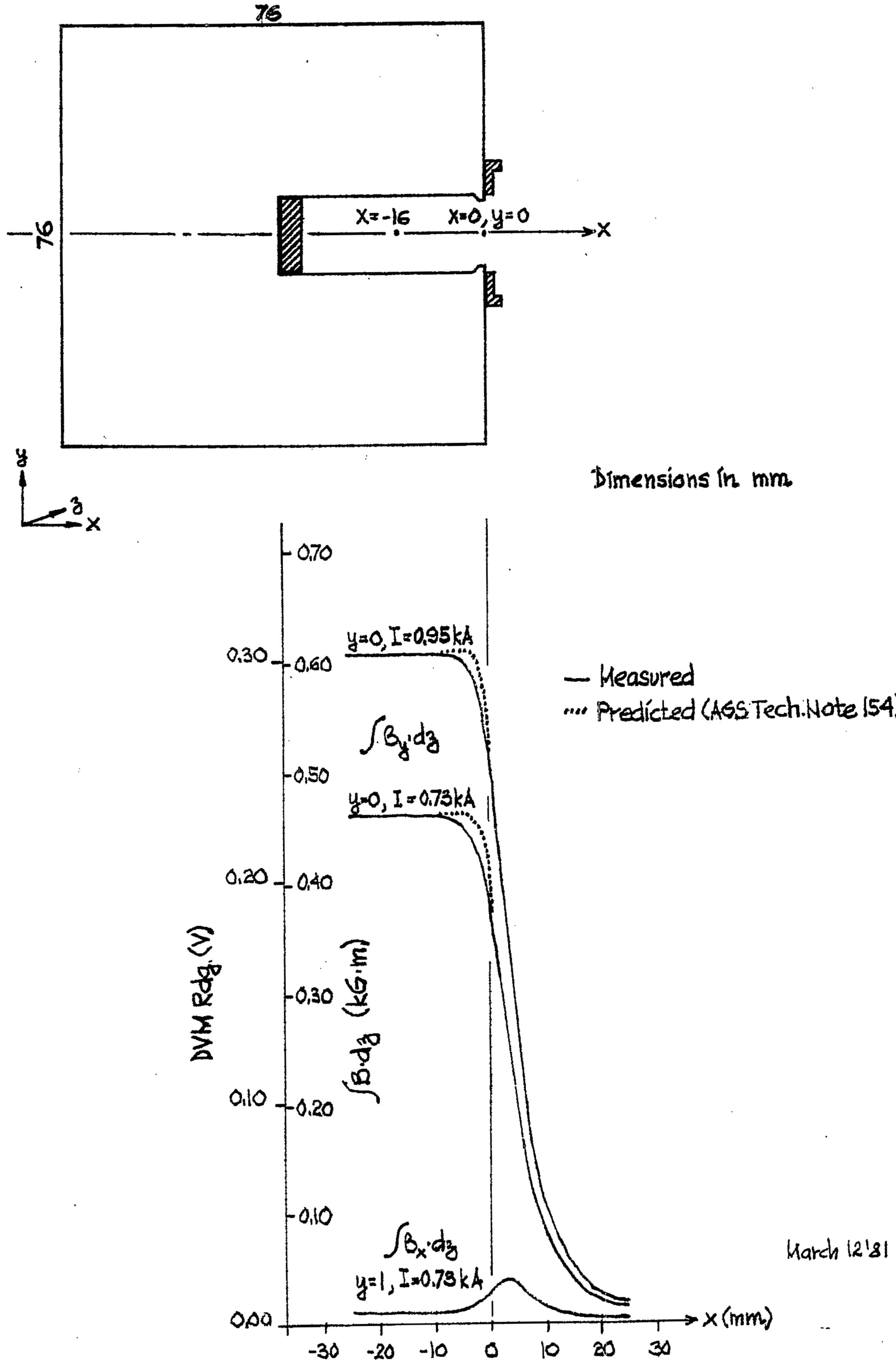


Fig. 4. $\int B_y(x,y,z,t)\,dz$ and $\int B_x(x,y,z,t)\,dz$ at $t = t^*$

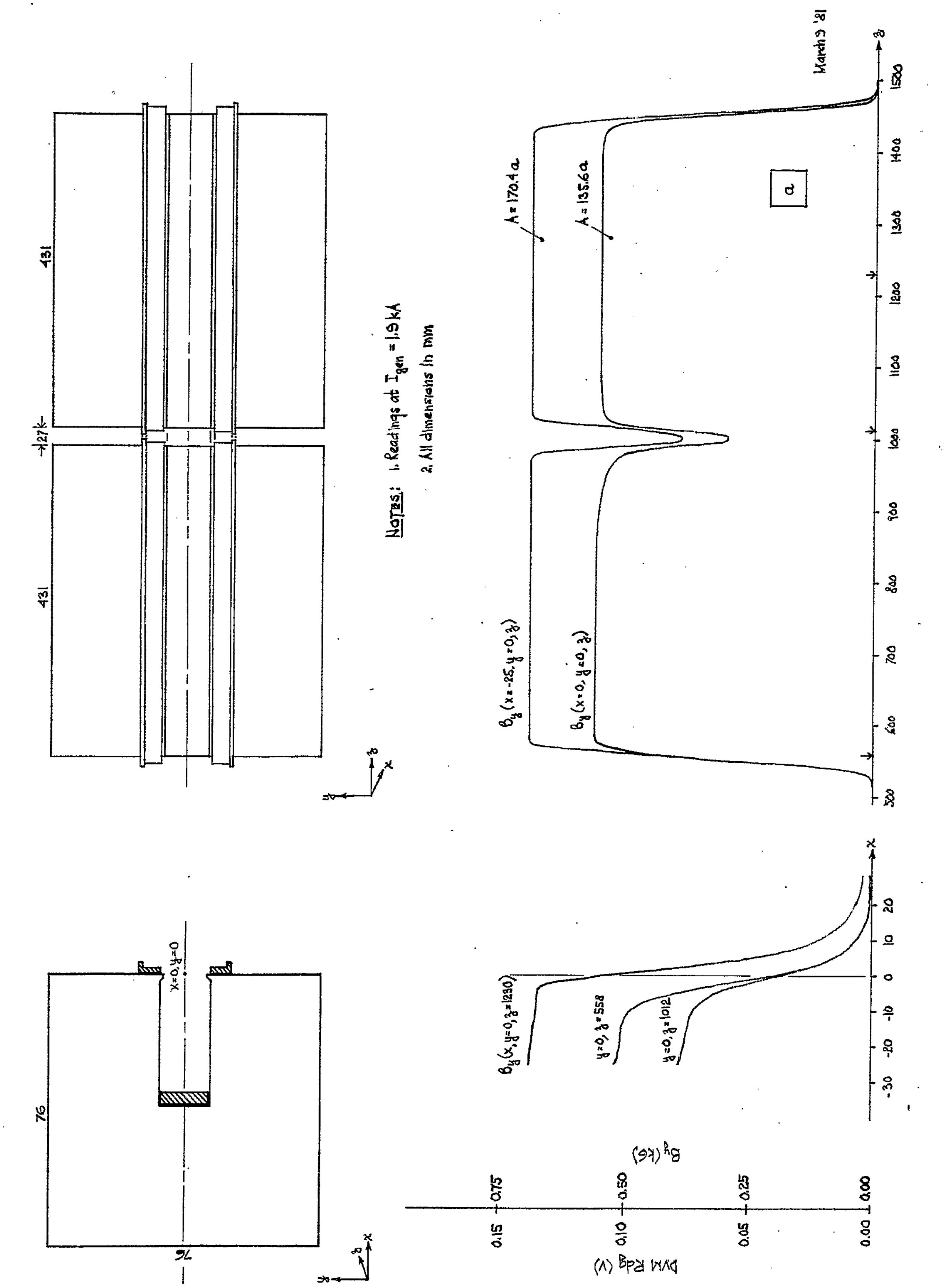


Fig. 5. $B_y(x,y,z,t)$ at $t = t^*$

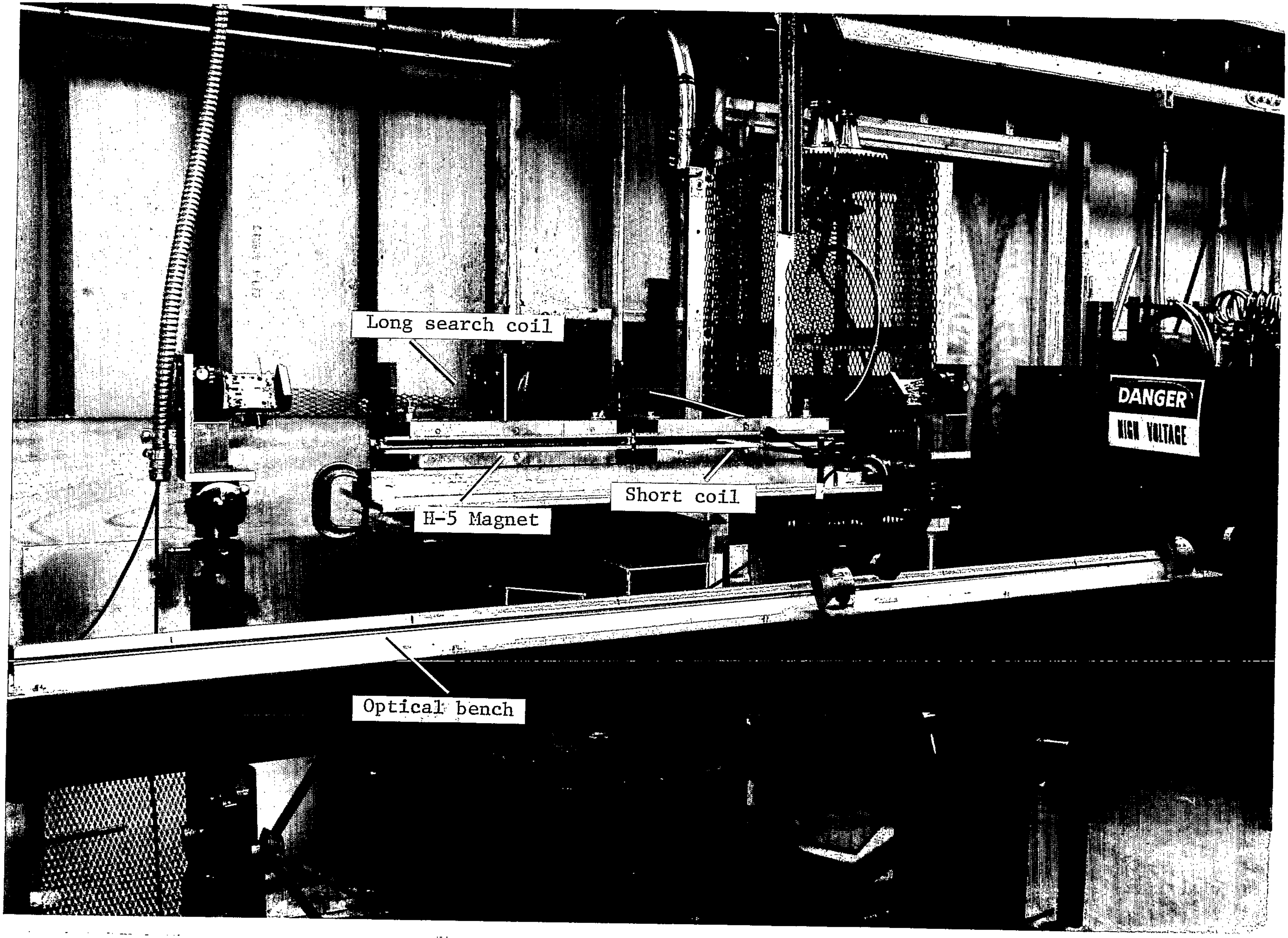
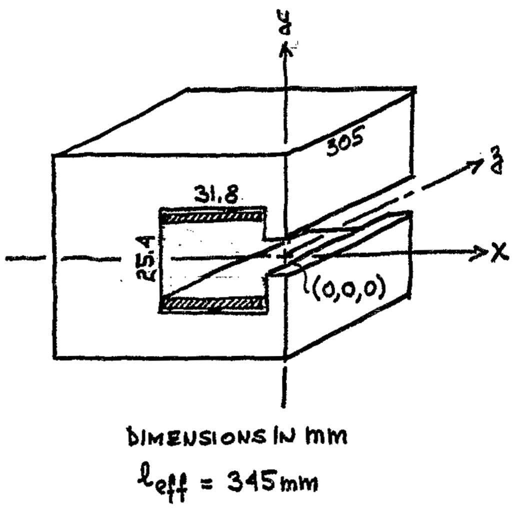


Fig. 6. Layout of test apparatus

APPENDIX

A. Test Magnet



Theoretically:

$$B_{x\ gap} = \frac{\mu_o NI(A)}{g(m)} \text{ Tesla} \tag{1}$$

thus, for N = 1,

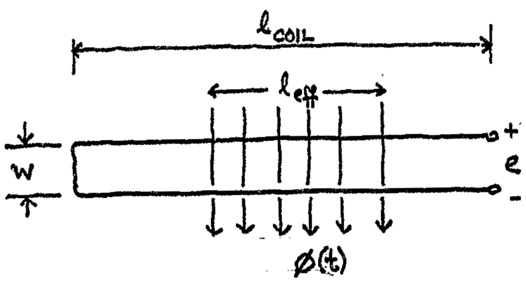
$$B_x/I = \frac{0.4\pi \cdot 10^{-6} \cdot 10^{4}}{31.8\ 10^{-3}}$$

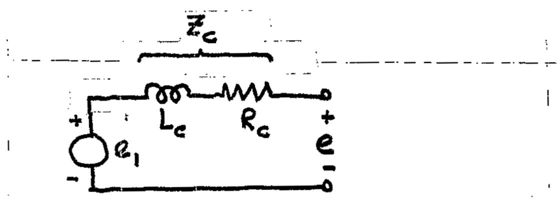
and for B_x = 1 kG, I = 2530.6 A.

Dc field measurement with gaussmeter:

With the center of probe at x = -16,
y = 0, z = 100, $B_{x\ gap}$ = 40 G at I = 100A
$\rightarrow B_x$ = 1 kG at I = 2500.0 A.

B. Calibration of the Long Coil and Integrator





$$e_1(t) = N\dot{\phi}(t) = N\,\ell_{eff}\,w\,\dot{B}(t) \tag{2}$$

Coil wire material = titanium

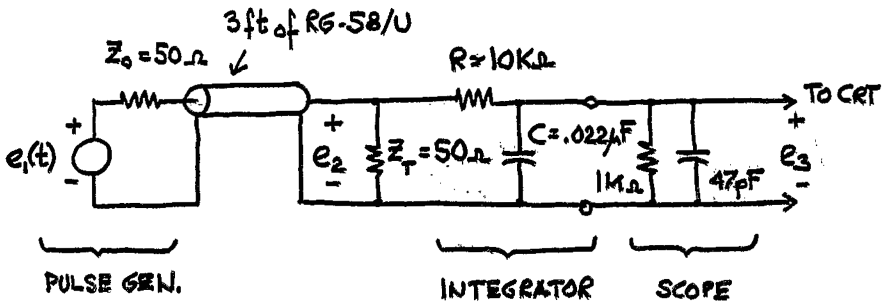
Wire OD = 0.3 mm

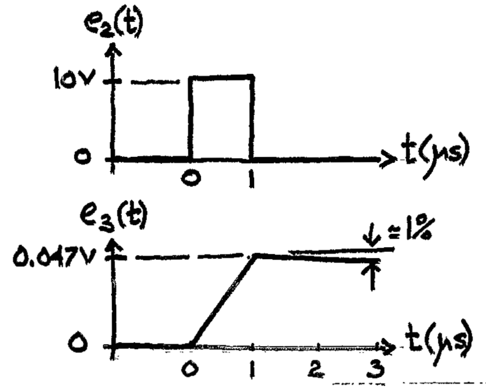
Center-center distance between wires, w = 1.53 mm

Coil length, ℓ_{coil} = 1300 mm

$R_{c\ dc}$ = 22.7 ohm

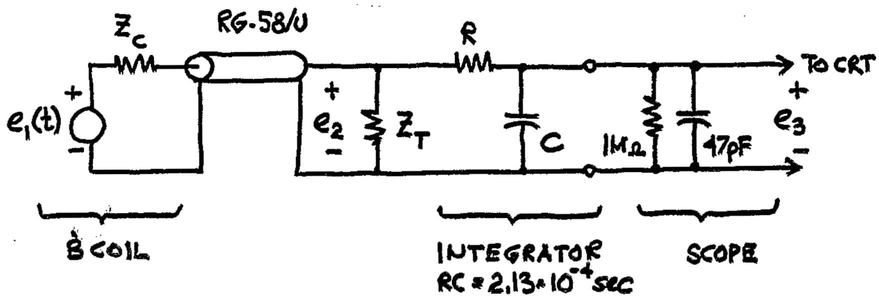
$L_c \simeq 1.0\ \mu H$

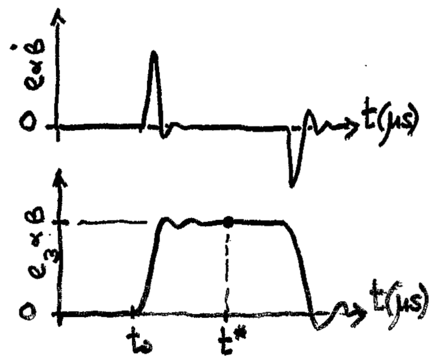




$$e_3(t) = \frac{1}{RC}\int_0^{t=1\mu s} e_2(\tau)\,d\tau = \frac{10\times10^{-6}}{RC} = 0.047V$$

$$RC = \frac{10^{-5}}{0.047} = 2.13\times10^{-4} \text{ sec.} \tag{3}$$





To determine Z_c of $\dot{B}$ coil, vary the value of Z_T and measure $e_3(t^*)$. At I = 1.5 kA we get

$Z_T(\Omega)$	$e_3(t^*)$ mV
∞	100
51.1	70

$\therefore Z_c = \frac{51.1(1-0.7)}{0.7} = 21.9\Omega$. Recall that earlier we measured $R_{cdc} = 22.7\Omega$, therefore take Z_c to be 22.7Ω.

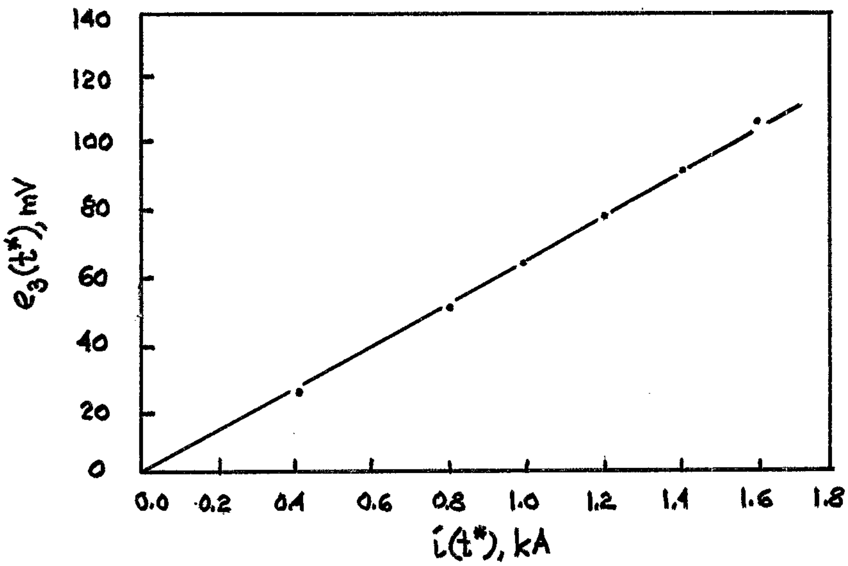
From above,

$$\frac{e_2}{e_1} = \frac{51.1}{51.1+22.7} = 0.6924\ . \tag{4}$$

Using (2), (3) and (4), we get for N = 1 that

$$B(t) = \frac{1}{\ell_{eff}\, w} \int_0^t e_1(\tau)d\tau = \frac{1}{0.6924\, \ell_{eff}\, w} \int_0^t e_2(\tau)d\tau = \frac{RC\, e_3(t)}{0.6924\, \ell_{eff}\, w} . \qquad (5)$$

With the search coil at x = -16 mm, y = 0, we measure



At $i(t^*) = 1.2$ kA, $e_3(t^*) = 0.078$V and we calculate

$$B_{pulsed}(t^*) = \frac{2.13 \cdot 10^{-4} \cdot 0.078 \cdot 10^4}{0.6924 \cdot 0.345 \cdot 1.53 \cdot 10^{-3}} = 454.6 \text{ gauss.}$$

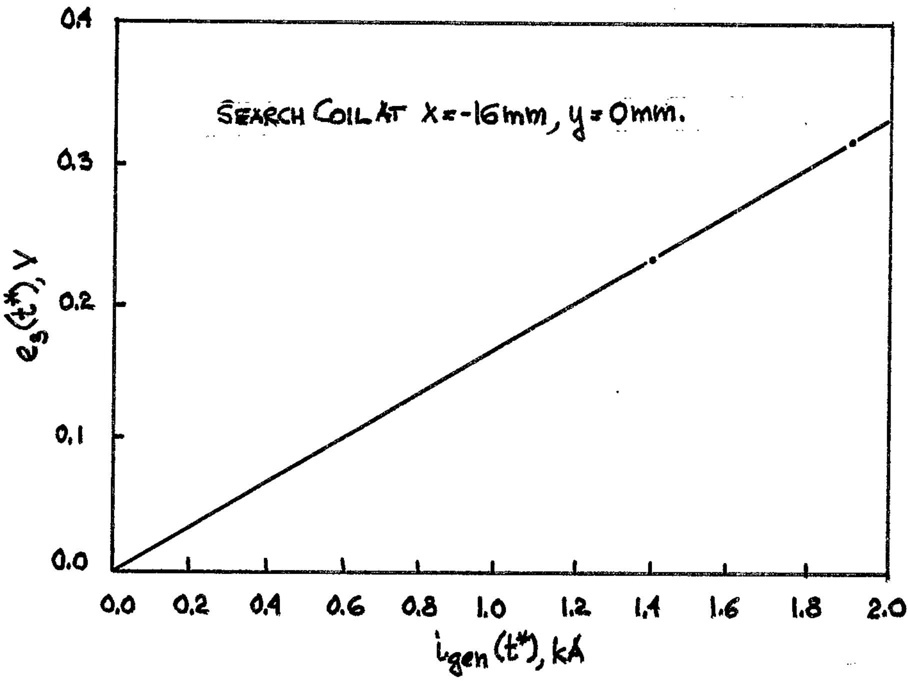
From (1),

$$B_{dc} = \frac{\mu_o I}{g} = \frac{0.4\pi \cdot 10^{-6} \cdot 1.2 \cdot 10^3 \cdot 10^4}{31.8 \cdot 10^{-3}} = 474.2 \text{ gauss.}$$

∴ For the test magnet,

$$\frac{B_{pulsed}}{B_{dc}} = \frac{454.6}{474.2} = 0.96, \text{ i.e., } B_{pulsed} \text{ is} \simeq 4\% \text{ lower than predicted. *}$$

C. Field Measured in the H-5 Kicker Magnet



For the H-5 magnet, ℓ_{eff} = 0.887 (from Table II)

$$i_{mag.} = i_{gen}/2$$

At $i_{gen}(t^*)$ = 1.9 kA, $e_3(t^*)$ = 0.302V, and we calculate

$$B_{pulsed} = \frac{2.13 \cdot 10^{-4} \cdot 0.302 \cdot 10^4}{0.6924 \cdot 0.887 \cdot 1.53 \cdot 10^{-3}} = 684.6 \text{ gauss},$$

$$B_{dc} = \frac{0.4\pi \cdot 10^{-6} \cdot 0.95 \cdot 10^3 \cdot 10^4}{14.2 \cdot 10^{-3}} = 840.7 \text{ gauss}$$

∴ For the H-5 magnet,

$$\frac{B_{pulsed}}{B_{dc}} = \frac{684.6}{840.7} = 0.814,$$ i.e., B_{pulsed} is $\simeq$ 18% lower than expected.*

D. Error Analysis

If we assume a 5% error in the measurement of the integrator time-constant, $i(t^*)$ and $e_3(t^*)$, then for the H-5 magnet

$$\frac{B_{pulsed}}{B_{dc}} = \frac{(1\pm0.05)^2}{(1\mp0.05)} \cdot 0.814 = 0.814 \pm 0.114$$

or $0.70\ B_{dc} < B_{pulsed} < 0.94\ B_{dc}$.