national accelerator laboratory

TM-434
0621.05

EPB DIPOLE MAGNETIC FIELD MEASUREMENTS

R. Juhala

July 26, 1973

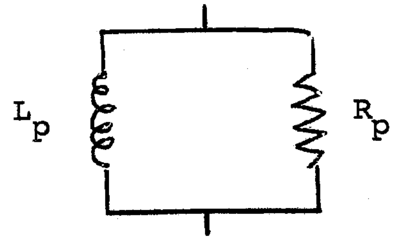
This report consists of a collection of measurements made over the past two years on the external proton beam 10' dipole magnet (NAL designation is 5-1.5-120). Three separate groups have measured the various aspects of the field. The resulting reports are included herein, each as a separate appendix.

The magnet is described in various NAL drawings[1], however the essential features are reproduced here in Figure 1. The magnet has 32 turns and a gap of approximately 4 cm. This design has a ratio of B/I of about 10kG/kA.

The d.c. resistance of this magnet is 17.4 ± 0.3 mΩ. The parallel inductance (L_p) and quality factor (Q) are shown in Figure 2 as a function of frequency. The Q is, of course, significantly smaller for magnets with a vacuum chamber in place. The relationship between parallel and series inductance is

$$L_s = \frac{Q^2}{1 + Q^2} \quad L_p$$

the quality factor is defined as $Q = \frac{R_p}{\omega L_p}$ where R_p is the parallel resistance in the diagram below.



[1] NAL Drawing Nos. 0621-ME-19417, 0621-MD-19418.

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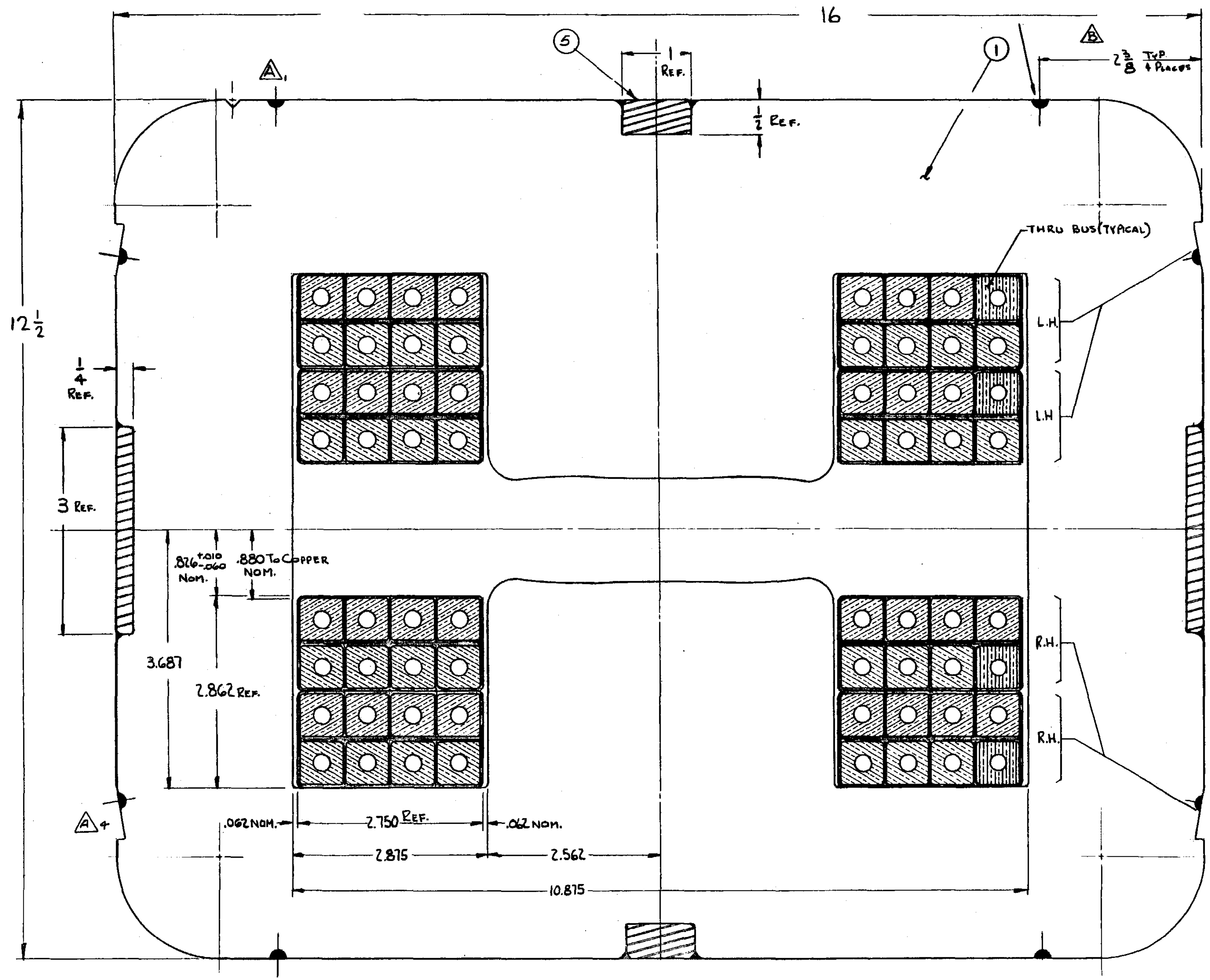
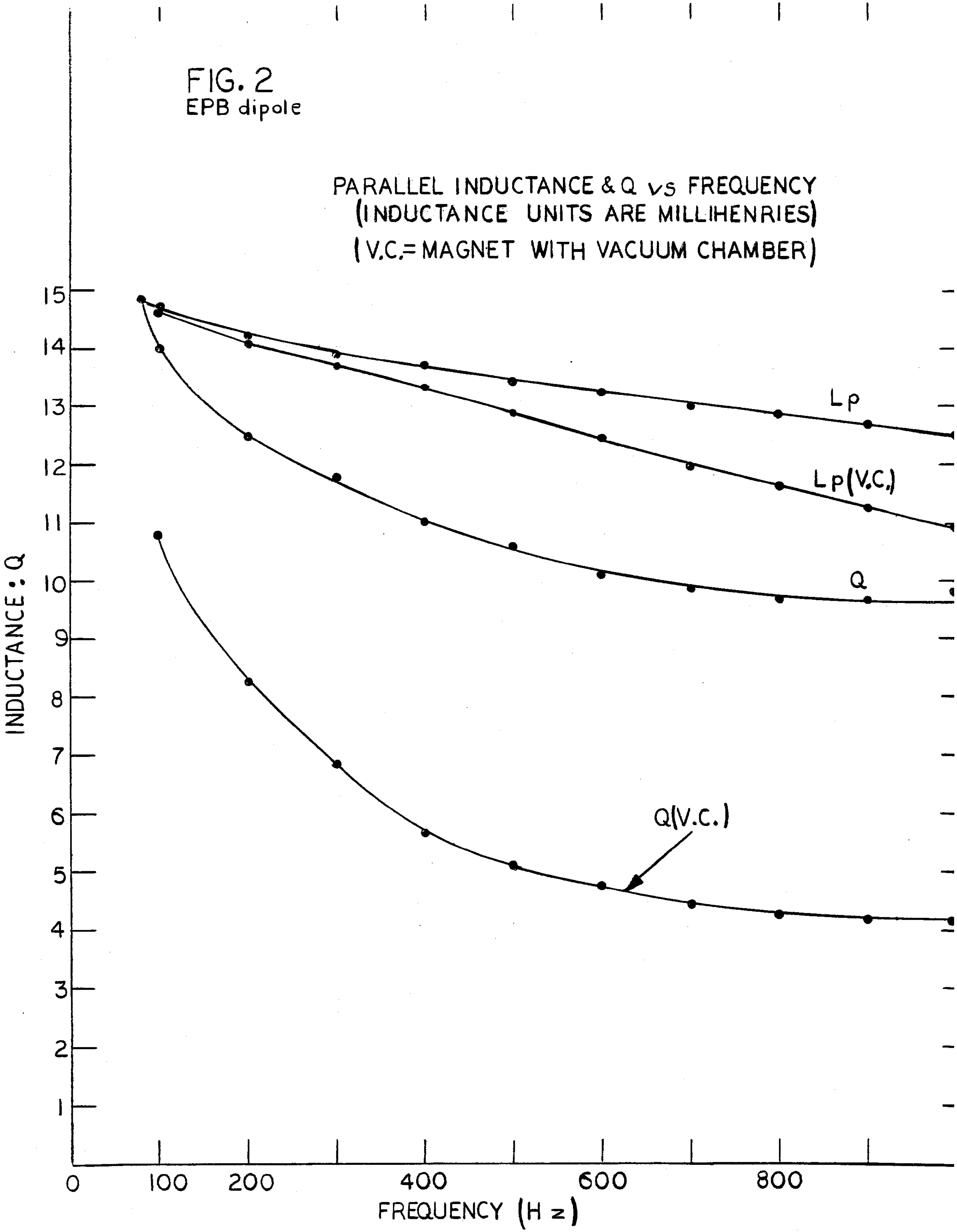
FIG. I Cross-sectional view of EPB dipole



TM-434
0621.05

FIG. 2
EPB dipole



APPENDIX A

TO: BEAM TRANSPORT MAGNET ENTHUSIASTS

FROM: TOM WHITE

SUBJECT: PROFILES & EXCITATION CURVE FOR "TYPICAL" B-T DIPOLE

DATE: JULY 5, 1972

The accompanying curves depict magnet measurements taken personally by me last 23 and 24 of February on a certain beam transport dipole made available to me. This particular magnet bore no serial number that anyone could find and has been designated by me (perhaps somewhat unjustly) as "typical". It's whereabouts is not known to me at this time, but I suspect it was destined for the M-2 meson lab beam. R. Juhala may know.

Fields were measured by a rotating coil Gaussmeter which, together with the power supply, was stable to $\pm$ .05%. Juhala calibrated it with an NMR device. The current was monitored using a toroidal transducer bucked by a null-reading Fluke meter. Our absolute uncertainty in current is limited to about $\pm$ .25% by knowledge of the resistance of a certain water-cooled shunt used to calibrate the transducer. (J. Ryk is the expert on this). This means that if anyone cares to measure the shunt more carefully, the current readings can probably be corrected to yield an absolute accuracy of around $\pm$ .05%, (the gaussmeter measures field at a point).

Thus, our data on fields are good to $\leqslant$.1%, and the current to $\sim\pm$.25%. The original data reside in a notebook labelled: Bill Lord...Magnet Testing Environmental & Special Magnets...6 May 71 to..."

APPENDIX B

CSTL Internal Report No.

D. J. Mellema
A. V. Tollestrup
January 29, 1973

M2B6 Magnet Measurements of January 21-22, 1973

This report describes a series of measurements made on an EPB dipole magnet located in the Meson Laboratory M2 beam line and designated M2B6. The magnet is powered by a Trans-Rex power supply in series with three other EPB dipoles (M2B7, 8, and 9). The maximum current obtained with four magnets in series was 2000 amp, limited by the Trans-Rex top DC voltage of 200 V. By shorting out M2B9, we were able to obtain a current of about 2500 amp at 200 V. Magnet current measurements were made using a DVM to read out the transductor voltage in the power supply. (Trans-Rex claims an accuracy of ± 0.15% over the full range of currents monitored.)

The value of $\int B\,dl$ was measured on January 22, 1973, as a function of current, by integrating the signal from a coil centered by eye on the beam center line and lying about 5/32" below the magnet midplane. (The field is known to be uniform to about 0.1% within ± 1" of the center line.) The probe consisted of one turn of magnet wire wound on a 1/2" wide Al bar, 12 feet in length. The Al bar was mounted on a piece of 3/4" Al angle to give it greater rigidity. The far end of the coil was centered between M2B6 and M2B7.

The effective width of our coil loop is 1.321 cm, probably good to 1%, and the time constant of our integrator is 0.02521 sec, probably good to 0.1%. The $\int B\,dl$ measurements were taken in two groups, each ranging from 100 to 2500 amp. Each measurement is the average of one integration from zero current to the current being measured, and another integration back down to zero. Drift currents contributed a typical uncertainty of 0.5% at 100 amp, the lowest current studied and proportionately less at higher currents. The results of our two groups of measurements are listed in Table I and illustrated in Figs. 1-3. Figures 2 and 3 show the high $\bar{B}$ region of Fig. 1 on an expanded scale. The crosses indicate measurements from group 1, and the dots or open circles represent the group 2 measurements.

The group 2 measurements were taken with somewhat smaller observed drift currents and should be more accurate than the group 1 measurements. Using a Hall probe with quoted accuracy of $\pm$ 1%, T. Yamanouchi obtained a central field measurement of 17.84 k Gauss at 2500 amp, in good agreement with our result. The I/$\bar{B}$ curve appears to have a slightly negative slope in the low $\bar{B}$ region, possibly due to nonlinearity of the transductor output at low current. There is also an anomalous point at $\bar{B}$ = 1.017 k Gauss which we cannot account for; since this was the first point taken in the first group of measurements, it may have been misread.

On January 21, 1973, we studied the water temperature rise in M2B6, 7, 8, and 9 as a function of current. The temperature was monitored by eight thermocouples, two on each magnet. There are four parallel LCW paths in each magnet. We monitored the uppermost path in each magnet at the elbow where the water exits. We also monitored the two innermost paths at the "tee" where they recombine. The change in temperature for each thermocouple was recorded, allowing about 15 minutes after each change in current for the magnet to reach thermal stability. (The temperatures were observed to remain constant after about 5 minutes.) The readings were corrected for changes observed in the supply temperature. Our results are shown in Fig. 4. The temperature rise is nearly linear with I^2, as expected. When we attempted to run at I = 2500 amp, the plastic connecting hoses on the LCW return lines ruptured before we reached thermal equilibrium.

Table I

$\int$ B dl Measurement on M2B6

I (transductor) [amp]	$\int$ B dl [k G - m]	$\overline{B} = \frac{\int B\,dl}{L}$ (L=10') [k G]	I/$\overline{B}$ [amp/k G]
First Group			
99	3.100	1.017	97.32
239.5	7.632	2.504	95.65
319.5	10.21	3.349	95.40
410.5	13.11	4.301	95.45
525	16.78	5.506	95.36
578.5	18.56	6.091	94.98
686	21.98	7.211	95.13
790	25.25	8.285	95.35
894	28.54	9.365	95.46
996.5	31.83	10.44	95.44
1093.5	34.78	11.41	95.82
1160.5	36.59	12.00	96.68
1291	39.59	12.99	99.39
1400	41.66	13.67	102.43
1481	42.97	14.10	105.06
1581	44.64	14.64	107.96
1664.5	45.85	15.04	110.65
1762.5	47.25	15.50	113.69
1873.5	48.65	15.96	117.37
1955	49.61	16.28	120.12
2011	50.24	16.48	122.01
2049.5	50.63	16.61	123.39
2151.5	51.65	16.95	126.97
2172	51.82	17.00	127.75
2232	52.37	17.18	129.92
2301.5	52.97	17.38	132.44
2334	53.17	17.44	133.81
2406	53.71	17.62	136.54
2463	54.08	17.74	138.81
2503.5	54.35	17.83	140.40

Table I (cont'd)

$\int$ B dl Measurements on M2B6

	I (transductor) [amp]	$\int$ B dl [k G - m]	$\overline{B} = \frac{\int B\,dl}{L}$ (L=1-') [k G]	I/$\overline{B}$ [amp/k G]
Second Group				
	125	3.988	1.308	95.54
	226	7.174	2.354	96.02
	325	10.34	3.393	95.79
	425	13.55	4.444	95.62
	512	16.37	5.371	95.33
	613.5	19.59	6.426	95.48
	712.5	22.73	7.459	95.53
	786	25.15	8.250	95.27
	893.5	28.46	9.337	95.70
	956	30.59	10.04	95.24
	1053.5	33.61	11.03	95.54
	1189	37.34	12.25	97.06
	1284	39.41	12.93	99.31
	1390	41.46	13.60	102.19
	1525	43.77	14.36	106.20
	1556	44.26	14.52	107.16
	1696.5	46.32	15.20	111.64
	1780	47.44	15.57	114.36
	1887.5	48.78	16.00	117.94
	2025	50.36	16.52	122.56
	2085.5	51.00	16.73	124.64
	2200.5	52.10	17.09	128.74
	2285.5	52.80	17.32	131.93
	2367.5	53.40	17.52	135.15
	2501	54.31	17.82	140.36

APPENDIX C

Relative and Absolute Measurements of the Quantity $\int B\,dl$ Across the Horizontal Gap an an EPB Dipole

P. Baranov[+], S. Rusakov[+] J. Orear[++] and R. Juhala

June 13, 1973

Using a long flip coil and an integrator, measurements were made of the integrated bending length in an EPB dipole. The absolute value of $\int B_y dz$ is tabulated in the table below and plotted in Figure 1 (B_y is taken here as the strong component of the transverse field, with z being the axial coordinate). Also shown are measurements of B_y at a point well inside the magnet vs. current. The measurements are accurate to within $\pm$ .15%.

The flip coil consisted of two turns of .004" diameter tungsten wire stretched between two supports. This stretched wire flip coil had a square cross-section .504" on a side and extended 1 1/2 feet beyond the ends of the magnet into essentially zero field. Figures 2 through 7 show the relative field strength as a function of the horizontal position (x coordinate) at 1400 and 1688 A. Measurements were made of $\int B_y dz$ on the midplane (y=o) and 3/8 in. below the midplane, and of $\int B_x dz$ 3/8 in. below the midplane. The relative shape for

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$\int B_y dz$ (Figures 2 through 5) is precise to better than .05% in the regions where it is essentially uniform ($x = \pm 1.5$ in.). Outside this region the finite width of the coil introduces errors on the order of $\pm$ .15% due to higher order components in the field. The relative shape for the component $\int B_x dz$ (Figures 6 and 7) is precise to within $\pm$ 2%. The most significant error in this measurement is due to the uncertainty ($\pm$ 1°) of the orientation of the flip coil. This same uncertainty introduces an error in $\int B_y dz$ of less than .02%. The variation of $\int B_y dz$ with the y coordinate was observed to be less than .04% over the region $y = \pm$ 3/8 in. and x=o.

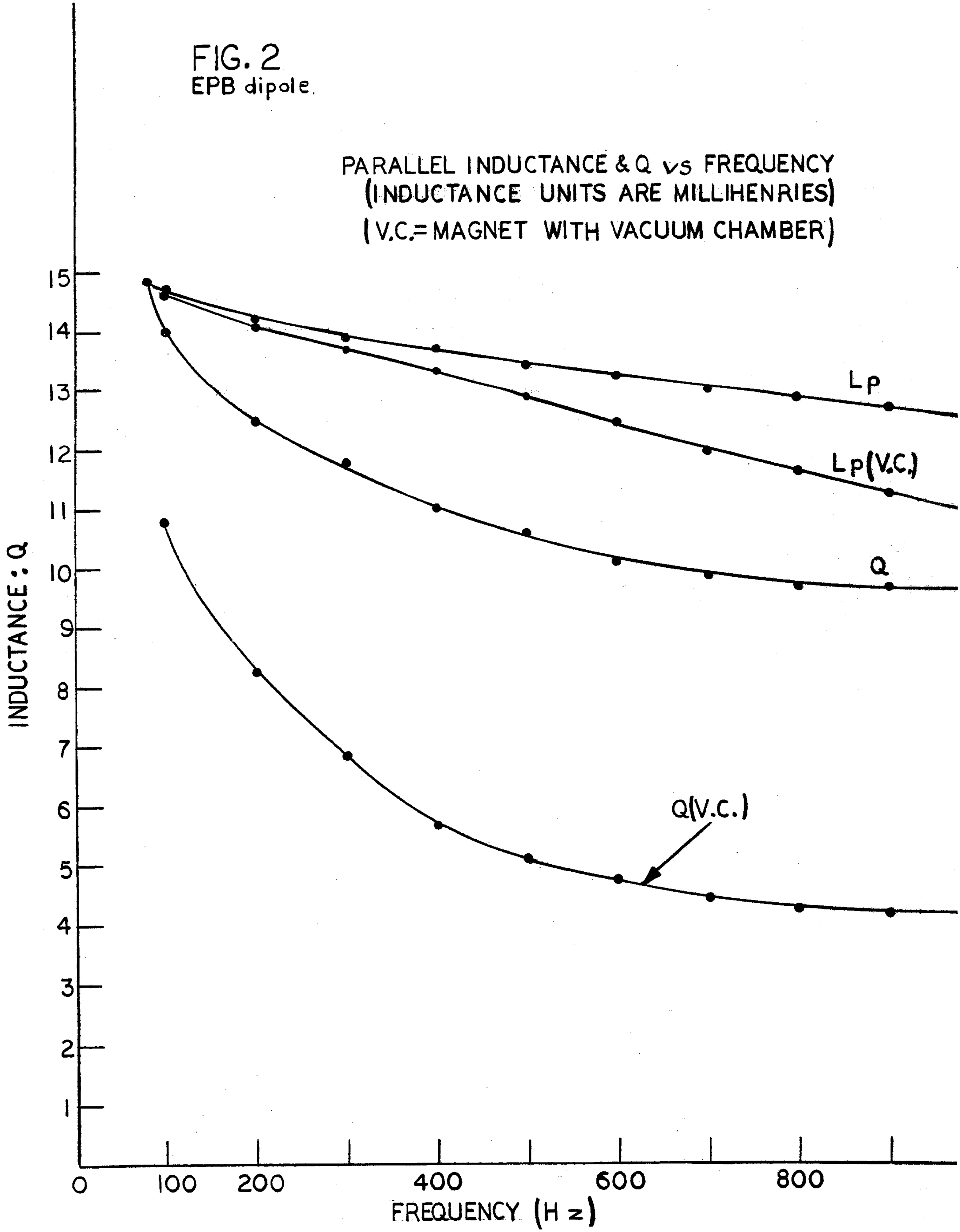
TABLE II

Measurements of $\int B_y dz$ and B_y as a function of current for an EPB dipole (AircoTemescal Magnet #71)

Current (A)	$\int B_y dz$ (kG-m)	Current (A)	B_y (kG)
0	--	0	<10 gauss
199.9	6.43	200.1	2.101
400.0	12.82	400.0	4.208
600.4	19.26	600.5	6.307
800.2	25.60	800.3	8.340
999.9	31.85	1000.4	10.43
1200.1	37.63	1199.9	12.34
1399.8	41.64	1400.5	13.65
1600.1	44.92	1600.2	14.72
1687.0	46.17*	1689.1	15.16
1700.2	46.35	--	--
1800.1	47.68	1800.7	15.67
1900.3	48.90	--	--
2000.5	50.05	--	--

*This is not a measured point.

FIG. 2
EPB dipole.



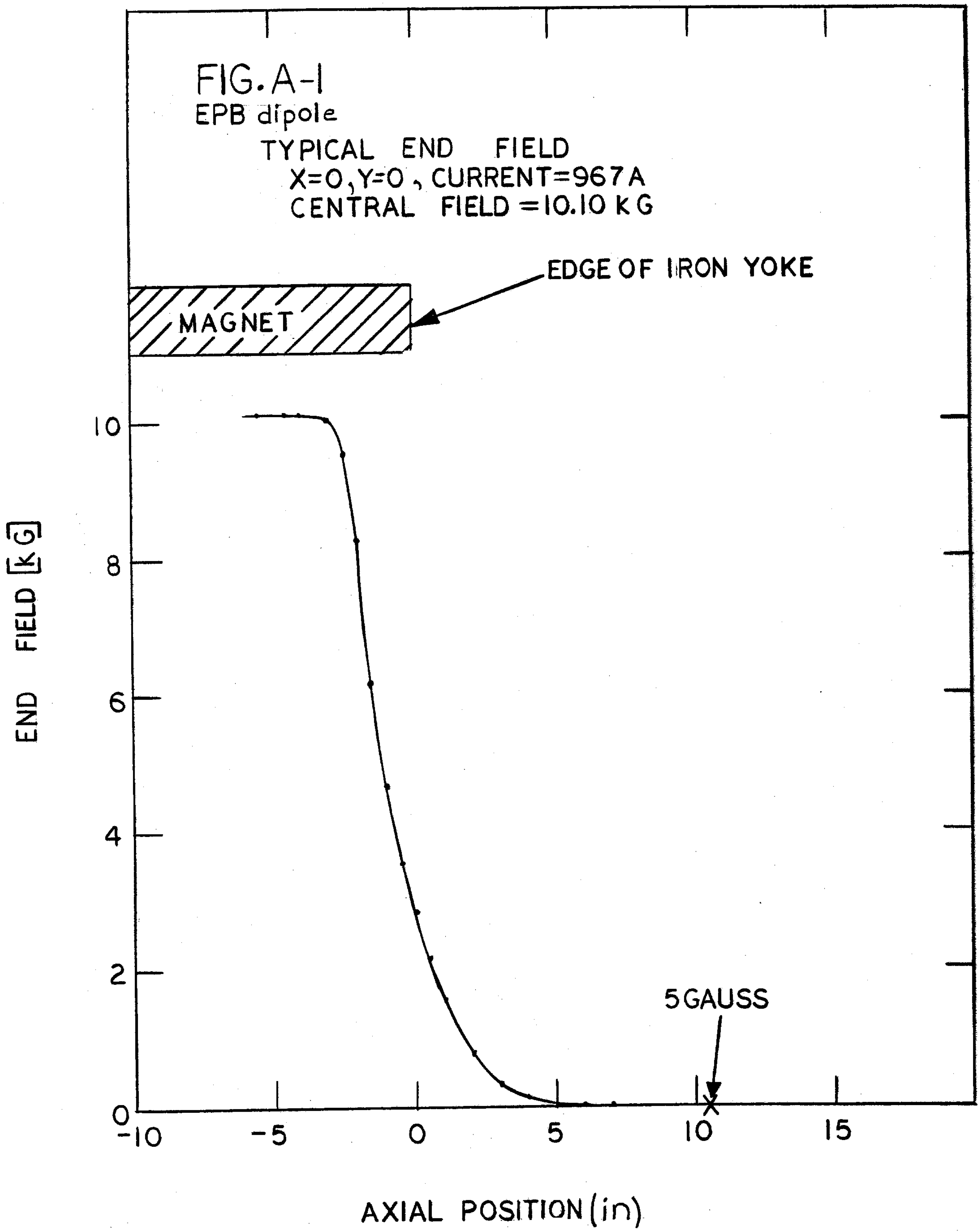


FIG. A-1
EPB dipole
TYPICAL END FIELD
X=0, Y=0, CURRENT=967 A
CENTRAL FIELD = 10.10 KG
EDGE OF IRON YOKE
MAGNET
END FIELD [kG]
10
8
6
4
2
0
5 GAUSS
-10
-5
0
5
10
15
AXIAL POSITION (in)

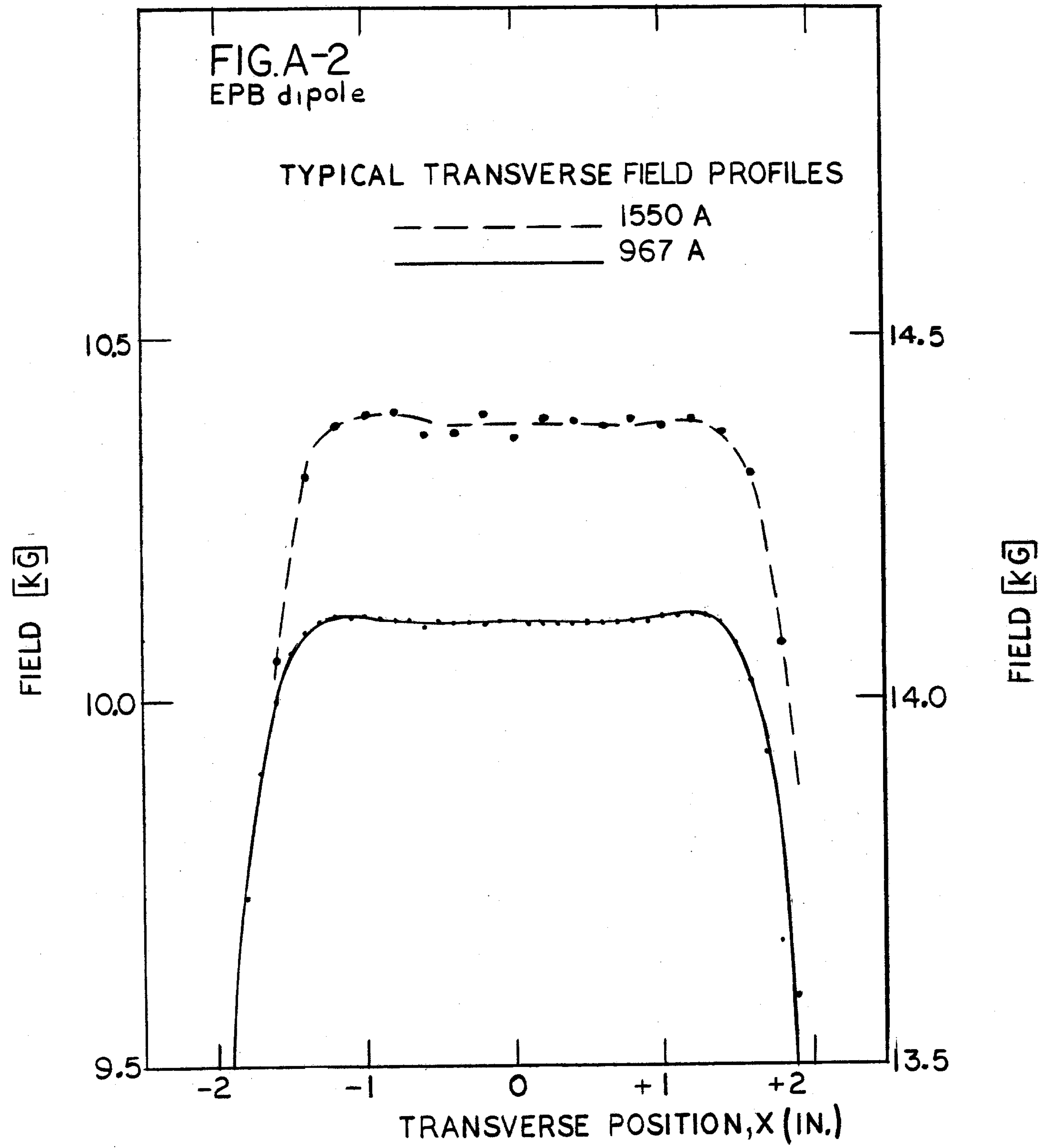


FIG. A-2
EPB dipole
TYPICAL TRANSVERSE FIELD PROFILES
1550 A
967 A
10.5
10.0
9.5
14.5
14.0
13.5
FIELD [KG]
FIELD [KG]
-2
-1
0
+1
+2
TRANSVERSE POSITION, X (IN.)

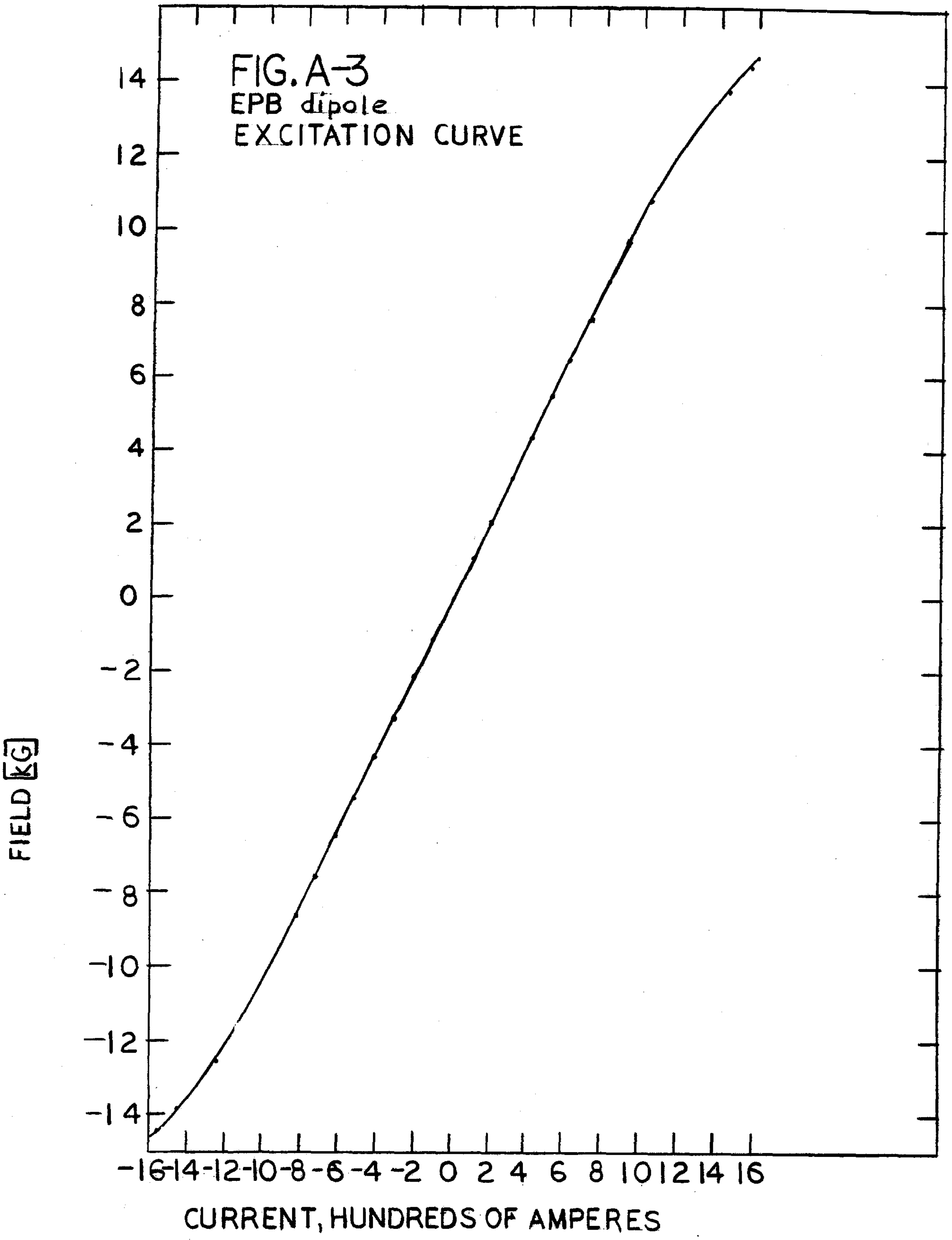
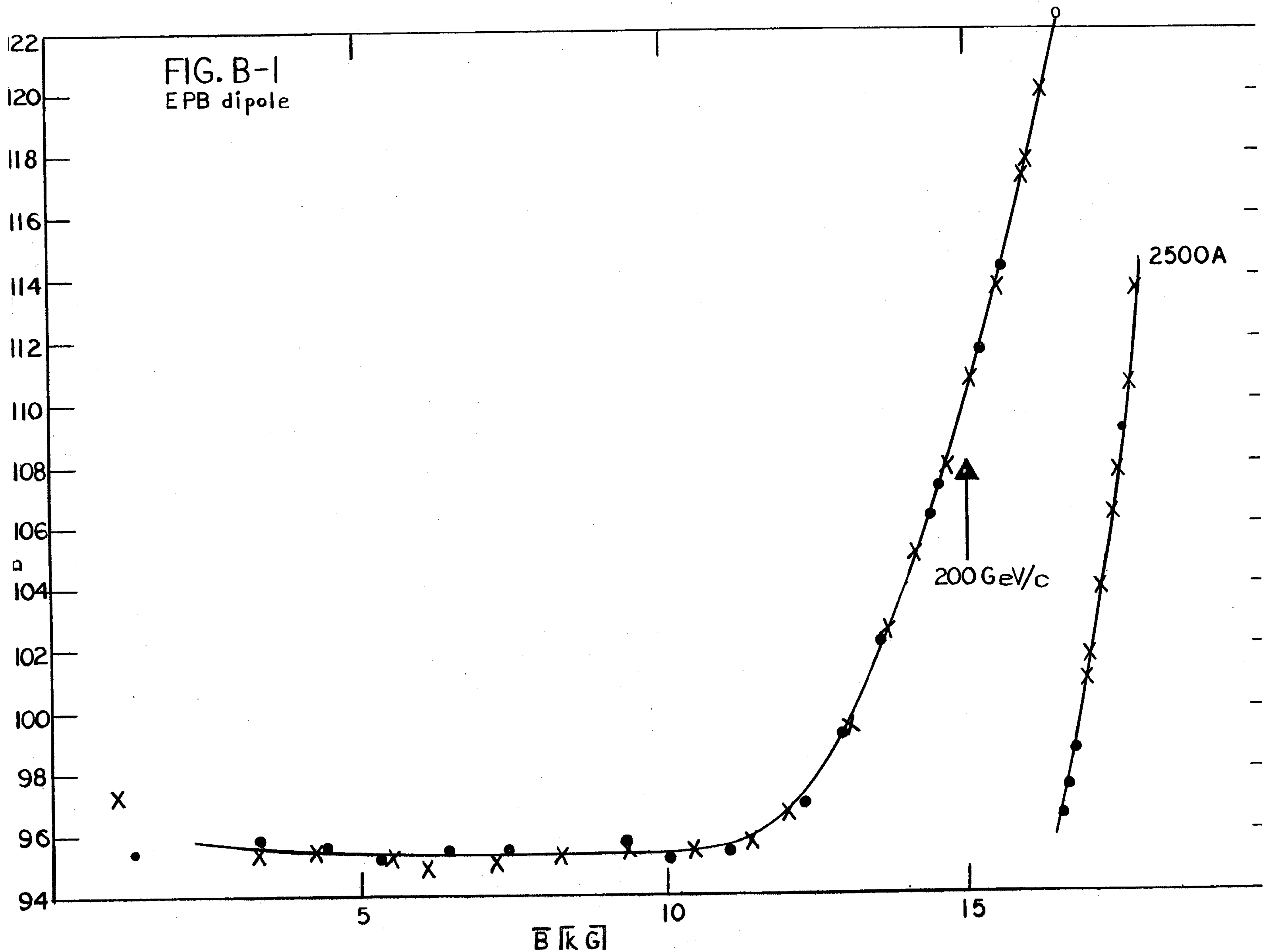


FIG. A-3
EPB dipole
EXCITATION CURVE
FIELD [kG]
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16
CURRENT, HUNDREDS OF AMPERES



17

TM-434
0621.05

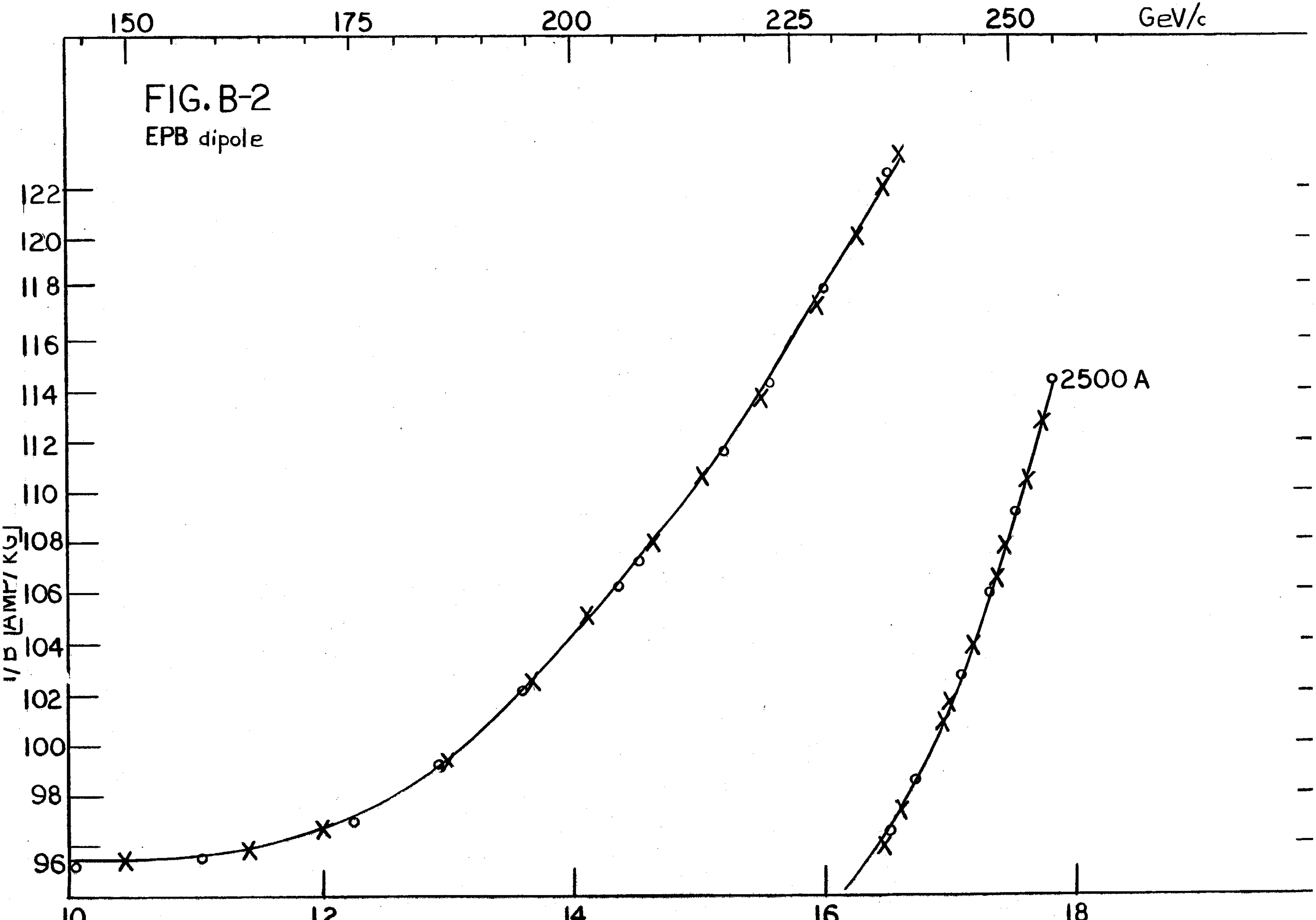


FIG. B-2
EPB dipole
150
175
200
225
250
GeV/c
122
120
118
116
114
112
110
108
106
104
102
100
98
96
2500 A
10
12
14
16
18
B̄ [kG]

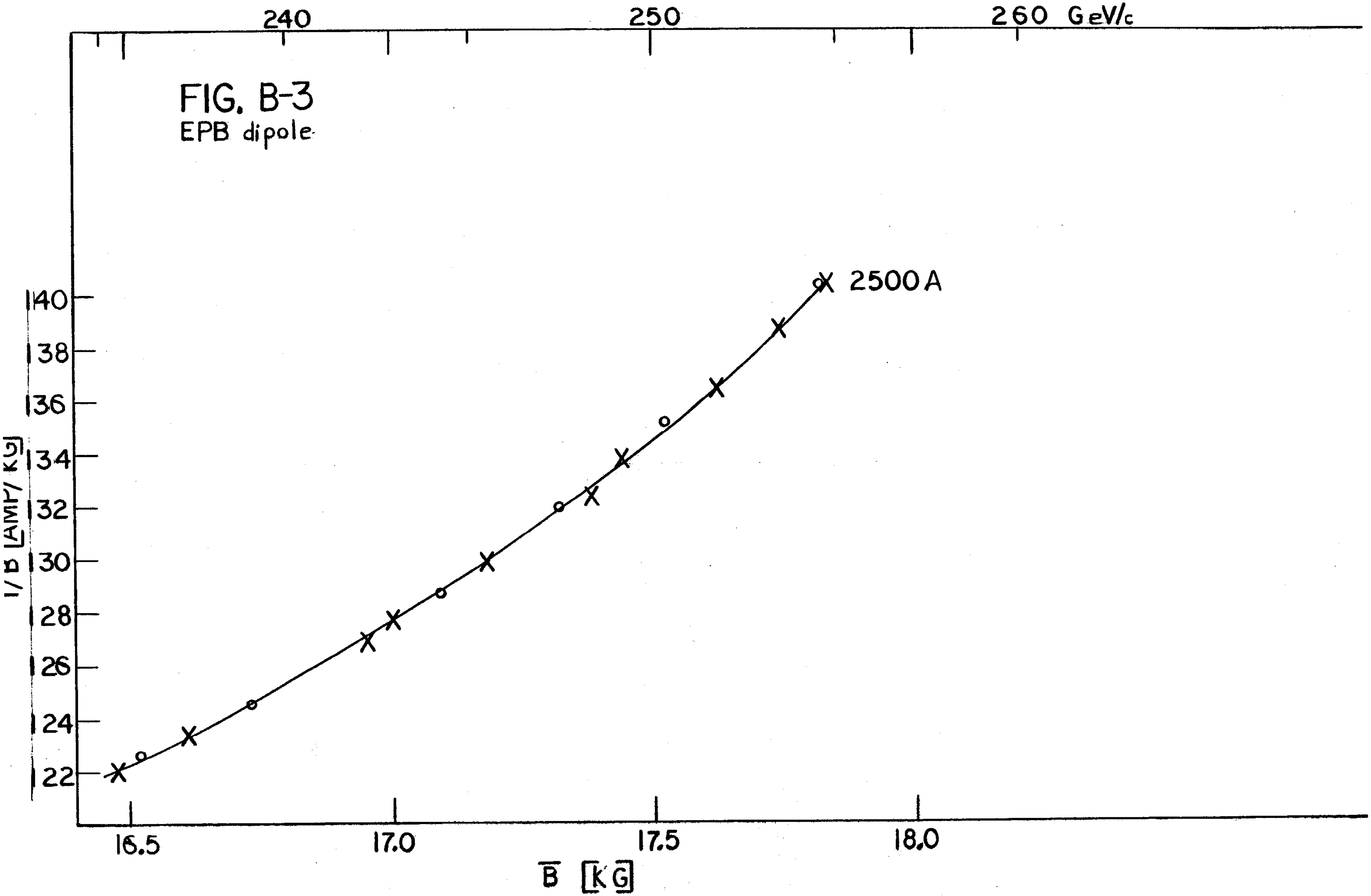
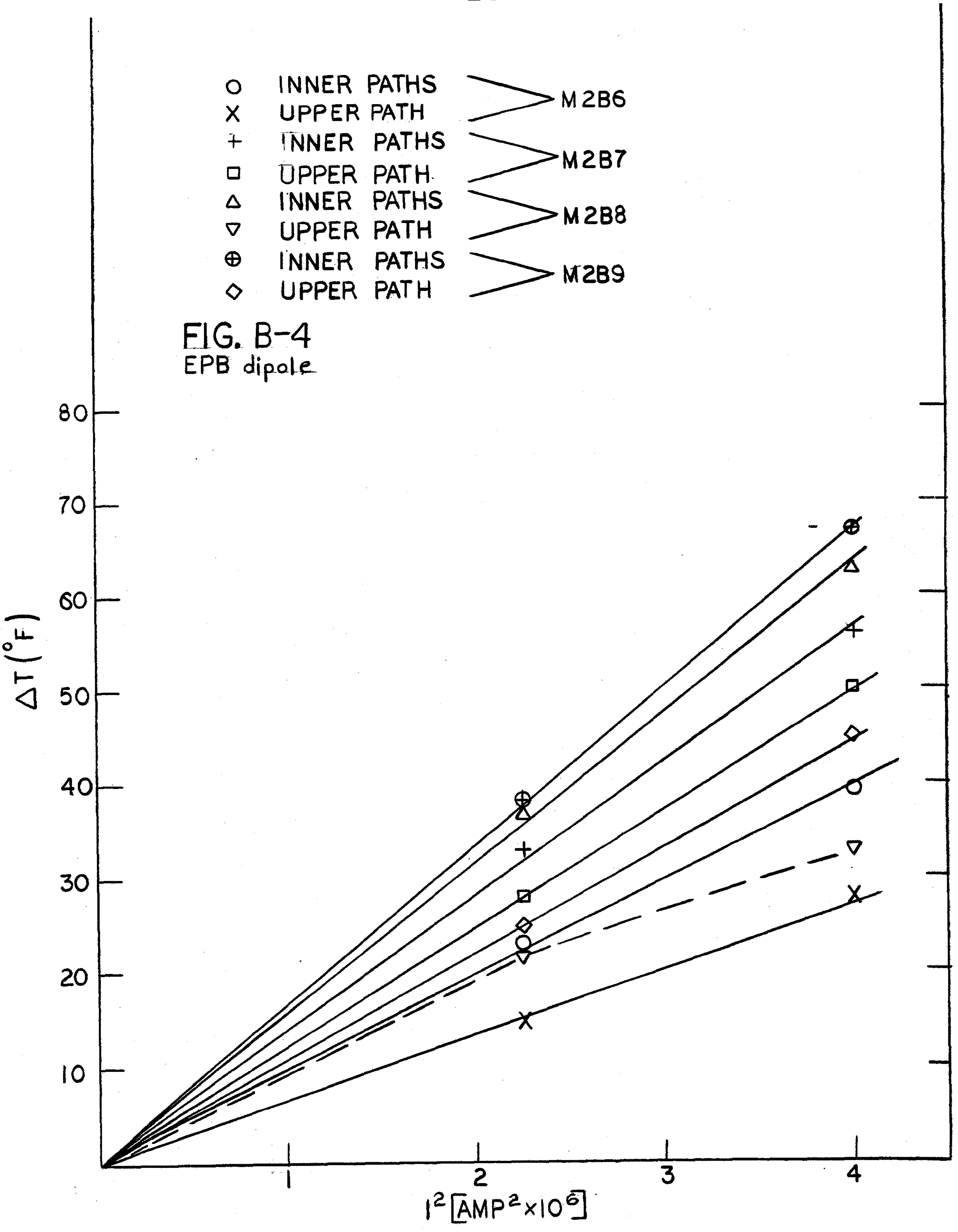


FIG. B-3
EPB dipole

TM-434
0621.05


○ INNER PATHS
X UPPER PATH
M2B6
+ INNER PATHS
□ UPPER PATH
M2B7
△ INNER PATHS
▽ UPPER PATH
M2B8
⊕ INNER PATHS
◇ UPPER PATH
M2B9
FIG. B-4
EPB dipole
ΔT (°F)
10
20
30
40
50
60
70
80
1
2
3
4
I² [AMP² × 10⁶]

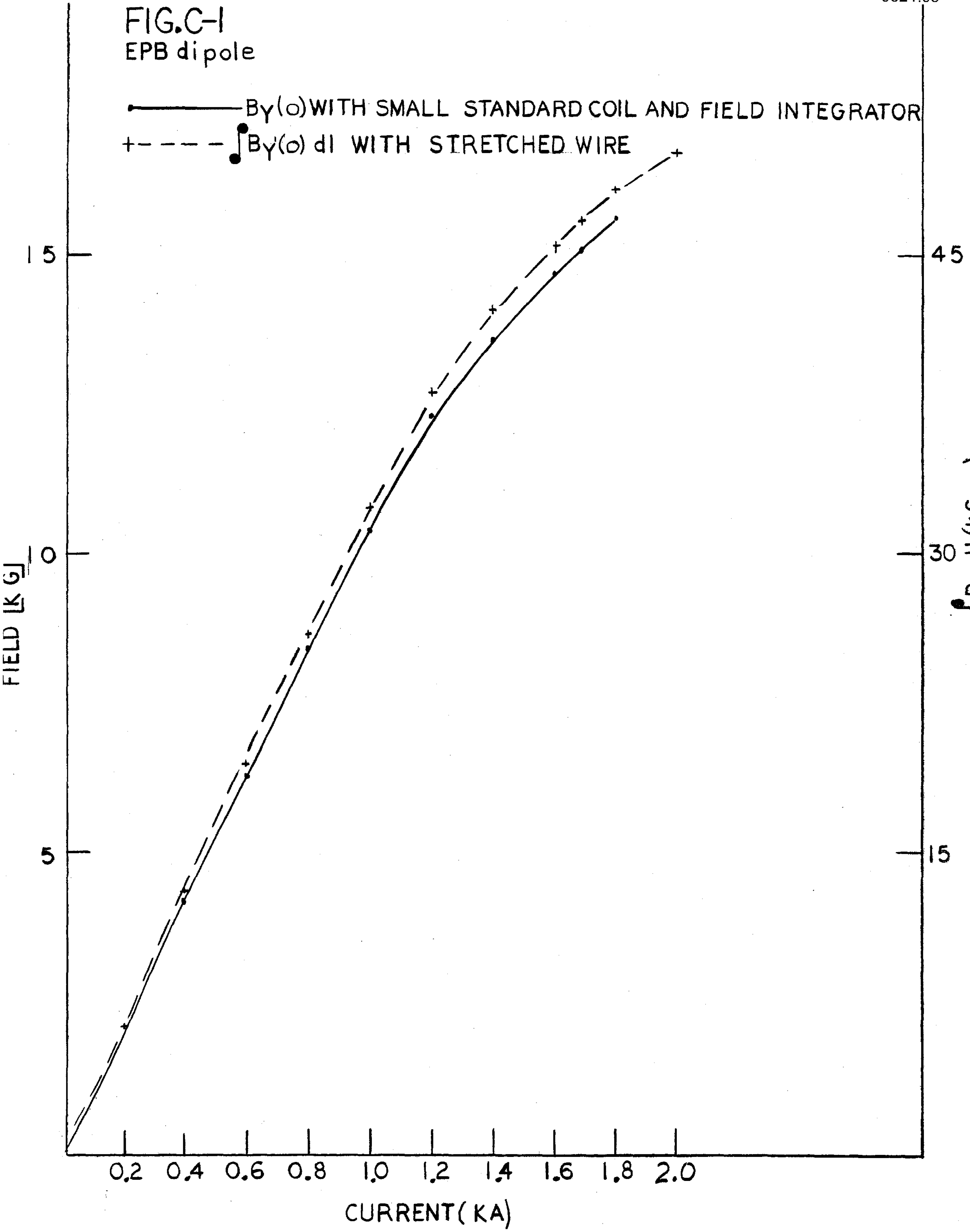
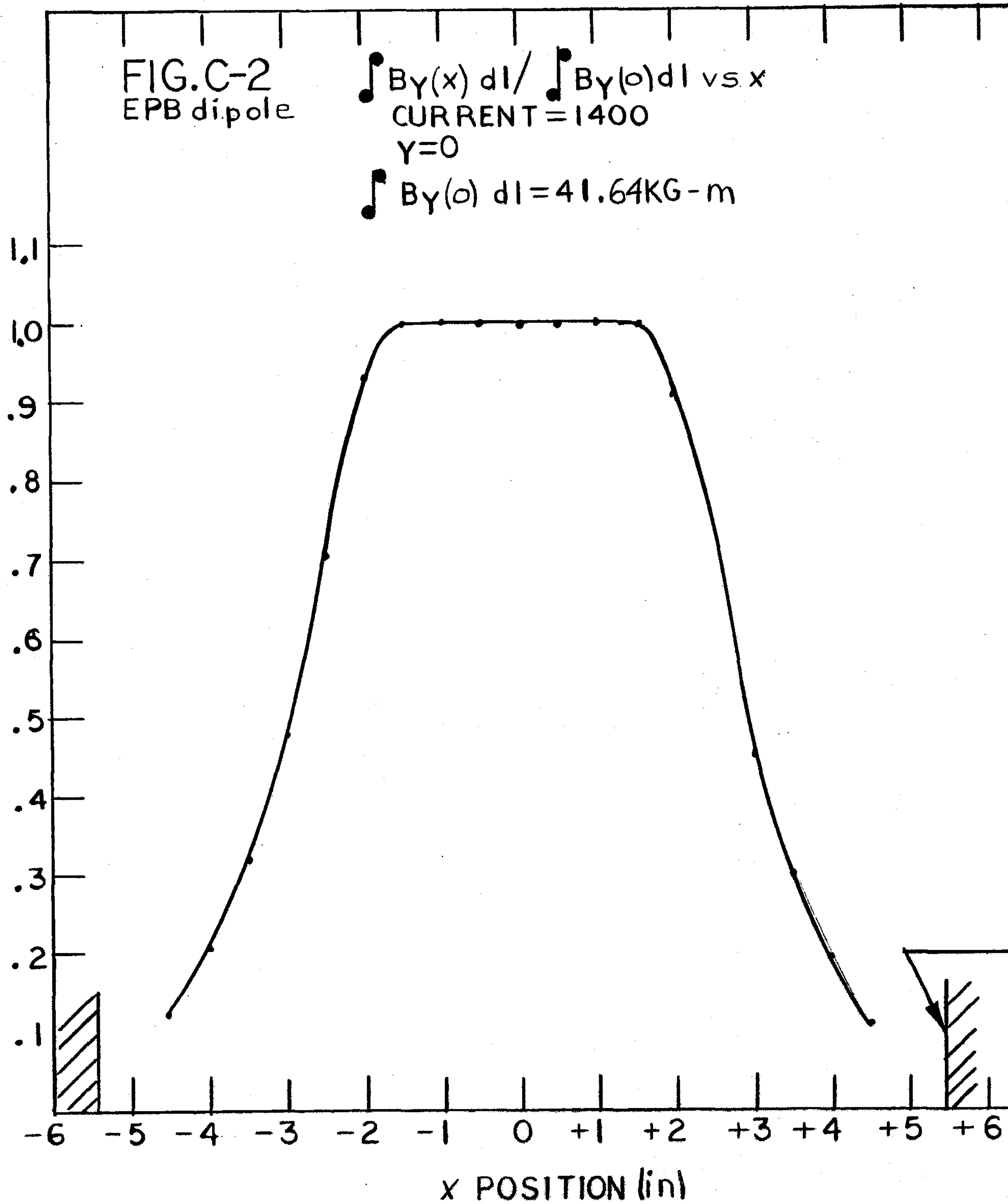
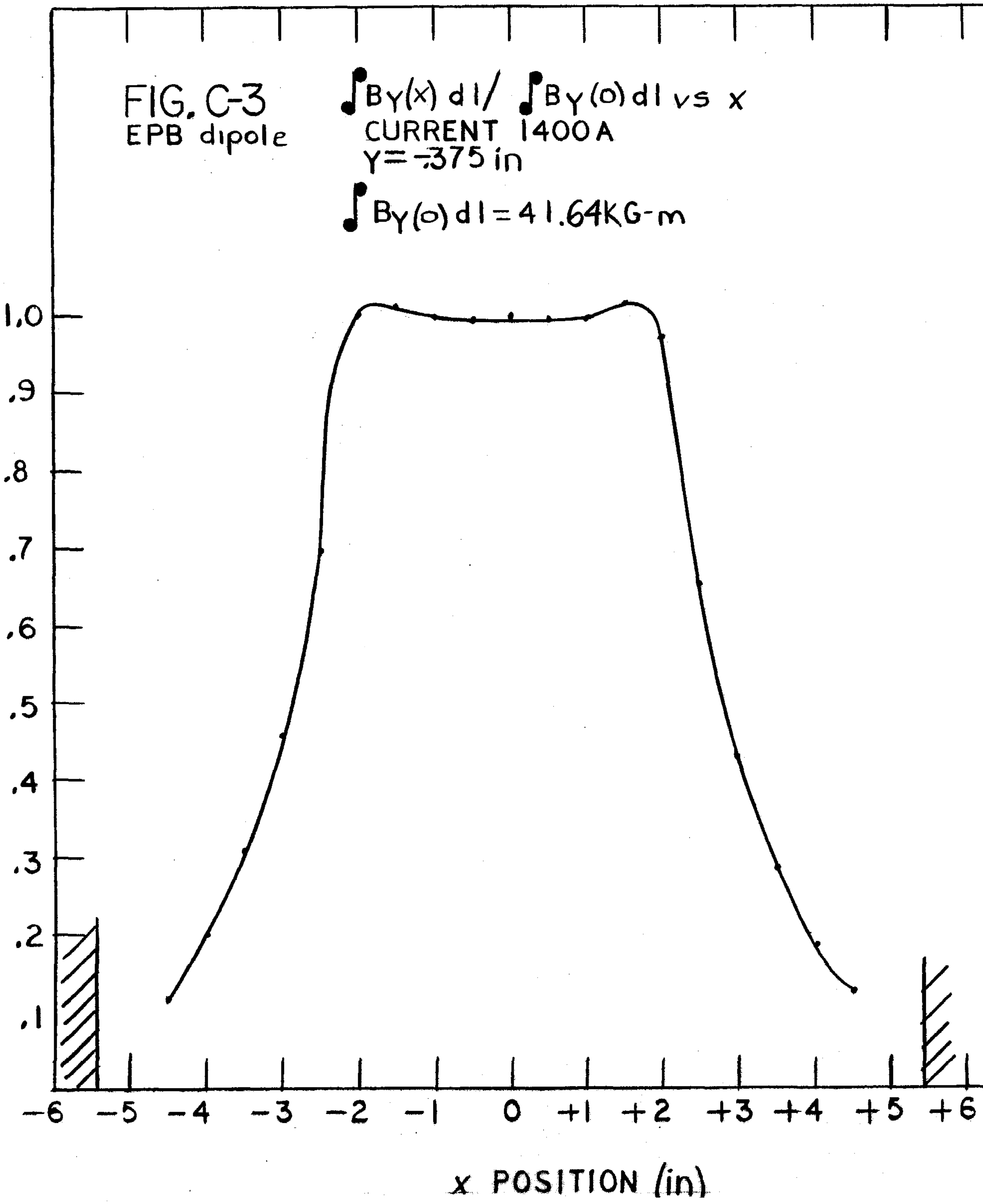


FIG.C-1
EPB dipole
BY(o) WITH SMALL STANDARD COIL AND FIELD INTEGRATOR
∫BY(o) dl WITH STRETCHED WIRE
15
10
5
45
30
15
FIELD [KG]
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
CURRENT (KA)



x(in)	$\int B_Y(x)\,dl / \int B_Y(o)\,dl$
−4.5	.1209
−4.0	.2063
−3.5	.3181
−3.0	.4773
−2.5	.7061
−2.0	.9327
−1.5	1.0002
−1.0	1.0001
− .5	.9999
0.0	1.0000
.5	.9999
1.0	1.0004
1.5	.9988
2.0	.9107
2.5	.6724
3.0	.4528
3.5	.3017
4.0	.1943
4.5	.1114



x(in)	$\int B_Y(x)dl / \int B_Y(0)dl$
-4.5	.1184
-4.0	.1997
-3.5	.3064
-3.0	.4574
-2.5	.6974
-2.0	1.0027
-1.5	1.0112
-1.0	.9989
- .5	.9997
0.0	1.0000
.5	.9999
1.0	.9991
1.5	1.0154
2.0	.9728
2.5	.6505
3.0	.4285
3.5	.2869
4.0	.1852
4.5	.1295

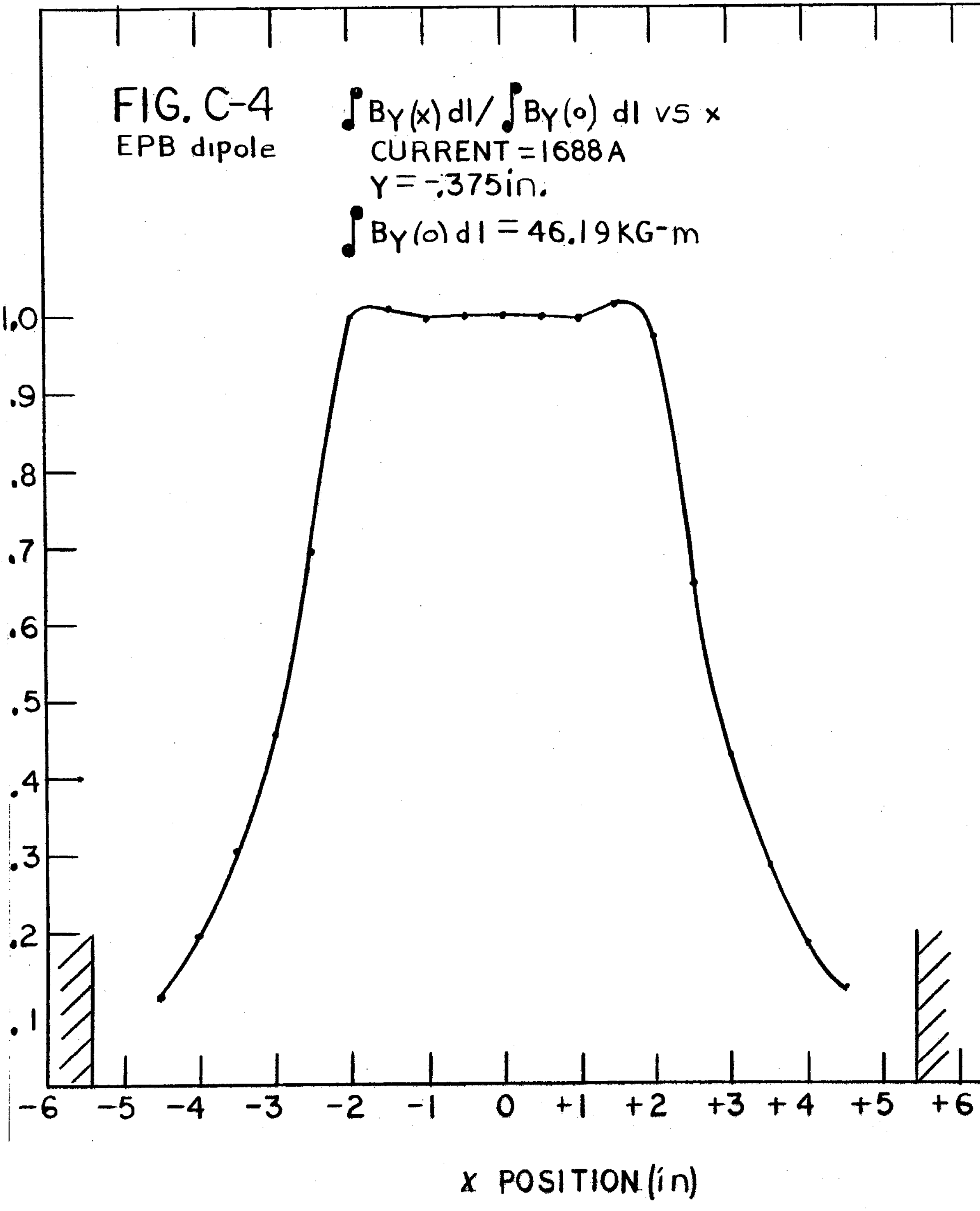


FIG. C-4
EPB dipole

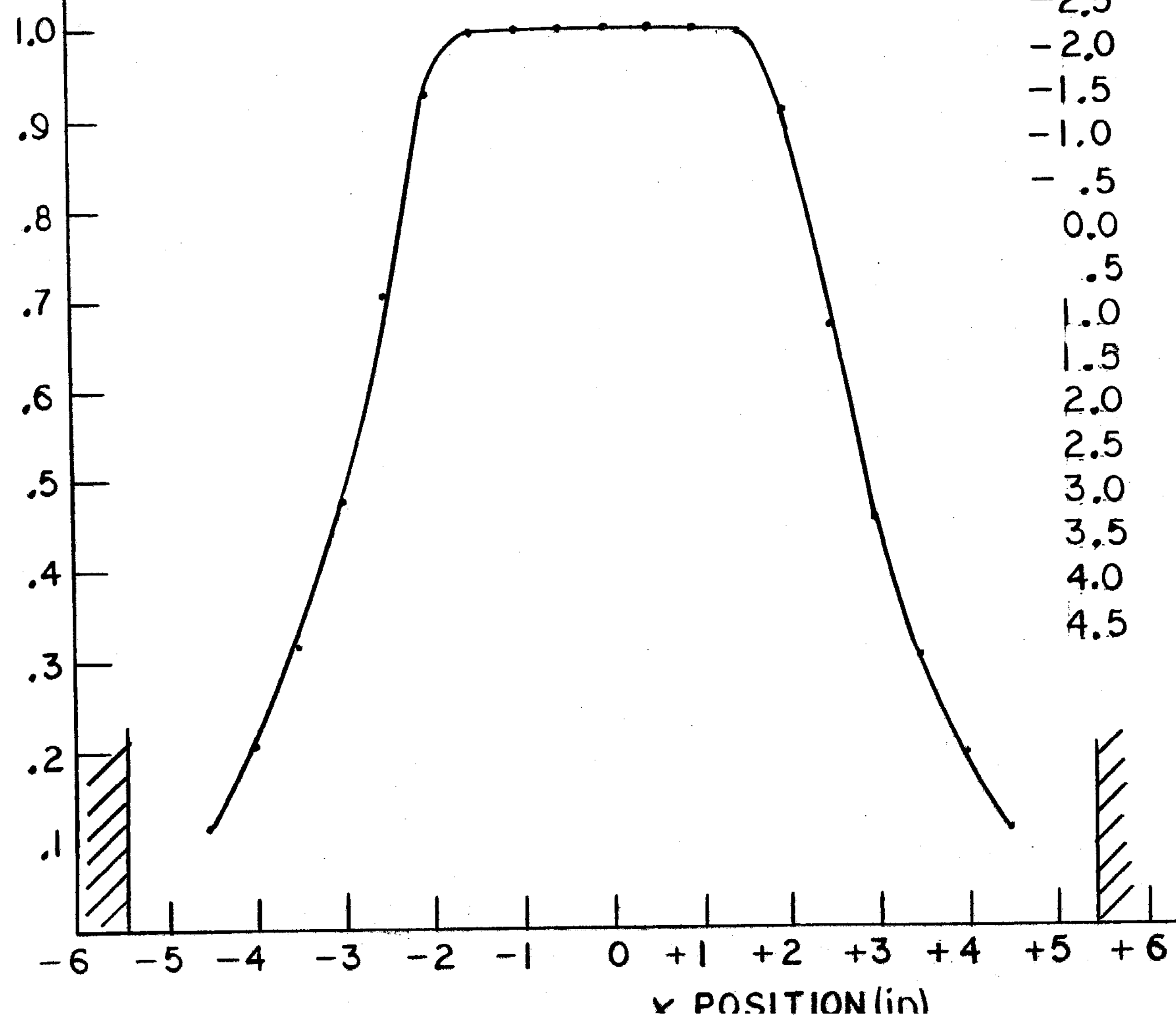
$\int B_Y(x)\,dl / \int B_Y(0)\,dl$ vs x
CURRENT = 1688 A
Y = -.375 in.
$\int B_Y(0)\,dl = 46.19$ KG-m

X (IN.)	$\int B_Y(x)\,dl / \int B_Y(0)\,dl$
-4.5	.1167
-4.0	.1973
-3.5	.3039
-3.0	.4541
-2.5	.6920
-2.0	.9984
-1.5	1.0091
-1.0	.9983
-.5	.9996
0.0	1.000
.5	.9997
1.0	.9983
1.5	1.0139
2.0	.9720
2.5	.6525
3.0	.4300
3.5	.2870
4.0	.1849
4.5	.1267

FIG. C-5
EPB dipole

$\int B_Y(x)\,dl / \int B_Y(0)\,dl$ vs x
CURRENT = 1688 A
Y = 0

$\int B_Y(0) = 46.19$ KG = m



x (in)	$\int B_Y(x)\,dl / \int B_Y(0)\,dl$
−4.5	.1191
−4.0	.2062
−3.5	.3182
−3.0	.4777
−2.5	.7044
−2.0	.9294
−1.5	.9983
−1.0	.9995
− .5	.9998
0.0	1.000
.5	.9997
1.0	.9996
1.5	.9964
2.0	.9071
2.5	.6701
3.0	.4520
3.5	.3008
4.0	.1926
4.5	.1090

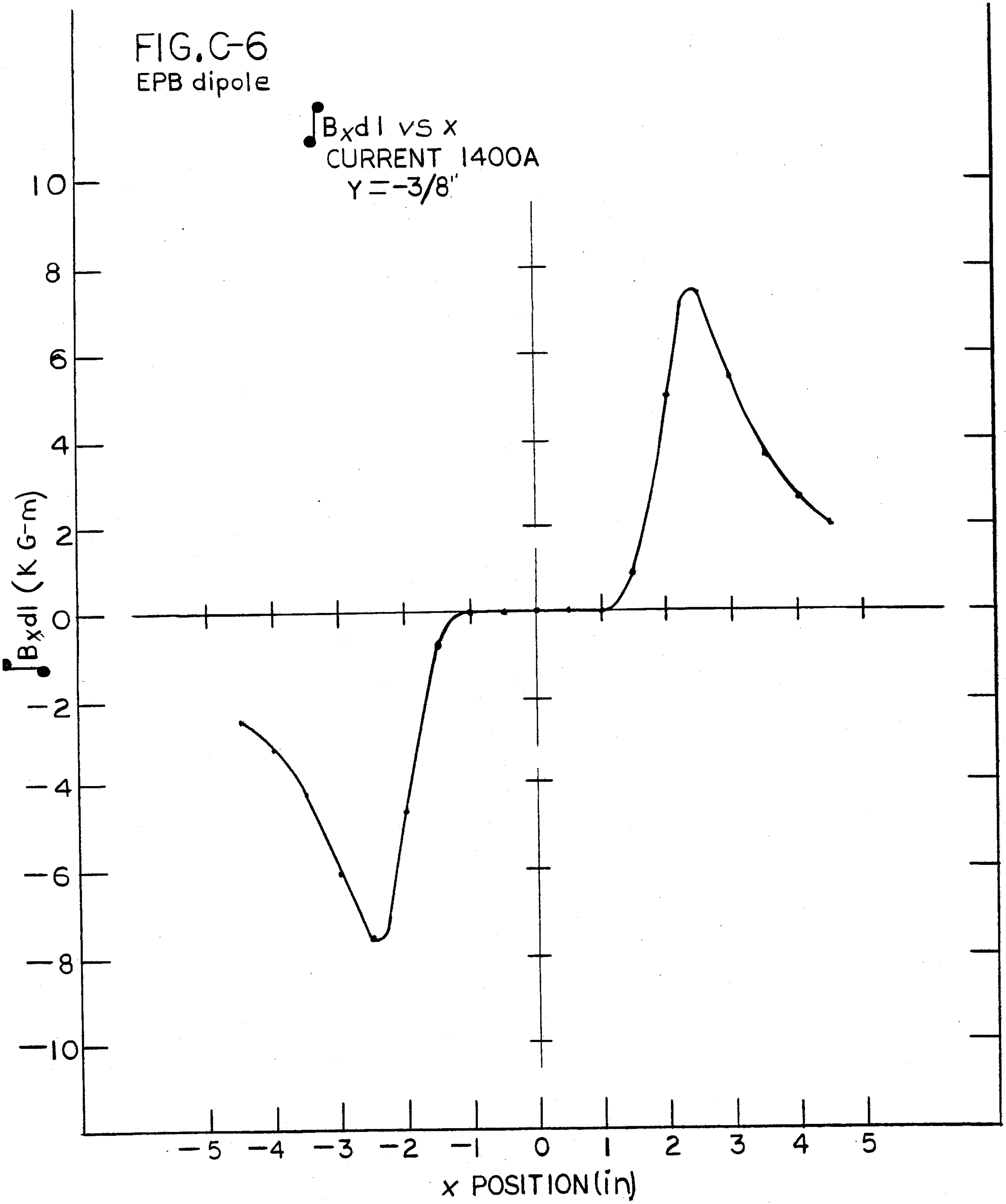


FIG. C-6
EPB dipole
∫Bx dl vs x
CURRENT 1400A
Y = -3/8"
10
8
6
4
2
0
-2
-4
-6
-8
-10
∫Bx dl (K G-m)
-5
-4
-3
-2
-1
0
1
2
3
4
5
x POSITION (in)

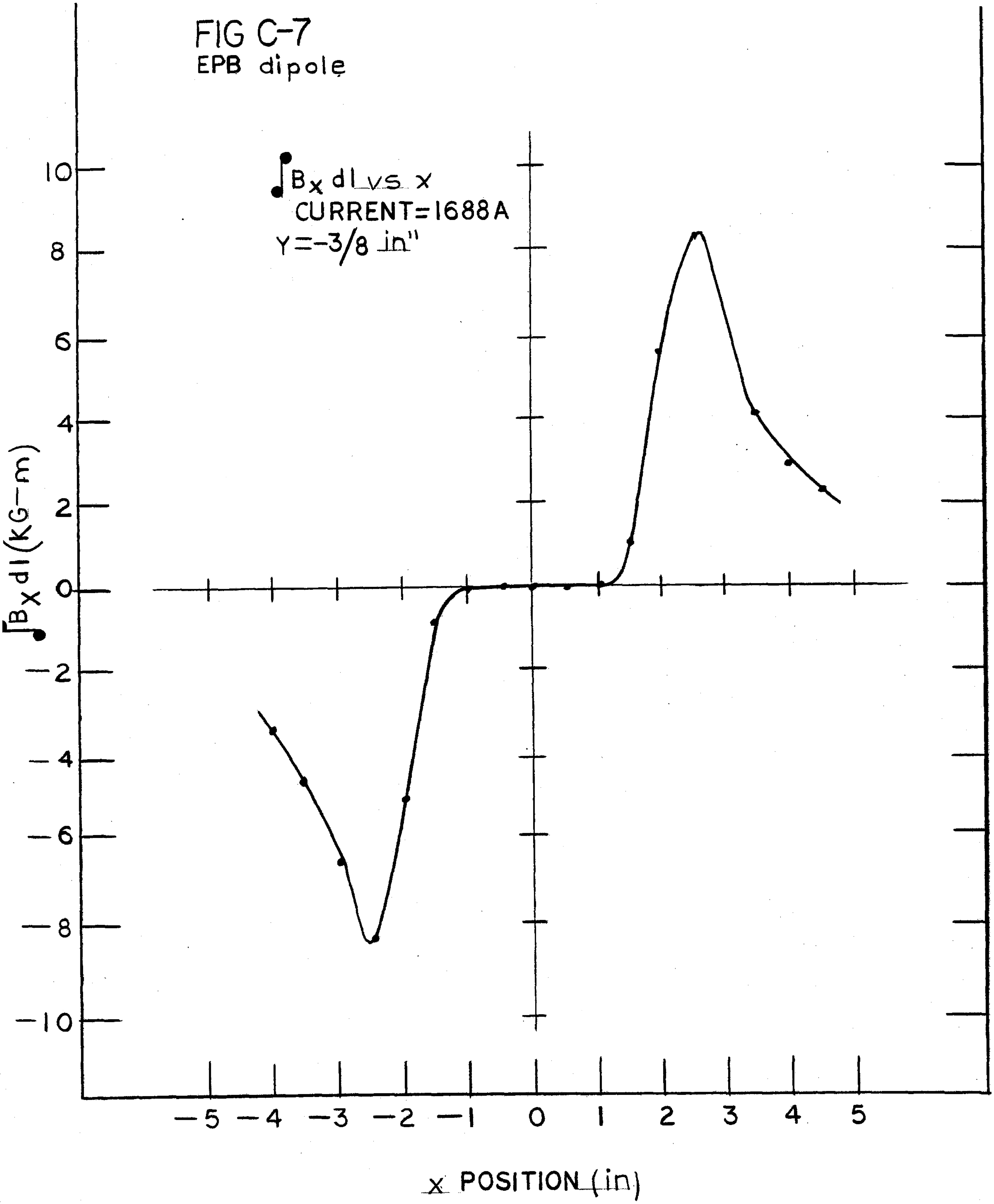


FIG C-7
EPB dipole
∫Bx dl vs x
CURRENT=1688A
Y=-3/8 in"
∫Bx dl (KG-m)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-5
-4
-3
-2
-1
0
1
2
3
4
5
x POSITION (in)