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ALTERNATE COIL CONFIGURATIONS FOR A SUPERCONDUCTING QUADRUPOLE

P.F. Dahl and K. Jellett

December 8, 1975

Accelerator Department

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ABSTRACT

Two superconducting quadrupole coil designs of the cos 2θ type are compared. One is a four-layer coil configuration, based on a relatively narrow braid conductor; the other consists of a single layer wound from wider conductor. Field computation and excitation requirements are presented, taking into account saturation of the circular iron shield surrounding the coils.

Magnet Geometry

Two alternate coil designs for a superconducting quadrupole of 12 cm (cold) aperture have been studied, octants of which are shown schematically in Figs. 1 and 2, respectively. Both coil configurations are multiblock approximations to a cos 2θ current distribution, surrounded by a circular iron shield. In the first design the ribbon conductor (braid) is arranged in four layers, each layer containing two blocks of ribbons per octant, i.e., superconductor plus "inert" spacer turns (black in the diagrams) for grading the current density azimuthally and spreading the conductors over the block areas. The layer thickness is 0.635 cm, layer spacing 0.127 cm, spacing between coils and iron 0.508 cm, and the iron shield is 11 cm thick. There are 203 conductors per octant, each 0.0689 cm (0.0271") thick and 0.635 cm (0.25") wide. The second design is a single layer 3-block configuration containing 39 turns, 0.0762 cm (0.030") thick and 1.7018 cm (0.67") wide (the conductor used in the present series of 4.25 meter ISABELLE prototype dipoles). The coil-iron spacing is again 0.508 cm, and the iron yoke 10.75 cm thick. This particular coil configuration is described in some detail in the Appendix.

Excitation Requirements and Field Distribution

a) $\mu = \infty$

With an infinite permeability iron shield the four-layer magnet has a gradient "load line" of 6.6 gauss/cm per ampere of conductor current at the aperture center; i.e., 1000 A are required to produce a central gradient G_o = 6.6 kG/cm. The gradient, or $\Delta G/G_o$, remains constant within 0.1% inside a circle of radius 4.1 cm (68% of the aperture). The load line and equivalent aperture fraction for the one-layer magnet is 1.56 gauss/cm per ampere and 5.2 cm (87%). Thus, the current requirements for the same 6.6 kG/cm is 4230 A in this case. The maximum field seen by the coil is approximately the same in both designs, or 43 kG for the 6.6 kG/cm gradient. These and various other parameters for the two magnets are also summarized in Table I.

b) Finite μ

Figures 3 and 4 show the calculated load line or current/turn versus gradient produced by the two magnets with iron shields of finite permeability.[1]

1. These calculations were performed with the computer program GRACY; G. Parzen and K. Jellett, Particle Accelerators 2, 169 (1971).

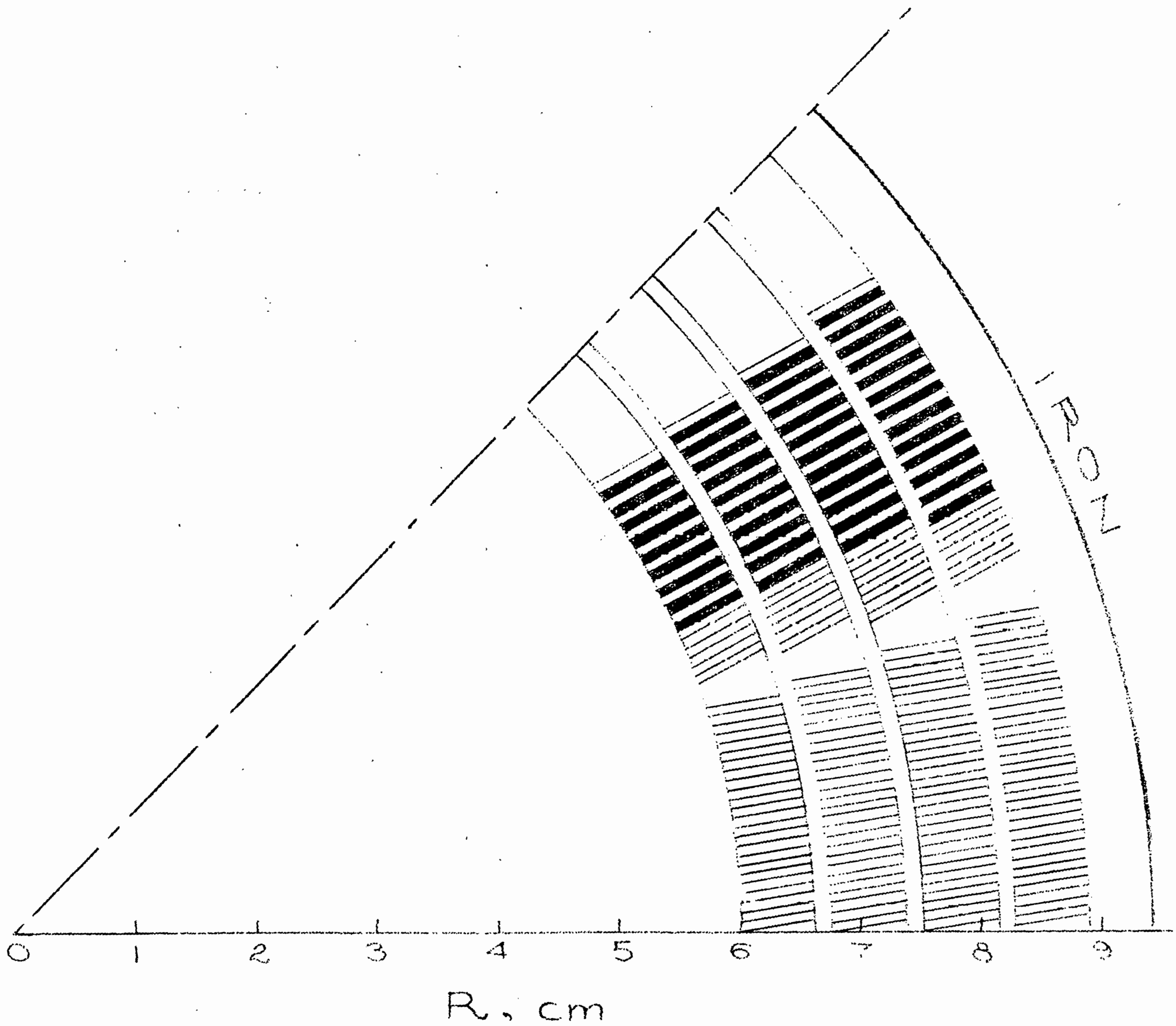


Fig. 1

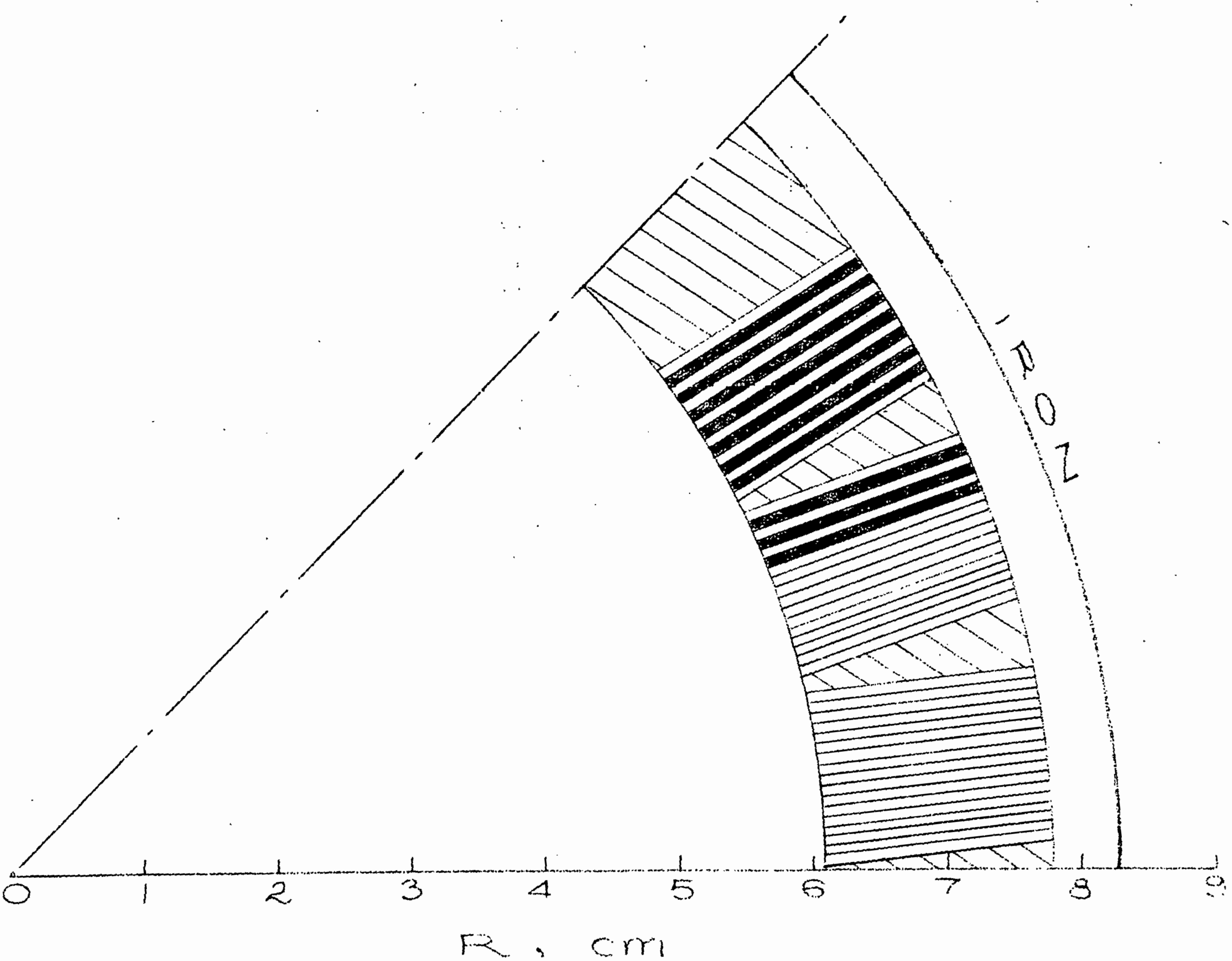


Fig. 2

TABLE I

Magnet Parameters*; $\mu = \infty$

	4-layers (203 turns)	1 layer (39 turns)
I (A)	1000	4230
NI (A-turns)	203000	164970
B_{max} (kG)	42.9	43.0
B_{max}/B_{max} (m.p.)	1.13	1.10
Stored Energy, Aperture + coil (kJ/m)	51.0	37.0
R, $\Delta G/G_o = 10^{-3}$ (cm)	4.1 (68%)	5.2 (87%)

* Where relevant, quantities refer to a design gradient $G_o = 6.6$ kG/cm.

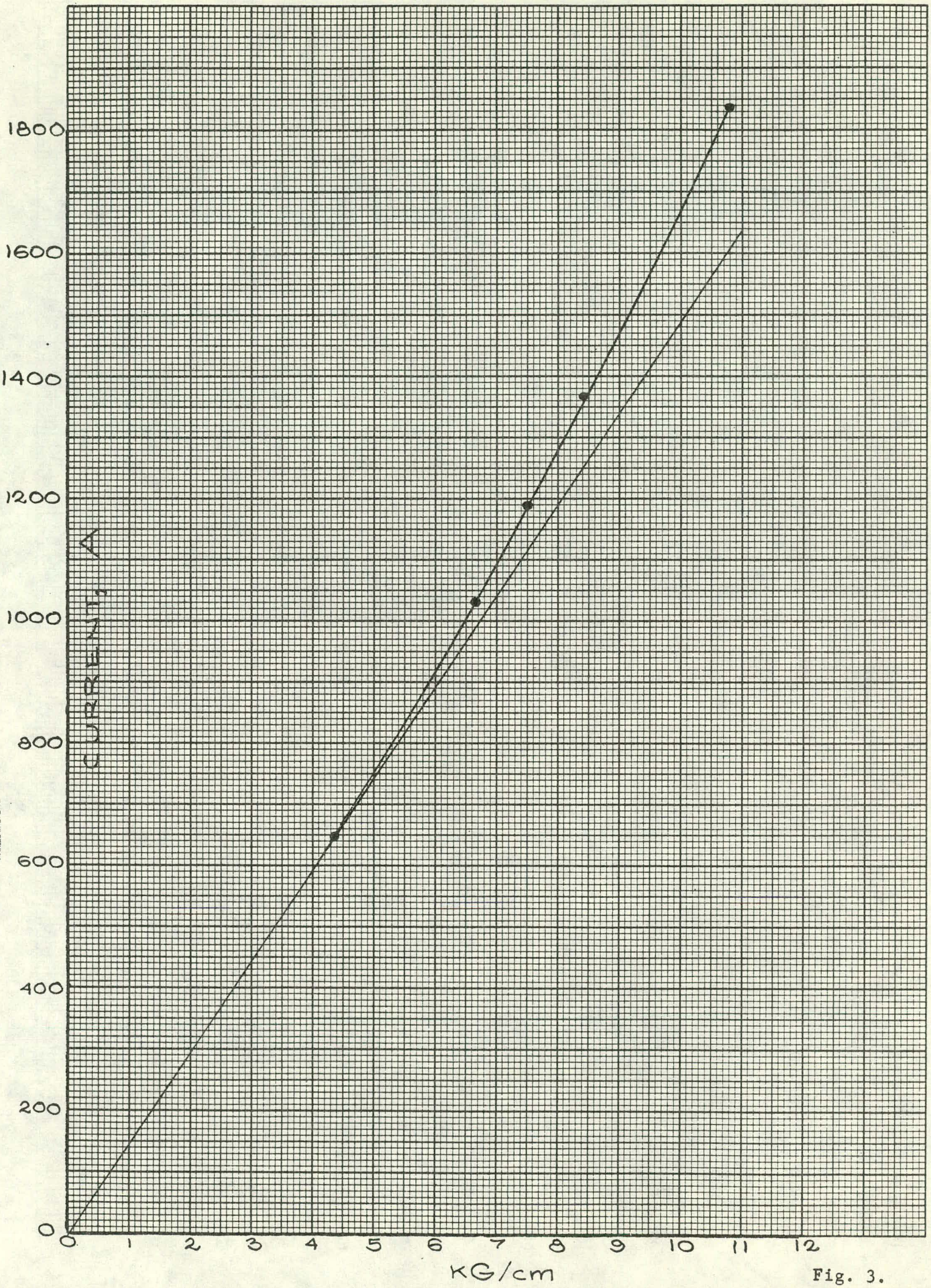

1800
1600
1400
1200
1000
800
600
400
200
0
CURRENT, A
0
1
2
3
4
5
6
7
8
9
10
11
12
KG/cm

Fig. 3.

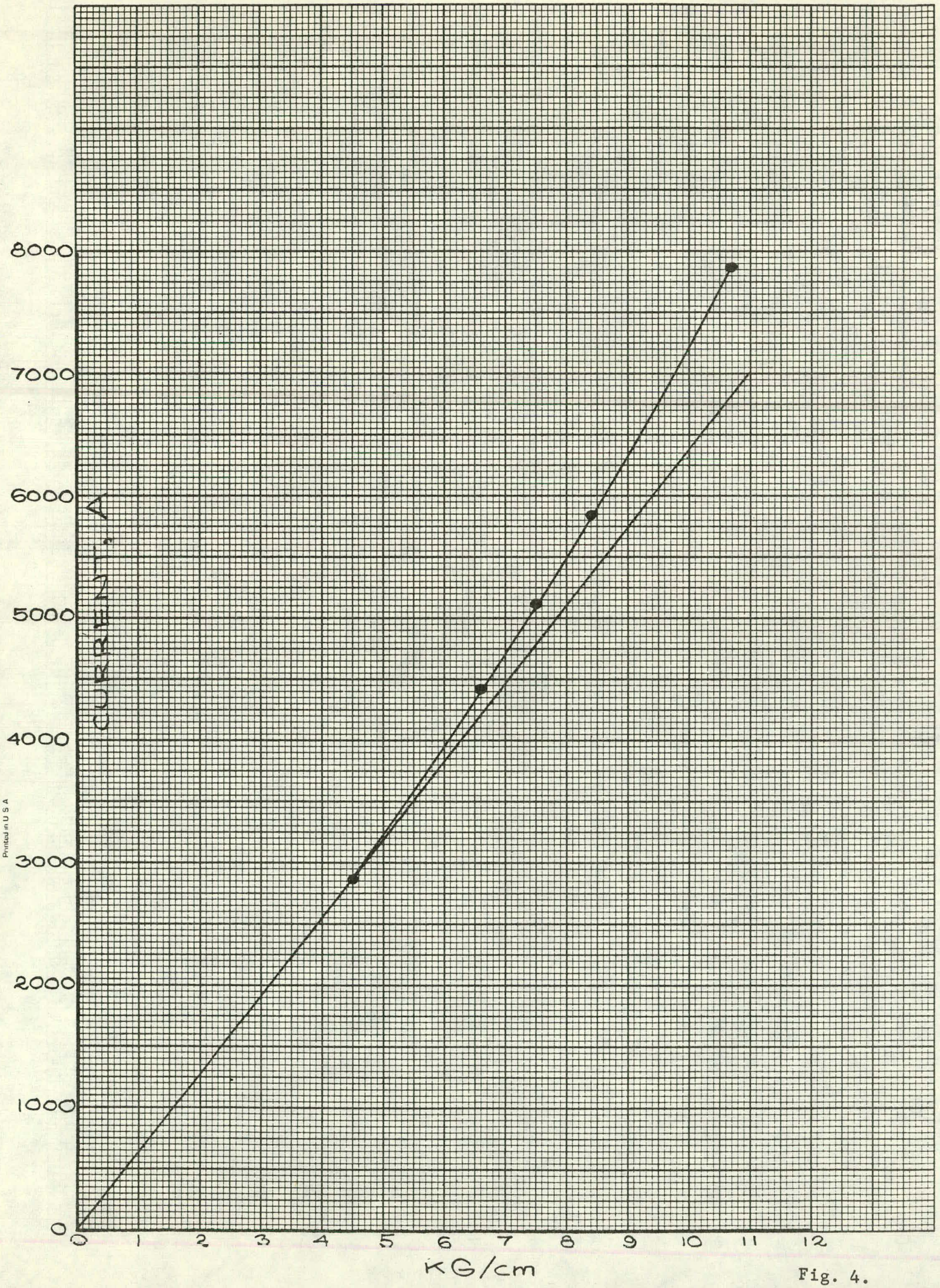

8000
7000
6000
5000
4000
3000
2000
1000
0
CURRENT, A
0
1
2
3
4
5
6
7
8
9
10
11
12
KG/cm

Fig. 4.

The departure from linearity due to iron saturation, also shown in Fig. 5, is not very different, approximately 4% in both cases. The spatial variation of the field gradient is substantially more than in the $\mu = \infty$ case, as shown in Fig. 6. In the four-layer magnet $\Delta G/G_o$ now remains constant within 0.1%. over ~ 43% of the aperture and in the one-layer magnet over ~ 37%. The two lowest (allowed by symmetry) induced multipole coefficients introduced by iron saturation, b_5 and b_9, defined by

$$B = G(x + b_5 x^5 + b_9 x^9 + \ldots)$$

are plotted against gradient in Figs. 7 and 8. A number of calculated parameters for the finite μ case are also listed in Table II.

Discussion

The chief virtue of the one-layer design is simplicity in construction which presumably may reflect in magnet performance from the point of view of premature quenching and training. The chief drawback is the higher current/turn inevitably accompanying a reduction in coil layers (assuming the same current density) — approximately four times the current/turn is required in the one-layer case, for the same gradient, even though the total ampere-turns is somewhat less due to the more efficient superconductor utilization. The current/turn is only slightly reduced (by less than 1%) in the one-layer case by using two current blocks per octant rather than three (which decreases the number of wedges and brings the coil effectively closer to the median plane). The maximum field in the two cases is the same, although the peak field enhancement (ratio of peak field seen by the coil to peak field on the median plane) is somewhat less in the one-layer case. Note that the (two-dimensional) peak field enhancement in quadrupoles of this type ($B_{max}/B_{max\text{-}m.p.} \approx 12\%$) tends generally to be substantially higher than the equivalent enhancement in dipoles, where B_{max}/B_o is typically 4%. The effect of saturation on the load line is about 4% for 6.6 kG/cm, (and not very different from the corresponding saturation in a 40 kG cosθ dipole of the same aperture, ~ 3%). The "region of good field" extends further in the one-layer case at low fields, or $\mu = \infty$, which may be significant or somewhat accidental due to a particularly successful coil block position optimization achieved in this particular design, but in any case for a finite μ the one-layer design is worse in this respect by about 6% compared

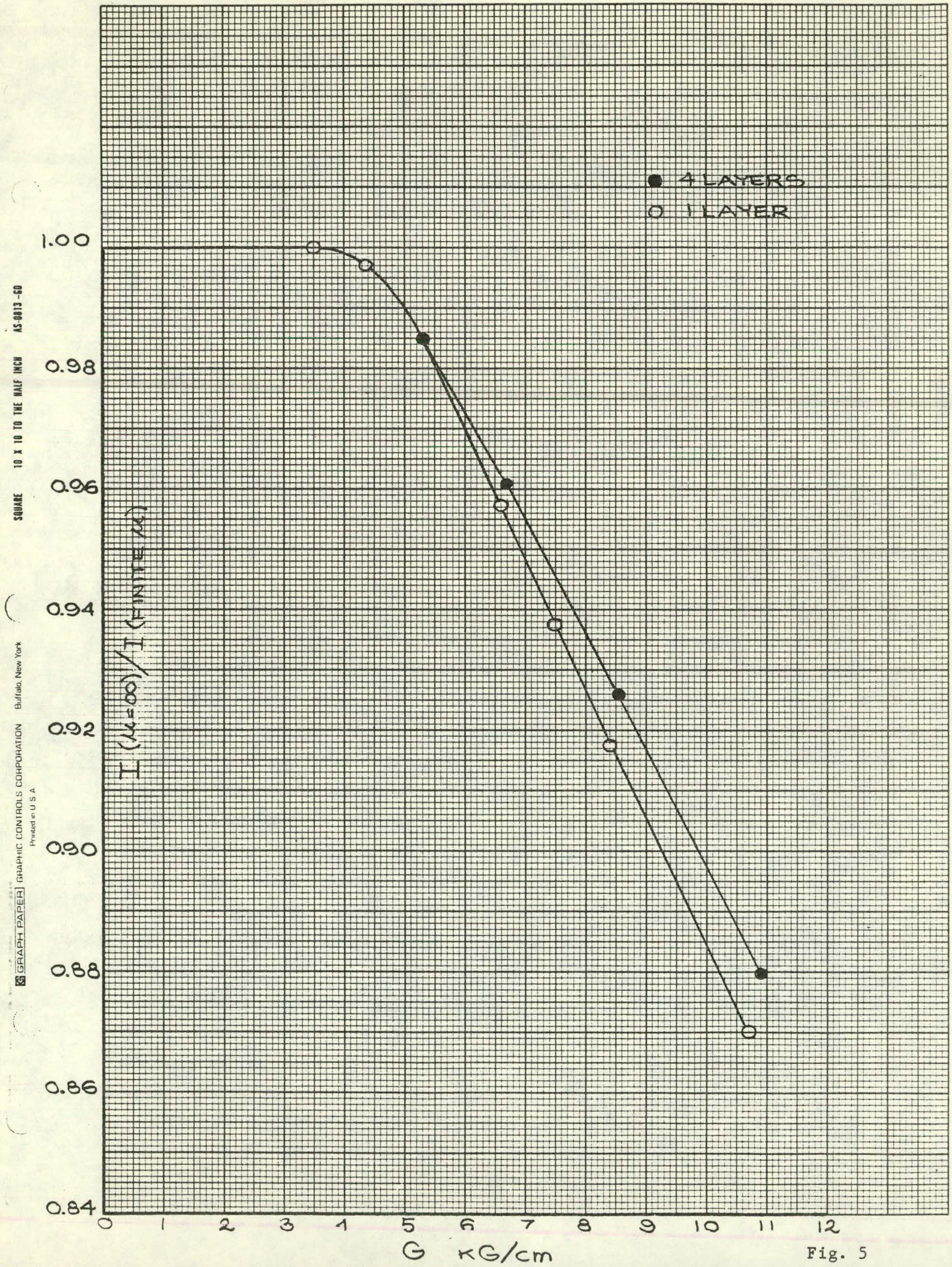

4 LAYERS
1 LAYER
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0
1
2
3
4
5
6
7
8
9
10
11
12
G kG/cm
I (μ=∞)/I (FINITE μ)
GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
Printed in U.S.A.
SQUARE 10 X 10 TO THE HALF INCH AS-0813-G0

Fig. 5

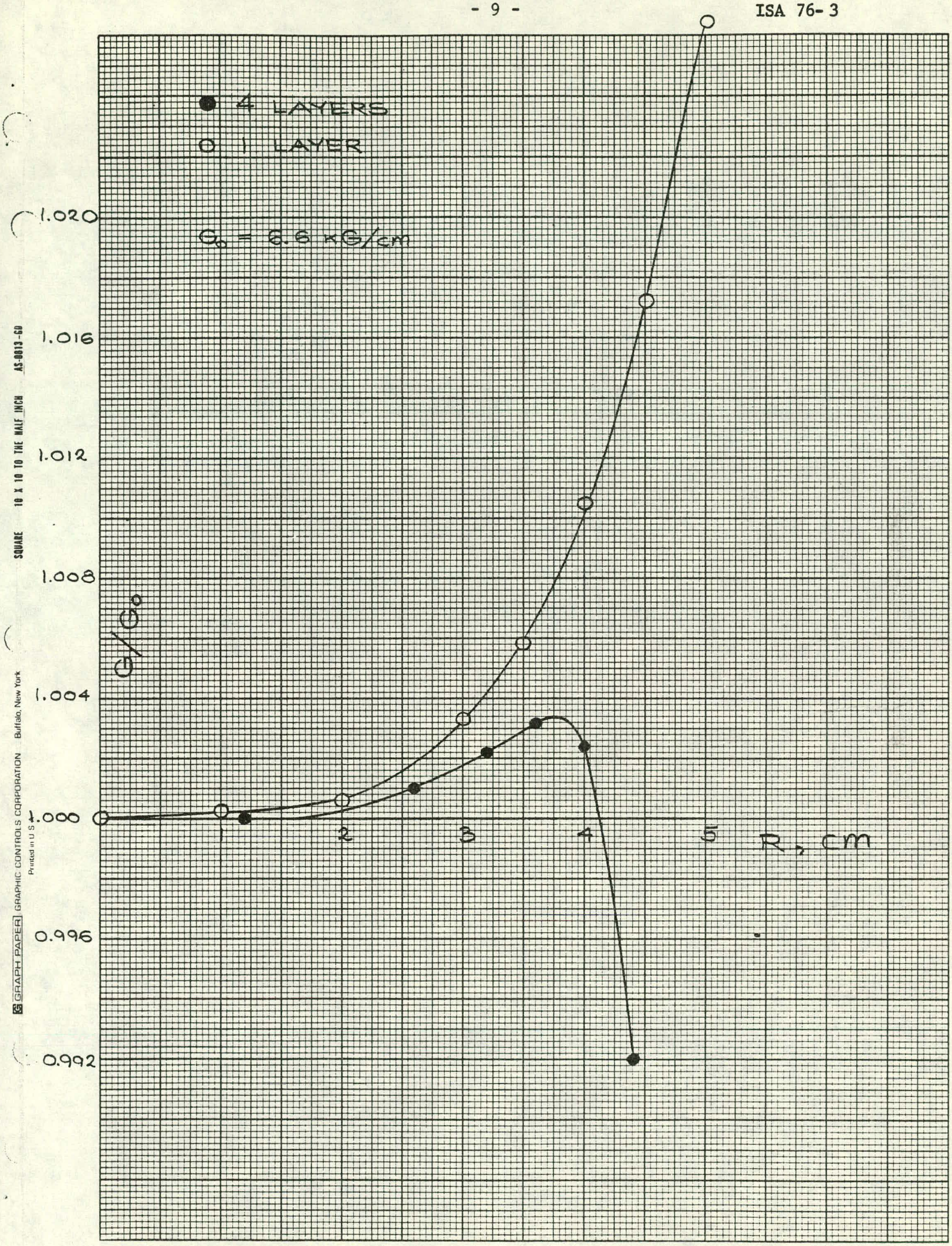

4 LAYERS
1 LAYER
G₀ = 6.6 kG/cm
1.020
1.016
1.012
1.008
1.004
1.000
0.996
0.992
G/G₀
1
2
3
4
5
R, cm
GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
Printed in U.S.
SQUARE 10 X 10 TO THE HALF INCH AS-0813-GD

Fig. 6

TABLE II

Magnet Parameters*; Finite μ

	4-layers	1-layer
I (A)	1035	4360
$I - I_{\mu=\infty}$ (%)	3.9	4.25
NI (A-turn)	210000	170000
B_{max} (kG)	42.5	42.5
$B_{max}/\bar{B}_{max}$ (m.p.)	1.13	1.10
$\bar{B}_{backleg}$ (kG)	17.0	15.3
$B_{external}$, (m.p.) (G)	20	10
$B_{external}$, pole (G)	300	160
Stored Energy, Aperture + Coil (kJ/m)	49.2	36.6
Stored Energy, Fe (kJ/m)	2.3	1.6
R, $\Delta G/G_o = 10^{-3}$ (cm)	2.6 (43%)	2.2 (37%)

* Where relevant, quantities refer to a design gradient G_o = 6.6 kG/cm

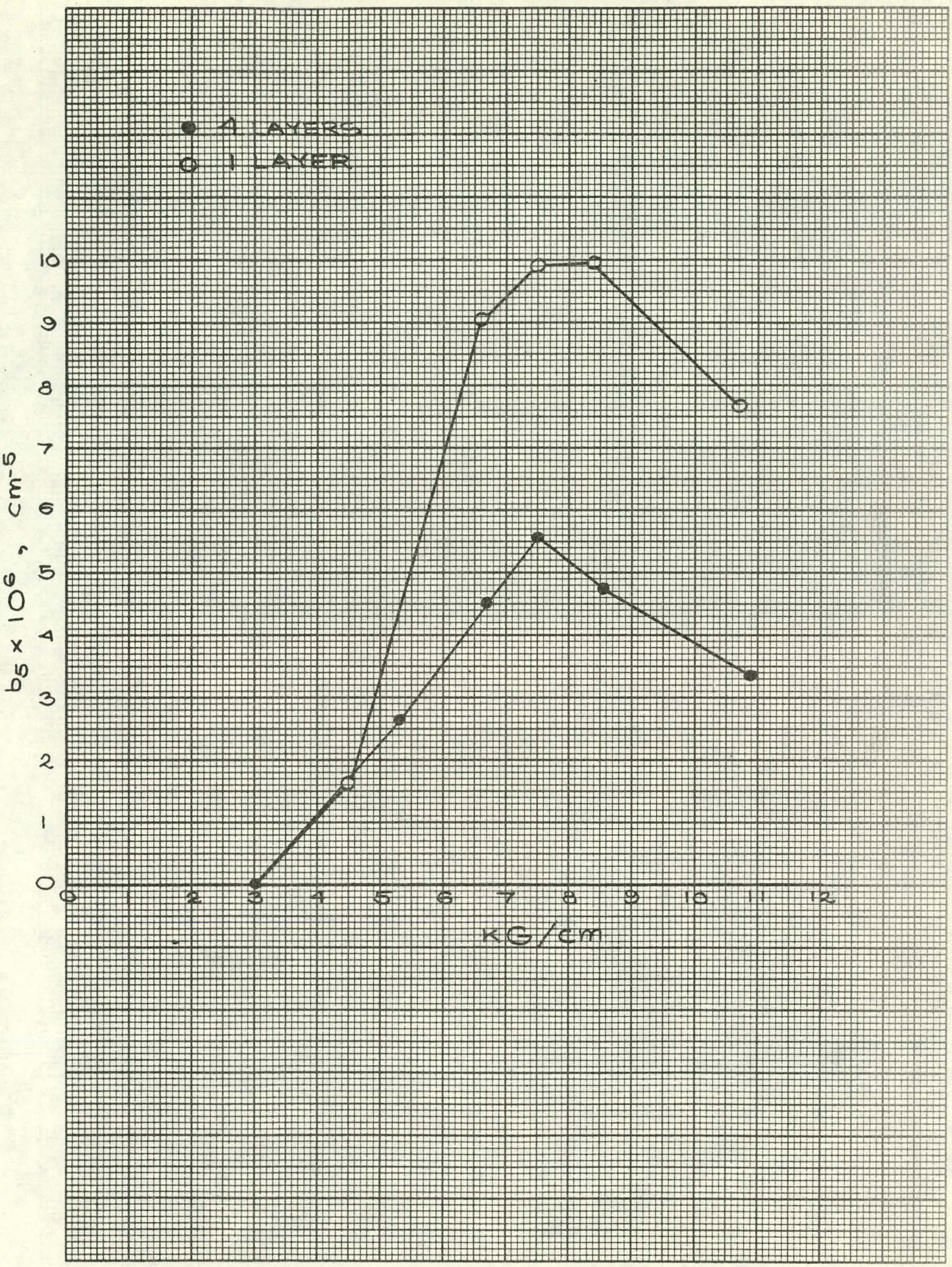

4 LAYERS
1 LAYER
$b_5 \times 10^6$, cm^{-5}
0
1
2
3
4
5
6
7
8
9
10
0
1
2
3
4
5
6
7
8
9
10
11
12
kG/cm

Fig. 7

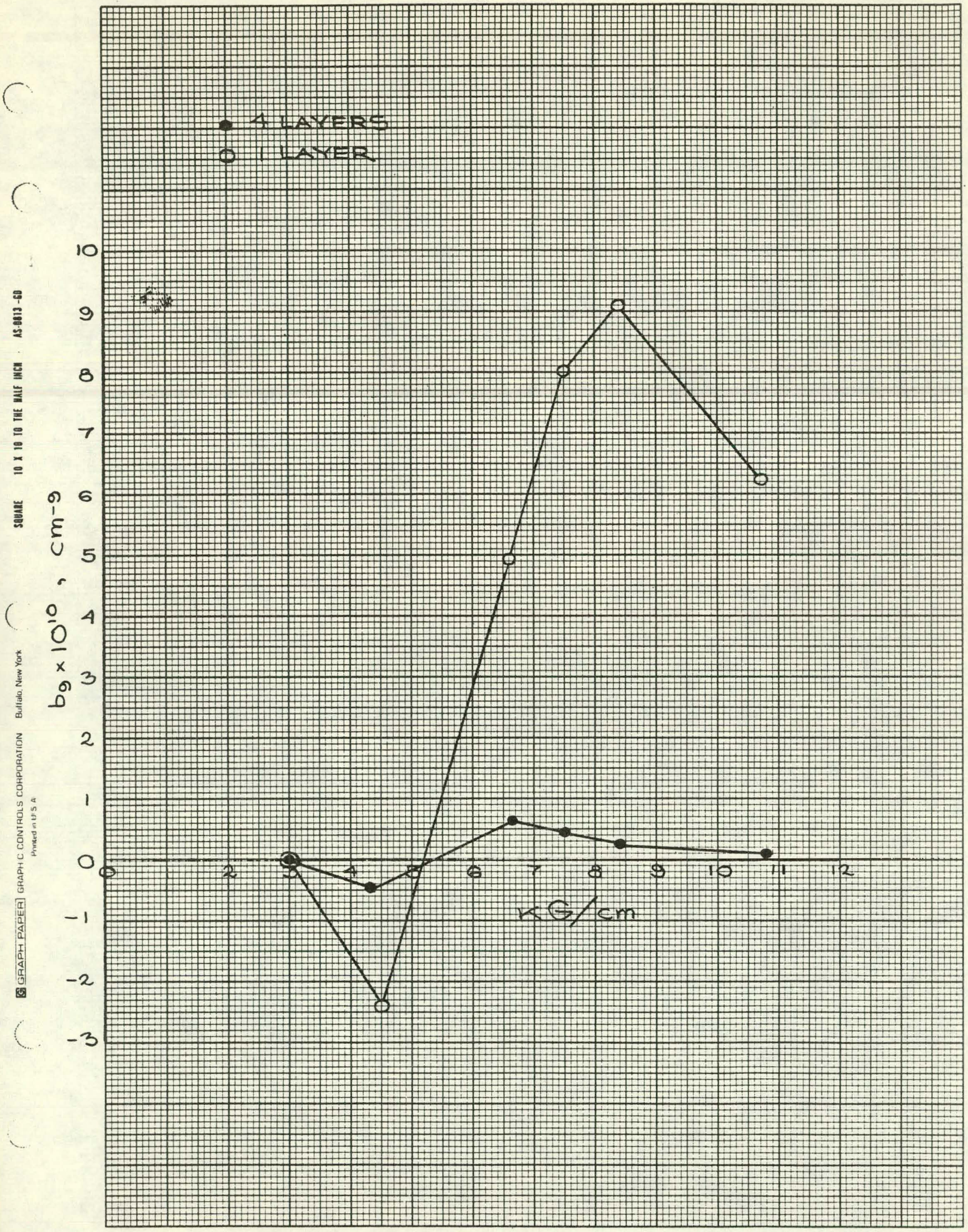

● 4 LAYERS
○ 1 LAYER
$b_9 \times 10^{10}$, cm^{-9}
KG/cm
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
0
2
3
4
5
6
7
8
9
10
11
12

Fig. 8

to the four-layer design. This is because of the increased saturation in the former case, brought about by the closer proximity of the iron boundary to the working aperture, reflected mainly in the higher multipole coefficients.

A reasonable compromise between mechanical simplicity and tolerable current requirements suggests perhaps a two-layer quadrupole instead. Preliminary calculations indicate that, for a given gradient (and $\mu = \infty$) I (2 layers)/I (1 layer) = 0.60; i.e., to obtain our 6.6 kG/cm the two-layer magnet requires 2650 A, instead of 4360 A as in the one-layer case.

The effect of varying the iron thickness can be seen in Fig. 9, Fig. 10, and Fig. 11, which are for the one layer quadrupole. Fig 9 shows the current required to produce 6.6 kG/cm as a function of iron thickness, and Fig. 10 shows the two lowest harmonic coefficients, corresponding to these current values, plotted against iron thickness. The external field depends strongly on iron thickness, as shown in Fig. 11 (although the external field values are very sensitive to the iron permeability table, assumed in the calculation, and should be viewed with caution).

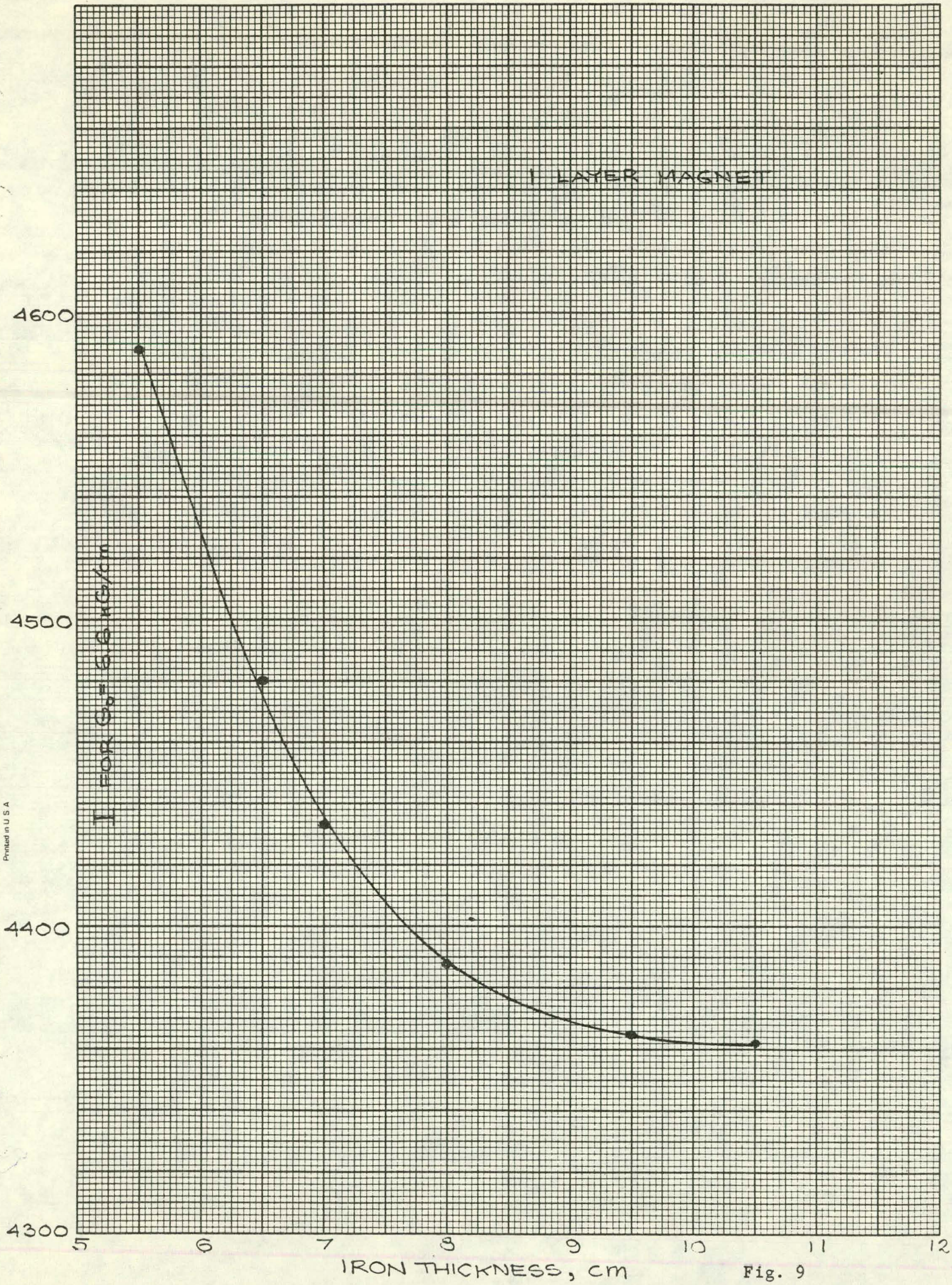

1 LAYER MAGNET
4600
4500
4400
4300
5
6
7
8
9
10
11
12
I FOR G0= 6.6 kG/cm
IRON THICKNESS, cm

Fig. 9

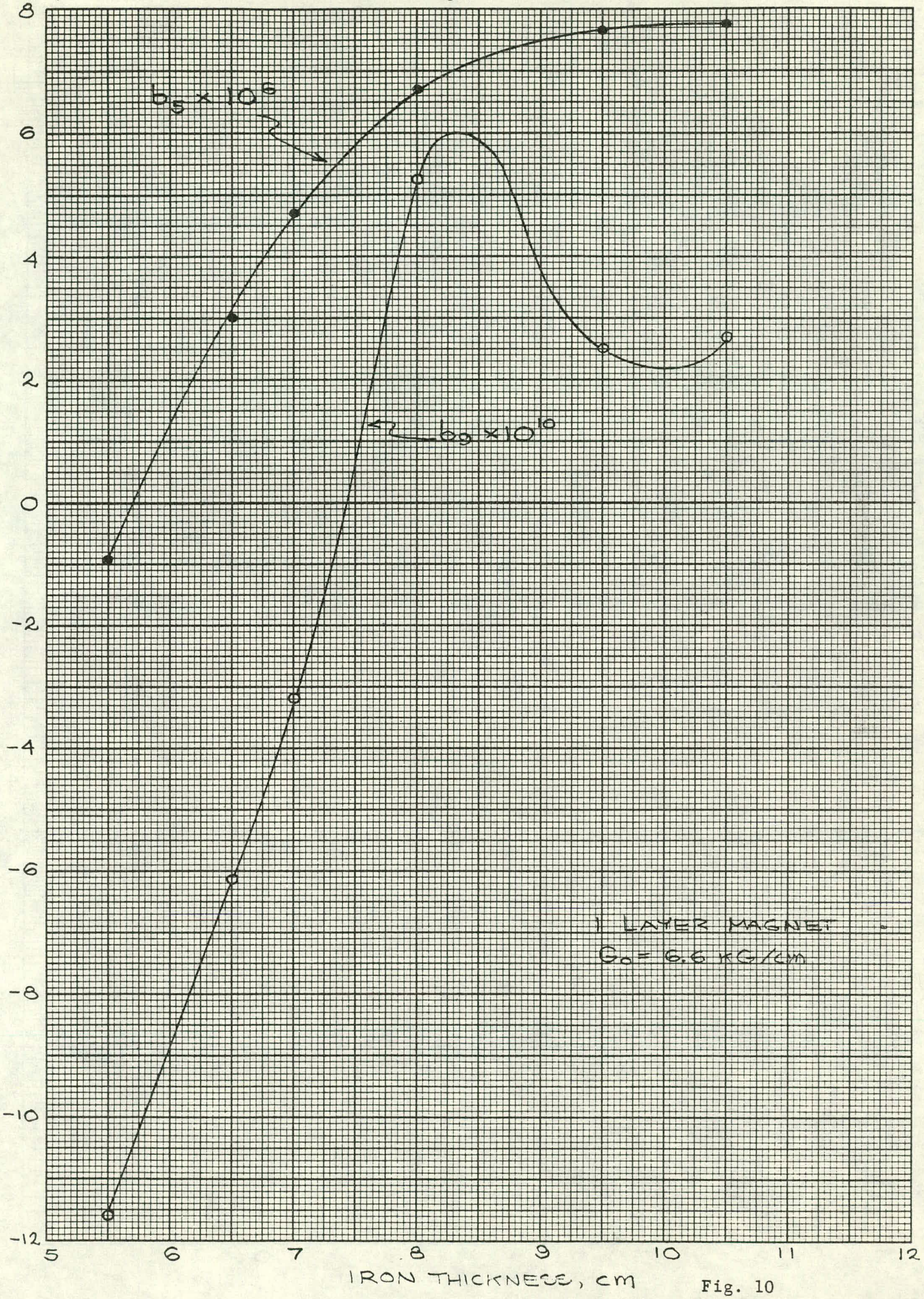

8
6
4
2
0
-2
-4
-6
-8
-10
-12
5
6
7
8
9
10
11
12
$b_5 \times 10^6$
$b_9 \times 10^{10}$
1 LAYER MAGNET
G_0 = 6.6 kG/cm
IRON THICKNESS, cm

Fig. 10

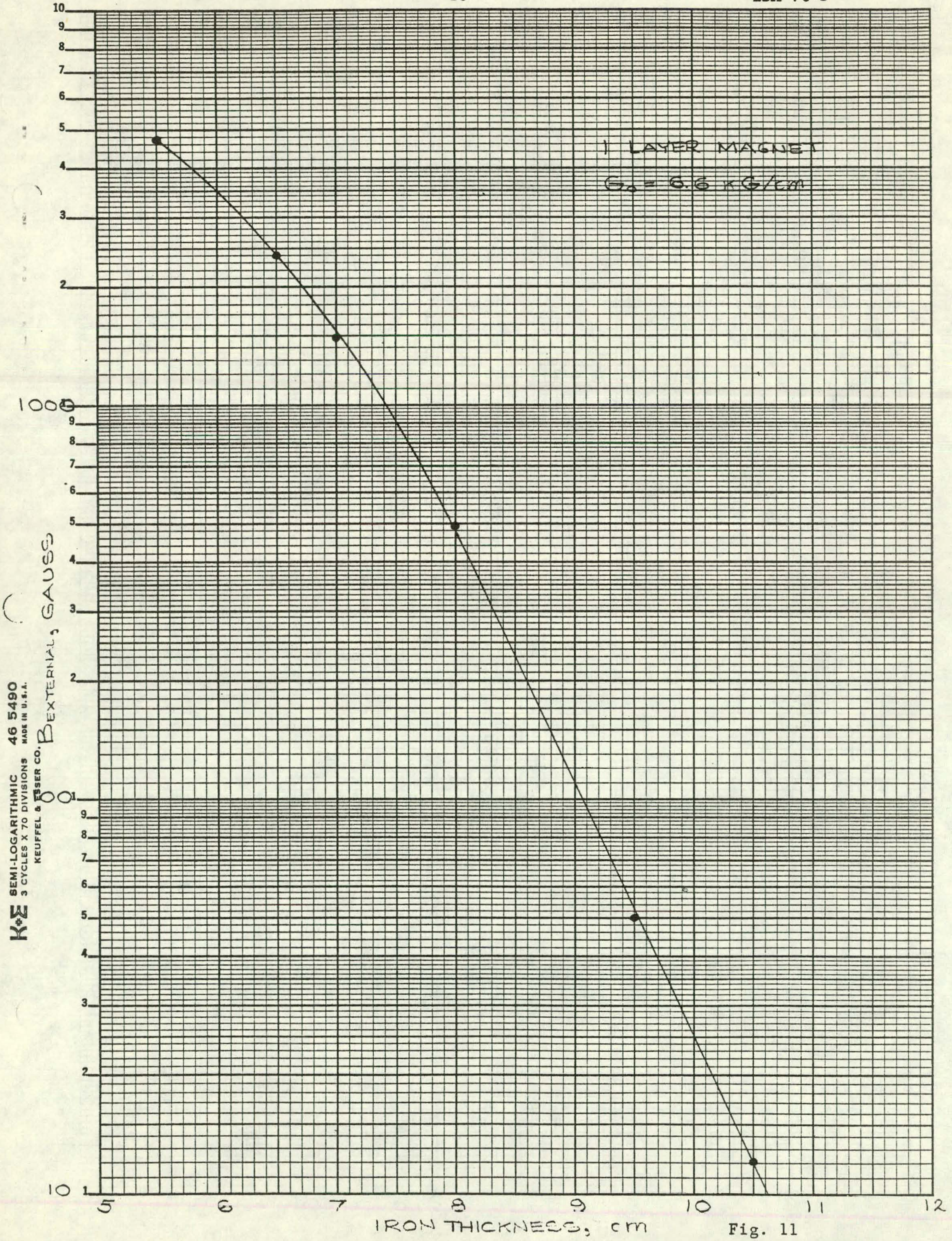

1 LAYER MAGNET
G_0 = 6.6 kG/cm
B EXTERNAL, GAUSS
IRON THICKNESS, cm
10
100
1000
10
5
6
7
8
9
10
11
12
K+E SEMI-LOGARITHMIC 46 5490
3 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

Fig. 11

APPENDIX A

An octant of the single-layer quadrupole is shown in Fig. 2, including the "inert" spacer turns (black), and the inner boundary of the iron shield, of radius 8.28675 cm. The block geometry is further defined in Figure A-1. There are 39 conductors, each 0.0762 cm thick and 1.7018 cm wide, arranged in blocks containing 8, 14, and 17 turns respectively from the pole. The conductor locations are listed in Table A-I. There are 10 spacer turns as well, of the same size as the conductors, and arranged in groups of 7, 3, and 0 turns. The turns are positioned such that the midpoint of the base of each one lies on a circle of radius 6.07695 cm. Dimensions of the wedges and center post are given in Fig. A-2.

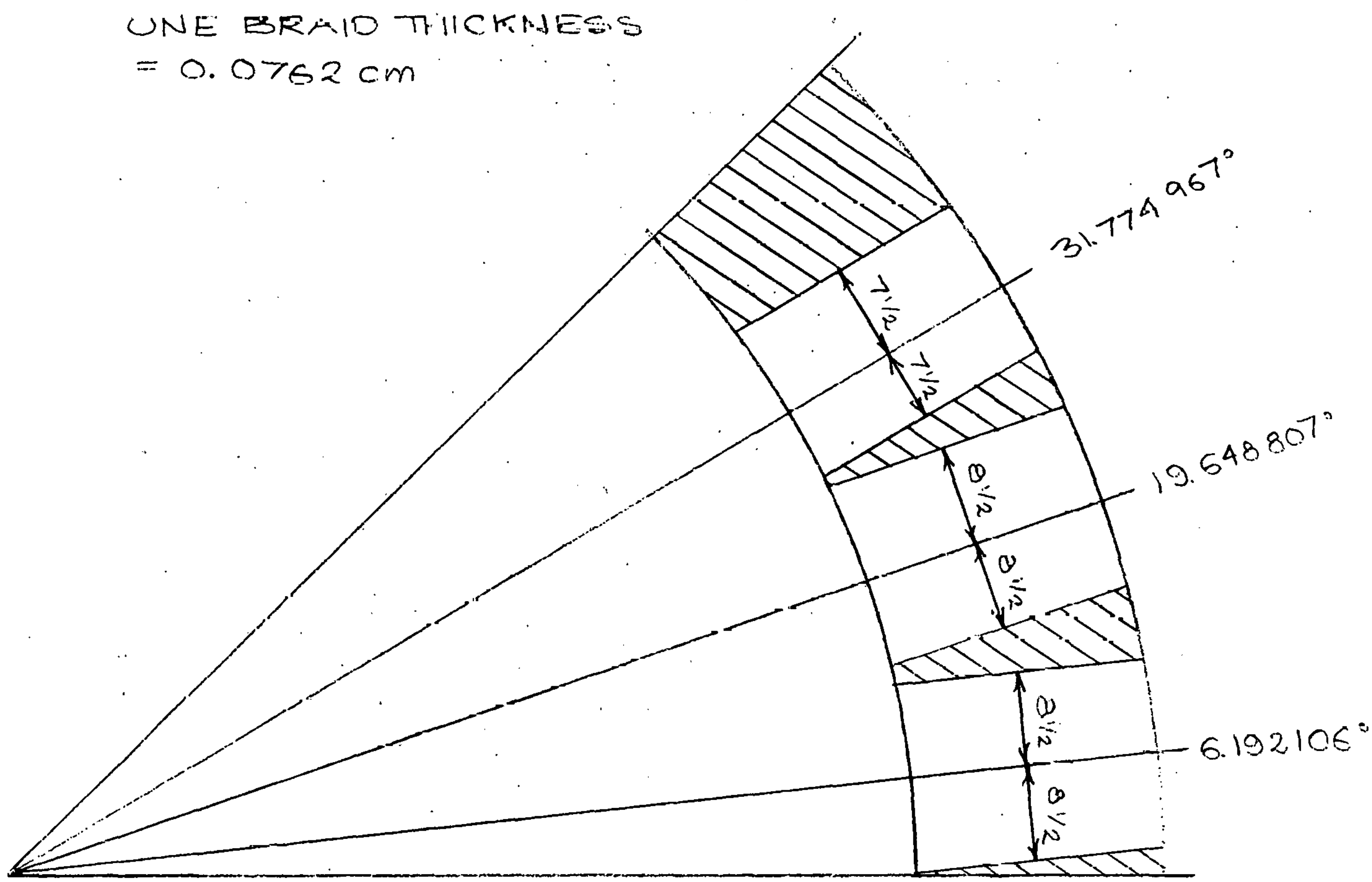
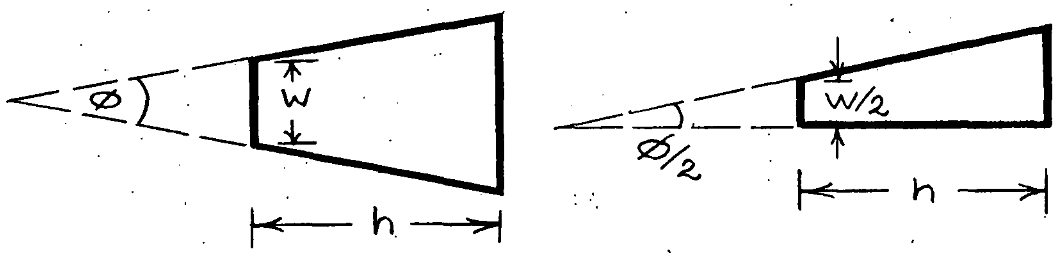

ONE BRAID THICKNESS
= 0.0762 cm
31.774967°
19.648807°
6.192106°
7½
7½
8½
8½
8½
8½

Fig. A-1

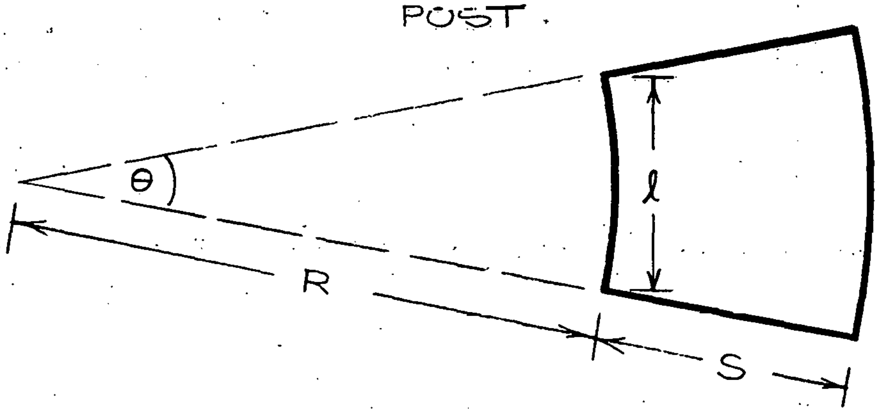
WEDGES 1, 2   WEDGE 3



WEDGE

1	W = 0.0655 cm	h = 1.6980 cm	Ø = 12.7915°
2	W = 0.1303 cm	h = 1.6980 cm	Ø = 12.7915°
3	W/2 = 0.0081 cm	h = 1.6985 cm	Ø/2 = 6.1921°

POST



R = 3.6182 cm
S = 1.7069 cm
ℓ = 1.6605 cm
θ = 26.4501°

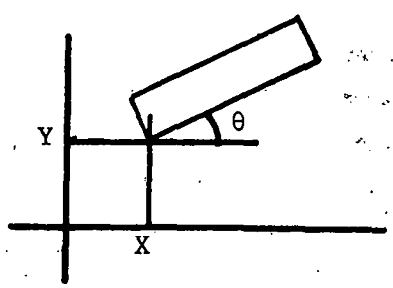
Fig. A-2

TABLE A-I

Conductor Thickness = 0.0762 cm

Conductor Width = 1.7018 cm

Block 1		Block 2		Block 3	
X (cm)	Y (cm)	X (cm)	Y (cm)	X (cm)	Y (cm)
5.447157	2.701831	5.912021	1.423106	6.080885	0.008247
5.376682	2.837446	5.893178	1.497289	6.079822	0.084779
5.302938	2.971035	5.873423	1.571147	6.077798	0.161206
5.225936	3.102607	5.852762	1.644682	6.074816	0.237530
5.145685	3.232165	5.831196	1.717894	6.070878	0.313750
5.062184	3.359711	5.808725	1.790782	6.065987	0.389867
4.975425	3.485238	5.785354	1.863348	6.060143	0.465879
4.885398	3.608742	5.761082	1.935594	6.053350	0.541790
8 turns		5.735908	2.007516	6.045605	0.617597
each at 31.774967°		5.709836	2.079120	6.036912	0.693300
		5.682864	2.150400	6.027268	0.768902
		5.626215	2.291997	6.016672	0.844399
		5.565953	2.432303	6.005125	0.919793
		5.502061	2.571314	5.992625	0.995084
		14 turns		5.979168	1.070272
		each at 19.648807°		5.964754	1.145355
				5.949379	1.220334
				17 turns	
				each at 6.192106°	



APPENDIX B

The single-layer quadrupole configuration under consideration here is to be utilized in the so-called "half-cell" assembly, which will consist of two 40 kG dipoles[2,3] and one quadrupole. Since the magnets are to be operated in series, electrically, and the current required to produce 40 kG in the dipoles is approximately 3300 A (taking iron saturation into account), Table B-I lists various calculated parameters for the one-layer quadrupole for the case of 3300 A (and finite μ iron), corresponding to a central gradient of G_o = 5.1 kG/cm.

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2. P.F. Dahl, BNL Informal Report AADD 74-10 (1974).
3. A.D. McInturff et al., IEEE Trans. Nucl. Sci., NS-22, 1133 (1975).

TABLE B-I

Further Parameters for 1-Layer Magnet; Finite μ

I(A)	3300
$I - I_{\mu=\infty}$ (%)	~ 1
G_o (kG/cm)	5.1
B_{max} (kG)	32.9
B_{max}/B_{max}, m.p.	1.11
Stored Energy, Aperture + Coil (kJ/m)	22.2
Stored Energy, Fe (kJ/m)	0.3
R, $\Delta G/G_o = 10^{-3}$ (cm)	2.85 (47%)