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A 2-DIMENSIONAL MAGNETOSTATIC MODEL OF THE BOOSTER RING QUADRUPOLE MAGNETS

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Brookhaven National Laboratory

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ALTERNATING GRADIENT SYNCHROTRON DEPARTMENT
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Of The

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ABSTRACT

In order to document some aspects of the Booster quadrupole magnet design, the magnetic fields, field gradients, and multi-pole coefficients of the magnetic field were calculated.

From these modelling computations, carried out for a magnet of perfect constructional symmetry, the field gradient in the horizontal midplane is flat out to 8 cm from the magnetic axis, for currents up to 5700 Amperes. The ratio of dodecapole to quadrupole harmonic coefficients decreases with current in this range. The magnitude of the saturation, at 5700 Amperes current is 4 to 5 percent, depending upon the stacking fraction of the magnet laminations.

Graphs of: calculated magnetic field gradient versus position in the magnet's horizontal midplane; quadrupole coefficient, ratio of dodecapole to quadrupole coefficient, and magnetic saturation versus magnet current are given. A table of calculated multipole coefficients versus magnet current is given.

1. Description Of The Computations

A two-dimensional magnetostatic analysis of the Booster ring quadrupole magnets was made, using the POISSON codes. The magnetic fields, field gradients and multipole coefficients were computed assuming perfect constructional symmetry.

The analysis was performed to study the onset of saturation in the magnet, as the magnet current increases to and beyond its full operating value. A 4-fold-symmetric geometry was assumed. A second set of computations, to be made subsequently, will examine the effects of magnet shape deformations due to constructional assymetries. It is hoped that such computations will contribute to an understanding of the observed magnet characteristics.

The magnet dimensions, including pole face profile, are given in BNL Booster quadrupole magnet construction drawings D36-M-0888-4A and D36-M-0917. The permeability input table used for the computation was taken from data curves of U.S.S. type M36 24-Gage fully-processed sheet steel. The data curve supplied by the manufacturer extends to 20.8 kilogauss, at a field intensity of 1 kilooersted. This range of data is sufficient to allow computation of the magnet fields. However, to insure computational stability during the calculation, the B-H table must be extrapolated to higher H fields, and in a manner that the steel's magnetization is non-decreasing in H and approaches saturation magnetization at high H fields. The B-field was set equal to $H + 4\pi M_{sat}$ for $H \geq 4$ kOe, and fitted smoothly in the interval from 1 to 4 kOe. A value of 22 kG was used for $4\pi M_{sat}$. For the range of currents used the computed fields do not depend on the detailed choice of points used in extending the B-H table.

The shape of lamination used here is that of the original design by J. Jackson and G. Danby. We note that the design by Jackson and Danby was chosen not only to minimize higher multipoles but also to allow the quadrupole magnets to track the Booster dipole magnets. The overall magnet design is much more subtle than indicated by the simplified POISSON picture presented in this note.

Minor simplifications were made in the computation. Small pin notches in the lamination arms, and water cooling spaces inside the conductors were omitted from the model. The insulation gaps between lamination arms were replaced by an increase of 0.006 cm in the length of each lamination quadrant arm; the computation was thereby carried out for a pole tip 2 radius of 8.2524 cm, instead of the nominal 8.255 cm specified in the Booster Design Manual (but within the mechanical tolerances of the design). These changes cause only minor perturbations in the results, and their adoption appreciably simplifies setting up of the model.

The POISSON family of codes is extensively described in the LANL Accelerator Code Group User's Guide [1] and Reference Manual [2]. The design, computation and symmetries of iron-dominated quadrupole magnets are described at length in an article by Fischer [3].

The quadrupole magnet is specified by an AUTOMESH file named BRQUAD.DAT;4. Only one octant is needed to describe the magnet. Six computational regions are used: to specify the magnet's outline, laminations, bolt-holes and coils; a seventh boundary region, a line boundary region, is used to impose a Dirichlet (parallel field) boundary condition along the pole's axis of symmetry and along the outer edge of the laminations.

2. Results

The calculated magnetic field configuration at 5500 Ampere current is shown in Fig. 1A. The magnet quadrant geometry is shown in Fig. 1B. The field gradient at the magnet's horizontal midplane is plotted in Fig. 2. The field gradient is nearly constant, for horizontal distances up to 8 cm from the magnetic axis.

The magnetic field at the center of an ideal quadrupole magnet is purely quadrupole, without higher harmonic terms. Since the pole width of the magnet as designed is limited by conductor windings, higher harmonic terms appear. The lowest term allowed by the 4-fold pole symmetry is the dodecapole. Its magnitude is a measure of the field quality, and the variation of the ratio of dodecapole to quadrupole coefficient as current changes is a measure of the invariance of the magnetic field shape with current. As part of the POISSON code solution of the magnet, the multipole coefficients are computed. These are listed, for several magnet currents, in Table 1.

The ratio of dodecapole to quadrupole coefficient, as a function of current, is plotted in Fig. 3. Here, we assume that the vertical magnetic field component at the horizontal midplane of the magnet is represented by the power series:

$$B_y(x) = B_0 + (B_1)x + (B_2)x^2 + (B3)x^3 + (B_4)x^4 + \dots,$$

when $y=0$, and the only non-zero coefficients belong to powers of x of the form $4n+1$, where n is a positive integer. One measure of the departure of the magnet field from linear variation with magnet current is the saturation, defined by:

$$\%\ \text{SATURATION (I)} = (100\%) \times \left[1 - \frac{B_1(\text{Iref})/\text{Iref}}{B_1(\text{I})/\text{I}} \right]$$

where $B_1(I)$ is the quadrupole harmonic coefficient at magnet current I, and the reference current, Iref, is chosen to be low enough that no part of the magnet core is in saturation. We choose our reference current to be 2500 Amperes. The fields in the core, at this current, are well below saturation, as shown by POISSON calculations. The value of percent saturation versus current is listed in Table 1, and is plotted in Fig. 5.

Maps of the magnetic field amplitude at selected regions of the laminated magnet core are also given. As a guide to reading these maps, an outline drawing of a magnet octant is provided (Fig. 4), giving logical coordinates at characteristic magnet positions. One notices that the steel approaches saturation locally, at the pole corners, as current increases to the upper end of its operating range. This leads to falloff of the ratio of dodecapole to quadrupole coefficients as current increases.

3. <u>Summary</u>

The Booster ring quadrupole magnets, as designed by J. Jackson and G. Danby, should have a uniform quadrupole field gradient across the midplane horizontal aperture of the magnet out to ± 8 cm of the magnetic axis, for currents up to 5700 Amperes.

The ratio of dodecapole to quadrupole coefficient decreases with increasing current. The computed multipole coefficients are listed in Table 1.

The percentage of saturation was calculated assuming lamination stacking fractions of 97% and 100%. For currents up to 5700 Amperes, the calculated percentage saturation was between 0 and -5 percent.

Acknowledgements

I wish to thank John Jackson and Gordon Danby for helpful comments relating to their design of the magnets.

I am indebted to Roy Thern for a critical discussion of the need for a properly extended permeability table in insuring the computational stability of the POISSON codes when operating near saturation, and to Ed Bleser for general discussions on multipole moments.

References

1. Los Alamos Accelerator Code Group. User's Guide For The Poisson/Superfish Group Of Codes. Los Alamos National Laboratory Report LA-UR-87-115, Los Alamos NM 87545, Jan. 1987.

2. Ibid. Reference Manual For The Poisson/Superfish Group Of Codes. LA-UR-87-126 . Jan 1, 1987.

3. G.E. Fisher, Iron Dominated Magnets. Article in AIP Conference Proceedings No. 153, M. Month and M. Dienes editors, American Institute of Physics, NY , 1987.

TABLE 1

B-Field Multipole Expansions

We list computed multipole coefficients of the series:

$$(1)\quad (B_y + jB_x) = \sum_n \{(B_n + jA_n)(\cos n\theta + j \sin n\theta)(r/1\text{cm})^{**}n\},$$

where the field components B_x and B_y are in Gauss.

For a symmetric quadrupole, all A_n vanish, and non-zero B_n are of the form $4n+1$ ($n=0,1,2, ...$).

In the horizontal midplane of the magnet ($\theta = 0$, $r=x$) the series reduces to:

$$(2)\quad B_y(x,y=0) = B_1x + B_5x^5 + B_9x^9 + B_{13}x^{13} + \dots .$$

Magnet Current (Ampere)	n	$\|B_1\|$ (Gauss)	Lamination Stacking Fraction	B_n/B_1	%Saturation
0200	1	036.657	1.00	1.0000	
	5			4.5415E-07	
	9			1.0105E-10	
	13			-1.8408E-14	
0600	1	110.244	1.00	1.0000	
	5			4.6189E-07	
	9			1.0099E-10	
	13			-1.8405E-14	
1100	1	202.300	1.00	1.0000	
	5			4.5906E-07	
	9			1.0135E-10	
	13			-1.8434E-14	
1500	1	275.968	1.00	1.0000	
	5			4.6035E-07	
	9			1.0138E-10	
	13			-1.8447E-14	

2500	1	460.040	1.00	1.0000	0.0000
	5			4.5655E-07	
	9			1.0131E-10	
	13			-1.8428E-14	
3500	1	643.690	1.00	1.0000	-0.0576
	5			4.5390E-07	
	9			1.0132E-10	
	13			-1.8428E-14	
4250	1	779.459	1.00	1.0000	-0.3347
	5			4.4612E-07	
	9			1.0040E-10	
	13			-1.8471E-14	
4750	1	864.321	1.00	1.0000	-1.129
	5			4.3089E-07	
	9			9.9495E-11	
	13			-1.8529E-14	
5000	1	902.465	1.00	1.0000	-1.952
	5			4.2302E-07	
	9			9.7507E-11	
	13			-1.8527E-14	
5250	1	940.084	1.00	1.0000	-2.768
	5			4.0926E-07	
	9			9.5817E-11	
	13			-1.8534E-14	
5500	1	977.638	1.00	1.0000	-3.524
	5			3.9118E-07	
	9			9.3494E-11	
	13			-1.8575E-14	
5700	1	1007.14	1.00	1.0000	-4.146
	5			3.6435E-07	
	9			8.9873E-11	
	13			-1.8634E-14	
2500	1	460.001	0.97	1.0000	-0.000
	5			4.5622E-07	
	9			1.0133E-10	
	13			-1.8425E-14	

3500	1	643.536	0.97	1.0000	-0.0729
	5			4.5335E-07	
	9			1.0128E-10	
	13			-1.8436E-14	
4250	1	778.320	0.97	1.0000	-0.475
	5			4.4145E-07	
	9			9.9815E-11	
	13			-1.8483E-14	
4750	1	859.957	0.97	1.0000	-1.635
	5			4.2547E-07	
	9			9.7806E-11	
	13			-1.8527E-14	
5000	1	897.493	0.97	1.0000	-2.507
	5			4.1451E-07	
	9			9.6488E-11	
	13			-1.8537E-14	
5250	1	935.018	0.97	1.0000	-3.314
	5			3.9749E-07	
	9			9.4322E-11	
	13			-1.8546E-14	
5500	1	971.755	0.97	1.0000	-4.142
	5			3.6725E-07	
	9			9.0295E-11	
	13			-1.9625E-14	
5700	1	1000.39	0.97	1.0000	-4.839
	5			3.3346E-07	
	9			8.5631E-11	
	13			-1.8714E-14	

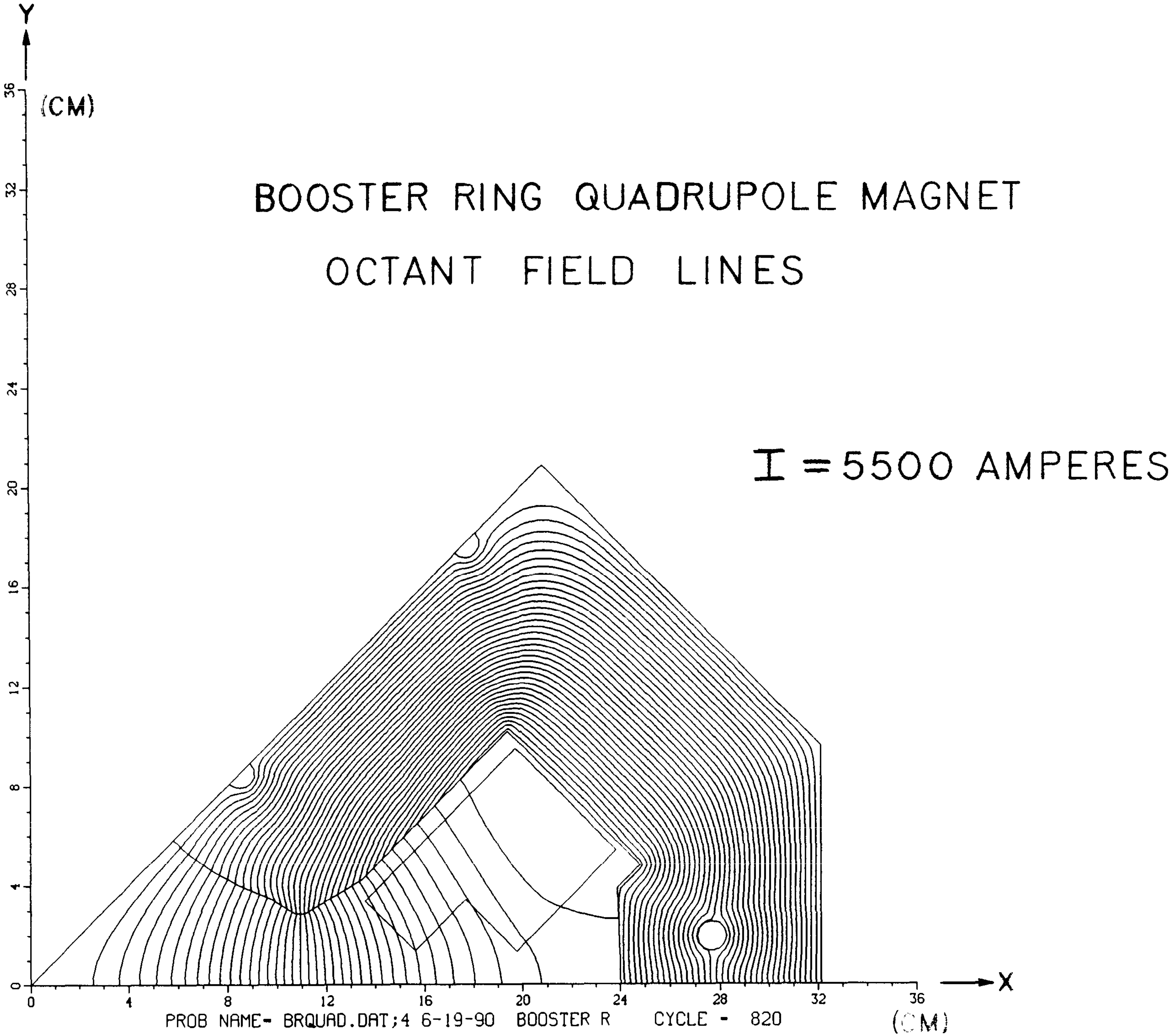

BOOSTER RING QUADRUPOLE MAGNET
OCTANT FIELD LINES
I = 5500 AMPERES
Y
(CM)
X
(CM)
0
4
8
12
16
20
24
28
32
36
PROB NAME- BRQUAD.DAT;4 6-19-90 BOOSTER R CYCLE - 820

FIG. 1A

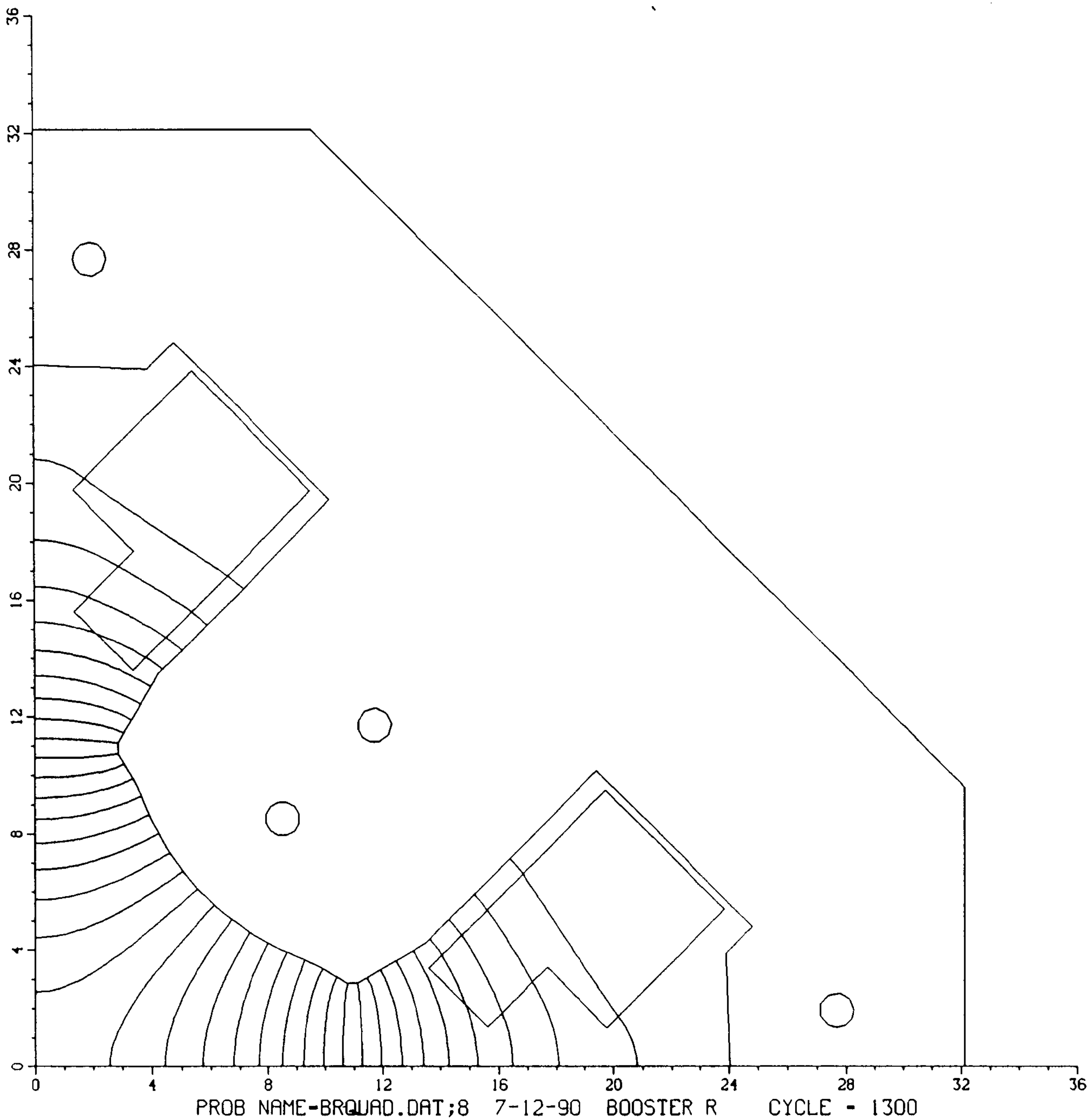
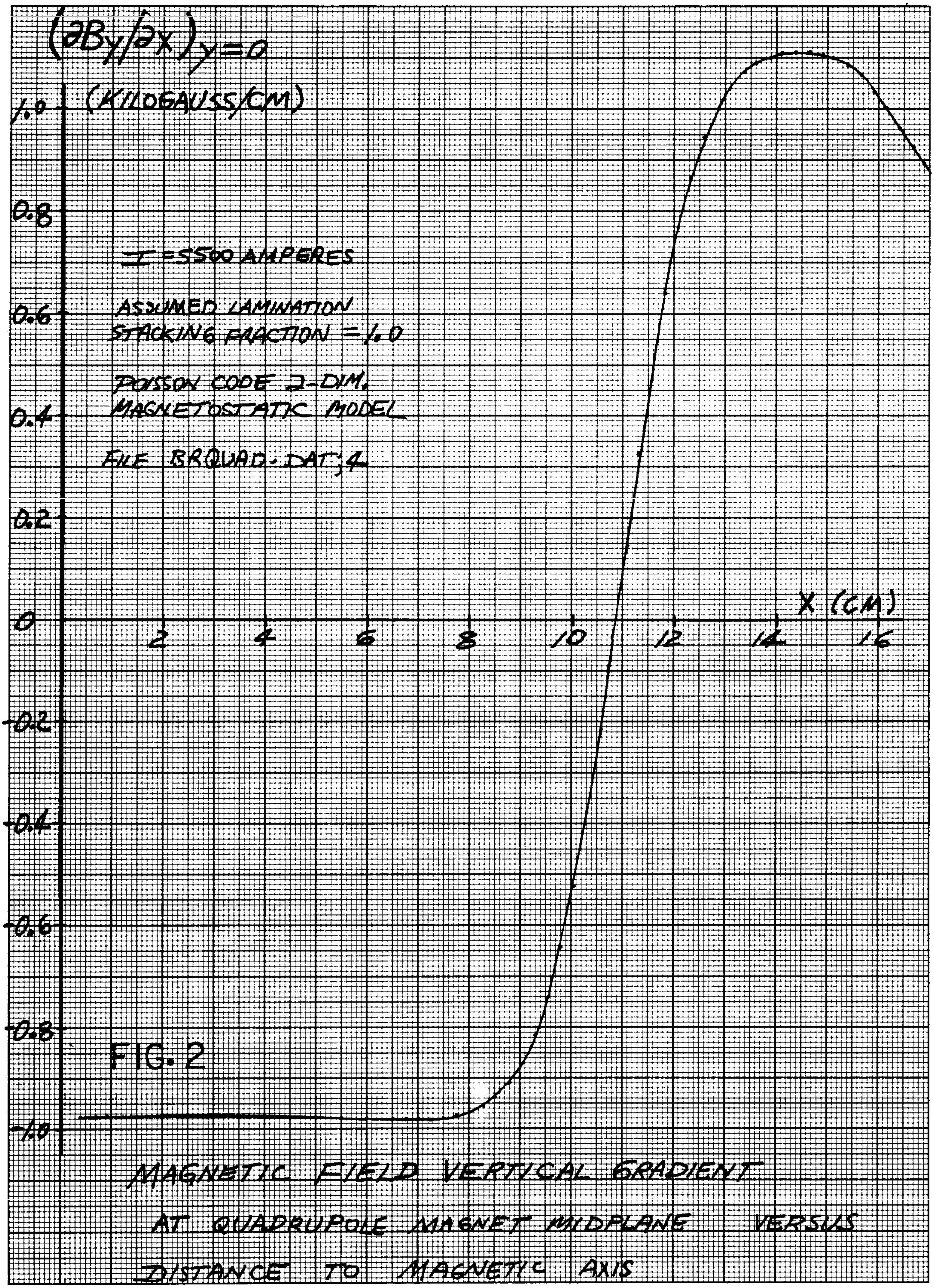

0
4
8
12
16
20
24
28
32
36
PROB NAME-BRQUAD.DAT;8 7-12-90 BOOSTER R CYCLE - 1300

FIG. 1B


$(\partial B_y/\partial x)_{y=0}$
(KILOGAUSS/CM)
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
X (CM)
I = 5500 AMPERES
ASSUMED LAMINATION
STACKING FRACTION = 1.0
POISSON CODE 2-DIM.
MAGNETOSTATIC MODEL
FILE BRQUAD.DAT;4
FIG. 2
MAGNETIC FIELD VERTICAL GRADIENT
AT QUADRUPOLE MAGNET MIDPLANE VERSUS
DISTANCE TO MAGNETIC AXIS

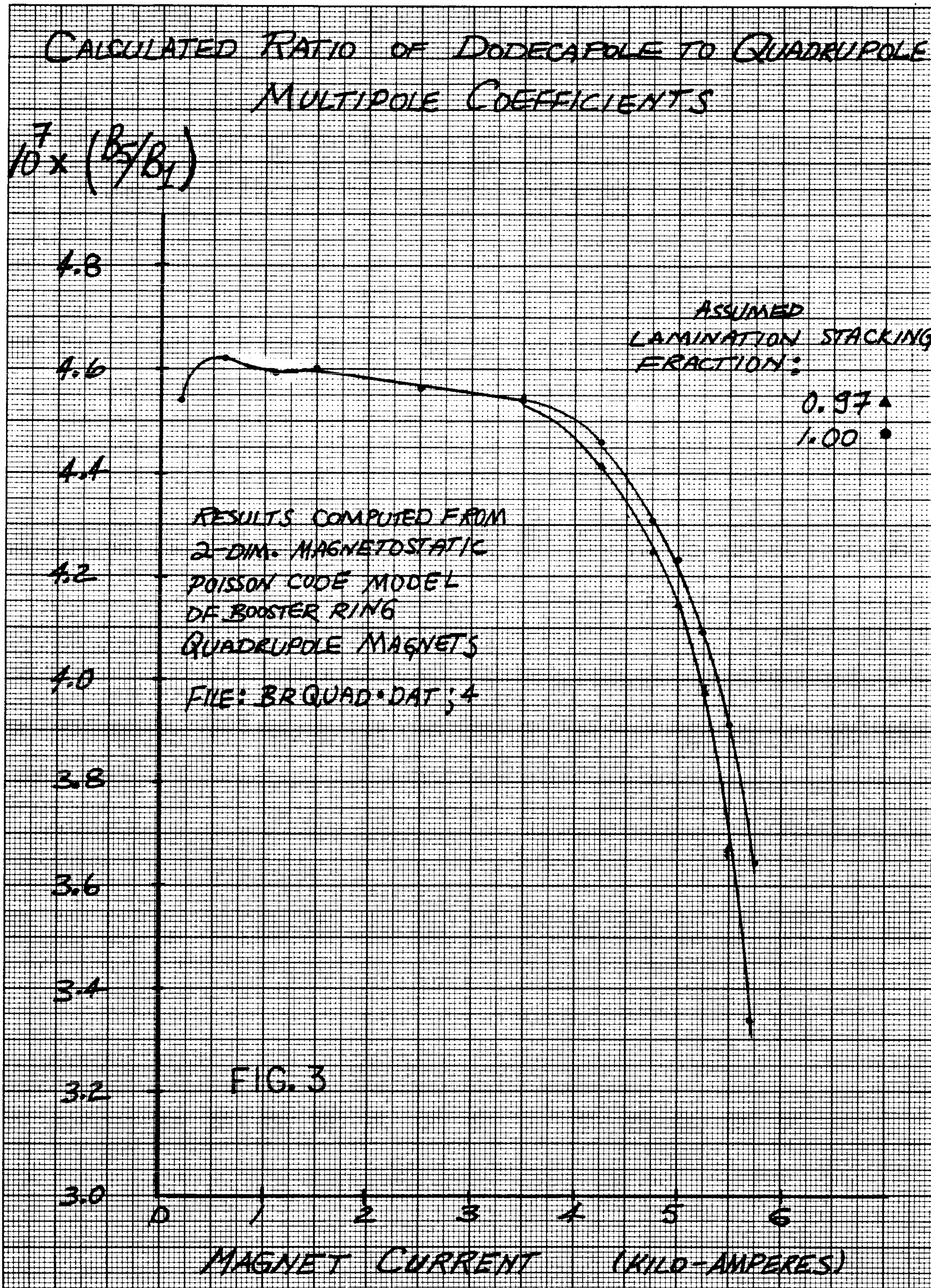

CALCULATED RATIO OF DODECAPOLE TO QUADRUPOLE MULTIPOLE COEFFICIENTS
$10^7 \times (B_5/B_1)$
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
ASSUMED LAMINATION STACKING FRACTION:
0.97 ▲
1.00 ●
RESULTS COMPUTED FROM 2-DIM. MAGNETOSTATIC POISSON CODE MODEL OF BOOSTER RING QUADRUPOLE MAGNETS
FILE: BRQUAD.DAT;4
0
1
2
3
4
5
6
MAGNET CURRENT (KILO-AMPERES)

FIG. 3

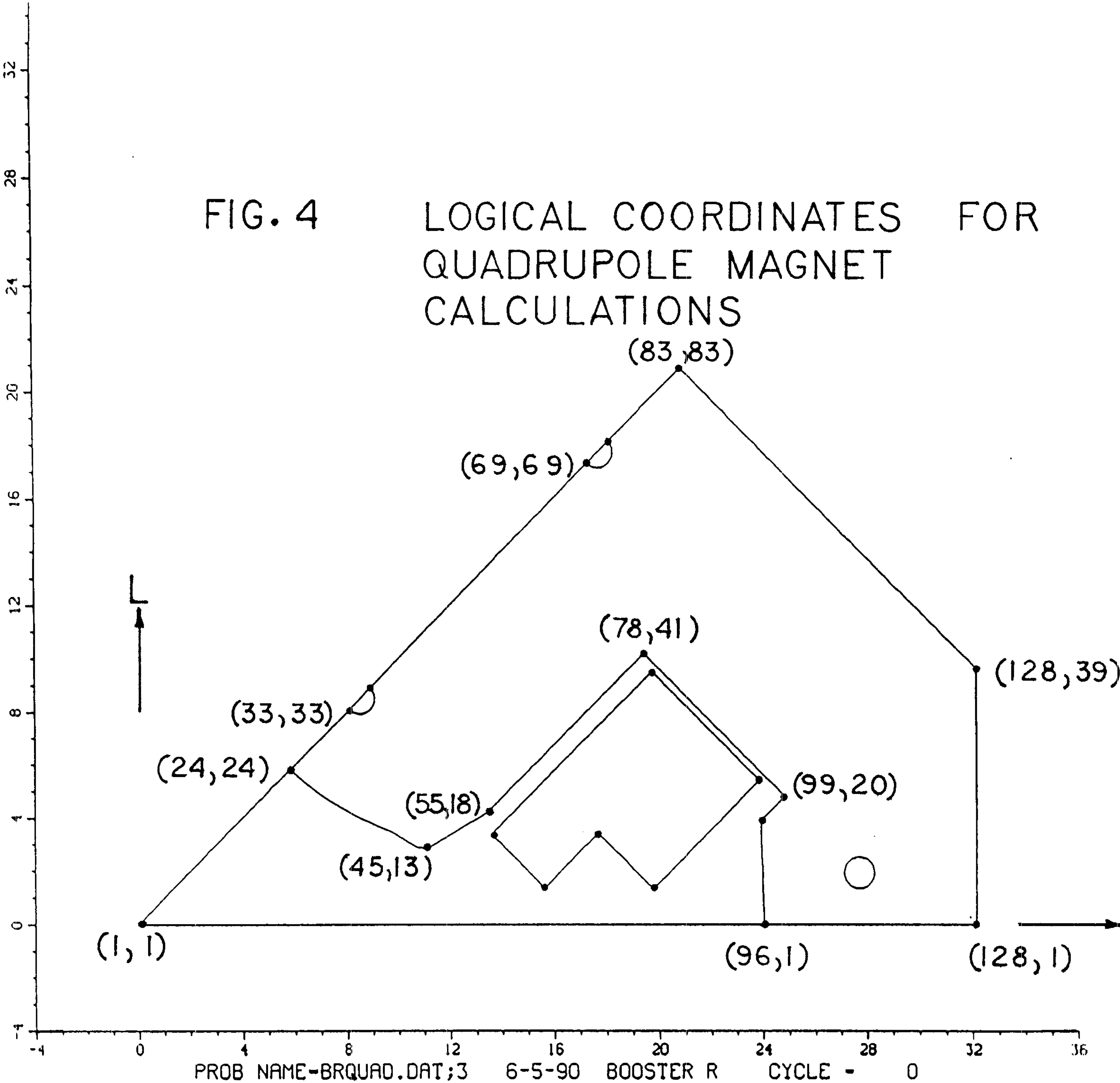


FIG. 4 LOGICAL COORDINATES FOR QUADRUPOLE MAGNET CALCULATIONS

	L	14.6	14.9	15.1	15.3	15.5	15.6	15.7	15.8	15.9	15.9	16.0	16.0	16.0	16.1	16.1	16.2	16.2	16.3	16.3	16.4
24	U	14.4	14.7	14.9	15.1	15.2	15.4	15.5	15.6	15.7	15.8	15.9	16.0	16.1	16.1	16.2	16.2	16.3	16.3	16.4	16.6
	L	14.0	14.3	14.6	14.9	15.1	15.3	15.4	15.5	15.6	15.7	15.8	15.9	15.9	16.0	16.0	16.1	16.1	16.2	16.3	
23	U	14.2	14.4	14.7	14.9	15.0	15.2	15.4	15.5	15.6	15.7	15.8	15.9	16.0	16.1	16.1	16.2	16.3	16.3		
	L	13.7	14.1	14.4	14.6	14.8	15.0	15.2	15.3	15.5	15.6	15.7	15.8	15.8	15.9	16.0	16.0	16.1	16.1		
22	U	13.7	14.0	14.2	14.4	14.6	14.8	15.0	15.1	15.3	15.4	15.6	15.7	15.8	15.9	16.0	16.1	16.1	16.3		
	L	13.2	13.5	13.8	14.1	14.4	14.6	14.8	15.0	15.1	15.2	15.4	15.5	15.6	15.7	15.8	15.9	16.0			
21	U	13.6	13.8	14.0	14.2	14.4	14.6	14.8	14.9	15.1	15.2	15.4	15.5	15.6	15.8	16.0	15.9				
	L	13.1	13.4	13.6	13.9	14.1	14.3	14.5	14.7	14.9	15.0	15.2	15.3	15.4	15.5	15.6	15.6				
20	U	13.3	13.5	13.7	13.9	14.1	14.2	14.4	14.5	14.7	14.8	14.9	15.1	15.3	15.4	15.5	16.0				
	L	12.9	13.1	13.3	13.5	13.7	13.9	14.1	14.3	14.5	14.6	14.8	14.9	15.0	15.2	15.4					
19	U	13.4	13.5	13.7	13.9	14.0	14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	15.3						
	L	13.0	13.1	13.3	13.4	13.6	13.8	14.0	14.1	14.3	14.4	14.5	14.6	14.6	15.0						
18	U	13.3	13.5	13.6	13.8	13.9	14.0	14.1	14.2	14.2	14.2	14.2	14.1	14.1	13.1						
	L	13.1	13.2	13.3	13.5	13.6	13.7	13.8	13.9	14.1	14.1	14.2	14.2	14.2							
17	U	13.5	13.8	14.0	14.2	14.2	14.3	14.3	14.3	14.3	14.3	14.2	14.2								
	L	13.6	13.8	13.9	14.0	14.1	14.1	14.1	14.1	14.2	14.2	14.2									
16	U	13.8	14.3	14.7	14.9	14.9	14.9	14.8	14.6	14.5	14.5	14.3									
	L	14.3	14.6	14.7	14.9	14.9	14.9	14.7	14.6	14.6	14.4										
15	U	15.3	15.7	15.9	16.0	15.9	15.6	15.3	15.2	14.7											
	L	15.8	16.0	15.9	16.0	16.0	16.0	15.7	15.3												
14	U	16.1	16.6	18.4	16.6	18.5	16.7	16.1	15.6												
	L		16.6	18.5	16.6	18.6	16.7														
13	U		17.6	19.5	19.4	17.7															
	L			19.7	19.8																
12	U				19.0																
	L																				
11	U																				
	L																				
10	U																				
	L																				
9	U																				
	L																				
8	U																				
	L																				
7	U																				
	L																				
6	U																				
	L																				
5	U																				
	L																				
4	U																				
	L																				
3	U																				
	L																				
2	U																				
	L																				
1	U																				

(K=45, L=13)

L

K

LOGICAL MAP OF $|\underline{B}|$ (KG) IN MAGNET STEEL NEAR A POLE CORNER

I = 5,500 AMPERES

LAMINATION STACKING FRACTION = 1.0

	L	18.6	18.7	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.8	18.9	18.9	19.0	19.1	20.1	19.5	15.6	14.8
42	U	18.6	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.9	18.9	18.9	19.0	19.0	19.2	19.4	20.0	18.2	18.1	15.7
	L	18.5	18.6	18.7	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.8	18.9	18.9	19.0	19.0	20.8	15.7	14.8
41	U	18.6	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.9	18.9	18.9	18.9	19.0	19.1	19.3	20.0	16.3	15.7	14.9
	L	18.4	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.8	18.9	18.9	19.0		15.6	14.8	14.4
40	U	18.6	18.6	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.9	18.9	18.9	18.9	19.0	19.0			15.6	14.8
	L	18.7	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.8	18.9	18.9				14.4
39	U	18.6	18.6	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.9	18.9	18.9	18.9	18.9	19.0					14.4
	L	18.5	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8	18.9						14.2
38	U	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.9	18.9	18.9	18.9						
	L	18.7	18.6	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.8						
37	U	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.9	18.9	18.9							
	L	18.5	18.6	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8								
36	U	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8	18.9								
	L	18.6	18.6	18.6	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8									
35	U	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8	18.8										
	L	18.5	18.6	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.7										
34	U	18.5	18.6	18.6	18.7	18.7	18.7	18.7	18.8	18.8	18.8										
	L	18.1	18.4	18.5	18.6	18.6	18.6	18.7	18.7	18.7											
33	U	18.6	18.6	18.6	18.7	18.7	18.7	18.7	18.8												
	L	18.6	18.5	18.5	18.6	18.6	18.6	18.7	18.7												
32	U	18.1	18.6	18.6	18.6	18.7	18.7	18.7	18.7												
	L	17.4	18.5	18.5	18.6	18.6	18.6	18.6													
31	U	18.5	18.6	18.6	18.6	18.7	18.7														
	L	18.3	18.5	18.5	18.6	18.6	18.6														
30	U	17.4	18.6	18.6	18.6	18.7	18.7														
	L	16.9	18.6	18.6	18.6	18.6															
29	U	18.2	18.6	18.6	18.6																
	L	17.6	18.5	18.5	18.6																
28	U	16.9	18.6	18.6	18.6																
	L	16.7	18.7	18.6																	
27	U	18.2	18.6																		
	L	17.6	18.5																		
26	U	17.3	18.6																		
	L	16.8																			
25	U																				
	L																				
24	U																				
	L																				
23	U																				
	L																				
22	U																				
	L																				
21	U																				
	L																				
20	U																				
	L																				
19	U																				
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18	U																				
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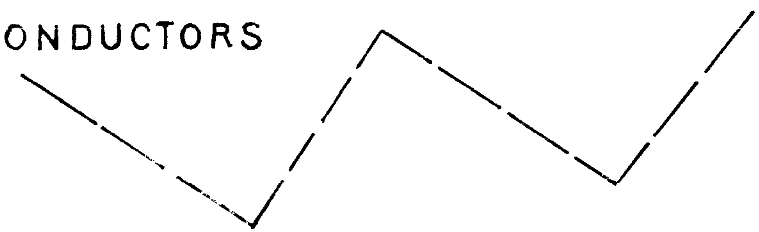
16	U																				
	L																				
15	U																				
	L																				
14	U																				
	L																				
13	U																				
	L																				
12	U																				
	L																				
11	U																				
	L																				
10	U																				

(78, 41)

POLE EDGE REGION ABOVE CONDUCTORS



	L	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.1
27	U	14.0	14.0	14.0	14.0	14.0	14.1	14.1	14.1	14.2
	L	14.0	14.0	14.0	14.0	14.0	14.1	14.1	14.1	14.2
26	U		14.0	14.0	14.0	14.1	14.1	14.2	14.2	14.3
	L			14.0	14.1	14.1	14.1	14.2	14.3	14.3
25	U			14.1	14.1	14.1	14.2	14.3	14.4	14.6
	L			14.1	14.2	14.2	14.3	14.4	14.5	14.6
24	U				14.1	14.2	14.3	14.4	14.6	14.7
	L					14.3	14.4	14.5	14.7	14.8
23	U					14.4	14.5	14.7	15.0	15.5
	L					14.6	14.8	14.9	15.0	15.2
22	U						14.5	15.0	15.2	16.1
	L							15.4	15.9	16.1
21	U							15.6	17.7	18.4
	L							15.7	16.7	17.7
20	U							(99, 20) →	19.8	19.3
	L								19.8	19.4
19	U							15.8	16.6	17.0
	L							15.6	17.5	17.9
18	U							15.3	15.8	15.9
	L						14.1	14.9	15.3	16.1
17	U					14.0	14.6	14.9	15.1	15.3
	L					12.8	13.8	14.5	14.9	15.5
16	U					12.4	13.7	14.4	14.8	15.0
	L					9.4	11.9	13.2	14.1	14.6
15	U				12.6	13.3	13.8	14.3	14.7	15.0
	L				12.6	12.7	12.6	13.1	13.7	14.2
14	U					14.0	14.1	14.2	14.5	14.8
	L					13.9	13.9	13.9	13.8	13.9
13	U				14.7	14.7	14.8	14.8	14.9	15.0
	L				14.7	14.7	14.7	14.7	14.7	14.6
12	U					15.2	15.3	15.3	15.3	15.4
	L					15.2	15.3	15.3	15.3	15.2
11	U				15.6	15.6	15.7	15.7	15.7	15.8
	L				15.6	15.6	15.7	15.7	15.7	15.7
10	U					15.9	15.9	15.9	16.0	16.0
	L					15.9	15.9	15.9	15.9	16.0
9	U				16.0	16.0	16.0	16.0	16.1	16.1
	L				16.0	16.0	16.0	16.1	16.1	16.1
8	U					16.0	16.0	16.0	16.0	16.1
	L					16.0	16.0	16.0	16.1	16.1
7	U					15.9	15.9	15.9	15.9	15.9
	L					15.9	15.9	15.9	15.9	15.9
6	U					15.6	15.6	15.6	15.6	15.6
	L					15.6	15.6	15.6	15.6	15.6
5	U					15.3	15.3	15.3	15.3	15.2
	L					15.3	15.3	15.3	15.3	15.2
4	U					14.9	14.9	14.9	14.9	14.8
	L					14.9	14.9	14.9	14.9	14.8
3	U					14.6	14.6	14.6	14.5	14.5
	L					14.6	14.6	14.6	14.5	14.4
2	U					14.4	14.4	14.4	14.4	14.3
	L					14.4	14.4	14.4	14.3	14.3
1	U					14.5	14.4	14.3	14.3	14.2

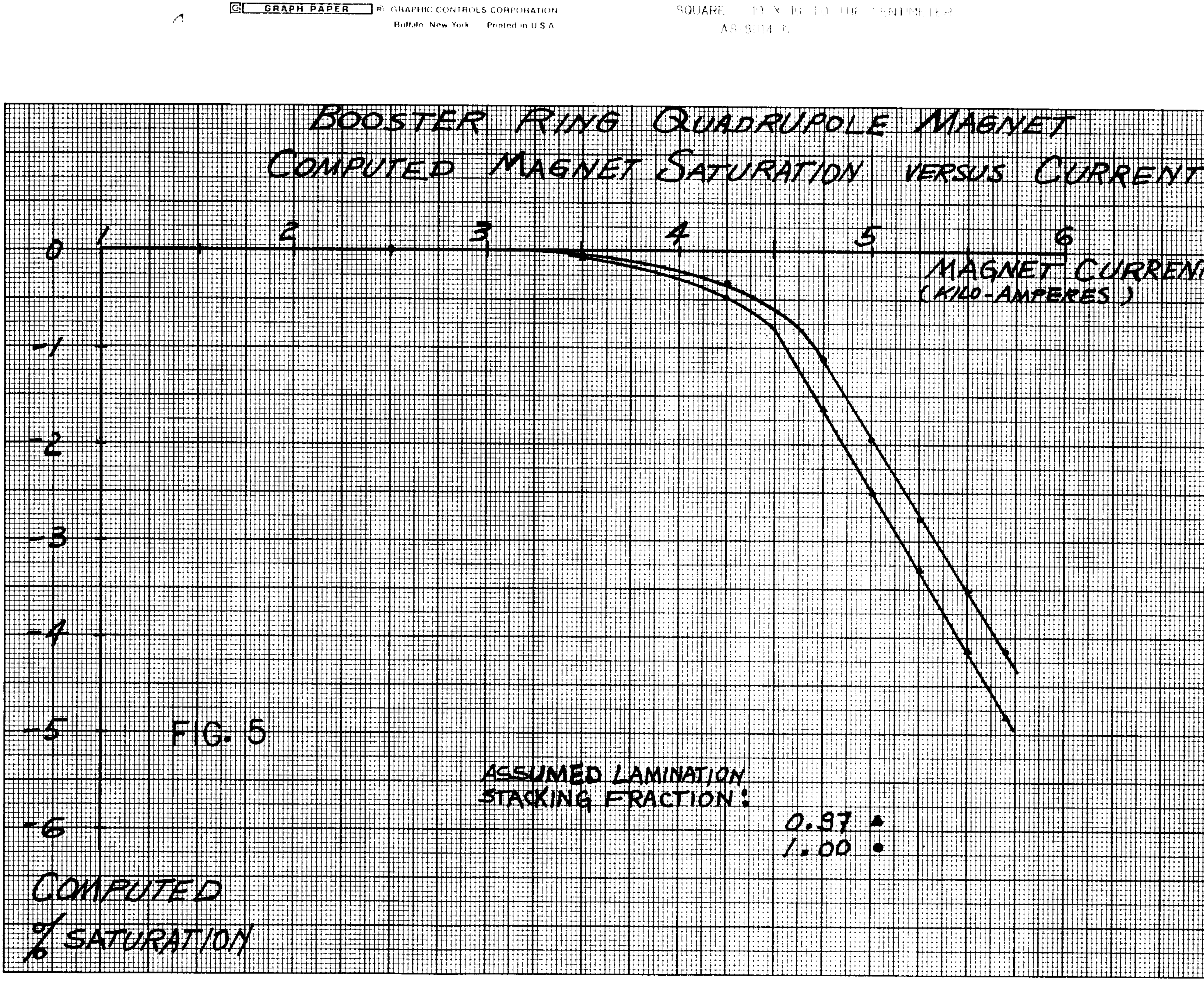

GRAPH PAPER
GRAPHIC CONTROLS CORPORATION
Buffalo, New York Printed in U.S.A.
BOOSTER RING QUADRUPOLE MAGNET
COMPUTED MAGNET SATURATION VERSUS CURRENT
1
2
3
4
5
6
MAGNET CURRENT
(KILO-AMPERES)
0
-1
-2
-3
-4
-5
-6
ASSUMED LAMINATION
STACKING FRACTION:
0.97
1.00
COMPUTED
% SATURATION

FIG. 5

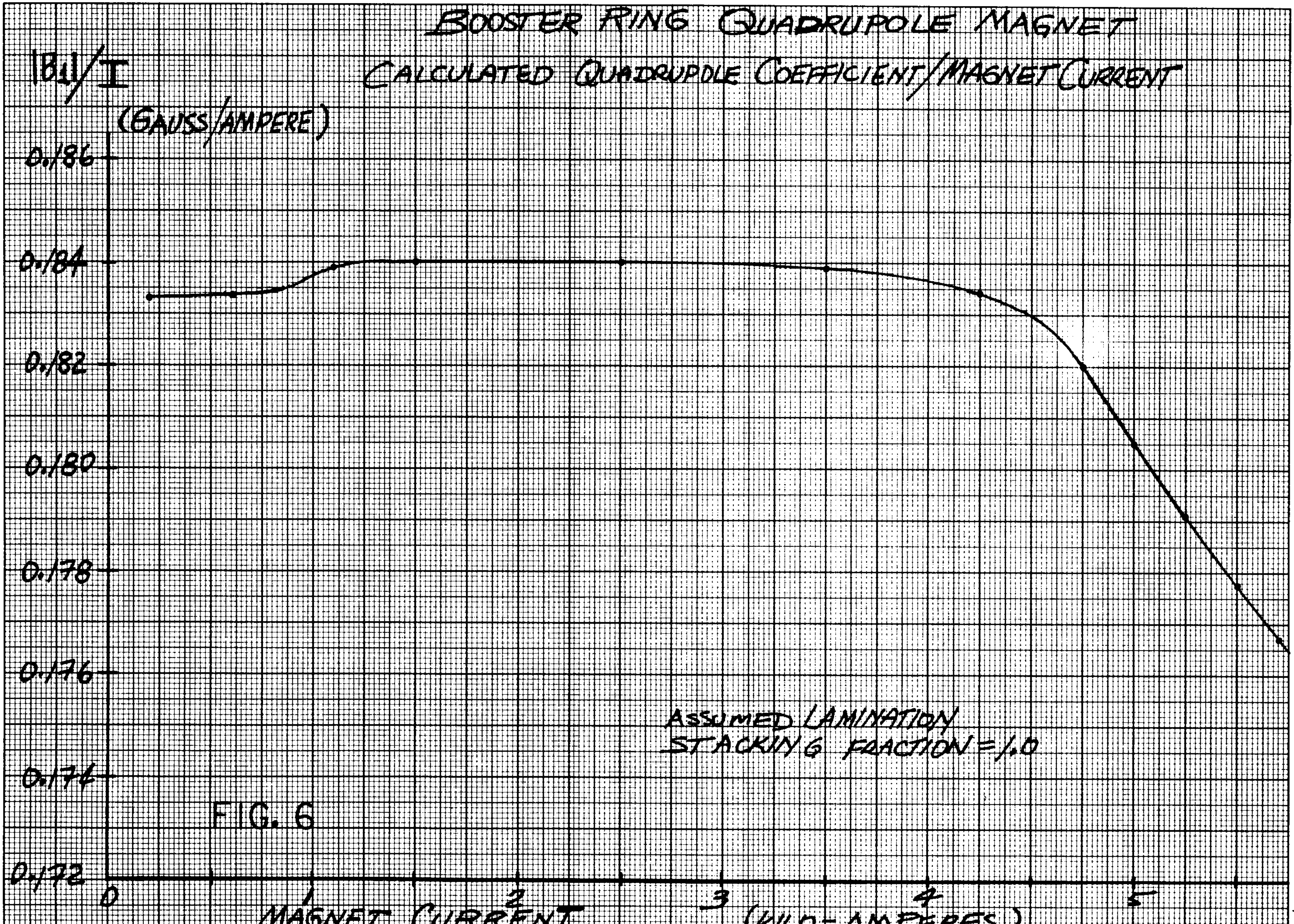

BOOSTER RING QUADRUPOLE MAGNET
CALCULATED QUADRUPOLE COEFFICIENT/MAGNET CURRENT
|B1|/I
(GAUSS/AMPERE)
0.186
0.184
0.182
0.180
0.178
0.176
0.174
0.172
0
1
2
3
4
5
MAGNET CURRENT
(KILO-AMPERES)
ASSUMED LAMINATION
STACKING FRACTION = 1.0

FIG. 6

MATERIAL NO. 4, STACK=1.000

U.S.S
A-36 STEEL
B-H TABLE

N	B-SQUARED	B(GAUSS)	GAMMA	MU	H(OERSTEAD)	D-GAM/D-B	D-GAM/D-BSQ
1	4.000000E+04	200.00	0.000500	2000.00	0.10	0.0000E+00	0.0000E+00
2	1.600000E+05	400.00	0.000500	2000.00	0.20	3.0303E-07	3.1898E-10
3	3.025000E+05	550.00	0.000545	1833.33	0.30	-3.1702E-07	-1.7136E-10
4	1.690000E+06	1300.00	0.000308	3250.00	0.40	-8.2418E-08	-2.4975E-11
5	4.000000E+06	2000.00	0.000250	4000.00	0.50	-3.6550E-08	-6.3017E-12
6	1.444000E+07	3800.00	0.000184	5428.57	0.70	-1.0754E-08	-1.0543E-12
7	4.096001E+07	6400.00	0.000156	6400.00	1.00	4.0064E-09	2.6016E-13
8	8.100000E+07	9000.00	0.000167	6000.00	1.50	1.8315E-08	9.4407E-13
9	1.081600E+08	10400.00	0.000192	5200.00	2.00	3.8633E-08	1.7886E-12
10	1.254400E+08	11200.00	0.000223	4480.00	2.50	3.3482E-08	1.4432E-12
11	1.440000E+08	12000.00	0.000250	4000.00	3.00	9.2801E-08	3.7571E-12
12	1.612900E+08	12700.00	0.000315	3175.00	4.00	1.2765E-07	4.9287E-12
13	1.742400E+08	13200.00	0.000379	2640.00	5.00	3.3980E-07	1.2679E-11
14	1.849600E+08	13600.00	0.000515	1942.86	7.00	5.8473E-07	2.0445E-11
15	2.250000E+08	15000.00	0.001333	750.00	20.00	1.7917E-06	5.7796E-11
16	2.560000E+08	16000.00	0.003125	320.00	50.00	3.1024E-06	9.4298E-11
17	2.856101E+08	16900.00	0.005917	169.00	100.00	4.7278E-06	1.2847E-10
18	3.960101E+08	19900.00	0.020101	49.75	400.00	3.1085E-05	7.6376E-10
19	4.326400E+08	20800.00	0.048077	20.80	1000.00	5.7442E-05	1.3990E-09<----(These Slopes are Estimated)

RECONSTRUCTION OF THE TABLE FOR MAT. NO. 4 WITH EQUAL INCREMENTS OF B-SQUARED

MAXIMUM B-SQUARED = 4.326400E+08, WITH EXTRAPOLATION OR TRUNCATION FOR HIGHER VALUES
(Truncation is used for MODE (PROB CON 6) = 1, and Extrapolation for MODE = 0)

B-SQUARED INCREMENT = 5.407946E+05

B-SQUARE GAMMA TABLE IS CONSTRUCTED USING CUBIC SPLINE IN B AND GAMMA.

MATERIAL NO. 4, STACK=1.000

N	B-SQUARED	B(GAUSS)	GAMMA	MU	H(OERSTEAD)	D-GAM/D-B	D-GAM/D-BSQ
1	4.000000E+04	200.00	0.000500	2000.00	0.10	0.0000E+00	0.0000E+00
2	1.600000E+05	400.00	0.000500	2000.00	0.20	3.0303E-07	3.1898E-10
3	3.025000E+05	550.00	0.000545	1833.33	0.30	-3.1702E-07	-1.7136E-10
4	1.690000E+06	1300.00	0.000308	3250.00	0.40	-8.2418E-08	-2.4975E-11
5	4.000000E+06	2000.00	0.000250	4000.00	0.50	-3.6550E-08	-6.3017E-12
6	1.444000E+07	3800.00	0.000184	5428.57	0.70	-1.0754E-08	-1.0543E-12
7	4.096001E+07	6400.00	0.000156	6400.00	1.00	4.0064E-09	2.6016E-13
8	8.100000E+07	9000.00	0.000167	6000.00	1.50	1.8315E-08	9.4407E-13
9	1.081600E+08	10400.00	0.000192	5200.00	2.00	3.8633E-08	1.7886E-12
10	1.254400E+08	11200.00	0.000223	4480.00	2.50	3.3482E-08	1.4432E-12
11	1.440000E+08	12000.00	0.000250	4000.00	3.00	9.2801E-08	3.7571E-12
12	1.612900E+08	12700.00	0.000315	3175.00	4.00	1.2765E-07	4.9287E-12
13	1.742400E+08	13200.00	0.000379	2640.00	5.00	3.3980E-07	1.2679E-11
14	1.849600E+08	13600.00	0.000515	1942.86	7.00	5.8473E-07	2.0445E-11
15	2.250000E+08	15000.00	0.001333	750.00	20.00	1.7917E-06	5.7796E-11
16	2.560000E+08	16000.00	0.003125	320.00	50.00	3.1024E-06	9.4298E-11
17	2.856101E+08	16900.00	0.005917	169.00	100.00	4.7278E-06	1.2847E-10
18	3.960101E+08	19900.00	0.020101	49.75	400.00	3.1085E-05	7.6376E-10
19	4.326400E+08	20800.00	0.048077	20.80	1000.00	3.4409E-05	8.0320E-10
20	4.857616E+08	22040.00	0.090744	11.02	2000.00	1.7477E-05	3.7962E-10
21	5.760000E+08	24000.00	0.125000	8.00	3000.00	2.1242E-05	4.2913E-10
22	6.502500E+08	25500.00	0.156863	6.38	4000.00	1.8882E-05	3.5965E-10
23	7.290001E+08	27000.00	0.185185	5.40	5000.00	2.9101E-05	5.2910E-10
24	7.840000E+08	28000.00	0.214286	4.67	6000.00	2.7094E-05	4.7532E-10
25	8.410001E+08	29000.00	0.241379	4.14	7000.00	2.5287E-05	4.2860E-10
26	9.000001E+08	30000.00	0.266667	3.75	8000.00	2.3656E-05	3.8780E-10
27	9.610000E+08	31000.00	0.290323	3.44	9000.00	2.2177E-05	3.5202E-10
28	1.024000E+09	32000.00	0.312500	3.20	10000.00	2.0833E-05	3.2051E-10
29	1.089000E+09	33000.00	0.333333	3.00	11000.00	1.9608E-05	2.9265E-10
30	1.156000E+09	34000.00	0.352941	2.83	12000.00	1.8487E-05	2.6793E-10
31	1.225000E+09	35000.00	0.371429	2.69	13000.00	1.7460E-05	2.4592E-10
32	1.296000E+09	36000.00	0.388889	2.57	14000.00	1.6516E-05	2.2625E-10
33	1.369000E+09	37000.00	0.405405	2.47	15000.00	1.5647E-05	2.0863E-10
34	1.444000E+09	38000.00	0.421053	2.38	16000.00	1.4845E-05	1.9279E-10
35	1.521000E+09	39000.00	0.435897	2.29	17000.00	1.4102E-05	1.7851E-10
36	1.600000E+09	40000.00	0.450000	2.22	18000.00	1.3360E-05	1.6423E-10<----(These Slopes are Estimated)

RECONSTRUCTION OF THE TABLE FOR MAT. NO. 4 WITH EQUAL INCREMENTS OF B-SQUARED

MAXIMUM B-SQUARED = 1.600000E+09, WITH EXTRAPOLATION OR TRUNCATION FOR HIGHER VALUES
(Truncation is used for MODE (PROB CON 6) = 1, and Extrapolation for MODE = 0)

B-SQUARED INCREMENT = 1.999980E+06

B-SQUARE GAMMA TABLE IS CONSTRUCTED USING CUBIC SPLINE IN B AND GAMMA.

LEAST SQUARES EDIT OF PROBLEM , CYCLE 820

SYMM QUA SYMMETRY TYPE

STORED ENERGY = 1.54841E+03 JOULES / METER OR RADIAN

XJFACT= 1.000000

MAGNET CURRENT = 5,500 AMPERES
27,500 AMPERE-TURNS
LAMINATION STACKING FRACTION = 1.0

K	L	A(VECTOR)	X (CM)	Y	BX(GAUSS)	BY(GAUSS)	BT(GAUSS)	DBY/DY(GAUSS/CM)	DBY/DX(GAUSS/CM)	AFIT
1	1	0.000000E+00	0.00000	0.00000	0.000	0.000	0.000	0.0000E+00	-1.0651E+03	-9.5E-01
2	1	2.626083E+01	0.20608	0.00000	0.000	-207.515	207.515	0.0000E+00	-1.0125E+03	3.9E+00
3	1	8.603213E+01	0.41217	0.00000	0.000	-400.126	400.126	0.0000E+00	-9.7728E+02	1.3E+00
4	1	2.174389E+02	0.66626	0.00000	0.000	-649.369	649.369	0.0000E+00	-9.7480E+02	-4.8E-01
5	1	4.144333E+02	0.92034	0.00000	0.000	-899.260	899.260	0.0000E+00	-9.7382E+02	-2.9E-01
6	1	6.746910E+02	1.17443	0.00000	0.000	-1148.074	1148.074	0.0000E+00	-9.7361E+02	-1.3E-01
7	1	9.979936E+02	1.42852	0.00000	0.000	-1396.539	1396.539	0.0000E+00	-9.7555E+02	-8.8E-02
8	1	1.384407E+03	1.68261	0.00000	0.000	-1644.957	1644.957	0.0000E+00	-9.7624E+02	-6.8E-02
9	1	1.833938E+03	1.93669	0.00000	0.000	-1893.364	1893.364	0.0000E+00	-9.7655E+02	-5.3E-02
10	1	2.346583E+03	2.19078	0.00000	0.000	-2141.772	2141.772	0.0000E+00	-9.7681E+02	-4.3E-02
11	1	2.922345E+03	2.44487	0.00000	0.000	-2390.186	2390.186	0.0000E+00	-9.7700E+02	-3.5E-02
12	1	3.561226E+03	2.69896	0.00000	0.000	-2638.605	2638.605	0.0000E+00	-9.7716E+02	-2.8E-02
13	1	4.263227E+03	2.95304	0.00000	0.000	-2887.037	2887.037	0.0000E+00	-9.7730E+02	-2.4E-02
14	1	5.028353E+03	3.20713	0.00000	0.000	-3135.480	3135.480	0.0000E+00	-9.7744E+02	-1.9E-02
15	1	5.856606E+03	3.46122	0.00000	0.000	-3383.946	3383.946	0.0000E+00	-9.7757E+02	-1.7E-02
16	1	6.747993E+03	3.71531	0.00000	0.000	-3632.430	3632.430	0.0000E+00	-9.7772E+02	-1.2E-02
17	1	7.702521E+03	3.96939	0.00000	0.000	-3880.943	3880.943	0.0000E+00	-9.7789E+02	-1.3E-02
18	1	8.720196E+03	4.22348	0.00000	0.000	-4129.495	4129.495	0.0000E+00	-9.7808E+02	-1.2E-02
19	1	9.801030E+03	4.47757	0.00000	0.000	-4378.089	4378.089	0.0000E+00	-9.7830E+02	-9.5E-03
20	1	1.094504E+04	4.73166	0.00000	0.000	-4626.744	4626.744	0.0000E+00	-9.7856E+02	-8.2E-03
21	1	1.215223E+04	4.98574	0.00000	0.000	-4875.464	4875.464	0.0000E+00	-9.7888E+02	-9.2E-03
22	1	1.342263E+04	5.23983	0.00000	0.000	-5124.268	5124.268	0.0000E+00	-9.7924E+02	-7.2E-03
23	1	1.475627E+04	5.49392	0.00000	0.000	-5373.176	5373.176	0.0000E+00	-9.7966E+02	-3.7E-03
24	1	1.615316E+04	5.74800	0.00000	0.000	-5622.197	5622.197	0.0000E+00	-9.8015E+02	-5.7E-03
25	1	1.761334E+04	6.00209	0.00000	0.000	-5871.346	5871.346	0.0000E+00	-9.8068E+02	-9.4E-03
26	1	1.913684E+04	6.25618	0.00000	0.000	-6120.629	6120.629	0.0000E+00	-9.8116E+02	-7.9E-03
27	1	2.072370E+04	6.51027	0.00000	0.000	-6370.035	6370.035	0.0000E+00	-9.8161E+02	-5.5E-03
28	1	2.237394E+04	6.76435	0.00000	0.000	-6619.545	6619.545	0.0000E+00	-9.8187E+02	-1.6E-02

29	1	2.408758E+04	7.01844	0.00000	0.000	-6869.079	6869.079	0.0000E+00	-9.8172E+02	-6.8E-03
30	1	2.586462E+04	7.27253	0.00000	0.000	-7118.490	7118.490	0.0000E+00	-9.8087E+02	-1.6E-02
31	1	2.770499E+04	7.52662	0.00000	0.000	-7367.557	7367.557	0.0000E+00	-9.7875E+02	-1.5E-02
32	1	2.960856E+04	7.78070	0.00000	0.000	-7615.865	7615.865	0.0000E+00	-9.7467E+02	-1.8E-02
33	1	3.157506E+04	8.03479	0.00000	0.000	-7862.793	7862.793	0.0000E+00	-9.6756E+02	-1.7E-02
34	1	3.360404E+04	8.28888	0.00000	0.000	-8107.389	8107.389	0.0000E+00	-9.5594E+02	-1.9E-02
35	1	3.569472E+04	8.54297	0.00000	0.000	-8348.275	8348.275	0.0000E+00	-9.3772E+02	-2.3E-02
36	1	3.784593E+04	8.79705	0.00000	0.000	-8583.442	8583.442	0.0000E+00	-9.1046E+02	-1.2E-02
37	1	4.005589E+04	9.05114	0.00000	0.000	-8810.214	8810.214	0.0000E+00	-8.7093E+02	-3.6E-02
38	1	4.232205E+04	9.30523	0.00000	0.000	-9025.058	9025.058	0.0000E+00	-8.1565E+02	-2.2E-02
39	1	4.464081E+04	9.55932	0.00000	0.000	-9223.496	9223.496	0.0000E+00	-7.4102E+02	-2.4E-02
40	1	4.700736E+04	9.81340	0.00000	0.000	-9400.216	9400.216	0.0000E+00	-6.4416E+02	-3.9E-02
41	1	4.941543E+04	10.06749	0.00000	0.000	-9549.336	9549.336	0.0000E+00	-5.2338E+02	-4.3E-02
42	1	5.185723E+04	10.32158	0.00000	0.000	-9664.736	9664.736	0.0000E+00	-3.7922E+02	-3.6E-02
43	1	5.432347E+04	10.57567	0.00000	0.000	-9740.857	9740.857	0.0000E+00	-2.1507E+02	-3.3E-02
44	1	5.680359E+04	10.82975	0.00000	0.000	-9773.337	9773.337	0.0000E+00	-3.7202E+01	-4.8E-02
45	1	5.928613E+04	11.08384	0.00000	0.000	-9759.727	9759.727	0.0000E+00	1.4603E+02	-4.1E-02
46	1	6.175931E+04	11.33793	0.00000	0.000	-9699.820	9699.820	0.0000E+00	3.2531E+02	-3.5E-02
47	1	6.421159E+04	11.59202	0.00000	0.000	-9595.772	9595.772	0.0000E+00	4.9198E+02	-1.2E-02
48	1	6.663224E+04	11.84610	0.00000	0.000	-9451.634	9451.634	0.0000E+00	6.3962E+02	-3.4E-02
49	1	6.901174E+04	12.10019	0.00000	0.000	-9272.828	9272.828	0.0000E+00	7.6437E+02	4.1E-03
50	1	7.134203E+04	12.35428	0.00000	0.000	-9065.368	9065.368	0.0000E+00	8.6518E+02	-2.5E-02
51	1	7.361661E+04	12.60837	0.00000	0.000	-8835.192	8835.192	0.0000E+00	9.4345E+02	-2.7E-02
52	1	7.583039E+04	12.86245	0.00000	0.000	-8587.762	8587.762	0.0000E+00	1.0017E+03	-2.6E-02
53	1	7.797962E+04	13.11654	0.00000	0.000	-8327.734	8327.734	0.0000E+00	1.0434E+03	-4.1E-02
54	1	8.006158E+04	13.37063	0.00000	0.000	-8058.876	8058.876	0.0000E+00	1.0720E+03	-3.5E-02
55	1	8.207442E+04	13.62471	0.00000	0.000	-7784.095	7784.095	0.0000E+00	1.0908E+03	-4.4E-02
56	1	8.401693E+04	13.87880	0.00000	0.000	-7505.540	7505.540	0.0000E+00	1.1023E+03	-6.2E-02
57	1	8.588835E+04	14.13289	0.00000	0.000	-7224.773	7224.773	0.0000E+00	1.1086E+03	-6.2E-02
58	1	8.768827E+04	14.38698	0.00000	0.000	-6942.916	6942.916	0.0000E+00	1.1114E+03	-5.7E-02
59	1	8.941652E+04	14.64106	0.00000	0.000	-6660.762	6660.762	0.0000E+00	1.1108E+03	-9.5E-02
60	1	9.107314E+04	14.89515	0.00000	0.000	-6379.218	6379.218	0.0000E+00	1.1071E+03	-6.9E-02
61	1	9.265840E+04	15.14924	0.00000	0.000	-6099.200	6099.200	0.0000E+00	1.0987E+03	-3.4E-02

62	1	9.417284E+04	15.40333	0.00000	0.000	-5822.017	5822.017	0.0000E+00	1.0844E+03	-4.6E-02
63	1	9.561738E+04	15.65741	0.00000	0.000	-5549.240	5549.240	0.0000E+00	1.0634E+03	-3.0E-02
64	1	9.699336E+04	15.91150	0.00000	0.000	-5282.653	5282.653	0.0000E+00	1.0355E+03	-2.0E-02
65	1	9.830256E+04	16.16559	0.00000	0.000	-5023.884	5023.884	0.0000E+00	1.0017E+03	-3.4E-02
66	1	9.954713E+04	16.41968	0.00000	0.000	-4774.096	4774.096	0.0000E+00	9.6492E+02	-8.9E-03
67	1	1.007294E+05	16.67376	0.00000	0.000	-4533.826	4533.826	0.0000E+00	9.2722E+02	-1.0E-02
68	1	1.018519E+05	16.92785	0.00000	0.000	-4303.035	4303.035	0.0000E+00	8.9105E+02	-2.0E-03
69	1	1.029169E+05	17.18194	0.00000	0.000	-4080.990	4080.990	0.0000E+00	8.5835E+02	-3.8E-02
70	1	1.039264E+05	17.43603	0.00000	0.000	-3866.821	3866.821	0.0000E+00	8.2975E+02	-1.3E-02
71	1	1.048824E+05	17.69011	0.00000	0.000	-3659.324	3659.324	0.0000E+00	8.0575E+02	-1.0E-01
72	1	1.057864E+05	17.94420	0.00000	0.000	-3457.276	3457.276	0.0000E+00	7.8691E+02	-4.9E-02
73	1	1.066397E+05	18.19829	0.00000	0.000	-3259.538	3259.538	0.0000E+00	7.7248E+02	-9.1E-02
74	1	1.074431E+05	18.45238	0.00000	0.000	-3064.855	3064.855	0.0000E+00	7.6262E+02	-5.5E-02
75	1	1.081974E+05	18.70646	0.00000	0.000	-2872.397	2872.397	0.0000E+00	7.5562E+02	-8.7E-02
76	1	1.089029E+05	18.96055	0.00000	0.000	-2681.386	2681.386	0.0000E+00	7.5070E+02	-4.1E-02
77	1	1.095601E+05	19.21464	0.00000	0.000	-2491.574	2491.574	0.0000E+00	7.4524E+02	-1.1E-01
78	1	1.101692E+05	19.46873	0.00000	0.000	-2303.440	2303.440	0.0000E+00	7.3716E+02	-5.6E-02
79	1	1.107308E+05	19.72281	0.00000	0.000	-2117.832	2117.832	0.0000E+00	7.2387E+02	3.3E-03
80	1	1.112458E+05	19.97690	0.00000	0.000	-1936.348	1936.348	0.0000E+00	7.0355E+02	1.5E-02
81	1	1.117154E+05	20.23099	0.00000	0.000	-1760.861	1760.861	0.0000E+00	6.7653E+02	1.2E-02
82	1	1.121413E+05	20.48507	0.00000	0.000	-1592.882	1592.882	0.0000E+00	6.4475E+02	2.1E-02
83	1	1.125256E+05	20.73916	0.00000	0.000	-1433.348	1433.348	0.0000E+00	6.1064E+02	-2.4E-02
84	1	1.128704E+05	20.99325	0.00000	0.000	-1282.554	1282.554	0.0000E+00	5.7650E+02	2.6E-02
85	1	1.131780E+05	21.24734	0.00000	0.000	-1140.326	1140.326	0.0000E+00	5.4355E+02	-1.9E-02
86	1	1.134506E+05	21.50142	0.00000	0.000	-1006.209	1006.209	0.0000E+00	5.1253E+02	-5.0E-02
87	1	1.136900E+05	21.75551	0.00000	0.000	-879.709	879.709	0.0000E+00	4.8432E+02	-2.0E-02
88	1	1.138982E+05	22.00960	0.00000	0.000	-760.069	760.069	0.0000E+00	4.5847E+02	-3.1E-02
89	1	1.140768E+05	22.26369	0.00000	0.000	-646.674	646.674	0.0000E+00	4.3545E+02	-1.2E-02
90	1	1.142273E+05	22.51777	0.00000	0.000	-538.896	538.896	0.0000E+00	4.1461E+02	-2.7E-02
91	1	1.143510E+05	22.77186	0.00000	0.000	-436.158	436.158	0.0000E+00	3.9608E+02	-1.9E-02
92	1	1.144492E+05	23.02595	0.00000	0.000	-337.838	337.838	0.0000E+00	3.7944E+02	-7.7E-02
93	1	1.145230E+05	23.28004	0.00000	0.000	-243.672	243.672	0.0000E+00	3.6430E+02	-1.3E-01
94	1	1.145732E+05	23.53412	0.00000	0.000	-153.583	153.583	0.0000E+00	3.4853E+02	-1.6E-01