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ENGINEERING NOTE

CODE	SERIAL	PAGE
MD 1111	M5827	1 OF 11

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PROGRAM — PROJECT — JOB
HIGH-FIELD MAGNET DEVELOPMENT
ANALYSIS

TITLE
PARAMETER STUDY: HORIZONTAL-BLOCK DIPOLES

In this report we consider the effects of some of the variables associated with a horizontal current block dipole magnet upon field quality and upon the field per ampere-turn, and other stuff.

The initial configurations were approximations to intersecting-ellipse configurations generated as described briefly later in this report, and in more detail in Ref. 1.

The position of the lowermost block was held fixed; the other blocks were allowed to move horizontally in such a way as to make certain higher-order multipole coefficients of the field zero. For a six-block configuration, for example, the upper five blocks were moved, making multipole coefficients of order 3, 5, 7, 9, and 11 exactly zero. (Except for one case; see note later.)

The intersecting-ellipse approximation was generated as follows (see Fig. 1):

An "aperture ellipse" is defined by specification of its semi-width R and its aspect ratio (width/height) Ar. The outside radius D is specified. The dimensions and positions

of a pair of "coil ellipses" are determined which match the radius of curvature of the aperture ellipse at their common points. The overall semi-height of the stack of blocks is specified along with the number of blocks. (The blocks are of equal height.) The area of the block is made equal to the corresponding area between the coil ellipses. The horizontal positions of the blocks is determined by a procedure that is too messy to describe here, but which is described in Eng. Note M5826

The parameters for the "base case" are as follows:

Semi-width of aperture ellipse = 100 mm
Aspect ratio of aperture ellipse = 1
Overall semi-width = 200 mm
Stack height = coil ellipse semi-height
Current density = 300 A/sq.mm
Number of layers = 4
Maximum filament spacing = 20 mm *

Except as otherwise stated, the above parameters apply to all cases investigated.

In the tables of results, the left column is the multipole-coefficient order. The other columns are C_n/C_1, where C_n is the field magnitude associated with the n-th multipole coefficient at a reference radius of 75 mm. (n is the corresponding number of pole pairs.)

A "figure of merit" is defined as the field at the origin produced by the coil divided by that produced by a thin cosine-theta winding having the same total ampere turns and a radius equal to that of the innermost block corner.

* for calculating the multipole coefficients of the field, each block is represented by a group of current filaments.

The calculations were performed for a coil without an iron shield. A shield having a circular inner boundary produces a much greater increase in the absolute value of lower-order m'pole coefficients than of the higher-order ones, and so the relative values of the higher order ones are reduced by as much as a factor of 1/IEF, where IEF is

$$IEF = \frac{\text{aperture field with iron shield}}{\text{" " without " "}},$$

at the very most, a factor of 0.5 for a thin coil with a close-fitting, unsaturated shield.

The results are summarized as follows:

1. Increasing the thickness of the coil reduces the field aberrations in rough proportion to the coil thickness, and reduces the figure of merit in rough proportion to the coil mean radius.

2. Changing the stack height affects the field quality in what appears to be an unsystematic way. However there might be an optimum. Increasing the height reduces the figure of merit.

3. Increasing the height of the aperture (decreasing the aspect ratio) improves the field quality and reduces the figure of merit

4. Increasing the number of blocks improves the field quality about a factor of 3 for each block added, and increases the figure of merit.

5. Cutting the maximum filament spacing in half has no significant effect on the calculated values of the m'pole coefficients (but increases the running time by a factor of 4.

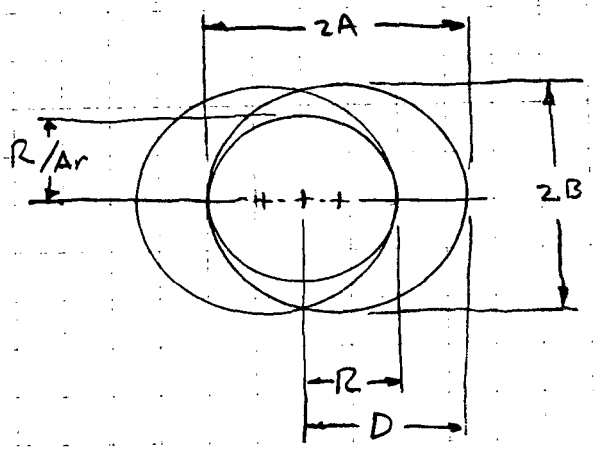

Fig 1.
(Sorry, I don't have any larger ellipse templates)

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Prob. No.	Ar	D	~B	Dtot	Nd	Smax	
1	1	200	122.5 →		4	10	
2	"	"	" →		"	20	
3	.9	"	136.1 →		"	"	
4	.8	"	153.1 →		"	"	
5	1	"	122.5	130	"	"	
6	1	"	"	135	"	"	
7	1	"	"	140	"	"	Did not converge
8	1	250	132.3 →		"	"	
9	1	300	141.4 →		"	"	
10	1	200	122.5 →		3	"	
11	1	300	141.4 →		3	"	
12	1	200	122.5 →		5	"	
13	1	200	122.5 →		6	"	
14	1	300	141.4 →		6	"	
15	.7	200	175.0 →		4	"	

Effect of:	Compare prob. nos...
Filament spacing, Smax	1, 2
Aperture ellipse asp. ratio, Ar	2, 3, 4, 15
Outside radius of ellipse, D	2, 8, 9; 10, 11; 13, 14
Stack height, Dtot	2, 5, 6, 7
No. of blocks	10, 2, 12, 13; 11, 9, 14

Note: Problem 14 would not converge for 5 variable blocks (Prob. 14c), but did converge for:
Upper four blocks variable (Prob. 14b)
Upper three blocks variable (Prob. 14a)

R = 100 mm
Curden = 300 A/mm²
Riron = ∞

EFFECT OF OUTSIDE RADIUS OF ELLIPSE

No. of blocks = 3

Case no	10	11
Outside radius (mm)	200	300
Fig. of merit	.684	.535
1	1.00000000	1.00000000
3	.00000000	.00000000
5	.00000000	-.00000000
7	.00204461	-.00282200
9	-.00525419	.00207801
11	.00324324	.00183574
13	.00120949	-.00028987
15	-.00040052	-.00027024
17	.00012469	-.00020637

No. of blocks = 4

Case no.	2	8	9
Outside radius (mm)	200	250	300
Fig. of merit	.693	.612	.558
1	1.00000000	1.00000000	1.00000000
3	-.00000000	.00000000	-.00000000
5	-.00000000	-.00000001	-.00000000
7	-.00000000	-.00000001	.00000000
9	.00040586	.00088683	.00020018
11	.00055786	-.00087815	-.00079800
13	-.00115258	-.00016491	.00048434
15	.00034254	.00056329	.00037925
17	.00030776	.00009058	-.00004814

No. of blocks = 6

Case no.	13	14a	14b
Outside rad. (mm)	200	300	300
Fig. of merit	.712	.619	.620
1	1.00000000	1.00000000	1.00000000
3	.00000000	.00000000	.00000000
5	.00000000	.00000000	.00000000
7	-.00000000	-.00000000	.00000000
9	-.00000000	.00000300	-.00000000
11	-.00000000	.00003839	.00004081
13	.00030889	-.00005816	-.00005950
15	-.00007574	.00006502	.00006528
17	-.00006622	-.00000200	-.00000193

EFFECT OF NUMBER OF BLOCKS

Outside radius = 200 mm

Case no.	10	2	12	13
No. of blocks	3	4	5	6
Fig of merit	.684	.693	.702	.712
1	1.00000000	1.00000000	1.00000000	1.00000000
3	.00000000	-.00000000	.00000000	.00000000
5	.00000000	-.00000000	-.00000000	.00000000
7	.00204461	-.00000000	-.00000000	-.00000000
9	-.00525419	.00040586	-.00000000	-.00000000
11	.00324324	.00055786	-.00050852	-.00000000
13	.00120949	-.00115258	.00006275	.00030889
15	-.00040052	.00034254	.00031014	-.00007574
17	.00012469	.00030776	-.00024212	-.00006622

Outside radius = 300 mm

Case no.	11	9	14a	14b
No of blocks	3	4	6	6
Fig. of merit	.535	.558	.620	.621
1	1.00000000	1.00000000	1.00000000	1.00000000
3	.00000000	-.00000000	.00000000	.00000000
5	-.00000000	-.00000000	.00000000	.00000000
7	-.00282200	.00000000	-.00000000	.00000000
9	.00207801	.00020018	.00000300	-.00000000
11	.00183574	-.00079800	.00003839	.00004081
13	-.00028987	.00048434	-.00005816	-.00005950
15	-.00027024	.00037925	.00006502	.00006528
17	-.00020637	-.00004814	-.00000200	-.00000193

EFFECT OF STACK HEIGHT

Case no.	2	5	6
Stack height (mm)	122.5	130	135
Fig. of merit	.693	.677	.664

1	1.00000000	1.00000000	1.00000000
3	-.00000000	.00000000	.00000000
5	-.00000000	-.00000000	.00000000
7	-.00000000	-.00000000	.00000000
9	.00040586	.00056483	.00012979
11	.00055786	-.00081834	-.00154745
13	-.00115258	-.00046765	.00039068
15	.00034254	.00079596	.00104228
17	.00030776	.00023154	.00001157

EFFECT OF APERTURE-ELLIPSE ASPECT RATIO

Case no.	2	3	4	15
Aspect ratio	1.0	0.9	0.8	0.7
Fig. of merit	.693	.684	.655	.621

1	1.00000000	1.00000000	1.00000000	1.00000000
3	-.00000000	-.00000000	-.00000000	.00000000
5	-.00000000	-.00000000	-.00000000	-.00000000
7	-.00000000	-.00000000	-.00000000	.00000000
9	.00040586	.00030341	.00004394	.00006875
11	.00055786	-.00021447	-.00005267	.00020570
13	-.00115258	-.00019396	.00024185	.00022126
15	.00034254	.00037325	.00019683	.00003913
17	.00030776	.00011025	-.00001314	-.00003487

EFFECT OF NUMBER OF FILAMENTS

Case no.	1	2
Filament spacing (mm)	10	20
No. of filaments	160	40
Fig. of merit	.689	.693

1	1.00000000	1.00000000
3	.00000000	-.00000000
5	.00000000	-.00000000
7	-.00000000	-.00000000
9	.00042853	.00040586
11	.00043059	.00055786
13	-.00112306	-.00115258
15	.00040813	.00034254
17	.00032222	.00030776

① Case No	② Coil cross section sq. mm	③ Field in aperture T	④ Min radius mm	⑤ Max radius mm	⑥ FM $\frac{10^4}{2\pi}\frac{③④}{300②}$
1	12017	17.063	91.49	200.77	.689
2	12017	17.167	91.47	200.77	.693
3	13352	18.057	95.34	201.32	.684
4	15021	19.169	96.81	203.84	.655
5	12017	16.922	90.60	200.87	.677
6	12017	16.838	89.38	200.93	.664
7	Did not converge				
8	19218	24.379	90.93	250.35	.612
9	27057	31.109	91.56	299.99	.558
10	12017	17.179	90.22	201.36	.684
11	27057	31.349	87.10	299.96	.535
12	12017	17.022	93.37	200.50	.702
13	12017	16.960	95.05	200.35	.712
14a	25057	31.074	94.15	300.00	.619
14b	25057	31.078	94.16	300.00	.620
15	17167	20.425	98.42	213.14	.621

Figure of merit FM

$$= \frac{B_0 r_{in}}{\frac{\mu_0}{2}(NI)}$$

SI units

$$= \frac{B_0 r_{in}}{2\pi JA} 10^7$$

(B_0: T, r_{in}: m, J: $\frac{A}{m^2}$, A: m^2)

$$= \frac{B_0 r_{in}}{2\pi JA} 10^4$$

(B_0: T, r_{in}: mm, J: $\frac{A}{mm^2}$, A: mm^2)

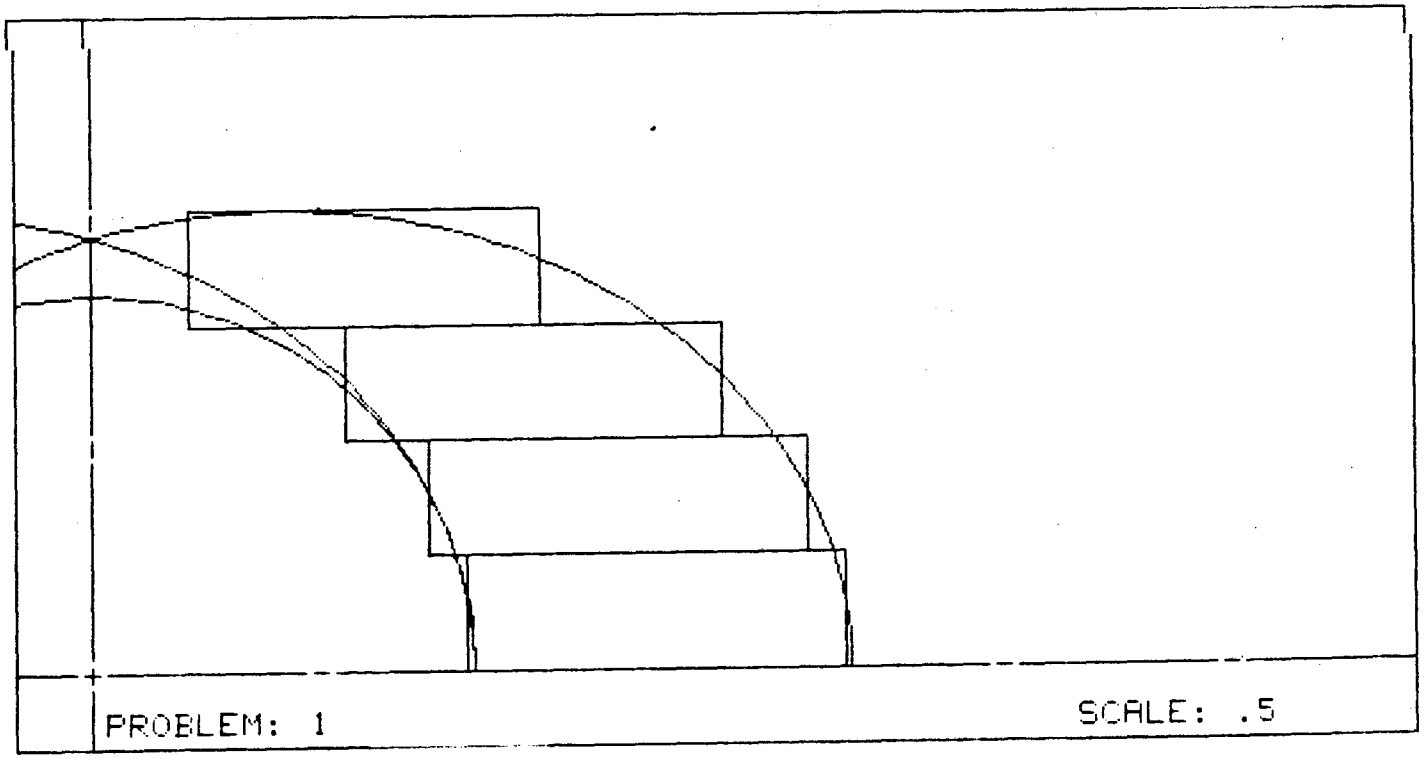
TYPICAL PRINTOUT (Case 1)

```
PROGRAM USED: DERIVED FROM ELIPS1, DISC 8
PROBLEM:                1
APERTURE RADIUS                              R =   100
APERTURE ASPECT RATIO, WIDTH/HEIGHT         Ar=   1
APERTURE RAD. OF CURV. ON X-AXIS          Rcurv=  100
RADIUS TO OUTSIDE OF COIL                    D =   200
COIL THICKNESS                         E = D-R =   100
SEMI MAJOR AXIS                              A =   150
SEMI MINOR AXIS                              B =   122.474487139
HORIZONTAL OFFSET OF VERT. AXIS              C =   50
VERTICAL COORDINATE OF INTERSECTION
   OF ELLIPSES WITH VERT. AXIS              Ym =   115.470053838
OVERALL HEIGHT OF STACK                   DTOT =   122.474487139
NUMBER OF LAYERS                            Nd =   4
```

Dimensions as generated from intersecting ellipses (dimensions in mm)

I	X1	X2	X2-X1	Y1	Y2	CASE
1	98.423	198.423	100.000	0.000	30.619	1
2	88.561	188.561	100.000	30.619	61.237	1
3	66.259	166.259	100.000	61.237	91.856	1
4	25.533	117.997	92.464	91.856	122.474	4

```
MIN. RADIUS =  90.22314  FOR BLOCK  3
MAX. RADIUS = 200.77100  FOR BLOCK  1
TOTAL AREA =          12016.7053714
TOTAL AREA =          12016.7053713
```



DIMENSIONS AFTER OPTIMIZATION:

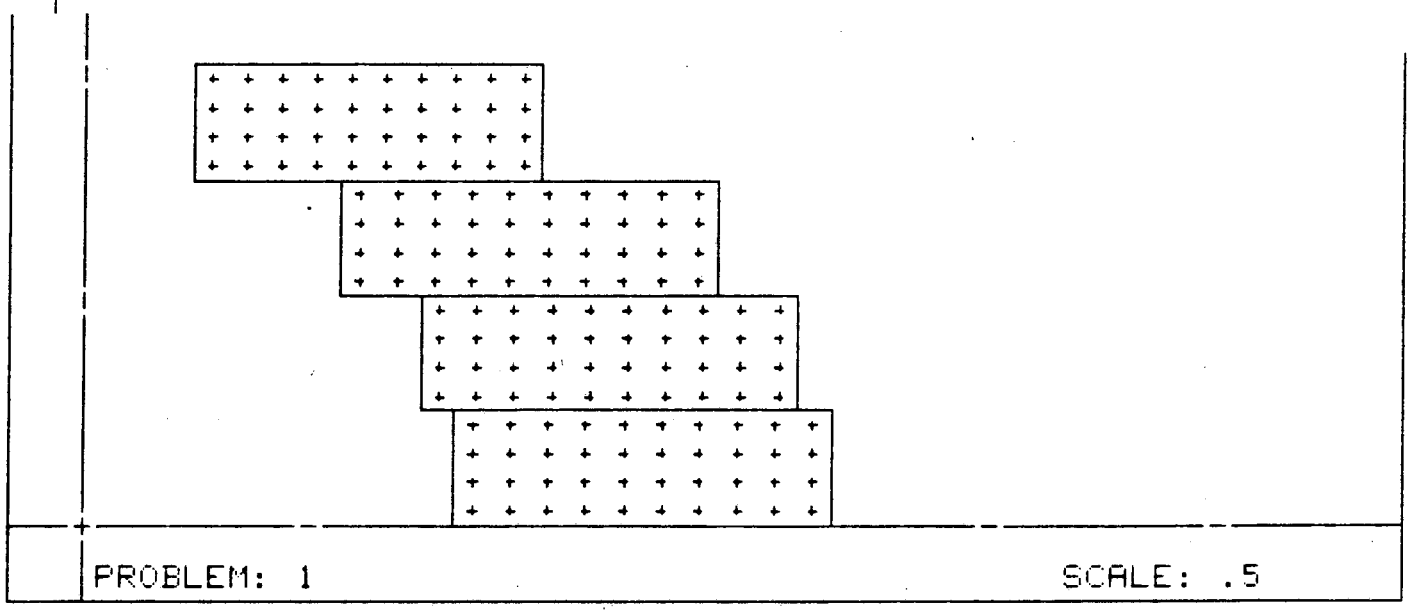
PROBLEM: 1
NUMBER OF BLOCKS, FIXED = 1
NUMBER OF BLOCKS, TOTAL = 4

BLK	NW	ND	X1	X2	Y1	Y2	CURDENS *1E-6)	FILAMENTS MIN	MAX
			m	m	m	m	A/sq mm		
1	10	4	.098423	.198423	0.000000	.030619	300.0000	1	40
2	10	4	.089286	.189286	.030619	.061237	300.0000	41	80
3	10	4	.067980	.167980	.061237	.091856	300.0000	81	120
4	10	4	.028979	.121443	.091856	.122474	300.0000	121	160

MIN. RADIUS = .09149 FOR BLOCK 3
MAX. RADIUS = .20077 FOR BLOCK 1

MULTIPOLE COEFFICIENTS.

ORDER	NORM RAD = .075000m TESLA	NORM	NORM RAD = .100000m TESLA	NORM
1	17.06315054	1.00000000	17.06315054	1.00000000
3	.00000000	.00000000	.00000000	.00000000
5	.00000000	.00000000	.00000000	.00000000
7	-.00000000	-.00000000	-.00000000	-.00000000
9	.00731211	.00042853	.07303859	.00428049
11	.00734714	.00043059	.13046857	.00764622
13	-.01916292	-.00112306	-.60495982	-.03545417
15	.00696392	.00040813	.39083738	.02290535
17	.00549813	.00032222	.54857297	.03214957



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