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Title IMPROVEMENT OF FERMILAB DIPOLE MAGNETS FOR ISABELLE

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M. A. Green	Mechanical	Berkeley June 30, 19		981
PROGRAM _ PROJECT _ JOB High Field Magnet	Development			
Two-Dimensional ar	nd Integrated Field Analysis	•		
Improvement of Fei	rmilab Dipole Magnets for ISABELLE	· · · · · · · · · · · · · · · · · · ·	<u></u>	<u> </u>

This engineering note describes a series of computer calculations which show how the basic Fermilab dipole magnet can be improved in order for it to be used in a storage ring similar to ISABELLE. The nominal Fermilab dipole produces a good integrated field good to about 12 parts in  $10^4$  at a 1-inch radius in the magnet aperture. This engineering note suggests a design which can produce a magnetic field good to about 4 parts in  $10^4$  at a 1-inch radius in the magnet aperture.

The basic Fermilab dipole was modeled using data given in Ref. 1. Since we do not have all of the data needed to describe the Fermilab dipole accurately, the basic Fermilab dipole calculated at LBL for this note must be considered an approximation of the real thing. The design used here has an integrated field good to about 12 parts in  $10^4$  at a 1-inch radius. The two-dimensional dipole field has a sextupole component about 19 parts in  $10^4$  at a 1-inch radius. The actual Fermilab dipole is probably not as bad as this in the two-dimensional field. In any event, the Fermilab design was checked to produce the best theoretical design within the constraints of that design. The best of these theoretical designs yielded an integrated field which was good to 11 parts in  $10^4$ . The base case used for comparison may not be the exact Fermilab dipole design, but it is close enough. (See Fig. 1 for the cross-section.)

Over 60 cases were run on the LBL computer program SCMAG1. This program, which is described in Ref. 2, permits one to design a dipole or quadrupole magnet with a given higher multipole field structure. (When one designs a dipole, one would like to set as many of the higher multipoles equal to zero.) The SCMAG1 code uses symmetry to set the even multipoles (N = 2, 4, 6, etc.; N = 2 is the quadrupole, N = 4 is the octopole, and so on) equal to zero in the dipole. Refs. 3, 4, and 5 discuss the role of symmetry in dipole or quadrupole magnet

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### IMPORTANT RADII

Usefull aperture radius	= 2.540 cm
Inner coil, inner radius	= 3.810 cm
Inner coil, outer radius	= 4.608 cm
Outer coil, inner radius	= 4.661 cm
Outer coil, outer radius	= 5.459 cm
Inner iron radius	= 9.563 cm



Figure 1. The Basic Fermi Lab Dipole Design with Finite Conductor (CASE 0)

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design. In a dipole,	the SCMAG1 code sets higher	odd multipole	es to zero (N	= 3,
5, 7, etc.) by solving	a set of simultaneous equat	ions. These	equations ar	e
usually non-linear, so	a set of successive approxi	imations is us	ed to conver	ge on
a solution. The conve	rgence on a solution is ofte	en difficult.	n n N N N	

The SCMAG1 code was used to design the magnets so that they have both a good two-dimensional field and a good integrated field simultaneously. The Fermilab dipoles do not possess this property. The combination of good integrated field and good two-dimensional field is only really important when the magnet length is a substantial part of a betatron wave length. The Fermilab magnet length is about 2.5 percent of a betatron wavelength in the Fermilab synchrotron.

#### The Search for Theoretical Solutions

The Fermilab dipole consists of two approximately equal current density layers and a block which is a return current on one side and a lower current density block on the other side. This block, which in the outer layer extends from 0° to 2.0°, is also found in all of our test cases. The current density in the return block is set to 30889  $Acm^{-2}$ . In the Fermi dipole, the outer layer extends from 2.00° to 36.50°; its current density is set to 35813  $Acm^{-2}$ . This current density is used in all of the outer layers of the test case dipoles as well. The inner layer of the Fermi dipole extends from 0.17° to 72.54°, and this layer current density is set to 35918  $Acm^{-2}$ . All the inner layers in our test cases are set to this current density.

At first, the desired method for improving field uniformity was to keep the coils within the confines of the 72.54° and 36.50° angles. It was thought that the coils could be split into two pieces in order to achieve more degrees of freedom in the design. (Hence, more multipoles could be eliminated). By keeping the 72.54° and 36.50° angles, the Fermilab collet design could be used. Fig. 2 shows a variety of solutions that were tried. The cases which included keeping

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Figure 2. Various coil configurations which have been run by SCMAGI in order to try to improve the Fermi Lab dipole magnet

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NOTE: The heavy shaded angles are the angles to be changed by SCMAG1

## Figure 2 continued

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NOTE: The heavy shaded angles are the angles to be changed by SCMAG1

## Figure 2 continued

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Fig. 2i Cases 25 and 31

Fig. 2j Cases 24 and 30



NOTE: The heavy shaded angles are the angles to be changed by SCMAG1

LAWRENCE BERKELEY LABORATORY - UNIVERSITY OF CALIFORNIA CODE SERIAL PAGE ENGINEERING NOTE PE1111 7 OF 36 15750 AUTHOR LOCATION DATE M. A. Green Mechanical Berkeley 1981 June 30 the 72.54° and 36.50° angles are illustrated in Fig. 2a, 2f, and 2h. Table 1 shows a number of cases which represent the attempts to find a solution. All cases failed except case 9, and its thin counterpart, case 21. Both of these cases yielded a central field which is less than eighty percent of the base line case. These cases were rejected.

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Next, I decided to freeze the 72.54° angle but allow the 36.50° angle of the outer layer to float. Fig. 2d, 2e, and 2j illustrate this approach. None of these tries yielded a solution. (Only one mathematical solution, case 30, was found; the rest didn't converge.) Next, I decided to try solutions where the 72.54° angle could float. These cases are illustrated by Figs. 2b, 2c, 2g, and 2i. None of these solutions converged except for the two layer, two block dipole illustrated in Fig. 2b.

The two layer, two block dipole illustrated in Fig. 2b was suggested by R. Palmer of Brookhaven during a talk he gave this last spring (Ref. 6). The computer had a difficult time converging on a solution for this case, but a solution for the Fermilab geometry was finally achieved in case 13. Theoretically, this solution is very good in both the two-dimensional and integrated fields. The higher multipoles up to N = 19 are less than 1 part in  $10^4$  of the dipole at Fermilab useful aperture radius of 2.54 cm. Case 13 was selected for further study in finite conductor form even though the central field is 96 percent of the baseline case and the highest angle is 5° above the 72.54° angle.

Since most of the block layer design tries were a failure, it was decided to look at sector block designs similar to ESCAR, Karlsruhe, and CERN designs. The computer immediately converged on solutions for three block inner coil plus two block outer coil (case 16, Fig. 2k), and solutions for three block inner coil plus three block outer coil (case 33, Fig. 21). Case 16 has a worst multipole of 3.8 parts in  $10^4$  at a radius of 2.54 cm. Case 33 has a multipole of 2.7 parts in  $10^4$  at a radius of 2.54 cm. Both cases 16 and 33 have highest sector angles

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	TAB	BLE 1	_		· ·	AUTHO M.
- - -	Various Cases Run on the SCMAGI	Code to	Improve	the Fermi Dipole		
			•	4		ICE B
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	MBE L	,	290° S		• •	ZLEY
		N.				
00	2 DESCRIPTION		OF WAT	REMARKS	******	
	VARIATIONS OF THE BASIC FERMILAB DIPOLE MAGNET	. •		•		PAL ORY
0	The Fermilab dipole as built (Fig. 1 and 2a)	yes	yes	$B_0 = 4.33$ T, 12.4 parts	in 10 <sup>4</sup>	ATM GUN
1	Theoretical Fermilab dipole variable angle (Fig. 2a	) yes	yes	$B_0 = 4.37$ T, 11.4 parts	in 10 <sup>4</sup>	ICa T
. 7	Theoretical Fermilab dipole variable J (Fig. 2a)	yes	yes	$B_0 = 4.55$ T, 12.3 parts	in 10 <sup>4</sup>	RSIT
- 19	Theoretical thin Fermi dipole variable J	yes	yes	same solution as case 7-		
	MODIFICATIONS OF THE FERMI DIPOLE, THEORETICAL SOLU	TIONS	9		٨	μ
3	Two layer, two block, ISABELLE dimensions (Fig. 2b)	yes	yes	good to 1.1 parts in 10	•	Z >
10				•		
10	Iwo layer, two block, different iron (Fig. 2b)	yes	yes			B 5 문 8
11	Same as 10, but thin, different radii(Fig. 2b)	yes	yes			DE 111 CATI
4	Fermi two layer, two block, 1st try (Fig. 2b)	no				ley LB
12	Formi two layer, two block, 2nd try (Fig. 2b)	no			. 104	
13	remin two layer, two block, srd try (rig. 20)	yes	yes	0 = 4.10 1, 0.2 parts	in 10	
5	Modification of Fermi (Fig. 2d)	no				ne ne
R S	Modification of Fermi (Fig. 2c)	no				30,
ט א	Modification of Fermi (Fig. 2e)	no				199
2	Modification of Fermi (Fig. 2f)	no				
9	Modification of Fermi (Fig. 2f) 2nd try	VAC	VAC	B - 3 40 T 7 2 parts	$in 10^4$	OF
	the try	yes	Jes	$0^{-5.70}$ i, <i>i.e</i> parts	111 10	36

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		TABLE 1 (cont.)	SE LEV	JI <sup>ON</sup>		AUTHOR M. A. Gre	
CASE MUIN	DESCRIPTION	Com Hr	LE RE P	REMARKS		en	
17 TH 18 TH 20 TH 21 TH	nin version of case 5 (Fig. 2d) nin version of case 6 (Fig. 2c) nin version of case 8 (Fig. 2e)	no no no	 		•	рерантме Mechani	RATORY - UNI
21 Tr 22 Tr 23 Tr 24 Tr	nin dipole (Fig. 2g) nin dipole (Fig. 2h) nin dipole (Fig. 2h)	yes no yes	no	angles clash	<b>,</b>	NT Cal	
25 TH 26 CT 27 CT	nin dipole (Fig. 2i) lose thin version of case 5 (Fig. 2d) lose thin version of case 6 (Fig. 2c)	no no no					
28 C 29 C 30 C	lose thin version of case 8 (Fig. 2e) lose thin version of case 22 (Fig. 2g) lose thin version of case 24 (Fig. 2j)	no no yes	  no	angles clash		Locatio Berkel	CODE PE1111
31 C	lose thin version of case 25 (Fig. 2i) ECTOR BLOCK FERMI DIMENSIONS, THEORETICAL S	no SOLUTIONS				ley Jun	U 414
14 Ir 15 Ou 16 Ca	nner layer with three blocks (Fig. 2k) uter layer with two blocks (Fig. 2k) ase 14 plus case 15 (Fig. 2k)	yes yes yes	yes yes yes	$B_0 = 2.17$ T, 5 parts in $10^4$ $B_0 = 2.36$ T, 7 parts in $10^4$ $B_0 = 4.53$ T, 3.8 parts in $10^4$	4	e 30, 1981	750
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	TABLE 1 (	(cont.)					AUTH M.	
·			NUL NO	101 101 102	· · · · ·		A. Gree	E Z
		J.				•	Ē	
2	DESCRIPTION	6 <sup>3</sup> .0	Ser Star	REMARKS		.* :		m;
32	Outer layer with three blocks (Fig. 21)	yes	yes	$B_0 = 2.30$ T, 0.5 parts	in 10 <sup>4</sup>			
33	Case 14 plus case 32 (Fig. 21)	yes	yes	$B_0 = 4.48$ T, 2.7 parts	in 10 <sup>4</sup>		Mec	
53	Case 14 and 15; all angles to eliminate 8 poles	no	<b></b> ·	v			han	K
54	Case 14 and 32; all angles to eliminate 10 poles	no	·	· ·			ica	101
59	Case 14 and 15; lengths vary to improve B dl	yes	no	solution is worse than	case 16			
60	Case 14 and 32; lengths vary to improve B dl	yes	no	solution is worse than	case 33			Z
				- -				
	OTHER THEORETICAL TRIES							m
34	Thick, coincident current density, 1st try	no		convergence was close	•			
35	Thick, coincident current density, 2nd try	no		convergence was close		· ·		
36	Inverse Fermi dipole	yes	no	angle greater than 90°		• •		
	Cases 13, 16, and 33 were conver	ted to	finite co	onductor models.		•	erk	EII
	EINITE CONDUCTOR VERSIONS OF REST THEORETICAL COUNTY						ele	
37	A version of ease 14 15 turns lower free	<u>1N2</u>		Post D 212 T E 6	nauta in	1.04		
38	A version of case 14, 15 turns, lower free	yes	yes	Best $B_0 = 2.13$ 1, 5.0	parts in	10		,
30	A version of case 14, 15 turns, lower free	yes	yes	N = 7 is too high			June	1575
- /10	A version of case 14, 16 turns, lower fixed	yes		anytes clash N - 7 is too high	1949 - A.			ŏ
-то Д1	A version of case 15, 23 turns, lower free	yes	yes	n = 7  is coviligh $Roct R = 2.22  T 7  F$	novto in	104		· :
- <b>T</b>	A version of case 13, 23 curits, tower free	yes	yes	0 = 2.33 + 7.5	parts in	TO	186	10
								0
		:				· .		36

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		TABLE 1	(cont.)	- <b></b>	· · · · · · · · · · · · · · · · · · ·	A A	5
						A.	N RE
				JEN .	II ST	Gr	Z
				E S		een	
			THE REAL	get At 2			
36	DESCRIPTION		St. M	S. M.	REMARKS		m
42	A version of case 15, 23 turns, lower fixed		yes	yes	N = 5 is too high		ΠÕŖ
43	A version of case 15, 24 turns, lower free		yes	no	blocks clash	Mec	TOR
44	A version of case 15, 24 turns, lower fixed		yes	yes	N = 5 is too high	chan	K K S S S
45	Case 37 plus case 41		yes	yes	$B_0 = 4.46$ T, 4.2 parts in $10^4$	i ca	
46	Two layer, two block, see case 13		yes	no	angles clash		RSIT
47	Two layer, two block, see case 13		yes	no	angles clash		4 OF
48	Two layer, two block, see case 13	د	yes	no	angles clash		
49 <sup>.</sup>	Two layer, two block, see case 13		yes	yes	$B_0 = 4.11$ T, 8.1 parts in $10^4$ , N = 7		mõ
50	Two layer, two block, see case 13		yes	no	angles clash		NNA
51	Two layer, two block, see case 13		yes	yes	OK, 4.11 T, 4 parts in 10 <sup>4</sup> , ends		
					difficult		
52	Two layer, two block, see case 13	. •	yes	yes	Best $B_0 = 4.11$ T, 4.2 parts in $10^4$	Berk	ODE E11
55	A version of case 32, lower free-		yes	no	anglesclash	ele	
56	A version of case 32, lower fixed, nom. $\Theta$		yes	yes	too large $N = 7$	14	
57	A version of case 32, lower fixed, min. $\Theta$		yes	yes	Best $B_0 = 2.30$ T, 2.1 parts in $10^4$		SE SE
58	Case 37 plus case 57	•	yes	yes	$B_0 = 4.43$ T, 3 parts in $10^4$	Junt	RIA1
61	Case 0 with $E = 10^{\circ}$ psi in coils		yes	yes	10.3 parts in 10 <sup>4</sup> added sextupole	e a	0
62	Case 45 with $E = 10^{\circ}$ psi in coils		yes	yes	8.6 parts in 10 <sup>4</sup> added sextupole		
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which are less than	72.54°. Both cases yield	l a central field w	which is 3 to	5
percent higher than	the base line case. The	magnetic length or	f these cases	is
somewhat longer than	the base line case for a	a given maximum co	il length.	

The base line case, case 0, and the theoretical Fermi dipole case, case 1, are given as computer runs in the appendix. The theoretical solutions selected for finite conductor studies (cases 13, 16, and 33) are also given in the appendix. In theory, a large improvement is possible over the base line case (case 0) or its theoretical equivalent (case 1) using either the two layer, two block dipole (case 13) or sector block dipoles (cases 16 and 33).

Before leaving the problem of theoretical coil design, it is useful to discuss why solutions could not be found for many of the cases. In general, three types of non-convergence occurred: 1) the optimization tried to converge on a solution, but couldn't quite make it; 2) the optimization converged on a solution close to the one desired but the desired solution did not exist; and 3) the optimization did not converge at all. In this case, the optimizer often went to very large angles in order to try and find a solution.

The third type of non-convergence was the most prevalent. This does not mean there is no solution, but the program optimizer did not find a solution. The optimizer itself should be changed if solutions that are difficult to find are to be found. A suggested course of action is to put limits in the program to keep the problem within bounds. Another approach is to have the computer move the starting case so that the starting case will be in a different potential well. A third approach is to use a DFP optimizer which uses second derivatives as well as first derivatives to optimize the solution.

Some cases, such as the sector blocks, always converged. The types of cases which did not work were cases when there was a solution which already eliminated or minimized a couple of multipoles, but one further subdivided the problem to improve the solution. The higher the multipole, the harder it is to eliminate

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with small changes.	As an example, one can go to t	he basic sec	tor block ca	ses
(cases 14, 15, and 32)	). If one combines, say, case	14 with 32	and tries to	
double the number of r	nultipoles eliminated, the pro	blem does no	t converge.	
(Case 54 was an examp	le of this.) Most of the modi	fications I	tried on the	
basic Fermi dipole des	sign are examples of this type	of non-conv	ergence.	•

#### Finite Conductor Versions of the Best Theoretical Solutions

Cases 13, 16, and 33 were selected for conversion into finite conductor magnets. The conductor assumed is keystoned Fermilab 23-strand Rutherford cable. The width of the cable with all of its barberpole wrap and insulation was assumed to be 1.52 mm based on the case 0 design. The return leg conductor on the midplane of the outer layer is wider. Each conductor on the inner layer is assumed to be 2.0711° wide. Each conductor on the outer layer is assumed to be 1.7228° wide. (The return leg conductor at the midplane on the outer layer is assumed to be 2.000° wide.)

The finite conductor design requires that each layer or block contains a finite number of conductors. In general, one puts the nearest number of conductors in which fits the theoretical solution. The layer or block has a midpoint angle which can be varied in order to eliminate some of the lower multipoles. Several runs of each of the theoretical cases are required in order to find the most suitable finite conductor solutions. All of the finite conductor cases converged mathematically. Most were eliminated either because they couldn't be built physically, or they had an excessive amount of a particular multipole.

The finite conductor version of case 16 is case 45. Case 45 consists of the sum of case 37 (the best finite conductor solution for case 14) and case 41 (the best finite conductor solution for case 15). The finite conductor version of case 33 is case 58. Case 58 consists of the sum of case 37 and case 57 (the best finite conductor solution for case 32). The finite conductor version of the

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Fermi-sized two layer	, two block dipole (case 13)	is case 52.	The multipol	e
structure of the two-	dimensional and integrated f	ield in cases	45, 58, and	52 is
found in the computer	printout in the appendix. 1	These cases ca	n be compare	d
directly with cases 10	5, 33, and 13, respectively,	which are als	o given in t	he
appendix.				

Table 2 compares cases 45, 58, and 52 with the base case (case 0). The use of finite conductor hardly affects the field uniformity which can be generated by a sector block dipole. (For example, the field error went from 3.8 parts in  $10^4$  in case 16 to 4.2 parts in  $10^4$  in case 45. The field error went from 2.7 parts in  $10^4$  in case 33 to 3.0 parts in  $10^4$  in case 58.) The two layer, two block dipole did not fare as well. (Case 13 showed 0.2 parts in  $10^4$  as compared to 4.2 parts in  $10^4$  in case 52.)

Case No.	Central Field	Number of Turns	Highest Angle (degrees)	Integrated Field Highest Multipole at R = 2.54 cm	
0	4.33	112	72.54	12.3 parts in 10 <sup>4</sup>	
45	4.46	120	71.72	4.2 parts in 10 <sup>4</sup>	
58	4.43	120	72.30	3.0 parts in 10 <sup>4</sup>	
52	4.11	108	79.66	4.2 parts in 10 <sup>4</sup>	• •

TABLE 2A Comparison of the Finite Conductor Cases Studied

The two layer, two block dipole does not look nearly as attractive as either of the two sector block designs. The highest angle approaches 80°. This probably makes the dipole design unsuitable for use with collets of the Fermilab

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type. Of the two central field and	sector block designs, case 45 is it has a lower outer coil angle.	simpler. It (66.76° in	also has a l case 45 versi	nigher us
72.30° in case 58.	)			•

For a full scale comparison of the improved Fermi-sized dipole with the Fermi dipole, case 0 and case 45 were run in the SCMAG2 computer code. Tables 3 and 4 compare a number of the parameters for the two designs. Fig. 3 shows the sector block design of case 45.

From Table 3, a number of advantages emerge. They are: 1) for a given current in the superconductor, the central field and integrated field are higher; and 2) for a given coil length, the magnetic length of the sector design is longer. The disadvantages of the sector design are: 1) it requires more superconductor (8 turns per magnet); and 2) considerable development work is required before the sector design can be used. The extra development is distinctly disadvantageous from the standpoint of magnet development for ISABELLE.

#### The Affect of Strain and Placement Errors on Magnetic Field Uniformity

Tables 4 and the cases in the appendix illustrate that the Fermilab dipole can be improved to produce a more uniform two-dimensional and integrated field. A real improvement of magnetic field quality is only partially tied to the coil design. Two other factors come into play. The first is the placement accuracy of coils, blocks, and conductors. The second is the symmetric and asymmetric effects of magnetic coil strain on the placement of the coils and conductors.

The whole problem of field errors due to asymmetric conductor, block, and coil displacement errors is discussed in Ref. 7. For a given coil design, the effects of random conductor and coil errors can be calculated using SCMAG3. In a dipole with a 50 mm useful bore, the following random tolerance limits should be applied if random errors are kept below 3 parts in  $10^4$ .

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## TABLE 3

## A Comparison of Finite Conductor Sector Block Dipole with the

Base Line Fermilab Dipole

	Base Fermi Magnet	Sector Block Magnet
	Case O	Case 45
Design Aperture Radius (cm)	2.54	2.54
Inner Coil Radius (cm)	3.81	3.81
Iron Radius (cm)	9.563	9.563
Coil Length (m)	6.226	6.226
Coil Design Current (A)	4350	4350
Central Induction (T)	4.328	4.456
Integrated Induction (Tm)	26.519	27.362
Magnetic Length (m)	6.127	6.141
Peak Induction in the Coil (T)	4.71	4.86
Magnet Inductance (H)	0.046	0.051
Number of Turns	112	120
Stored Magnet Energy at Design Current (J)	$4.38 \times 10^5$	$4.81 \times 10^5$
Superconductor Matrix Current Density (Am <sup>-2</sup> )	5.12 × 10 <sup>8</sup>	5.12 × $10^8$
$EJ^2$ one coil $JA^2m^{-4}$	$1.15 \times 10^{23}$	$1.26 \times 10^{23}$

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			TABLE	4			
Two-Dime	ension	al and Inte	grated Field Mul	tipole R	atios at R	= 2.54 cm for	the
Base	Fermi	Dipole (Cas	se O) and the Sec	tor Bloc	k Magnet De	esign (Case 45	5)
• • • •		• •	Described in	Table 3			
			• •			• • • • • •	•
			Mu1	tipole Ra	atio		
		Two-Dime	nsional Field	•	Integr	ated Field	
Multipole		. ~		· · · ·	·. · · · ·	•	
Number	·	Case O	Case 45		Case O	Case 45	
1		1.00000	1.00000		1.00000	1.00000	
3		0.00187	· · · · · · · · · · · · · · · · · · ·			-	
5		0.00000	-		-0.00013	-0.00010	
7	.** .	0.00073	-0.00000		0.00072	-0.00010	
9		-0.00123	-0.00041		-0.00123	-0.00042	
11		0.00037	-0.00000		0.00037	0.00006	
13	•	-0.00008	-0.00026		-0.00008	-0.00026	
15		0.00000	0.00009		0.00000	0.00009	
17		-0.00000	0.00002		0.00000	0.00002	
19		-0.00000	-0.00001		-0.00000	-0.00000	1
		······································					
Central					· .		
Induction (	<b>T</b> )	4.328	4.456				
Integrate	d						′
Induction (	Tm)			• · ·	26.519	27.362	
		,					
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	÷ .						

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#### IMPORTANT ANGLES

Inner	coil,	lst b	lock,	lower	angle	=	0.50
Inner	coil,	lst b	lock,	upper	angle	=	31.57
Innér	coil,	2nd b	lock,	lower	angle	=	36.05
Inner	coil,	2nd b	lock,	upper	angle	=	52.62
Inner	coil,	3rd b	lock,	lower	angle	, = ·	63.44
Inner	coil,	3rd b	lock,	upper	angle	Ξ	71.72
Outer	coil,	lst b	lock,	lower	angle	=	2.21
Outer	coil,	lst b	lock,	upper	angle	=	41.84
Outer	coil,	2nd b	lock,	lower	angle	Ξ	51.25°
Outer	coil,	2nd b	lock,	upper	angle	=	66.76
Outer	coil,	retur	n leg	angle		=	2.00

#### CURRENT DENSITY

Inner coil	=	35918 <sup>°</sup> A/cm <sup>2</sup>
Outer coil	=	35813 A/cm²
Return leg	=	30889 A/cmª





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Single 4350	A conductor	Ø	0.5 mm		
Sector block	20 block magnet	8	0.07 mm		
Coil half pl	acement 4 parts	2	0.04 mm		
Placement ir	iron*	2	0.02 mm		

Symmetric field errors, such as those caused by strain in a magnetic field, are also discussed in Ref. 7. I used the SCMAG2 code to calculate the magnetic forces within the coil. Once the forces are calculated, stress the radial, and azimuthal direction can be estimated. Within the Fermi dipole (case 0) peak azimuthal stresses of  $4.8 \times 10^7 \text{ Nm}^{-2}$  (7000 psi) are calculated. Similar stresses are found in the sector block design (case 45). If the coil is not prestressed so that the pole angle is allowed to move, considerable strain can occur within the coil.

The angle change of various key angles in case 0 and case 45 was calculated. No prestress was assumed. The coil structure modulus was assumed to be 7 x  $10^9$  Nm<sup>-2</sup> ( $10^6$  psi). Runs 61 and 62 (see the appendix) estimated the field structure which would be generated at a current of 4350 A at a radius of 2.54 cm in the Fermi dipole (case 0) and its improvement (case 45). The magnetic field changes which result from magnetic strain are given in terms of multipole ratios. Table 5 shows ratios for N = 3, 5, 7, and 9. At an elastic modulus of 7 x  $10^9$  Nm<sup>-2</sup> ( $10^6$  psi) the sextupole error approaches 10 parts in  $10^4$ . Proper prestress of the coil will reduce the error considerably but it appears that a minimum coil modulus of 1.4 x $10^{10}$  Nm<sup>-2</sup> ( $2.0 \times 10^6$  psi) is needed.

From Table 5, it is clear that in order to use the field improvement possible in the sector block design, one must increase the modulus of the coil.

\*This is a guadrupole error which can be corrected after magnetic measurement.

ENGINEERING NOTE UTHOR M. A. Green Mechanical TABLE 5 Elastic Coil Defor Errors in Case 0 and Case 45 Dur	PE1111 LOCATION Berkeley	June 30, 1	20 <sub>oF</sub> 3 981
M. A. Green Mechanical TABLE 5 Elastic Coil Defor Errors in Case 0 and Case 45 Dur	Berkeley	June 30, 1	981
TABLE 5 Elastic Coil Defor Errors in Case 0 and Case 45 Dur	rmation	June 30, 1	981
TABLE 5 Elastic Coil Defor Errors in Case 0 and Case 45 Dur	rmation		
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Errors in Case 0 and Case 45 Du	rmation	A STREET STREET	·
Errors in Case 0 and Case 45 Du			
	e to Magnetic Fo	rces	· · · ·
when the Coll Structure has an Elastic Mod	ulus of 7 x $10^9$	Vm <sup>-2</sup> (10 <sup>6</sup> psi	i).
Mul	tipole Ratio		
Multipolo Eormi Dipolo			
remit prote	Secto	r Dipole	
Number Case 61 - Case 0	Case 62	– Case 45	
3 0.00102		0000	·
5 0.00103	0.0	0086	
5 -0.00044	-0.0	0010	
7 0.00017	0.0	0008	
9 -0.00006	0.0	0001	
	• •	- 	
	• •		
•			

coil, and block placement errors. It is clear that additional development work is needed in order to improve the quality of the field in the Fermi-type dipole magnets.

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#### APPENDIX

This appendix shows the computer printouts for cases 0, 1, 13, 16, 33, 45, 52, 58, 61, and 62. Some of the cases have the SCMAG1 code change parameters to get the desired multipole structure in both the two-dimensional and integrated field. In other cases, the integrated field is the only field which has higher multipoles eliminated. There are also a number of cases where the field and integrated field structures are calculated for a given geometry.

A sample case is shown on the next page. This case (case 41) has SCMAG1 eliminate two multipoles (N = 3 and N = 5) in the two-dimensional field. One multipole (N = 3) is eliminated in the integrated field. The first group of data is the input parameters to the problem. The meaning of the symbols NT, R1, R2, A1, A2, SLEN, XJ, A3, and MK are explained in Table 6 and Fig. 4 which come from Ref. 2. There are three lines of data starting with NT = 1 or NT = 2 which describe the magnet coils. Round, equal length ends are assumed. XLEN is the straight section length of the coils between the ends. The definition of A1, A2, R1, and R2 is given in Fig. 4 depending on the value of NT. The three lines below the lines which have NT = 1 or 2 start with NT = -0. These lines have a 1 in the A1 or A2 column. This tells one that that value is changed to optimize the two-dimensional field multipole structure. In the line which starts with NT = -0, a 2 in the XLEN column states that the length of that coil straight section can be changed in order to improve the multipole structure of the integrated field.

The second group of data in the sample run is the iterated values of the twodimensional field multipole coefficients. This only is printed when there is a two-dimensional optimization. The third group of data in the sample run is twodimensional and integrated field multipole solutions. This is printed in all cases. The data applies to the final solution for the coil. The fourth group

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TITLE BLOCK TEST CASE 41, BLOCK DIPOLE WITH FERMI BORE, SEE CASE 15 END TYPE RO = USEFULL APERATURE RADIUS RIIRON = IRON SHELL INNER RADIUS INPUT PARAMETERS 2.5400 9.5630 -0. 1 20 -0. -0 -0 -0 -0 -0. -0 -0.-0. -0. -0. -0. -0. - Desired multipolo values N=3, 5, 7. 1 R1 A1 A2 R2 NT XLEN ХJ Å3 MK 2 5.4590 22.1900) 19.8122 590.0000 35813. 4.6610 .1500 1 2 4.6610 5.4590 59.2765/m 7.7526 590.0000/\* 35813. .1500 2 2.0000 590.0000 l 4.6610 5.4590 0. 30889. 3 .1500 -0. -0. 1.0000 -0. -0 -0. -0. -0. -0 1.0000 2.0000 -0 -0. -0. -0. -0. -0. -0 -እ -0. -0 -0. -0. -0. -0. -0. -0 to be changed by program To be changed by programs INTEGRATED SIONAL FIELD) field (2 DIMENSIONAL FIELD) ITERATED VALUES OF THE MULTIPOLE COEFFICIENTS -.002814 -.000003 -.000002 .000011 ONLY TWO HULTIPOLES CAN BE CHANGED IN 2D FIELD .000000 -.000000 ONLY ONE MULTIPOLIE CAN BE CHANGED IN INTEGRATED FIELD N=5N=3TWO DIMENSIONAL AND INTEGRATED FIELD MULTIPOLE SOLUTIONS 2D FIELD INTG. FIELD -13,99764 ł -2.33472 -.00000 -.00000 3 .00000 .00266 5 .00002 .00089 7 9 .00181 .01061 11 .00036 .00215 13 .00006 .00035 15 .00003 .00020 17 .00000 -.00000 19 .00000 -.00001 **DUTPUT MAGNET PARAMETERS** C ... MK R2 **A**2 XLEN NT R1 A1 хJ AЗ 4.6610 .1500 1 2 5.4590 7 22.0236 19.8122 590.0000 35813. 59.0047 2 4.6610 5.4590 7.7526 (582.9321 35813. .1500 2 A590.0000 0. 4.6610 5.4590 2.0000 30889. .1500 3 1 1.0000 -0. -0. -0. -0. -0 -0 -0. -0. -0. 1.0000 -0. 2.0000 -0. -0. -0 ~0 -0. -0 -0 -0. -0--0. -0. -0. -0. -0. PROGRAM CHANGED BY

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of data is the output magnet parameters. This gives the new angles and lengths needed to calculate the multipole coefficients in the final solution. Note all multipole coefficients give at RO the useful aperture radius (for all cases, RO = 2.54 cm). If there is no change in angle or coil length (no optimization is done) the output magnet parameters are eliminated. (The integrated values of multipole coefficients are also eliminated.)

All of the cases have NT = 1 or NT = 2. Case 0 optimizes the integrated field only. Case 1, case 13, and case 52 optimize both the two-dimensional and integrated field. Case 16, case 33, case 45, case 58, case 61, and case 62 have no optimization in them. The two-dimensional and integrated fields are calculated for the given input parameters.

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Figure <b>4</b> - Var pro wou Sym	ious dipole coil grams. (Note: fo ld be confined to metry is used in	configuration or quadrupole an angle bet these codes.	is case calculate s these configur ween O and 45 de )	ed by the rations egrees.	
R <sub>2</sub> R <sub>1</sub> A <sub>2</sub>	X J A1		R <sub>2</sub> R <sub>1</sub>	A <sub>2</sub>	-X J
Case 1 - Se	ector Coils	· · · ·	Case 2 - S	ector Coils	•
				A <sub>2</sub>	
R <sub>2</sub> R <sub>1</sub> A <sub>2</sub>	X J		R <sub>2</sub> R <sub>1</sub> A <sub>1</sub>		ХJ

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Table <b>6</b> .	Input da each of	ta whic the par	ch descr rameters	ibes the is showr	magnet 1.	coils in the S	CMAG progr	ams. The dimensi	on of		, Green	
	Coil Type	( R Para	Coil ameters	Co A Para	oil ameters	Coil Straight Sect. Leng.	Coil Current Density	Cond. spacing in A direct. or cond. cur.	Assembly Number			
	NT	$R_1$	R <sub>2</sub>	A1	A <sub>2</sub>	XLEN	XJ	A <sub>3</sub>	MK			
Case 1	1	Cm	CŴ	deg	deg	cm	A cm-2	ст	N.D.		Mechar	
Case 2	2	ст	ст	deg	deg	CM	A cm-2	ĊM	N.D.	•	лемт 11 са	
Case 3	3	ст	СШ	deg	deg	CM	A cm-2	СМ	N.D.			
Case 4	4	СМ	ст	deg	ст	ст	A cm <sup>-2</sup>	ст	N.D.			Ō
Case 5	5	cm .	ст	ст	ст	СМ	A cm <sup>-2</sup>	cm	N.D.	1 m 10		
Case 6	6	CM	cm	ст	cm	cm	A cm-2	ст	N.D.			
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Case 8	8	ст	cm	deg	deg	CM	A cm-2	А	N.D.		Berk	pE11
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$A \ cm^{-2} = $	Coil c	urrent	densitie	s are gi	ven in a	amps per square	e centimete	er.	• • •		ате June	1575
A =	Conduc	tor cur	rents gi	ven in a	mperes.				•	•	30,	
N.D. =	Not di	nension	alized (	this is	an integ	ger number).			• 	•	1981	26

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## TEST CASE 1, FERMI LAB DIPOLE

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- 1	EST C	SE 13, MO	DIFICATION	9 OF FER	MI DIPOLE	с	•			
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		INPUT PA	RAMETERS							
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	1	3.8100	4.6080	.1700	65.6700	590.0000	35918.	.1500	1	
	· ···· · 1 ·	3.8100	- 4.6080	70.5300	77.9100	590.0000	35918.	.1500	2	; · ·
	· 1	4.6610	5.4590	2.0000	25.5000	590.0000	35813.	•1500	3	
z	· 1 ·	4.6610	5.4590	29.3500	41.2500	590.0000	35813.	• 1500	4	
	1	4.6610	5.4590	0.	-2.0000	590.0000	30889.	•1500	5	
	0	-0.	-0.	-0.	1.0000	2.0000	-0.	-0.	-0	
	-0	-0.	-0.	-0	1.0000	2.0000	-0.	-0.	-0	
	-0-	-0.	-0.	1.0000	1.0000	2,0000	-0.	-0.	-0	· ·
•	-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0	
	v	. • •							~	·
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	ITER	ATED VALU	ES OF THE	MULTIPOLE	COEFFICIEN	TS				
••••		0091	480014	640003	540002	25000080	0000	16		
		0022	760007	460002	910000	.000014	.0000	23		
•••		• 0000	66 .0000	31 .0000	010000	04 .000000	0000	01		
		0000	0000000	0000	00 - 0000	0.0 - 000000	.0000	00		
	TWO	N=3 DIMENSION	AL AND INTE 2D FIFE	N=7 EGRATED FIN	N=9 ELD MULTIP	OLE SOLUTION	N = 1 S	<b>3</b>	, , , , , , , , , , , , , , , , , , ,	
• • • • •	TWO	N≃3 DIMENSION N	AL AND INTE 2D FIEL -4-157	N=7 EGRATED FIN	N=9 ELD MULTIP INTG. F -24.531	OLE SOLUTION	N = 1 S			
	TWD		N=5 AL AND INTE 2D FIEF -4.157 .0000	N=7 EGRATED FIN _D 31 D0	N=9 ELD MULTIP INTG. F -24.531 000	DLE SOLUTION IELD 27	N = 1 S			· · · · · · · · · · · · · · · · · · ·
	TWD	N 2 3 DIMENSION N	N=5 AL AND INTE 2D FIEE -4.157 .0000 .0000	N=7 EGRATED FIR _D 31 20 20	N=9 ELD MULTIP INTG. F -24.531 000 .000	DLE SOLUTION IELD 27 00	N = 1 S			· · · · · · · · · · · · · · · · · · ·
	TWO	N 2 3 DIMENSION N 3 5	N=5 AL AND INTE 2D FIEE -4.157 .0000 .0000	N=7 EGRATED FI LD 31 20 20	N=9 ELD MULTIP INTG. F -24.531 000 .000 000	0LE SOLUTION IELD 27 00 00	N ≂ I S			· · · · · · · · · · · · · · · · · · ·
	TWO	N 2 3 DIMENSION N 1 3 5 7 9	N=5 AL AND INTE 2D FIEE -4.157 .0000 .0000 .0000	N=7 EGRATED FI LD 31 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000	0LE SOLUTION IELD 27 00 00 24	N ≂ I S		· · · · · · · · · · · · · · · · · · ·	
	TWO	N 2 3 DIMENSION N 3 5 7 9 1	N=5 AL AND INTE 2D FIEE -4.157 .0000 .0000 .0000 .0000 .0000	N = 7 EGRATED FIN D 31 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 .000	N=11 OLE SOLUTION IELD 27 00 00 24 00	N ≂ I S		· · · · · · · · · · · · · · · · · · ·	
· · · · · · · · · · · · · · · · · · ·	TWO 	N 2 3 DIMENSION N 1 3 5 7 9 1 3	N=5 AL AND INTE 2D FIEE -4.157 .0000 .0000 .0000 .0000 .0000 .0000 .0000	N = 7 EGRATED FIN D 31 D 00 D 00 D 00 D 00 D 00 D 00 D 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 .000 .000 .000 .000	N=11 OLE SOLUTION IELD 27 00 00 24 08 01	N = 1		· · · · · · · · · · · · · · · · · · ·	
	TWO 1	N 2 3 DIMENSION N 1 3 5 7 9 1 3 5 7	N=5 AL AND INTE 2D FIEE -4.157 .0000 .0000 .0000 .0000 0000 0000	N = 7 EGRATED FIN _D 31 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 .000 .000 .000 .000 .000	N=II       OLE SOLUTION       IELD       27       00       00       00       00       01       54	N = 1 S		· · · · · · · · · · · · · · · · · · ·	
	TWO 1 1	N 2 3 DIMENSION N 1 3 5 7 9 9 1 3 5 7 8	N=5 AL AND INT 2D FIE -4.157 .0000 .0000 .0000 0000 0000 .0000	N = 7 EGRATED FIN _D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 .000 .000 .000 .000 .000 .0	N=II       OLE SOLUTION       IELD       27       00       00       24       08       01       56	N = 1			
	TWO 1 1 1 1	N 2 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9	N=5 AL AND INT 2D FIE -4.157 .0000 .0000 .0000 0000 0000 .0001 0000	N = 7 EGRATED FIN D 31 D 00 D 00 D 00 D 00 D 00 D 00 D 00	N=9 ELD MULTIP INTG. F -24.531 000 000 .000 .000 000 .000 000 .000 000	N=II       DLE     SOLUTION       IELD       27       00       00       24       08       01       41       56       24	N = 1 S			
•	TWO 1 1 1 1 1	N 2 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9	N=5 AL AND INT 2D FIE -4.157 .0000 .0000 .0000 0000 0000 0000 .0001 0000	N = 7 EGRATED FIN D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 .000 .000 000 .000	DLE     SOLUTION       IELD     27       00     00       24     00       03     01       41     56       24     00	N = 1 S			
	TWO 1 1 1 1 1 1 0UTP	N 2 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9	N=5 AL AND INT 2D FIE -4.157 .0000 .0000 .0000 0000 0000 0000 0000 .0000 0000 .0000 0000 .0000 0000	N = 7 EGRATED FIR D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 .000 .000 .000 .000 .000 .0	0LE     SOLUTION       IELD     27       00     00       24     00       00     00       24     00       01     41       56     24	N = 1			
	TWO 1 1 1 1 1 1 1 0UTP	N 2 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 0000 0000 .0000 0000 .0000 0000 .0000 0000 .0000 0000 .0000 .0000	N = 7 EGRATED FIR D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 .000 .000 .000 .000 .000 .0	0LE     SOLUTION       IELD     27       00     00       24	N = 1			
	TW0 1 1 1 1 1 1 1 0UTP	N = 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 0000 0000 .0001 0000 .0001 0000 .0001 0000 .0001 0000	N = 7 EGRATED FIR _D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 .000 000 .000	0LE     SOLUTION       IELD     27       00     00       24     00       01     41       56     24	N = 1			
	TWO 1 1 1 1 1 1 1 1 1	N = 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 0000 0000 .0000 0000 PARAMETERS 4.6080	N = 7 EGRATED FIN D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 000 .000 000 .000 000 .000 000	DLE SOLUTION IELD 27 00 00 24 08 01 41 56 24 577.2557	N = 1 S 35918.	. 1500		
	TW0 1 1 1 1 1 1 1 1 1 1 1 1	N=3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 0 1 8 10 0 1 0 1 0 1 0 1 0 1 0 1 0 1	AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 .0000 0000 .0000 0000 .00000 .00000 .00000 .000000	N = 7 EGRATED FIN _D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 000 .000 000 .000 000 .000 000	0LE       SOLUTION         IELD       27         00       00         00       00         24       00         01       141         56       24         577.2557       576.7550	N = 1 S 35918. 35918.	• 1500 • 1500		
	TW0 1 1 1 1 1 1 1 1 1 1	N=3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 3 5 7 9 1 1 3 5 7 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 .0000 0000 .0000 0000 .00000 .00000 .00000 .000000	N = 7 EGRATED FIN _D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 000 .000 000 .000 000 .000 000 .000 000	N=II         OLE       SOLUTION         IELD         27         00         00         00         00         00         00         01         41         56         24         577.2557         576.7550         590.0000	N=1 S 35918. 35918. 35918. 35918.	.1500 .1500 .1500 .1500	1 2 3	
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	TWO 1 1 1 1 1 1 1 1 1 1 1 -0 -0	N=3 DIMENSION N 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 1 9 1 1 1 1 1 1 1 1 1 1 1 1 1	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 0000 0000 .0001 0000 .0001 0000 .0001 0000 .0001 0000 .0001 0000 .0001 0000 .0001 .0000 .0001 0000 .0001 .00000 .00000 .00000 .00000 .00000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .00000 .00000 .00000 .00000 .000000	N = 7 EGRATED FIN D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 000 .000 000 .000 000 .000 000 .000 000 .000 000 .0000 .00000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000 .0000	577.2557 576.7550 590.000 24 08 01 41 56 24	N=1 S 35918. 35918. 35918. 35813. 35813. 3089. -0. -0.	-1500 .1500 .1500 .1500 .1500 .1500 .1500 .1500	1 2 3 4 5 -0 -0	
	TWO 1 1 1 1 1 1 1 1 1 1 1 -0 -0 -0	N=3 DIMENSION N 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 3 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 1 1 9 1 1 1 3 5 1 1 9 1 1 3 5 1 1 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 0000	N = 7 EGRATED FIN D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 -000 -000 -000 -000 -000 -000 -0	DLE       SOLUTION         IELD       27         00       00         24       00         00       00         24       00         00       00         24       00         05       00         24       00         00       00         24       00         56       24         577.2557       576.7550         590.0000       575.2013         590.0000       2.0000         2.0000       2.0000	N=1 S 35918. 35918. 35918. 35813. 35813. 30889. -0. -0. -0. -0.	.1500 .1500 .1500 .1500 .1500 .1500 .1500 .0.	1 2 3 4 5 -0 -0 -0 -0 -0	
	TWO 1 1 1 1 1 1 1 1 1 1 1 1 -0 -0 -0 -0 -0	N=3 DIMENSION N 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 3 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 100 3 3 8100 3 5 8100 4 5 6610 4 5 6610 4 5 6610 4 5 6610 4 5 10 9 1 5 7 7 9 1 1 3 5 8100 3 5 8100 4 5 5 10 9 1 1 3 5 8100 1 4 5 6 10 1 4 5 10 1 5 10 1 1 5 10 1 1 5 10 1 1 5 10 1 1 5 10 1 1 1 1	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 00000 000000 00000 000000 00000 00000 0000000 000000 00000000	N = 7 EGRATED FIN D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 -000 -000 -000 -000 -000 -000 -0	N=II         DLE       SOLUTION         IELD         27         00         00         24         08         01         41         56         24         08         01         41         56         24         577.2557         576.7550         590.0000         590.0000         2.0000         2.0000         2.0000	N=1 S 35918. 35918. 35918. 35813. 35813. 30889. -0. -0. -0. -0. -0.	<pre>.1500 .1500 .1500 .1500 .1500 .1500 .1500 .1500 .0.0.00 .000 .0</pre>	1 2 3 4 5 -0 -0 -0 -0 -0 -0	
	TWO 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0	N= 3 DIMENSION N 1 3 5 7 9 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 5 7 7 9 9 1 1 3 5 1 7 9 9 1 1 3 5 1 7 9 9 1 1 3 5 1 7 9 9 1 1 3 5 1 1 3 5 1 7 9 9 1 1 3 5 1 1 9 1 1 3 5 1 1 9 1 1 3 5 1 1 9 1 1 3 5 1 1 1 3 5 1 1 9 1 1 3 5 1 1 1 3 5 100 1 3 5 100 1 4 5 610 1 4 5 10 1 4 5 10 1 4 5 10 1 4 5 10 1 4 5 10 1 4 5 10 1 1 5 1 1 1 1 1 1 1 1 1 1 1 1 1 1	N=5 AL AND INTE 2D FIEL -4.157 .0000 .0000 .0000 00000 000000 00000 00000 00000 00000 00000 0000000 000000 00000000	N = 7 EGRATED FIN D 31 00 00 00 00 00 00 00 00 00 00 00 00 00	N=9 ELD MULTIP INTG. F -24.531 000 .000 -000 .000 .000 000 .000 .000 000 .0000 .0000	N=II         DLE       SOLUTION         IELD         27         00         00         00         00         00         00         00         00         00         00         00         00         00         00         00         00         00         00         00         24         00         24         08         01         41         56         24         577.2557         576.7550         590.0000         575.2013         590.0000         2.0000         -0.         2.0000         -0.         2.0000	N = 1 S 35918. 35918. 35918. 35813. 30889. -0. -0. -0. -0. -0. -0. -0. -0.	-1500 .1500 .1500 .1500 .1500 .1500 .1500 .0. -0. -0. -0. -0. -0. -0. -0. -0.	1 2 3 4 5 -0 -0 -0 -0 -0 -0 -0 -0	

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#### TEST CASE 16, THEORETICAL SECTOR BLOCK 1, CASE 14 PLS CASE 15

INPUT PARAMETERS

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1	3.8100	4.6080	.1700	32.3743	590.0000	35918.	•1500	1
1	3.8100	4.6080	36.3041	52.6675	584.2200	35918.	.1500	2
1	3.8100	4.6080	63.0582	71.6283	587.7600	35918.	.1500	3
1	4.6610	5.4590	2.0000	42.3799	590.0000	35813.	.1500	. 4
1	4.6610	5.4590	51.5902	66.9627	582.8200	35813.	.1500	5
1	4.6610	5.4590	0.	2.0000	590.0000	30889.	.1500	6
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0

TWO DIMENSIONAL AND INTEGRATED FIELD MULTIPOLE SOLUTIONS

N	2D FIELD	INTG. FIELD
1	-4.53126	-27.12436
3	00000	00001
5	.00000	.00274
7	00000	.00234
. 9	.00169	.01042
11	00039	00228
13	.00106	.00624
15	00039	00228
17	00010	00059
19	.00007	.00042

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JEST CASE 33, THEORETICAL SECTOR BLOCK 2, CASE 14 PLS CASE 32 INPUT PARAMETERS' 1 20 4 2.5400 9.5630 -0. -0--0 -0. -0. -0. -0. -0 -0 1 -0. -0. 1 -0. -0. -0. 35918. 590.0000 1 3.8100 4.5080 .1700 32.3743 .1500 3.8100 4.6383 36.3041 52.6675 584.2200 35918. .1500 1 .1500 35918. . 71.6283 1 3.8100 4.6080 63.0682 587.7600 .1500 35813. 1 5.4590 2.0000 31.8597 590.0000 4.6610 35813. .1500 1 4.6610 5.4590 35.8965 52.4172 583.0900 .1500 1 4.6610 5.4590 62.9207 71.5183 586.8500 35813. 0. 2.0000 30889. .1500 1 4.6610 5.4590 590.0000 -0. -0. -0. -0. -0. -0 -0. -0. -0. -0 -0. -0--0. -0. -0. -0 -0. -0. -0. -0. -0. -0 -0. -0. -0. -0. -0. -0. -). -0. -0. -0 -0. -0. -0. -0. -0. -0. -0. -0 -0. -0. -0. -0. -0. -0. -0 -0. -0. -0. -0. -0. -0. TWO DIMENSIONAL AND INTEGRATED FIELD MULTIPOLE SOLUTIONS 20 FIELD INTG. FIELD Ν 1 -4.47660 -26.77811 3 -.00000 -.00001 5 .00000 .00000 7 .00219 .00000 9 .00067 .00000 .00003 11 -.00000 13 .00726 .00124 15 -.00264 -.00045 -.00061 17 -.00010 19 .00008 .00044 

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•	TEST	CASE	45,	BLOCK	DIPOLE	HTIK	FERMI	BORE,	CASE	37	PLS	CASE	41
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C	·	•	INPUT PA	RAMETERS				· · ·		
C	· •	1 1	1 20 -0. -0.	4 -0.	2.5400 -0. -0.	9.5630 -0 -0.	-0. -0.	-0. -0	-0.	
С		-		и - Сталана - С				· · · ·		
C		2 2 2	3.8100 3.8100 3.8100	4.6080 4.6080 4.6080	16.0380 44.3352 67.5853	15.5333 8.2844 4.1422	590.0000 584.3700 587.6800	35918. 35918. 35918.	• 1500 • 1500 • 1500	
C	<b>*</b> 	2 2 1	4.6610 4.6610 4.6610	5.4590 5.4590 5.4590	22.0236 59.0047 0.	19.8122 7.7526 2.0000	590.0000 582.9300 590.0000	35813. 35813. 30889.	<pre>.1500 .1500 .1500</pre>	•
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TWO DIMENSIONAL AND INTEGRATED FIELD MULTIPOLE SOLUTIONS

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والمراجعة أيستري التراري

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TEST CASE 52, PALMER TYPE MODIFICATION OF FERMI DIPOLE, FINITE WIRE, SEE CASE 13

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τωο	DIMENSION N	AL AND INTE 20 FIEL -4.1068	EGRATED FI LD 85	ELD MULTIP INTG. F -24.385	OLE SOLUTIO IELD	NS	••••••••••••••••••••••••••••••••••••••		
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#### TEST CASE 58, BLOCK DIPOLE WITH FERMI BORE, CASE 37 PLS CASE 57

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2	3.8100	4.6080	16.0380	15.5333	590.0000	35918.	.1500	. 1
2	3.8100	4.6080	44.3352	8.2844	584.3700	35918.	.1500	2
2	3.8100	4.6080	67.5853	4.1422	587.6800	35918.	.1500	3
2	4.6610	5.4590	16.6438	14.6438	590.0000	35813.	.1500	4
2	4.6610	5.4590	43.7469	8.6140	583.2800	35813.	.1500	5
2	4.6610	5.4590	67.9895	4.3070	586.7200	35813.	.1500	6
1 -	4.6610	5.4570	0.	2.0000	590.0000	30889.	.1500	7
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0
-0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0

TWO DIMENSIONAL AND INTEGRATED FIELD MULTIPOLE SOLUTIONS

N	2D FIELD	INTG. FIELD
1	-4.42981	-26.49702
3	.00000	.00001
5	• 00000	00000
7	.03041	•00451
9	00024	00070
11	.00037	•00226
13	.00136	•0079 <b>7</b>
15	00046	00270
17	00010	00061
19	• 00007	•00043

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TEST CASE 61, TEST CASE O WITH E = 1000000 PSI

· ·		INPUT PA	RAMETERS			* • • • • •			· · · ·	
1	1	20 -0. -2.	4 -0.	2.5400 -0. -0.	9.5630 -0 -0.	-0. -0.	-0. -0	-0.		
		· .				• •				
	1 1 1 0 - 0 -	3.8100 4.6610 4.6610 -0. -0.	4.6080 5.4590 5.4590 -0. -0. -0.	•1700 2•0000 0• -0• -0• -0•	72.1740 36.4550 2.0000 -0. -0. -0.	603.5800 590.0000 590.0000 -0. -0. -0.	35918. 35813. 30889. -0. -0. -0.	• 1500 • 1500 • 1500 -0. -0. -0.	1 2 3 -0 -0 -0	
									·.	
Т	WO DI	IMENSION	AL AND INT	EGRATED FI	ELD MULTIP	OLE SOLUTIO	NS .			
	N		20 FIE	LD	INTG. F	IELD				
	1 3 5 7 9 11 13 15 17 19		-4.324 -012 001 -033 005 -001 000 000 -000 -000	58 59 87 79 45 59 29 00 03 02	-26.303 027 .014 022 .033 009 .001 .000 000 .000	97 20 99 73 14 62 80 02 16 13			•••	
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TEST CASE 62, TEST CASE 45 WITH E = 1000000 PSI

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INPUT PARAMETERS -0. -0. 9.5630 20 2.5400 1 4 -0. -0 ~0. -0 -0. -0 1 -0. -0. 1 -0. -0. -0. -0. 15.9640 3.8100 4.6080 15.5333 590.0000 35918. .1500 1 Z .1500 3.8100 35918. Ζ 4.6080 44.1520 8.2844 584.3700 Z, .1500 3.8100 3 35918. 4.6080 67.3820 4.1422. 587.6800 2 .1500 4 590.0000 35813. 2 4.6610 5.4590 21.9300 19.8122 .1500 5 582.9300 35813. 7.7526 2 4.6610 5.4590 58.8200 2.0000 30889. .1500 5 590.0000 5.4590 Ο. 1 4.6610 -0. -0. -0. -0. -0. -0 -0. -0 -0. -0. -0. -0. -0. -0 -0 -0. -0. -0. -0. -0. -0. --0. -0 -0 -0. -0. -0. -0 -0. -0 -0. -0. . -0. -). -0. -0. -0 -0. -0. -0. -0. -0. -0. -0 -0. -0. -0. -0 -0 -0. -0. -0. -0. -0.

#### THO DIMENSIONAL AND INTEGRATED FIELD MULTIPOLE SOLUTIONS

N	2D FIELD	INTG. FIELD
1	-4.46662	-26.73713
3	00388	02298
5	.00044	.00518
· · · · · ·	00035	• 00022
· · ·	.03177	.01093
11	00011	00051
13	.00116	.00682
15	00037	00219
17	00011	00065
19	.00007	•00040

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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