MAGNET DIVISION NOTES

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Task Force: Coil Geometry Analysis

Title: Collarless, Close-in, Elliptical Aperture Designs for the SSC Dipole

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In this note we examine the use of an elliptical aperture in the two layer SSC dipole. It has been shown previously [1] that an elliptical iron aperture (instead of a conventional circular one) allows one to bring the iron closer to the coil with the ellipticity reducing the change in sextupole harmonic due to iron saturation. Closer iron with the same amp-turns gives a significantly higher transfer function at all field levels. The elliptical shape of the aperture is modified to reduce the variation (due to iron saturation) in higher order harmonics over the specified range of operating field.

The procedure used to perform this analysis and to come up with designs satisfying the required performance is basically the same as was used [2] for "Single Layer Coil 6.1 Tesla SSC Dipole". The only difference is that instead of using program MDP, we have now used POISSON for performing the field computations. POISSON (AUTOMESH) was upgraded to permit an analytic, user-defined iron boundary. Setting up a model on POISSON is somewhat more complicated and requires some approximation in the coil structure. However the correction required (to offset harmonics due to this approximation) is never more than 0.15×10^{-4} in any field harmonic for a normalization radius of 1 cm.

We present three models. The first one, referred to as Design SSCEL36, has a coil structure with 36 turns in it (the same number as in the current SSC design, C358D), the second, referred to as SSCEL35, has 35 turns, and the third, SSCEL34 has 34 turns. The iron aperture shape is different in two of the three cases. At 4.2 K and above, NbTi has a rapidly decreasing J_c with field at 7 T, and a design with 37 turns gives very little increase in quench field.

In the SSC, systematic harmonics b_2 and b_4 in the dipole are corrected by trim coils in each dipole, so these two allowed systematic errors are relatively large. The allowed systematic errors are $b_2 = \pm 1.0$, $b_4 = \pm 0.2$, $b_6 = \pm 0.04$ and $b_8 = \pm 0.10$. With some exception in the case of b_2, the three coil and iron aperture combinations satisfy these requirements at all field levels up to 6.6 T. The sextupole term in EL34 and EL35 has a peak value slightly in excess of the specification.

The design process controls the harmonics at zero field and at a single high field. At intermediate fields there is a peak in b_2 at 5.5 to 5.7 T, followed by a rapid drop. The choice of high field at which the harmonics are controlled determines in part the size of the peak and the extent of drop above the peak. In all three cases, the optimization field was about 6.3 T. It should be realized that a harmonic which is changing rapidly is sensitive to details of the iron cross-section configuration, the packing factor (assumed to be 97.5%) and iron impurities.

In all models, the gap between coil and iron at the midplane is 5.07 mm. A smaller value is undesireable because the electrical insulation may be compromised, and because optimization is more difficult. A larger value results in reduced field enhancement by the iron, and reduces the size of the b_2 peak.

Details of the designs

The cable dimensions are the same as used in the C358D design[3]. The iron aperture radius at the midplane is 45 mm, 10.7 mm less than the SSC standard. There is no pole notch and the midplane notch is the same size as in the current SSC design. The SSC collar would be replaced with a cast plastic sleeve having a circular interior cross-section.

Table 1 gives the turn configuration and block tilt of the 3 designs; C358D is included for comparison.

Table 1

	turns		block tilt			
	inner	outer	2	3	4	6
EL34	3-5-4-3	8-11	0.00	0.00	0.00	0.00
EL35	4-6-4-2	8-11	0.00	0.00	0.00	0.00
EL36	4-5-4-3	7-13	5.87	3.83	0.00	1.83
C358D	4-5-4-3	11-9	8.73	9.58	-.43	9.00

Table 2 gives the semi-minor (a) and semi-major (b) axes and bump sizes (in cm) used in the iron aperture design and the harmonic offsets used to compensate for the elliptical iron aperture.

Table 2

	bump sizes				offsets used			
	a	b	b_4	b_6	b_2	b_4	b_6	b_8
EL34	4.500	4.983	0.225	-.076	-14.3	-.80	-.03	-.05
EL35	4.500	4.983	0.225	-.076	-14.5	-.80	-.09	-.10
EL36	4.500	5.090	0.219	-.122	-16.7	-.68	-.01	-.10
C358D	5.571	5.571	0.0	0.0	-2.7	-.51	0.08	-.06

In the case of C358D in Table 2, the offests used compensate for b_i observed in C358A due to constructional errors.

Figure 1 shows the EL36 coil design and Figure 2 shows the POISSON model of it and the iron yoke. Figures 3 and 4 are the POISSON models of EL34 and EL35, respectively and also show the iron aperture.

Performance

The harmonics at 1 cm are given in Tables 3 thru 5 and in Figures 5 thru 7 for EL34 thru 36, respectively, as a function of central field. Higher harmonics than those listed are all less than 0.1 unit.

Table 3
EL34

I, kA	B_0, T	b_2	b_4	b_6	b_8
∞ μ		0.111	0.003	-.029	-.092
2.950	3.0885	0.077	0.003	-.028	-.092
4.720	4.9211	0.762	-.009	-.029	-.092
5.310	5.4968	1.230	-.002	-.029	-.093
5.900	6.0469	0.820	0.003	-.028	-.094
6.136	6.2598	0.330	-.005	-.028	-.094
6.490	6.5698	-.790	-.034	-.029	-.095
6.785	6.8200	-1.986	-.069	-.030	-.095

Table 4
EL35

I, kA	B_0, T	b_2	b_4	b_6	b_8
∞ μ		-.193	0.014	0.034	0.070
2.950	3.1752	-.224	0.014	0.034	0.070
4.720	5.0549	0.622	0.001	0.034	0.070
5.310	5.6427	1.040	0.011	0.036	0.071
5.900	6.2038	0.434	0.009	0.038	0.072
6.195	6.4737	-.342	-.007	0.038	0.072
6.490	6.7352	-1.440	-.038	0.038	0.073
6.785	6.9904	-2.710	-.074	0.039	0.073

Table 5
EL36

I, kA	B_0, T	b_2	b_4	b_6	b_8
∞ μ		0.022	0.004	0.029	0.010
2.950	3.2419	-.010	0.004	0.029	0.010
4.720	5.1580	0.544	0.030	0.026	0.010
5.310	5.7557	0.680	0.060	0.027	0.010
5.900	6.3251	-.212	0.064	0.028	0.010
6.136	6.5445	-.917	0.053	0.028	0.011
6.490	6.8632	-2.349	0.020	0.027	0.011

The critical performance is determined by the peak field and the Ic(B,T) surface [4]. The ratios of peak field to central field are given in Table 6.

Table 6

Ratio of peak field to central field

Model	EL34	EL34	EL35	EL35	EL36	EL36	C358A	C358A
B_0	6.5698	6.8200	6.4737	6.7352	6.5445	6.8632	6.6938	7.0454
inner	1.0515	1.0521	1.0402	1.0407	1.0473	1.0480	1.0499	1.0504
outer	0.8417	0.8417	0.8376	0.8375	0.8476	0.8475	0.8418	0.8419

The remaining parameters of interest are low and high field transfer function and their ratio, critical field and current in the inner with Cu/sc = 1.3 and $J_c(5,4.22)$ = 2475 A/mm^2, margin in I_c in the outer with Cu/sc = 1.8 at the same current, and stored energy, E. Table 7 lists these data for EL34, EL35, EL36 and C358A for comparison.

Table 7

		EL34	EL35	EL36	C358A
T.F., T/kA,	low B_0	1.0472	1.0766	1.1050	1.0395
	6.6 T	1.0114	1.0414	1.0649	1.0157
	ratio	.9659	.9673	.9637	.9771
E, kJ/m @ 6.6 T		63.5	62.8	63.3	66.1
Critical field, T		6.844	6.948	6.955	6.867
current, kA		6.813	6.730	6.592	6.788
margin in outer, %		3.64	3.49	3.74	3.49

Note that the loss of transfer function with field is less with C358A than with any of the other designs; this is presumedly because more of the flux returns in the air gap between coil and iron, with resultant reduced iron saturation, even though the yoke is wider at the midplane in the elliptical aperture designs.

Discussion

The decrease in stored energy of the close-in iron designs will be accompanied by a 4 to 5 % reduction in axial forces on the coil ends.

The slightly over-specification b_2 shift could be reduced by increasing the semi-minor axis a, or perhaps by optimizing at a B_0 nearer the b_2 peak.

Since the total superconductor cost in the SSC dipoles is about $250 M, a reduction of 1 turn per quadrant gives a saving of about $7 M; magnetization effects are reduced in the same ratio.

No dipoles have been built with an elliptical aperture. The RHIC dipole design uses close-in, circular iron without a collar; it currently exhibits slight training. Calculations by M. Rehak and C. Goodzeit of the prestress obtainable in a collarless SSC design indicate an adequate level is possible.

References

1) G. Morgan, "Reduction of iron saturation is cosine theta dipoles", RHIC Tech Note 10 (7/29/85)

2) R. Gupta, G. Morgan and P. Thompson, "A Single Layer Coil, 6.1 Tesla SSC Dipole", Magnet Division Note No. 186-1 (6/25/86)

3) G. Morgan, "C358D: A Revision of the SSC Coil Design C358A", Magnet Division Note No. 255-1 (SSC-MD-183) (1/29/88)

4) G. Morgan and W. Sampson "New Coefficients for a $J_c(B,T)$ Analytic Form" SSC Tech. Note No. 76 (SSC-N-519), (6/10/88)

EL36
file =DUA0:[MORGAN]FOR010.DAT;2

10-MAY-88 14:03:04
Run 10-MAY-88 14:16:28

CHISQ= 0.037809 + PENALTY= 0.042189 (X 0.1E+08)
TRANSFER FUNCTION= 11.24692 POLE ANGLE= 74.56934

TURNS	TILT	WEDGE	Face Angles	
4.0			-0.23	-8.79
- - - - - - - - - - - -		1.4600		
5.0	5.8676		0.60	-10.09
- - - - - - - - - - - -		1.5630		
4.0	3.8260		1.18	-7.36
- - - - - - - - - - - -		3.8206		
3.0	0.0000		3.20	-3.20
7.0			0.00	0.00
- - - - - - - - - - - -		0.9925		
13.0	1.8286		-0.17	-7.19

HARMONICS (0-10TH)

10000.00
-16.70
-0.68
0.02
0.01
0.07
-0.01
0.01
0.00
0.00

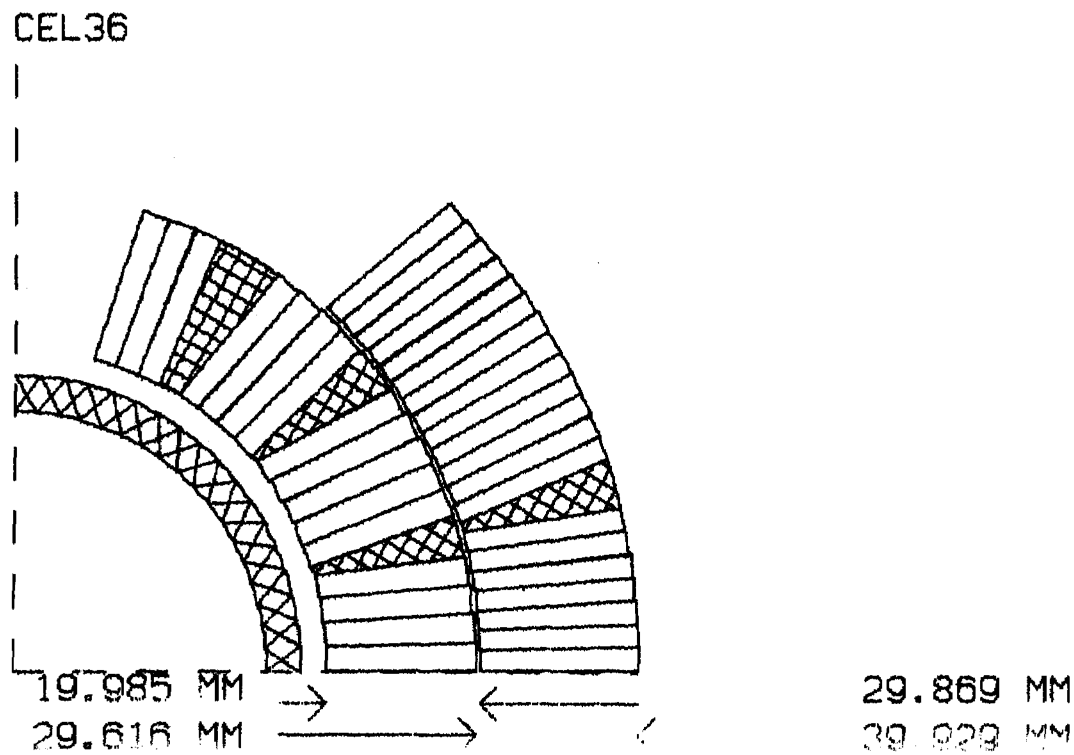


FIGURE 1

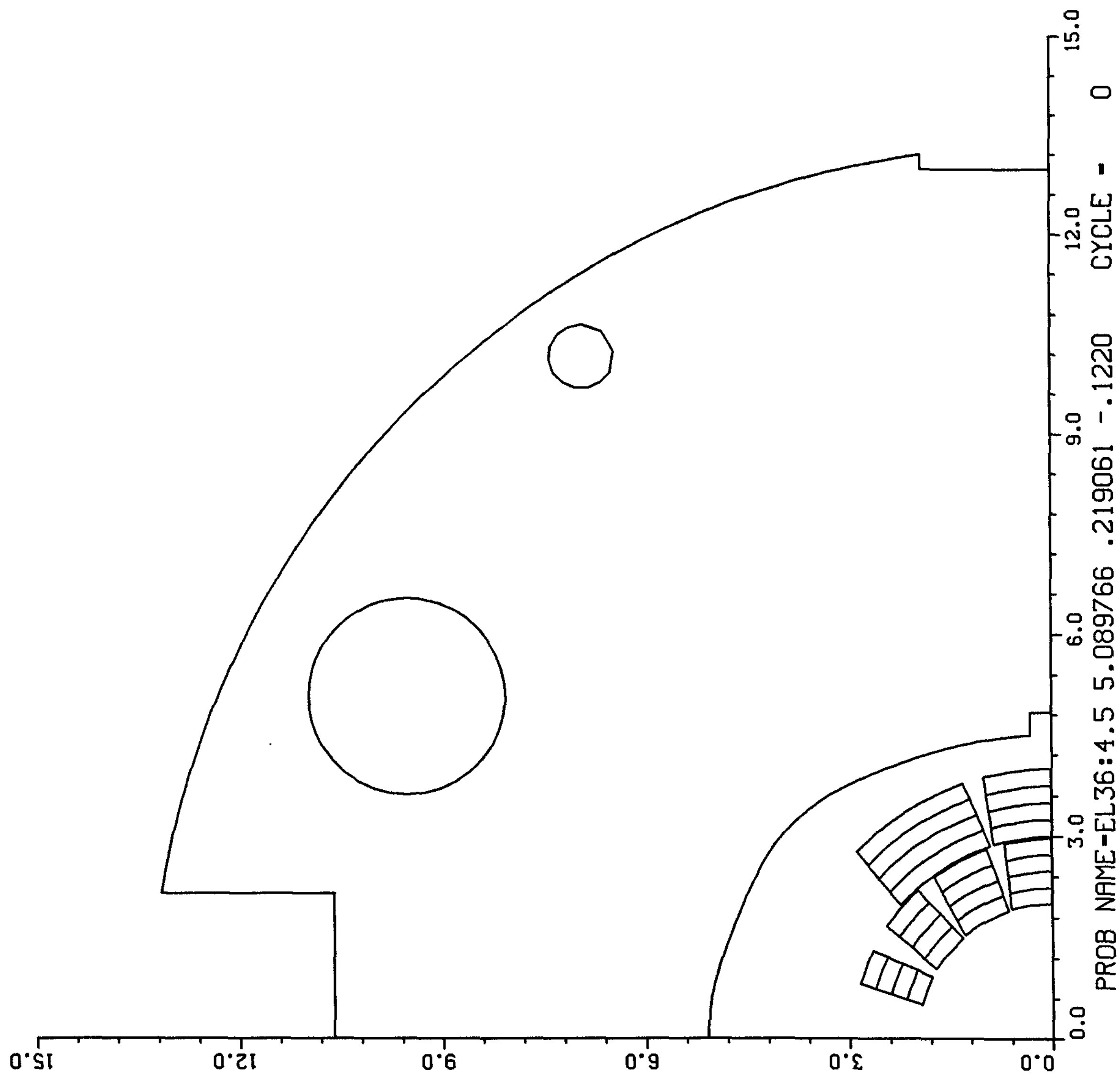

PROB NAME-EL36:4.5 5.089766 .219061 -.1220 CYCLE - 0
0.0
3.0
6.0
9.0
12.0
15.0

FIGURE 2

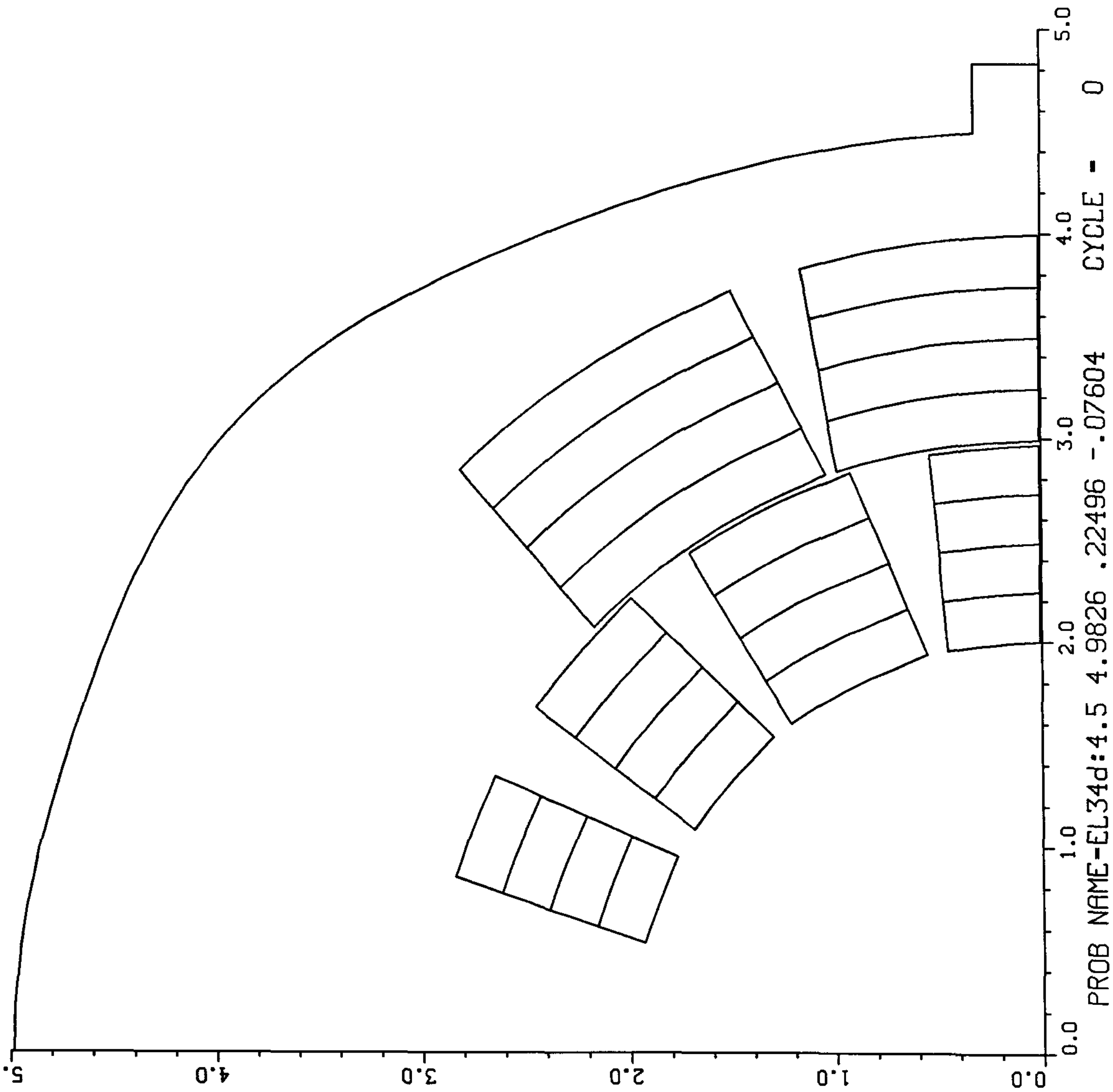


FIGURE 3

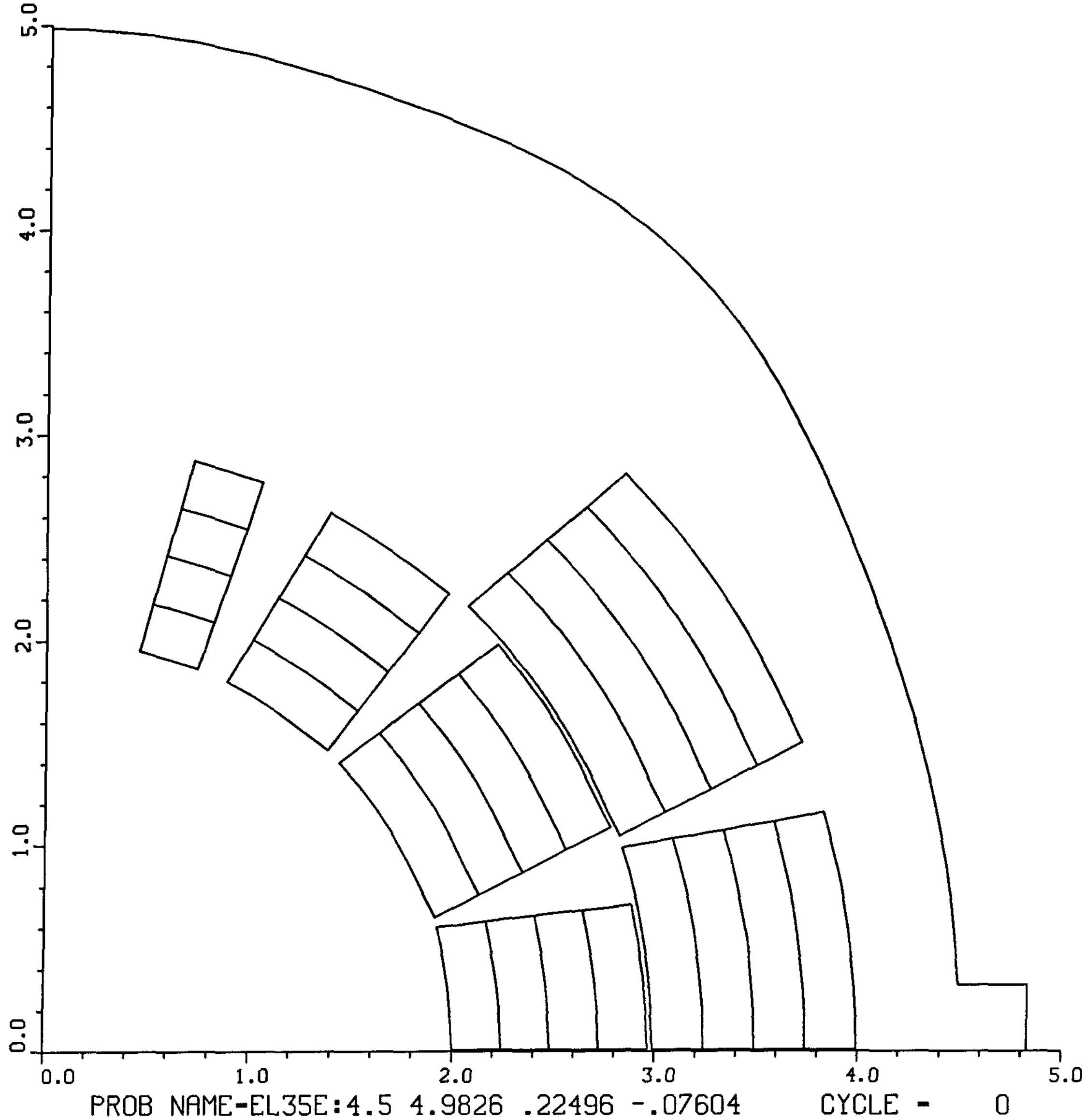
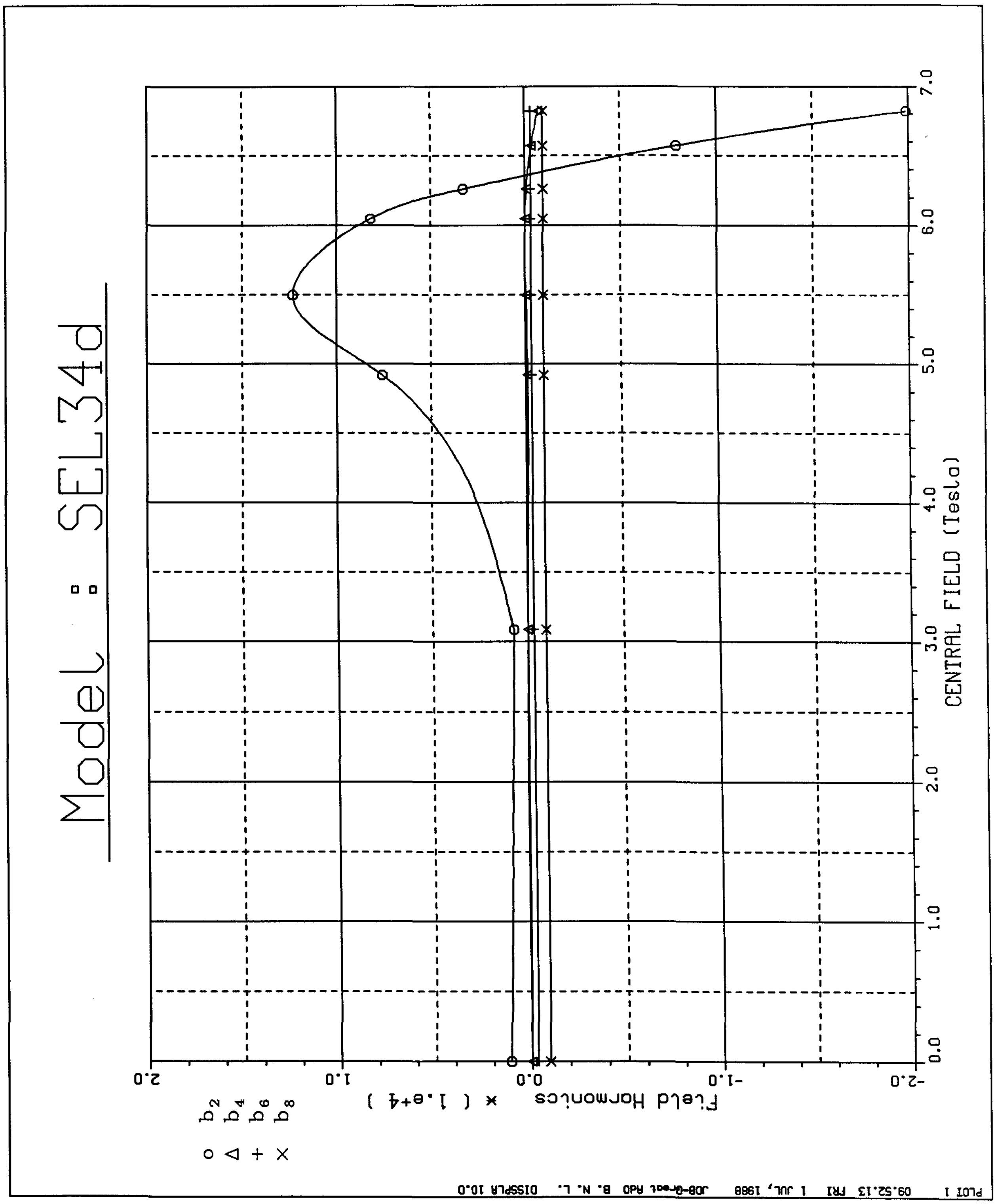


FIGURE 4

FIGURE 5



Model : SEL34d
CENTRAL FIELD (Tesla)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Field Harmonics * (1.e+4)
2.0
1.0
0.0
-1.0
-2.0
o b_2
Δ b_4
+ b_6
× b_8
PLOT 1 09.52.13 FRI 1 JUL, 1988
B. N. L. DISSPLA 10.0

FIGURE 6

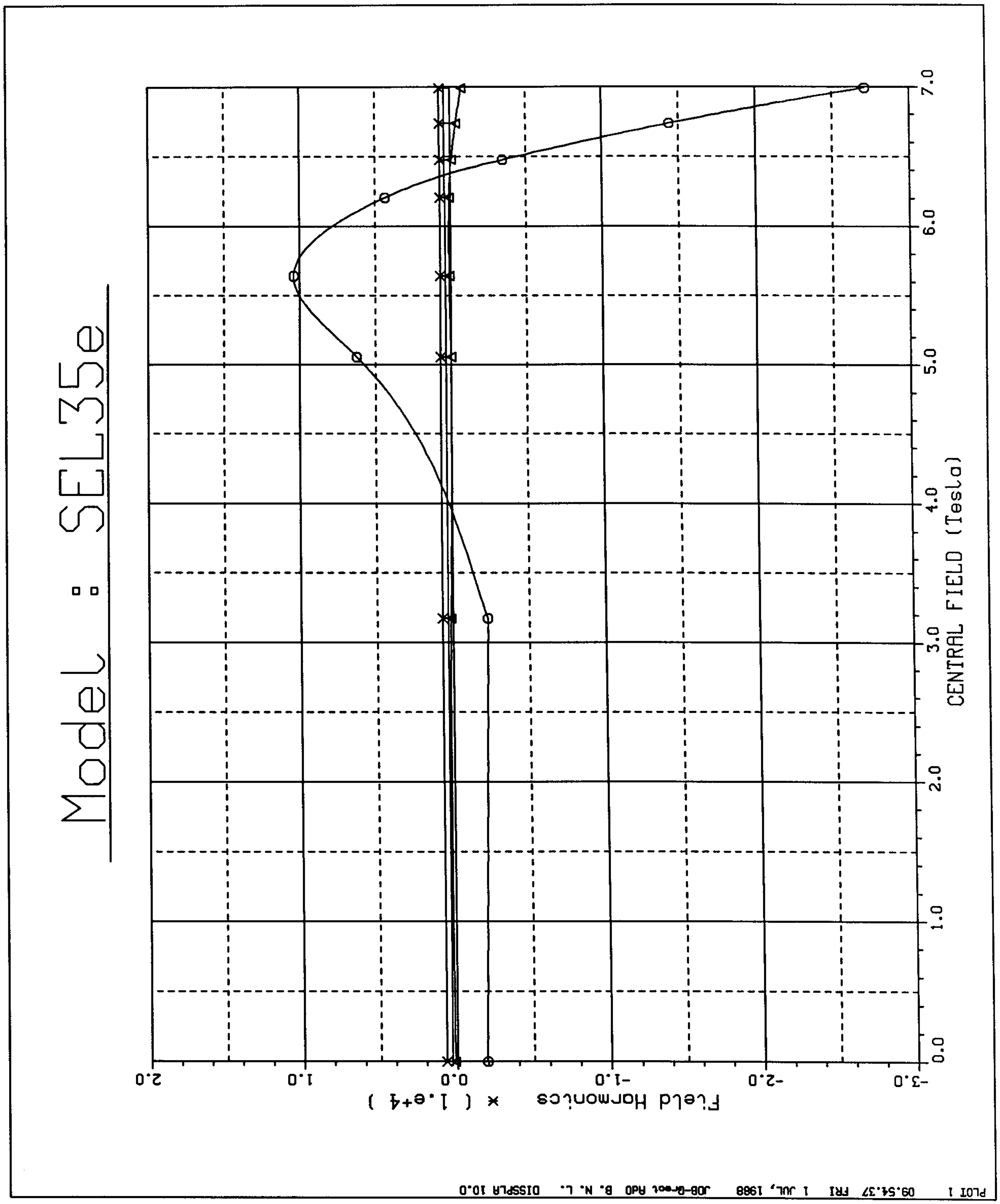
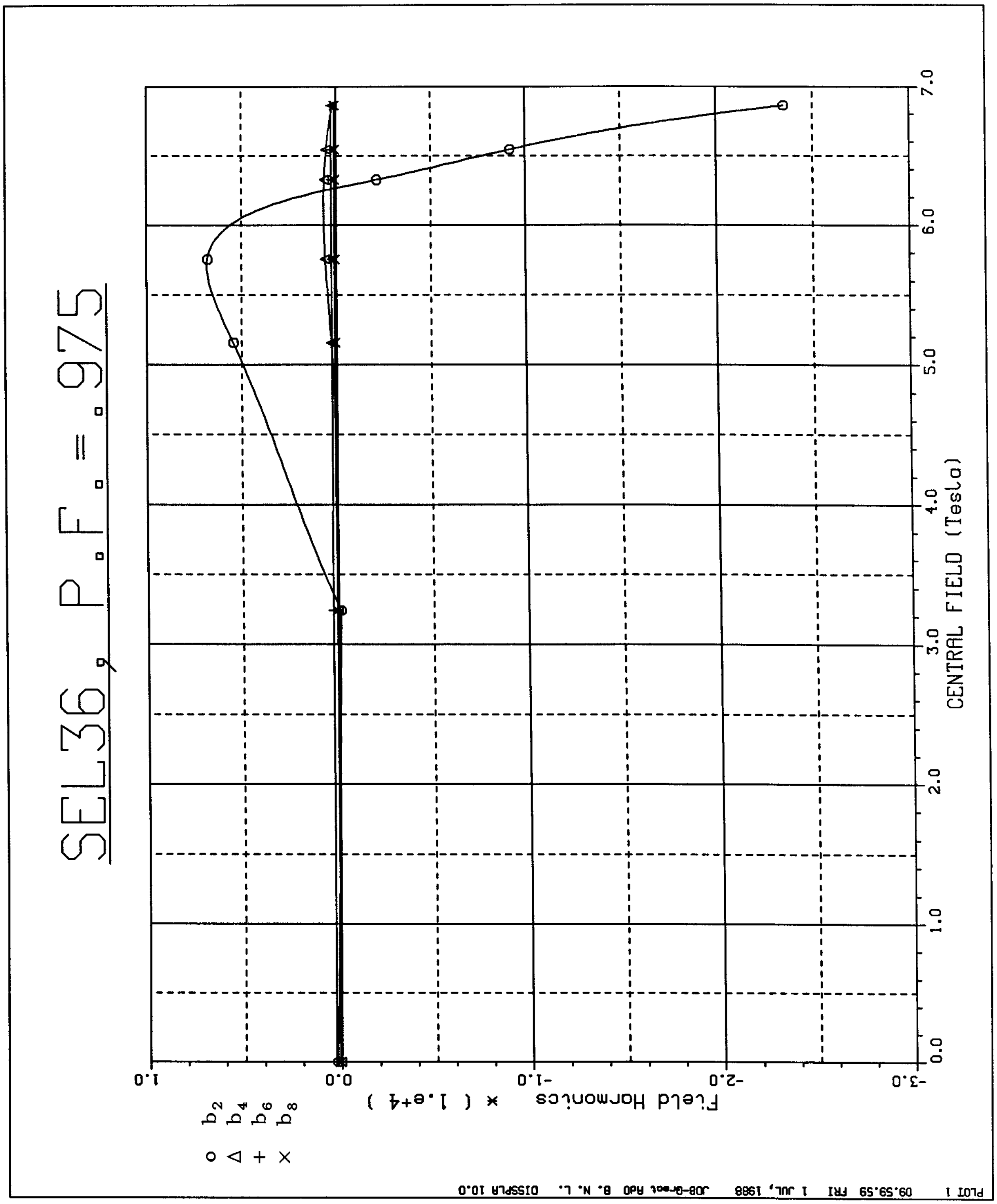

Model : SEL35e
Field Harmonics × (1.e+4)
2.0
1.0
0.0
-1.0
-2.0
-3.0
CENTRAL FIELD (Tesla)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
PLOT 1 09.54.37 FRI 1 JUL, 1988 B. N. L. DISSPLA 10.0

FIGURE 7


SEL36, P.F. = .975
CENTRAL FIELD (Tesla)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Field Harmonics * (1.e+4)
1.0
0.0
-1.0
-2.0
-3.0
o b2
Δ b4
+ b6
× b8
PLOT 1
DISSPLA 10.0