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The Effect of Iron Saturation on the SSC Dipole Magnet*

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This report compares recent computation on the effect of iron saturation on the sextupole harmonic with measurements from magnets D14-B1,-B2, and -B3. In addition we have computed the effect of circular OD iron, elliptical ID iron, and examined non-uniformity contributions from notches and holes in the iron.

Based on these studies we point out possible ways of reducing sextupole using a smaller OD iron, using elliptical ID iron and/or modifying the inner notches' dimensions.

Effect of Iron Saturation on b2

We have used the program POISSON to compute the multipoles at 1 cm from the center of the bore, varying the excitation from ~0.6 T to over 8.0 T. The coil cross-section was of the NC515 type (LBL 20946) in which each layer was radially split in half and each half assigned 50% of the total current of that layer.

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Two sets of calculations were made: one for smooth circular ID iron with no holes, and the other with a more realistic iron design that included notches and holes (Fig. 1). In both cases the multipoles were first computed with $\mu = \infty$ iron and these values used as offsets. Fig. 2 shows the behavior of the sextupole for the two cases with additional data from the measurements of magnets D14-B1, -B2, and -B3. Since the measured data includes magnetization we have used the 3000 A sextupole value as a reference from which subsequent values were subtracted. Because measured multipole values do no repeat on up and down swings of current we have placed a symbol (Fig. 2) at the <u>average</u> of the two and added an "error" bar which corresponds to the increasing field sextupole only. The average sextupole is of interest from a design standpoint, while the increasing field sextupole is of interest from an operational standpoint. Measurements should be compared with the computations of the notched iron case, which most closely models the iron used in the three real magnets. (The effect of stacking the iron laminations was not included in the computations and a stacking factor of 1.0 was used). Also plotted are b_2 measurements from magnet SLN008, a C-5 cross-section, measured by BNL. A 2000A reference was used in this case.

The agreement between computation and measurement as well as between magnets is fair, typically 0.5 to 1.0 units difference at a given Bo. However variations in sextupole of this magnitude can easily come from coil distortion due to such effects as pre-compression, Lorentz forces, and friction. The transfer functions corresponding to the same computations and measurements are shown in Fig. 3.

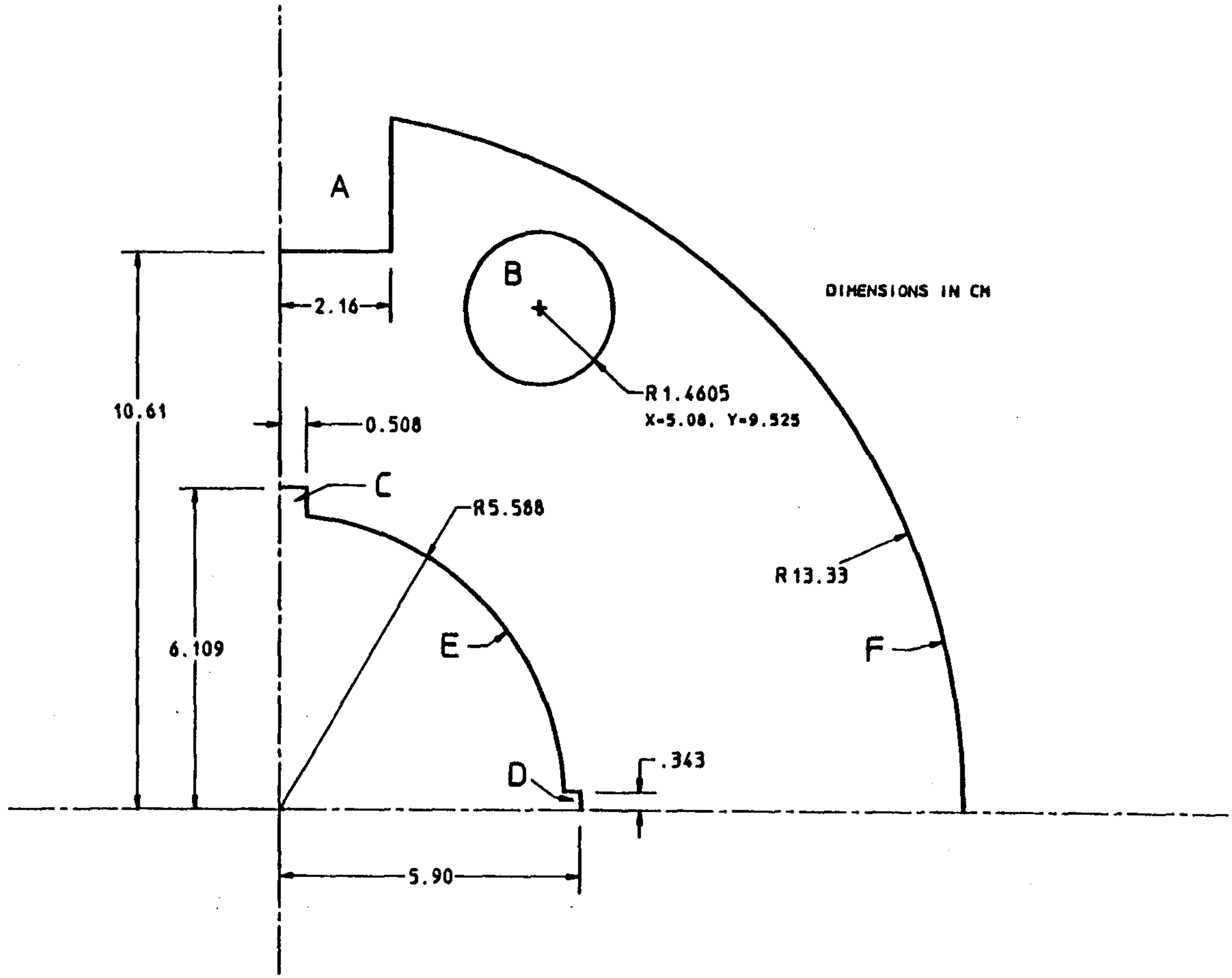


Fig. 1 Nominal iron dimensions for the SSC dipole magnet

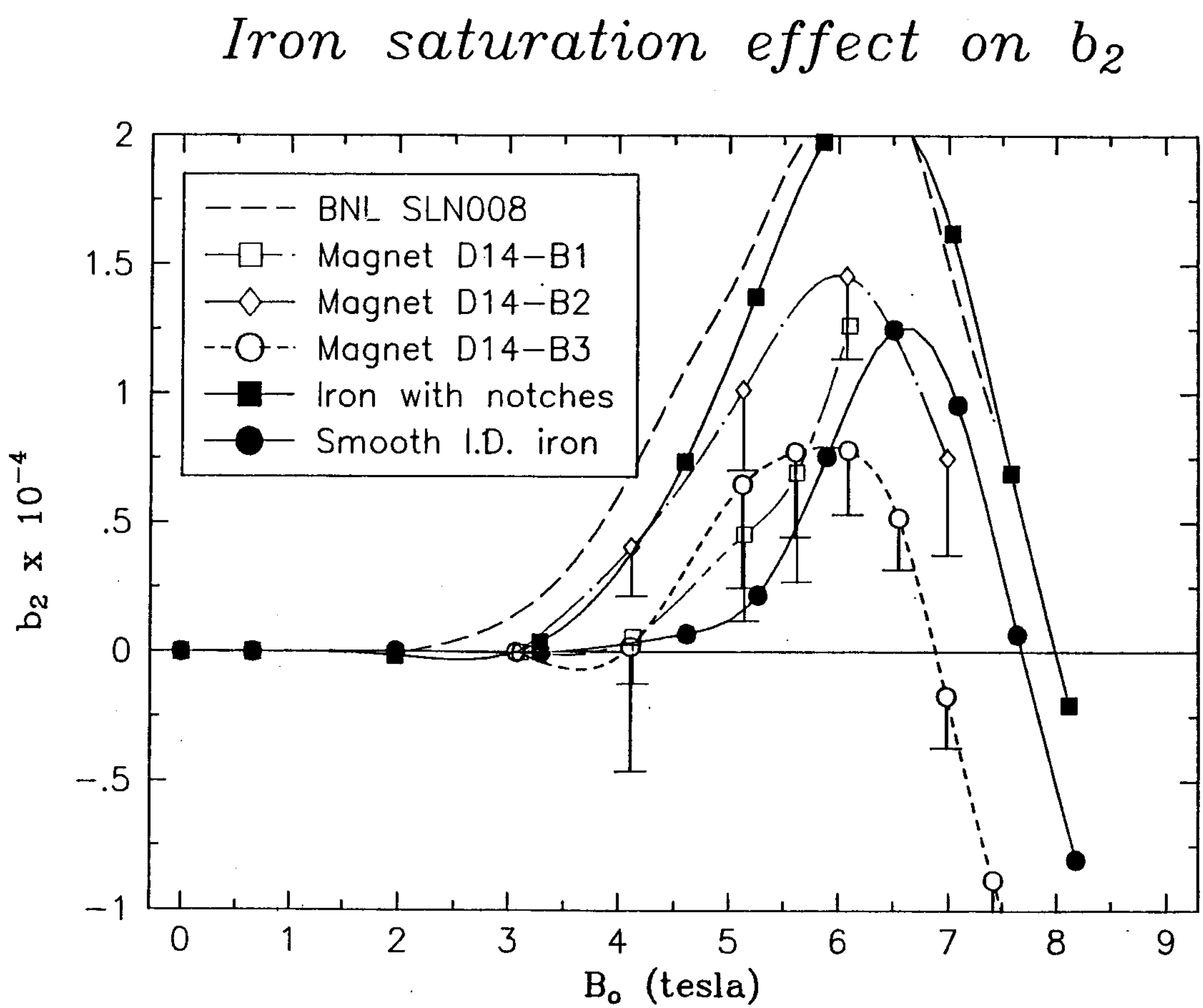


Fig. 2 Computation and Measurement of Saturation Effect on b2

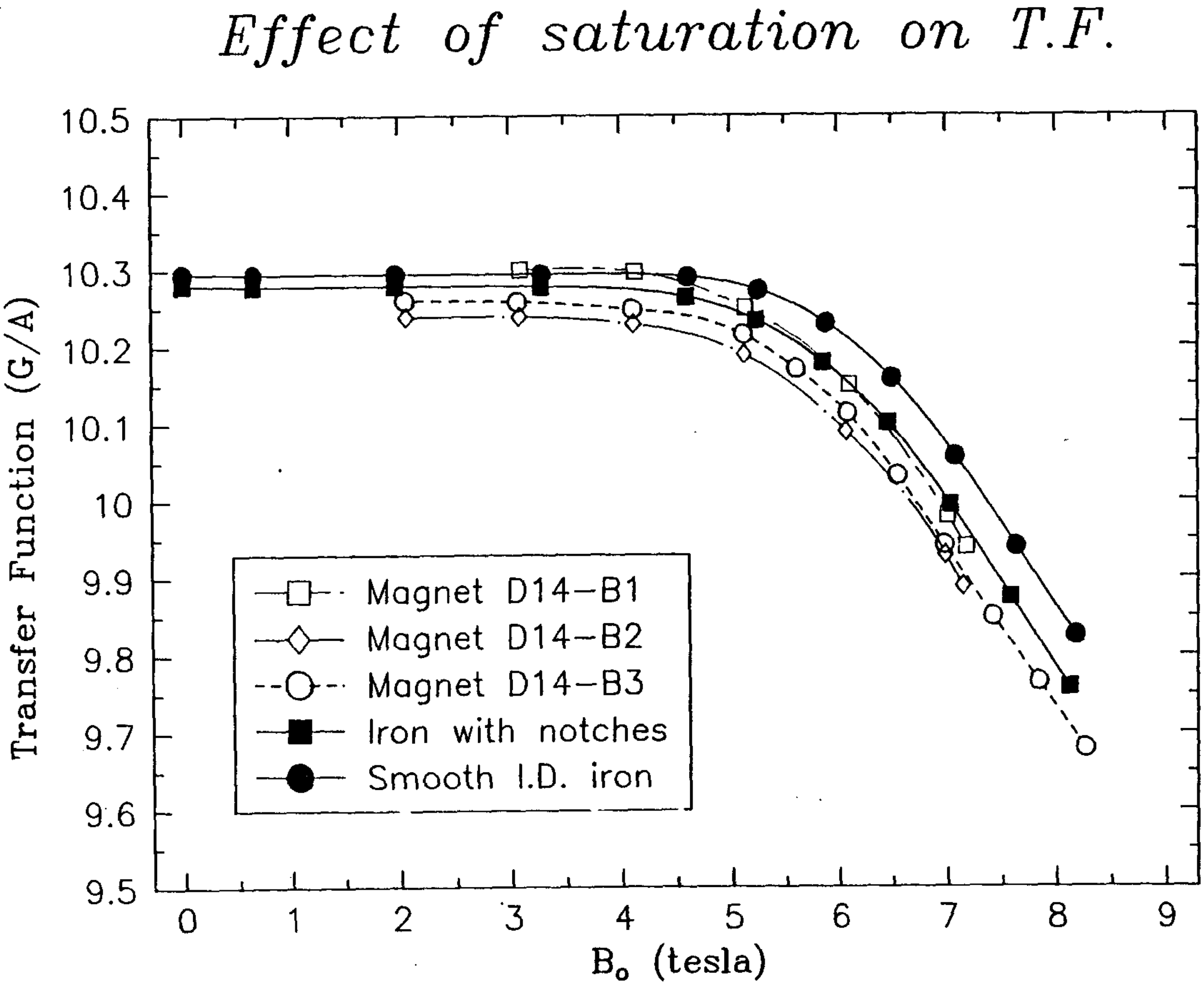


Fig. 3. Computation and measurement of the transfer function with increasing field

Effect of Iron OD on b2

Based on our computational experience the iron affects the sextupole in the following ways:

a) A positive contribution arises as the iron saturates along its inner diameter.

b) A negative contribution arises from the fringe field along the iron outer diameter.

It is of course desirable to match both contributions so as to cancel each other. Such an attempt was made on an iron yoke that is smooth and circular along its ID with a notch at 90 degrees on the OD. The ID was held fixed but the OD was varied from 10.5" to 10.0" to 9.0". In each case an offset corresponding to $\mu = \infty$ iron was computed and later subtracted from real iron harmonics. These results are plotted in Fig. 4 for b2 and Fig. 5 for the reduction in the transfer function. Reducing the iron OD by 0.5" from the current 10.5" reduces b2 due to saturation by 75% with reduction of 0.5% in the transfer function. A flux plot for a 10.0" OD iron at 6.5 T is given in Fig. 6.

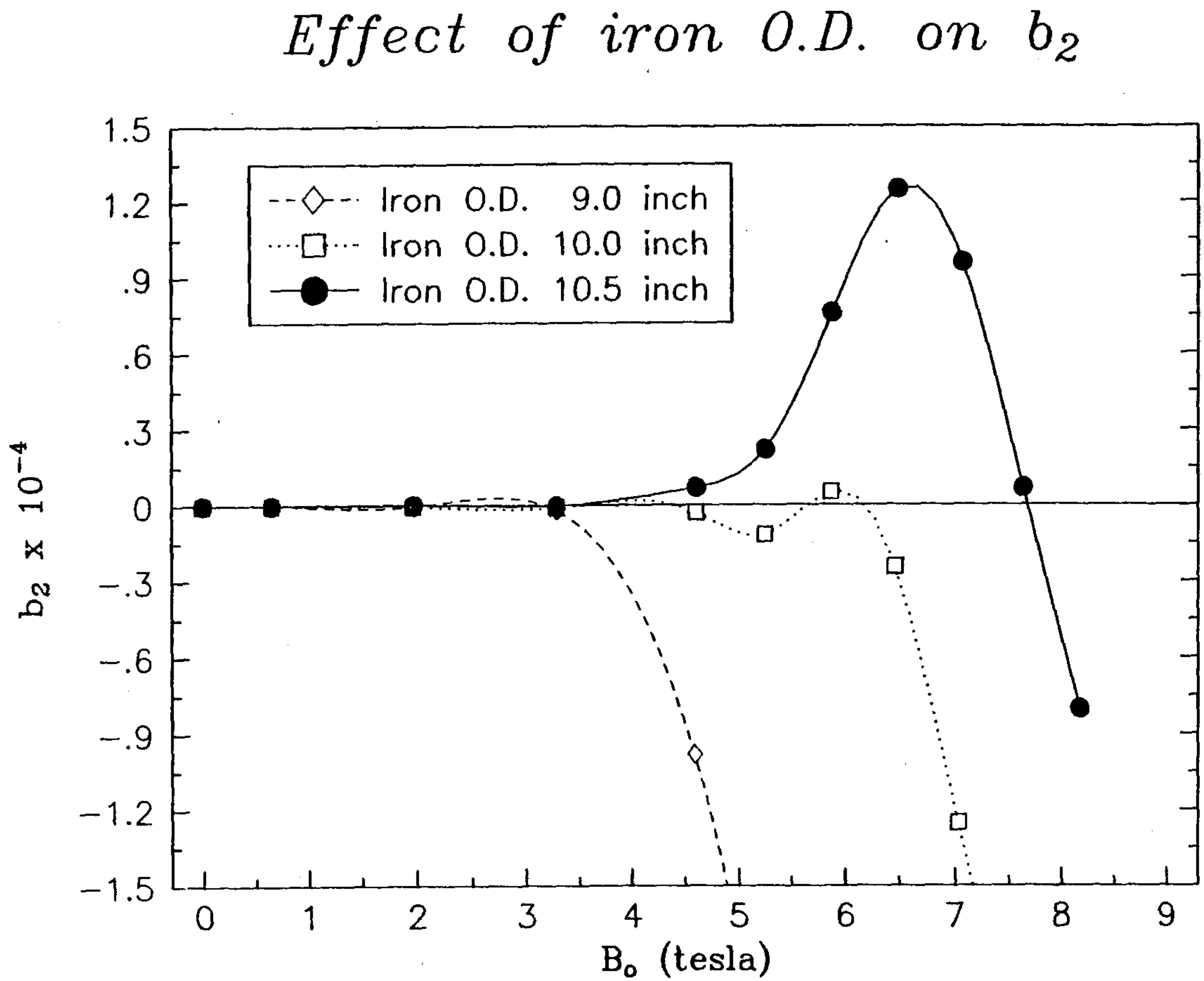


Fig. 4. Computed Values of b2 with real iron for a smooth inner bore iron R = 5.588 cm, and variable iron O.D., the present SSC O.D. is 10.5".

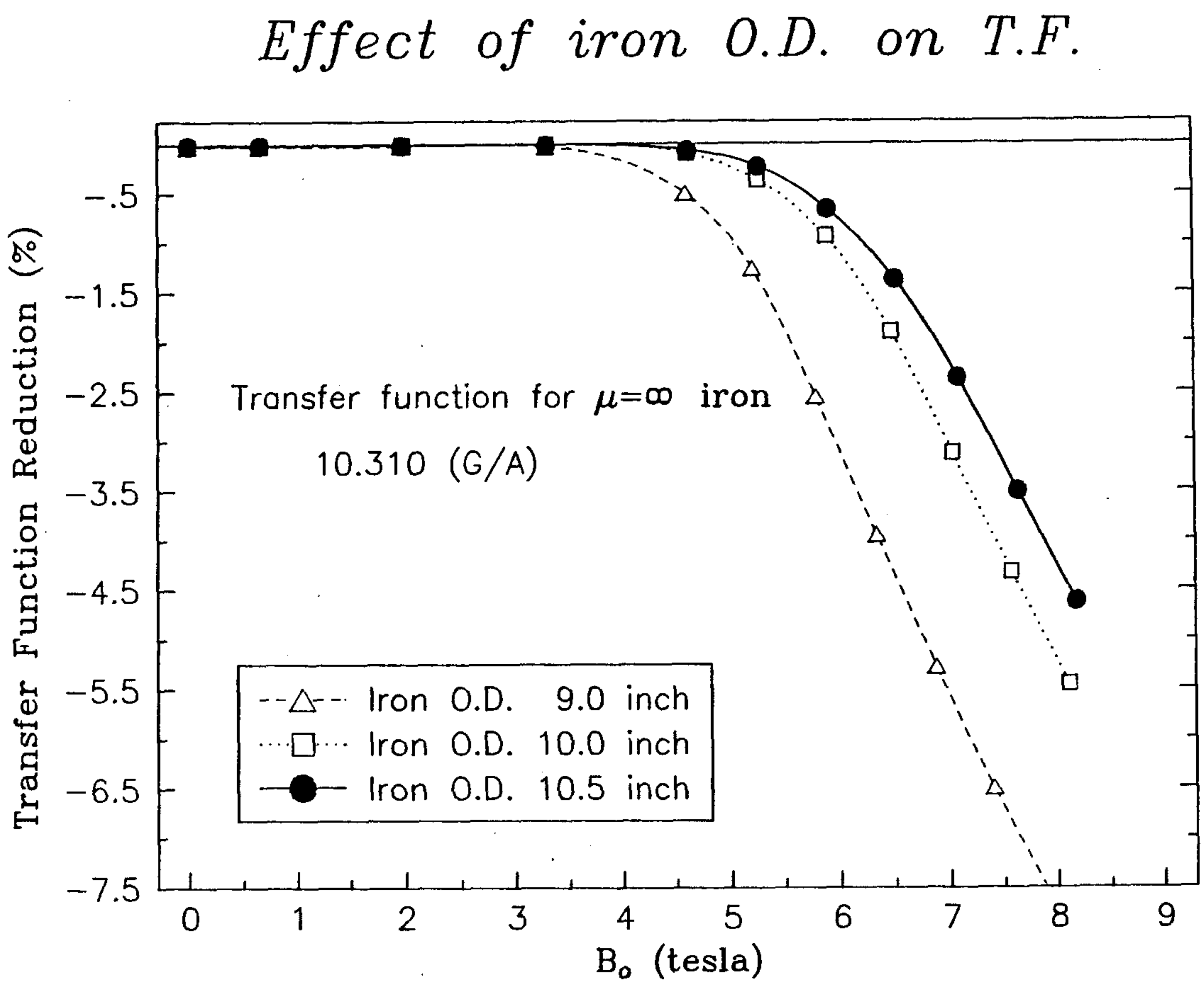


Fig. 5 Computed effect of iron O.D. size on the transfer function

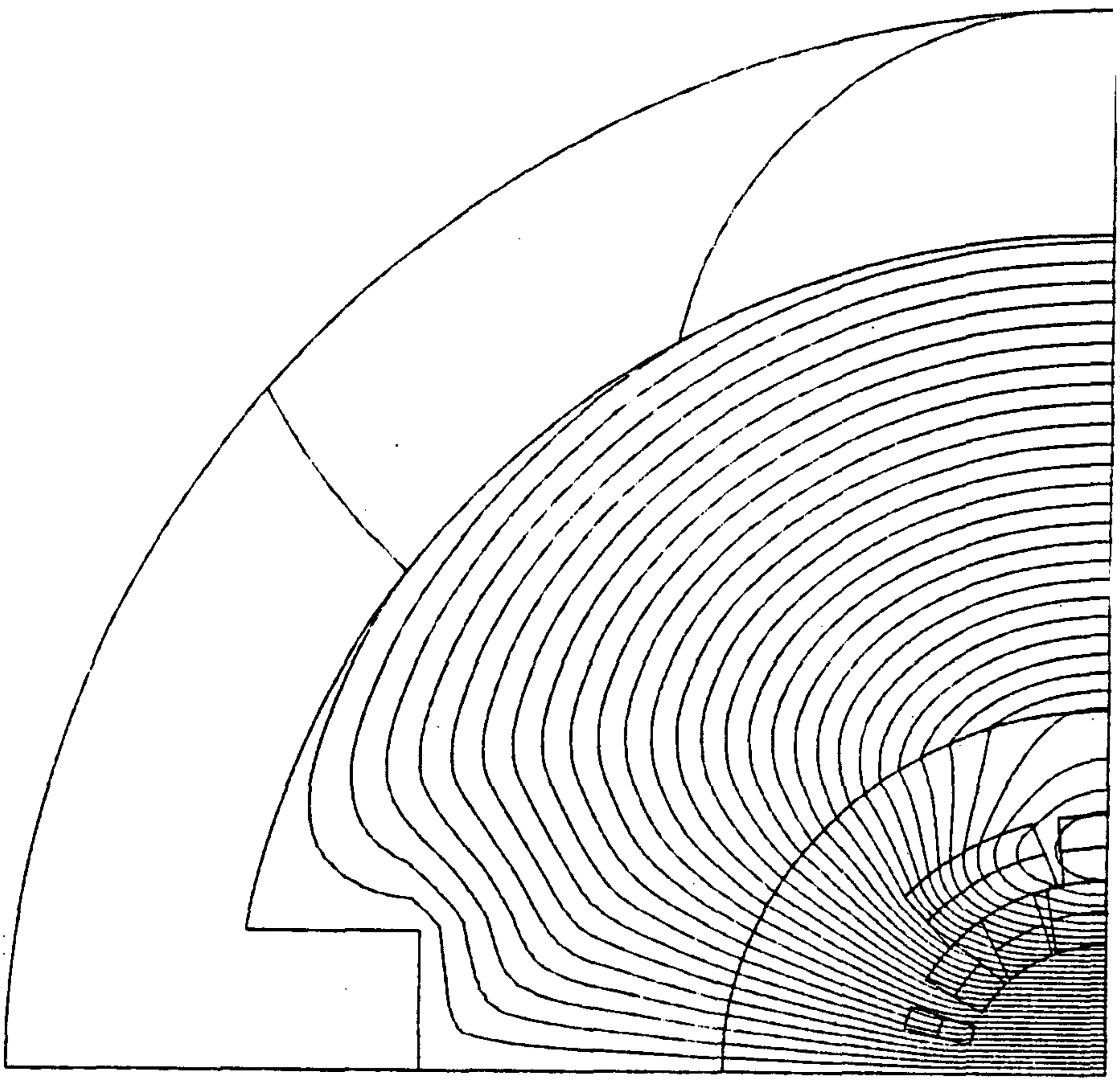


Fig. 6 Flux lines at 6.5 T for a 10.0" O.D. iron

Effect of Iron Notches on b2 and b4 -- Circular ID

The effect of notches or holes in the iron on the sextupole and decapole was studied at various excitation levels. In all cases the iron inner and outer boundaries were kept circular. The geometries of the cases studied are plotted in Fig. 7a, 7b, and results tabulated in Table 1a and 1b respectively.

Decapole

The effect of iron saturation on the decapole for circular smooth iron is b4 = -0.04 units at 6.5 T. The introduction of cuts in the iron (A, B, C, D Fig. 1) will increase the departure of b4 from its low field value of 0.0 to -0.07 units.

Sextupole

The change in sextupole at 6.5 T due to iron saturation is 1.129 units for iron with no notches or holes. The introduction of a large notch A along the iron OD (case b) contributes an additional 0.06 units at 6.5 T. Adding a circular "cryogenic" hole B adds 0.144 units at 6.5 T. Introducing the I.R. notch C, at the pole increases the sextupole by 1.081 units; however, the contribution of the mid-plane notch, D, is -0.313 units for a total of 2.101 units at 6.5 T.

It is worth noticing that in the current design the introduction of notch C doubles the magnitude of the sextupole at 6.5 T and therefore decreasing its size will eliminate 1 unit of sextupole due to saturation. It is also worth noticing that introducing a mid-plane notch, D, decreases the positive value of the sextupole at high field and therefore its size should be increased.

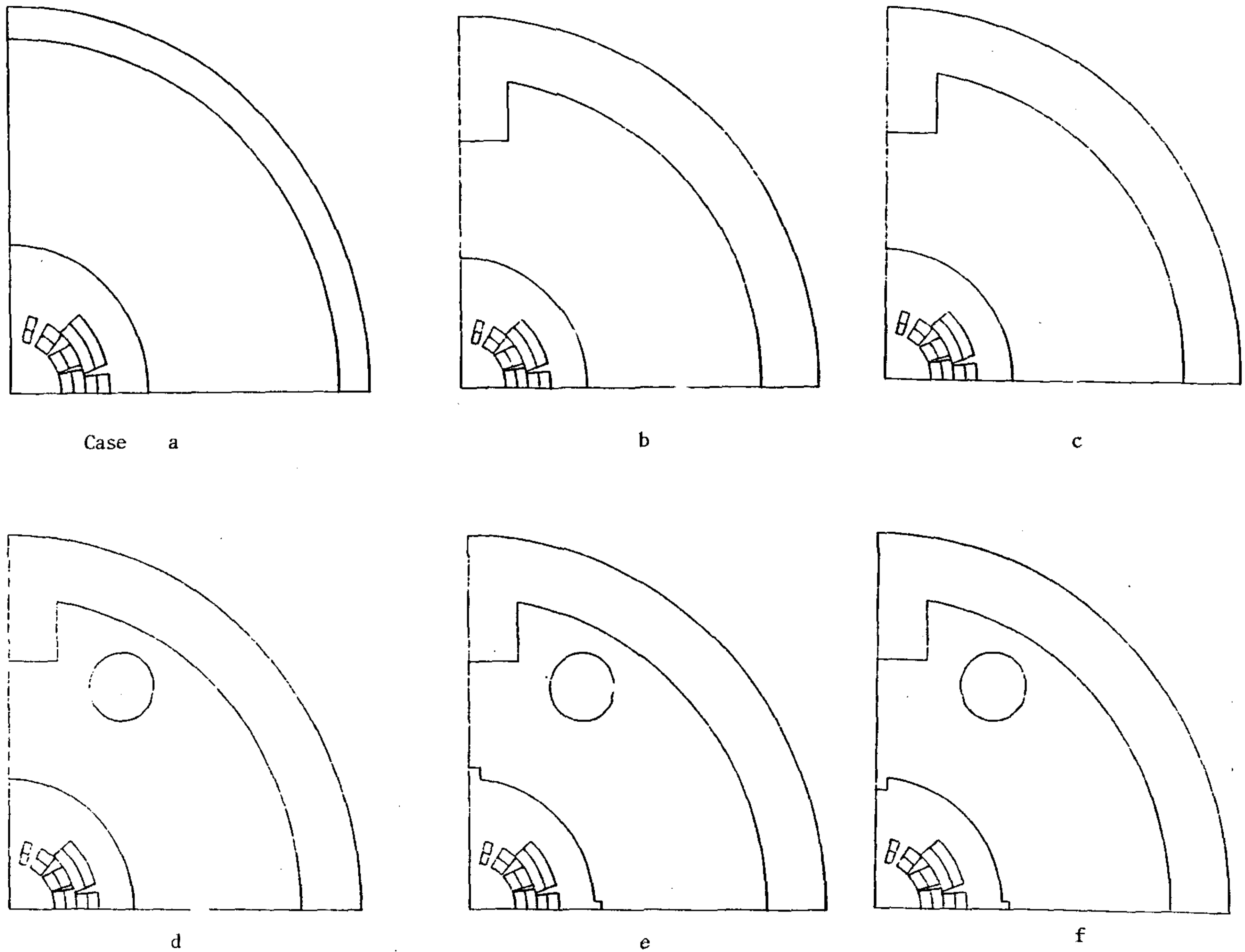
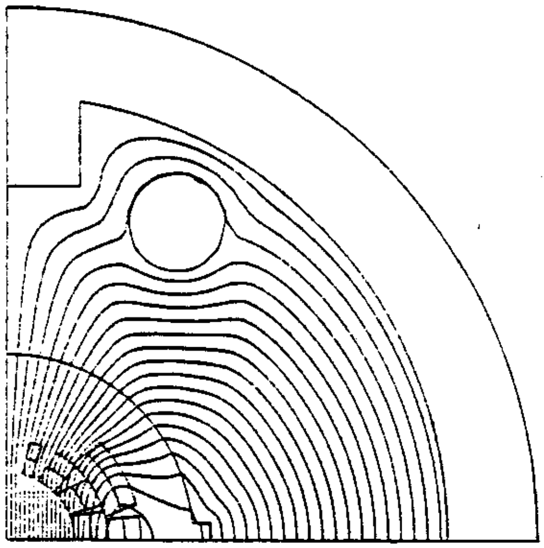
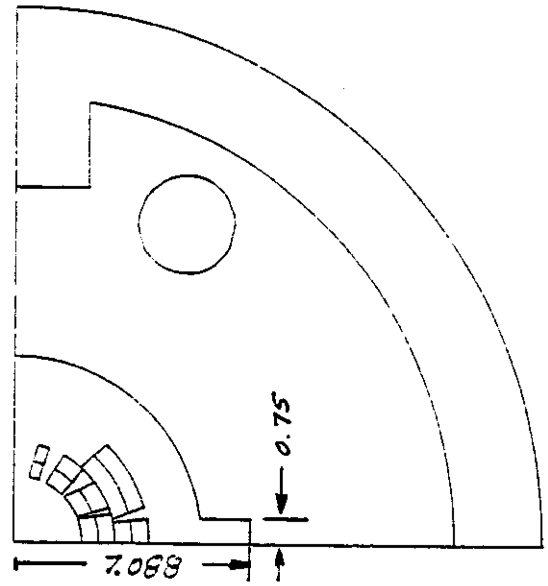


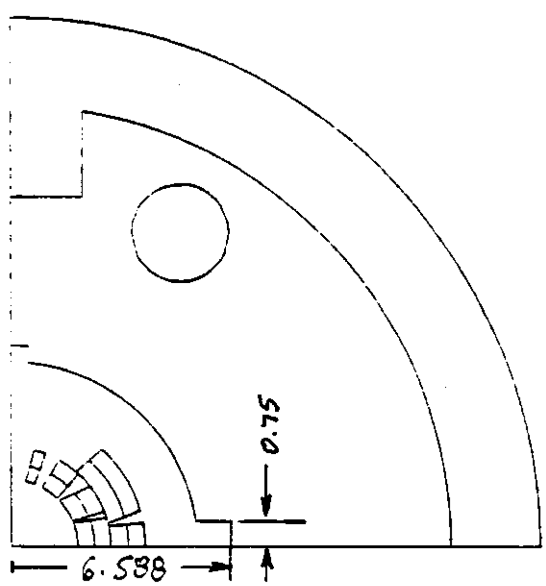
Fig. 7a Variations in iron geometry use for computations catalogued in Table Ia





Case c1 horizontal notch same as I.D. pole notch

Case d1 larger midplane notch



Case f1 Combination midplane and pole notch

Fig. 7b Variations of the mid-plane notch for computations catalogued in Table 1b

Case	a			b			c			d			e			f		
Comments	R = 5.57 cm, circular			R = 5.57 cm, circular +A			R = 5.588, circular +A			R = 5.88 cm, circular +A, +B			R = 5.88 cm, circular +A, +B, +C, +D			R = 5.588, circular +A, +B, +C, +D, C inverted		
Current (A)	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$
6400.0 $\mu = \infty$ as calculated	6.6022	-2.215	-1.335	6.5988	-2.073	-1.3895	6.5892	-2.075	-1.4023	6.5898	-2.032	-1.6975	6.5794	-0.5168	-1.7757	6.6591	-11.95	-1.138
640.0	0.6598	0.0	0.0	0.6598	0.005	0.009	0.6588	-0.0007	-0.0006				0.6578	-0.008	-0.008			
1920.0	1.9794	-.01	-0.013	1.9793	0.003	-0.006	1.9764	0.001	-0.001				1.9735	-0.015	-0.009			
3200.0	3.2988	-0.008	-0.008	3.2989	-0.002	-0.005	3.2939	-0.0095	-0.0014				3.2887	0.037	-0.010			
4480.0	4.6163	0.065	-0.007	4.6159	0.071	-0.001	4.6096	0.0794	-0.0021				4.5978	0.738	-0.035			
5120.0	5.2672	0.1587	-0.01	5.2666	0.2216	-0.014	5.2594	0.1947	-0.013				5.2392	1.376	-0.072			
7560.0	5.8999	0.6891	-0.03	5.8994	0.7598	-0.022	5.8918	0.6808	-0.032				5.8627	1.977	-0.068			
6400.0	6.5091	1.19	-0.043	6.5081	1.25	-0.037	6.5010	1.189	-0.037	6.4884	1.333	-0.031	6.4641	2.101	-0.072	6.5012	8.15	-0.445
7040.0	7.0887	0.899	-0.061	7.0873	0.959	-0.06	7.0802	0.904	-0.068				7.0355	1.622	-0.067			
7680.0				7.6408	0.069	-0.089	7.6339	0.0188	-0.096				7.5837	0.693	-0.076			
8320.0				8.1817	0.8	-0.111	8.1798	-0.821	-0.118				8.1197	-0.205	-0.091			
low field		-2.215	-1.335		~0.0	~0.0		-2.075	1.402		~0.0	~0.0		+1.56	-0.37		-9.9	0.26

Table 1a Saturation effect on sextupole and decapole for circular I.D. iron

Case	a1			b1			c1			d1			e1			f1		
	+A, +B, +D notch C removed			+A, +B, +C horizontal notch D removed			+A, +B, +D D size = C			+A, +B, +D D size > C			+A, +B, +C D same as case d1			+A, +B, +C, +D D intermediate size between case c1 and e1		
Current (A)	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$	B_o(T)	$b_2 x10^{-4}$	$b_4 x10^{-4}$
6400.0(A), $\mu=\infty$ as calculated	6.5899	-2.04	-1.70	6.5793	-0.5188	-1.776	6.5900	-1.77	-1.324	6.5898	-2.082	-1.713	6.5793	-0.565	-1.796	6.5793	-0.5492	-1.7848
640.0	0.6589	-0.01	-0.006															
1920.0	1.9766	-0.01	-0.006															
3200.0	3.2942	-0.02	-0.006															
4480.0	4.6090	0.04	-0.008															
5120.0	5.2559	0.10	-0.016										5.2215	0.228	-0.093	5.2309	0.824	-0.083
5760.0	5.8834	0.547	-0.032										5.8304	0.0036	-0.136	5.8466	0.969	-0.113
6400.0	6.4838	1.02	-0.045	6.4687	2.414	-0.059	6.4773	0.6151	-0.057	6.4367	-1.808	-0.14	6.4173	-0.658	-0.164	6.4365	0.442	-0.133
7040.0	7.0523	0.926	0.058										6.9862	-1.251	-0.171	7.0037	-0.2654	-0.143
7680.0	7.5984	0.326	-0.08										7.5404	-1.825	-0.172	7.5554	-0.997	-0.149
8320.0	8.1331	-0.313	-0.10										8.0813	-2.44	-0.175	8.0942	-1.7361	-0.156

Table 1b The effect of midplane notch, D, on b_2 and b_4

Offsets

There is an offset we have factored out in the transition from the program PK, which deals with the conductor cable turn by turn and circular iron only, to POISSON which simulates the conductor in terms of blocks but can model more realistic iron shapes. Whereas PK produces a design in which b2 ~ 0, for $\mu = \infty$ iron the equivalent POISSON value is b2 ~ -2.0 units. From this we conclude that POISSON, for the mesh used, introduces an offset of ~ -2.0 units from which subsequent cases' sextupole values should be subtracted. Employing this principle we observe that the introduction of the notches in the iron ID causes an offset of b2 = +1.5 units and b4 = -0.35 units (at low field or $\mu = \infty$ iron) compared to smooth circular iron. The offset of b_4 is rather large and additional confirmation is needed.

Therefore a design with PK that gives virtually no b2 or b4 has a <u>systematic</u> <u>offset</u> due to the physical use of notches in the iron ID.

Effect of Elliptical ID Iron on b2

A number of runs were made to compute the effect on b2 and b4 of a prelate and oblate elliptical shape for the iron ID. The cases run are catalogued in Fig. 8 and results tabulated in Table 2.

One method of reducing the saturation effect on b2 is to make the iron ID a prolate ellipse with a midplane minor axis dimension of 5.588 cm (same dimension as at present), and a major axis dimension of 5.796 cm along the pole. Including notches, the change in the sextupole due to saturation is b2 < 0.5 units (Fig. 9). The reduction in the transfer function compared with the circular iron of r = 5.588 cm is ~0.7%.

The built-in offsets with respect to a PK circular design is +4.2 units for b2 and -0.17 for b4.

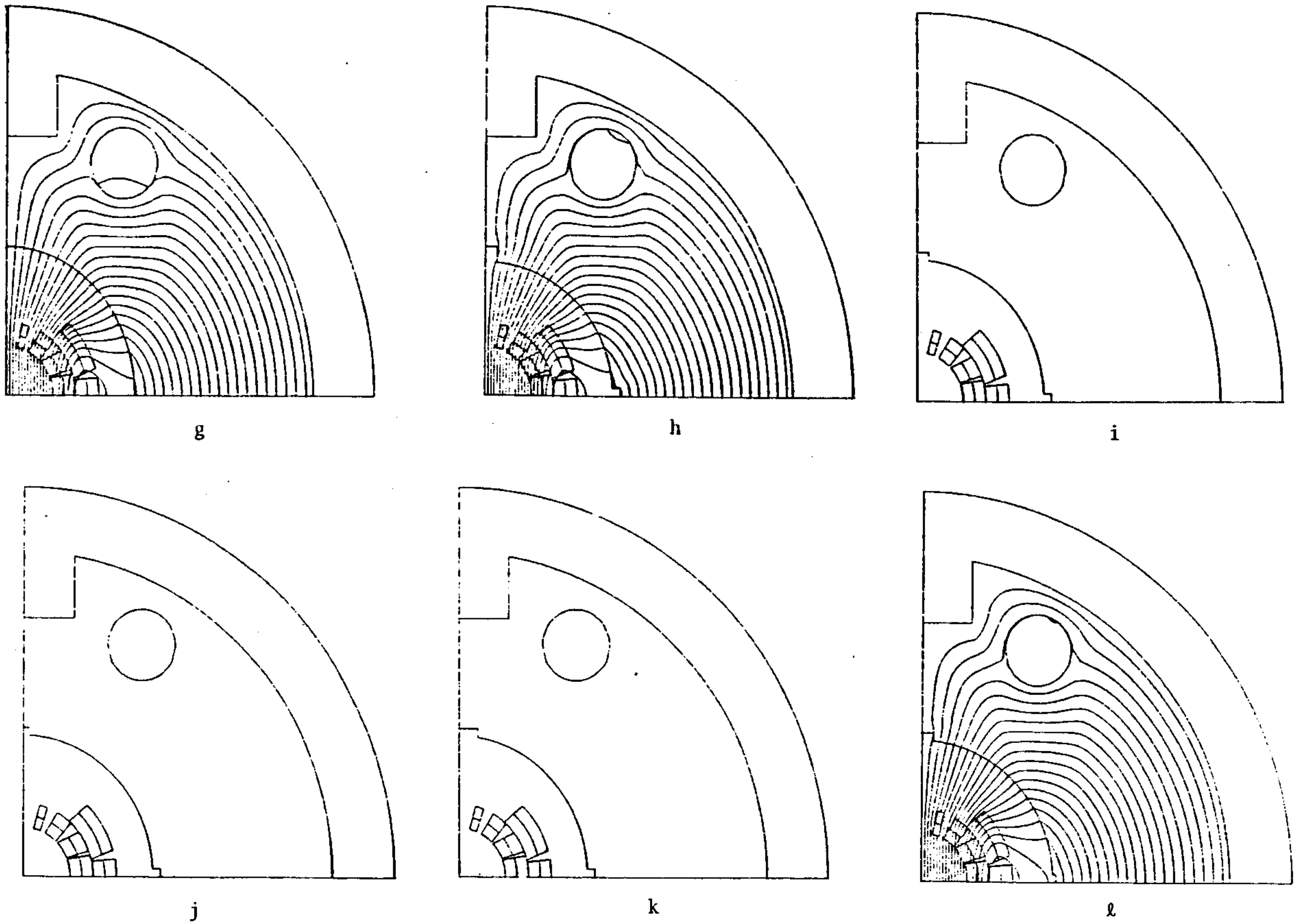


Fig. 8 Variations in iron geometry used for computations cataloged in Table 2

Case	g			h			i			j			k			l		
Comments	E = elliptical prolate b_x = 5.588, a_y = 6.109 +A, +B			E = elliptical oblate a_x = 5.588, b_y = 5.484 +A, +B, +C, +D			E = elliptical prolate b_x = 5.588, a_y = 5.796 +A, +B, +C, +D			E = elliptical prolate b_x = 5.588, a_y = 5.796 C 50% skinner			E = elliptical prolate a_x = 5.588, b_y = 5.796 +A, +B, +C, +D C 50% wider			E = 5.796 cm, circular +A, +B, +C, +D		
Current (A)	B_o(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$	B_o(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$	B_o(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$	B_o(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$	B_o(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$	B_o(T)	$b_2 \times 10^{-4}$	$b_4 \times 10^{-4}$
6400.0 μ=∞ as calculated	6.4102	5.325	-1.6891	6.6226	-1.953	-1.799	6.5036	2.35	-1.765	6.5085	1.6614	-1.7236	6.4966	3.299	-1.8066	6.4746	-1.838	-1.597
640.0							0.6502	-0.003	0.012									
1920.0							1.9508	-0.002	0.008									
3200.0							3.2511	0.007	0.016									
4480.0							4.5488	0.186	0.012									
5120.0							5.1891	0.304	-0.003									
7560.0							5.8153	0.4465	-0.020									
6400.0	6.3607	-0.6875	-0.010	6.4877	3.172	-0.073	6.4203	0.3926	-0.028	6.4260	0.3333	-0.037	6.4138	0.2844	-0.023	6.3932	0.855	-0.032
7040.0							6.9960	-0.1676	-0.03									
7680.0						-	7.5462	-1.112	-0.046									
8320.0						-	8.083	-2.01	-0.066									

Table 2 Saturation effect on sextupole and decapole for elliptical I.D. iron

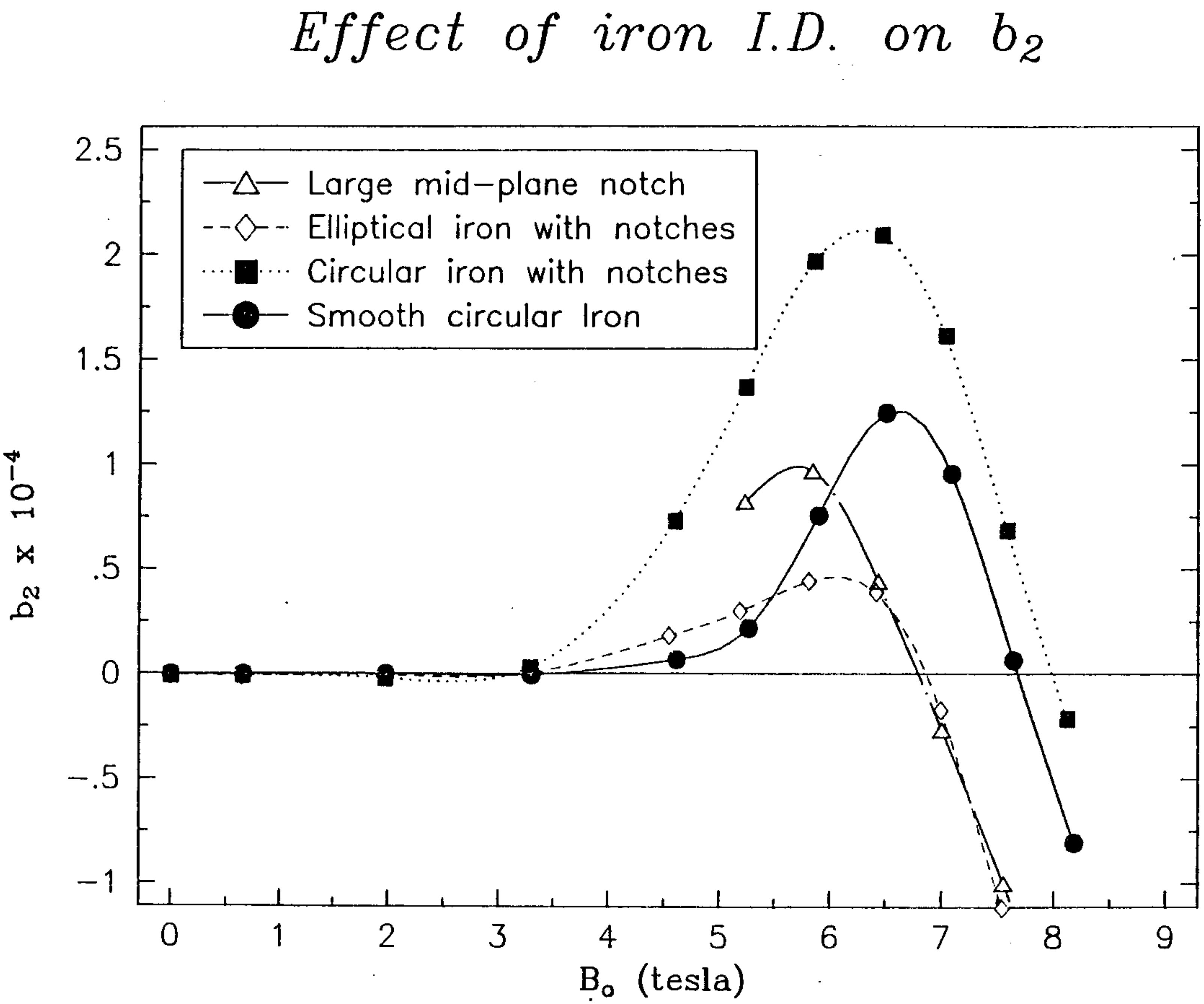


Fig. 9 Sextupole for various I.D. iron configuration