MAGNET DIVISION NOTES

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The Effect of Notch in the Aperture of SSC Dipole

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Abstract

This note describes the effect of a large notch in the aperture of the design D SSC Dipole magnet. The notch, which is 376 mils wide by 208 mils high, matches a tab on the collar for alignment. It changes the low field values of harmonics and it also changes the shift in these values of harmonics at high field due to iron saturation. The recent calculations at LBL<1> confirm these observations. Plots are made for variations in the size of notch so that a compromised size can be obtained both from the magnetic and the mechanical properties point of view.

We have made these calculations independently with two codes, namely POISSON and MDP(GFUN). Our model on POISSON is a very close representation of the real structure (both for the coils and for the iron yoke). The model of the coil on the code MDP is the exact representation of the geometry. The harmonics reported in this note are the actual values as computed by the programs; no offsets are used. We have compared these values with those computed with the analytic formulas for the infinite mu case. At low field, all harmonics are found to be in agreement within 0.2 unit. This tells that our models are reliable.

Finally the calculations are compared with the measurments.

The Computer Models

We have tried to make the model of this magnet as close to the design structure as possible. This is essential if the correct values of the harmonics are to be expected from the calcutations. In the code MDP one can can always describe the coils without having to make much approximation. However, the same is not so straightforward in the code POISSON in which limitations on mesh size always require some degree of approximation of coils made from partially keystoned conductors. But we have developed procedures and programs with which we can describe the structure with sufficient accuracy. The model discussed in this section is for SSC Design - D Magnet with C5 coils.

The reliability of the model for coil structure can be examined when the harmonics computed with these codes are compared with those obtained with analytic formulas. This comparison can be made when the aperture is circular and the central field is so low that the permeability of the iron is practically infinite. The values of harmonics from the analytic formulas are obtained with the program PAR2DOPT. We compare these values with those obtained with POISSON and MDP at low field for the same aperture and coil structure. The results are shown in Table 1 in the next page. We observe that all harmonics ($b_i = 10^4\ B_i/B_o$ @ 1 cm) are in agreement to 0.2 units. This gives us confidence that we can rely on our models. Therefore, thruout this report we print the actual harmonics as given by programs; <u>no offsets</u> are used to compensate for imperfect models.

The model of the magnet on MDP is shown in Fig 1(a) and on POISSON in Fig 1(b). We have put all the notches and holes in the iron. The coil structure is shown in more detail in Fig 2(a) for MDP and in Fig 2(b) for POISSON. It can be seen that the two layers of the coils are separated in both models as they are in the actual magnet. The midplane gap of 6 mils between upper and lower coil halves is also incorporated as shown in Fig 2(c) for POISSON.

Table 1.

Comparison of the harmonics as computed with the analytic formulas and with the computer code POISSON and MDP. The iron aperture is a smooth circle with no notches.

Harmonics	Analytic	POISSON	MDP
TF, T/kA	1.0361	1.0350	1.0336
b_2	-0.16	-0.19	0.02
b_4	0.00	0.24	0.00
b_6	0.12	0.19	0.12
b_8	0.87	0.89	0.87
b_{10}	-0.03	-0.03	-0.03
b_{12}	-0.04	-0.04	-0.04

To obtain a realistic current density distribution (1/r type) instead of constant current density, we use two different approaches in these two programs. In MDP each turn of the cable is modified from the trapezoidal shape to the rectangular shape. In POISSON each blocks is divided in four radial block with each having the same radial width. Please see Fig 2(a) and Fig 2(b) for details.

The mesh of our model on POISSON is shown in Fig 3(a). The mesh is made much denser in the coil region so that the details of the coil structure can be described while keeping the total number of mesh points to a reasonable size. In addition, the mesh in the coil region is further modified to pull the nodes in the areas where a still finer mesh is required - e.g. to separate the inner and outer layers of the coils and to incorporate the midplane gap. The mesh of the coil region is shown in Fig 3(b).

Effect of the Notch on the Harmonics

The central field is decreased by the notch; both MDP and POISSON predict a decrease of 0.17% in the transfer function from the case of a smooth circular iron aperture. The transfer function at low field is 1.0318 by MDP and 1.0332 by POISSON. The relative decrease with excitation is given in Table 2.

Table 2
Variation of the relative transfer function with excitation

I,kA	3.0	4.0	5.0	6.0	7.0	7.2	8.0
MDP	1.000	.999	.995	.987	.973	.970	.964
POISSON	1.000	.999	.994	.983	.965	.961	.945
Measured	1.000	.999	.996	.982	.969	.967	N/A

The measurements are the average of SLN008 and SLN009. The more rapid decrease in TF as computed by POISSON may be due to the "finite universe" of the POISSON model as shown in Fig 3(a). The agreement between measurement and calculation is only fair at the highest current run in both magnets, 7.2 kA; the MDP calculation is 0.3% high and the POISSON calculation is 0.6% low, compared to measurement.

The low field transfer function was measured accurately using an NMR device and reported recently<2>. The value is the average of 6 magnets. Since the coil positioning shims differ from magnet to magnet and the transfer function is affected by the shimming, a correction to the shims used in SLN008 (the first of the 6) was made to the transfer function of the other 5 magnets. The value calculated by MDP and POISSON must be corrected to the same shim sizes; the factor is 1.0018. Since the measurements are made at a temperatue of 4 degree K, and the calculations are based on room temperature dimensions, a correction to the calculated values for the decrease in coil and iron sizes must also be made. This correction is estimated to be 1.0027. Both corrections multiplied are 1.0045. With this correction, the transfer function calculated by MDP is 1.0365 (at 2.0 T), by POISSON is 1.0379(at 2.95 T) and the measured value is 1.0358 $\pm$.003 T/kA at 1.8 T. There is an additional correction, the magnitude of which is known for only one magnet : SLN011; this arises from the distortion of the coil which which takes place during curing and collaring. SLN011 was sectioned, photographed and the conductor locations determined by an x,y measuring device<3>. It was found to have an oblateness (increase of the radius at the midplane and decrease of the vertical radius) of about 10 mil. Calculations using this amount of ellipticity indicate it would increase the transfer function by a factor of 1.0009. There was considerable variation in curing and assembly pressures in the remaning magnets and it is not known if this amount of distortion is typical. If it is, the MDP TF is then 0.16% and POISSON's 0.29% higher than measurement.

By both MDP and POISSON calculations, the notches introduce a low field value of b_2 of about 1.1 units compared to smooth circular iron. Coil distortion and shimming may cause non-zero b_2 of varying amounts in the magnets as built, so the calculated offset due to notches is not directly observable.

The standard SSC Design D Dipole has a measured peak b_2 shift (difference between high field and low field values) of 2.05 units due to the iron saturation. Since this is more than the desired value of 1.0, a study was taken up on how to reduce it. A method has been developed by Morgan<4> to reduce such shift by using an approximately elliptical iron aperture and it was recently used in eliminating about 20 units of b_2 shift in a single layer design of an SSC dipole<5>. It was thought that the same should be used to get rid of this modest shift in the Design D magnet. However, during the study we observed that the shift is mainly due to the notch at the pole. The notch on the midplane, on the other hand, actually helps in reducing it. Similar observations were made earlier by Thompson in the case of the RHIC dipole magnet<6>.

These results were reported in the June, 1986 meeting of the Central Design Group at the Brookhaven National Laboratory. Following the discussions the computations on this aspect of SSC dipole were also done at LBL<1> and similar results were obtained.

A systematic analysis of the effect on b_2 of varying the size of the notch in the horizontal and vertical direction is made in Fig 4. We start with zero notch size and go to the full value first by varying the horizontal size while keeping the vertical size constant (original value) and then by varying the vertical size while keeping the horizontal size constant. These computations are done with the code POISSON and the peak shift in the sextupole harmonic due to saturation is plotted in Fig 4. A narrow notch (horizontal variation) is not as effective in reducing the shift as a shallow notch.

In Fig 5(a) and 5(b) we plot the results of computations for sextupole harmonic from low field to the maximum value of over 8 Tesla for different types of aperture with the codes MDP and POISSON. The types of apertures considered are described below. The size of the midplane notch is the same as in the aperture of SSC Design D magnet in the cases 1, 2 and 4. The pole notch in case 1 is the same as in the Design D magnet.

	Plot character POISSON	MDP
1. Notch at the midplane and at the pole.	×	○
2. Only midplane notch - no notch at pole.	◇	□
3. Circular aperture - no notch.	□	△
4. The new pole notch - original midplane notch.	+	+

From Fig 5, it is seen that MDP finds a b_2 saturation shift of 0.36 without the pole notch and 2.0 with it. POISSON gives 0.23 without the pole notch and 1.55 with it. Without any notches, i.e., with circular iron, MDP gives 0.7 and POISSON 0.6 units of b_2 saturation shift. From these results, it was expected that reducing the pole notch area by a factor of four would give an adequate b_2 saturation shift without other modifications to the iron. The new notch will be first used in a BNL 1.8 m research magnet, construction of which will begin this November, with testing next spring. The width of this reduced notch (case 4) is 200 mils and height 105 mils. MDP predicts a b_2 shift for it of about 1.0 and POISSON about 0.7.

In Fig 6 we compare computed b_2 results with measurements of magnet SLN008 and SLN009.

The measurements of both magnets show a shift in b_2 from the 2 T value to the peak value of about 2.05 units. The shift computed by POISSON is about 1.6 and by MDP about 2.0. The lesser value obtained with POISSON is thought to be due to the "finite universe" which increases the flux density in the yoke return leg. The effect of pole and return leg iron saturation were described by Morgan<4> and by Caspi and Helm<1>.

Fig 6 shows that POISSON predicts the onset of the b_2 shift more accurately then does MDP, but overestimates the decrease in b_2 on the higher current side of the peak. The latter effect is also thought to be a result of the "finite universe" of the POISSON model. The low current downturn of the measured b_2 is either a consequence of inefficient eradication (by averaging up and down ramp measurements) of superconductor magnetization or possibly a result of the Nitronic 40 stainless-steel collar. The magnitude of this latter effect is computed to be -0.5 units<7>.

The notches in the iron aperture produces only a very small effect on b_4; MDP predicts a decapole offset due to notches of -0.07 and POISSON an offset of -0.03 units. The change in decapole with excitation is less than 0.1 units, by both calculation and measurement. MDP gives a -0.03 decrease at 5 to 6 kA, POISSON about -0.06, and the measurements of the two magnets are -0.05 and -.10, all with rise back to or above the low field value above 7 kA. At 3 kA, the value of b_4 by MDP, POISSON, SLN008 and SLN009 are -0.07, +0.21, -0.15 and -0.5, respectively.

Caspi and Helm<1> have computed cases 1 and 3, obtaining a b_2 shift of 2.14 units, for the notched iron case 1. They calculate a b_2 shift of about 1.25 for circular iron (case 3). It is expected that their use of 100% packing factor (we use 97.5% and the experimental value is 97.34%) would increase height of the peak by delaying the down turn due to return leg saturation.

Their calculation differ in two ways. Their version of POISSON does not have the "finite universe" limitation present in the BNL version. For most of their calculations, they use an iron radius of 5.588 cm; the design D value is 5.57. We use 5.556 cm in our calcutations and the magnets were 5.556 $\pm$ .0025 cm. The increased i.r. used by Caspi and Helms can be expected to decrease the low field Transfer Function slightly. The decreased return leg thickness should result in a slightly reduced b_2 shift and a greater decrease in TF at high field. Their cases b and c (Table 1a) indicate a low field TF change of -0.15% due to i.r. increase. At 6.5 T the b_2 shift decrease 0.56 units and the TF changes -0.11%, the latter being unexpectedly somewhat less than at low field.

A packing factor (PF) of 100% instead of 97.5% is equivalent to an increase in return leg thickness in the amount of 0.194 cm. The effect of this on b_2 can be estimated both from the i.r. increase described above and from the iron outer-diameter decrease also calculated by Caspi et al, the results of which are presented in his Fig 4 which shows that an 0.25 inch decrease in iron thickness decreases b_2 1.2 units, or 1.9 units per cm; the average of the two is 2.5 units per cm. The sum of the effective return leg thickness increase of 0.194 cm due to 100% PF and the actual decrease of 0.32 from i.r. increase is 0.162 cm; this means their peak b_2 should have subtracted from it (0.162)2.5 = 0.4 units to compare them with our calcutations and measurements. If one does so, the LBL numbers for b_2 saturation shift become 1.7 for the magnets as built and 0.6 if the pole notch is absent.

A comparison of these adjusted values with the BNL calculations and measurements is given in Table 3.

Table 3
Shift in b_2 due to iron saturation

	with all notches	without pole notch	without any inner notche	with new pole notch
LBL, POISSON	1.7	0.6	0.9	-
BNL, POISSON	1.5	0.2	0.6	0.7
BNL, MDP	2.0	0.5	0.7	1.0
BNL, Meas. (2 Magnets)*	2.05	-	-	-
LBL, Meas. (3 Coils)**	1.5, 1.3#, 0.8			

* Two different yokes and coils.

** One yoke, 3 coils, one stainless steel collar(1.5), two aluminium collars (1.3# and .8).

\# The curve stopped before the peak was reached.

Summary and Discussion

Our calculations of b_2 shift are in good agrrement with measurements made on the two magnets having large pole notches; the magnets have a b_2 shift of 2.05. Using MDP a shift of 2.0 is calculated and using POISSON a shift of 1.6 is calculated. We compute that a pole notch reduced by a factor of four in area will decrease the shift in b_2 due to saturation to a value of 1.0 or less, which is sufficient to meet Chao's requirement. For this reduced notch, with MDP and POISSON, a shift of 1.0 and 0.7 respectively is calculated. The reduced notch will have the serendipitous effect of raising the transfer function 0.1%, whereas either an elliptical aperture or a reduced iron od would decrease the transfer function.

LBL calculations of the b_2 shift, after adjustment for iron packing factor, are in agreement with ours to within about 0.3 units. But measurements on their magnets give an 0.5 unit lower shift than do measurements on the BNL magnets.

References

<1> S. Caspi and M. Helm, "The Effect of Iron Saturation on the SSC Dipole Magnet", SSC-MAG-93, LBID 1195 (7/86).

<2> P. Wanderer "B/I : Calculation v/s Measurement for SLN008-SLN015", Magnet Division Note 191-11 (SSC-MD-142) 8/29/86.

<3> S. Kahn, "Conductor Placement From Magnet Cross-section Measurements", Mag. Div. Note 189-1 (SSC-MD-141) 7/28/86.

<4> G.H. Morgan, "Use of an Elliptical Aperture to Control Saturation in Closed-coupled, Cold Iron, Superconducting Dipole", IEEE Trans. Nucl. Sci., Vol NS32, No. 5 (10/85).

<5> R.C. Gupta, G.H. Morgan, P.A. Thompson, "A Single Layer Coil, 6.1 Tesla SSC Dipole", Magnet Division Note 186-1 (SSC-MD-138) 6/25/86.

<6> P.A. Thompson, "Magnetic Analysis of RHIC Iron Designs", Magnet Division Note 158-16 (RHIC-MD-39) 9/24/85.

<7> R.C. Gupta, "Effect of the Steel Collar on the Magnetic Properties of SSC Dipole", Magnet Division Note 153-1 (SSC-MD-116) (8/5/85).

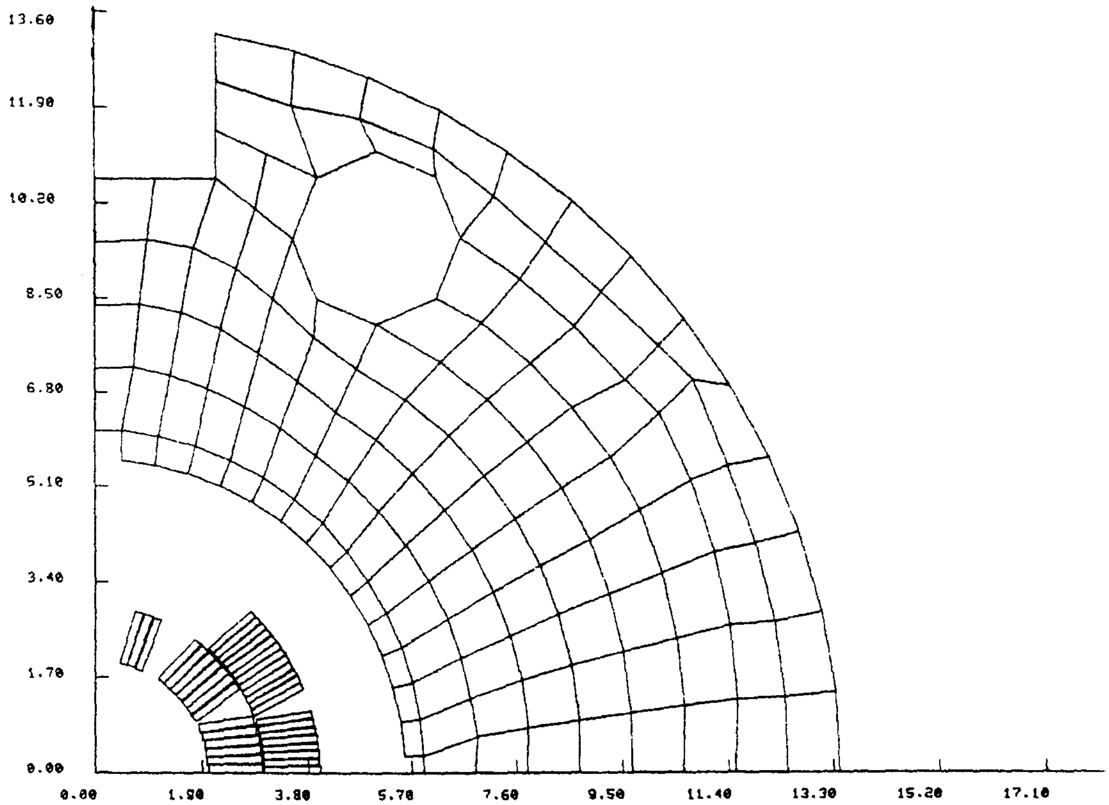

Fig 1(a). The Model of the SSC Design D Magnet on MDP.

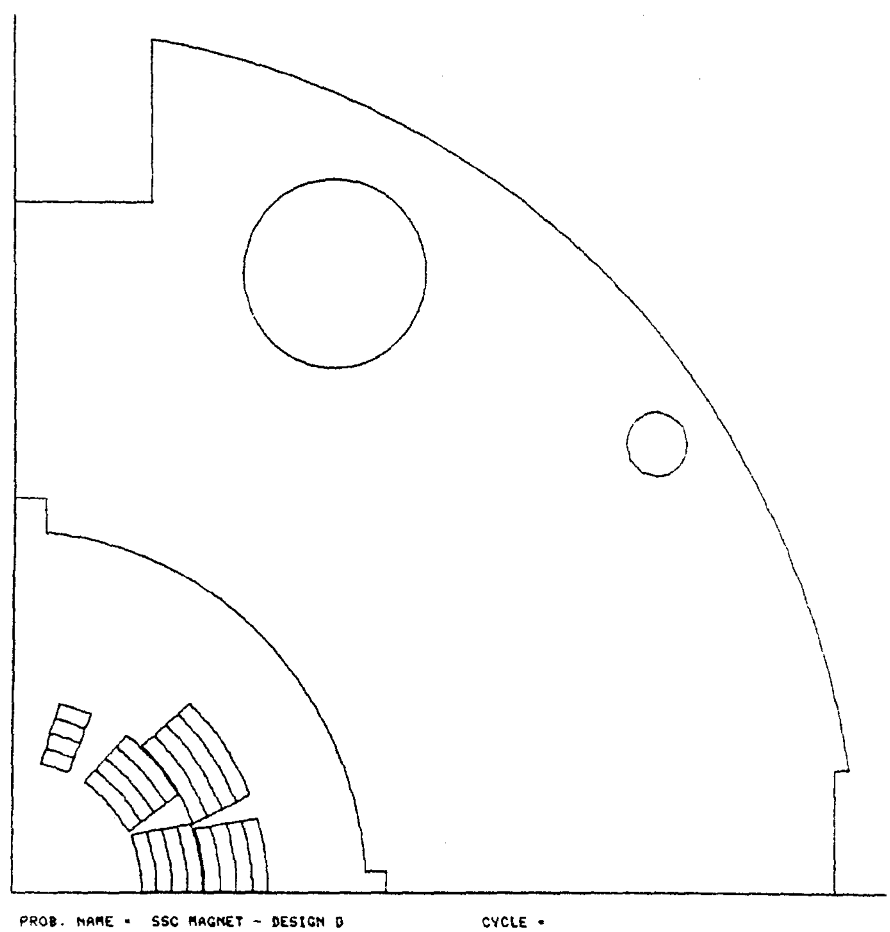

Fig 1(b). The Model of the SSC Design D Magnet on POISSON.

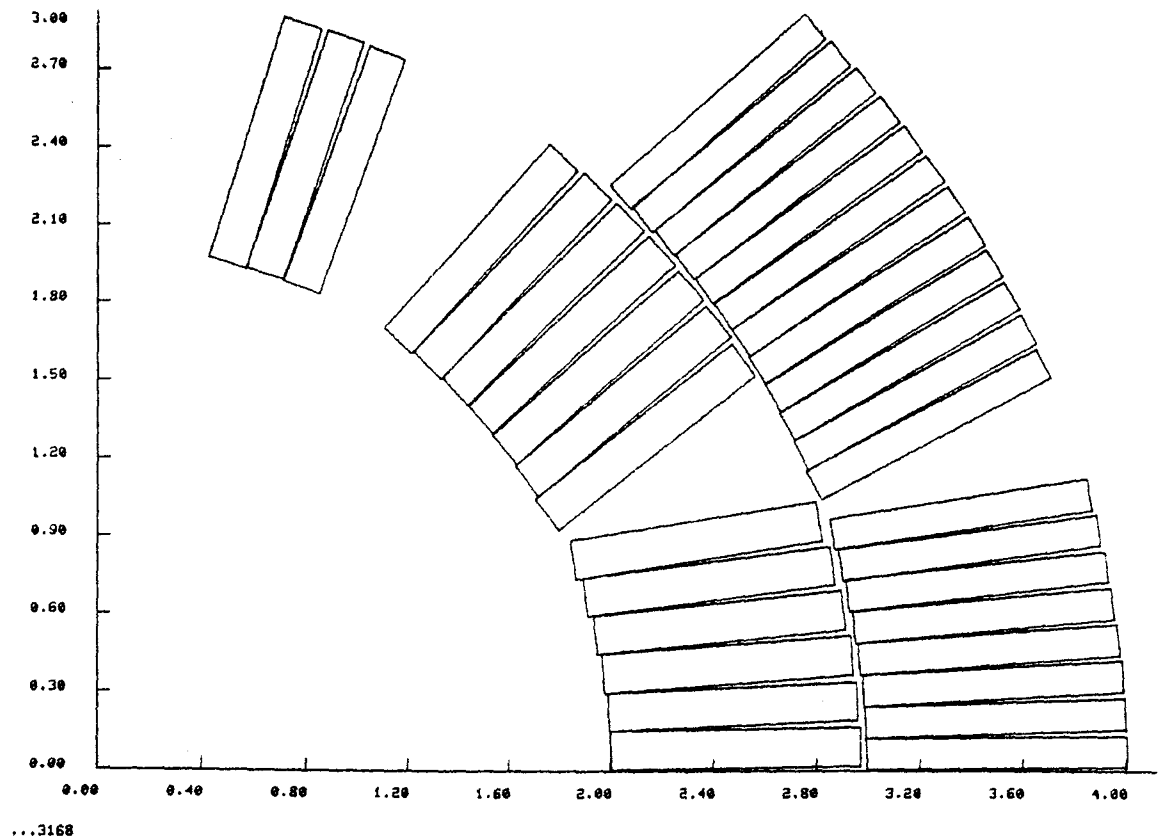

Fig 2(a). The details of coil structure on MDP for 1/r type current density distribution. The inner and outer layers of the coils are separated.

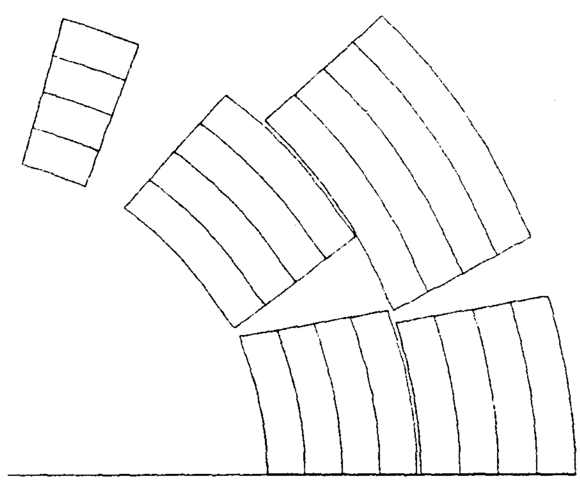

Fig 2(b). The details of coil structure on POISSON for 1/r type current density distribution. The inner and outer layers of the coils are separated.

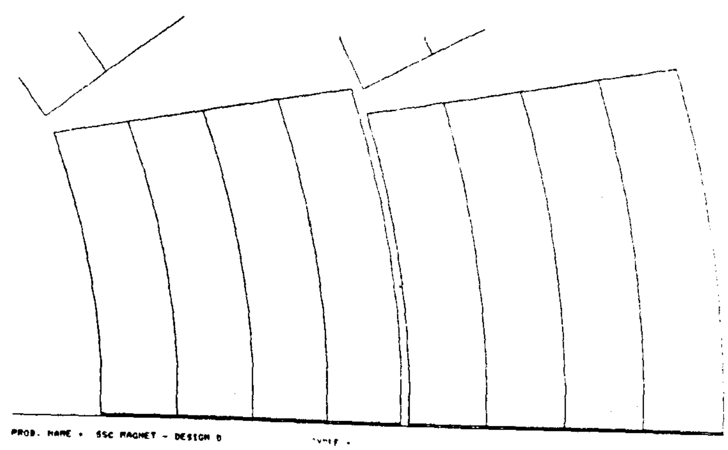

Fig 2(c). The part of the model of coil structure on POISSON emphasizing the presence of the midplane gap.

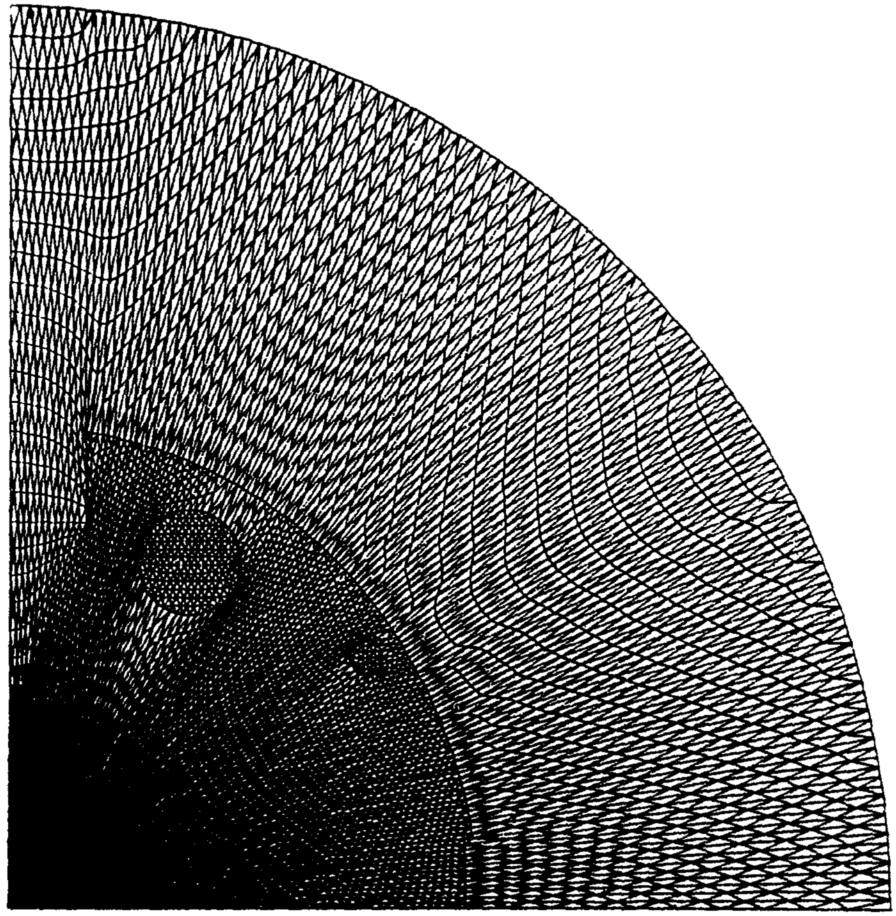

Fig 3(a). The mesh of the complete model. The mesh in the coil region is made dense so that the coil can described with sufficient accuracy.

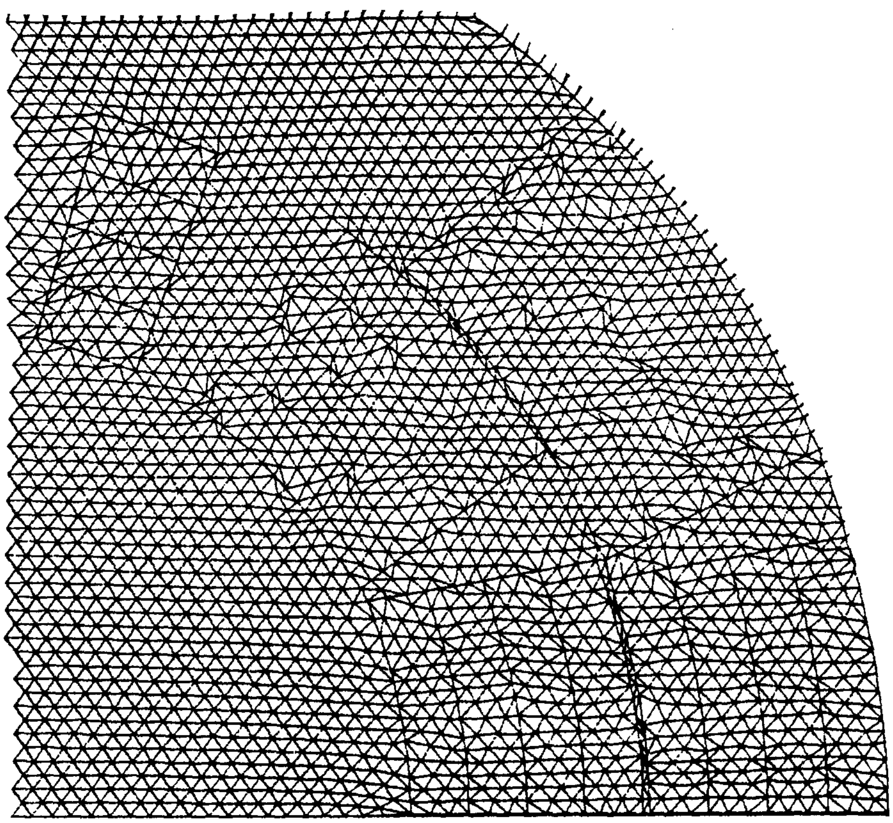

Fig 3(b). The mesh in the coil region. As appears in Fig 3(a) it is much denser than at any other place in our model.

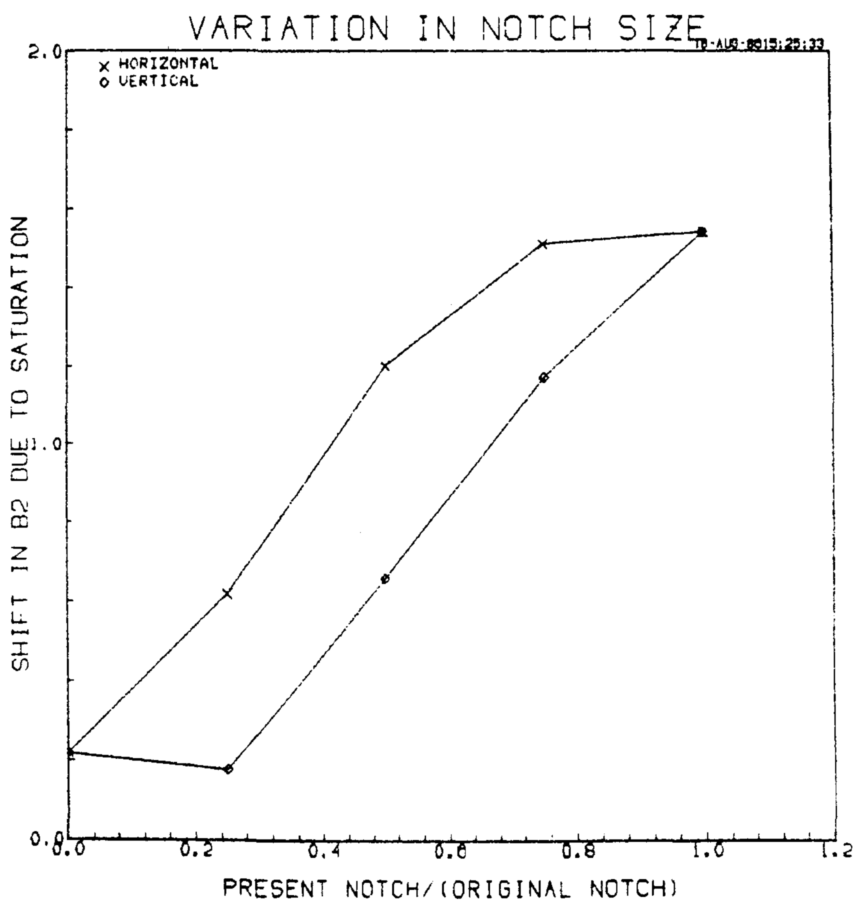

Fig 4. The effect of varying the size of the pole notch on the shift of sextupole harmonics due to iron saturation. The vertical size is held constant when the horizontal size is varied and vice-versa.

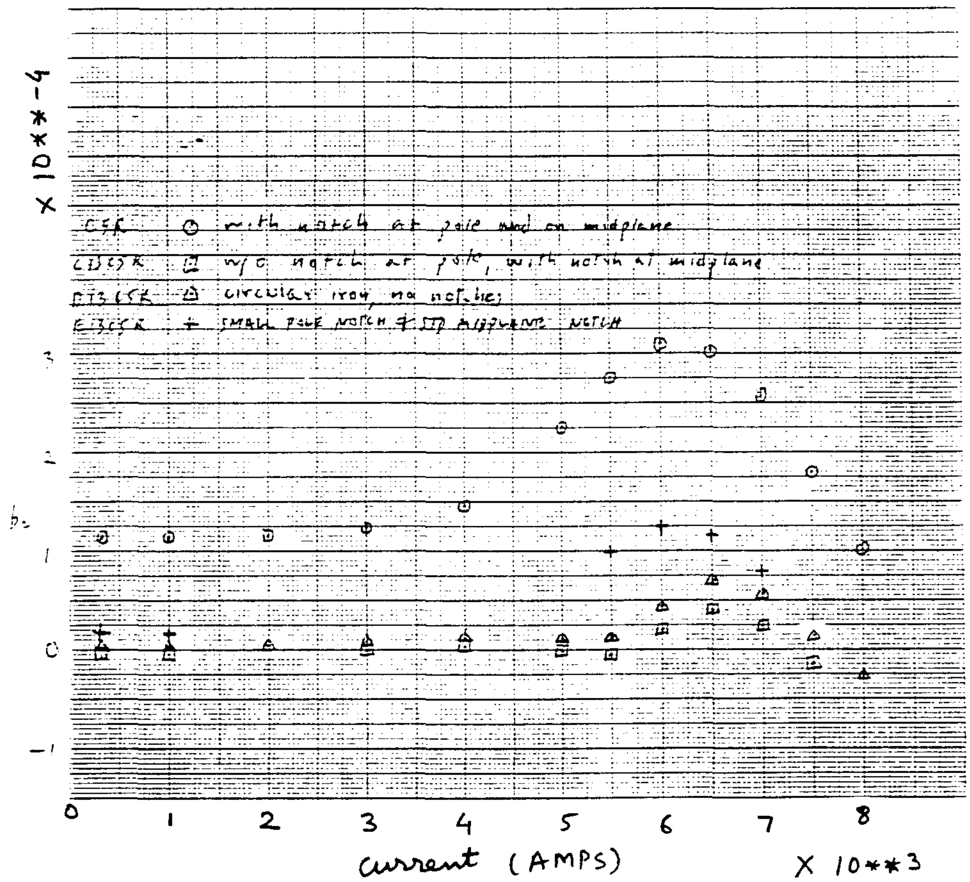

Fig 5(a). The sextupole harmonic for different types of aperture as computed by the code MDP.

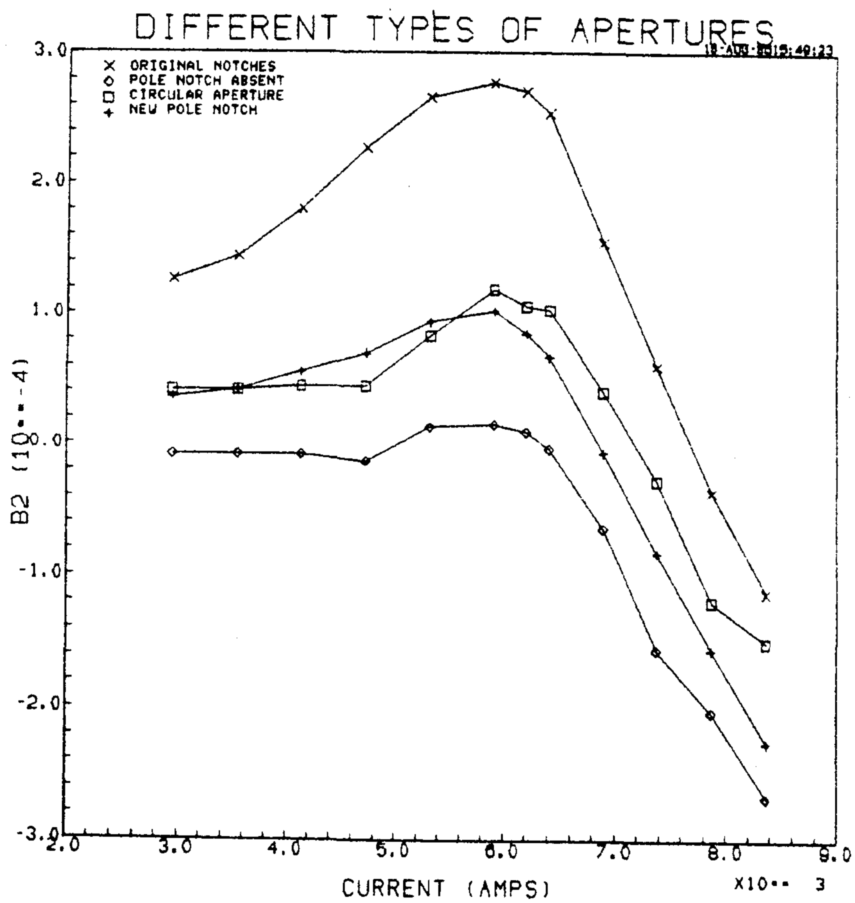

Fig 5(b). The sextupole harmonic for different types of aperture as computed by the code POISSON.

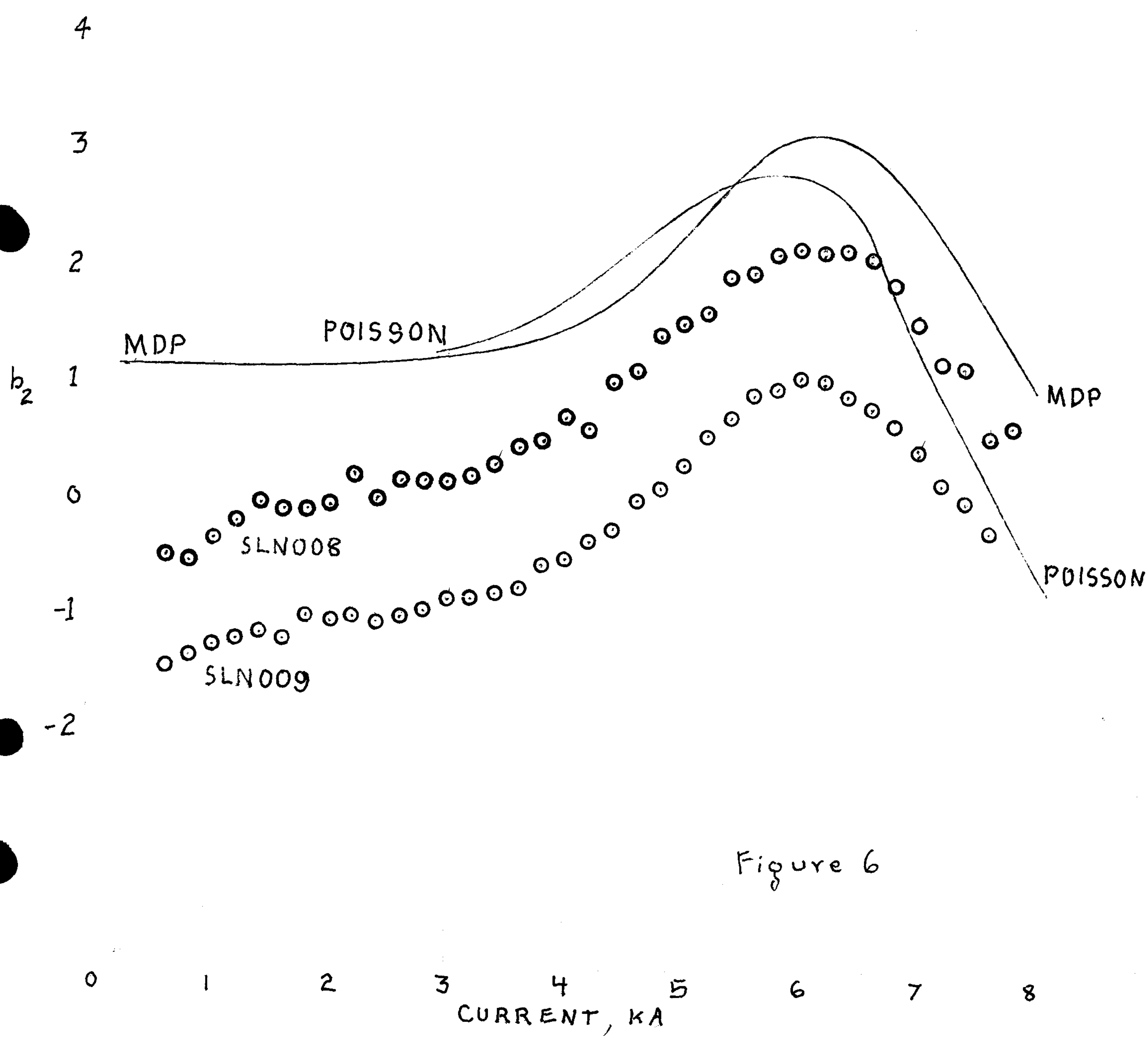
4
3
2
1
0
-1
-2
b_2
MDP
POISSON
SLN008
SLN009
MDP
POISSON
0
1
2
3
4
5
6
7
8
CURRENT, KA

Figure 6