MAGNET DIVISION NOTE

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Date: June 25, 1986

No: 186-1 (SSC-MD-138)

Task Force: Coil Geometry Analysis

Title: A Single Layer Coil, 6.1 Tesla SSC Dipole

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GM:vm (This paper consists of 14 pages excluding cover sheet.)

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A Single Layer Coil, 6.1 Tesla SSC Dipole

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I. Introduction

The purpose of this computer study is to determine if a dipole having a realistic, single-layer coil design, using a cable having the same size as that used in the present SSC outer layer, can achieve 6.1 T central field. The affirmative answer assumes a superconductor current density approaching the best achieved thus far in production, close coupled cold iron with at most a very thin collar, a high but not unreasonable current density in the copper at quench, and operation below 4.2 K.

To minimize the computational effort, only one value of coil-to-iron gap at the mid-plane was used, namely 5 mm. To reduce saturation effects the iron aperture is shaped using the procedure described by Morgan.(1) With a 5 mm gap and relatively high ratio of coil thickness to coil inner radius (about 0.5), the higher harmonics (14 pole and above) arising from iron saturation are computed to be small enough to require no correction, so that the optimization process is relatively easy. If a 5 mm thick collar is used, its strength will be insufficient for full coil prestress, and in any case the Lorentz forces must be transferred through the iron to an outer stainless steel jacket, as presently done for the RHIC dipole. The iron outer diameter initially used for the present study was 10.5 inch (13.3 cm o.r.) the same as the present SSC iron. The o.r. was later reduced to 11.6 cm.

II. Cable

The present SSC outer layer utilizes a cable having 30 strands of 25.5 mil diameter. The cable is keystoned to 1.2 degree. The wire has a copper-to-superconductor ratio (CSR) of 1.8:1 and the 6504 A required for 6.6 T in the present 2-layer SSC design implies a current density S in the copper of 1024 A/mm^2 immediately following quench. For the present study, two values of S are used, 1100 A/mm^2 and 1500 A/mm^2. The latter is thought to be safe if active quench protection is used, and the former if passive is used. At a given field and current, S determines the actual copper area present, but the superconductor area and hence CSR vary with $J_c(T)$. The finished cable thickness (including insulation) is 1.317 mm, and width is 10.06 mm.

Except where indicated, the actual value of superconductor current density is not given in the figures which follow but rather the performance under standard conditions of 4.2 K and 5 T required to give the stated performance. Finally, except where indicated, the only margin in these calculations is the 6% by which the "critical field" is usually underestimated.

Elliptical Aperture Design

As mentioned before, an approximately elliptical aperture is used in the present magnet design, to minimize the shift in harmonics due to iron saturation. The procedure obtaining the aperture is summarized as follows. First an elliptical aperture is obtained which gives low shift in harmonics for a coil which has all harmonics zero for a circular aperture. A single layer coil geometry with non-integer turns is then optimized for the above elliptical aperture with the code MAG2(2), to produce zero harmonics for infinite permeability iron. Following this procedure an aperture and the coil geometry combination is obtained which gives both low harmonics and low shift in these values of harmonics.

The coil geometry used in this optimization has fully keystoned cable and is not the one which will be used in the final design. (The optimization of the partially keystoned cable is discussed in the next section.) This was done to speed up the procedure. Several computer programs have been developed to automate this procedure. These programs generate a mesh and also generate input for the code MDP for the given b_2, b_4 and b_6 bumps in the original circular aperture. The mesh is displayed on the VAX before a job file for MDP on CYBERVAX is created. The iron geometry so obtailned is shown in Fig. 1.

The values of semi-minor and semi-major axes are 3.586 and 4.484 cm, respectively. The value of b_4 bump is 0.153 cm and no b_6 bump was required. The outer radius of the iron is taken to be 11.6 cm.

Coil Design

The aperture shown in Fig. 1 has non-zero harmonics when used with a coil designed for a circular aperture. Therefore, to cancel these harmonics the coil for circular aperture should be designed to have the harmonics of same magnitude but opposite sign. Several structures have been examined for a total number of turns ranging from 16 to 19. The attempt was to maximize the transfer function with the maximum pole angle remaining close to 70 degrees. We looked for solutions with four or five blocks and minimum two turns in any block. There are several possible premutations to initiate the optimization, which is done with PAR2DOPT(3). PAR2DOPT is a computer code which optimizes the real coil structure with partially keystoned cable to obtain the desired harmonics. The procedure was again automataed to submit multiple jobs on the CDC-7600 computer for the given number of blocks and for the permitted minimum and maximum turns in a block to add to a particular total number of turns.

The chosen coil structure is shown in Fig. 2. It has four blocks with a total of 18 turns in them. The pole angle is 70.38 degrees. Wedges between the blocks and the tilt angles of those blocks and the other relevant parameters are displayed in the same figure. The geometry and the dimensions of the three wedges are given in more detail in Fig. 3.

Quench Limit Parameters

The critical current density depends on the bath temperature and on the peak field in the cable. We show several plots at various values of central field with the current density in copper being 1500 A/mm^2 (Fig. 4) and 1100 A/mm^2 (Fig. 5), respectively. From these figures one can obtain the bath temperature required for the available value of critical figures one can obtain the bath temperature required for the available value of critical current density, J_c (4.2 K .5 T), at a particular design value of central field. Figures 6 and 7 give the required cross-sectional area of copper and superconductor and the copper to superconductor ratio, CSR, in the cable to produce the design value of central field.

The Magnet

The complete magnet cold mass, based on the aperture and coil geometry discussed in the last two sections, is shown in Fig. 8. This is the model on the code MDP and the picture is obtained from the same code. The performance of this model is summarized in Table 1 and the harmonics are plotted in Fig. 9. We observe a very small shift in the harmonics — within 0.01 in all harmonics except in sextupole where it is 0.1 up to a field level of 6.1 Tesla. The stored energy at 6.1 Tesla is 0.7 MJ for a magnet of length 17.35 m.

Discussion

Please see Fig. 1, Fig. 2 and Table 2 for the following discussion. If a copper current density of 1515 A/mm^2 is acceptable, a 6.35 T central field at quench can be obtained with a current of 10410 A, J_c (at 4.2 K and 5 T) = 3200 A/mm^2 and an operating temperature of about 2.5 K. If run at 6.1 T this magnet at 9967 A current will have a safety margin of 13.5%; in the past, quench fields have been underestimated by 6%, suggesting that there is an additional margin of 12%. If operation at 4.35 K is desirable, the best that can be achieved is about 5.6 T at 9130 A with $J_c = 3200$ A/mm^2.

If the copper current densilty is restricted to 1100 A/mm^2, the best that can be done with $J_c = 3200$ is about 5.3 T at 2.5 K. With a J_c of 2750, about 4.7 T can be achieved at 4.35 K or 5.0 T at 8140 A and 3.2 K.

The coil design used in these calculations has 18 turns arranged in four blocks, and a maximum pole angle of 70 degrees. The present SSC Reference Design (NC-515) inner has a pole angle of 77 degrees, so that conceivably a coil having 19 or 20 turns could be found. A higher pole angle configuration would be slightly less efficient in its use of superconductor compared to the present design.

References

1. G.Morgan, "Reduction of iron saturation in $\cos\theta$ dipoles," RHIC Tech. Note 10 (July 29, 1985).

2. R. Fernow, "MAG2", Magnet Division Note No. 23, (June 20, 1983).

3. PAR2DOPT is a revised version by P. Thompson of a collection of routines called PARTIAL, mostly written by R. Fernow with some by G. Morgan.

Table 1.

The results of the field computations

I (Amps)	B (T)	B/I (G/A)	b'_2 10^{-4}	b'_4 10^{-4}	b'_6 10^{-4}	b'_8 10^{-4}	b'_{10} 10^{-4}	b'_{12} 10^{-4}
1000	0.614	6.143	-0.27	0.20	0.17	0.24	0.25	0.0
5000	3.072	6.143	-0.26	0.20	0.17	0.24	0.25	0.0
7000	4.300	6.143	-0.29	0.20	0.17	0.24	0.25	0.0
8000	4.912	6.141	-0.31	0.20	0.17	0.24	0.25	0.0
9000	5.521	6.135	-0.32	0.21	0.17	0.24	0.25	0.0
10000	6.120	6.120	-0.24	0.19	0.18	0.24	0.25	0.0
10700	6.524	6.097	-0.49	0.21	0.18	0.24	0.25	0.0

where the harmonics are defined as follows :

$$B = B_o + B_o \sum_n b_n (r/r_o)^n , \qquad (n = 1,2,3,...)$$

with r being the radius on the midplane and r_o the normalization radius.

These harmonics have been computed for 1 cm normalization radius.

Table 2

Few possible combination of parameters for a single layer SSC Magnet

B_o, Central Field (T)	6.35*	5.6	5.3	5.0	4.7
Current, KAmp	10.41*	9.13	8.64	8.14	7.65
Bath Temp (K)	2.5	4.35	2.5	3.2	4.35
J_c(@5T,4.2K), (A/mm**2)	3200	3200	3200	2750	2750
J in Cu, (A/mm**2)	1515	1500	1100	1100	1100

*B_o = 6.1 T for 13.5% safety margin and 9.97 KAmp current.

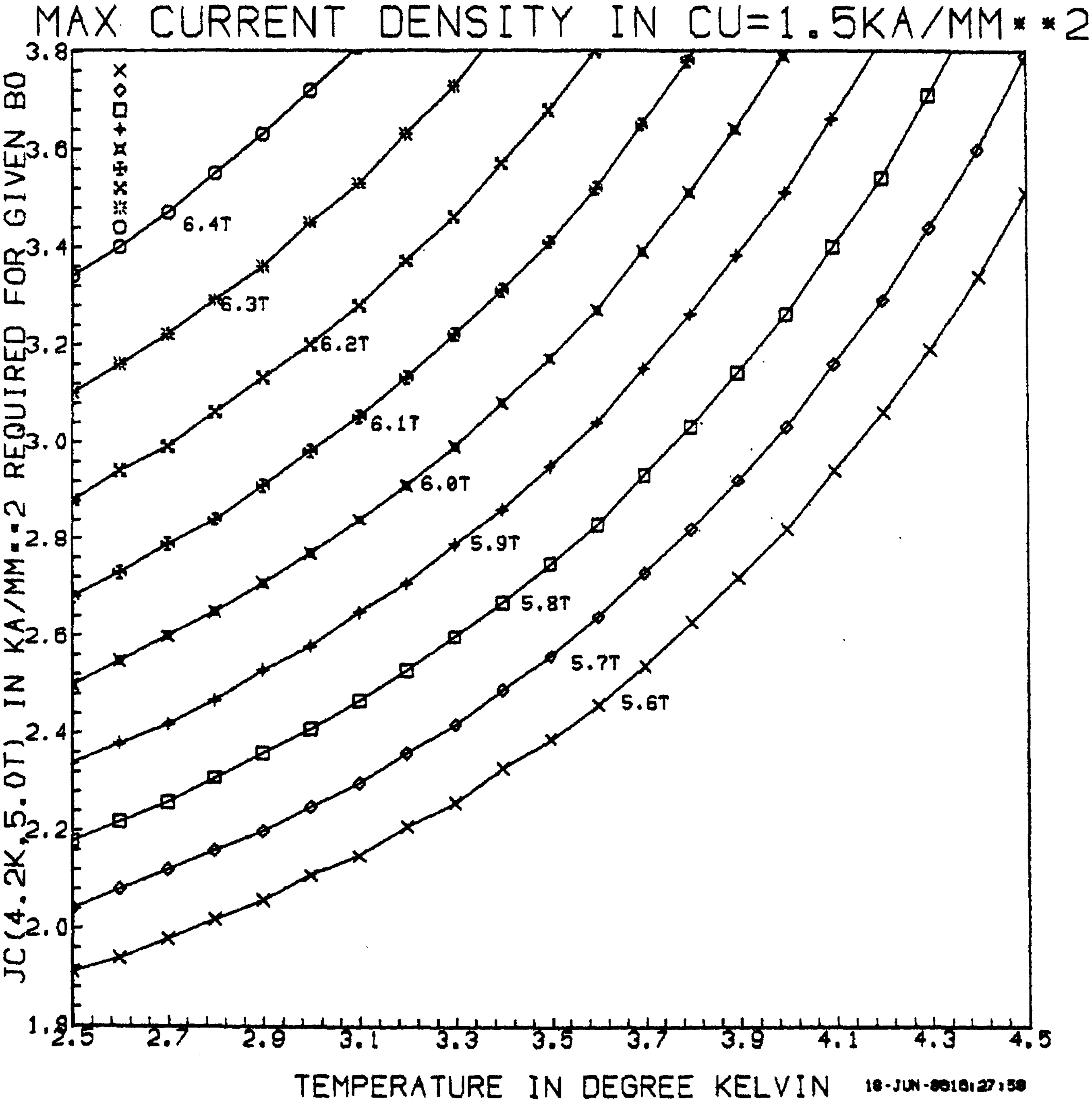

Fig 1. The required specifications for the critical current density, J_c(at 4.2K and 5T), and the operating bath temperature to obtained the field indicated on the curve for active quench protection scheme.

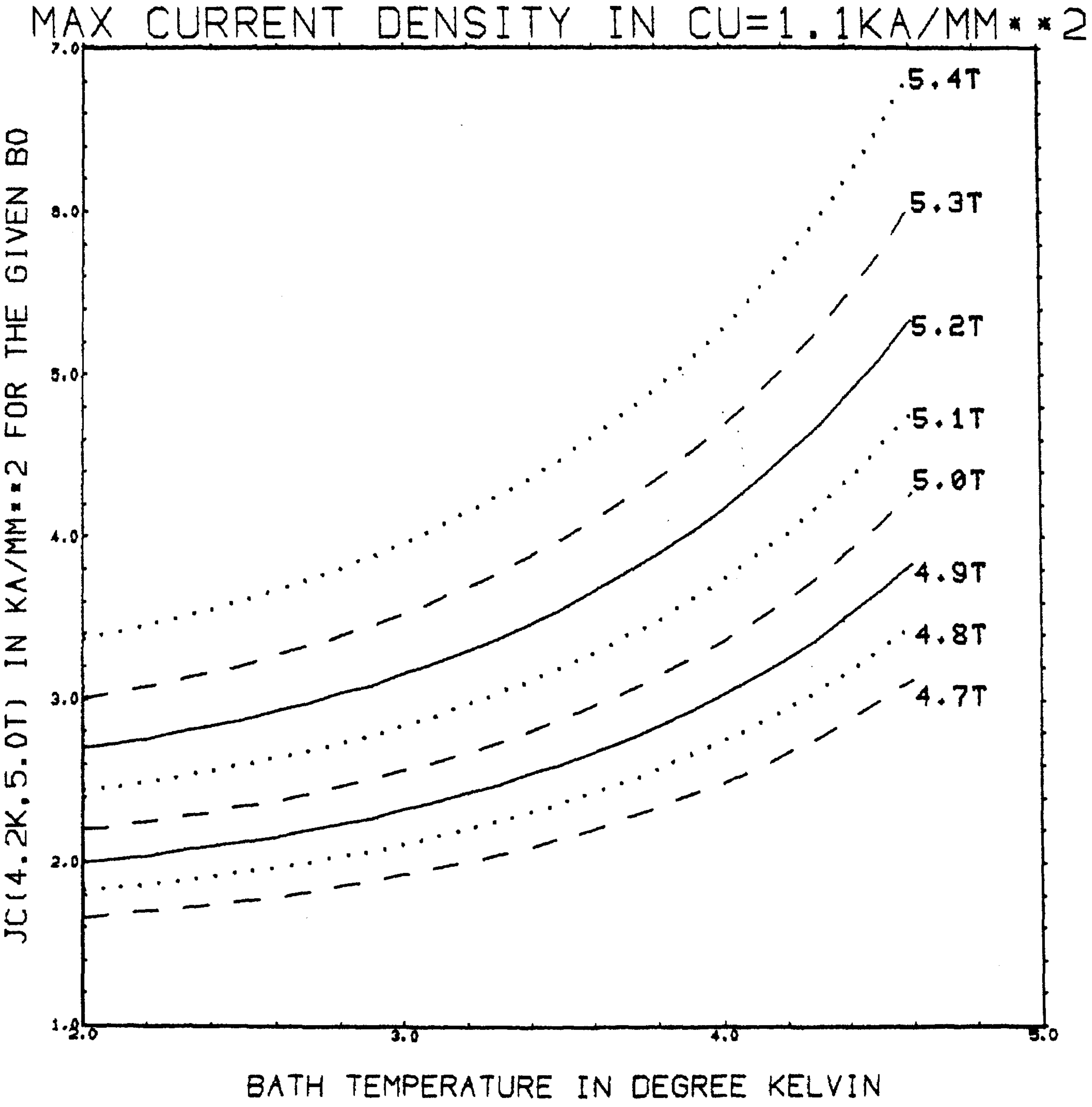

Fig 2. The required specifications for the critical current density, J_c(at 4.2K and 5T), and the operating bath temperature to obtained the field indicated on the curve for passive quench protection scheme.

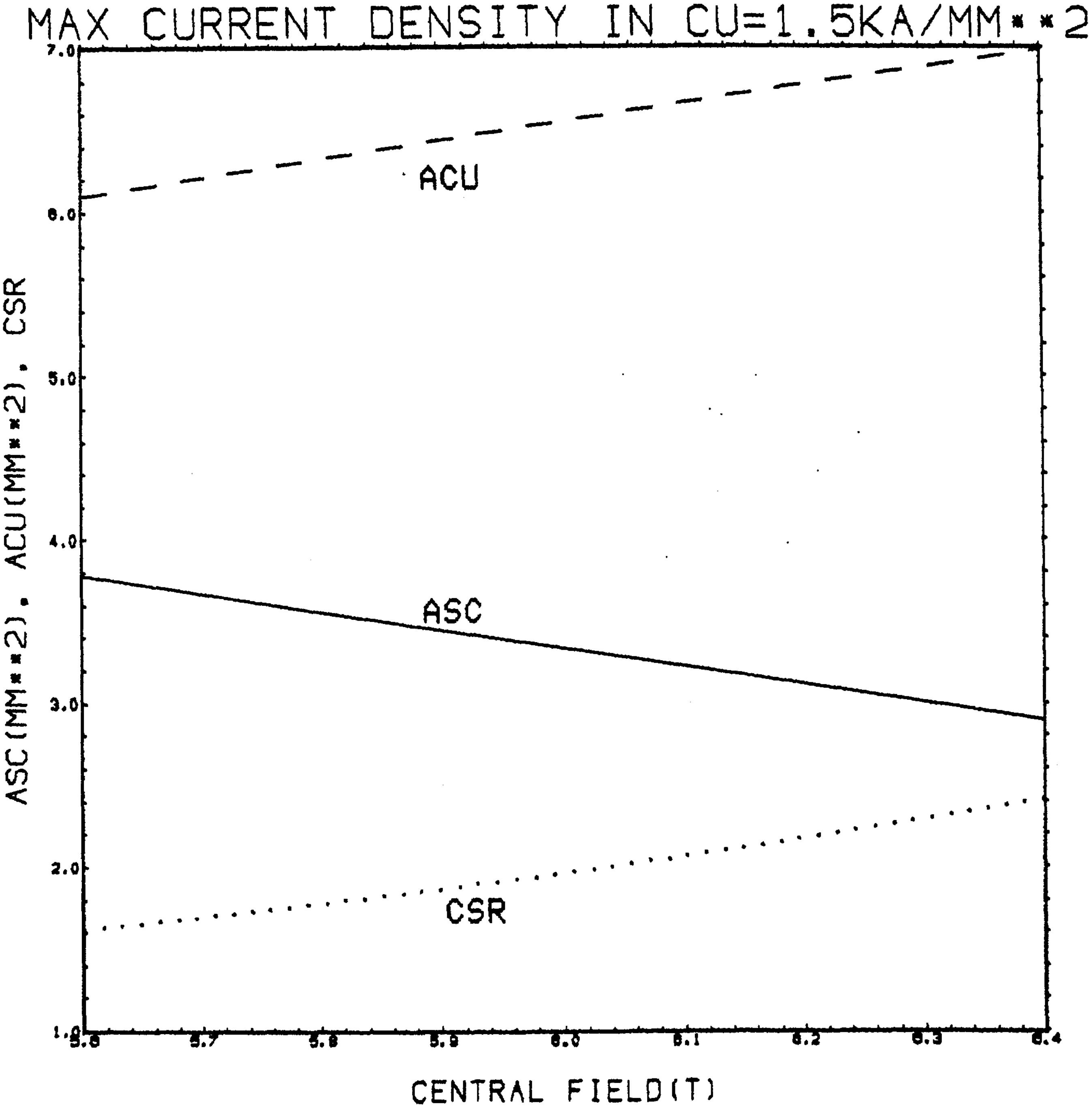

Fig 3. The variation in the requirement of the cross-section area of superconductor(ASC), copper(ACU) and copper to superconductor ratio, CSR, to achieve the desired maximum field in the case of active quench protection scheme.

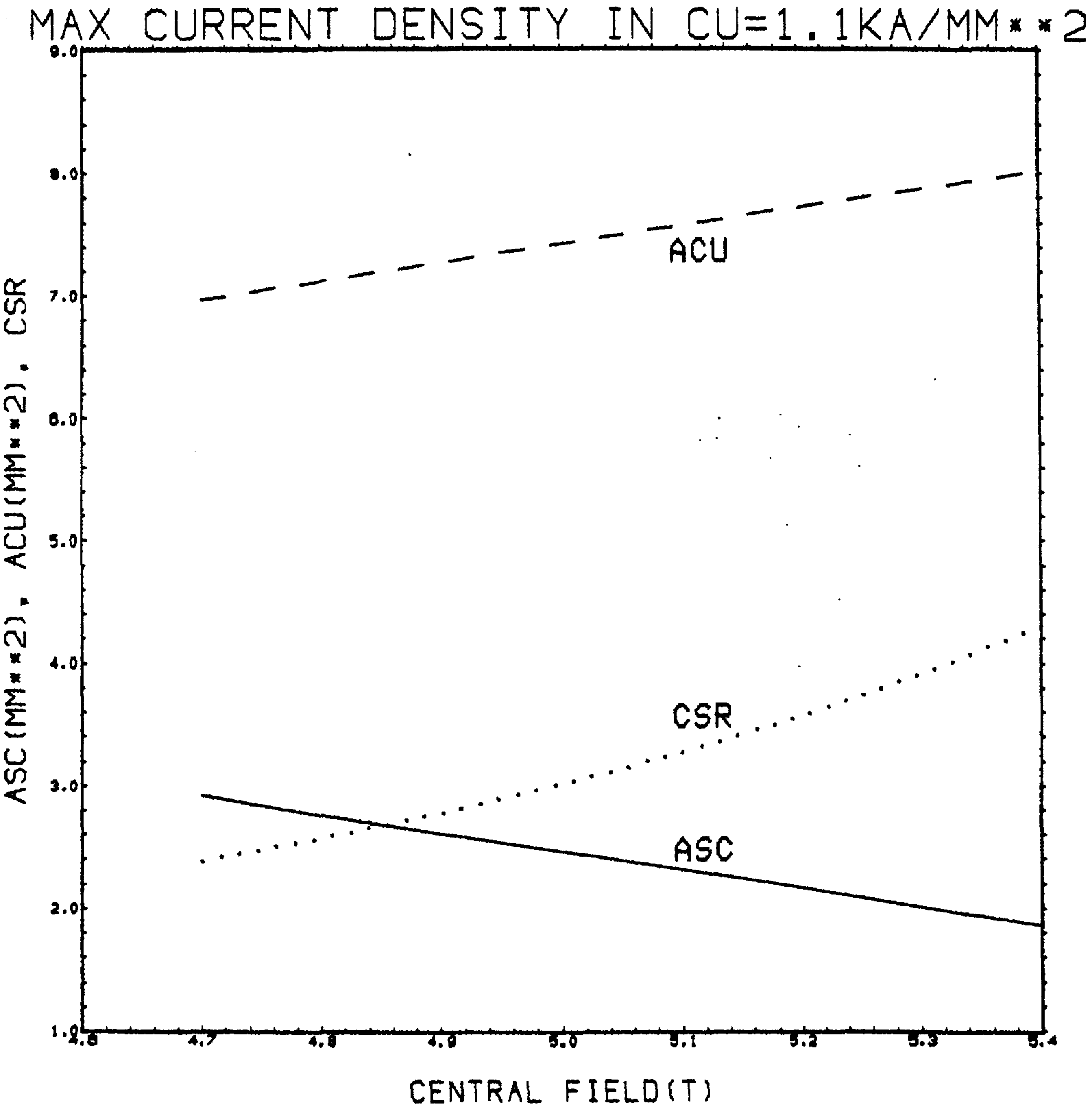

Fig 4. The variation in the requirement of the cross-section area of superconductor(ASC), copper(ACU) and copper to superconductor ratio, CSR, to achieve the desired maximum field in the case of passive quench protection scheme.

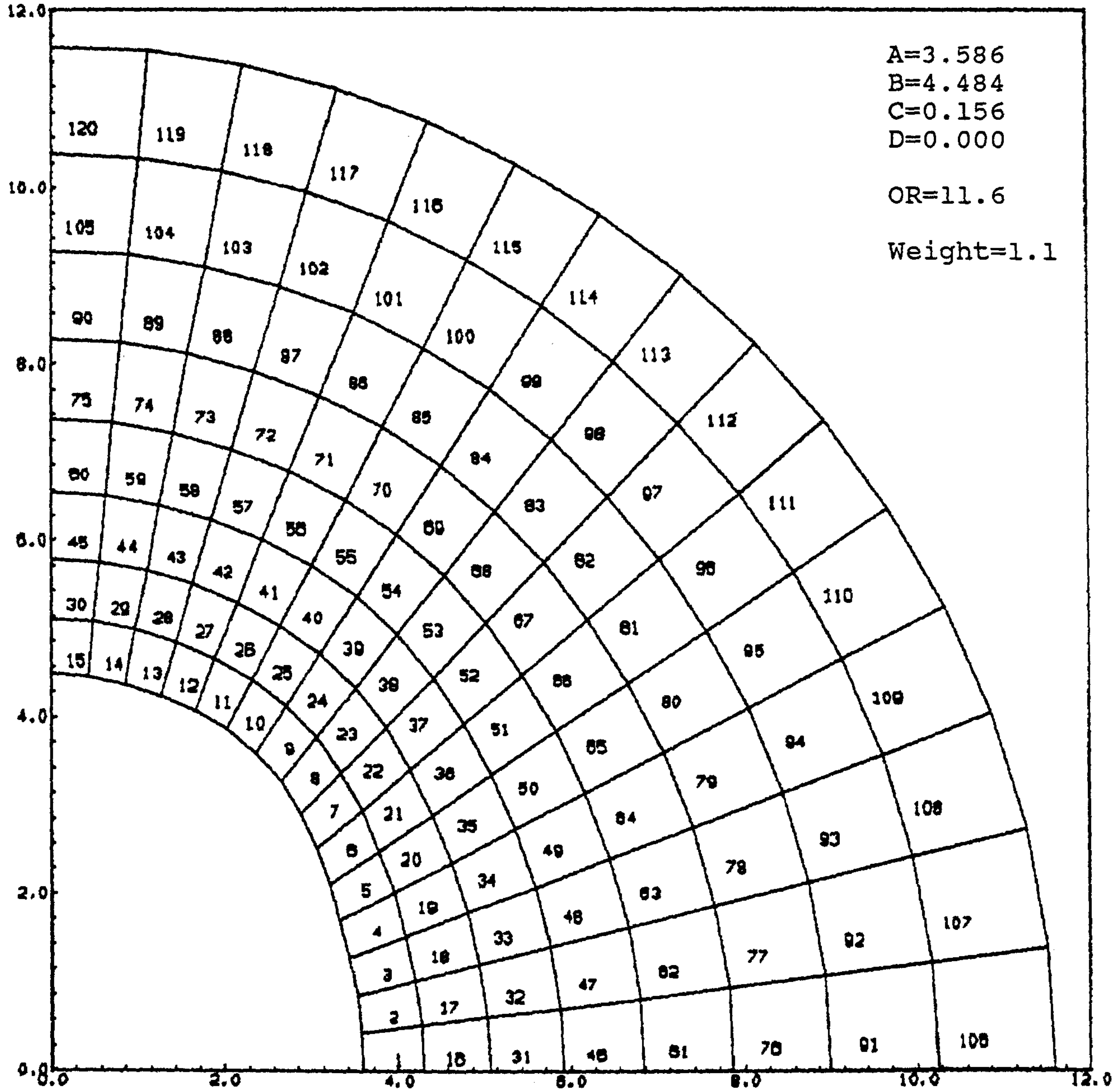

Fig 5. The mesh of the iron with aperture optimized to reduce the shift in harmonics due to saturation. A & B are the semimajor and semiminor axis of the elliptical aperture, C & D are the deviation from ellipse to create b_4 and b_6 harmonic bumps. OR is the outer radius. Weight is a parameter used in creating mesh, it makes inner elements smaller than the outer.

```
CHISQ=    0.084077 + PENALTY=    0.084077 (X 0.0E+00)
TRANSFER FUNCTION=   6.80675  POLE ANGLE=  70.37743
  TURNS        TILT          WEDGE

   6.0
 - - - - - - - - - - - -   1.6000
   7.0       8.6518
 - - - - - - - - - - - -   2.4711
   2.0      10.0000
 - - - - - - - - - - - -   6.4334
   3.0      10.0000

   harmonics (0-4th)          (5th-9th)
        10000.00               0.27
          -59.50              -0.04
           -1.46               0.00
            0.15               0.00
            0.20               0.00
```

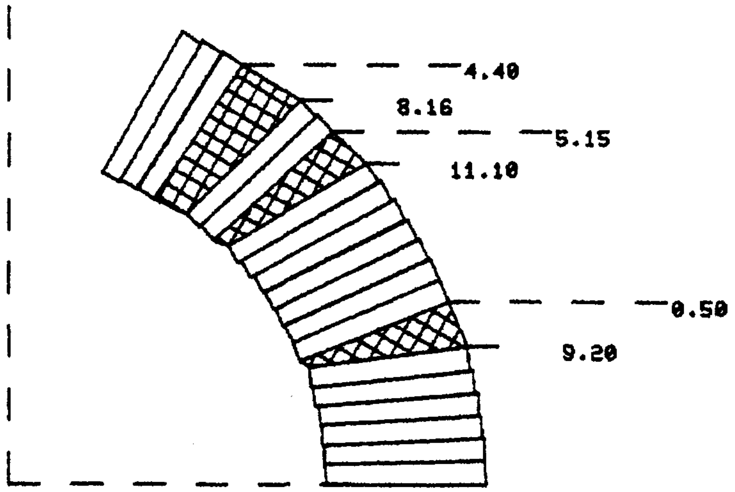

Fig 6. The optimized coil structure and its parameters.

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                     . WEDGE COORDINATES
                 x1  y1             x2  y2           x3  y3           x4  y4

 cm        1.895  0.728        1.845  0.768      2.778  1.143      2.893  0.855
inch        0.000  0.000      -0.018  0.018       0.366  0.118       0.396  0.000
face angles     133.666       14.598   -75.611

 cm        1.395  1.489        1.302  1.516      2.054  2.184      2.263  1.997
inch        0.000  0.000      -0.026  0.028       0.362  0.105       0.396  0.000
face angles     133.603       11.281   -72.113

 cm        1.125  1.683        0.918  1.775      1.480  2.609      1.849  2.382
inch        0.000  0.000      -0.034  0.083       0.354  0.165       0.396  0.000
face angles     112.065       12.025   -75.663
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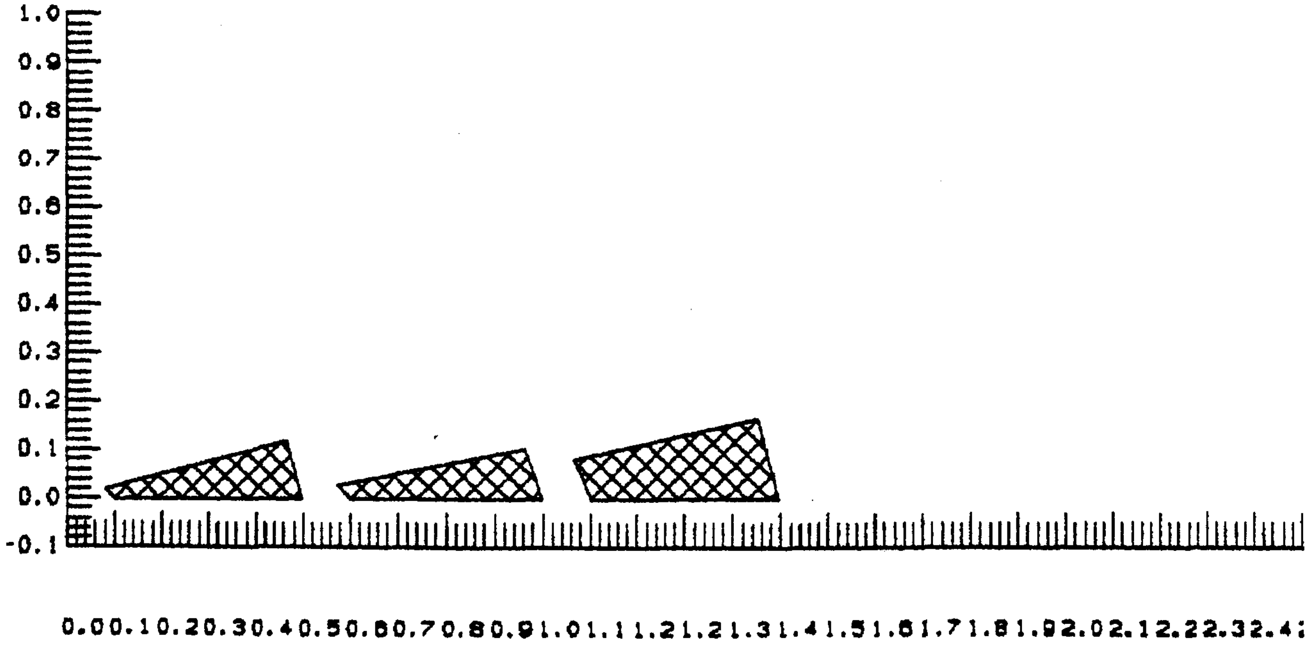

Fig 7. The geometry of the wedges and their dimensions.

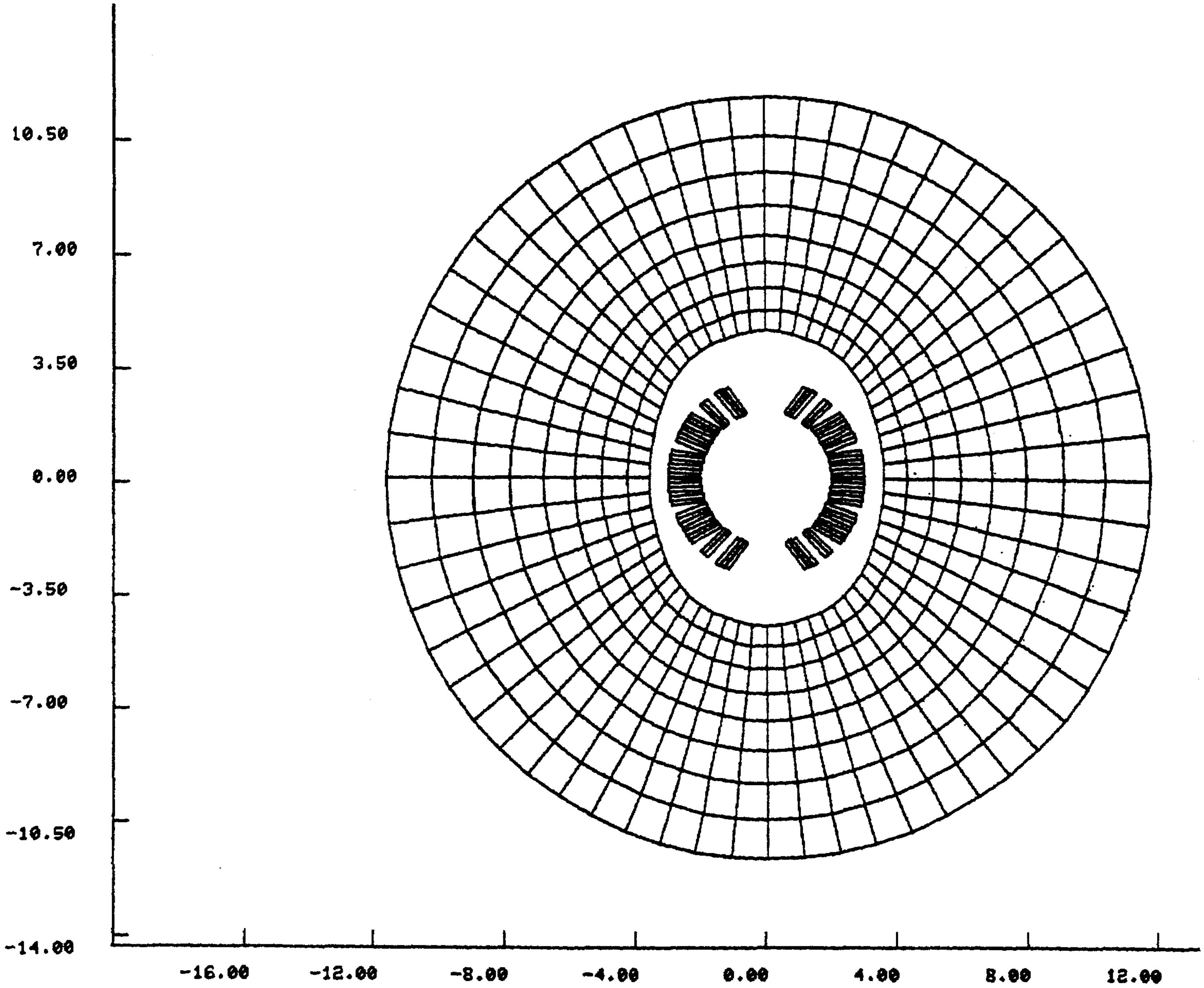

Fig 8. The complete magnet geometry and its model on MDP.

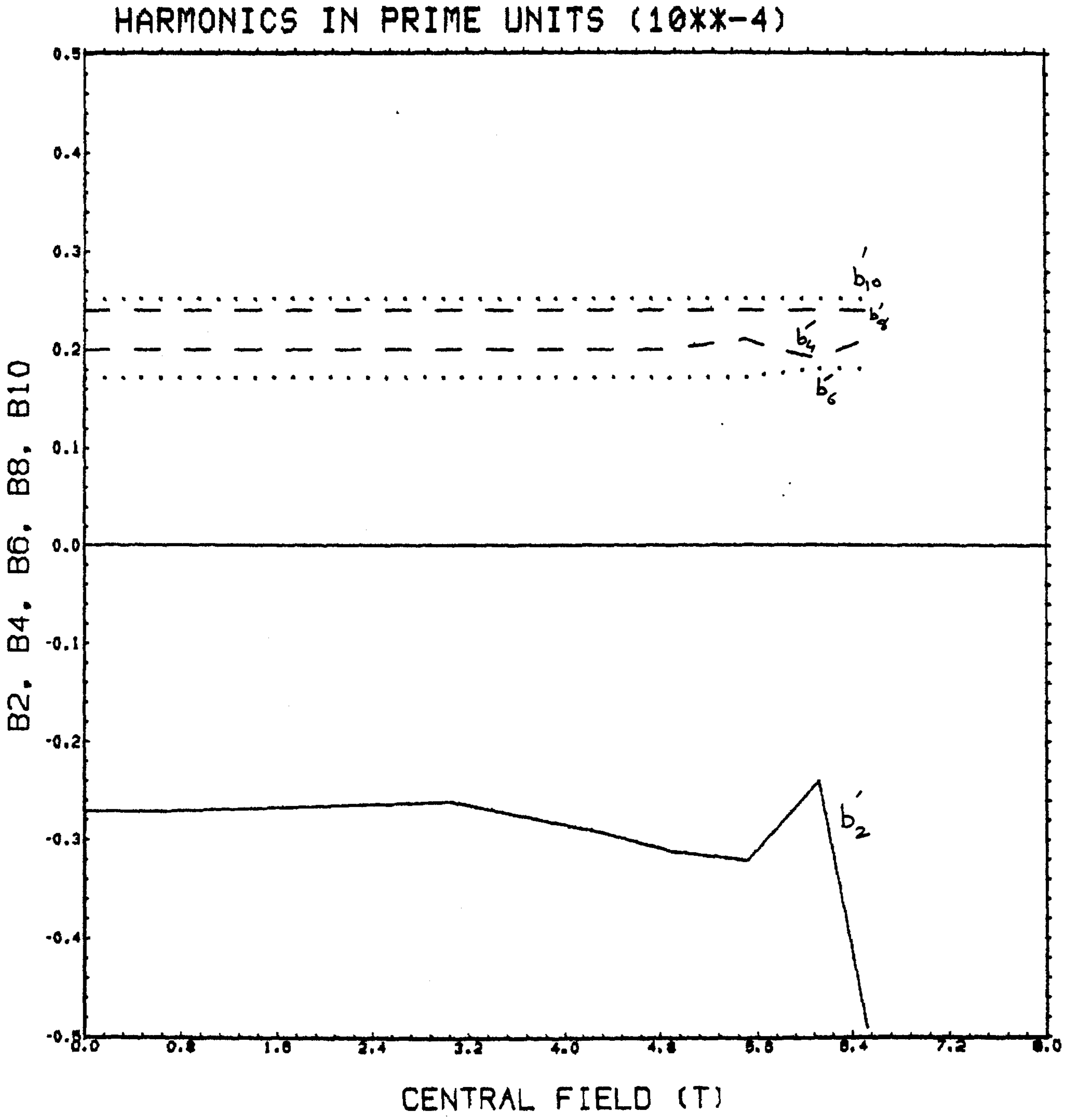

Fig 9. The variation of the harmonics with the magnetic field.