BROOKHAVEN
NATIONAL LABORATORY

Superconducting Magnet Division

Magnet Note

Author: Ramesh Gupta

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Title: Optimum Integral Design for Maximizing Field in Short Magnets

M. Anerella
J. Cozzolino
J. Escallier
G. Ganetis
M. Garber
A. Ghosh
R. Gupta
H. Hahn
M. Harrison
J. Herrera
A. Jain
P. Joshi
S. Kahn
W. Louie
J. Muratore

S. Ozaki
B. Parker
S. Peggs
F. Pilat
S. Plate
C. Porretto
W. Sampson
J. Schmalzle
J. Sondericker
S. Tepikian
R. Thomas
D. Trbojevic
P. Wanderer
J. Wei
E. Willen

Optimum Integral Design for Maximizing Field in Short Magnets

Ramesh Gupta
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An optimum integral design is introduced that could extend the magnetic length to overall coil length without diluting the field. Since in most conductor-dominated dipoles, the waste in magnetic length due to ends is generally of the order of a coil diameter, the benefits of such designs are particularly overwhelming in short magnets where the coil length is comparable to or a few times the coil diameter. The concept is developed for the designs where the wire/cable bend radius can be small as compared to the coil diameter. However, the general approach can be applied to any design. A preliminary magnetic design of corrector dipole for AGS helical magnet based on this concept is presented. In this concept, the ends and body harmonics are optimized together to create an integral cosine ($n\theta$) *azimuthal current distribution. A particular example of this optimization process is that the length of successive turn follows a cosine theta variation in going from midplane to pole. Thus, the coil mechanical length becomes the magnetic length. Furthermore, the design also allows a larger number of turns in the coil than the typical 2/3 of maximum physical space available on circumference, since turn-to-turn spacing by itself need not generate a cosine* ($n\theta$) *modulation.*

In a typical conductor dominated design, the coil cross section is optimized to create a cosine $(n\theta)$ type azimuthal current distribution:

$$I(\theta) = I_o\, COS(n\theta)$$

The ends are then optimized to minimize the field harmonics along with the peak field. In most dipoles (for example see SSC or RHIC), the combined mechanical length of the two ends is of the order of two diameters and the contribution to magnetic length is about a diameter. The serpentine design proposed by Brett Parker does not require an end optimization, as ends contribute none or little to the dipole field. However, in both cases (in conventional ends and in serpentine ends), dipole ends waste a length that is of the order of a coil diameter.

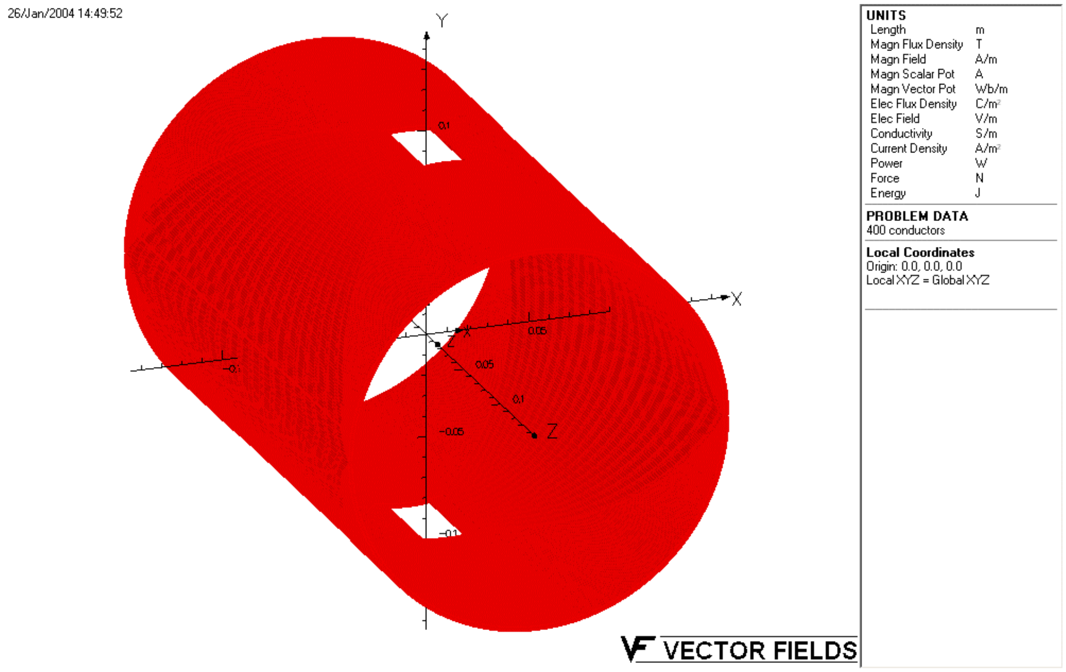
In the design proposed here, we start with the initial constraint that the coil length is the magnetic length. Then the integrated cosine theta angular distribution is obtained by modulating both the length (with the help of end spacers) and the angular distribution of turns (with the help of wedges). Thus, the integral optimization can be represented as:

$$I_L(\theta) \;=\; I(\theta)\,.\,L(\theta) \;\propto\; COS(n\theta)$$

In principle, it is possible to optimize a cosine *(nθ)* type distribution, by modulating the end spacers between the end blocks alone, i.e. without using any wedge (or equivalent insert) between the turns in cross section. However, in a more practical and optimum design one would take advantage of both, as needed. In short magnets, where the coil length is only a few times the coil diameter, there is no straight section type magnetic region (field having a flat top to certain length), an integral description of the field is more appropriate.

The above concept is applied to AGS Helical corrector dipole with the help of EXCEL spread sheet and FOTRAN optimization codes. The preliminary design discussed here, though sufficient to serve the purpose, is not intended to show the best or a typical solution possible. The purpose of this informal note is to explain the concept rather than present an optimized design. The FOTRAN code also makes an OPERA3d model which can be combined with the existing model of AGS snake with helical and solenoidal coils.

The OPERA 3d model (Fig 1 through Fig. 4) is of a 2-layer coil having an aperture of 181.6 mm. The coil is made with the same 1 mm cable that is used in AGS helical magnet and has a turn-to-turn spacing of 1.25 mm. The desired field of 0.008 T.m is obtained in only 300 mm long coil (end-to-end) at ~25 A. This suggest that the use of ~0.3 mm wire, rather than the ~1 mm cable, may serve the purpose.



UNITS

Length	m
Magn Flux Density	T
Magn Field	A/m
Magn Scalar Pot	A
Magn Vector Pot	Wb/m
Elec Flux Density	C/m^2
Elec Field	V/m
Conductivity	S/m
Current Density	A/m^2
Power	W
Force	N
Energy	J

PROBLEM DATA
400 conductors

Local Coordinates
Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ

Fig 1: OPERA 3d model of 181.6 mm diameter, 300 mm long 2 layer coil made with ~1 mm cable (1.25 mm turn-to-turn spacing) for AGS helical corrector dipole.

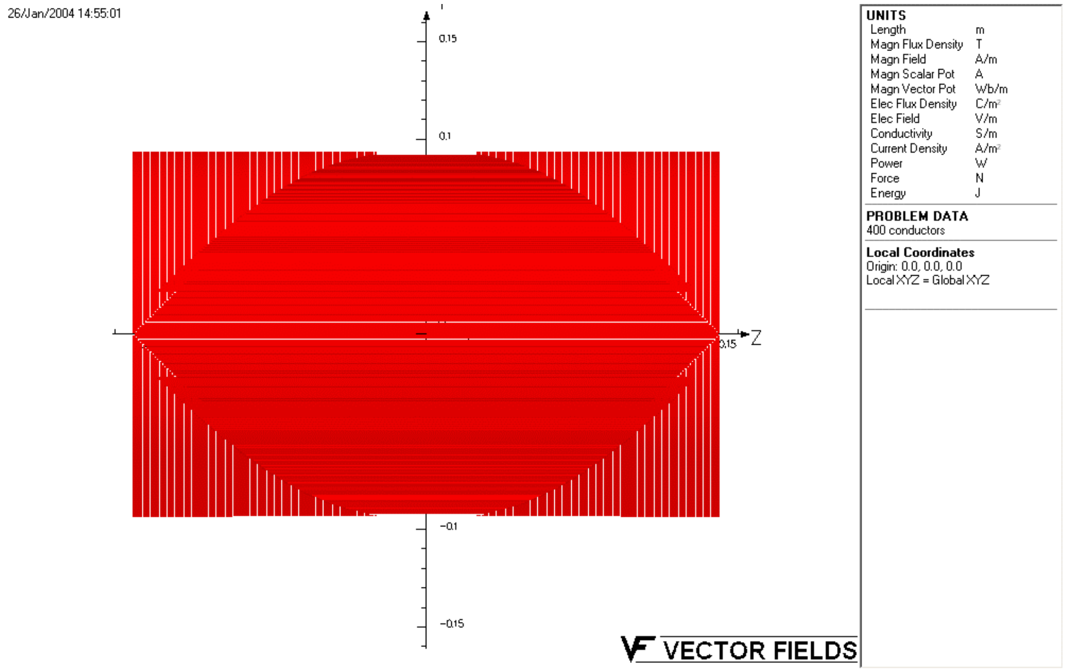


Fig 2: OPERA 3d model of 181.6 mm diameter, 300 mm long, AGS helical corrector dipole, as viewed from the X-axis. A darker area indicates the conductor along z-axis and lighter area (vertical lines) indicate magnet end.

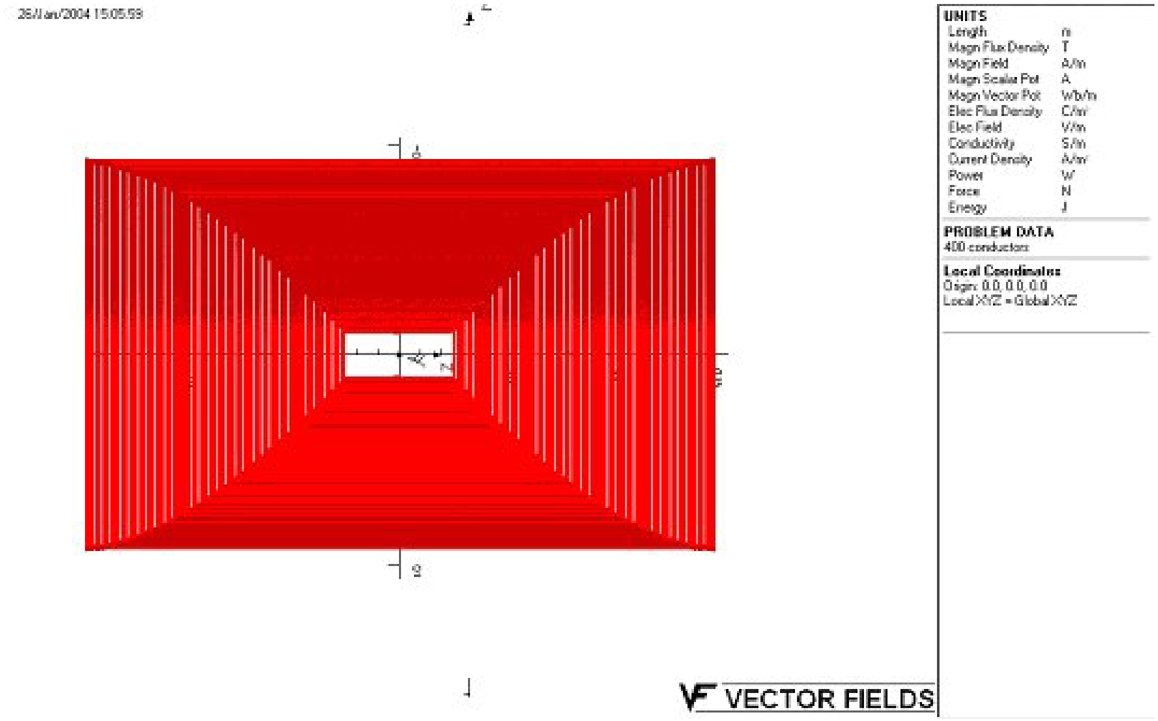


Fig 3: OPERA 3d model of 181.6 mm diameter, 300 mm long, AGS helical corrector dipole, as viewed from the Y-axis. A darker area indicates the conductor along z-axis and lighter area (horizontal lines) indicate magnet end.

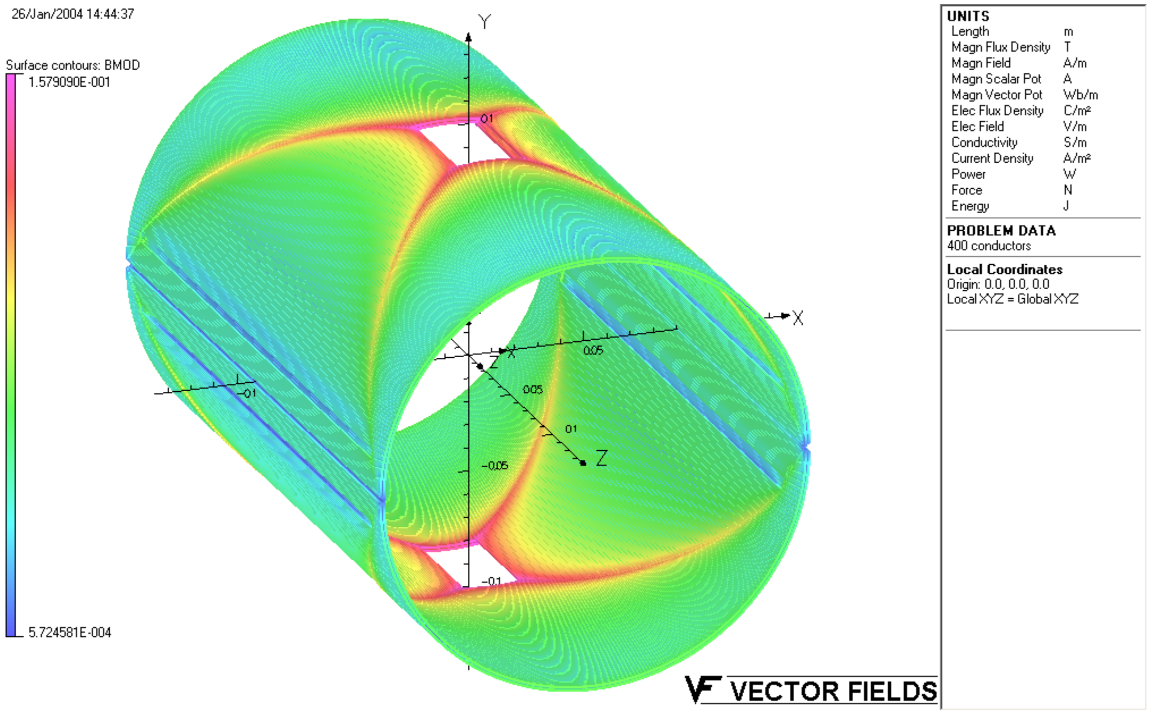


Fig 4: OPERA 3d model of 181.6 mm diameter, 300 mm long, AGS helical corrector dipole. This picture shows the peak field on the conductors.

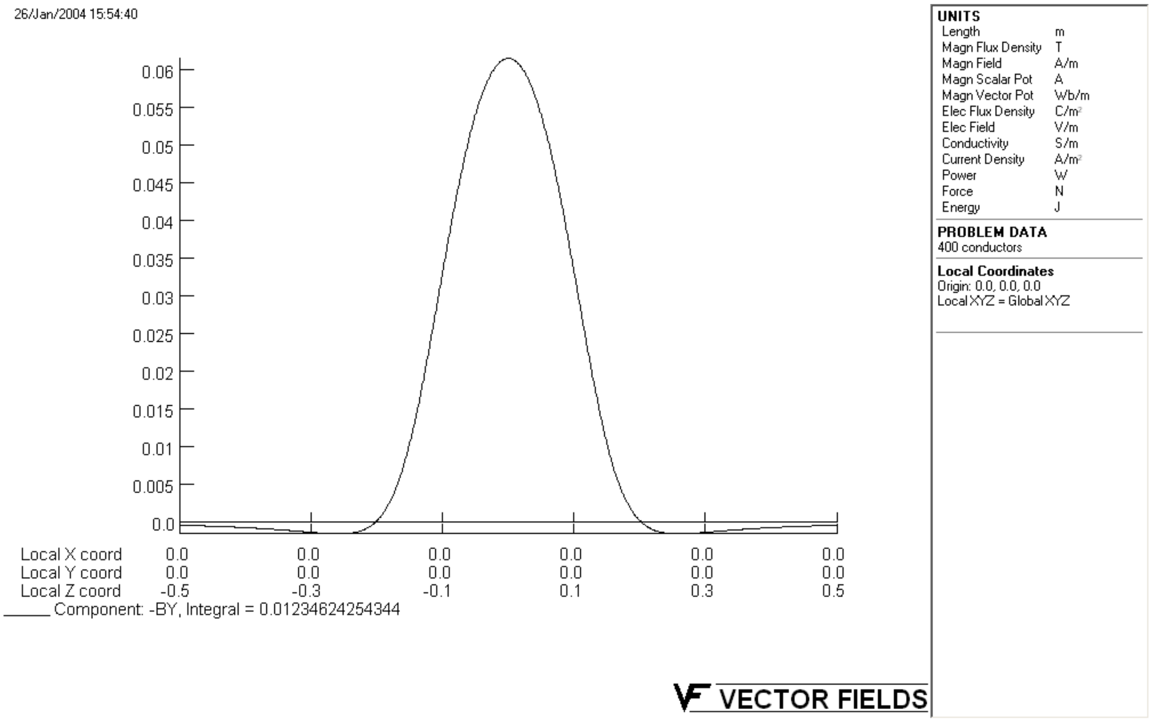


Fig 5: Vertical component of the field as a function of axial position at ~38 A.

As compared to a preliminary SERPENTINE design optimized by Brett Parker, this design is estimated to give about a factor of two higher field. Though the program accommodates coils with non-zero bend radii, the above model assumes sharp ends.

The following OUTPUT from a FOTRAN Program lists the basic parameters of the corrector dipole for AGS helical magnet. The result of field optimization with a FORTRAN code are also listed. This agrees well with OPERA3d calculations.

```
 IRON RADIUS (MM) =   150.2000
 REFERENCE RADIUS (MM) =   65.00000
 NUMBER OF LAYERS =           2

 PARAMETERS FOR LAYER No.           1
WIRE DIAMETER(mm), COIL LENGTH(m), COIL RADIUS(mm)
   1.250000      0.3000000      90.80000
 CURRENT PER WIRE (AMP):   50.00000
 NUMBER OF CROSS SECTION BLOCKS AND No. OF END-SPACERS
          2          2
 REFERENCE PARAMETRS BY COUNTING FROM MIDPLANE

 PARAMETERS FOR LAYER No.           2
 WIRE DIAMETER(mm), COIL LENGTH(m), COIL RADIUS(mm)
   1.250000      0.3000000      92.30000
 CURRENT PER WIRE (AMP):   50.00000

LAYER NO.    BLOCK No.    TURNS   WEDGE (DEGREE)   C2C-BODY(DEG)
     1            1          30      0.00000         0.00000
     1            2          70      0.16981         0.00000
LAYER NO.    BLOCK No.    TURNS   END-SPACER(MM)   C2C-END(MM)
     1            1          20      0.00000         0.00000
     1            2          80      0.00000         0.00000
LAYER NO.    BLOCK No.    TURNS   WEDGE (DEGREE)   C2C-BODY(DEG)
     2            1          10      0.00000         0.00000
     2            2          90      6.03181         0.00000
LAYER NO.    BLOCK No.    TURNS   END-SPACER(MM)   C2C-END(MM)
     2            1           5      0.00000         0.00000
     2            2          95      0.00000         0.00000

 INTEGRATED FIELD HARMONICS  AT 65 MM REFERENCE RADIUS:
  No.   Bn(T.m)     bn*10^4(units)  bn(des)     weight
   0   0.16650E-01  10000.0000      0.0000      0.0000
   2   0.24941E-06      0.1498      0.0000    200.0000
   4   0.85136E-06      0.5113      0.0000    200.0000
   6  -0.65799E-05     -3.9519      0.0000     60.0000
   8   0.87265E-05      5.2411      0.0000     50.0000
  10   0.18526E-04     11.1266      0.0000     40.0000
  12   0.78435E-05      4.7108      0.0000      0.0000
  14   0.73330E-05      4.4041      0.0000      0.0000
  16   0.24409E-05      1.4660      0.0000      0.0000
  18   0.16569E-05      0.9951      0.0000      0.0000
  20   0.42517E-06      0.2554      0.0000      0.0000
  22   0.19293E-06      0.1159      0.0000      0.0000
```

Single Layer Wire Design

The inherent efficiency of the design allows the required integral field of 0.008 T.m to be obtained in a single layer, 13 mil diameter wire (18.5 insulated and 25 mil turn-to-turn spacing), operating at ~25 A with a total end-to-end coil length of 0.3 meter. The inner coil radius is 90.8 mm and the bend radius of each turn in the end is 0.25 inches. There are 195 turns per quadrant and there is one spacer in the body of the magnet after 23 turns (counting from midplane).

OPERA 3d model of this design is shown in Figure 6 and Figure 7. The output of the coil optimization FOTRAN program is given below:

```
IRON RADIUS (MM)  =   150.2000
REFERENCE RADIUS (MM) =   65.00000
TURN BEND RADIUS (MM) =   6.350000
NUMBER OF POINTS ON BEND RADIUS   =     100
NUMBER OF LAYERS  =          1
PARAMETERS FOR LAYER No.          1
MAXIMUM NUMBER OF TURNS          195
WIRE DIAMETER(mm), COIL LENGTH(m), COIL RADIUS(mm)
 0.6350000      0.3000000       90.80000
CURRENT PER WIRE (AMP)   25.00000

LAYER NO.     BLOCK No.     TURNS   WEDGE (DEGREE)   C2C-BODY(DEG)
     1            1            23       0.00000         0.00000
     1            2           172       2.79093         0.00000
LAYER NO.     BLOCK No.     TURNS   END-SPACER(MM)   C2C-END(MM)
     1            1           195     0.00000           0.00000

CHI SQUARE =    90.5528765157823

INTEGRATED FIELD HARMONICS AT 65 MM REFERENCE RADIUS:
 No.   Bn(T.m)     bn*10^4(units)   bn(des)    weight
  0   0.81737E-02    10000.00       0.0000     0.0000
  2   0.50907E-06     0.6228        0.0000     1.0000
  4   0.66527E-06     0.8139        0.0000     1.0000
  6  -0.89664E-05   -10.9698        0.0000     0.6000
  8   0.30649E-05     3.7498        0.0000     0.5000
 10   0.87918E-05    10.7562        0.0000     0.4000
 12   0.43427E-05     5.3130        0.0000     0.0000
 14   0.42456E-05     5.1942        0.0000     0.0000
 16   0.15132E-05     1.8514        0.0000     0.0000
 18   0.10685E-05     1.3072        0.0000     0.0000
 20   0.26321E-06     0.3220        0.0000     0.0000
 22   0.13610E-06     0.1665        0.0000     0.0000
 24  -0.70026E-08    -0.0086        0.0000     0.0000
 26  -0.15507E-07    -0.0190        0.0000     0.0000
 28  -0.21148E-07    -0.0259        0.0000     0.0000
 30  -0.14073E-07    -0.0172        0.0000     0.0000
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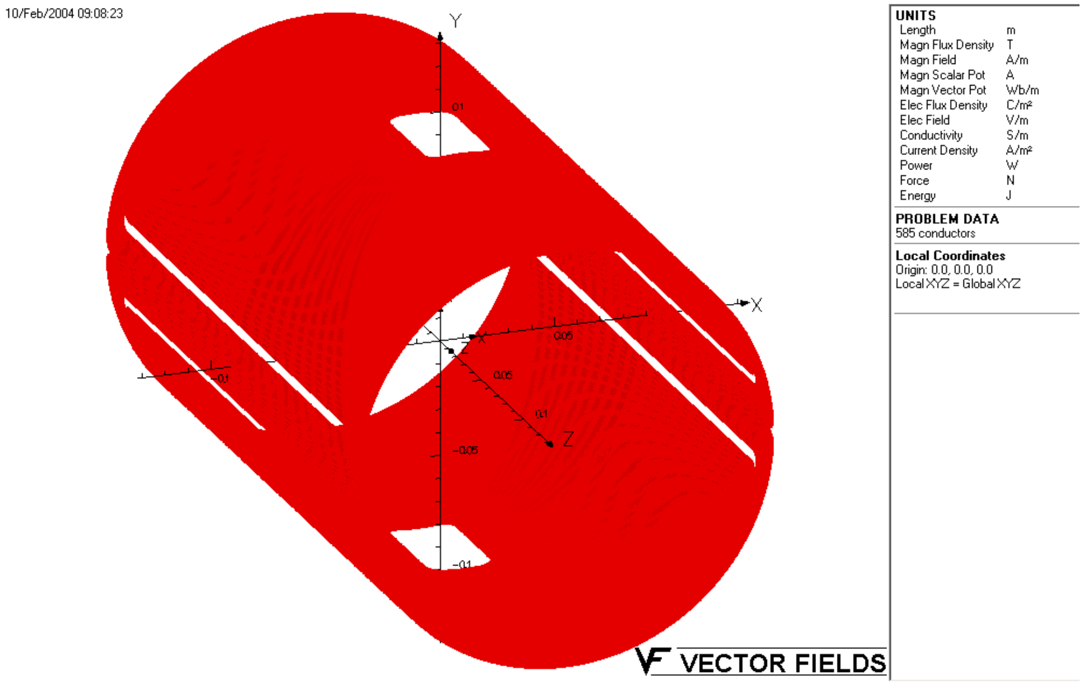

Fig 6: OPERA 3d model of 181.6 mm diameter, 300 mm long single layer coil made with ~13 mil wire (25 mil turn-to-turn spacing) for AGS helical corrector dipole.

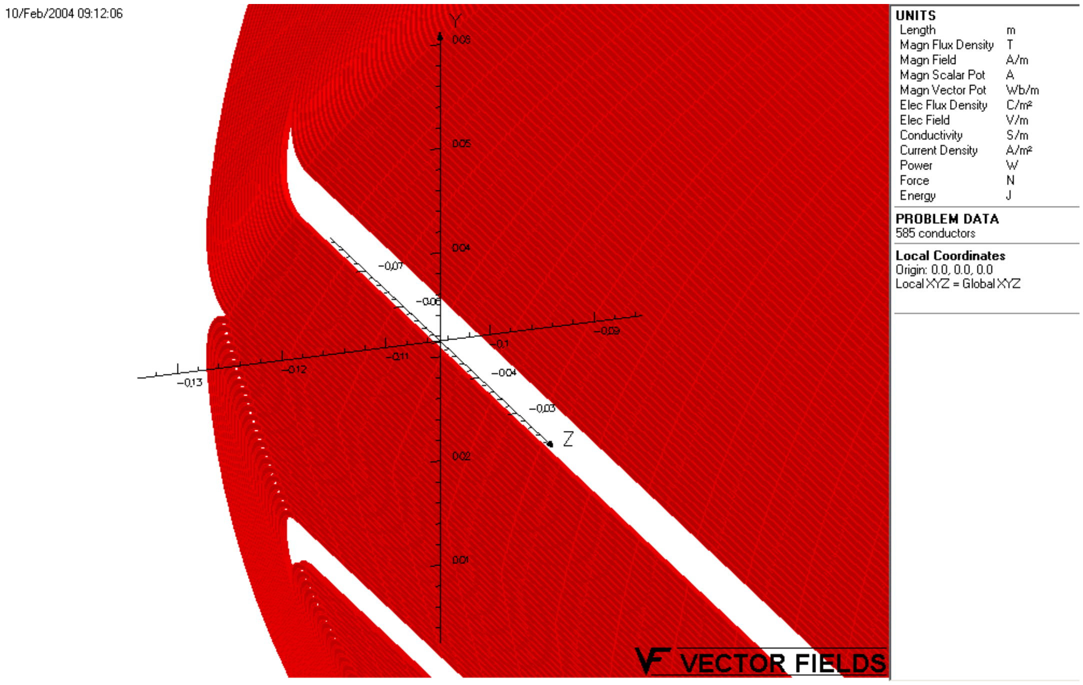

Fig 7: Another view of OPERA 3d model of 181.6 mm diameter, 300 mm long single layer coil made with ~13 mil wire) for AGS helical corrector dipole. The bend radius of each turn in the two ends is 0.25 inches.