Magnetic Design Studies of the Dipole

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Prototype Lattice Magnet Design Review

January 28, 2008

Overview

Magnetic Design of 35 mm Aperture Dipole

• 2-d and 3-d magnetic design and analysis

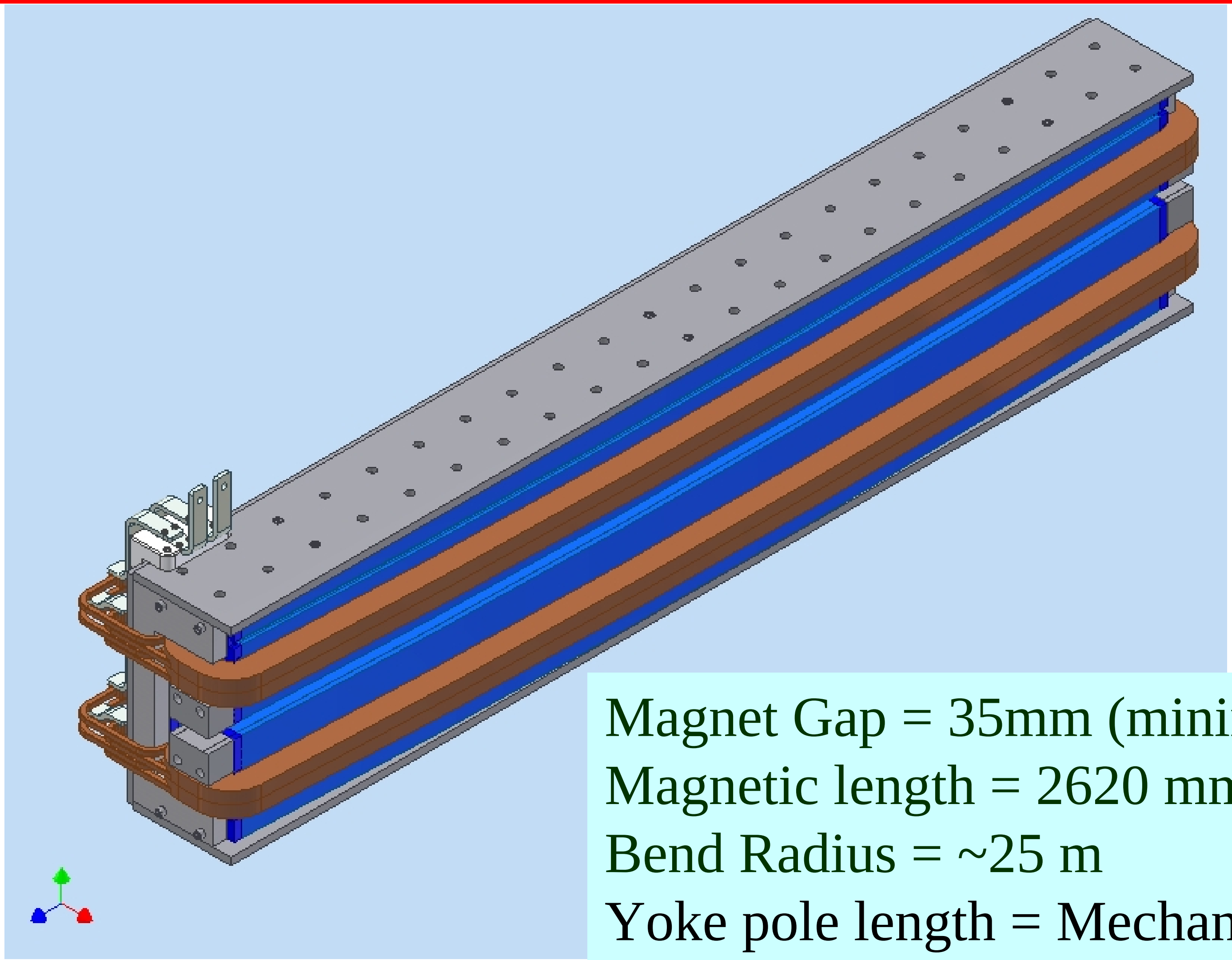
- **Special feature:**
  Extended pole to increase effective magnetic length

Magnetic Design of 90 mm Aperture Dipole

• 2-d and 3-d magnetic design and analysis

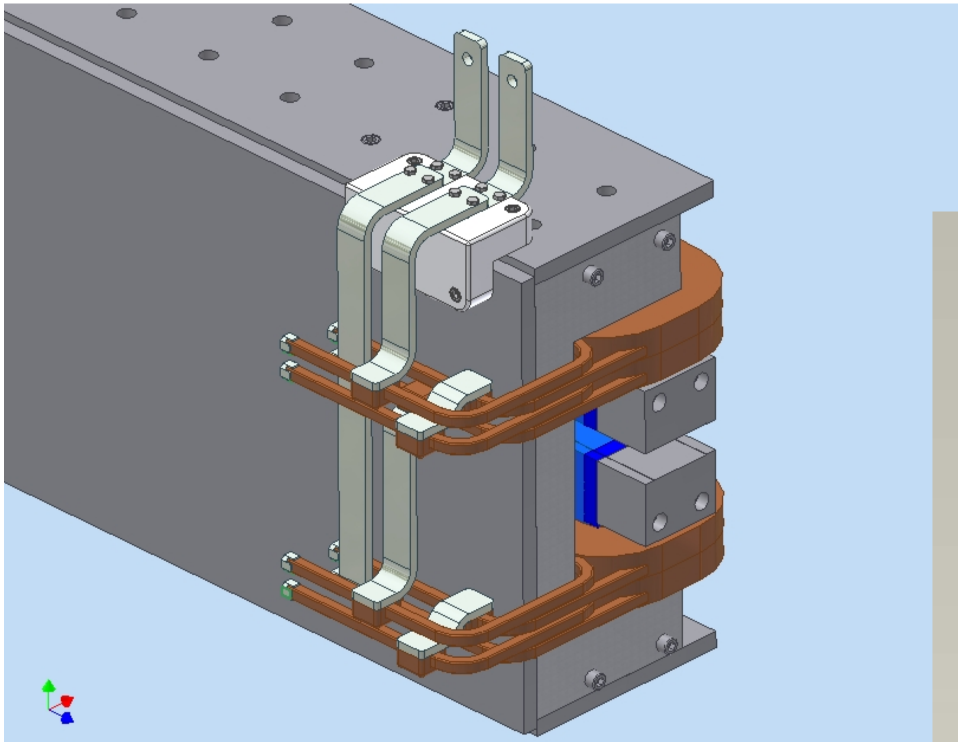
- **Special consideration:**
  Transfer function tracking between 35 mm and 90 mm aperture dipoles

35 mm Aperture Dipole

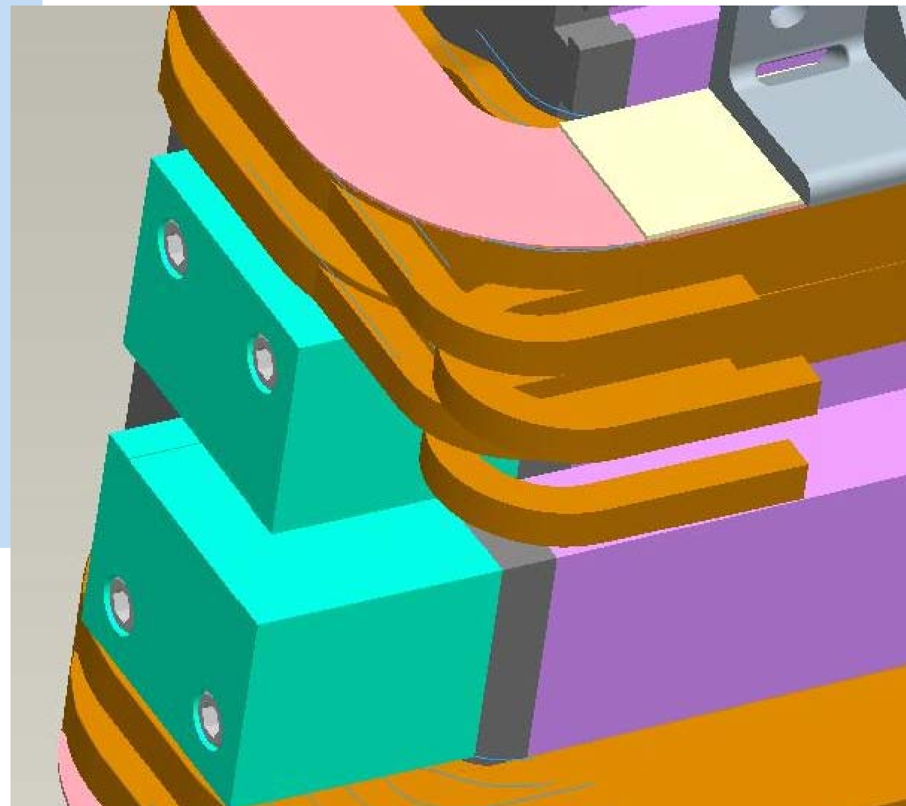


Magnet Gap = 35mm (minimum)
Magnetic length = 2620 mm
Bend Radius = ~25 m
Yoke pole length = Mechanical Coil length

Unique Feature : Extended Pole (Nose)



We take advantage of the low field requirements (0.4 T)



Magnetic length >
Mechanical length

Magnetic Design Requirements

- Magnet Gap – 35mm (minimum clearance)
- Nominal Field – B_o = 0.40 T (+20%)
- Field Homogeneity in B_X & B_Y = 1×10^{-4}
- Good field region B_X : +/- 20mm, B_Y : +/- 10mm
- Systematic field error harmonics (as per design):

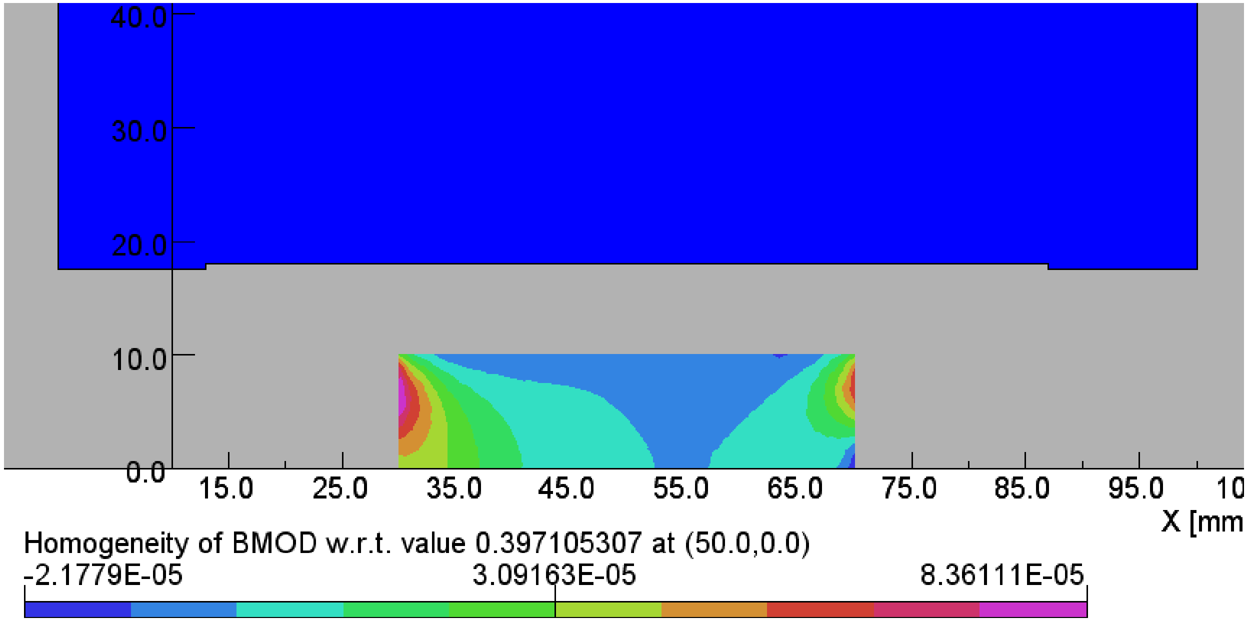
  < 1 unit at 20 mm radius; harmonics are specified at 10 mm

Note: Harmonic description is ideal for circular beams.
In this case, field quality should be good in a rectangular area.

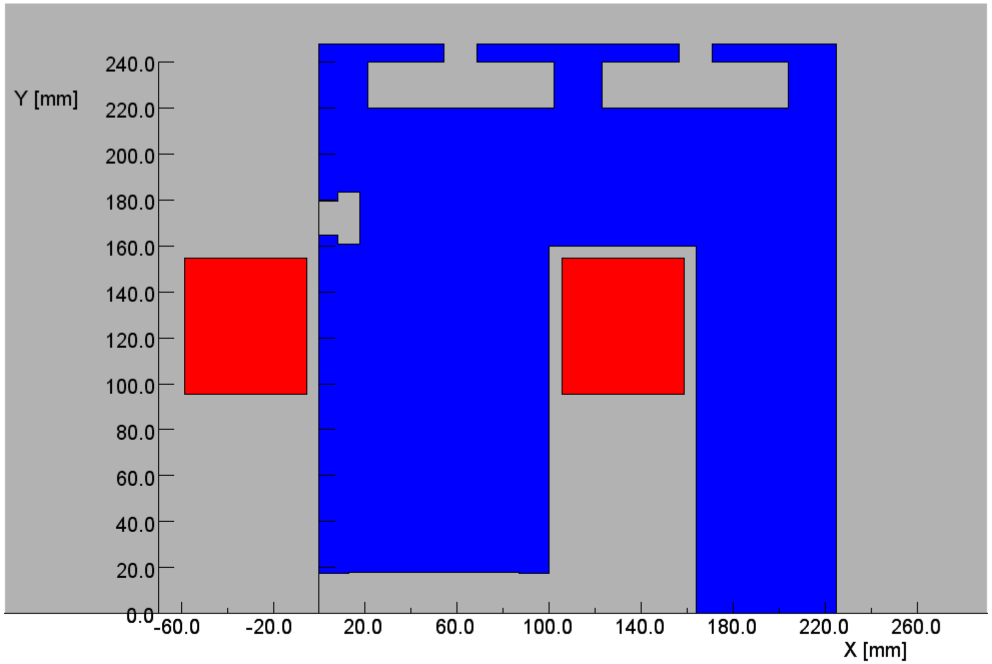
We would show field errors both in terms of
(a) error harmonics and
(b) deviation from the ideal field inside the rectangular area.

2-d Magnetic Design of 35 mm Aperture Dipole

- Required minimum vertical gap (clearance) is 35 mm (half-gap = 17.5 mm).
- Since pole bumps are used for field shaping, the gap at the mid-plane is higher.
- Vertical size of the bump is kept small (0.5 mm) to avoid a large increase in the pole gap at the center. Thus vertical clearance is 35 mm and pole gap is 36 mm.
- To keep the vertical size of the bump small, the horizontal size of the bump was made larger and kept as a free parameter to obtain a good field quality.



2-d Magnetic Model of 35 mm Aperture Dipole



Coil Parameters:

16 turns, 13 mm X 13 mm each
With circular cooling water holes.

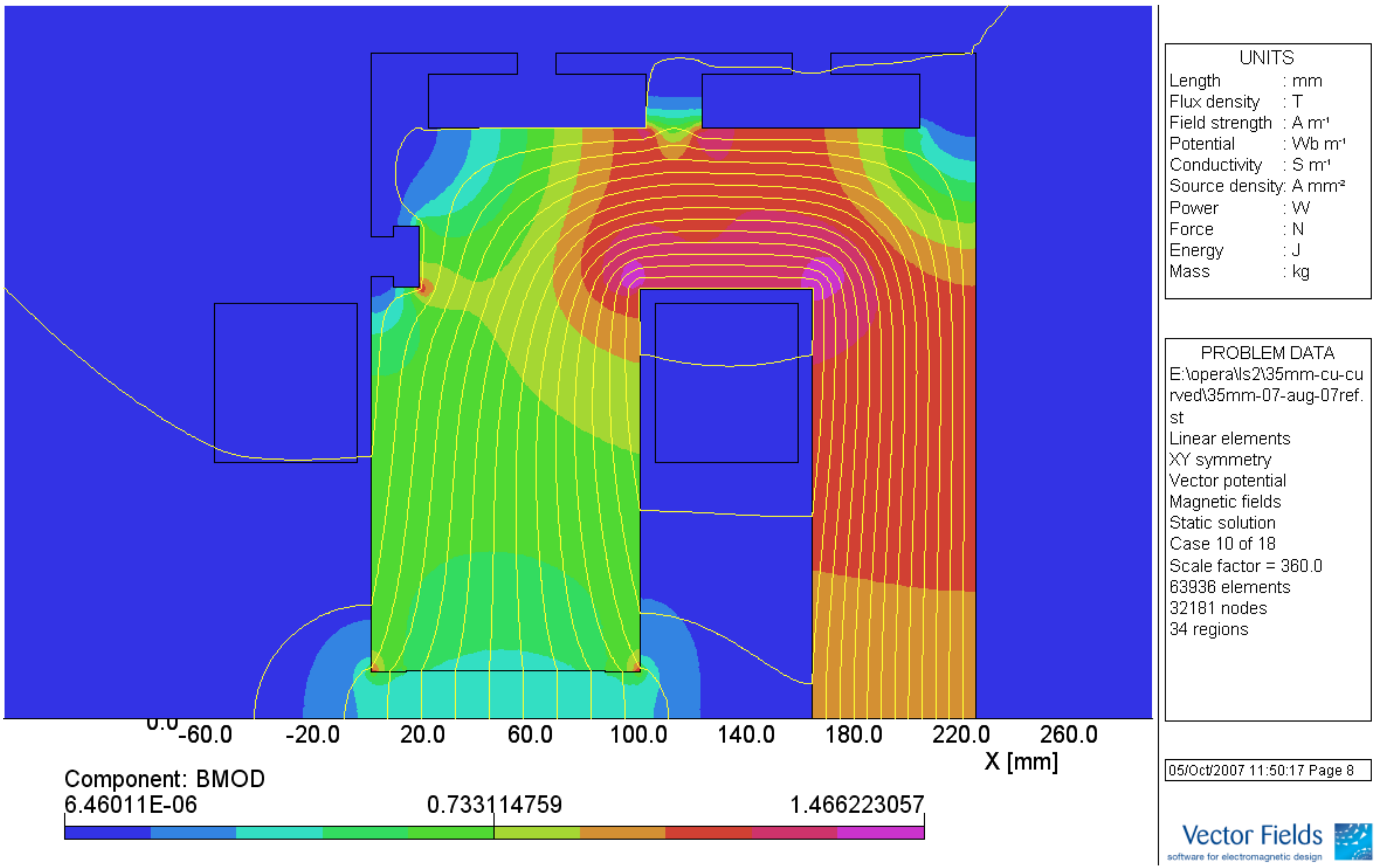
Overall current density for 0.4 T ~ 1.8 A/mm^2.

Space is left above the main coil for installing trim coil cable of doing 1% field adjustment.

Yoke: Minimum pole half gap is 17.5 mm (18 mm at the center)

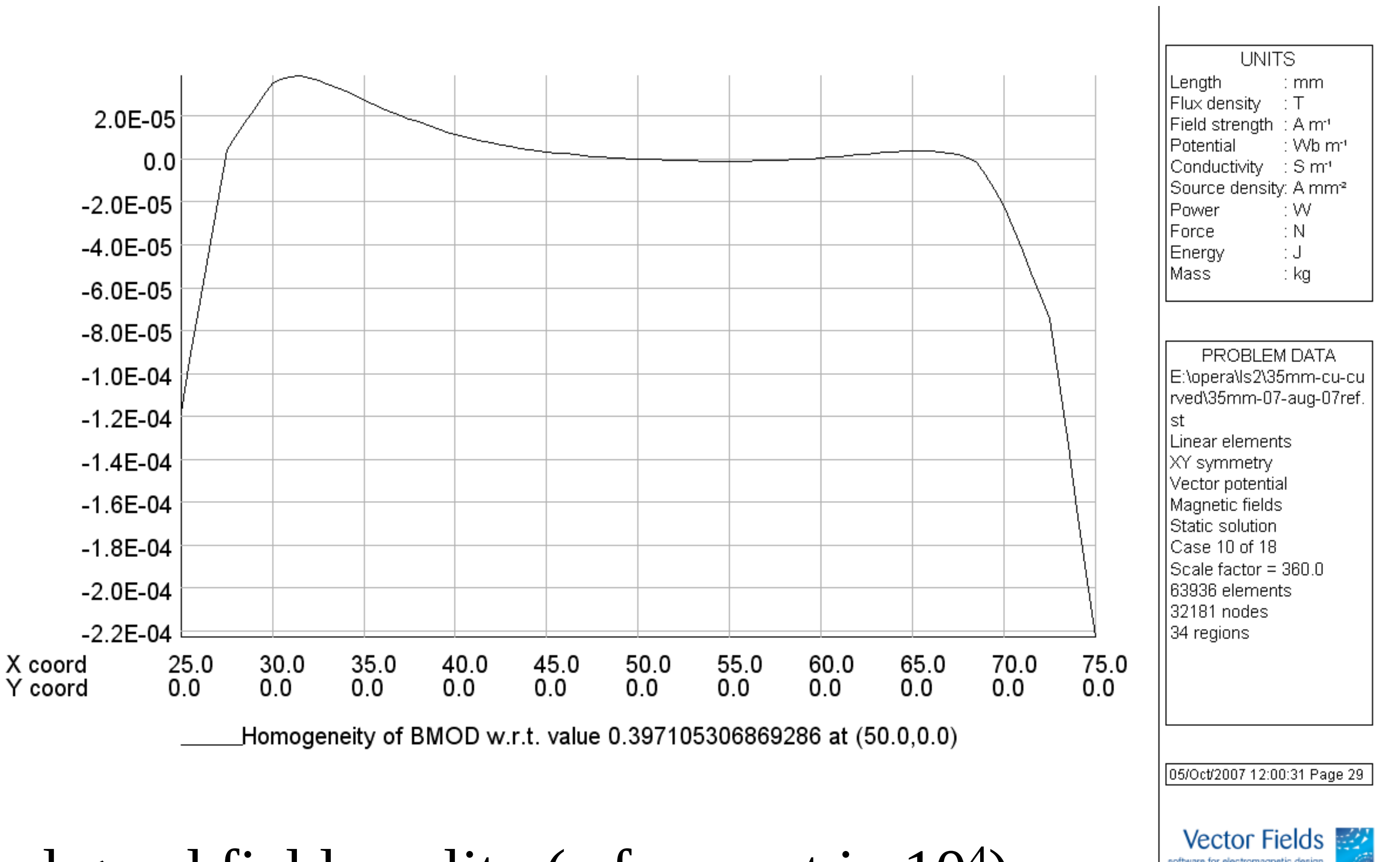
- To optimize field quality, 13 mm wide and 0.5 mm high pole bumps are used on either side.
- Since coils are sufficiently above midplane, asymmetric pole bumps were not required for removing quadrupole-type terms despite the yoke having a C-shape.

2-d Magnetic Model of 35 mm Aperture Dipole



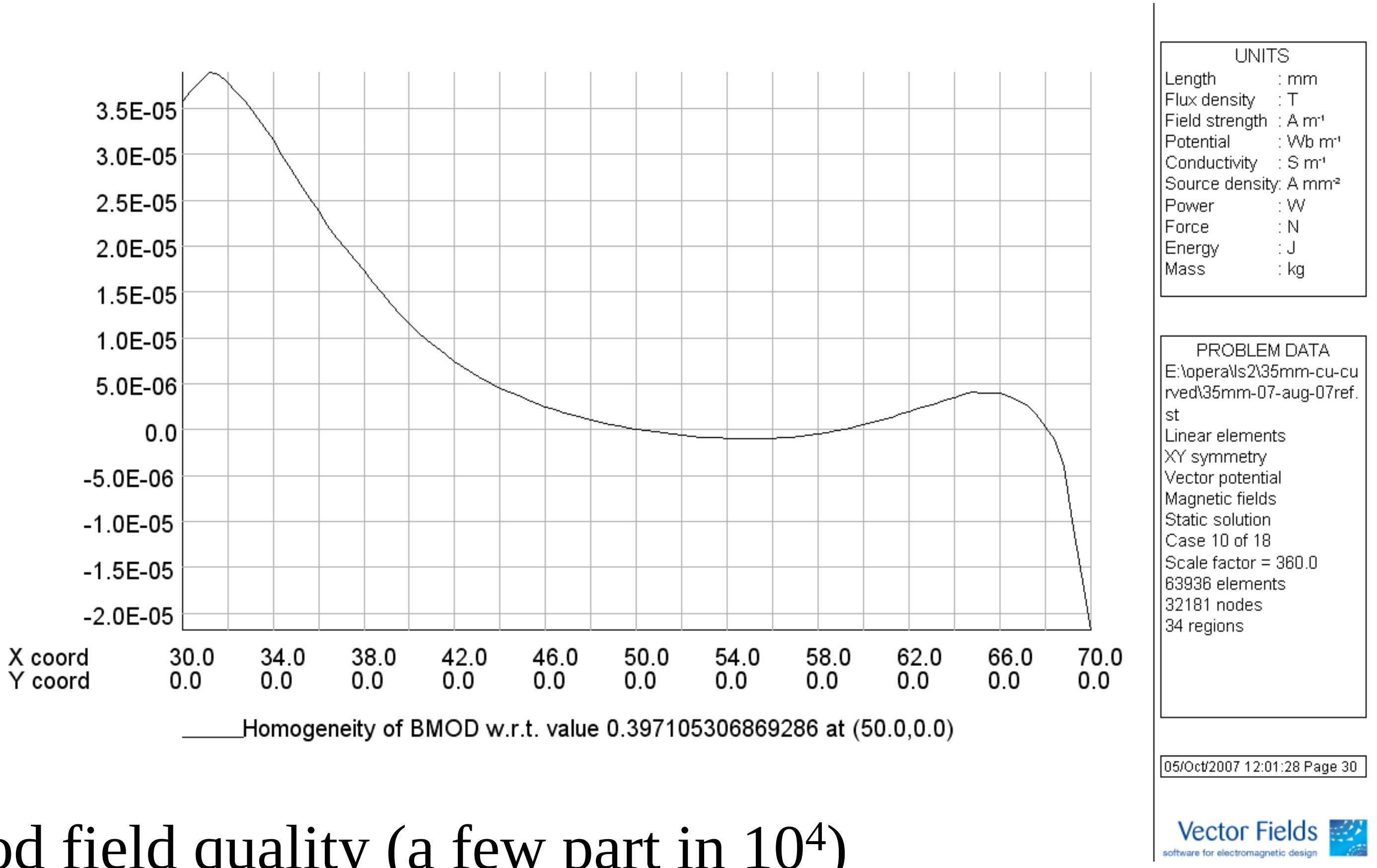
Field contour at the design field (0.4 T)

Relative Field Error On Midplane



Need good field quality (a few part in 10^4)
in +/-20 mm (40 mm total width); above plot has a range of 50 mm

Relative Field Error On Midplane

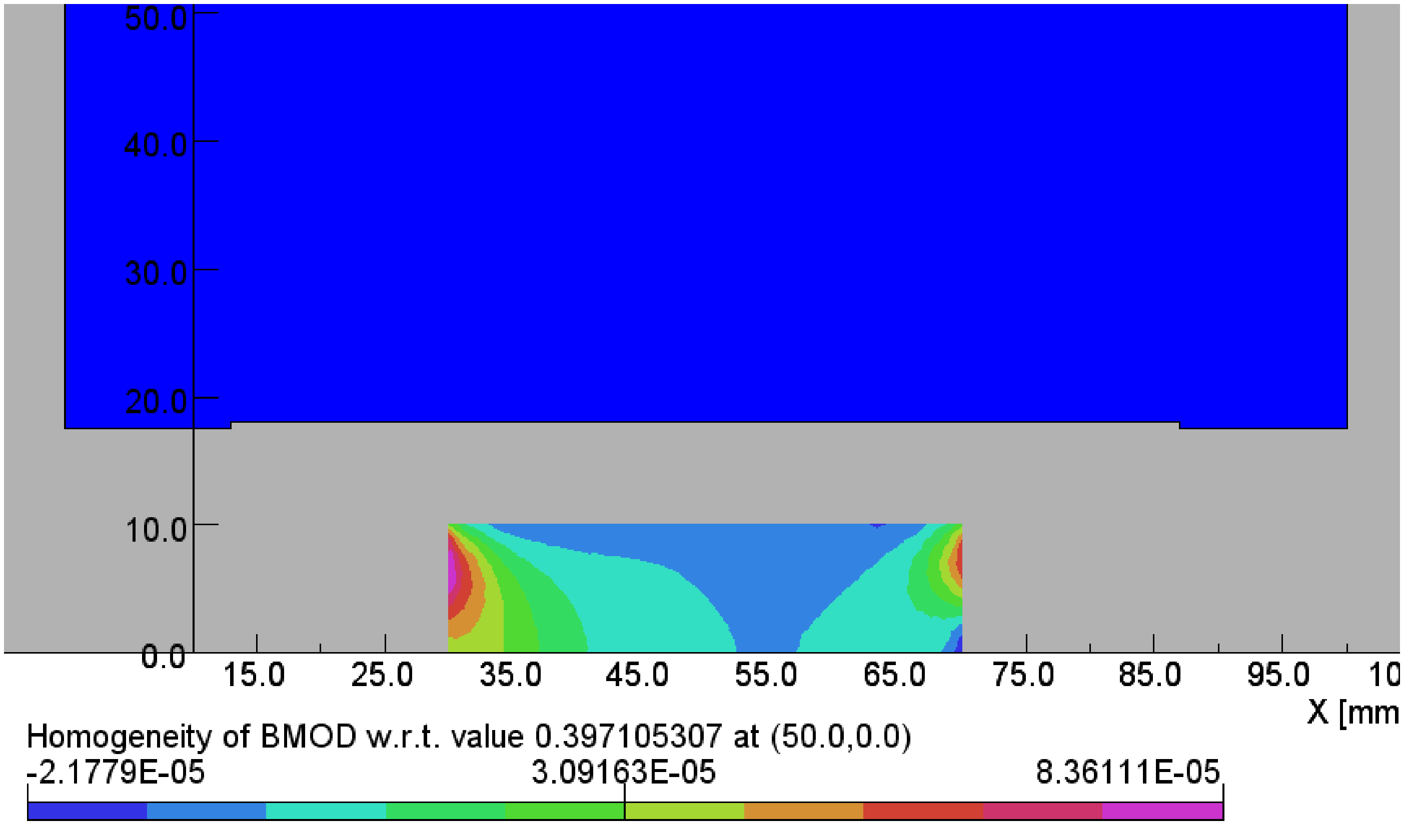


Need good field quality (a few part in 10^4)
in +/-20 mm (40 mm total width).
As shown above, we meet this requirement comfortably on the mid-plane

2-d Magnetic Model of 35 mm Aperture Dipole

Required good field region is: Horizontal +/-20 mm; Vertical +/- 10 mm

Examine relative field errors (relative to central field) in this rectangular region

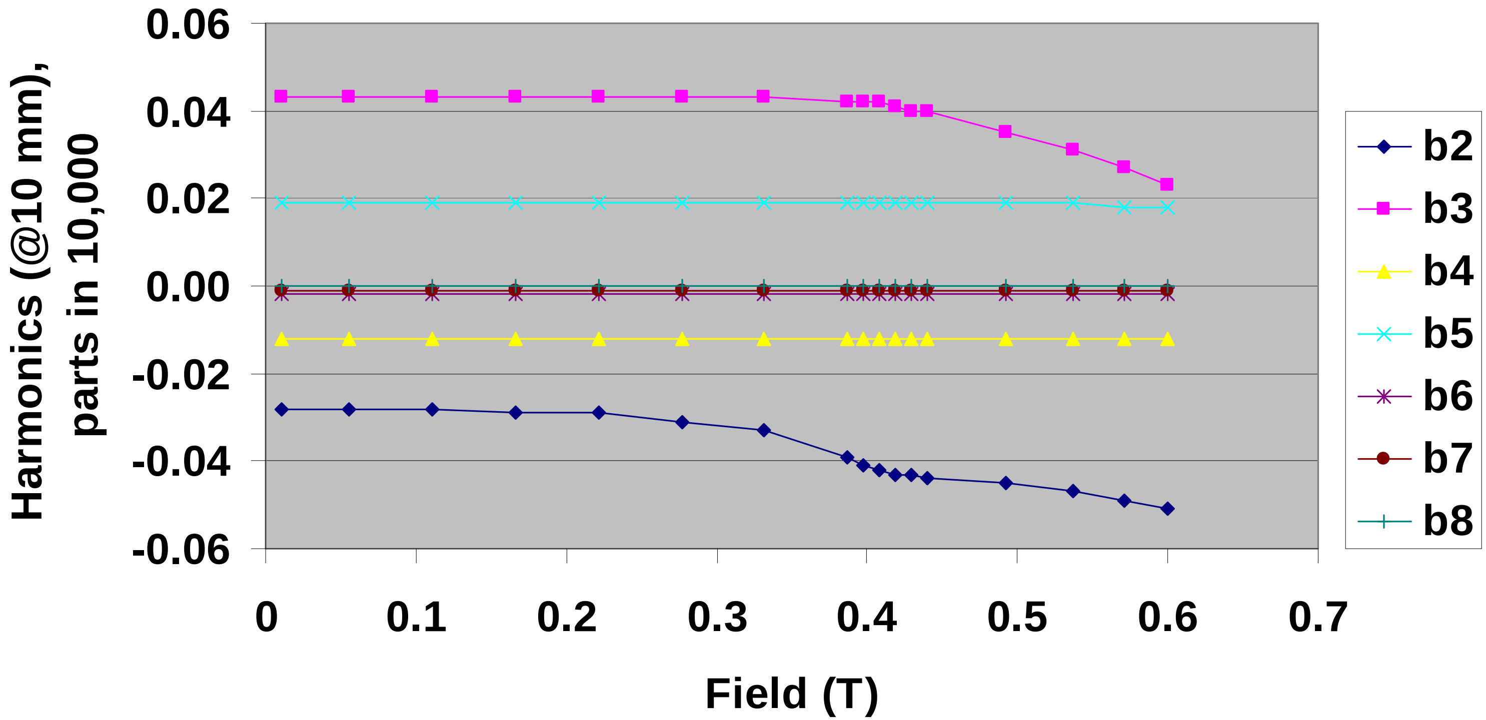


Note:
Relative field errors in this rectangular area is below 10^{-4}

(stated requirement)

Computed 2-d Harmonics in 35 mm Dipole

Field harmonics are normalized to fundamental harmonic and are given in the units of 10^{-4}. b2 is quadrupole.



All harmonics are very small (given in units of 10^{-4}). They are only a few parts in 10^5 even at 20 mm reference radius. Therefore, the good field requirements are met both in terms of harmonics (see above) and in terms of the good field region (last slide).

August Review Finding # F03

The dipole magnetic design has a small quadrupole term. The pole bump optimizations were performed such that this component is small or practically zero at the excitation planned for at the maximum energy of the electron beam. However, since possible future operation may include increasing the energy to 3.6 GeV, one should investigate the size of this error at the higher excitation. The project crew may want to investigate the option of optimizing the pole tip for a wider good field region. The cost and reliability of a simpler straight magnet design should be investigated. The dominant error term for the dipole magnet is the quadrupole error. This error is important since it affects the distribution of the betatron function, and thus the transverse beam size around the ring. However, if the quadrupole term can be minimized at the design beam energy and/or the anticipated upgrade energy, it may be found that the same field quality can be achieved without increasing the pole width.

Response:

Sorry. We were not careful in emphasizing that the harmonics are given in units of 10^{-4}.
Relative quadrupole term is only 3 to 5 part in 10^6 up to 4.8 T (3.6 GeV). See next slide.
This is also well within manufacturing tolerances and in the range of measurement errors.

Computed 2-d Harmonics in 35 mm Dipole

Harmonics at 10 mm reference radius

(Note: Harmonics are given as parts in 10^4; b2 is quadrupole)

Case#	I(Amp)	Bo(T)	TF(T/kA)	dTF(%)	b2	b3	b4	b5	b6	b7	b8
1	10	0.01107	1.107	0	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
2	50	0.05535	1.107	0.00	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
3	100	0.11069	1.107	-0.01	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
4	150	0.16603	1.107	-0.01	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
5	200	0.22133	1.107	-0.03	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
6	250	0.27649	1.106	-0.09	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
7	300	0.33151	1.105	-0.18	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
8	350	0.38623	1.104	-0.31	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
9	**360**	**0.39711**	**1.103**	**-0.35**	**-0.04**	**0.04**	**-0.01**	**0.02**	**0.00**	**0.00**	**0.00**
10	370	0.40795	1.103	-0.40	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
11	380	0.41875	1.102	-0.45	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
12	390	0.42951	1.101	-0.51	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
13	400	0.44021	1.101	-0.58	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
14	450	0.49191	1.093	-1.25	-0.05	0.04	-0.01	0.02	0.00	0.00	0.00
15	500	0.53723	1.074	-2.94	-0.05	0.03	-0.01	0.02	0.00	0.00	0.00
16	550	0.57142	1.039	-6.15	-0.05	0.03	-0.01	0.02	0.00	0.00	0.00
17	600	0.60008	1.000	-9.65	-0.05	0.02	-0.01	0.02	0.00	0.00	0.00

Small values of field harmonics (only a few parts in 10^5 even at 20 mm radius).

Field Harmonics by +/-25 micron Relative error in Pole Opening Between Left side and Right side

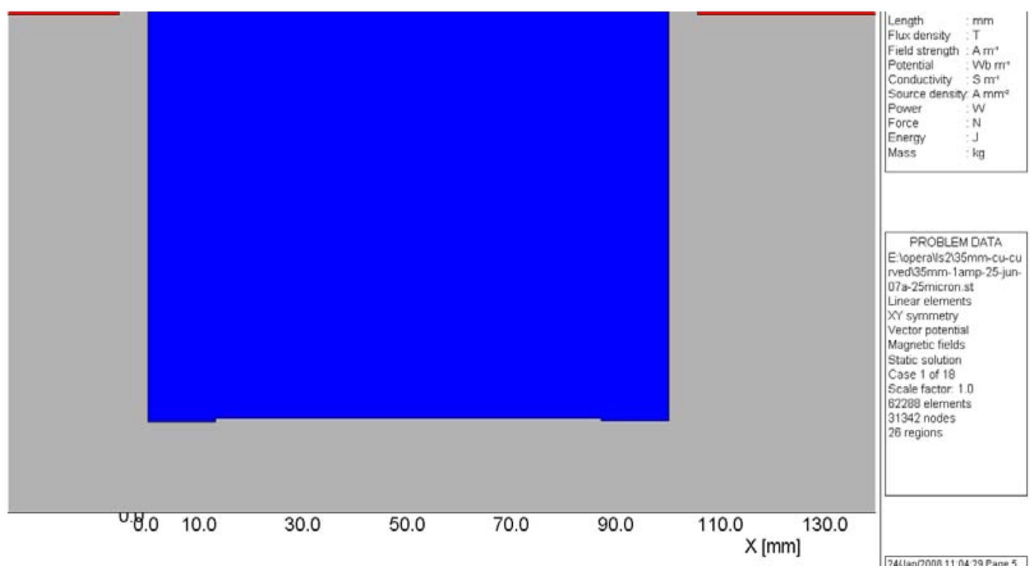
Current = 370 Amp
By = 0.407655

n	bn
1	10000
2	-1.457
3	0.039
4	-0.013
5	0.018
6	-0.002
7	-0.001
8	0.000
9	-0.001
10	0.000
11	0.000
12	0.000

An angular error in pole angle is assumed.

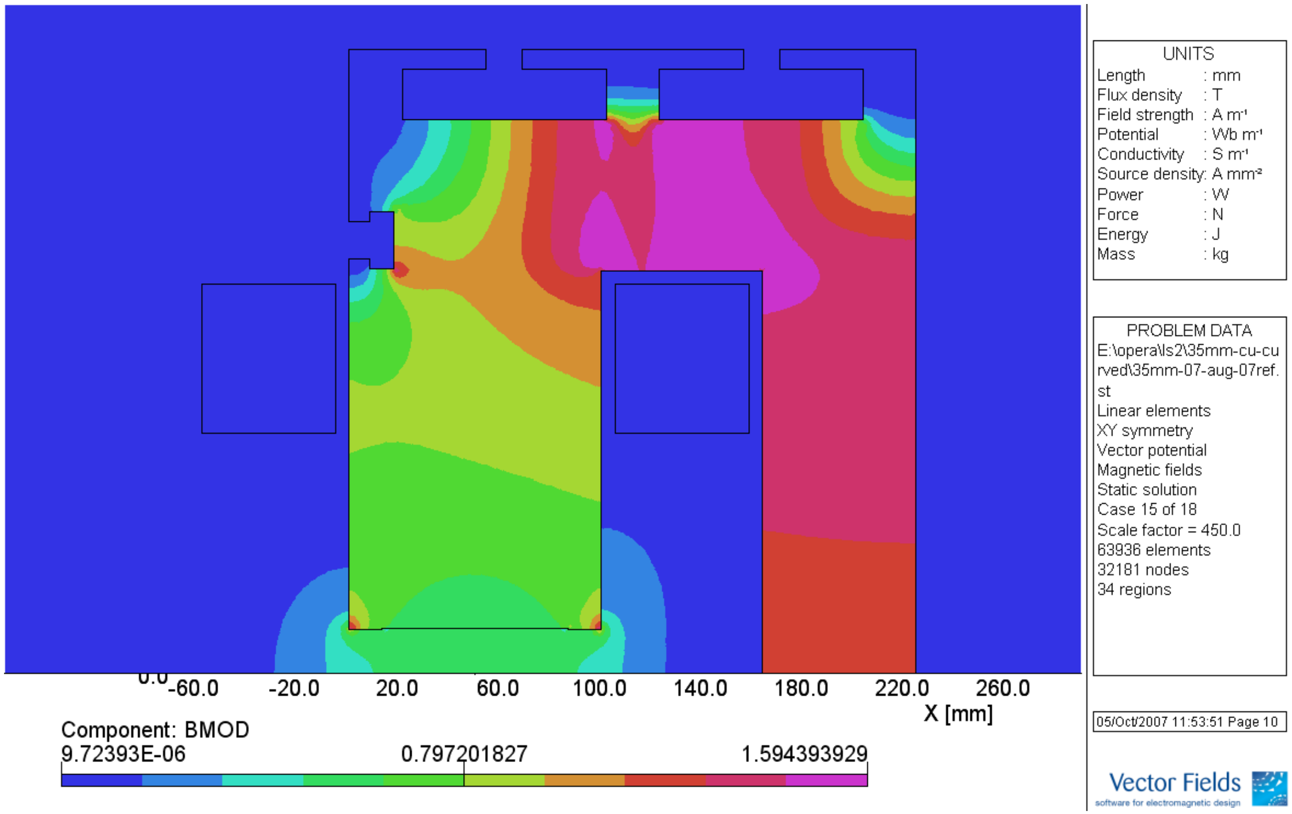
- **Pole gap on left side: 35 mm**
- **Pole gap on right side: 35.0508 mm**

- **0.05 unit of b2 in magnetic design is well below the mechanical tolerances.**
- **Mechanical deflections of pole by magnetic forces is less than half of this (see Steve Plate's talk).**



b2 is quadrupole in units of 10^{-4}, normalized to dipole

Possible High Field Run



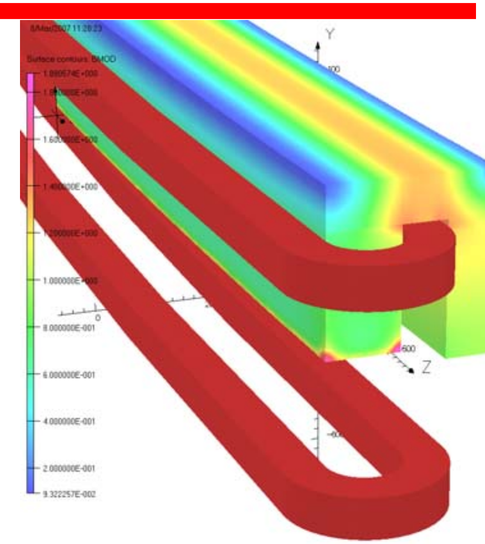
Field contour at a central field of ~0.49 T @450 A (>3.6 GeV).

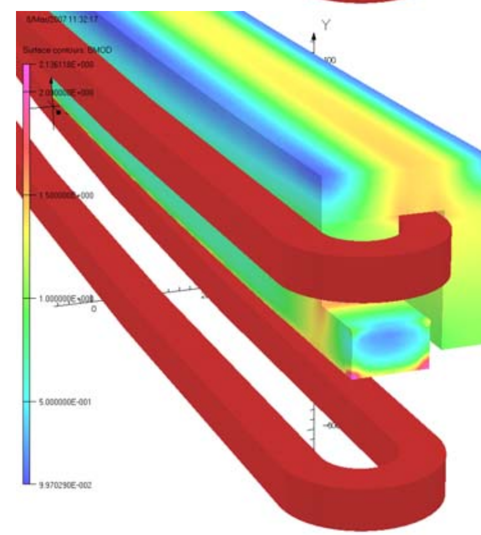
Nominal design value is 0.4 T (@~360 A) and required margin is 20% in design.

Note: Yoke (particularly the pole) is not saturating. Situation is better at the top of the yoke, as low carbon steel magnetic rod would be used in the area used as air in the model.

Special Feature: Extended Pole (Nose)
(Saves a significant amount of space in tunnel)

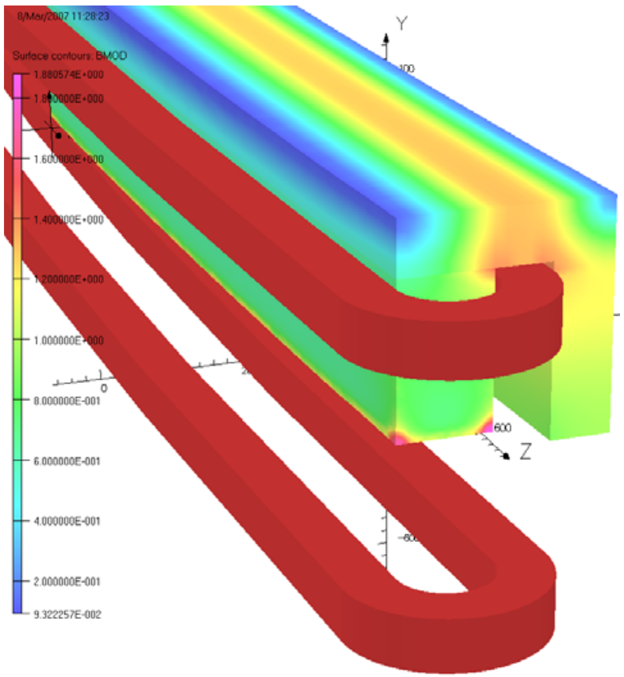
- In most iron dominated magnets, the magnetic length is determined by the length of the yoke and mechanical length by the length of the coil. Thus the mechanical space taken by the coil ends is wasted.
- The proposed *"Pole Extension"* or *"Nose"* practically eliminates this waste. For all practical purpose, yoke length becomes the same as the coil length. This works particularly well in low field magnets.
- In this proposal the coil ends are placed above an extended yoke. The surface of the pole remains an equi-potential, and the magnetic field for the beam remains at the full value, as long as the pole extension is not saturated.
- The coils must be raised above (or at least lifted above at the ends) to allow space for this extension.
- The nose will consist of one or more pieces. As an added benefit, it allows easy 3-d tuning of the field (design and machine these solid pieces after field measurements).
- The large vertical space (gap) between the upper and lower coils is also used by an internal support structure in the body of the magnet.



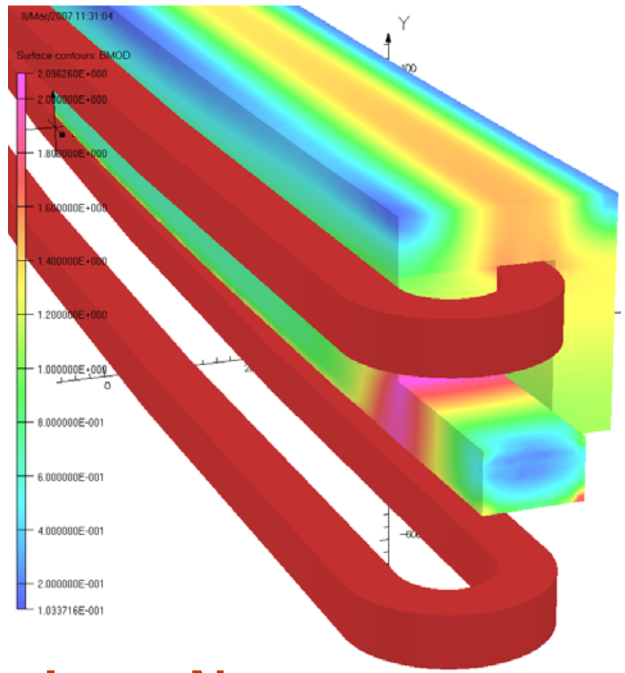


Optimization of Extended Pole (Nose)

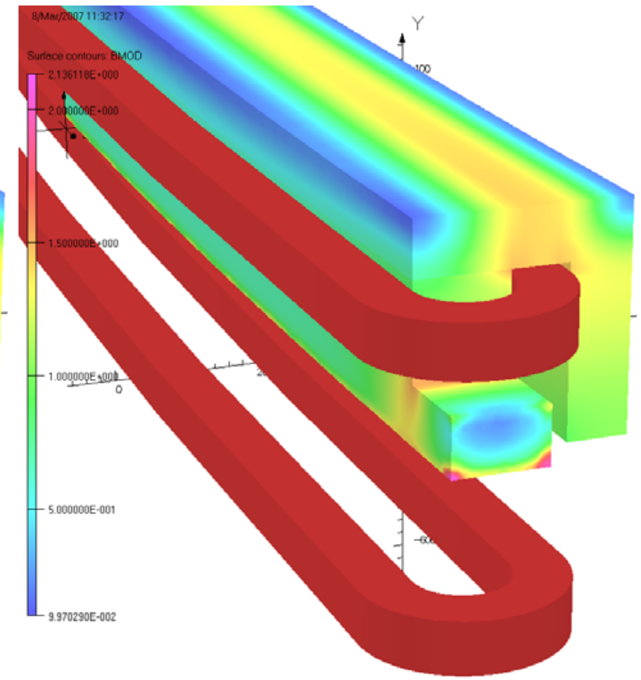
A number of studies were done to optimize axial extension and height of the the extended pole (nose).



No Nose

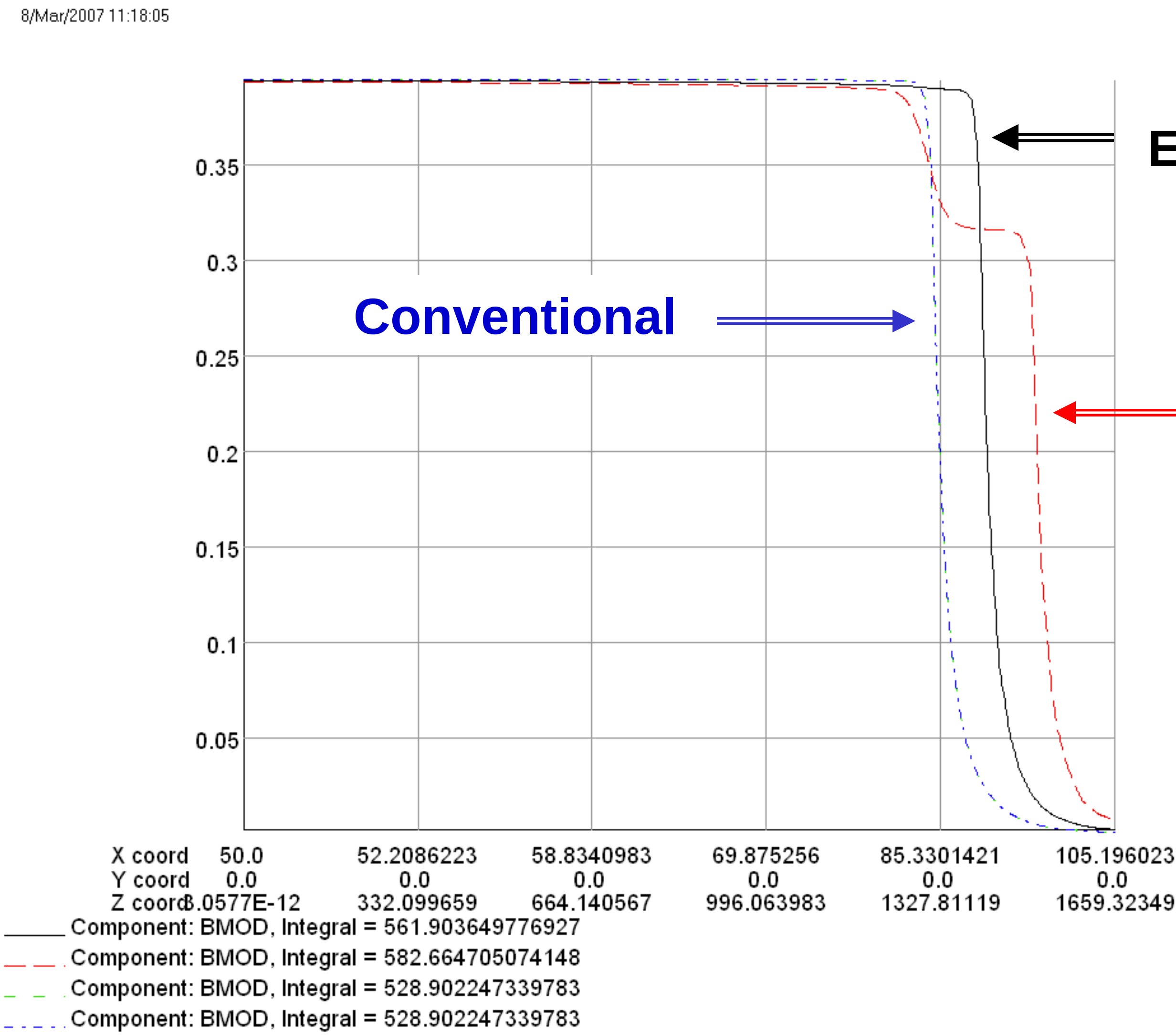


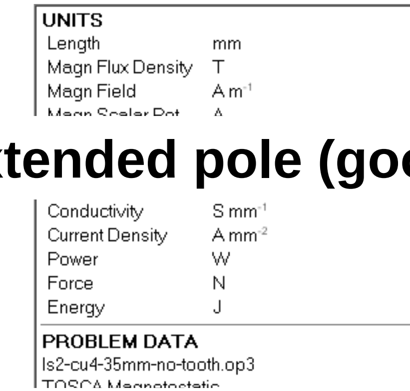
Long Nose (too greedy, note saturating nose)



Good Nose (extended pole)

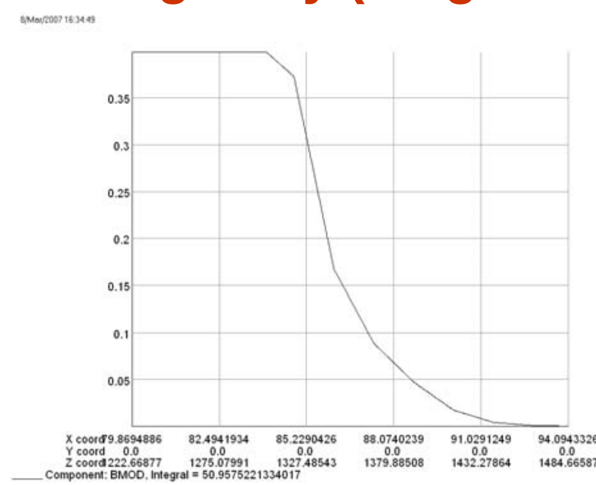
Space Recovery (Saving) by Extending Pole





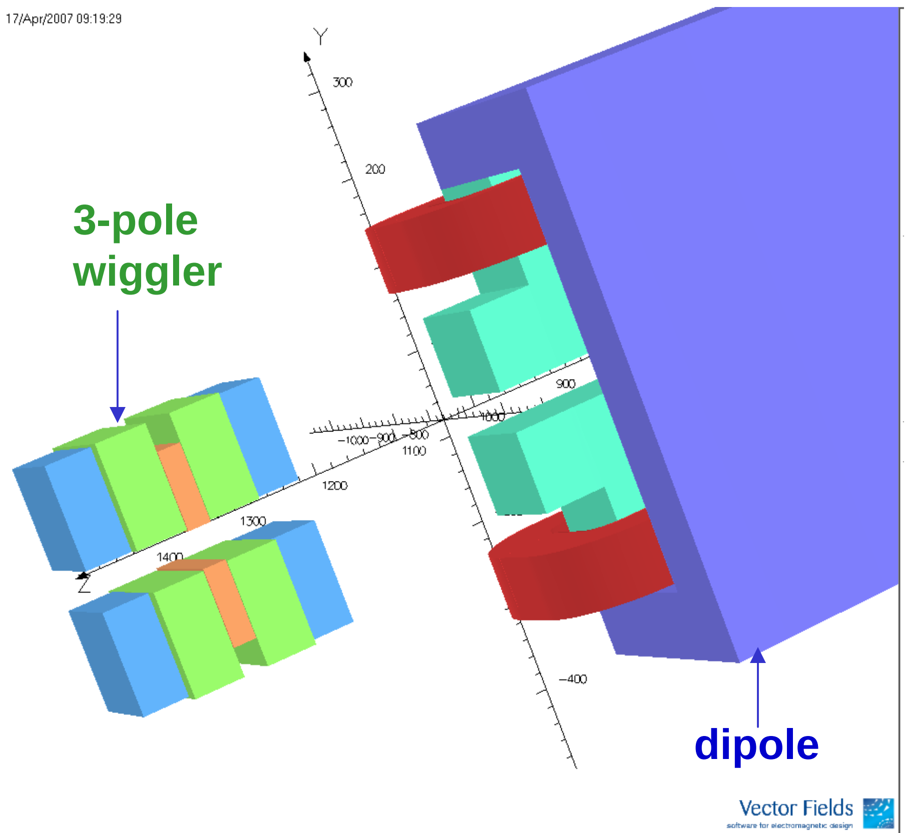
Extended pole (good nose)

Too greedy (long nose)



Field fall off in conventional case (scale adjusted for more details)

Current Design with 1" Radius Racetrack Coils and Open Back-leg Yoke



This design allows racetrack coils and ~18 cm of free space between dipole and 3pole wiggler.

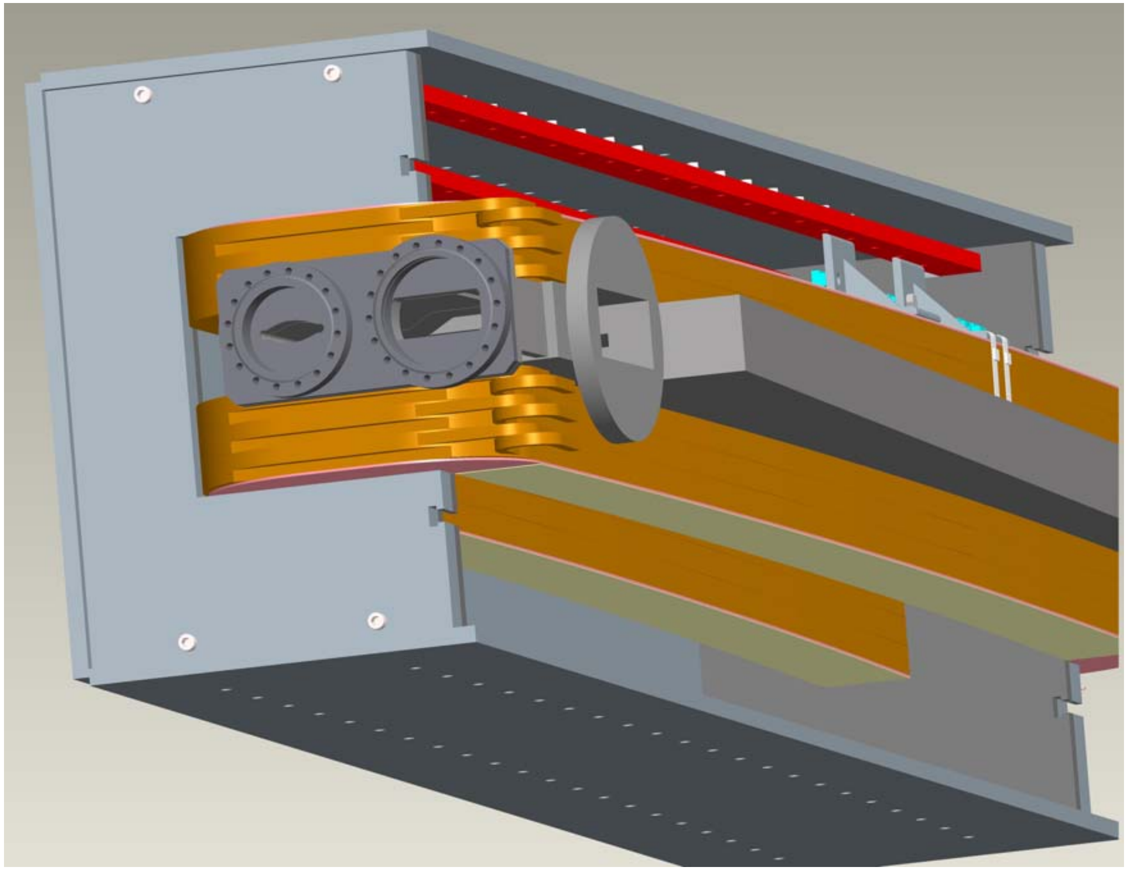
More extra space for vacuum system is made available by opening the back-leg side of the yoke.

This also makes end field more symmetric (missing C-shape in the ends).

Extended pole (nose) frees-up ~ 10 meters in tunnel
(plus more extra space for vacuum system with open beg-leg).

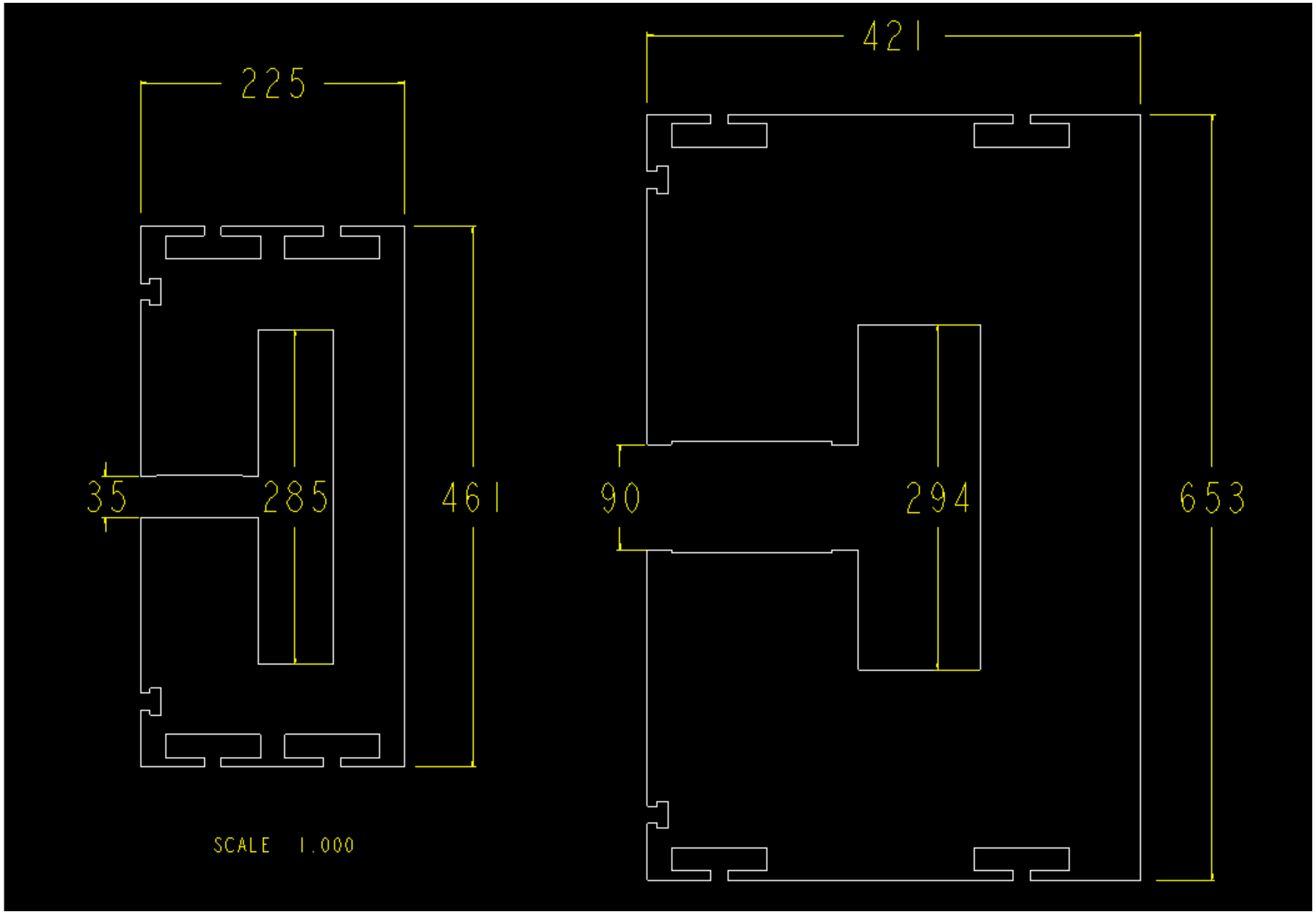
Magnetic Design
of
90 mm Aperture Dipole

90 mm aperture dipole



Coils and mechanical features (such as enclosure) are shown.
Yoke is hidden in side this box.

Laminations of 35 mm and 90 mm Aperture Dipoles



Note: Width has not grown as much as the pole gap

Design Parameters of 90 mm Aperture Dipole

- Magnet Gap – 90 mm (minimum clearance)
- Nominal Field – B_o = 0.40 T (+20%)
- Field Homogeneity in B_X & $B_Y = 1 \times 10^{-4}$
- Good field region B_X : +/- 20mm, B_Y : +/- 10mm
- Magnetic length – 2620 mm
- Nominal Current density in the coil cross section 2 Amps/mm^2
- Maximum allowable temperature rise 10 degrees C
- Maximum Pressure across the Magnet 60 psi.
- Bend Radius ~25 m

• Except for the gap, all design parameters are the same as in 35 mm dipole.
• Since the relative value of good field aperture is small in this magnet, the pole width to pole gap ratio can be made smaller.
• 35 mm and 90 mm dipole should run on the same power supply and therefore the transfer function of the two magnets should match.

2-d Magnetic Design of 90 mm Aperture Dipole

➢ Required minimum vertical gap (clearance) is 90 mm. Since pole bumps are used for field shaping, the conventional pole gap will be higher.

➢ Pole gap was adjusted to match (fine tune) the transfer function with 35 mm dipole.

➢ Optimized bumps are : 2.58 mm high and (a) 20.5 mm wide on left and (b) 23 mm wide on right. They are made asymmetric to compensate for the inherent asymmetry of C-shape dipole (asymmetry was not required in 35 mm as coil was high).

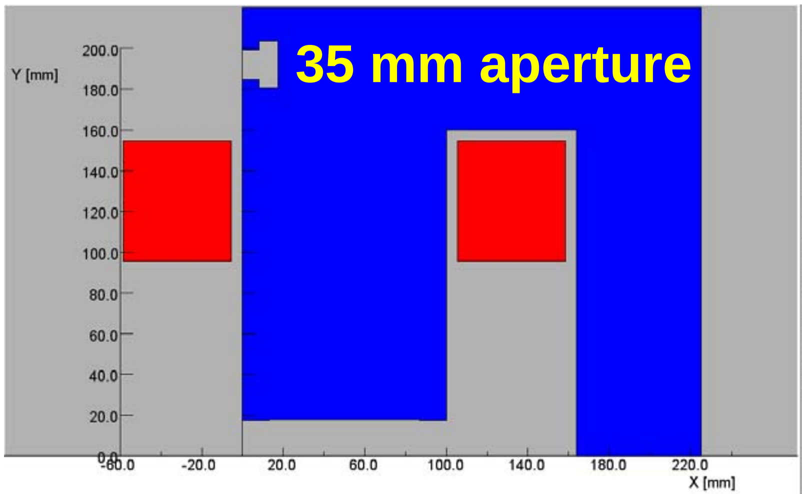
➢ By comparison, in 35 mm dipole, bumps were 0.5 mm high and 13 mm wide on either side (symmetric). Height was kept smaller in 35 mm but not required here.

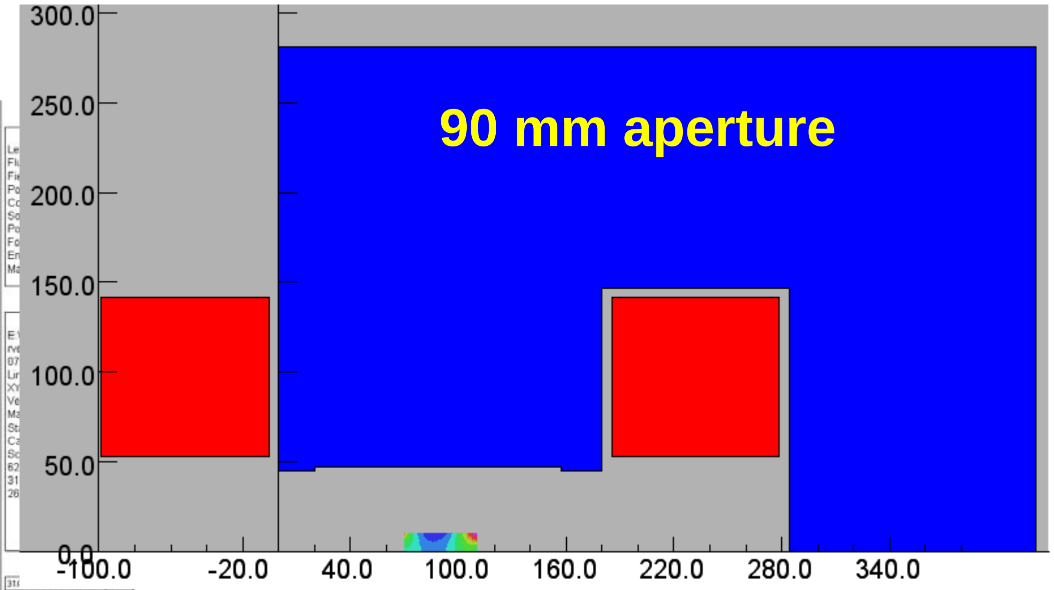
➢ Calculation of pole overhang factor (x) for 1 part in 10^4 for relative field errors. Half gap h=47.58 mm, good field aperture/2=20 mm, pole overhang a=90-20=70 mm

- x=a/h = 70/47.58 = ~1.47.
- By comparison, overhang factor was 1.67 in case of 35 (36) mm aperture dipole.
- Pole width/Pole gap is ~1.9 (by comparison it was ~2.8 in 35 (36) mm dipole).

Comparison of 35 mm and 90 mm Aperture Dipoles

Overall design



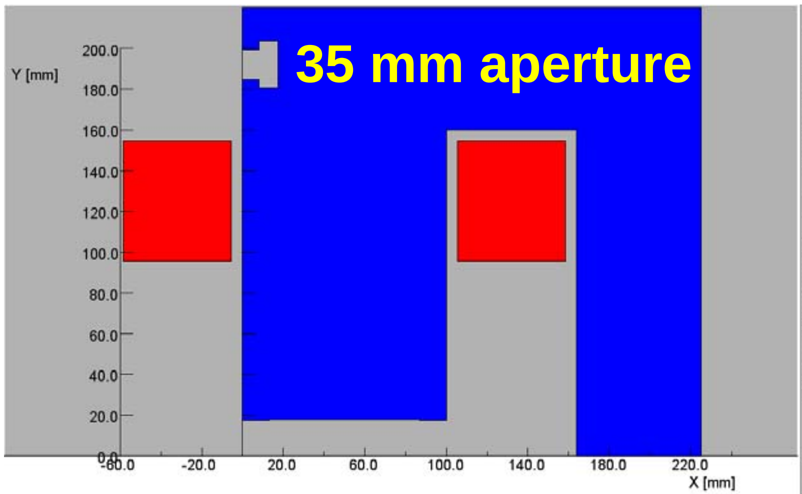


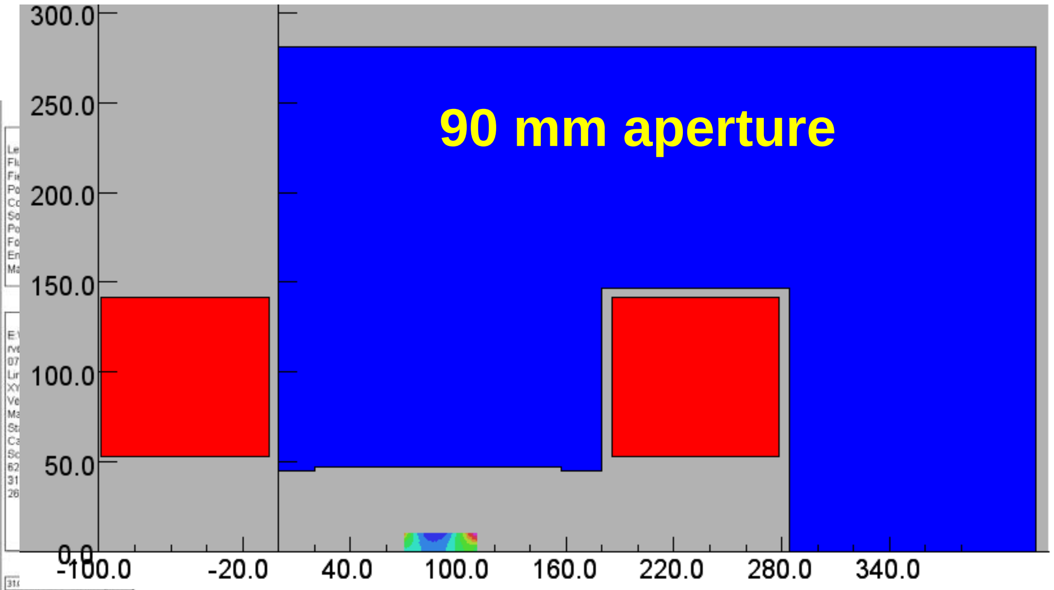
Note: 90 mm is the minimum vertical clearance. Pole gap at the magnet center is higher.

- Same conductor chosen for both dipoles (number of turns are adjusted) - 16 turns (4 X 4) in 35 mm aperture case and 42 turns (6 X 7) in 90 mm aperture case.

Matching of Transfer Function (current) between 35 mm and 90 mm Aperture Dipoles

They should match within 0.1%
(during last review it was 1%)





First matching is done by carefully choosing the conductor and number of turns.

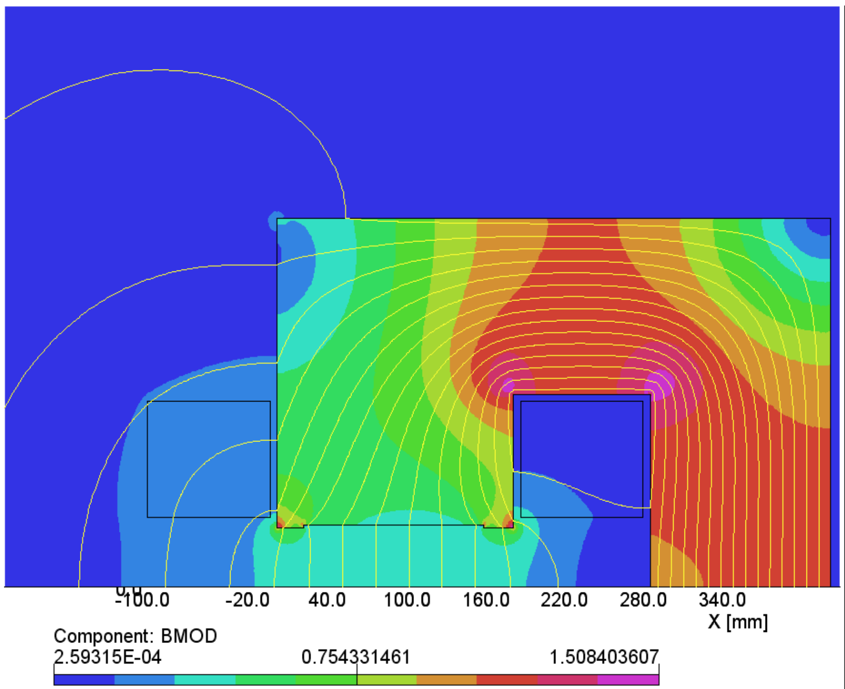
Then the pole gap at the center is adjusted to obtain a more closer match.

Field quality optimization needs to be carried out again as it changes the pole bumps.

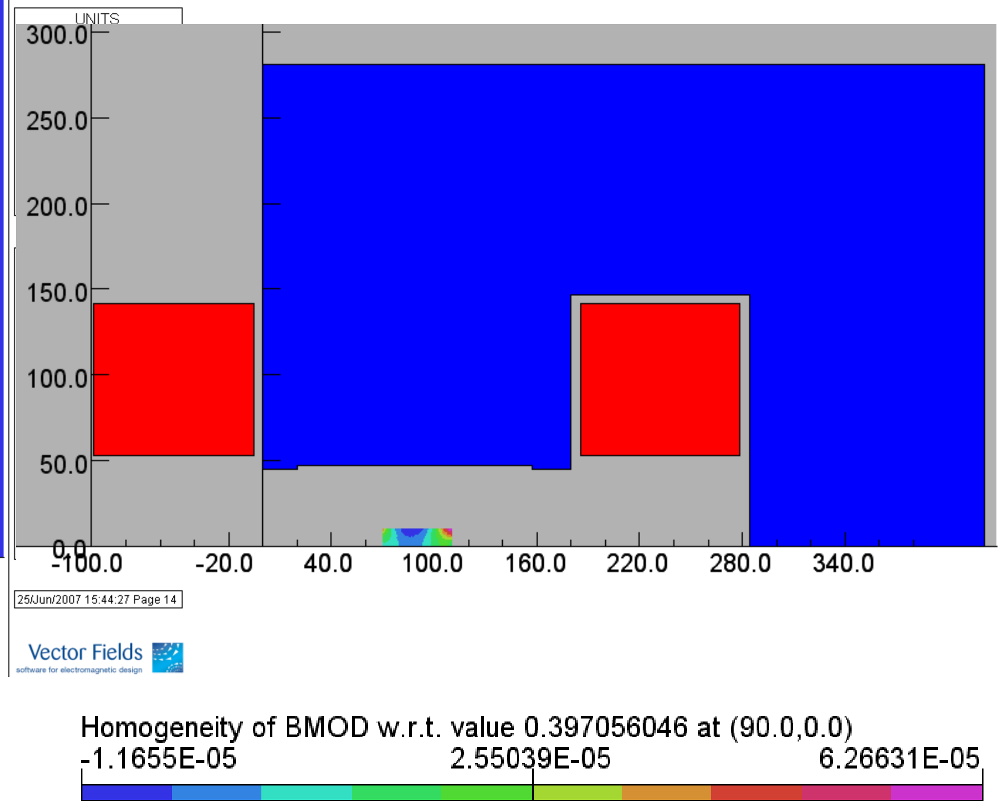
Finer adjustment after magnetic measurements (as discussed later) may be carried out by fine tuning the length of the extended pole (nose) in 35 mm aperture dipole.

2-d Magnetic Model of 90 mm Aperture Dipole

Relative field errors in the good field region



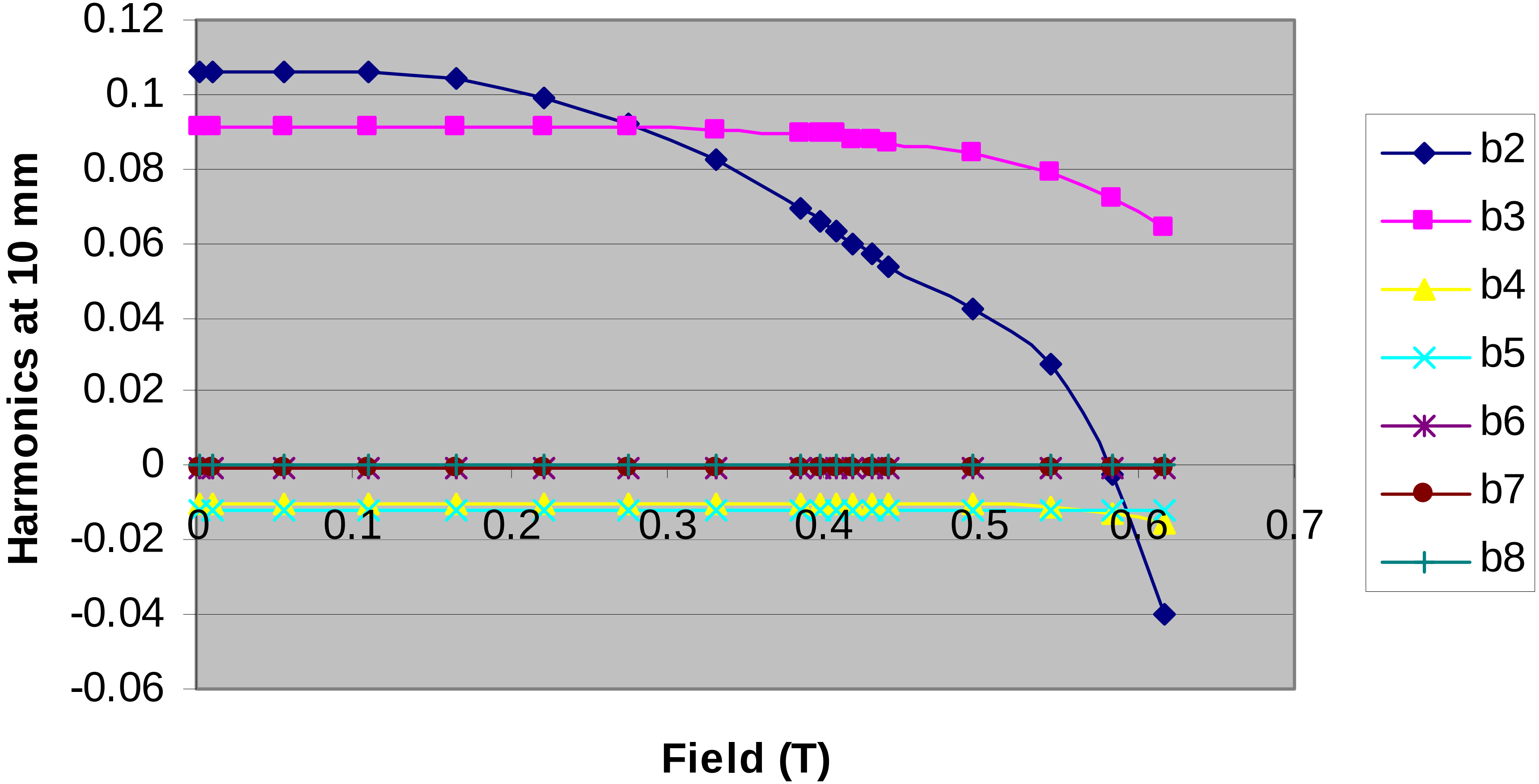
Field contour at the design field



Computed 2-d Harmonics in 90 mm Dipole

Harmonics at 10 mm reference radius

(Note: Harmonics are given as parts in 10^4; b2 is quadrupole)



Note: Small values of field harmonics (only a few parts in 10^5 even at 20 mm radius).

Computed 2-d Harmonics in 90 mm Dipole

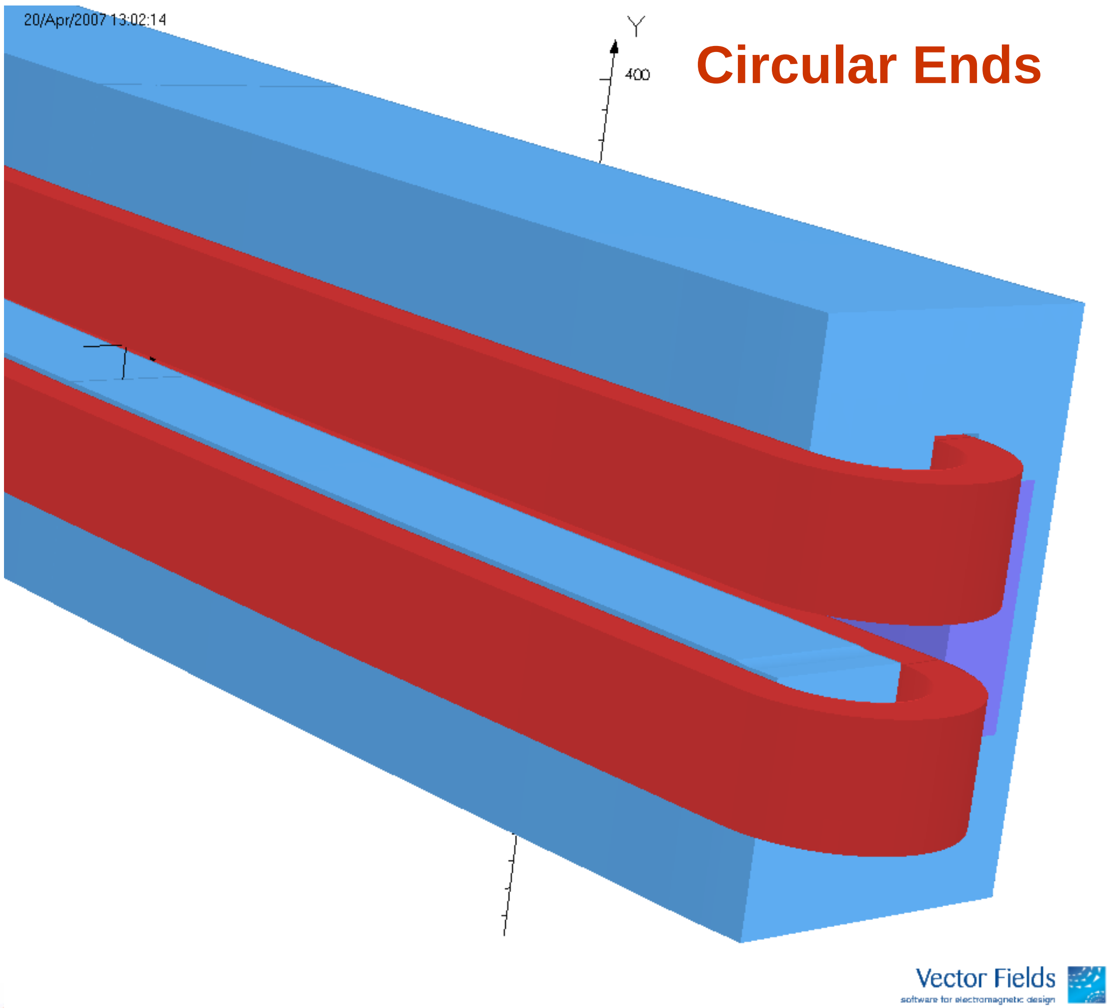
Harmonics at 10 mm reference radius

(Note: Harmonics are given as parts in 10^4; b2 is quadrupole)

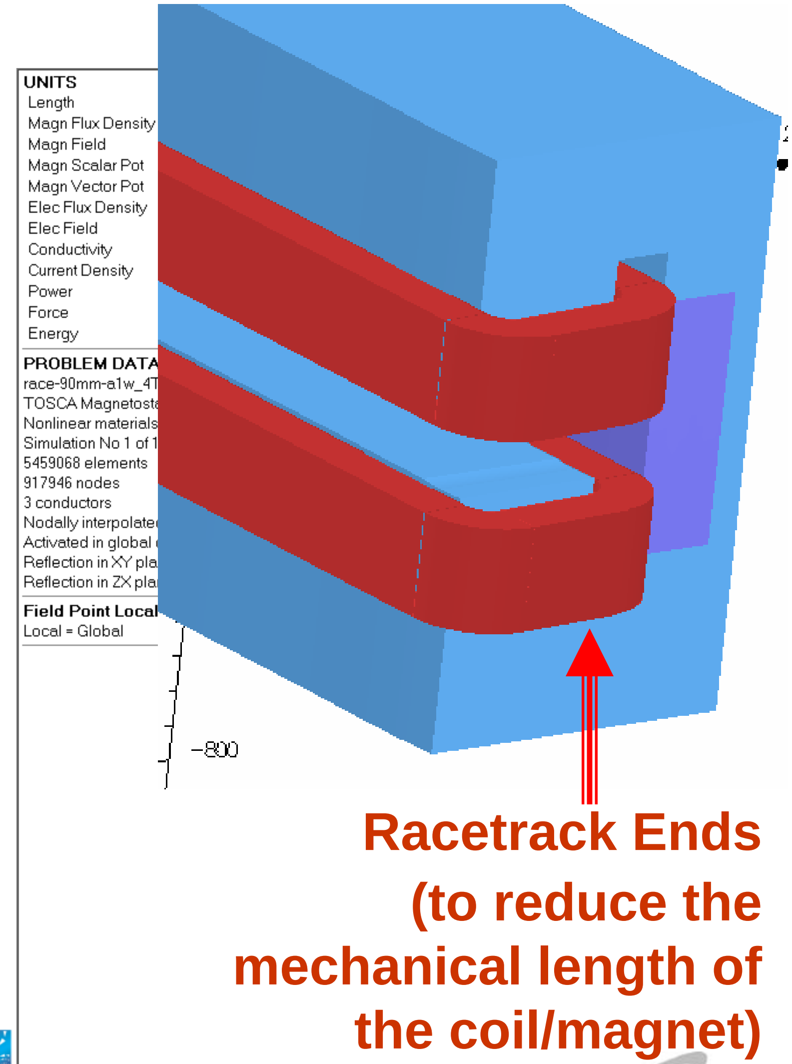
Case#	I(Amp)	Bo(T)	b2	b3	b4	b5	b6	b7	b8
1	1	0.0011	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
2	10	0.01105	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
3	50	0.05524	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
4	100	0.11048	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
5	150	0.16572	0.10	0.09	-0.01	-0.01	0.00	0.00	0.00
6	200	0.22093	0.10	0.09	-0.01	-0.01	0.00	0.00	0.00
7	250	0.27608	0.09	0.09	-0.01	-0.01	0.00	0.00	0.00
8	300	0.33116	0.08	0.09	-0.01	-0.01	0.00	0.00	0.00
9	350	0.3861	0.07	0.09	-0.01	-0.01	0.00	0.00	0.00
10	360	0.39706	0.07	0.09	-0.01	-0.01	0.00	0.00	0.00
11	370	0.408	0.06	0.09	-0.01	-0.01	0.00	0.00	0.00
12	380	0.41893	0.06	0.09	-0.01	-0.01	0.00	0.00	0.00
13	390	0.42984	0.06	0.09	-0.01	-0.01	0.00	0.00	0.00
14	400	0.44072	0.05	0.09	-0.01	-0.01	0.00	0.00	0.00
15	450	0.49433	0.04	0.08	-0.01	-0.01	0.00	0.00	0.00
16	500	0.54469	0.03	0.08	-0.01	-0.01	0.00	0.00	0.00
17	550	0.5849	0.00	0.07	-0.01	-0.01	0.00	0.00	0.00
18	600	0.61708	-0.04	0.06	-0.02	-0.01	0.00	0.00	0.00

Note: Small values of field harmonics (only a few parts in 10^5 even at 20 mm radius).

3-d Analysis of ~90 mm Aperture Dipole



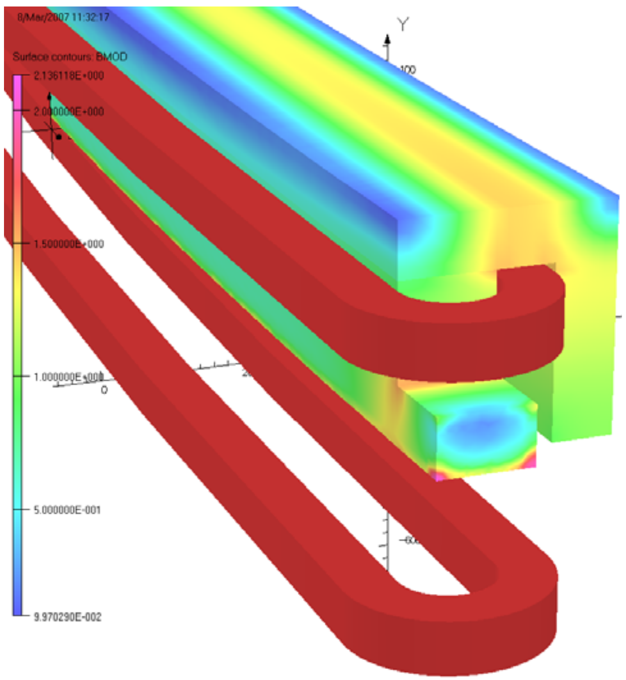
Circular Ends

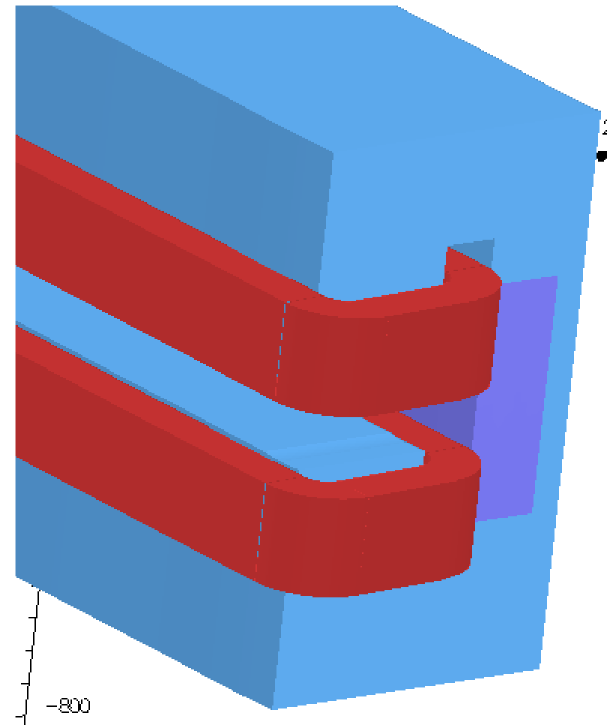


Racetrack Ends
(to reduce the
mechanical length of
the coil/magnet)

Fine Tuning of Transfer Function Matching (between 35 mm and 90 mm aperture dipoles)

Ends of 35 mm Dipole





Ends of 90 mm Dipole

In addition to obtaining the desired low integral harmonics in both magnets, the integral transfer function between the two must also match

- Computed B at 360 A: 0.39711 T in 35 mm and 0.39706 T in 90 mm. Difference <0.02%; this is within manufacturing errors/BH curve and calculation and measurement errors
- Fine tuning of the integral field, if needed, may be done by adjusting the length of the nose piece of 35 mm dipole after the field measurements of both 35 mm and 90 mm dipoles

SUMMARY

- Design of 35 mm dipole is nearly complete. Field quality specs are met.
- We have taken advantage of the low operating field in mitigating space constraint by introducing the extended pole (or nose) design.
- Whereas, in most magnets, the magnetic length is between yoke length and coil length (or magnet mechanical length), in the proposed design the magnetic length is larger that the mechanical length of the magnet.
- This new design feature will be monitored during the magnet development program. Nose will be used to optimize end harmonics, etc.
- Design of 90 mm dipole is nearly completed. Field quality specs are met.
- Integral transfer function and integral field harmonics will be nearly the same in 35 mm aperture and 90 mm aperture dipoles.