Dipole and Sextupole Magnetic Designs

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Review of NSLS II Storage Ring Magnets, Vacuum Systems and Front Ends

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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
- Interaction with 3 Pole Wiggler

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
- Relatively small good field aperture

Magnetic Design of 66 mm Aperture Sextupole

- Present design
- Attempt to improve field quality

Design Parameters of 35 mm Aperture Dipole

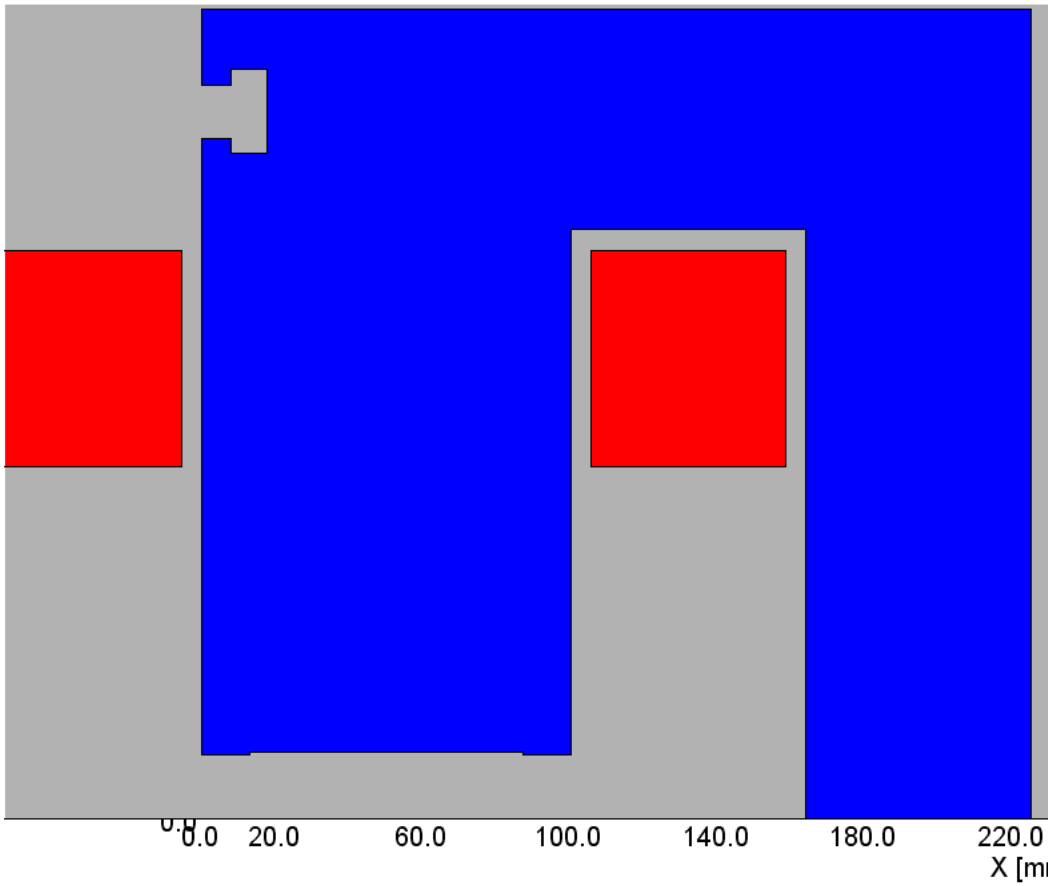
- Magnet Gap – 35mm (minimum clearance)
- Nominal Field – B_o = 0.40 T (+20%)
- Field Homogeneity in B_X & B_Y = 1 x 10^{-4}
- Good field region B_X : +/- 20mm, B_Y : +/- 10mm
- Magnetic length – 2620 mm
- Nominal Current density in the coil cross section 2 Amps/mm^2
- Maximum allowable temperature rise 10 degrees C
- Maximum Pressure across the Magnet 60 psi.
- Bend Radius ~25 m

This is a low (and fixed) field magnet.
We will take advantage of this in some unique ways.

2-d Magnetic Design of 35 mm Aperture Dipole

- Required minimum vertical gap (clearance) is 35 mm. Since pole bumps are used for field shaping, the conventional pole gap will be 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. As a result, the pole width (100 mm) is a little larger than minimum (slight penalty).
- Calculation of pole overhang factor (x), with half gap h = 18 mm, good field aperture/2 = 20 mm, pole overhang a = 50-20 = 30 mm
  - x = a/h = 30/18 = ~1.67
  - For 1 part in 10^4 for relative field errors, x is generally ~2.5 in an un-optimized design and $\sim 1^+$ in a well optimized design with no constraints (such as above).
  - A larger and more sophisticated vertical bump might have reduced pole width from 100 mm to 80 mm, but at the expense of increasing pole gap (and hence Amp-turns). Moreover, the field errors in our case are actually lower than 10^4.

2-d Magnetic Model of 35 mm Aperture Dipole



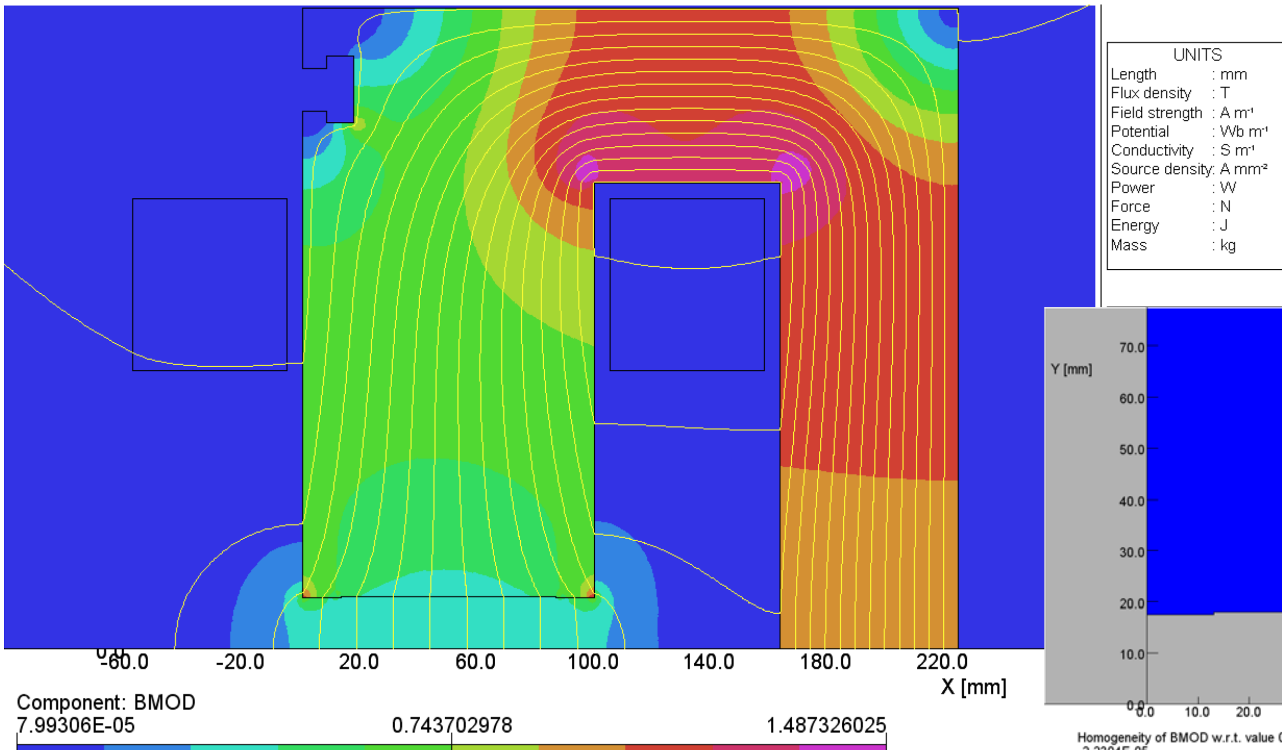
Coil Parameters:

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

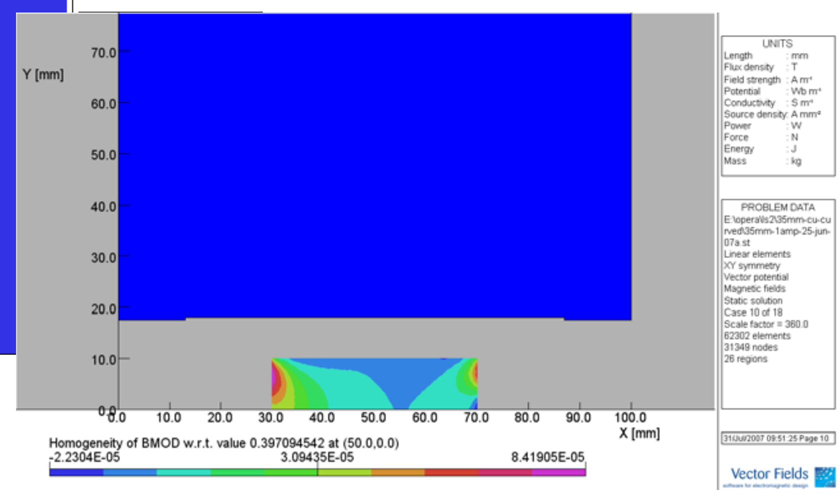
Overall current density for 0.4 T ~ 1.8 A/mm^2.

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

2-d Magnetic Model of 35 mm Aperture Dipole

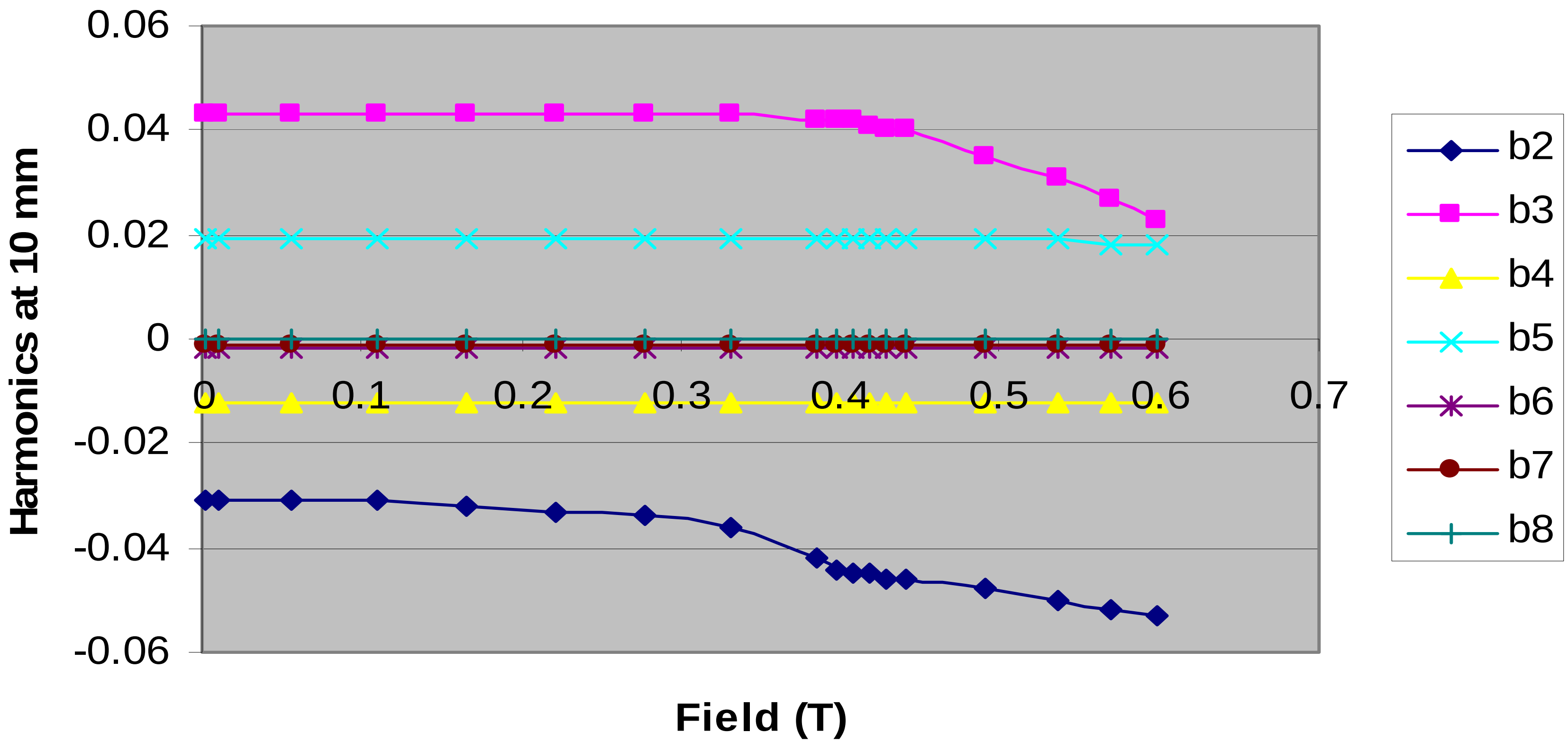


Field contour at the design field



Relative field errors in the good field region

Computed 2-d Harmonics in 35 mm Dipole



Note: Small values of field harmonics.
They are only a few parts in 10^5 even at 20 mm reference radius (remember the required good field region is +/-20 mm horizontally and +/-10 mm vertically).

Harmonics Definition

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty}\left[B_n(R_{ref}) + iA_n(R_{ref})\right]\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

From A. Jain's internal presentation

Computed 2-d Harmonics in 35 mm Dipole

Harmonics at 10 mm reference radius

I(Amp)	Bo(T)	b2	b3	b4	b5	b6	b7	b8
1	0.00111	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
10	0.01107	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
50	0.05535	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
100	0.11069	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
150	0.16603	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
200	0.22133	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
250	0.27649	-0.03	0.04	-0.01	0.02	0.00	0.00	0.00
300	0.33151	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
350	0.38622	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
360	0.39709	-0.04	0.04	-0.01	0.02	0.00	0.00	0.00
370	0.40794	-0.05	0.04	-0.01	0.02	0.00	0.00	0.00
380	0.41873	-0.05	0.04	-0.01	0.02	0.00	0.00	0.00
390	0.42948	-0.05	0.04	-0.01	0.02	0.00	0.00	0.00
400	0.44017	-0.05	0.04	-0.01	0.02	0.00	0.00	0.00
450	0.49174	-0.05	0.04	-0.01	0.02	0.00	0.00	0.00
500	0.53648	-0.05	0.03	-0.01	0.02	0.00	0.00	0.00
550	0.56993	-0.05	0.03	-0.01	0.02	0.00	0.00	0.00
600	0.59795	-0.05	0.02	-0.01	0.02	0.00	0.00	0.00

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

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.

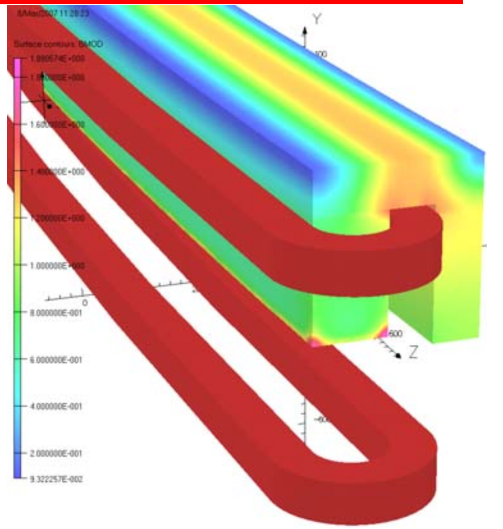
• The proposed *“Pole Extension”* or *“Nose”* practically eliminates this waste. For all practical purpose, yoke length becomes the same as the coil length. This works particularly well in low field magnets.

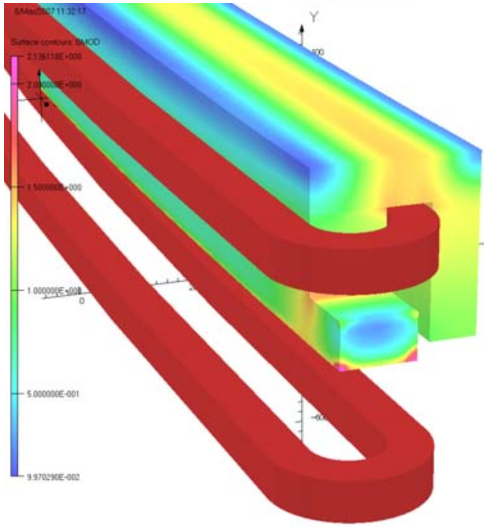
• In this proposal the coil ends are placed above an extended yoke. The surface of the pole remains an equi-potential, and the magnetic field for the beam remains at the full value, as long as the pole extension is not saturated.

• 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).

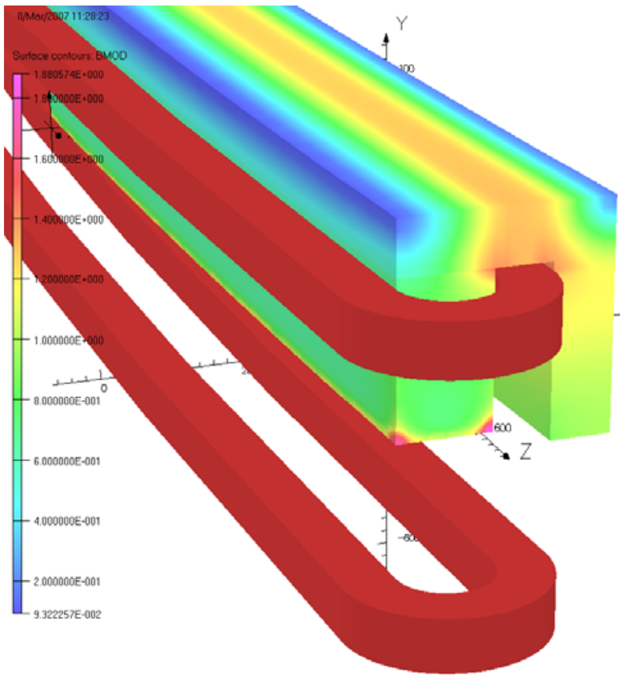
• The large vertical space (gap) between the upper and lower coils is also used by an internal support structure in the body of the magnet.



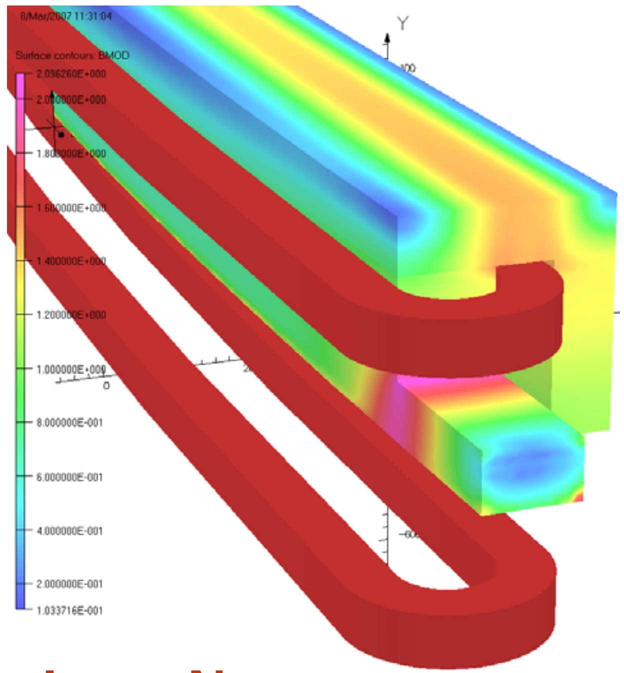


Optimization of Extended Pole (Nose)

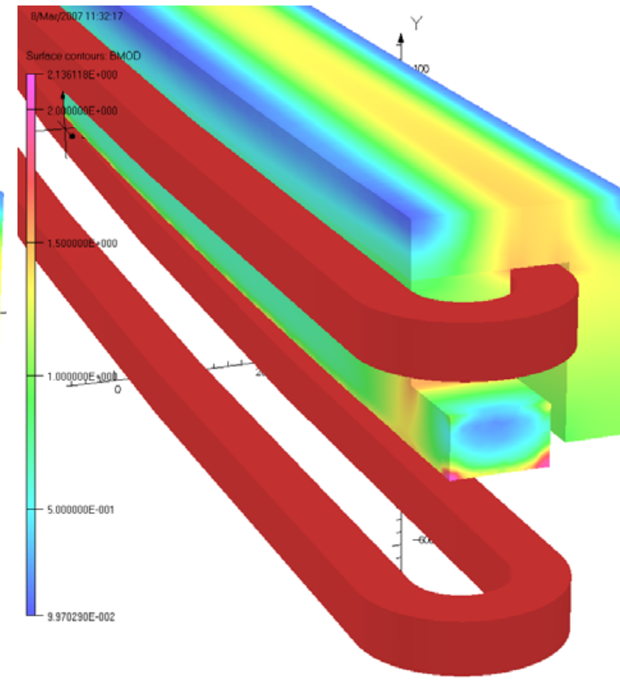
A number of studies were done to optimize axial extension and height of the the extended pole (nose).



No Nose

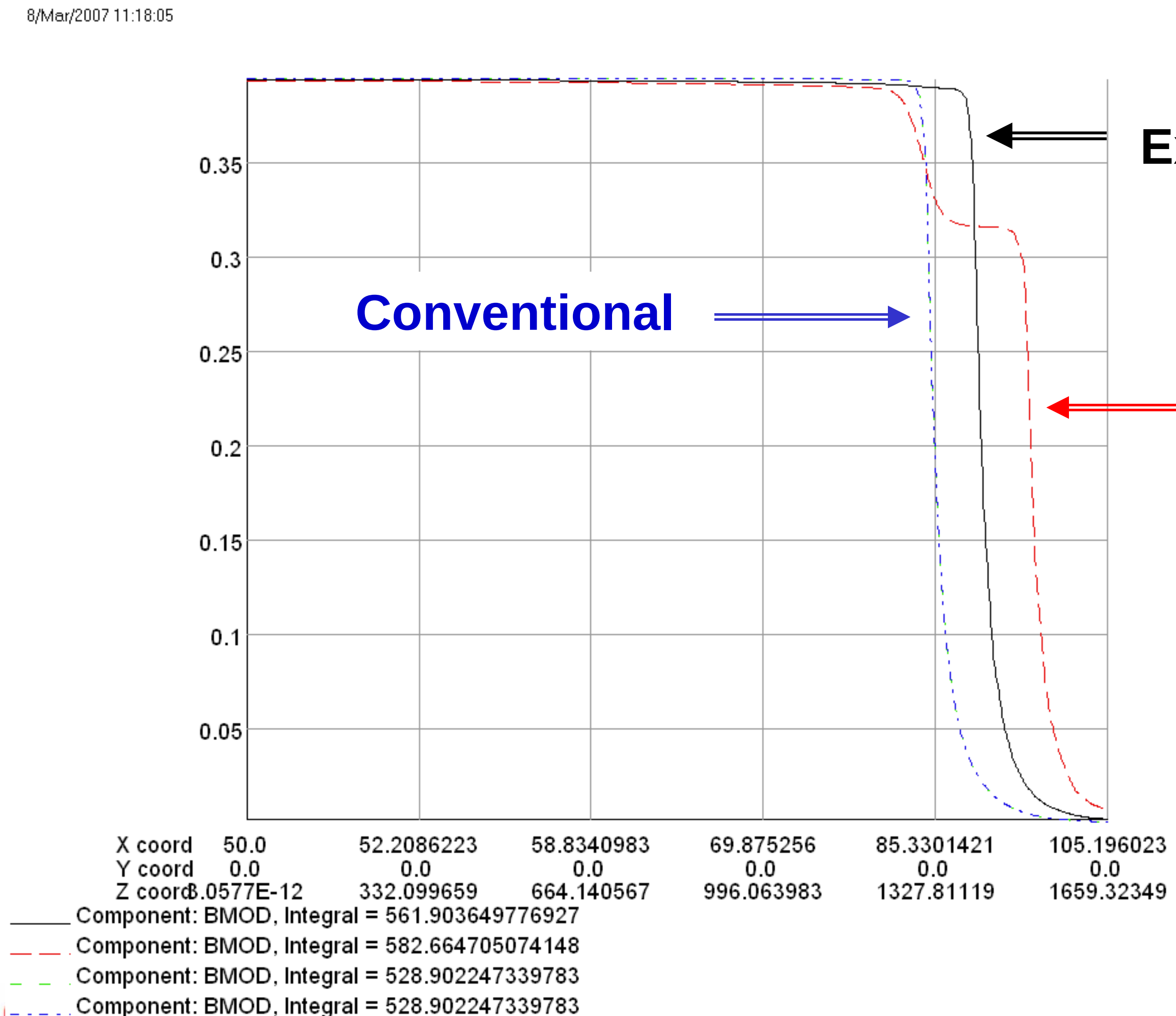


Long Nose
(too greedy,
note saturating nose)



Good Nose
(extended pole)

Space Recovery (Saving) by Extending Pole



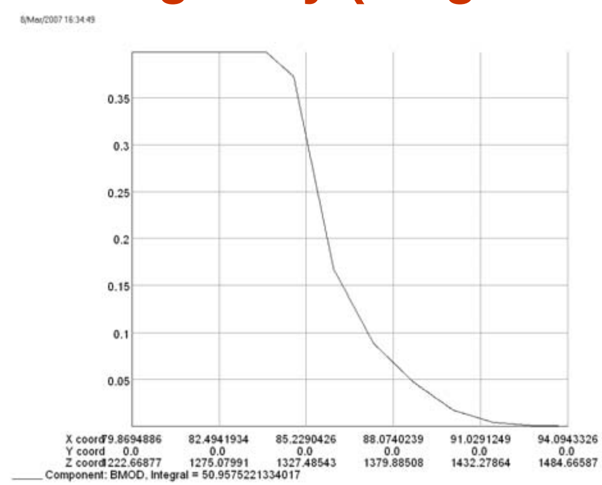
UNITS
Length mm
Magn Flux Density T
Magn Field A m⁻¹

Extended pole (good nose)

Conductivity S mm⁻¹
Current Density A mm⁻²
Power W
Force N
Energy J

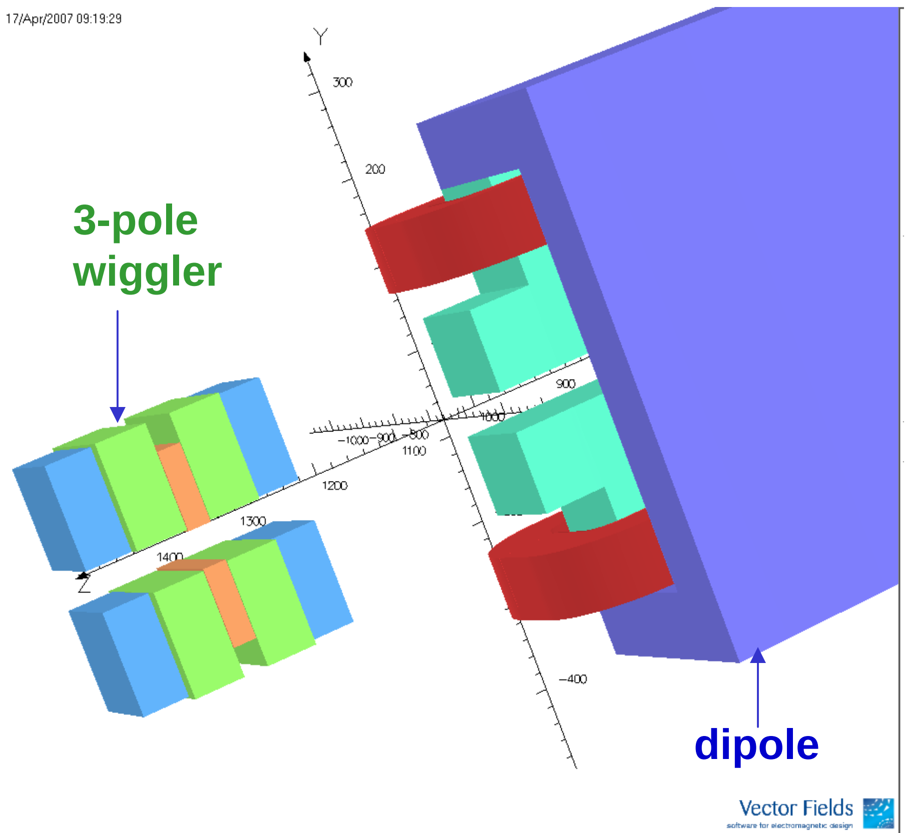
PROBLEM DATA
ls2-cu4-35mm-no-tooth.op3

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.

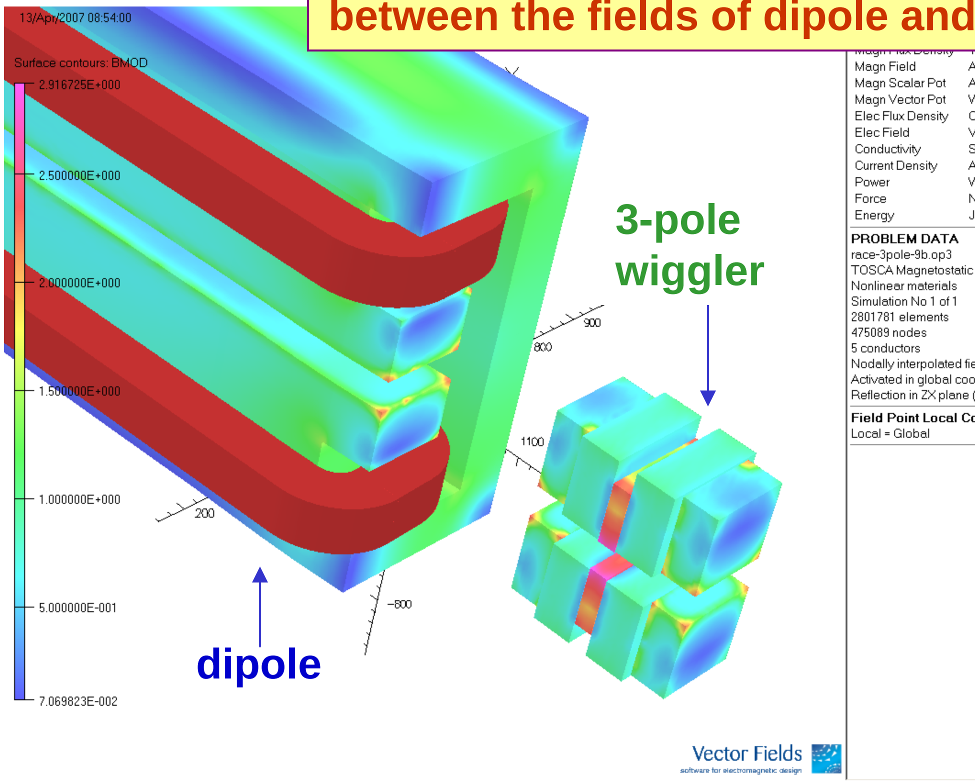
This also makes end field more symmetric (missing C-shape in the ends).

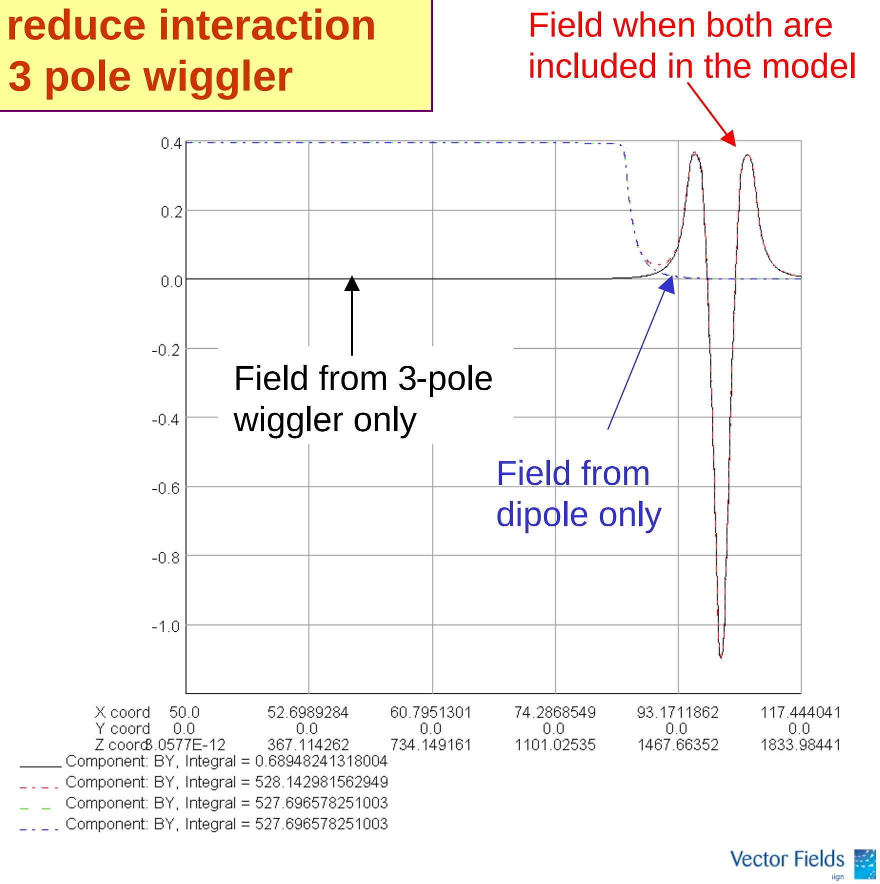
Extended pole (nose) frees-up ~ 10 meters in tunnel

(plus more extra space for vacuum system with open beg-leg).

Interaction Between the Dipole and 3-pole Wiggler

A significant effort was made to reduce interaction between the fields of dipole and 3 pole wiggler

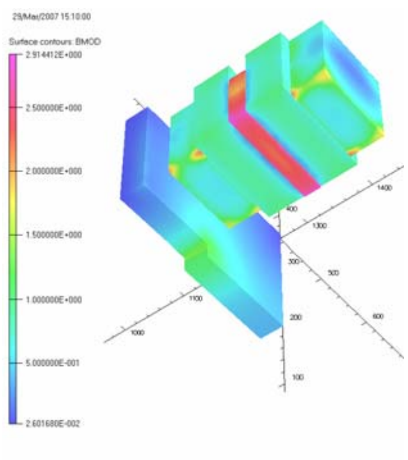




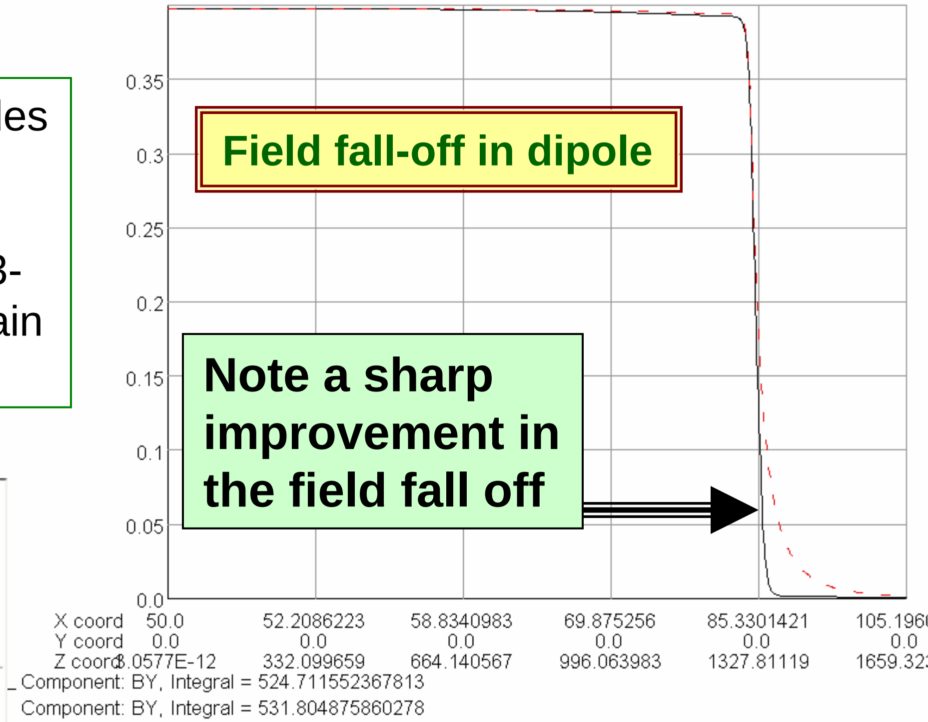
There is virtually no interference (< few parts in 1,000) between the fields of three pole wiggler and dipole as the model calculations of the two magnets give essentially the same results as the sum of the field of two individual magnets.

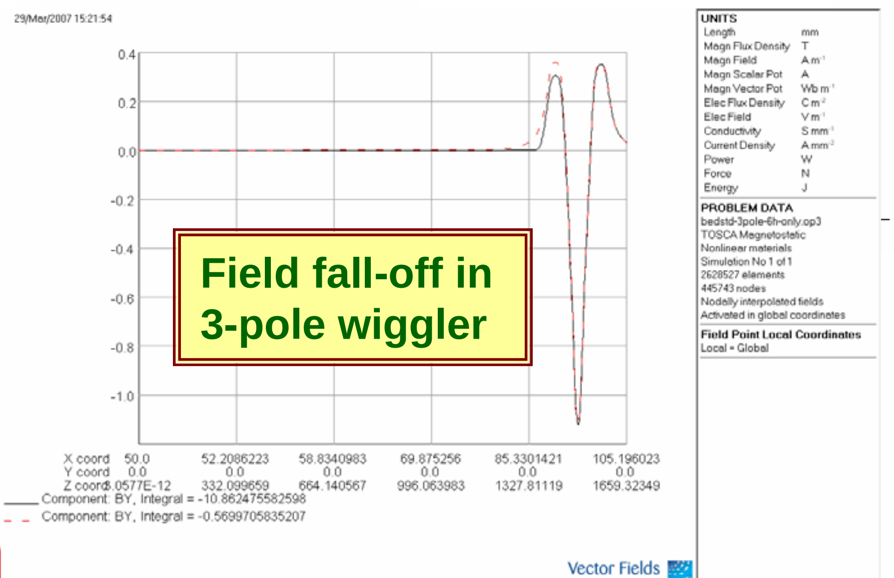
Incorporation of Magnetic Shield Between Dipole and 3 Pole Wiggler ?

- The goal was to reduce the cross-talk between the two magnets and to hasten the field fall-off.



Put shield on both sides for symmetry. Would need to adjust iron in two outside poles of 3-pole wiggler to maintain zero integral.





Magnetic shielding was studied but not used as a convincing case was not made to introduce additional complications.

Magnetic Design
of
90 mm Aperture Dipole

Design Parameters of 90 mm Aperture Dipole

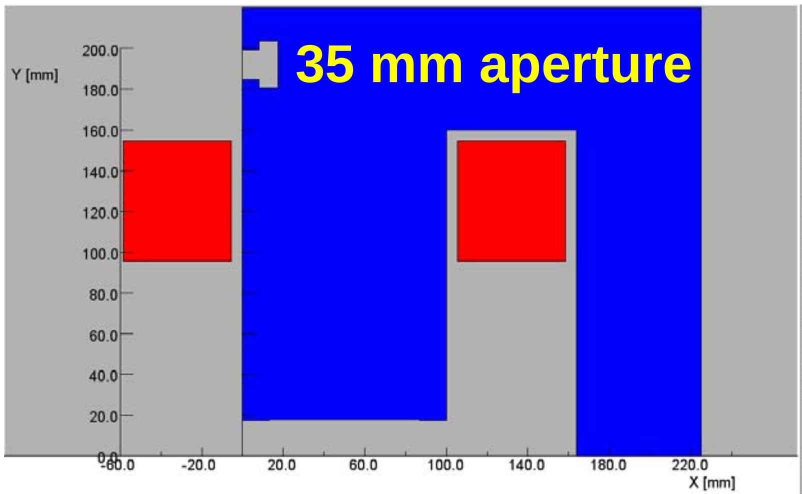
- Magnet Gap – 90 mm (minimum clearance)
- Nominal Field – B_o = 0.40 T (+20%)
- Field Homogeneity in B_X & B_Y = 1×10^{-4}
- Good field region B_X : +/- 20mm, B_Y : +/- 10mm
- Magnetic length – 2620 mm
- Nominal Current density in the coil cross section 2 Amps/mm^2
- Maximum allowable temperature rise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

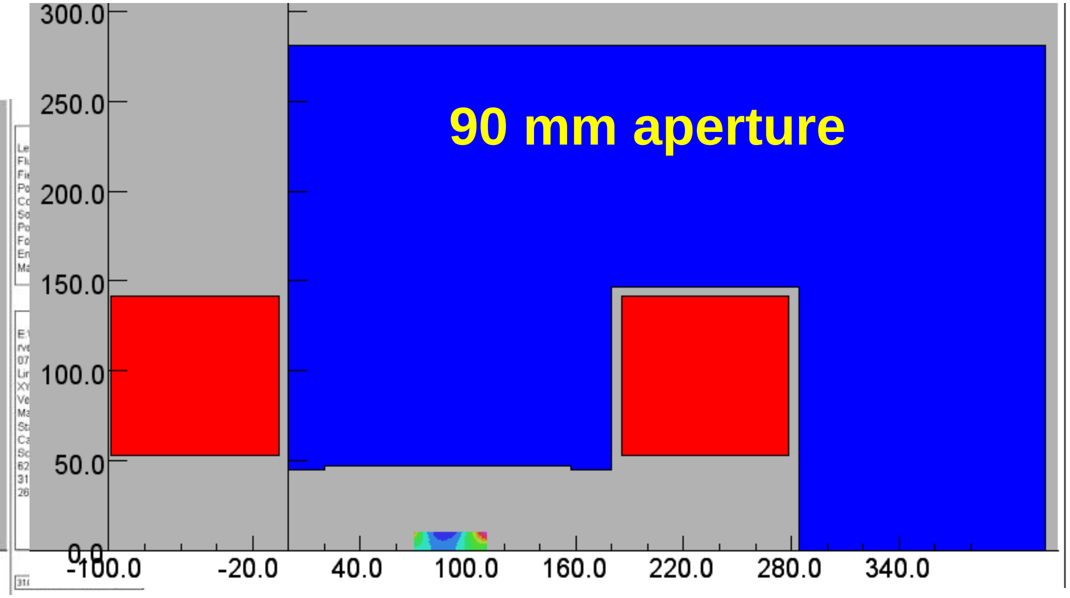
• Except for the gap, all design parameters are the same as in 35 mm dipole.
• Since the relative value of good field aperture is small in this magnet, the pole width to pole gap ratio can be made smaller.
• 35 mm and 90 mm dipole should run on the same power supply and therefore the transfer function 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 bump are : 2.58 mm high and 20.5 mm wide on left and 2.58 mm high and 23 mm on right. They are made asymmetric to compensate for the inherent asymmetry of C-shape dipole.
- By comparison bumps were 0.5 mm high and 13 mm wide in 35 mm dipole (height was kept small) and they were symmetric.
- 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





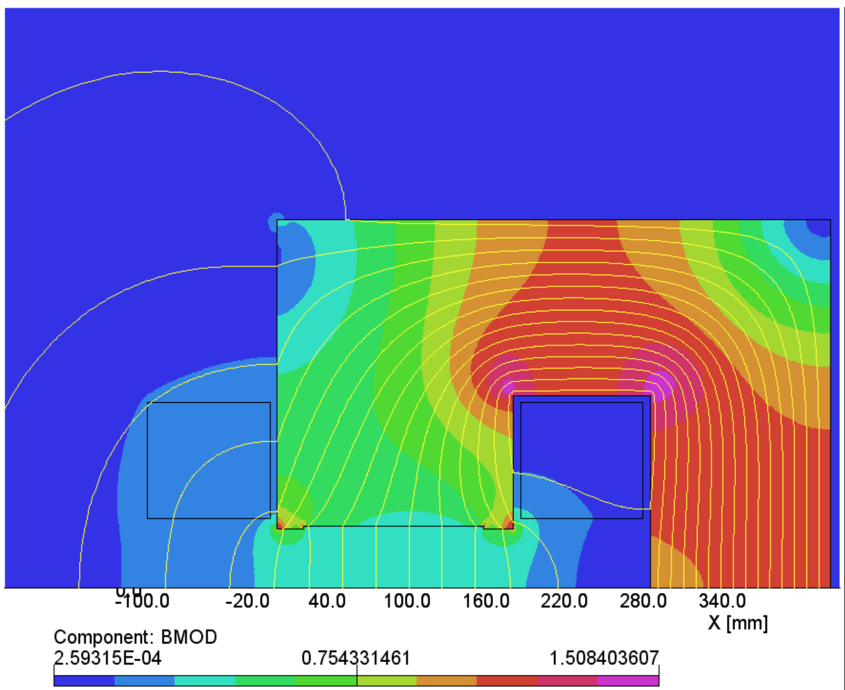
Note: 90 mm is the minimum vertical clearance. Pole gap at the magnet center is higher.

Adjust number of turns and then pole gap of 90 mm dipole to match transfer function with 35 mm aperture dipole to allow the same power supply for both magnets.

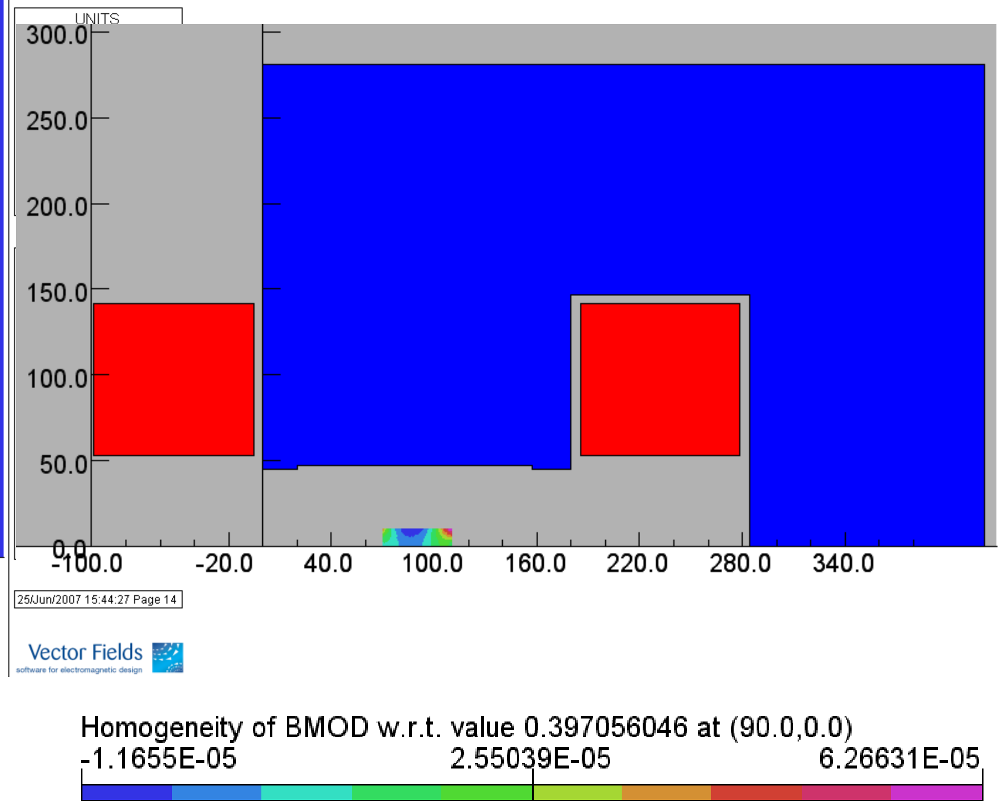
- Same conductor chosen for both dipoles (number of turns are adjusted) - 16 turns (4 X 4) in 35 mm aperture case and 42 turns (6 X 7) in 90 mm aperture case.
- Transfer function of the two dipoles is similar with a maximum ~1% deviation.

2-d Magnetic Model of 90 mm Aperture Dipole

Relative field errors in the good field region

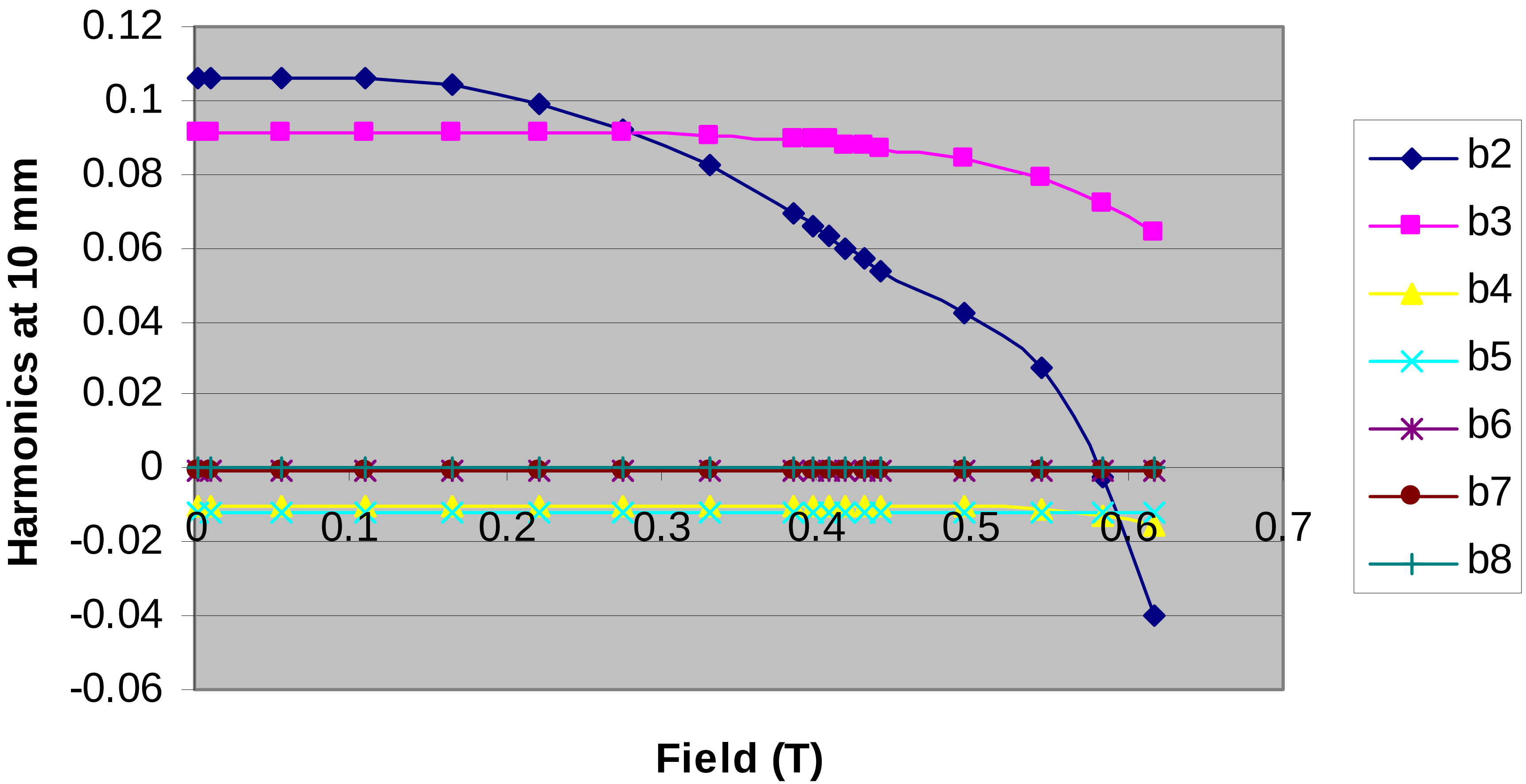


Field contour at the design field



Computed 2-d Harmonics in 90 mm Dipole

Harmonics at 10 mm reference radius



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

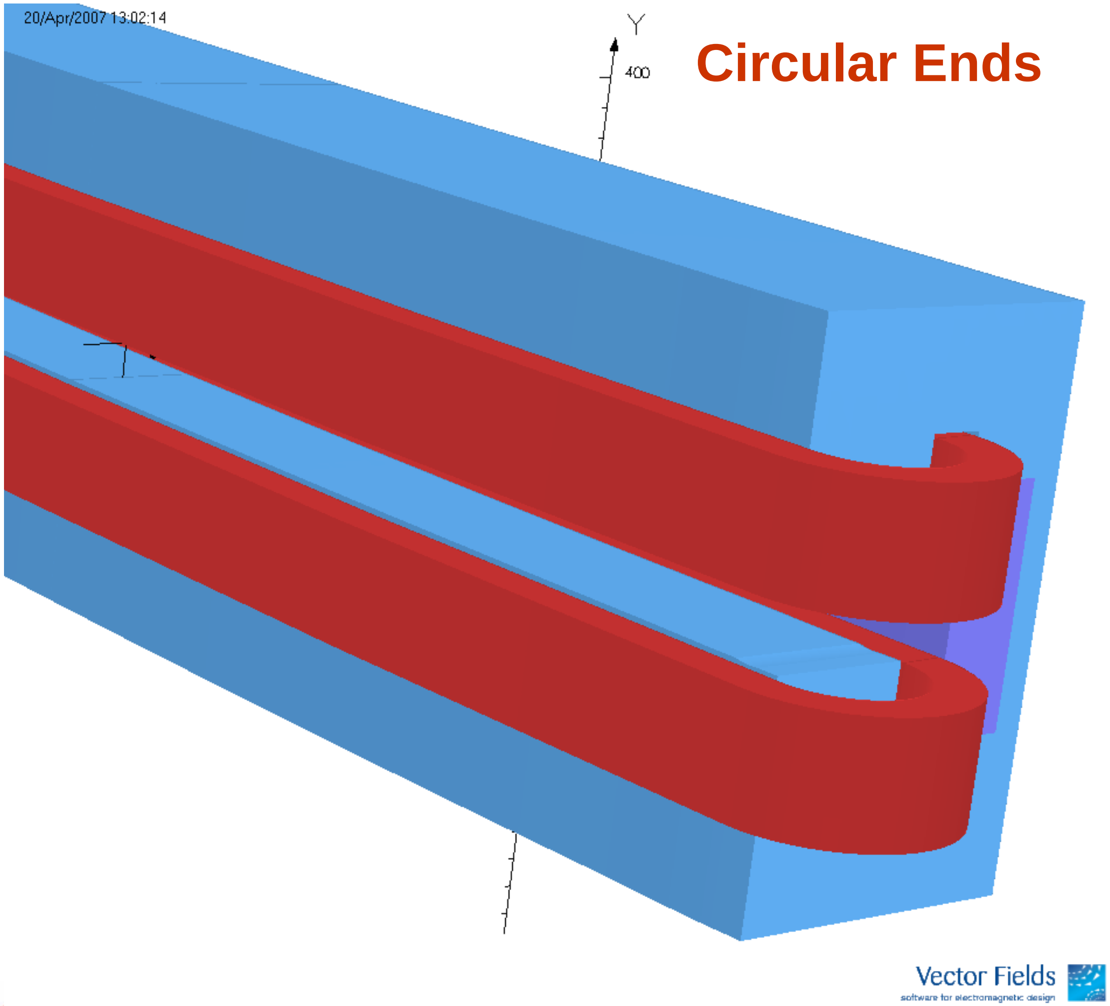
Computed 2-d Harmonics in 90 mm Dipole

Harmonics at 10 mm reference radius

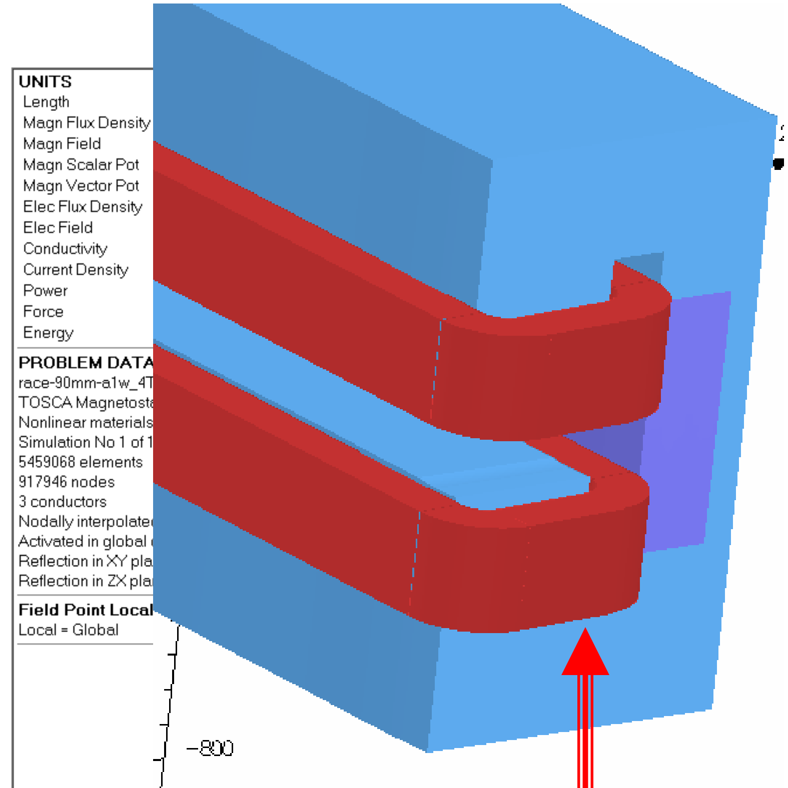
Case#	I(Amp)	Bo(T)	b2	b3	b4	b5	b6	b7	b8
1	1	0.0011	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
2	10	0.01105	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
3	50	0.05524	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
4	100	0.11048	0.11	0.09	-0.01	-0.01	0.00	0.00	0.00
5	150	0.16572	0.10	0.09	-0.01	-0.01	0.00	0.00	0.00
6	200	0.22093	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).

Preliminary 3-d Analysis of ~90 mm Aperture Dipole



Circular Ends



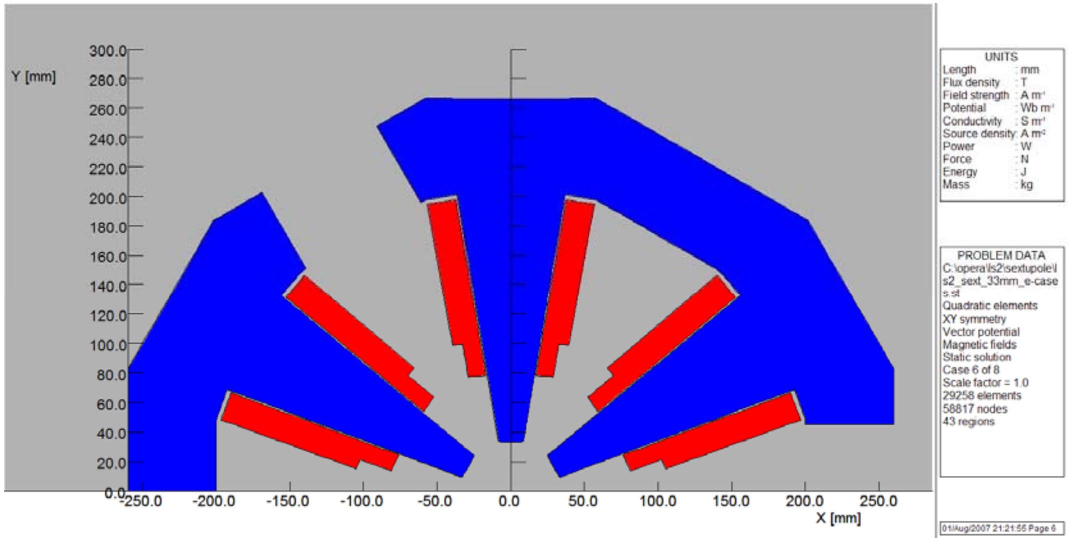
Racetrack Ends (to reduce the mechanical length of the coil/magnet)

Magnetic Design

of

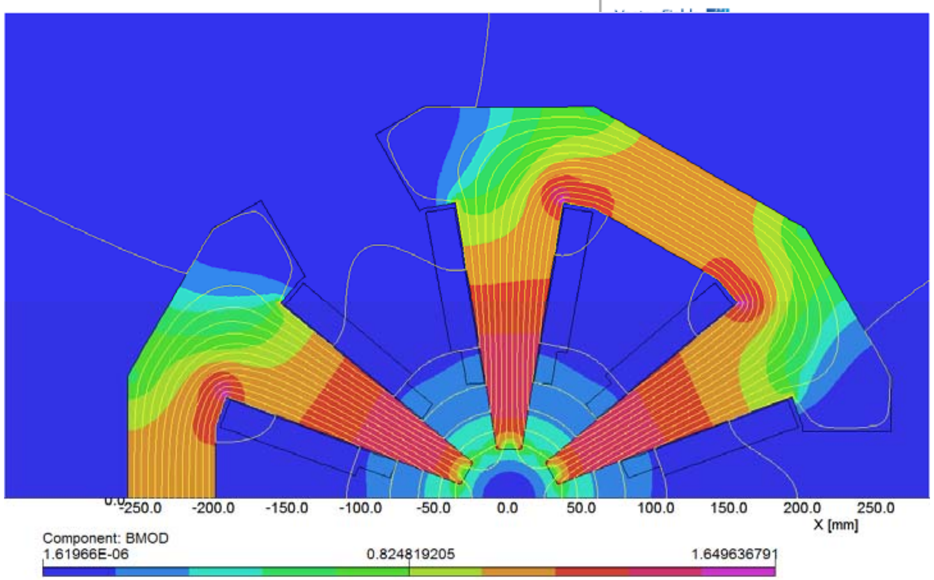
66 mm Aperture Sextupole

CDR Design of 66 mm Aperture Sextupole



Design Optimized by Wuhzeng Meng
Model: ls20sext-33mm-e

Field contours and field lines at the design field



The iron yoke will be closed in newer design (continuous with no break in magnetic circuit).

Field Harmonics in 66 mm aperture Sextupole

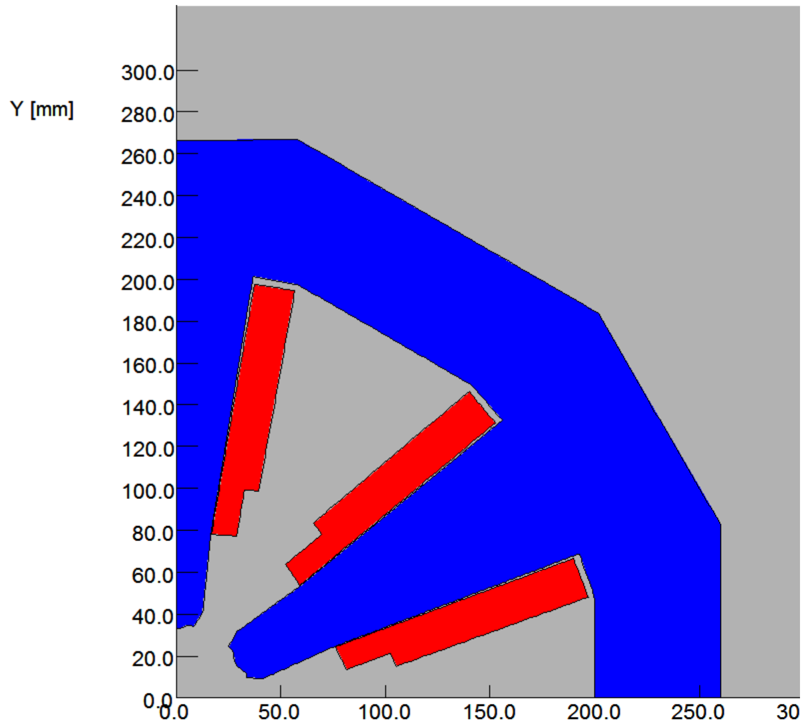
Harmonic Values as a function of excitation at 22 mm reference radius (2/3 of pole radius 33 mm) in an earlier CDR design (Model: ls20sext-33mm-e)

Strength	TF	b3	b5	b7	b9	b11	b13	b15
49.87	498.69	10000	0.02	-0.04	-0.70	-0.01	0.00	-12.85
100.00	499.98	10000	0.02	-0.04	-0.68	-0.01	0.00	-12.85
200.56	501.40	10000	0.02	-0.04	-0.66	-0.01	0.00	-12.85
300.45	500.74	10000	0.02	-0.04	-0.68	-0.01	0.00	-12.85
399.93	499.91	10000	0.02	-0.04	-0.70	-0.01	0.00	-12.85
497.08	497.08	10000	0.02	-0.04	-0.73	-0.01	0.00	-12.85
582.42	485.35	10000	0.02	-0.03	-0.85	-0.01	0.00	-12.84
642.22	458.73	10000	0.02	-0.03	-1.11	-0.01	0.00	-12.83

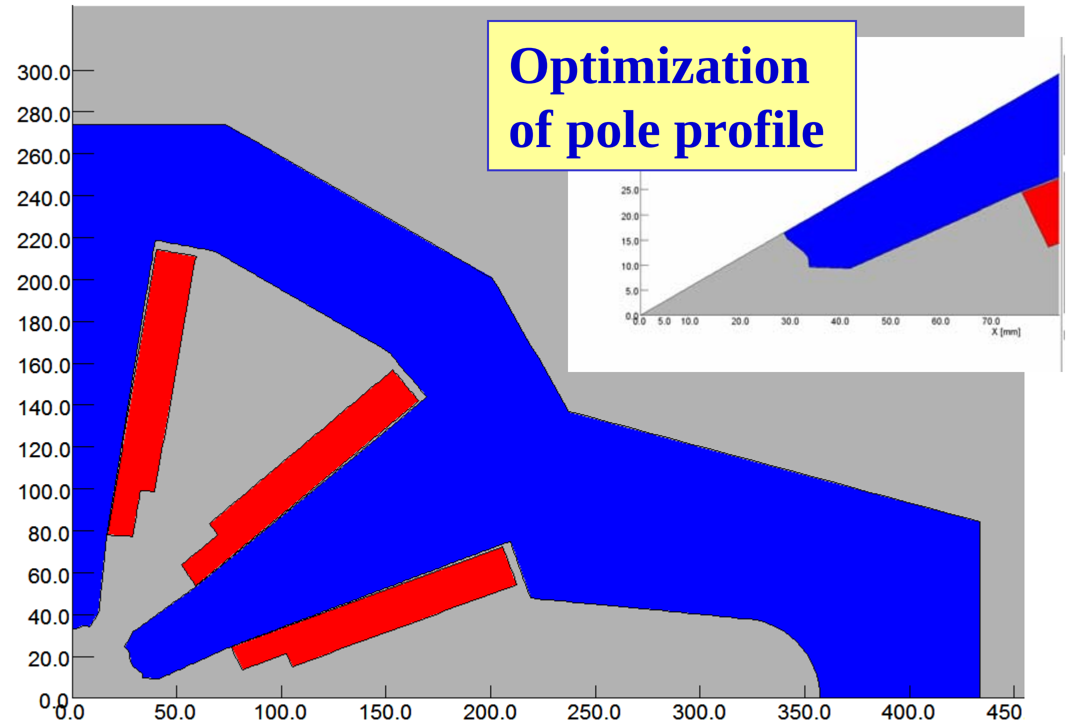
Attempt will be made to reduce b15 in addition to modifying iron yoke.

Spec is for all harmonics to be less than 5 (desired ~1).

New Design for 66 mm Aperture Sextupole
(work in progress)



Standard Sextupole

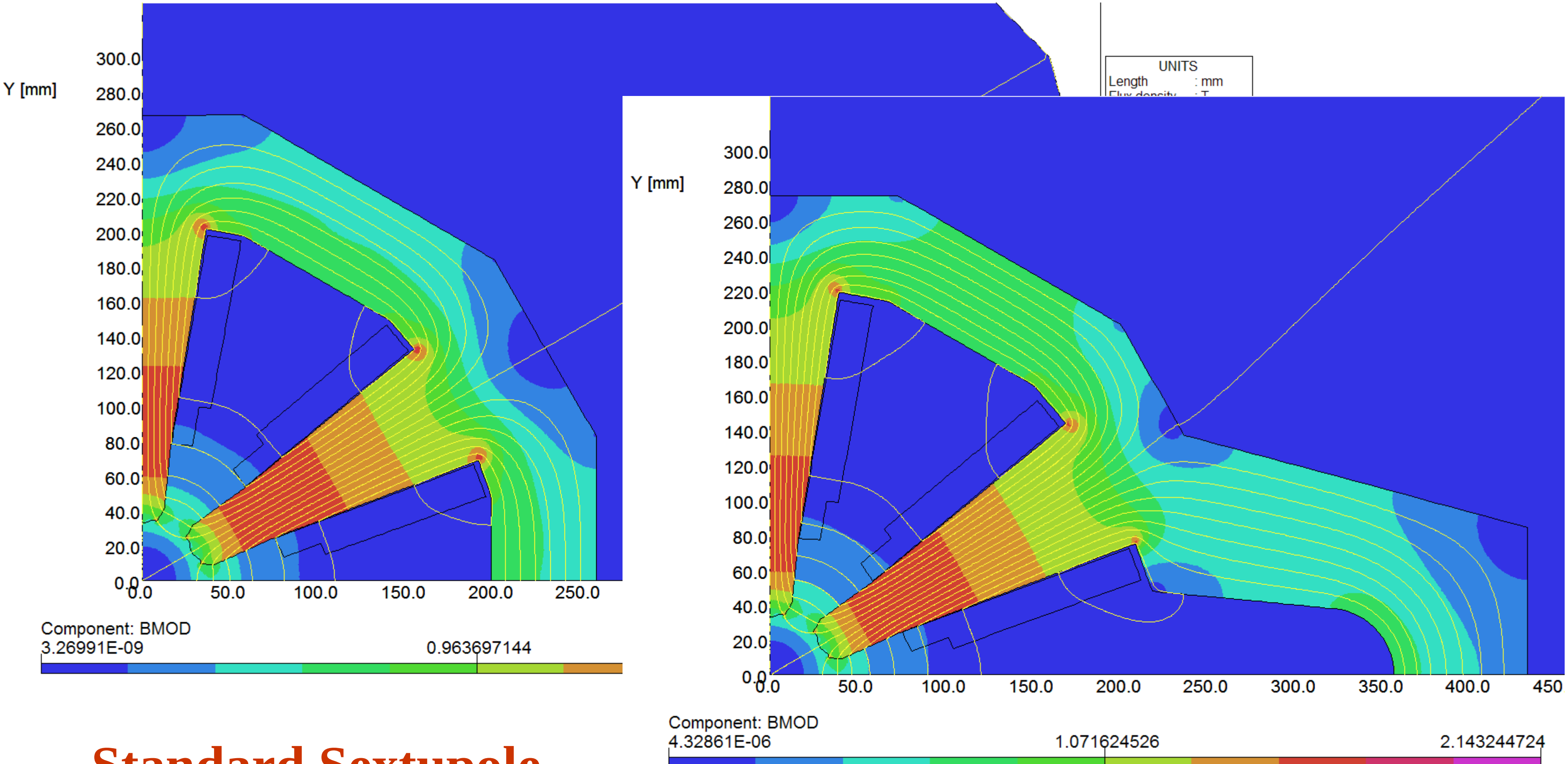


Wide-opening Sextupole

Pole shape is re-optimized within the confine of same overall geometric constraints.

(six points were used to optimize the pole profile for low allowed terms)

New Design for 66 mm Aperture Sextupole (field contour and field lines at the design field)



Standard Sextupole

Wide-opening Sextupole

Field Harmonics in New 66 mm aperture Sextupole (work in progress)

Harmonic Values at the design field at 22 mm reference radius (2/3 of 33 mm) in the partially optimized design.

	b5	b7	b9	b11	b13	b15
Wider (New)	-2.268	-0.133	-0.128	0.056	-0.023	-1.693
Standard (New)	-0.063	0.049	0.074	0.027	-0.024	-1.704
CDR design (old)	0.018	-0.036	-0.696	-0.008	0.004	-12.851

- **Allowed harmonics b_9 and b_{15} have been reduced. A special effort was made to reduce b_{15}, as it was well above 5. b_9 is essentially zero.**

- Semi-allowed harmonics b_1, b_5, b_7, b_{11} and b_{13} in wider sextupole are not yet optimized. Their non-zero value in standard sextupole is due to computational error.

Note all harmonics are now less than 5 (well within the spec). They can perhaps be reduced to < 1 with further optimization.

2-d optimization will continue. 3-d optimization is yet to be carried out.

Latest Results (after your slides were printed)

A technique for reducing semi-allowed harmonic:

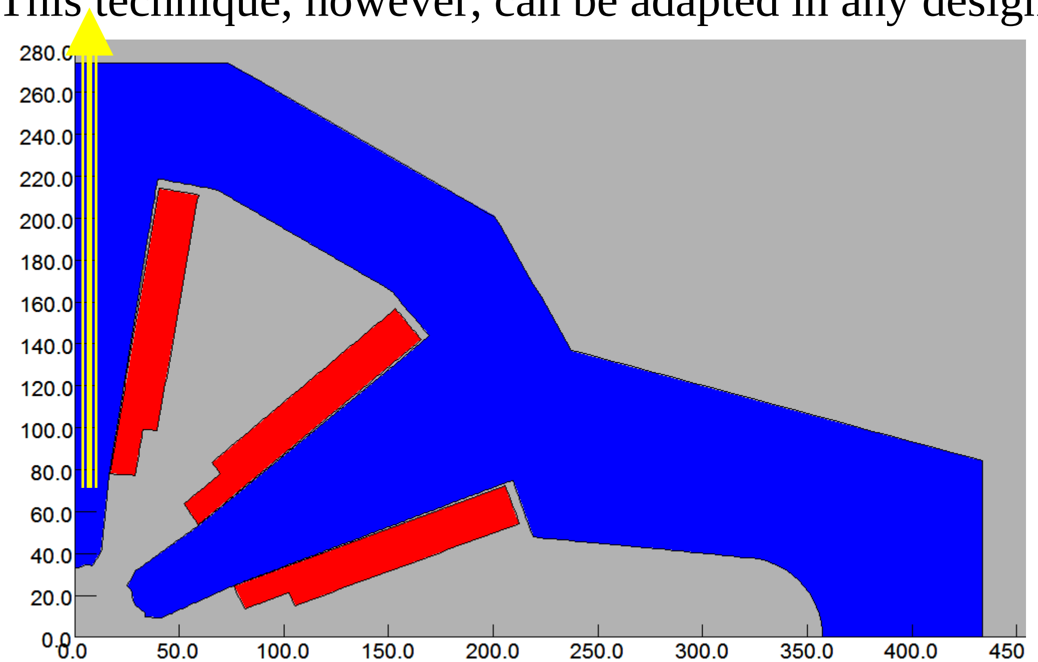
These harmonics are created because removing the iron at horizontal plane breaks the symmetry.

Compensate this by moving the poles at vertical plane away from the center….

This is natural in case of floating pole design (shim it).

This technique, however, can be adapted in any design

N	bn(new)	bn(old)
1	-2.676	-15.2
3	10000	10000
5	-0.015	-2.27
7	-0.046	-0.133



Moreover, b15 is reduced by further optimizing pole profile:

N	NORMAL(bn)	
3	10000	
9	0.102	
15	-0.487	(old -1.7)
21	-0.719	
27	0.064	

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 well underway. Field quality specs are met.
- Good progress is made in newer 66 mm aperture sextupole design with yoke having no break in magnetic circuit. Pole shape is re-optimized to significantly reduce field errors and comfortably meet the spec.