Modeling and Strategies for Obtaining Good-Field Quality

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Prototype Lattice Magnet Design Review
January 28, 2008

Introduction (1)

The primary purpose of the magnet modeling at this stage of the program is to:

- **Produce designs that meet or exceed the machine requirements**
- **Give feed back to machine physicists on what errors to expect, and also what is the level of our confidence in those calculations, so that they can use this information in designing the machine**
  - Of particular challenge is the interaction harmonics between magnets, as some of them are placed very close to each other (examples will be presented)

Introduction (2)

A good understanding of field quality is required.
Components are:

- 2-d and 3-d magnetic modeling (significant progress in software and in hardware) and analysis (remains as challenging as ever)
- Magnetic measurements (significant improvements over time)
- Manufacturing errors (both in parts and in assembly)

We communicate this understanding to machine physicists through harmonics so that they are neither overly optimistic and nor overly conservative

➢ **Develop strategies now on how we are going to get those promised harmonics**

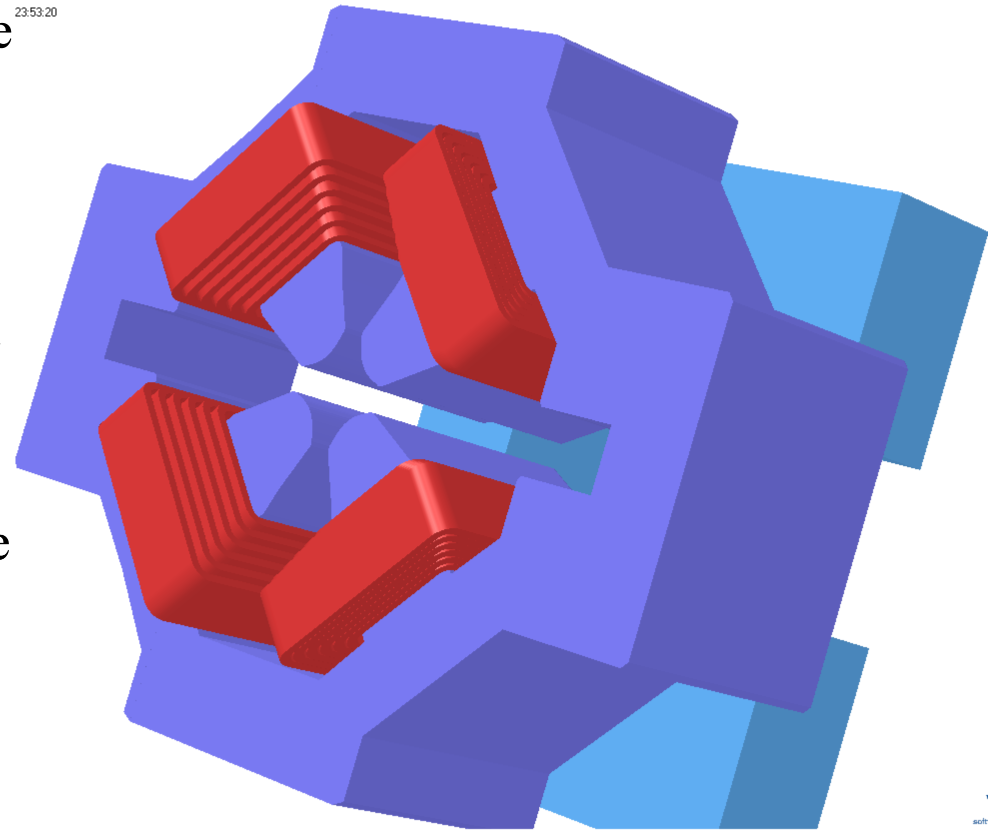
Modeling for Interaction Between Magnets with Small Separation

- In NSLS2, magnets are placed in close proximity (i.e., small axial separation between two magnetic elements).

- We want to know the distortion in the field of one magnet from the proximity of another magnet.

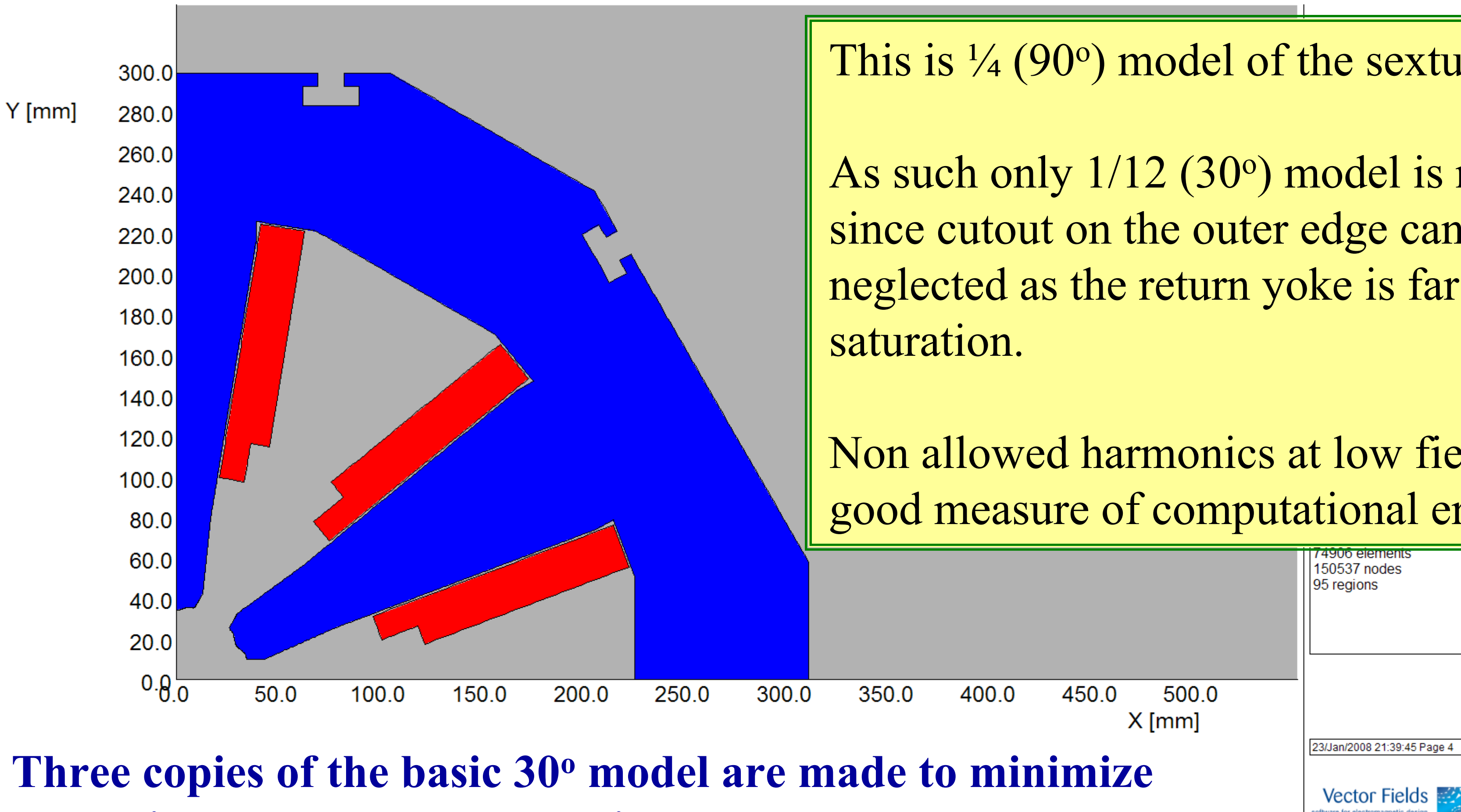
- We are making 3-d models to simulate combinations of various magnet types.

- The question is how reliable are these 3-d calculations, specially if the interference harmonics are small. As far as we know, there are not too model calculations to provide some guidance.



A good approach may be to study the criteria of reliability in 2-d models first (where there is a lot of experience) and then apply that to 3-d modeling.

2-d Modeling Case Study – NSLS2 Sextupole



This is ¼ (90^o) model of the sextupole.

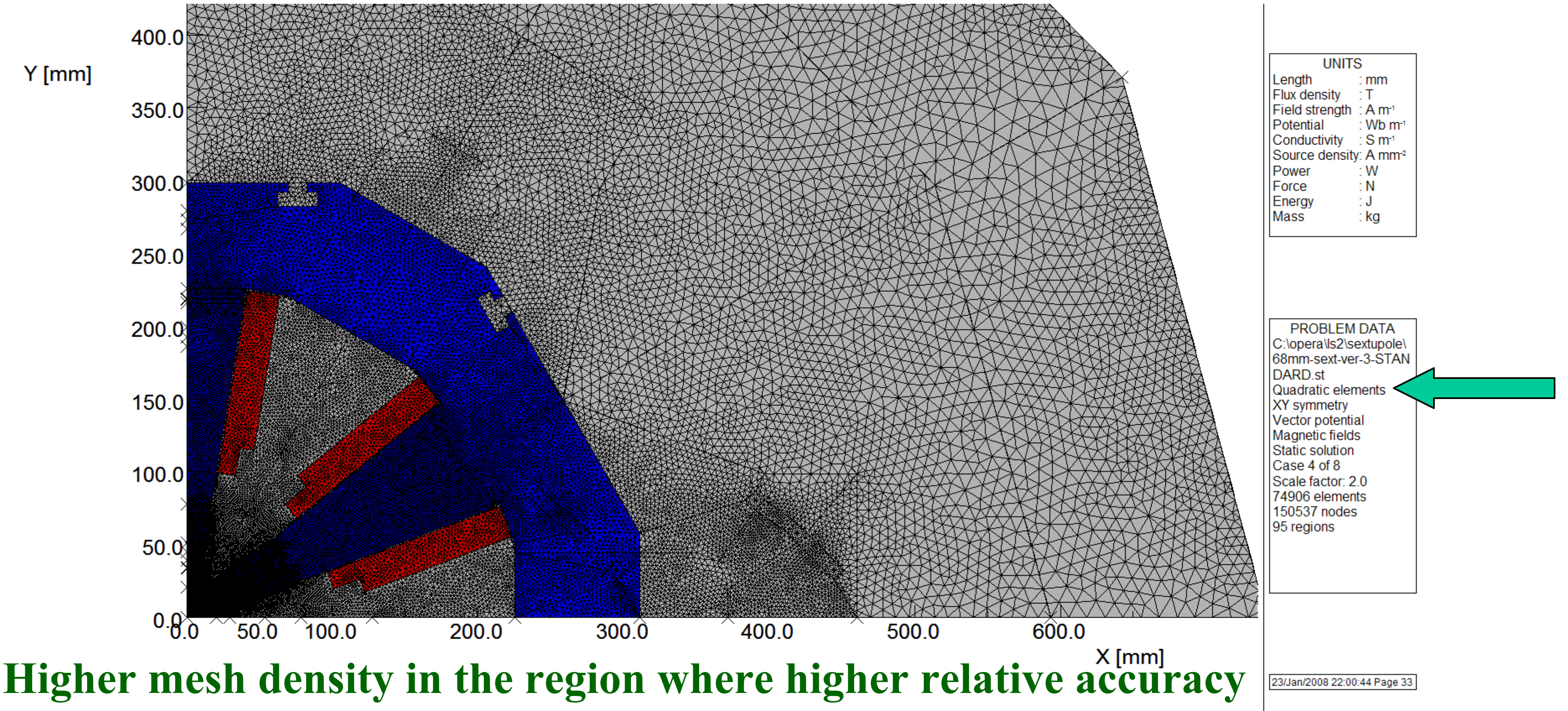
As such only 1/12 (30^o) model is needed, since cutout on the outer edge can be neglected as the return yoke is far from saturation.

Non allowed harmonics at low fields are good measure of computational errors.

Three copies of the basic 30^o model are made to minimize errors in non-allowed harmonics.

Finite Element (OPERA 2d) Model of Sextupole

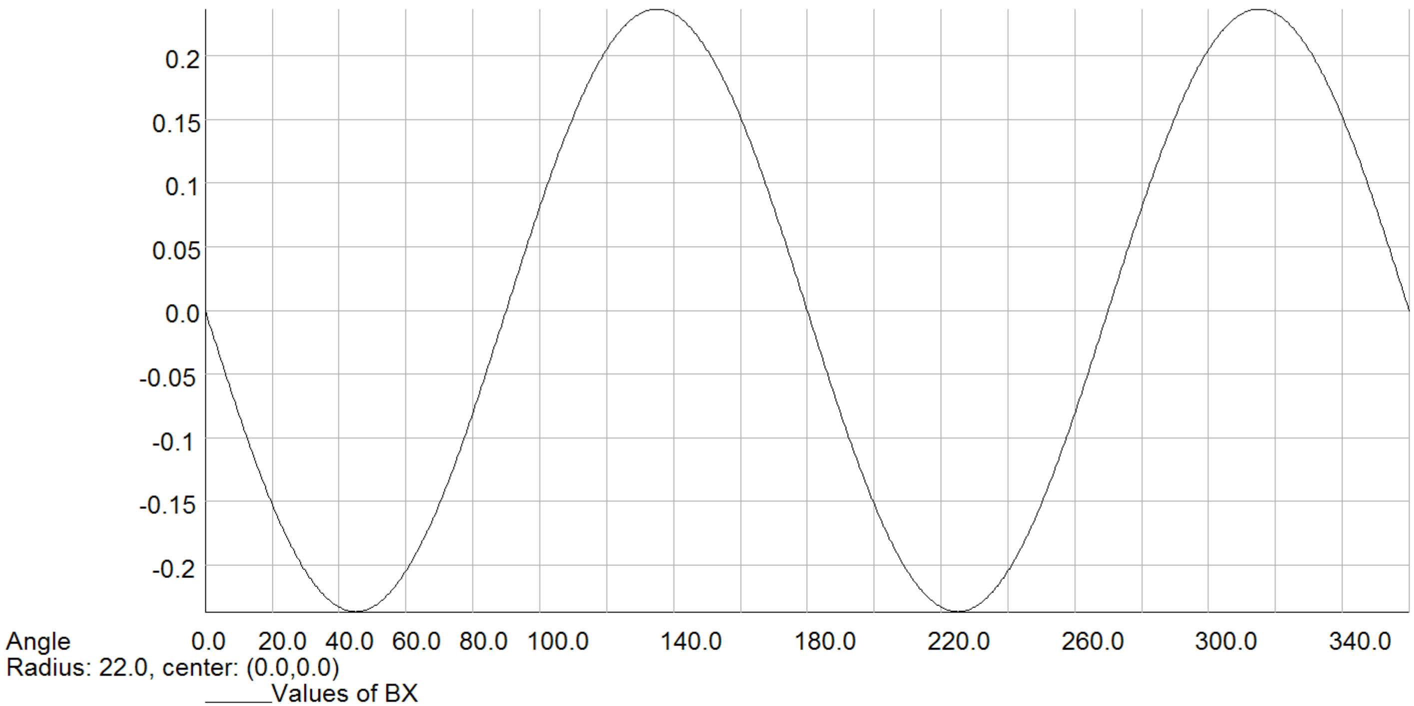
Use quadratic elements. This increases accuracy of calculations significantly in quadrupoles and sextupoles. Linear elements are OK in dipoles where vector potential changes linearly.

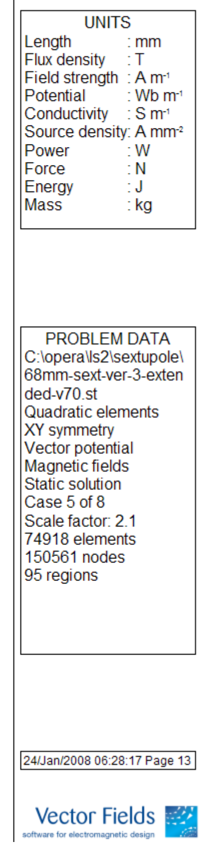


Higher mesh density in the region where higher relative accuracy is needed for computing field harmonics

Horizontal Component on a Circle (inside the aperture of the sextupole)

Symmetry in post-processor is used to create 360 degree field profile from 90 degree model.



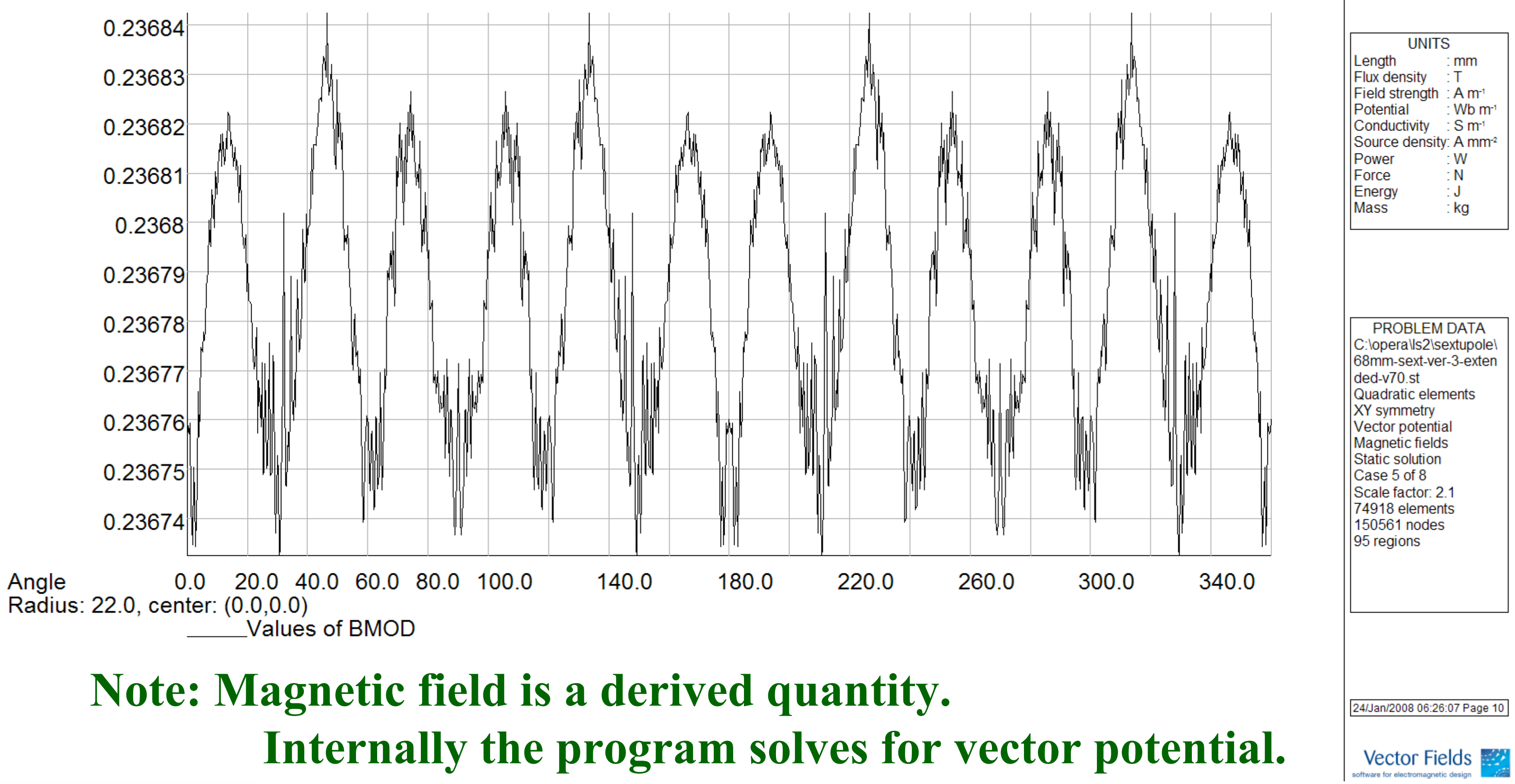


This curve must look smooth at this scale for a target 10^{-4} relative accuracy.

Magnitude of the field on a Circle (inside the aperture of the sextupole)

This will be constant in an ideal sextupole (or any multipole magnet)

Field is uniform to a few parts in 10^4 and local deviations are a few parts in 10^5. This seems to be a reasonably good model.

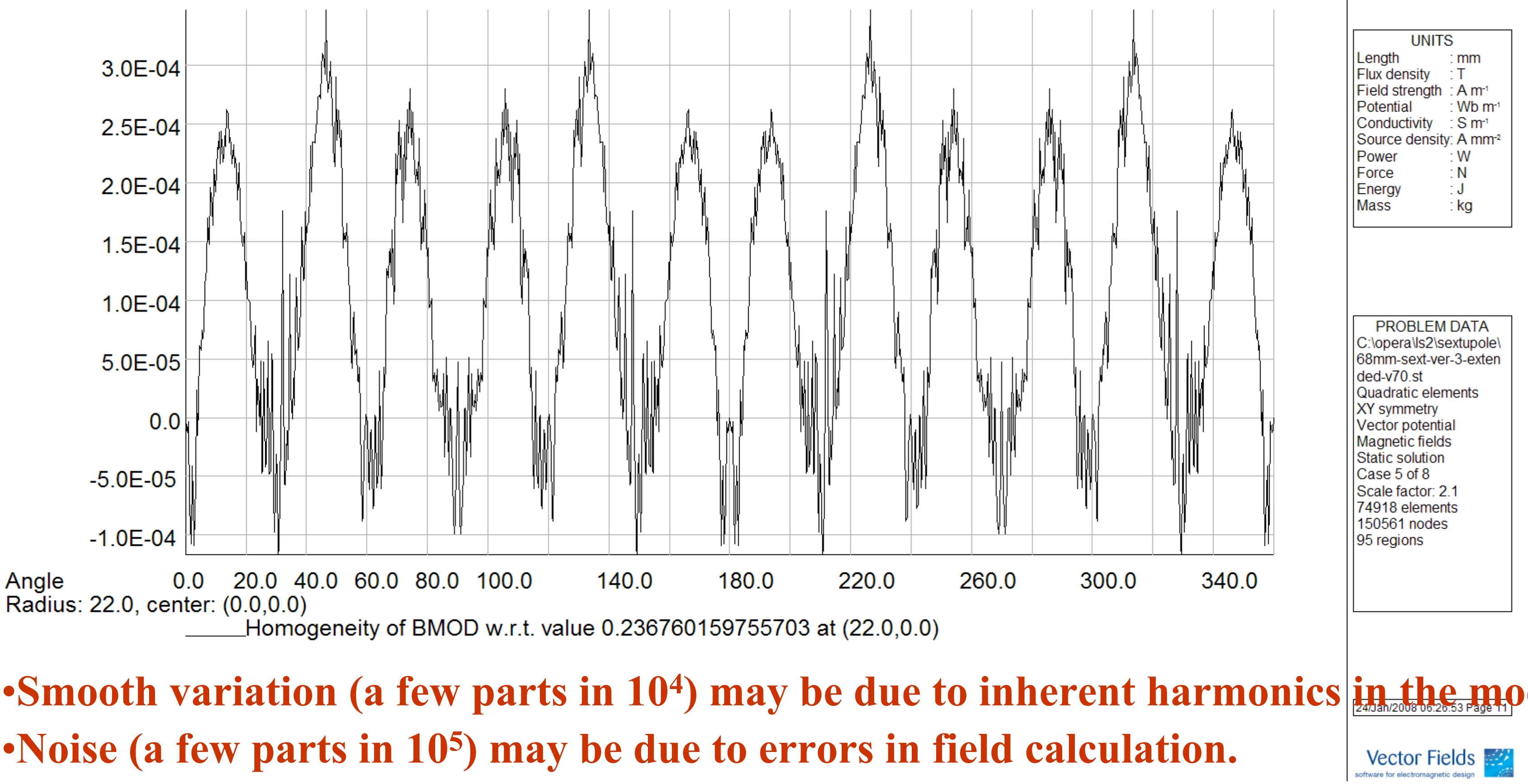


Note: Magnetic field is a derived quantity.

Internally the program solves for vector potential.

Relative Errors in the Magnitude of the Field

Relative field errors on a circular arc are computed with respect to its value at x=R



- Smooth variation (a few parts in 10^4) may be due to inherent harmonics in the model.
- Noise (a few parts in 10^5) may be due to errors in field calculation.
- This suggest that the calculations should be reliable to a few parts in 10^5.
  - ➢ This seems to be a reasonably good model giving reasonably good results.

Harmonics in Standard Sextupole

Harmonics at 22 mm reference radius in NSLS2 68 mm aperture sextupole - standard aperture
File: 68mm-sext-ver-3-standard

Case#	Scale	Fundamental	Sext (T/m^2)	T.F.	d(TF),%	1	**3**	5	7	**9**
1	0.5	0.0578	**115.7**	**231.3**	**0**	2.52	**10000**	0.316	0.023	**0.497**
2	1	0.1158	**231.6**	**231.6**	**0**	2.37	**10000**	0.297	0.022	**0.504**
3	1.5	0.1734	**346.7**	**231.2**	**0**	2.21	**10000**	0.277	0.020	**0.481**
4	2	0.2279	**455.7**	**227.9**	**1**	3.14	**10000**	0.391	0.029	**0.476**
5	2.1	0.2375	**475.0**	**226.2**	**2**	3.35	**10000**	0.418	0.031	**0.473**
6	2.5	0.2672	**534.5**	**213.8**	**8**	3.26	**10000**	0.406	0.031	**0.451**
7	3	0.2882	**576.5**	**192.2**	**17**	2.46	**10000**	0.306	0.023	**0.416**
8	3.5	0.2999	**599.7**	**171.4**	**26**	2.07	**10000**	0.258	0.019	**0.387**

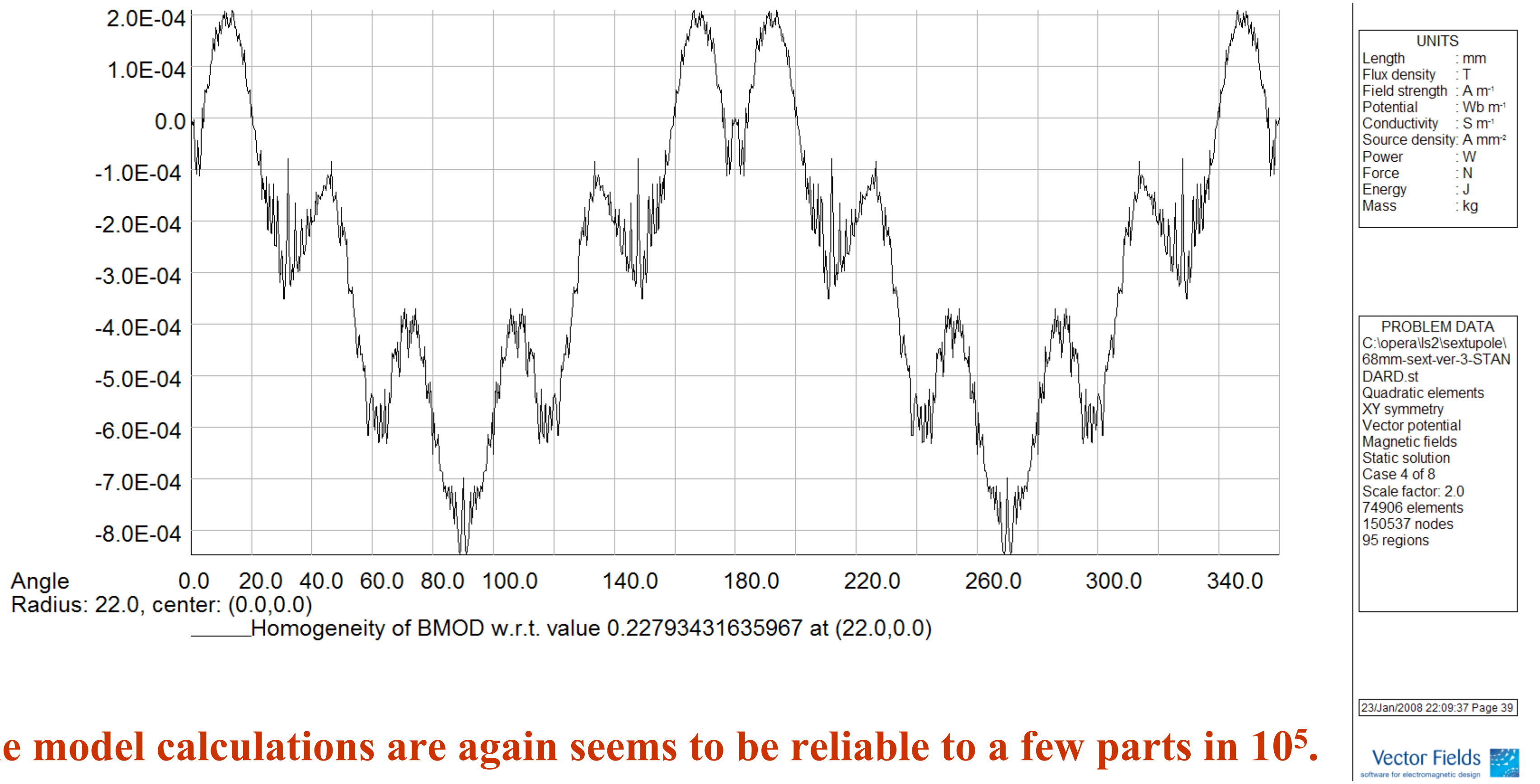
Case#	Scale	Fundamental	Sext (T/m^	11	13	**15**	17	19	**21**	23	25	**27**
1	0.5	0.0578	**115.7**	-0.003	0.000	**-1.425**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
2	1	0.1158	**231.6**	-0.003	0.000	**-1.426**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
3	1.5	0.1734	**346.7**	-0.003	0.000	**-1.424**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
4	2	0.2279	**455.7**	-0.004	0.000	**-1.424**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
5	2.1	0.2375	**475.0**	-0.004	0.000	**-1.424**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
6	2.5	0.2672	**534.5**	-0.004	0.000	**-1.423**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
7	3	0.2882	**576.5**	-0.003	0.000	**-1.421**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**
8	3.5	0.2999	**599.7**	-0.003	0.000	**-1.420**	0.000	0.000	**-0.294**	0.001	0.000	**0.022**

Values of non-allowed harmonics in black indicates the modeling errors.

In many terms harmonics are not reliable to the third decimal places.

Relative Errors in Another Sextupole (this has more inherent harmonics)

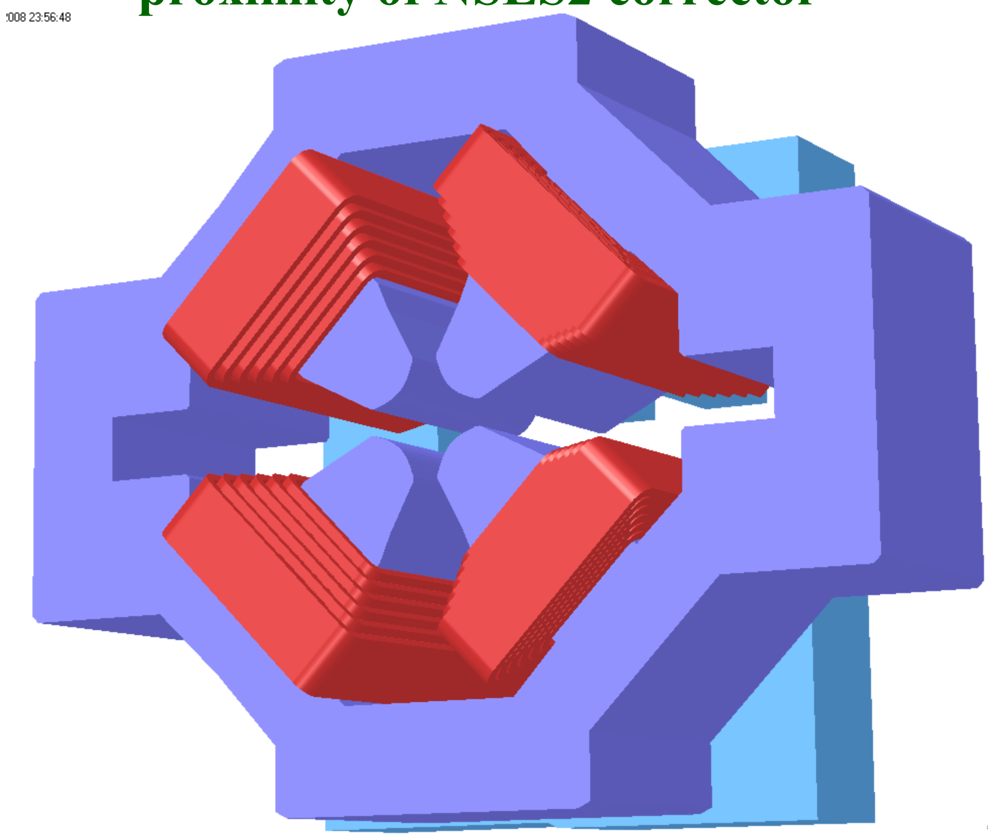
This sextupole has certain other inherent harmonics and, therefore, the angular profile is different. The model still has the same mesh as before.



The model calculations are again seems to be reliable to a few parts in 10^5.

Considerations in 3-d Modeling

Model of SLS quadrupole in the proximity of NSLS2 corrector

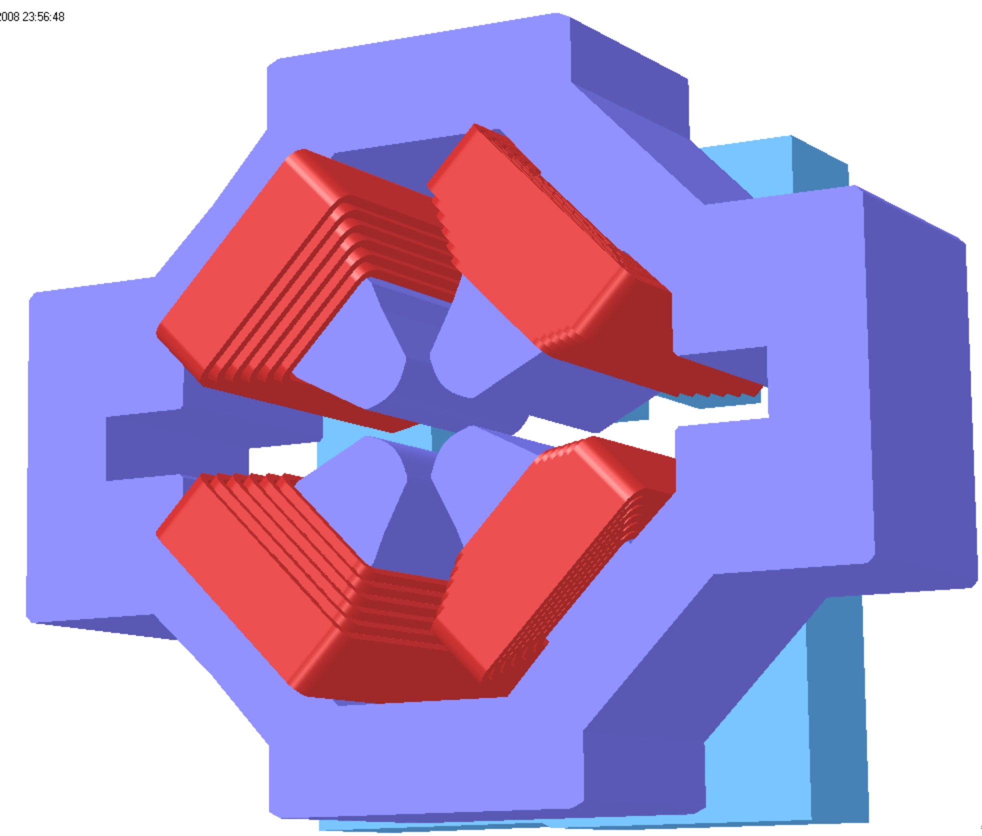


Measurements to be performed soon

- In 3-d, we can not afford the mesh density and the kind of mesh of 2-d.
- Because even if we had only 100 mesh points in 3rd dimension, the total number of mesh points will increase by 10^2, and the computational time will increase by the order of 10^4.
- We obviously need to be much more considerate in making 3-d models.
- We also need to be more vigilant about the reliability of the computed field harmonics.
- Modern 3-d modeling software are very powerful and easy to use. We want the results to be just as good. There are certain other additional issues in 3-d modeling software.

Comparison between Measurements and Calculations

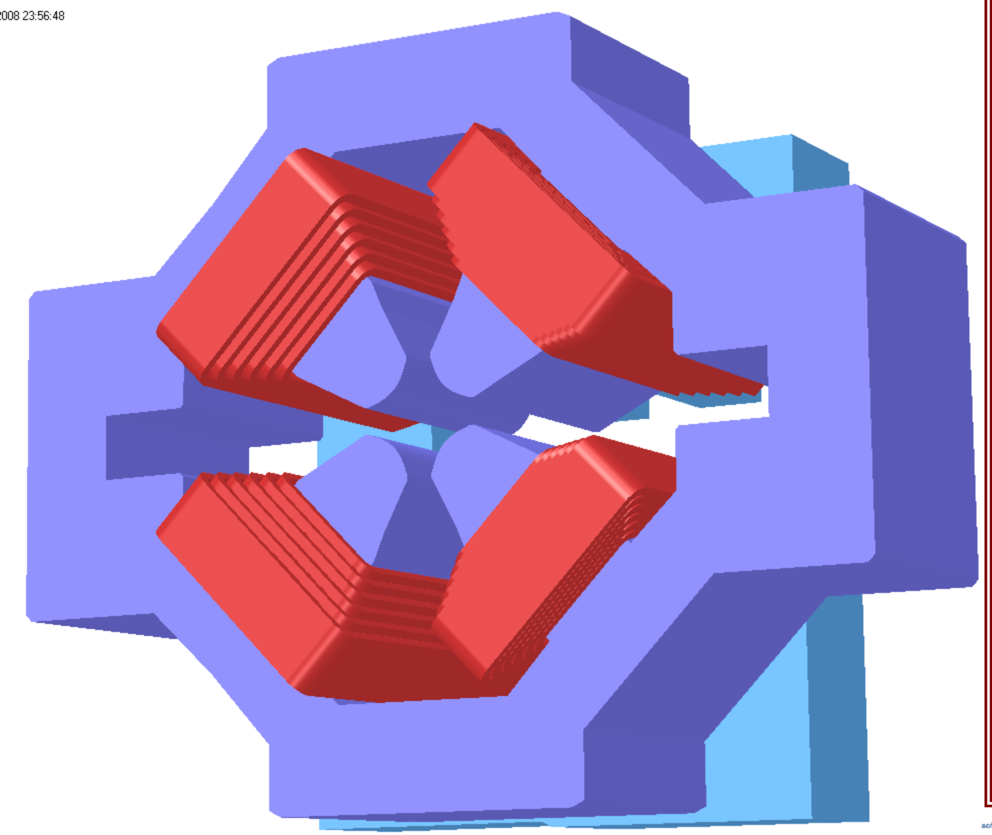
Model of SLS quadrupole in the proximity of NSLS2 corrector



- We have measured the field harmonics of individual magnets - 156 mm NSLS2 corrector and SLS quadrupole (See Animesh Jain's presentation).
- We plan to place these two magnets close to each other. We will then measure harmonics in quadrupole (powered) with the distance beween the corrector (not powered) varied from minimum to sufficient distance away.
- We will compare the difference between the measurements and the calculations for the change in quadrupole harmonics due to presence of corrector. These are interference harmonics.

Strategies in 3-d Modeling (1)

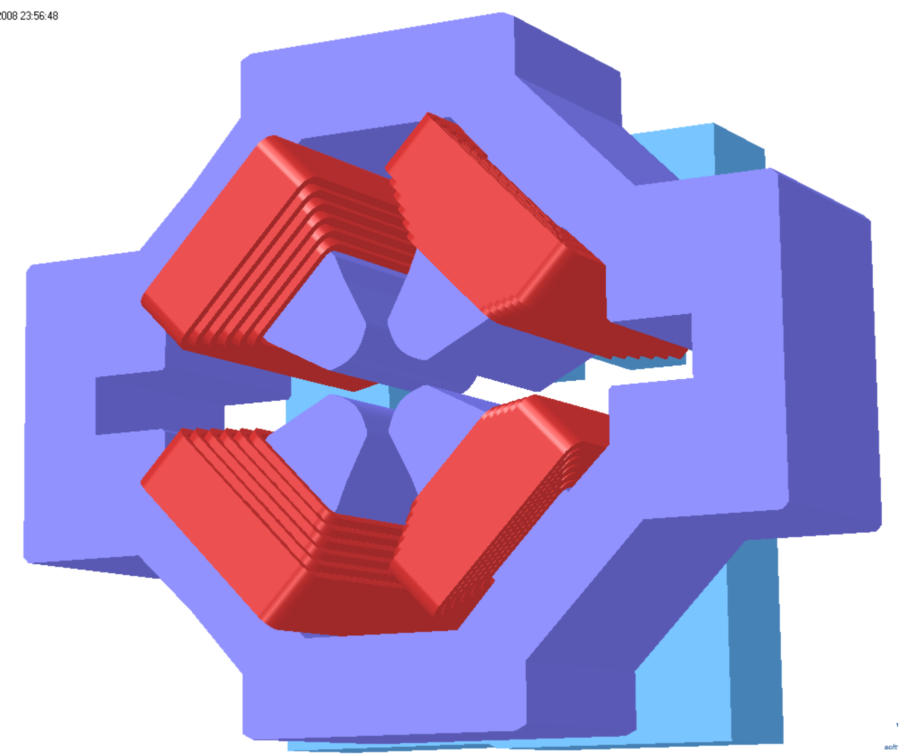
The following is a moderately complex model to make but very demanding in terms of accuracy of calculations.



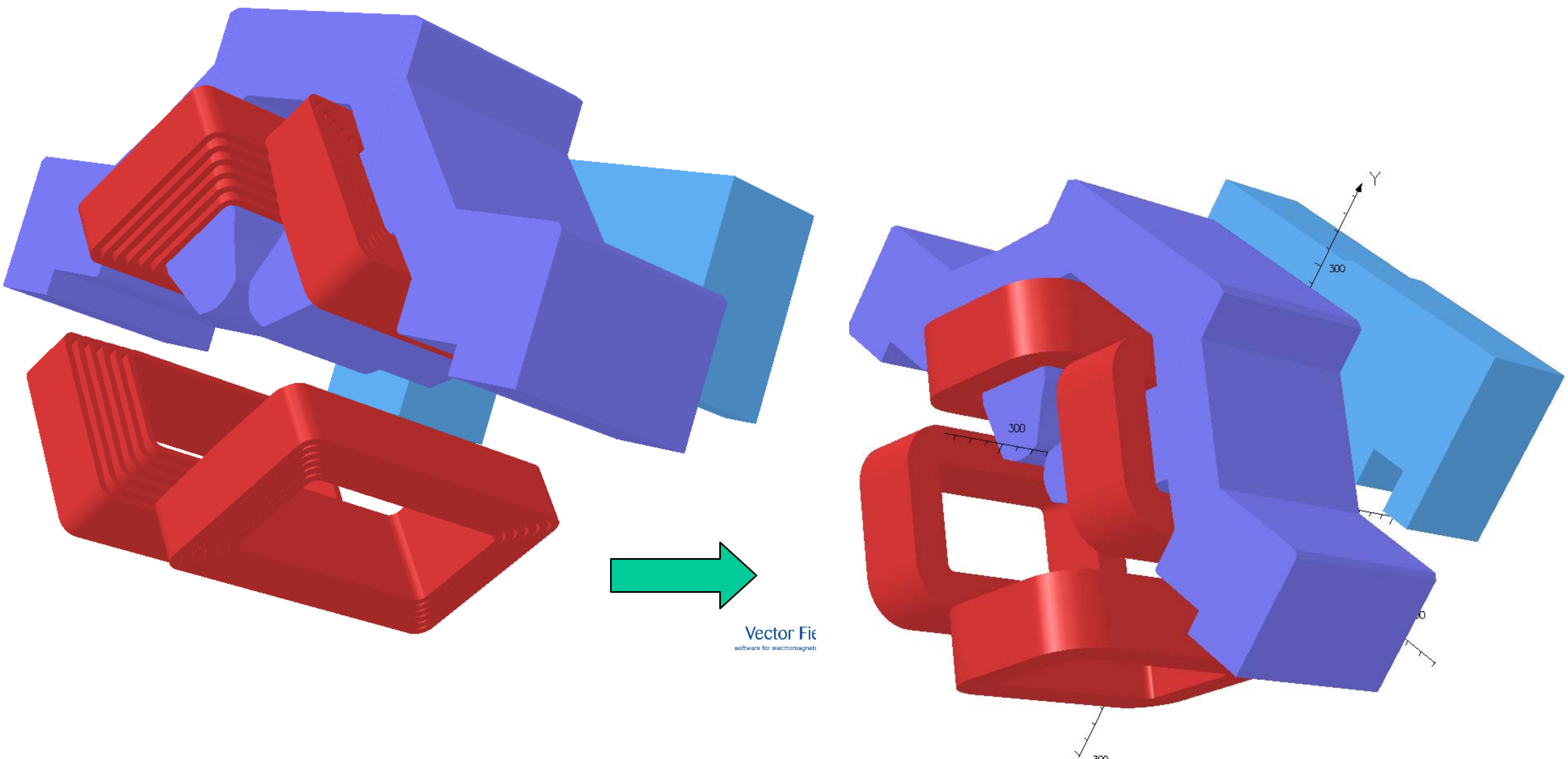
- We have to do a sufficiently large number of calculations – vary current in quadrupole and vary the distance between the magnets.
- Ideally we want accuracy to be high and computation time to be low. But let us make reasonable compromises - say four cases per day so that we have the complete set of calculations in ~a week.
- One should also allow another week for making models and making sure that the models are reliable.

Strategies in 3-d Modeling (2)

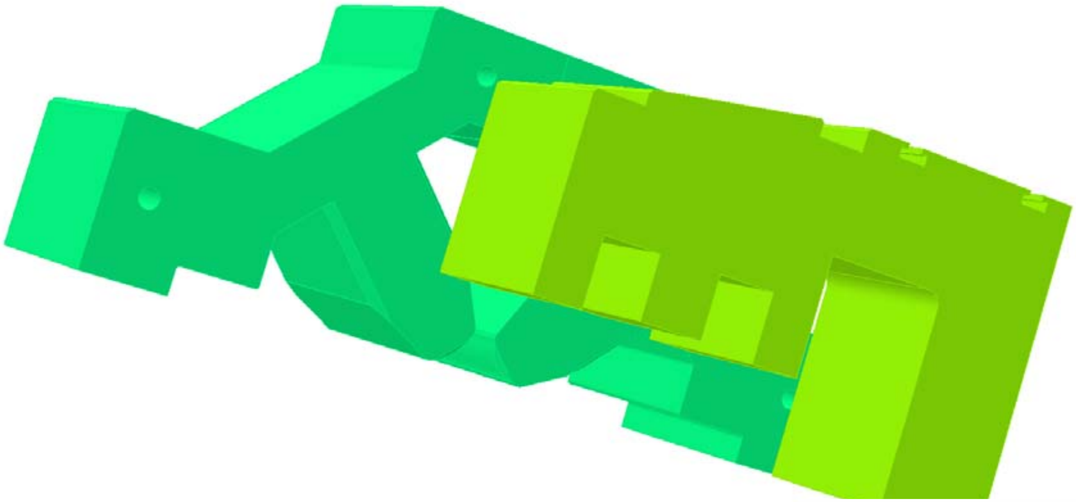
Note: We are looking for potentially small change in harmonics. Computational errors must be small.

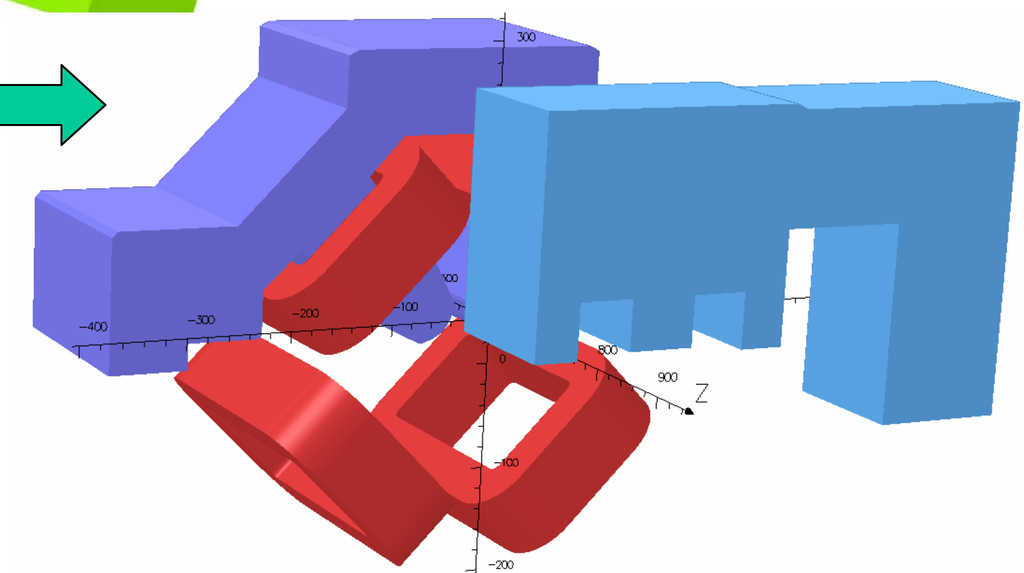


- **To minimize the errors in calculations, we will keep the mesh same whether the corrector is present or not. We will just change the material type.**
- **Thus for every distance we would have two models. In first case, the material of corrector magnet will be iron and in the second case air (which means no corrector).**
- **Then we take the difference between the two runs to determine the change in harmonics due to the proximity of corrector.**
- **This approach cancels out a number of errors, making results much more reliable.**
- **We also pay more attention to the model - simpler coils to reduce computer time, and quadratic mesh to increase accuracy.**
- **Similarly, we make mesh more dense in the area of interest and sparse in the rest.**



Simplifying the coil does not decrease the accuracy of the calculations of the interference harmonic but significantly reduces the computational time.

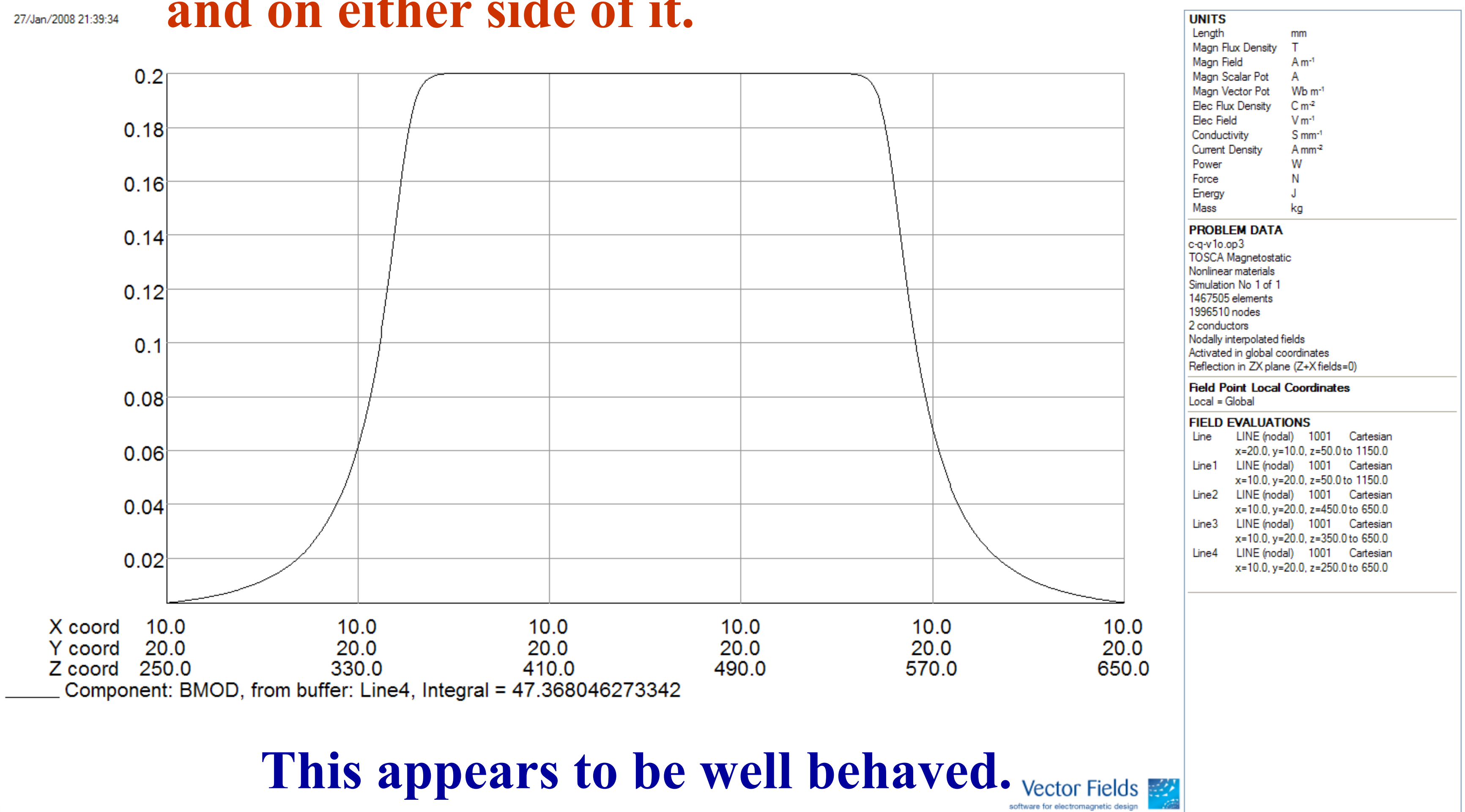




Simplifying certain details of iron structure does not decrease the accuracy of the calculations of the interference harmonic but significantly reduces the computational time.

Error in Field Calculations
Magnitude of Field Parallel to z-axis

The field is computed inside the quadrupole and on either side of it.



This appears to be well behaved.
Let's zoom on it.

Error in Field Calculations
Magnitude of Field Parallel to z-axis

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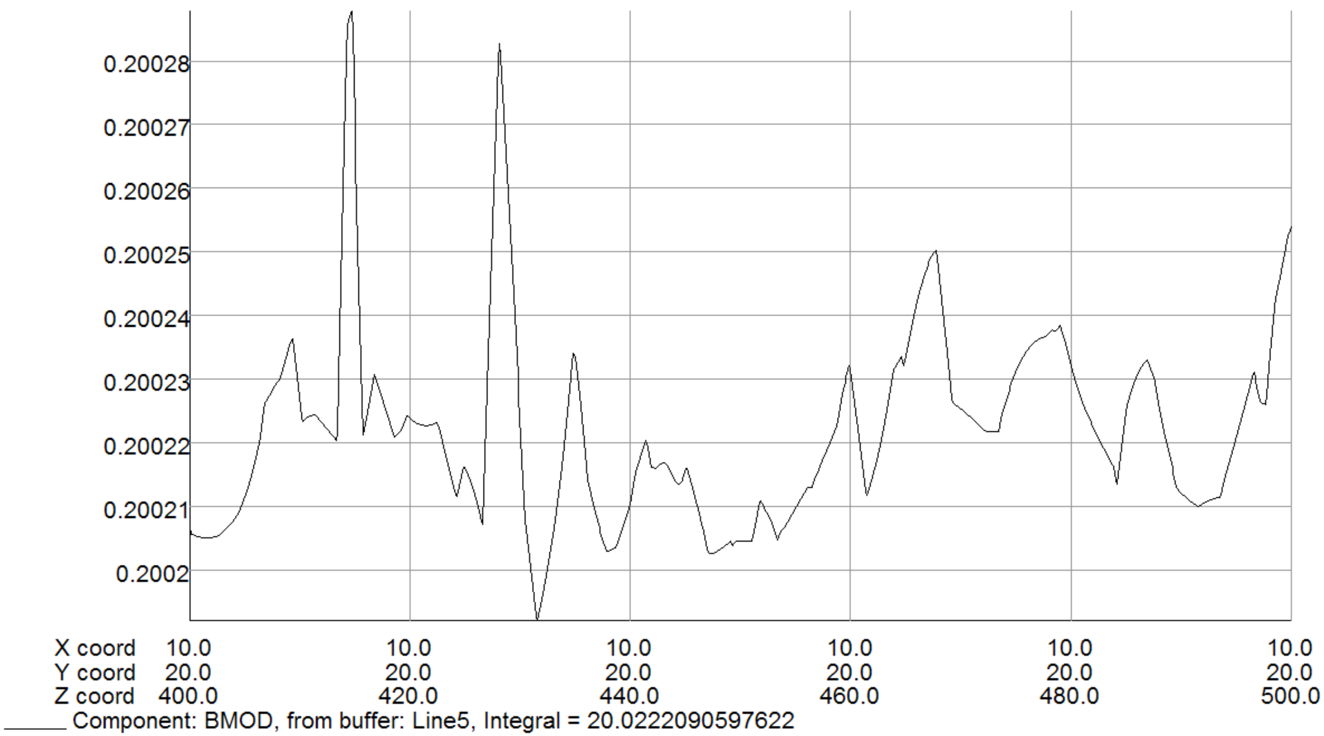
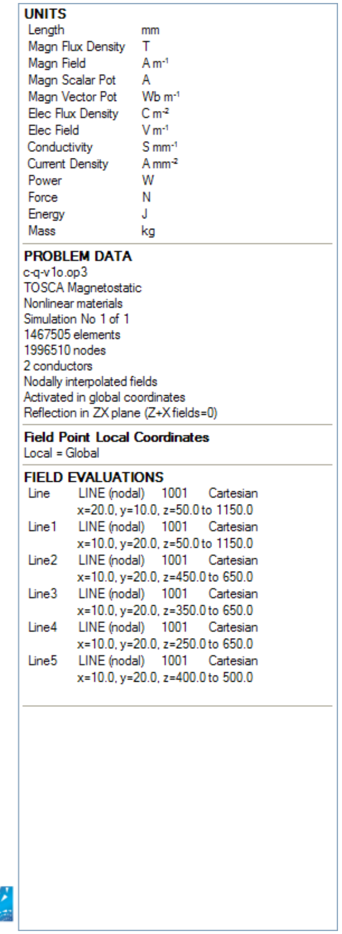
This is well inside the quadrupole.

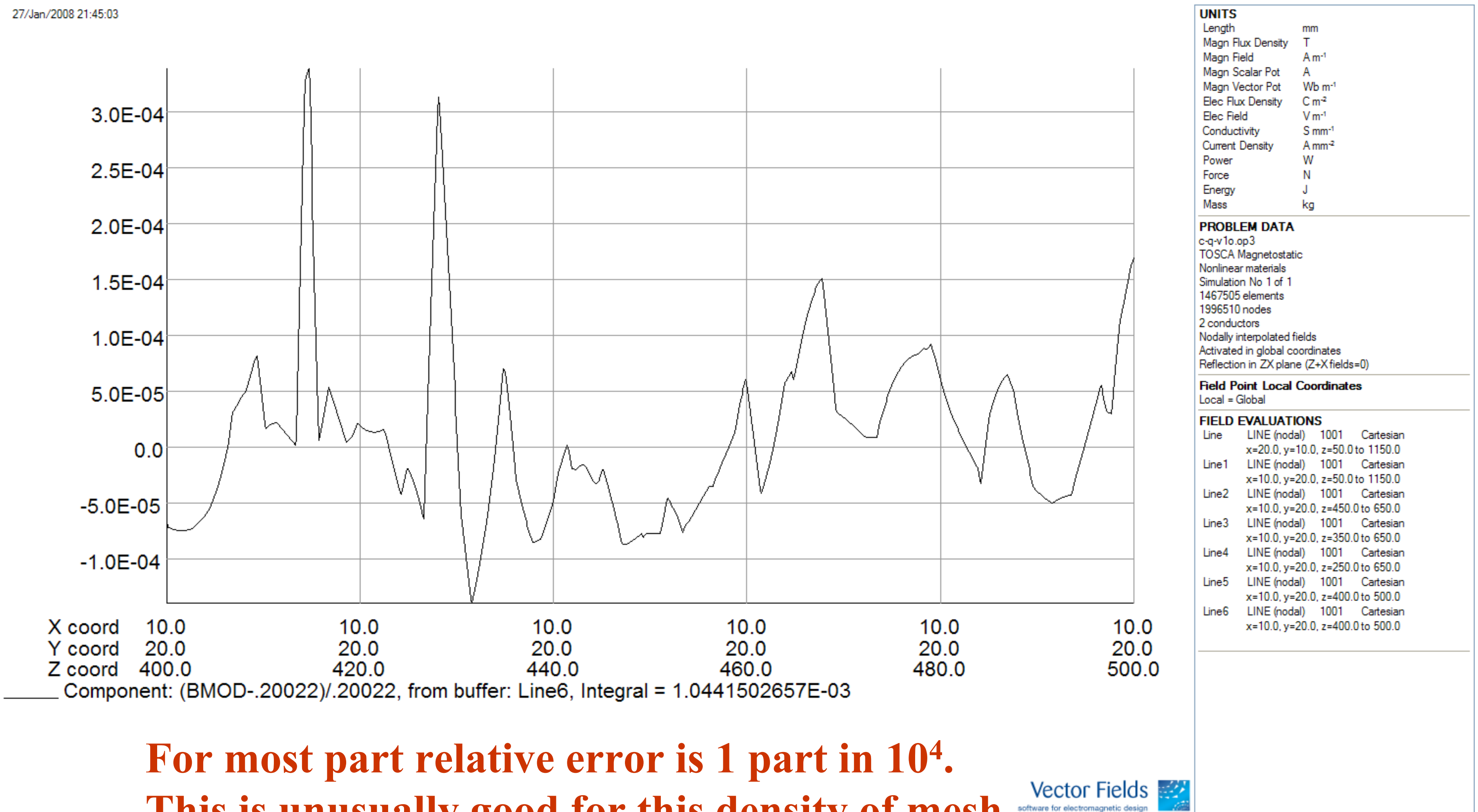




This field is very uniform for a 3-d model.

Vector Fields
software for electromagnetic design

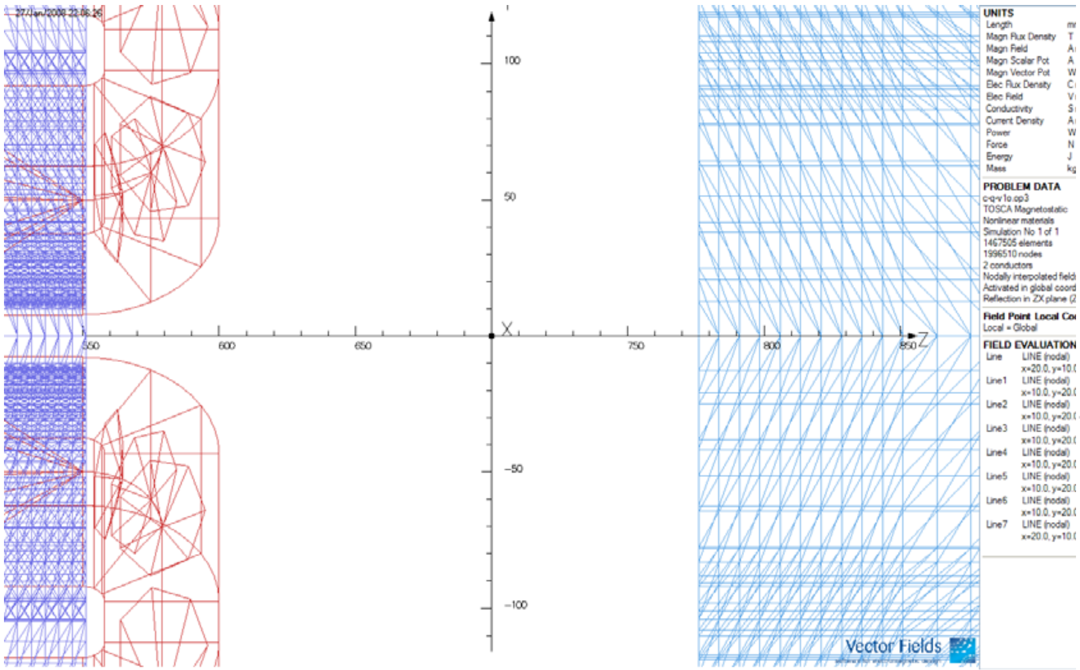
Relative Error in Field Calculations
Magnitude of Field Parallel to z-axis

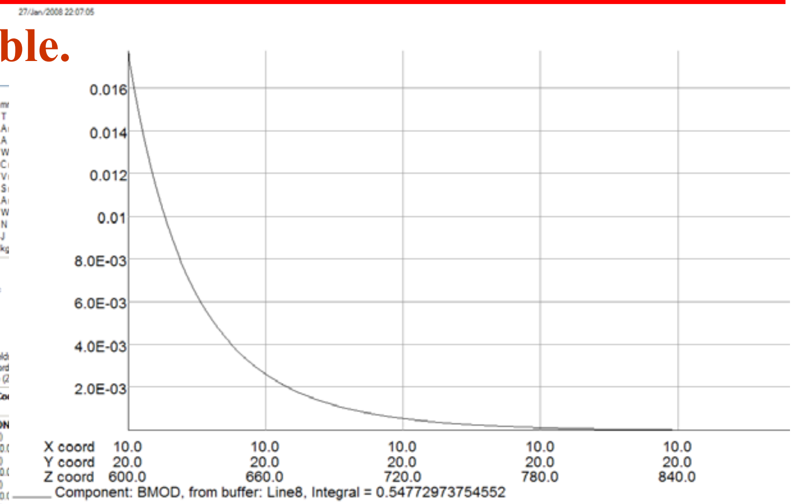


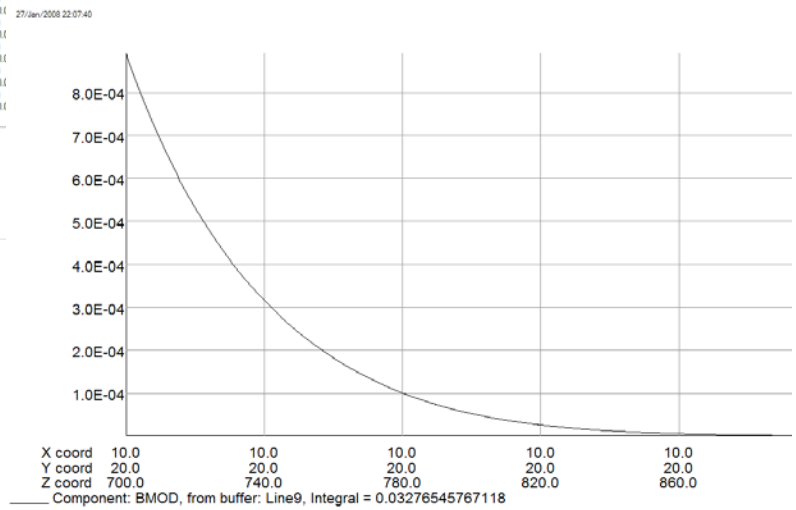
For most part relative error is 1 part in 10^4.
This is unusually good for this density of mesh.
We are perhaps hitting a nodal position at (10,20).
Other places the error is more.

Field Outside the Quad (thru corrector)

Field is falling smoothly; calculations should be reliable.







Difference calculations between harmonics with corrector (material iron) and without corrector (material air) should give good results for change in harmonics due to proximity of corrector. This removes the geometrical errors in the model.

Computed Change in Harmonics in Quadrupole Due to Corrector (iron-to-iron separation = 150 mm)

Change in harmonics at 25 mm
iron-to-iron separation = 150 mm

bn	~52 A	~104 A	~156 A
1	-0.03	-0.23	-1.60
3	0.03	-0.03	-0.03
4	-0.16	-0.18	-0.18
5	0.00	0.03	0.03
6	0.02	0.09	0.09
7	0.00	0.08	0.08
8	0.00	0.09	0.09
9	0.00	0.06	0.06

These interference harmonics are small. This is a good news. Larger number would have indicated noise.
Smaller values were expected as this is a larger aperture (156 mm) corrector.

- **150 mm appears to be minimum practical iron-to-iron separation.**
- **Calculations have been performed from 100 mm to 300 mm.**

Calculations seem to be OK when comparing with measurements for iron saturation. Computed change in b6 between ~52 A and ~104 A is -1.3 unit. Measured was ~ -1 unit.

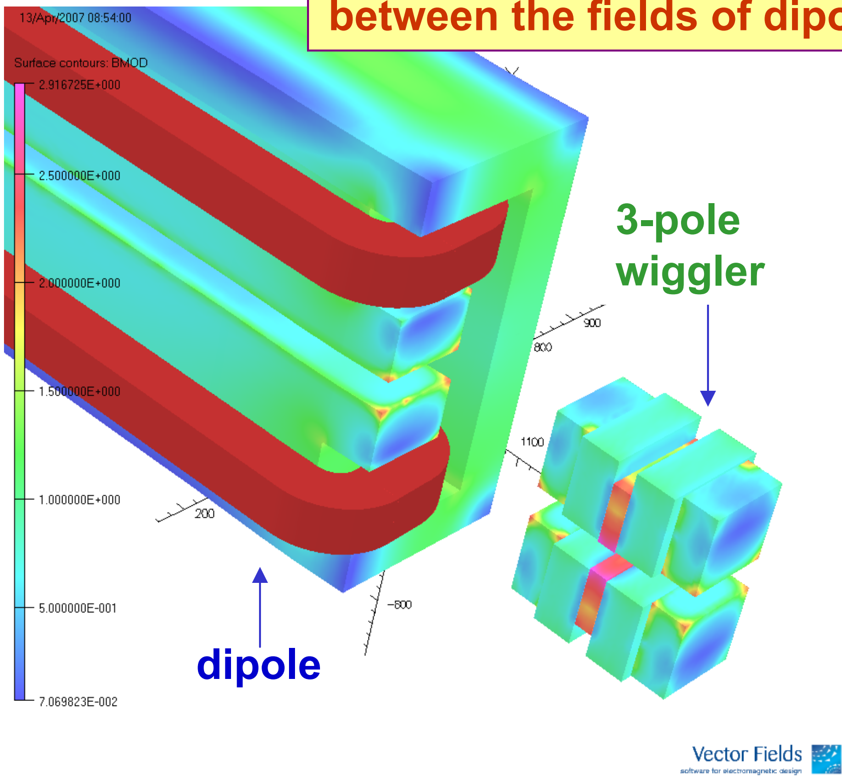
This is good for 3-d calculations given the approximation in iron geometry and use of generic BH table in the model.

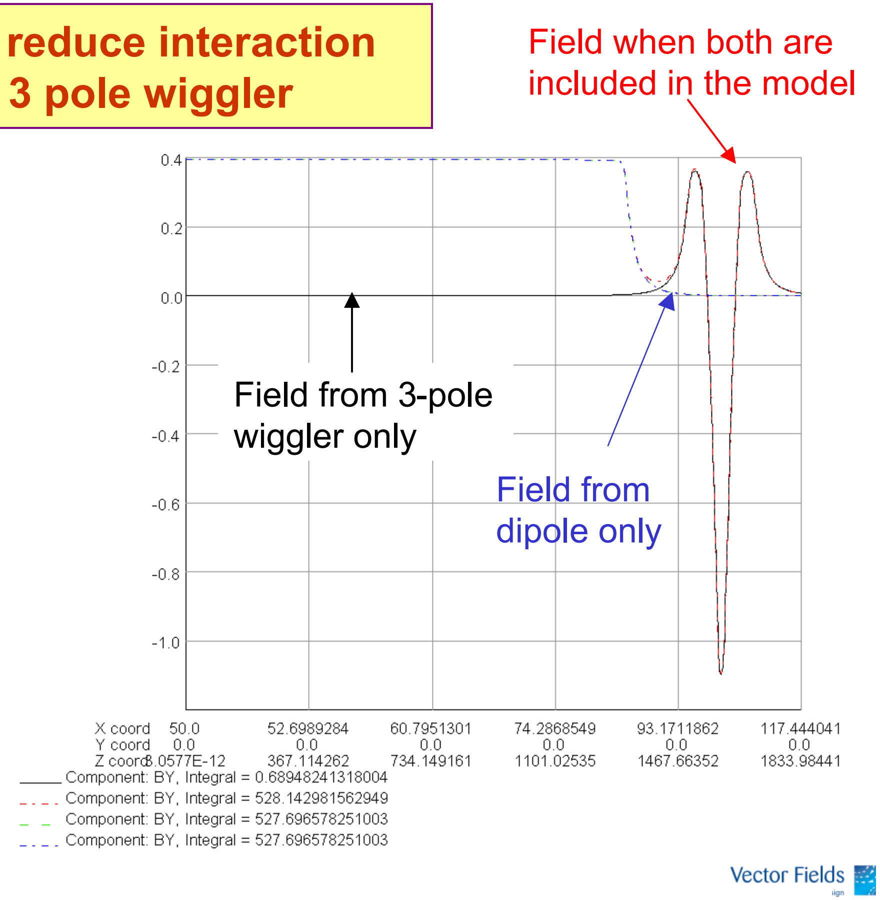
Computed b6 saturation between 52 A and 156 is -3.4 unit.

Computed b10 saturation: -0.12 and -0.34.

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

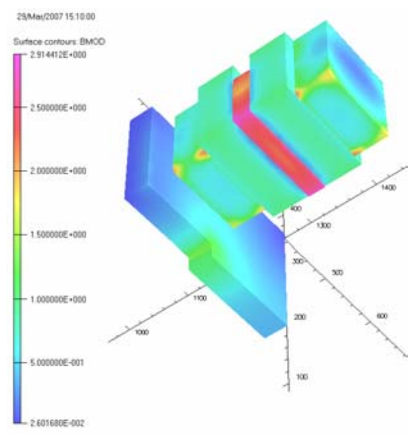




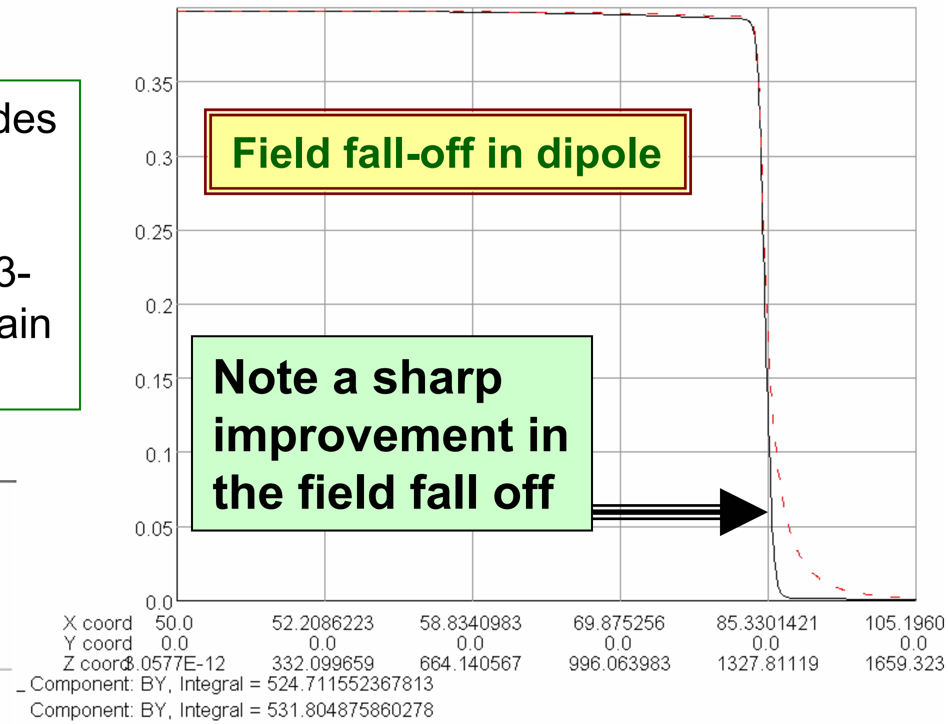
There is virtually no interference (< few parts in 1,000) between the fields of three pole wiggler and dipole as the model calculations of the two magnets give essentially the same results as the sum of the field of two individual magnets.

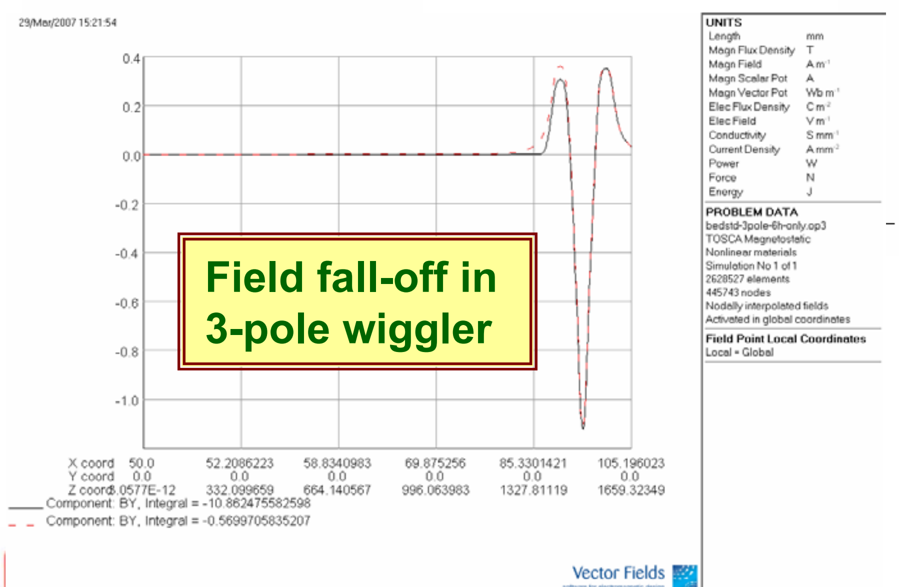
Incorporation of Magnetic Shield Between Dipole and 3 Pole Wiggler ?

- The goal was to reduce the interference 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.

Strategy for Achieving the Required Performance

It is useful to plan such strategies before the production starts. Then things just move a bit more smoothly during production with a better chance of success.

- **First of all, carefully optimize 2-d designs for low field harmonics**
- **Make 3-d models to calculate end harmonics**
- **Measure 2-d and 3-d (integral) harmonics for the baseline design in magnet#1**

- **Compute the size/profile of the chamfer to reduce these measured harmonics**
- **Do magnetic measurements to see how close we are to the required values**
- **Do iterations, as necessary, till the desired performance is obtained**
- **One may use above chamfer in the following magnets from the beginning**

- **Give information about this chamfer to magnet manufacturers. They can this as is. If not they must prove the new chamfer (do field measurements)**
- **Do iterations in chamfer after measurements, if necessary**

SUMMARY

- With careful modeling we should be able to compute 2-d and 3-d harmonics to the level required for NSLS2 project.

- With the design and magnet development strategy outlined, we should be able to meet the design requirements of NSLS2 (some are still going through minor iterations).