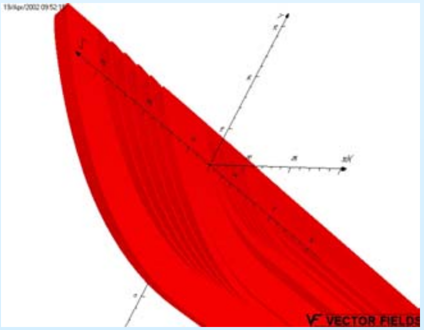
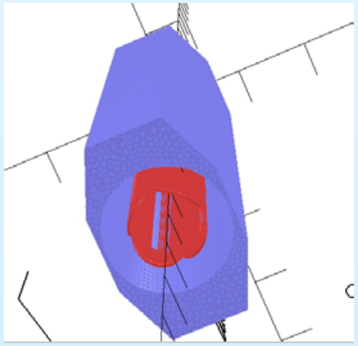
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Progress Report on Magnetic and Mechanical Design of Coil Ends



Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory
Upton, NY 11973 USA



With contributions from Dr. Gerry Morgan (consultant)

Goals of End Design

Magnetic Design

- Optimize for low integrated harmonics
- Guide design towards lower peak field without large increase in length
- Compute cross talk and fringe fields

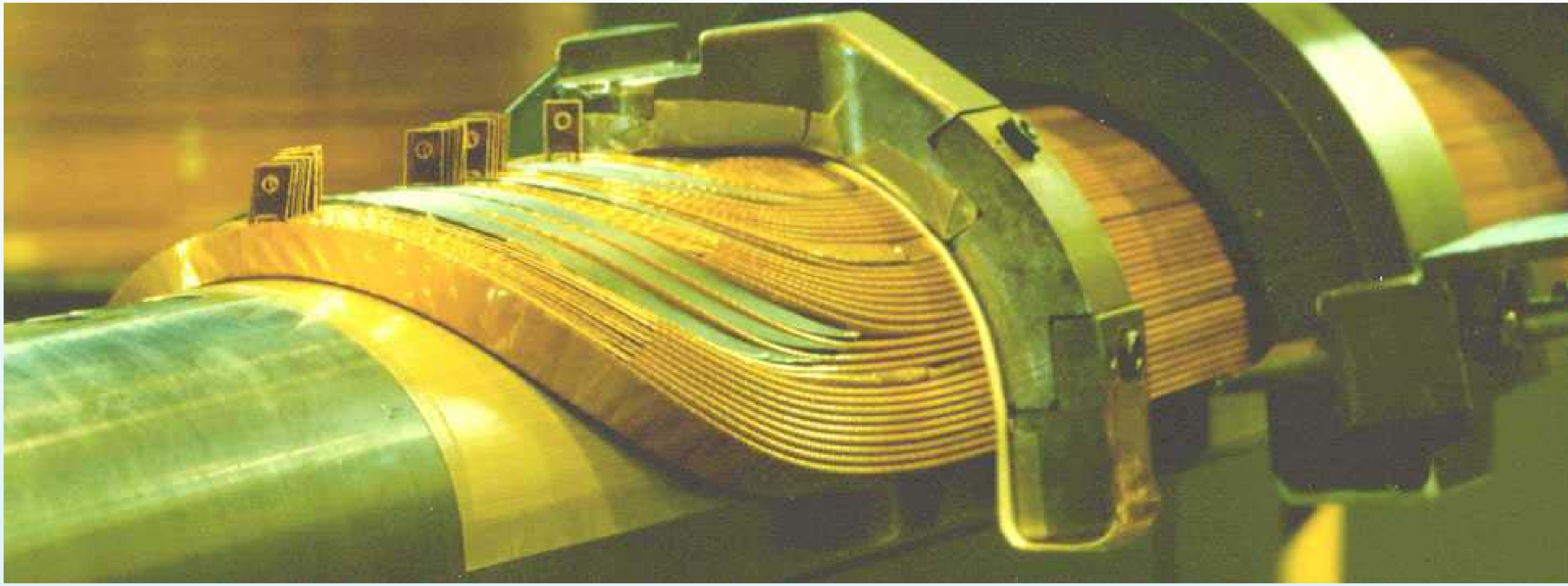
Mechanical Layout

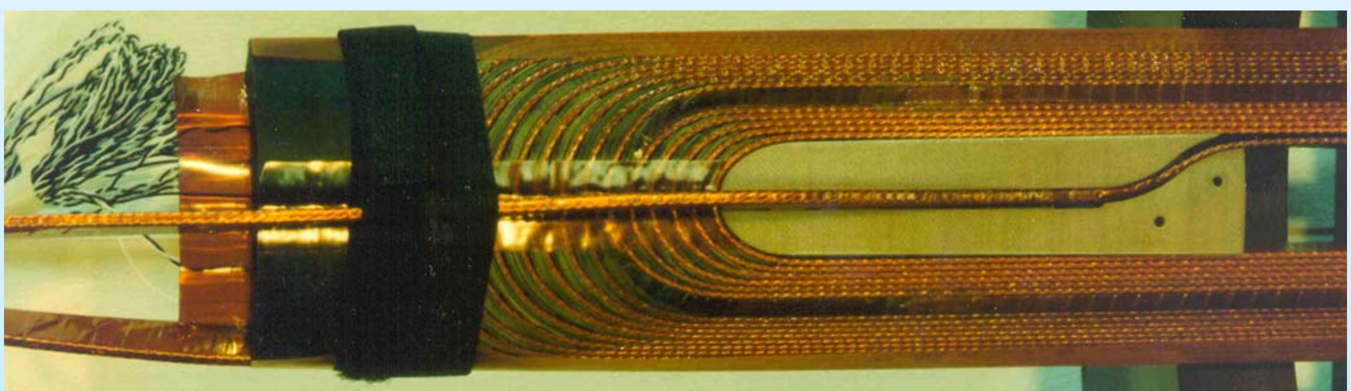
- Minimize strain and tilt of the cable in the end. Minimize large changes
- Cable and entire ends should be well supported (constrained)

In low field magnets, magnetic design drives the end design, whereas, in high field (high force) magnets, the mechanical design must!

These guiding principle are common to our all high force magnet designs (including 12 T common coil dipole design).

Ends of Cosine Theta Cable Magnets





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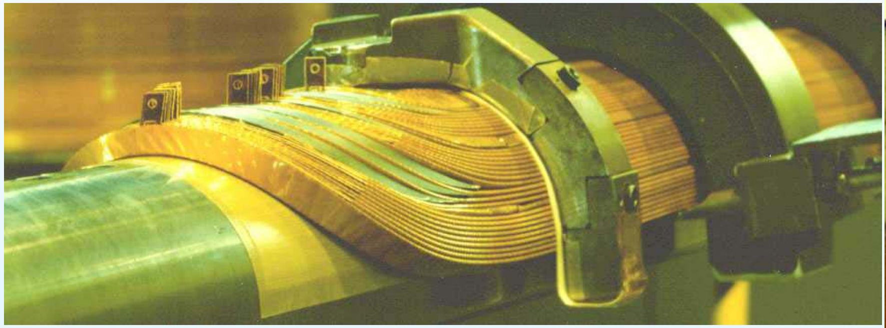
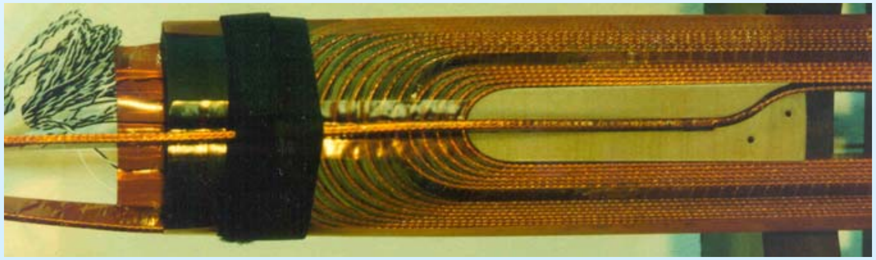
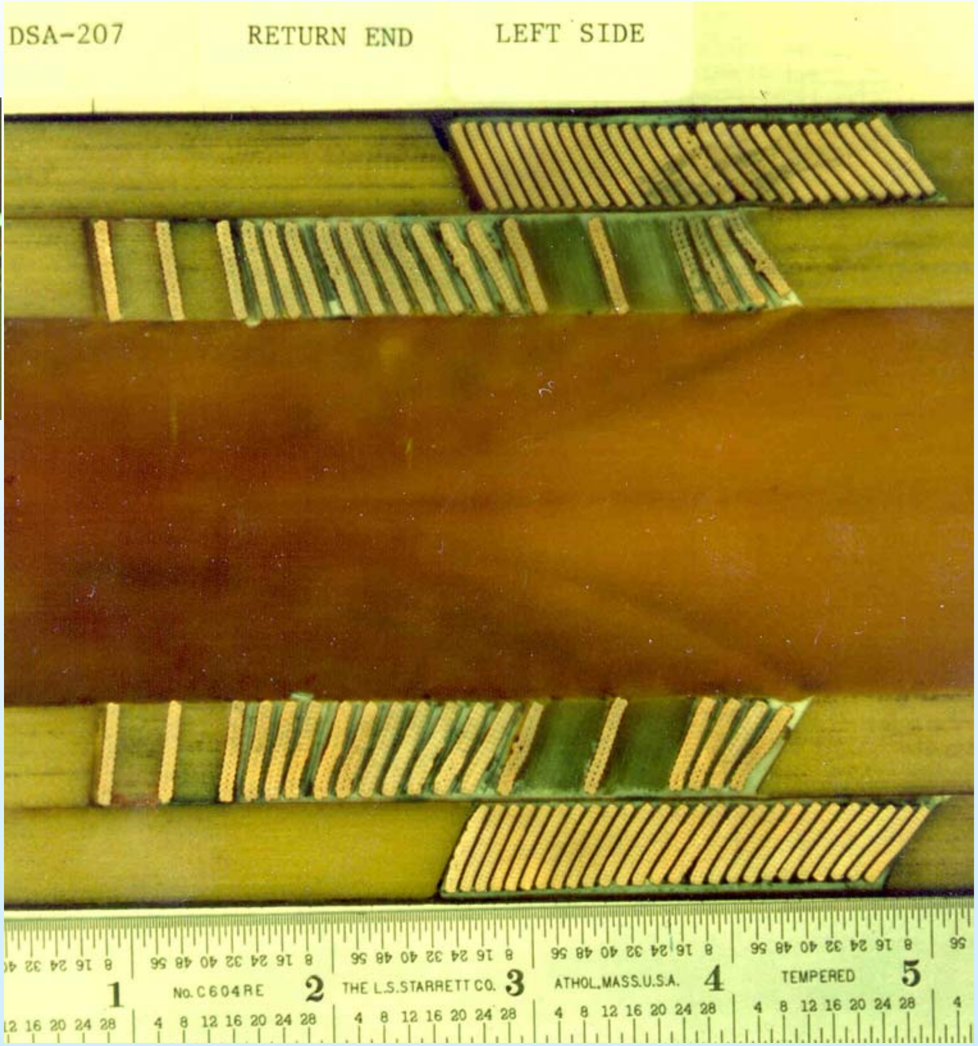
Ends of Cosine Theta Cable Magnets







End Design Optimization: Design A

Design A

• The design is well optimized magnetically

Produces low integral field harmonics.

• Mechanical turn layout is developed based on prior experience

•Large radius means lower tilt and lower strain on cable in ends

Large bend radius, however, also means dealing with large forces.

The magnetic design optimization process will be discussed in detail for this design.

End Design Optimization: Design B

Design B

Design philosophy: Let mechanical design drive the ends

Start with a good mechanical lay out of each turn and relationship between the subsequent two

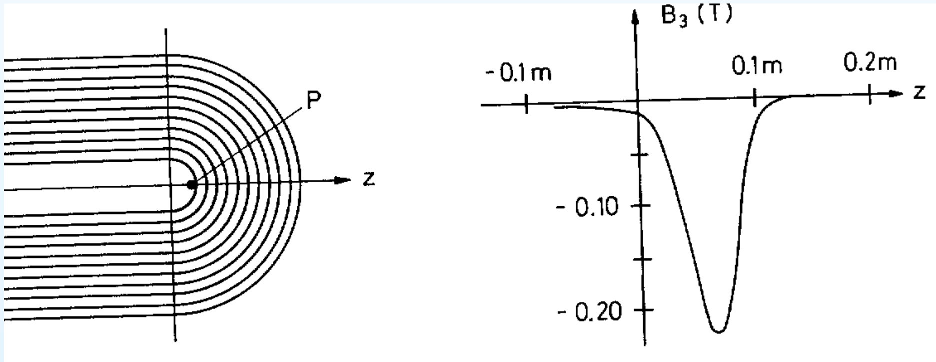
Adjust end spacers to minimize integrated harmonics and peak fields.

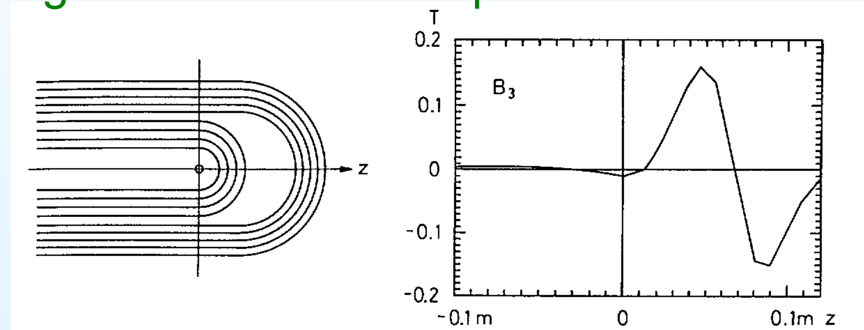
This is a magnet where end forces are large!

The ends would play a major role on quench performance of the magnet.

End Harmonic Optimization (conceptual)

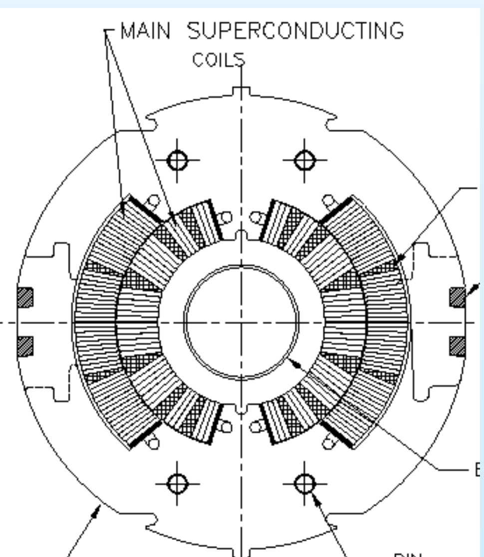
Ends without spacer	Ends with spacer
(large harmonics and peak field)	(integrated harmonics & peak field reduced)





a) Schematic view of HERA coil head with spacers

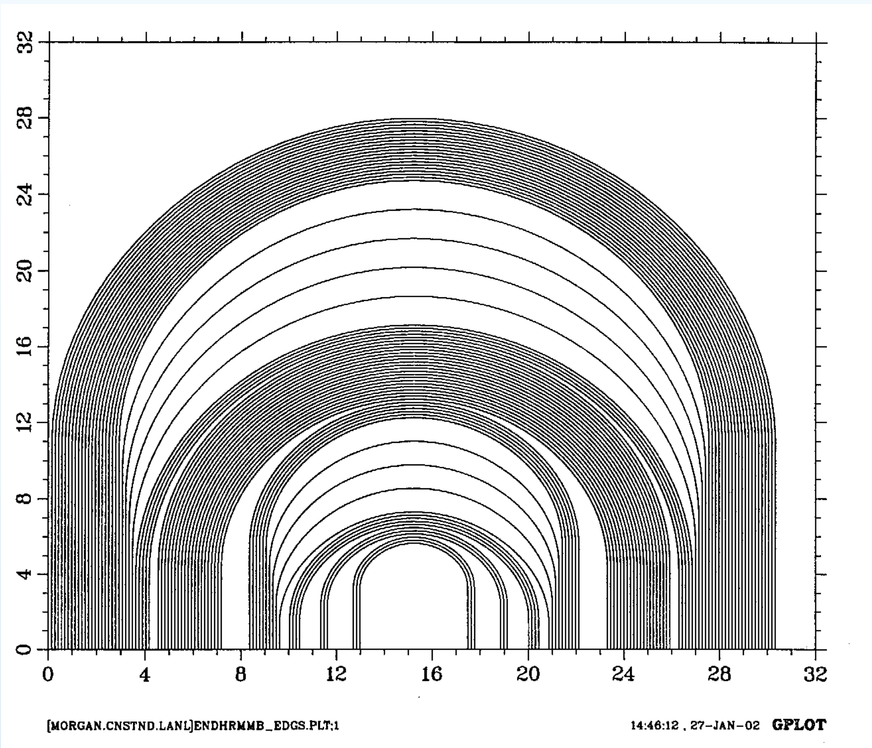
b) Computed sextupole field of HERA dipole



- End spacers increase the straight section length of some turns (turns at midplane go further out)
- Now consider the integral field generated by each turn. The harmonic component generated by a turn will depend on the angular location of it. The integral strength will depend on the length.
- A proper choice of end spacer can make integral end-harmonics small. However, note that the local values are large.
- Spacer also reduce the maximum value of field on the conductor (peak field) in the end.

Layout of Turns in Return End

Design A (Gerry Morgan)



P. Walstrom concept (LANL)

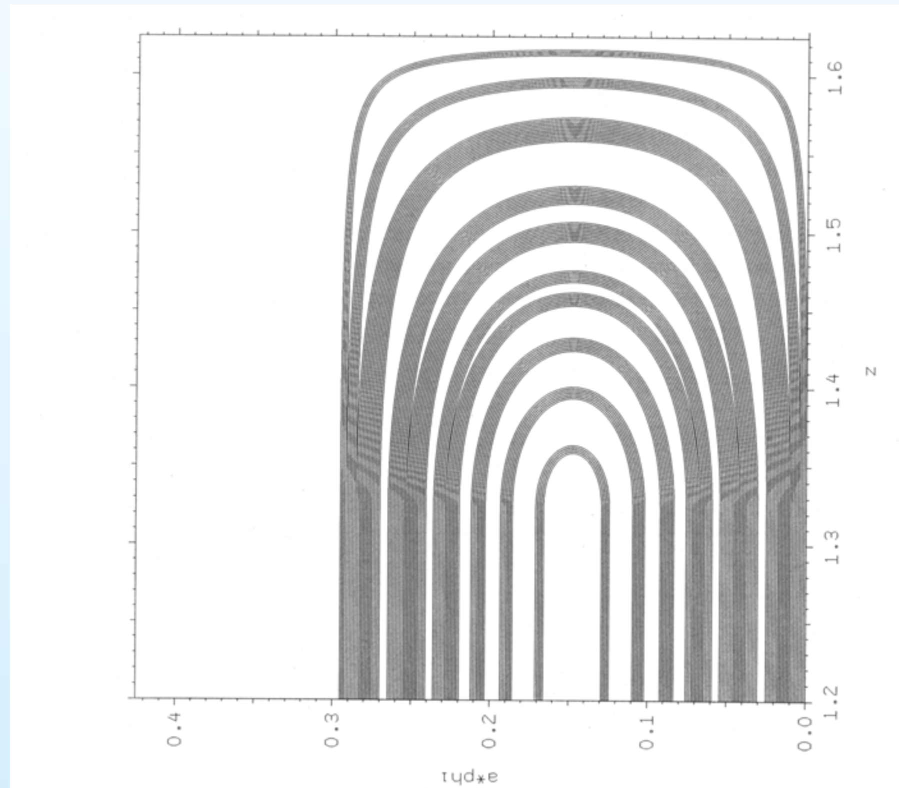


Fig. 4. End-turn layout on the developed winding cylinder with the shape function of Fig. 1, the 2-D design of Table II, and the block group definition of Table II, showing individual turns.

Design B will use best of all features in keeping with a good mechanical layout

End Optimization: Design A (details)

Modified constant perimeter end: Find a good combination of tilt and strain

The following codes are used for end optimization:

CNSTND15: Used for first turn. Starting ellipses. Designs end post.

CNSTND22MB: Designs relative mechanical layout of all turns.

Optimize tilt and deviation from constant perimeter (parameter AKF)

SMINSQ22MB: Minimize harmonics by adding straight sections to turns

ENDHRM22MB: Generates 3-d coordinates of Return end for all turns.

Also generates end spacers and wedge tips.

LENDHRM22MB: Same as ENDHRM22MB but for lead end

Past practical experience is incorporated in how these programs optimize ends.

Block Structure

Straight section (6 blocks, 70 turns):

30 20 10 4 3 3

(counting from midplane)

3 3 4 10 20 30

(counting from pole)

End section (8 blocks, 70 turns):

10 5 8 4 13 4 6 20

(counting from pole)

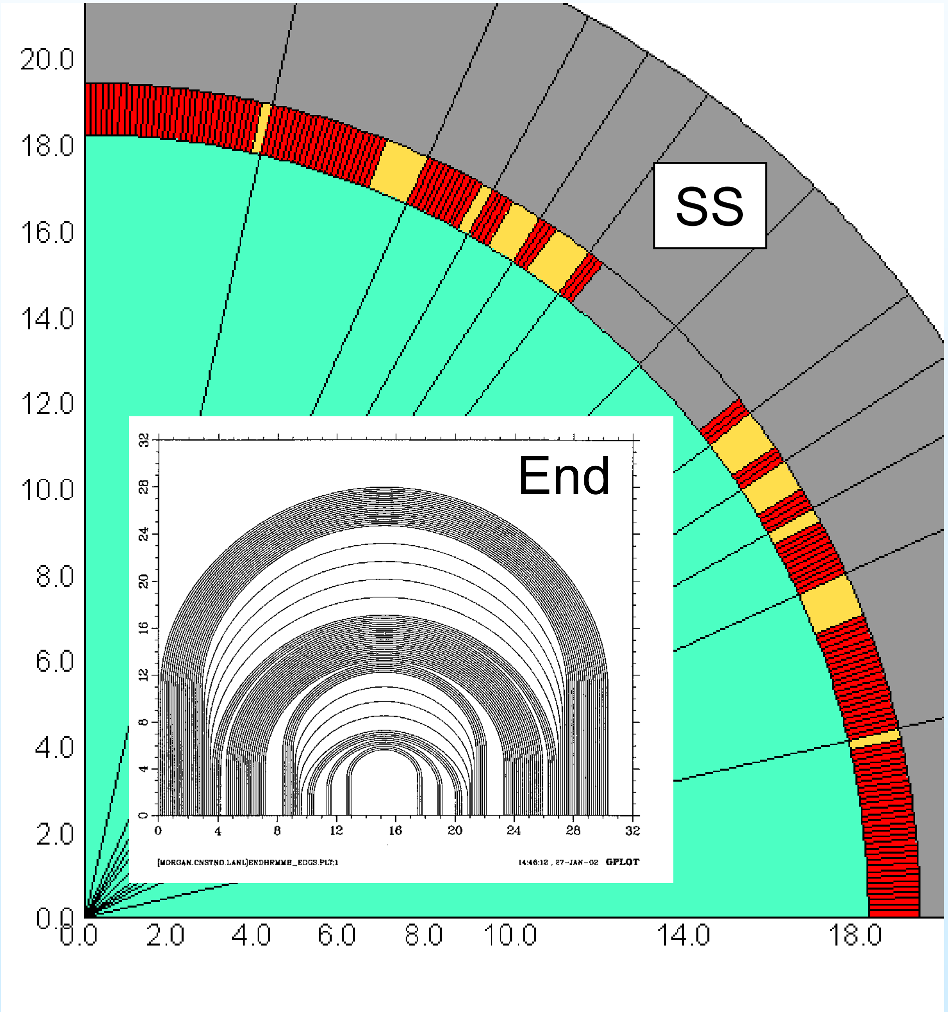
Straight section => pole

3,3,4 => 10

4,10, 20 => 5, 8, 4, 13

30 => 4, 6, 20

Must avoid large Ultum spacers (subdivide, if necessary)



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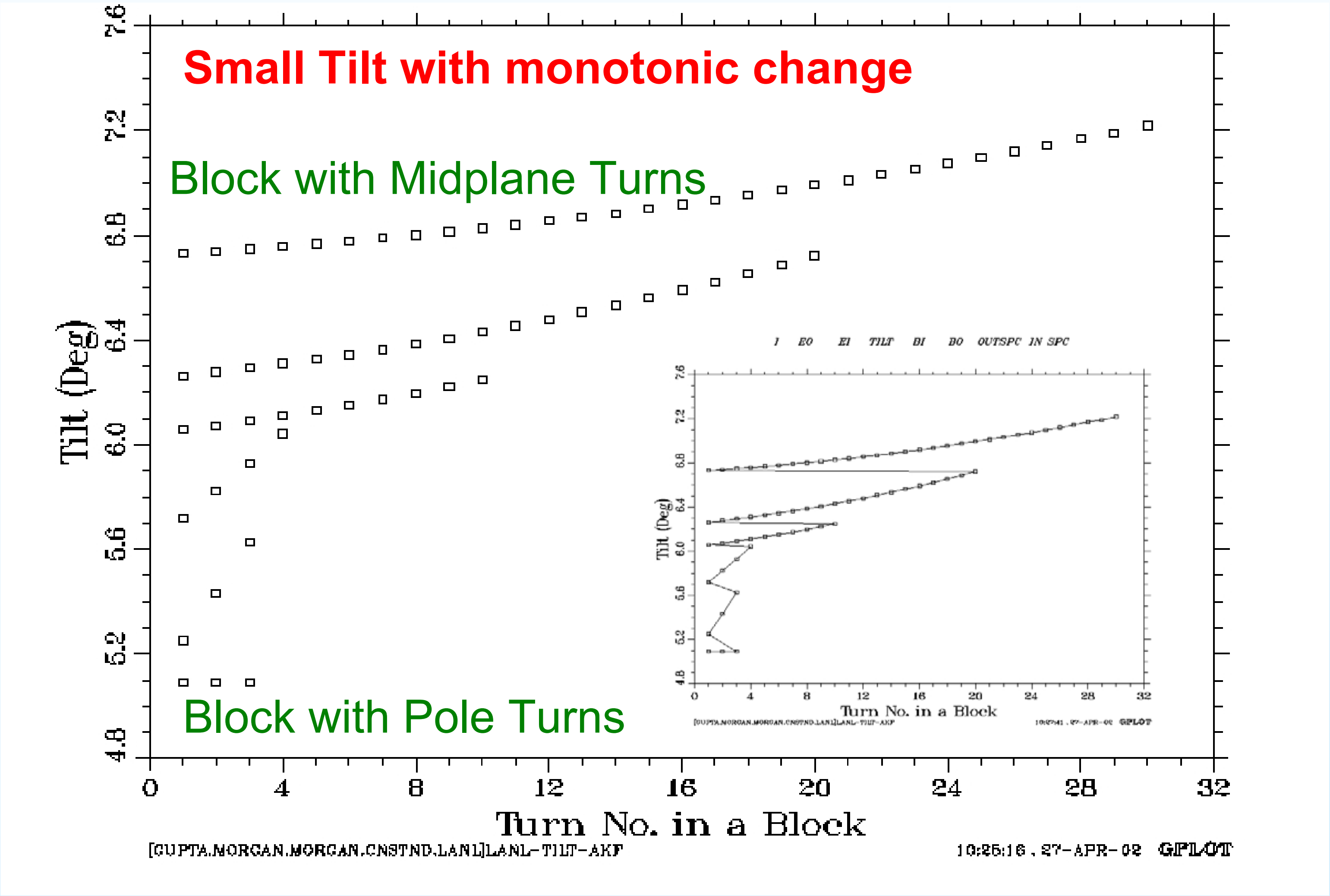
Tilt of Turns in Various End Blocks (at far out position)



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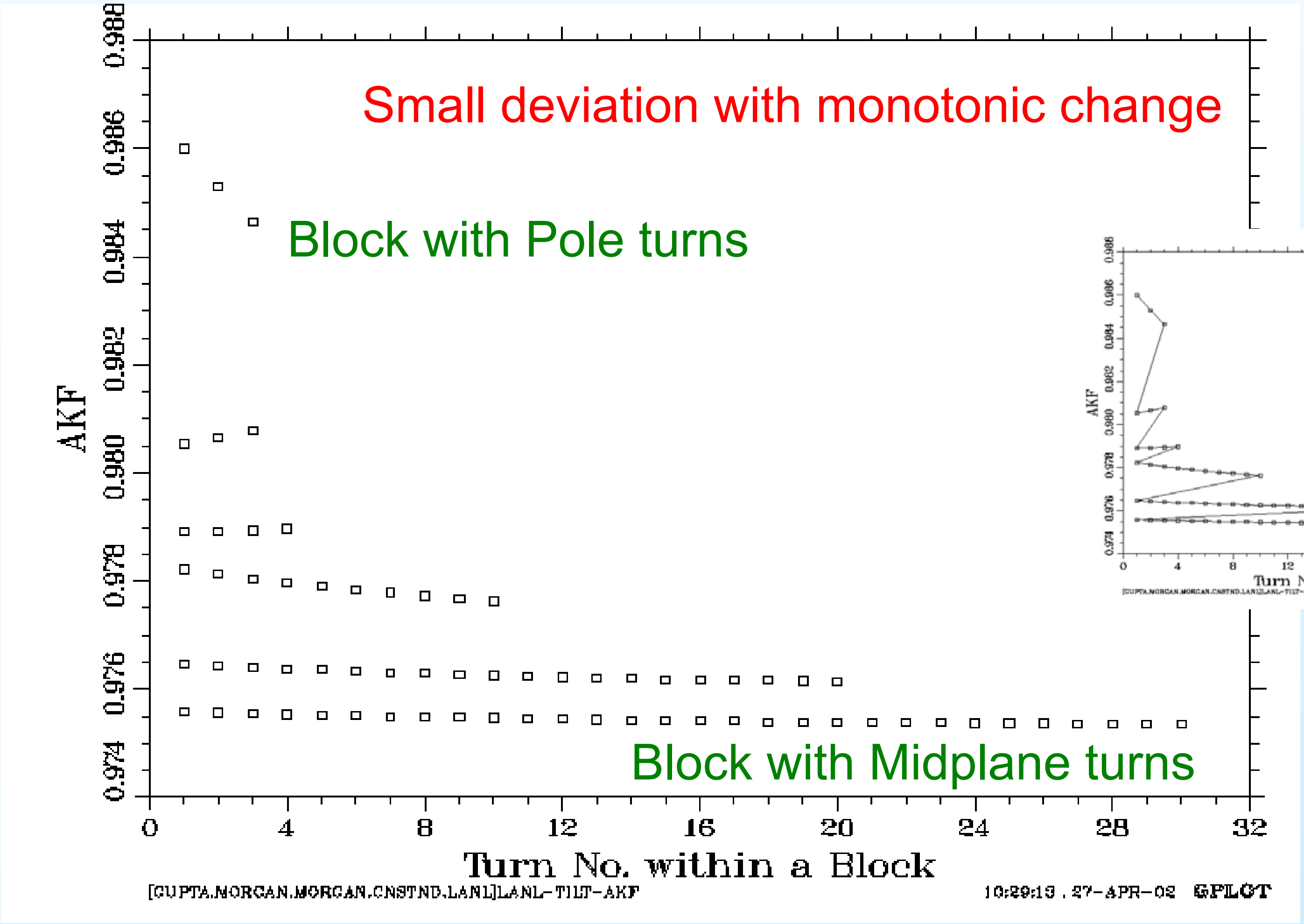
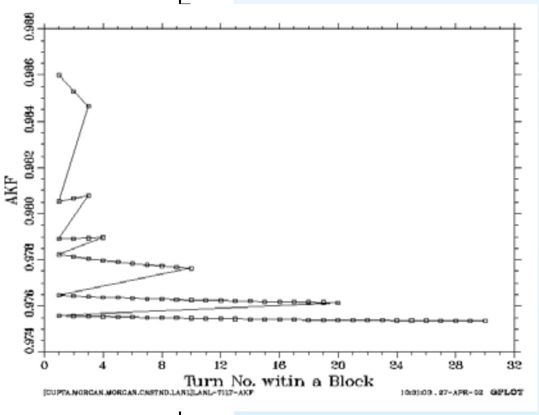
The AKF Parameter of Turns in Various End Blocks

AKF indicates the deviation from constant perimeter (hence strain on the cable)

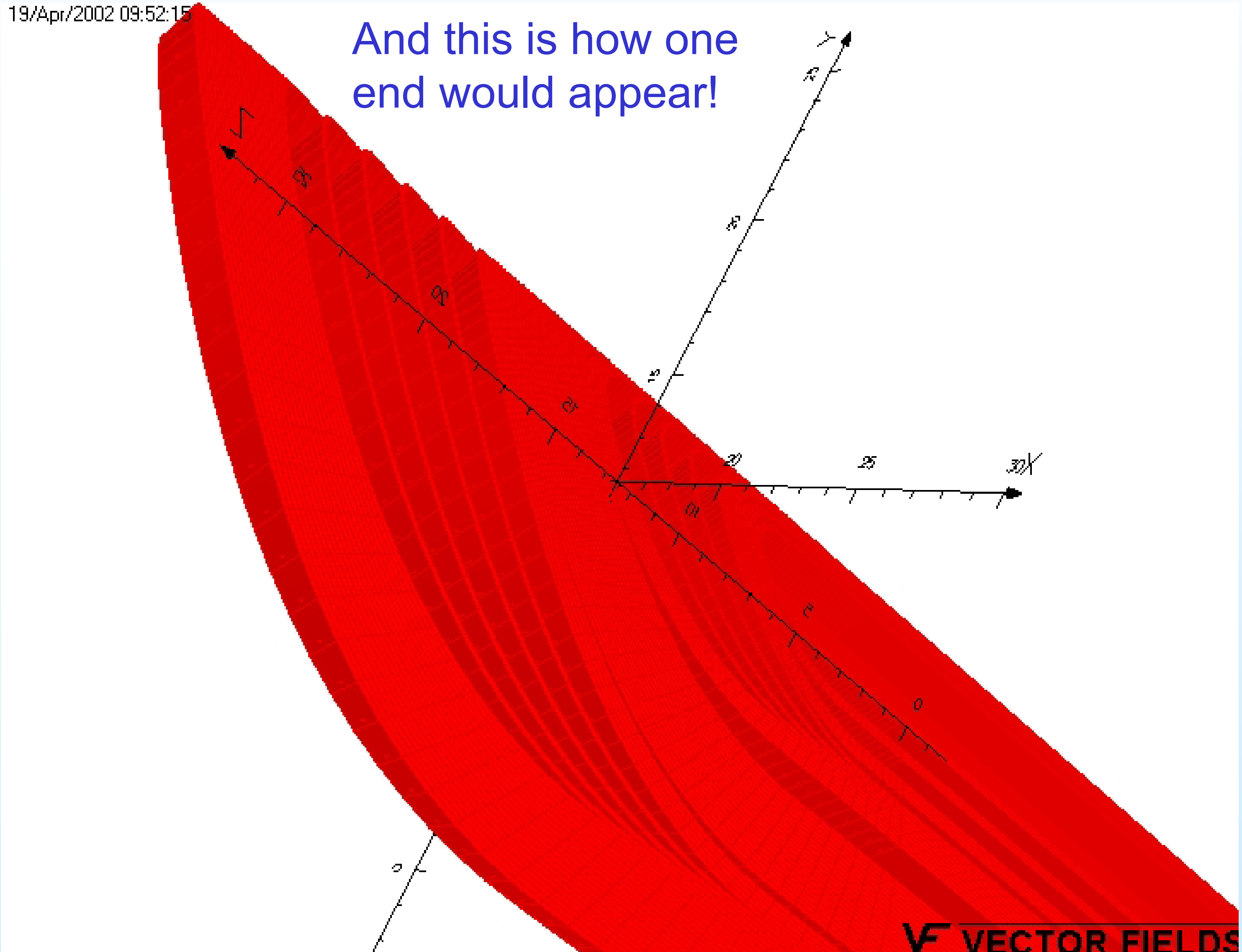
Large Deviation from 1.0 is bad





Coil Ends: Design A

And this is how one end would appear!



Programs have been written that take PARENDOPT output and generate input for OPERA3d

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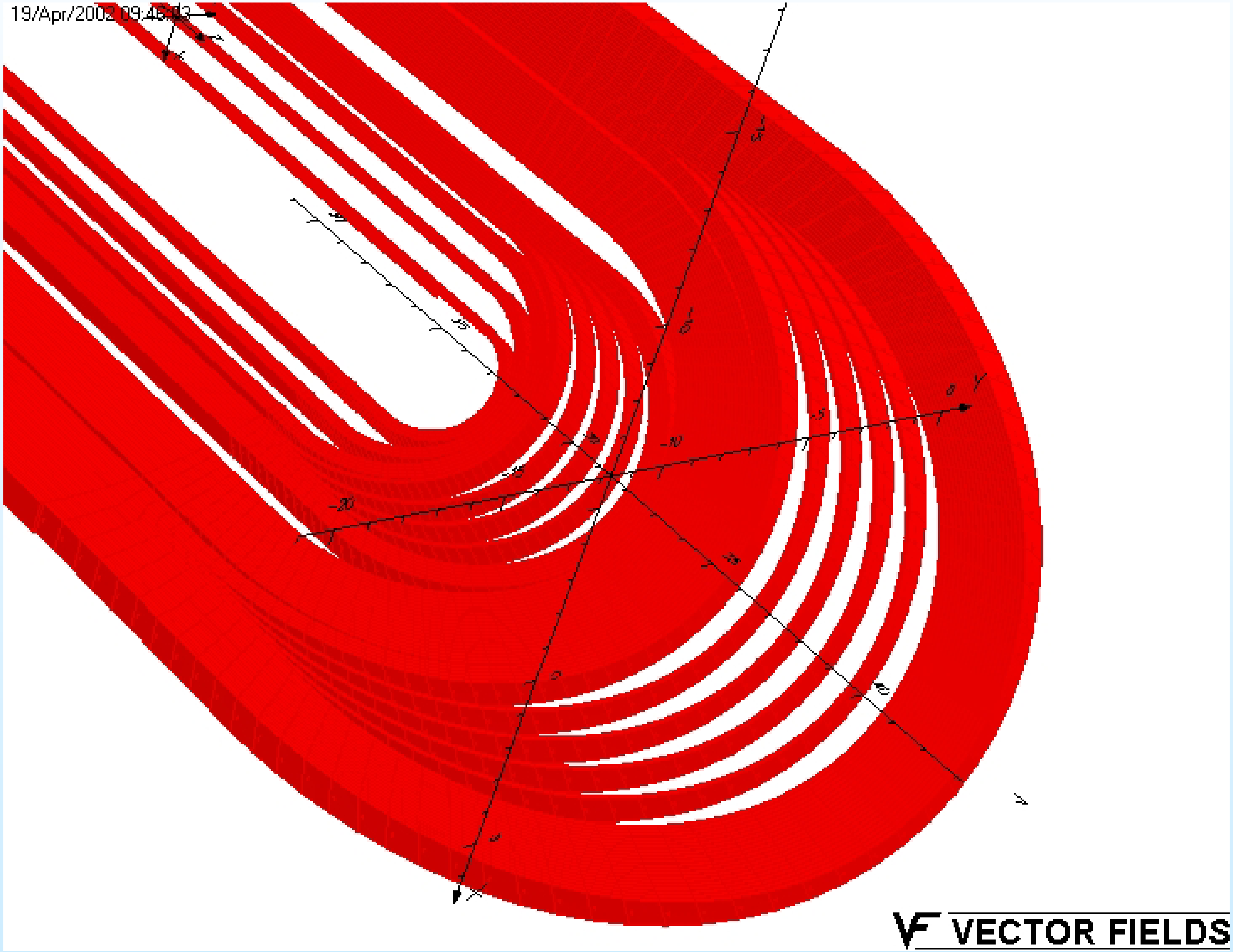
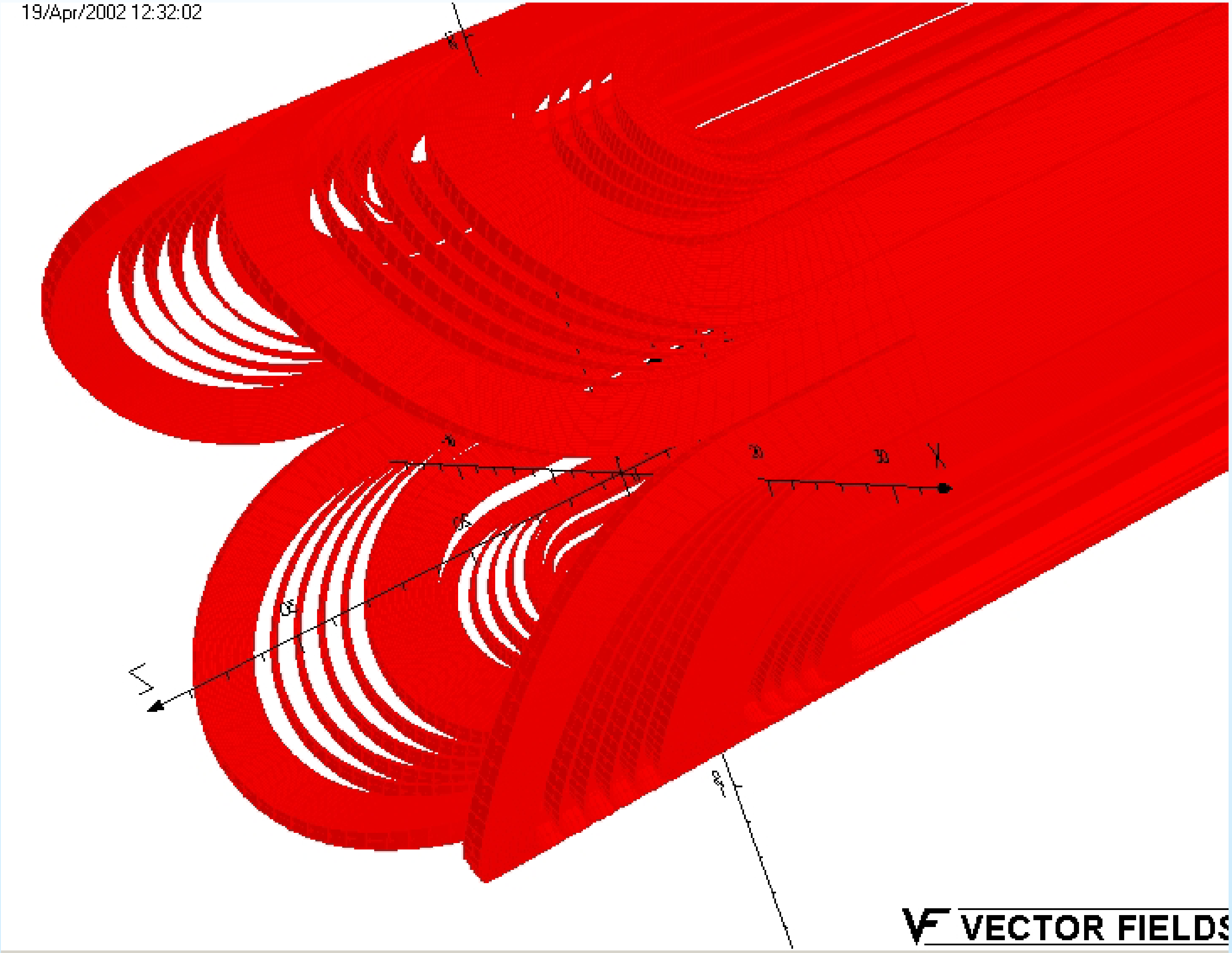
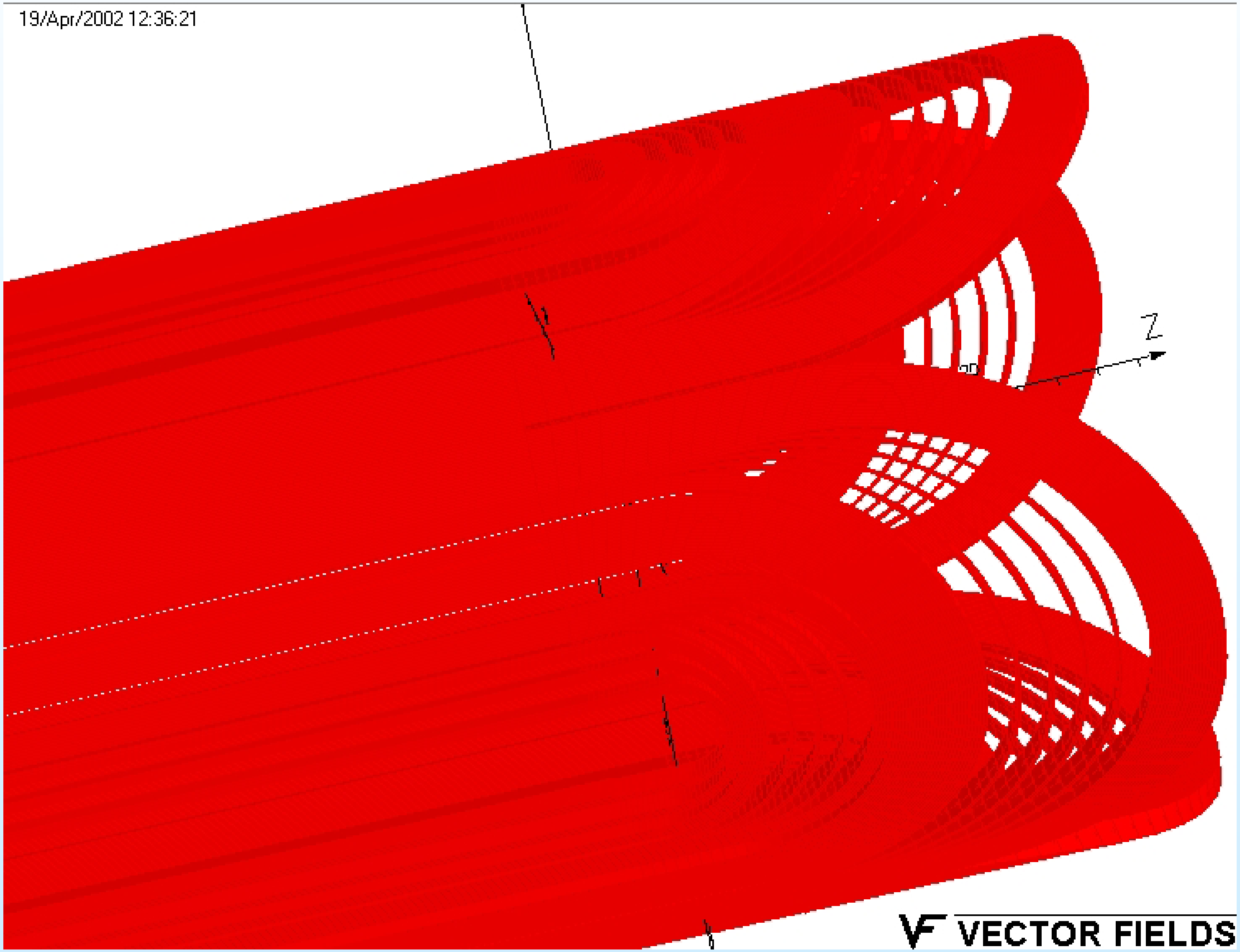
Coil Ends: Design A



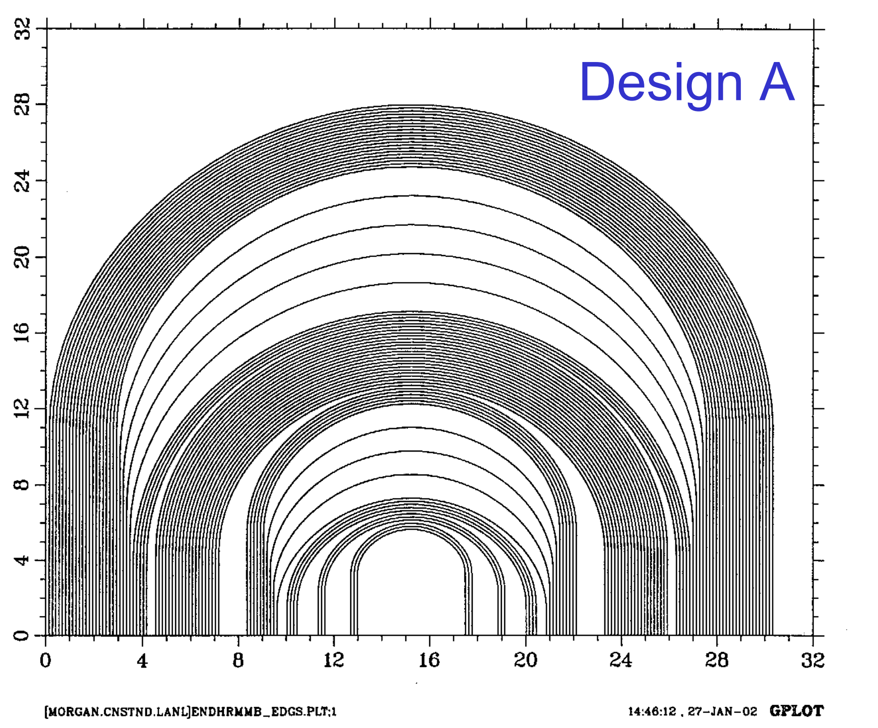
Coil End: Design A



Coil Ends: Design A



End Harmonic Optimization: SMINSQ



Block configuration:

(8 blocks, 70 turns):

10, 5, 8, 4, 13, 4, 6, 20

(counting from pole)

Parameters optimized:

End spacers in block #2 (with 5 turns) and end spacer in block #7 (with 4 turns).

All spacers with in a block have the same size.

Changing the size of two group of end spacers was adequate to get all harmonics small.

Computed values:

B_5< 1 unit-meter;

B_9 and B_{13} <0.1 unit-m

Effective Magnetic Length ~15.6 cm

Mechanical Length ~28 cm

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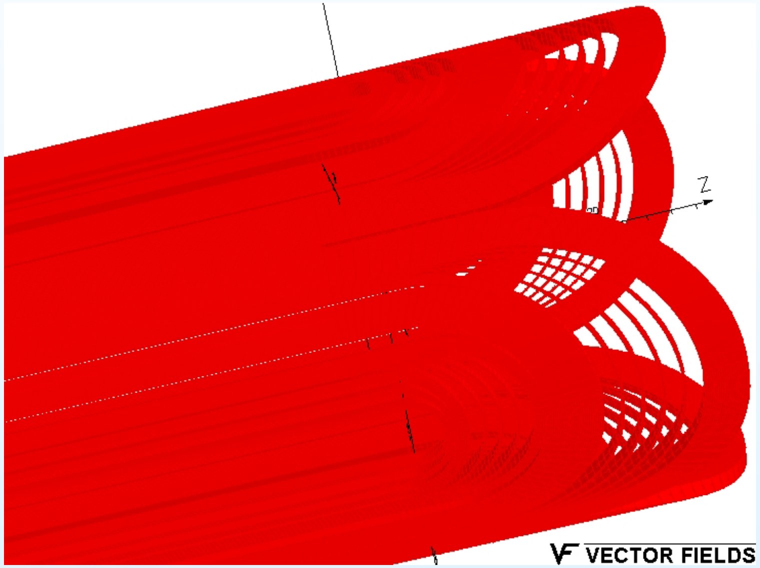
Harmonic Calculations with Opera-3d (Z-scan)

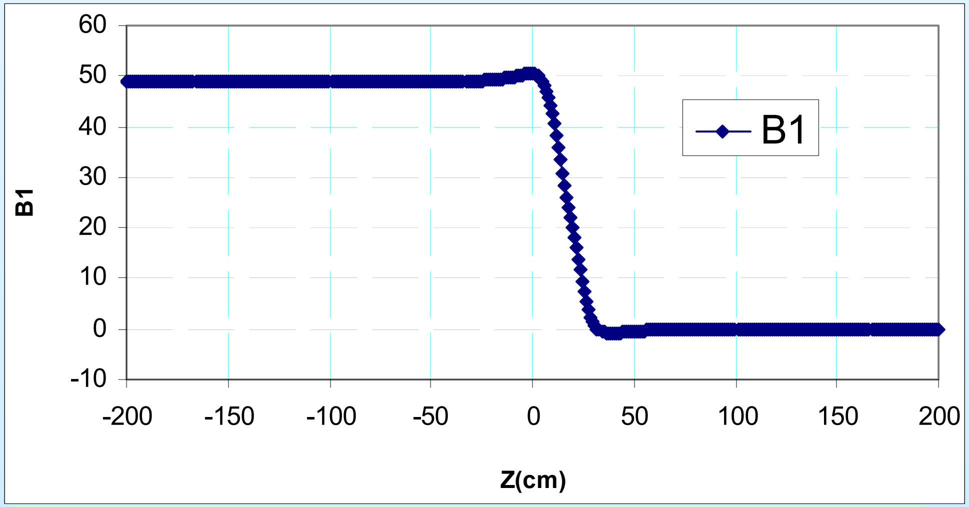


A set of programs are written to automatically generate/manipulate OPERA-3d input

Harmonics (including gradient) are computed at an interval of 1 cm.

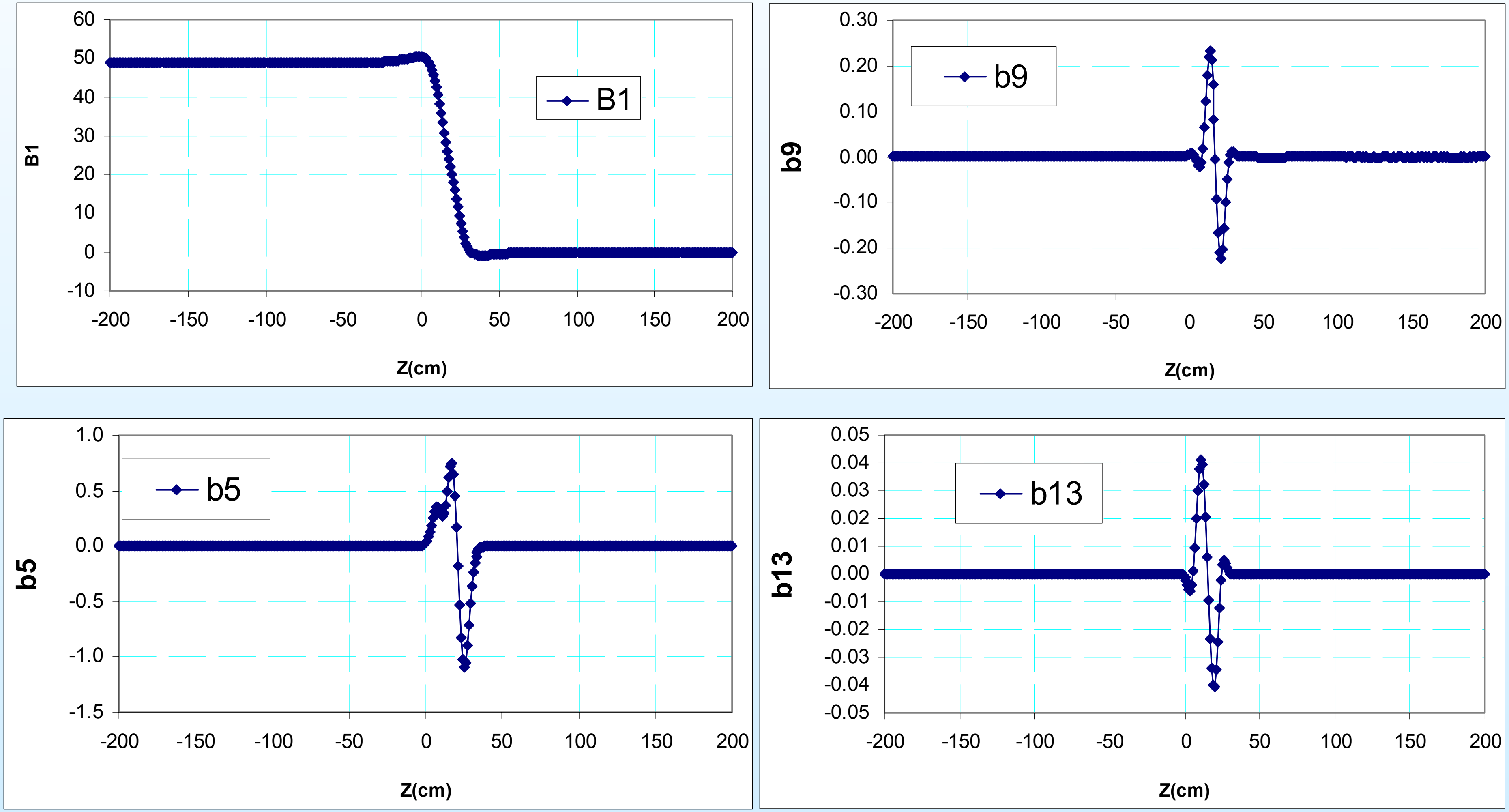
These calculations don't include iron.

Iron will not change behavior qualitatively. Calculations with iron to be done next.



Gradient from Straight section to End

Harmonic Calculations with Opera-3d (Z-scan)

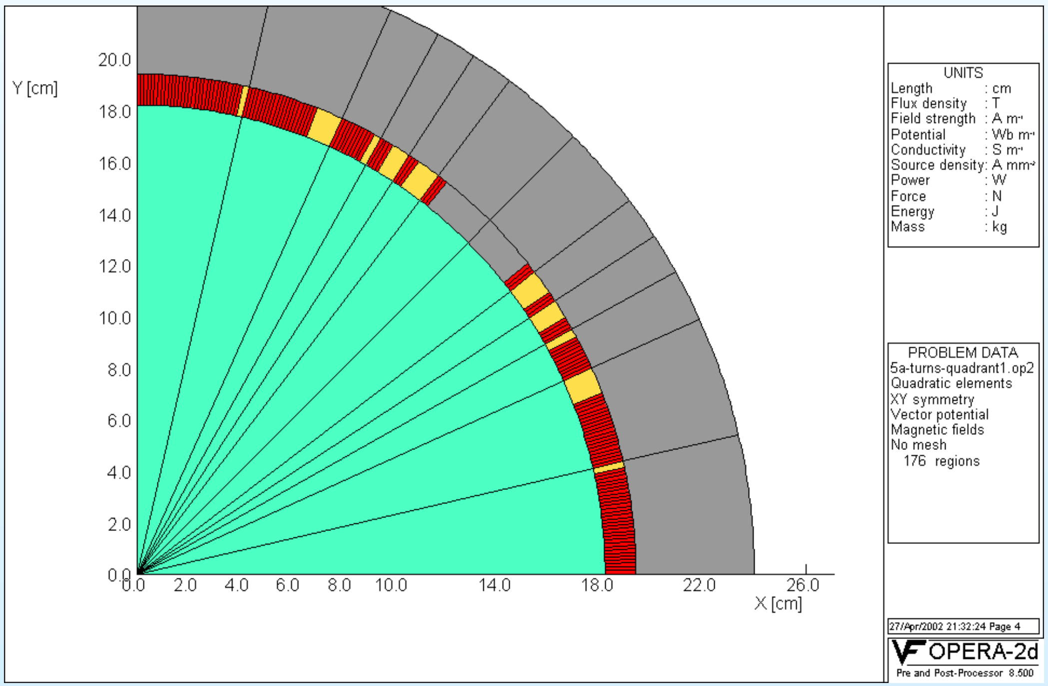


Peak Field Minimization

A high peak field reduces the magnet quench performance.

➢ **A large effort was undertaken in 2-d optimization.**

About thousand cases were examined to :



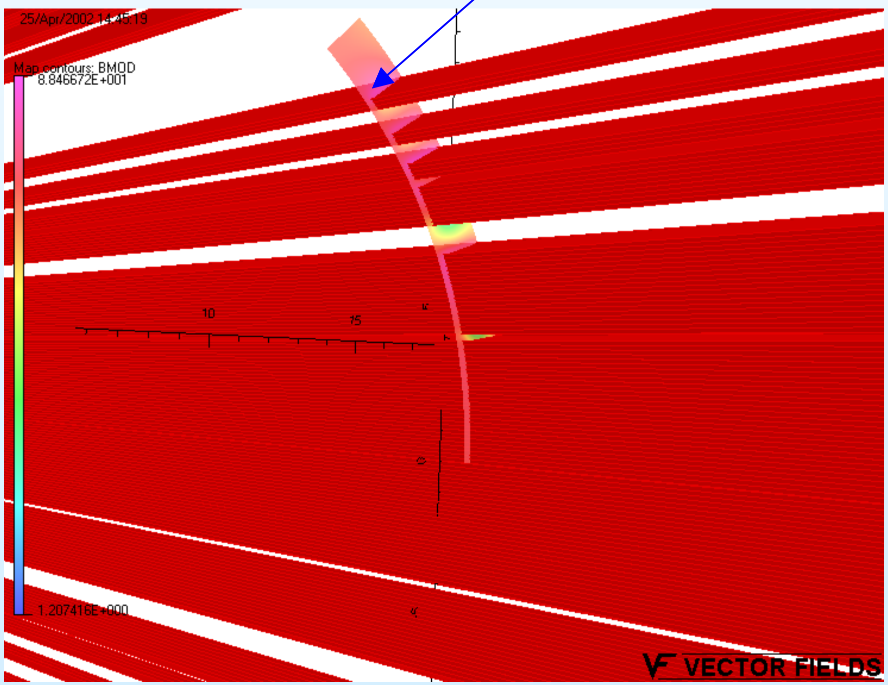
- Minimize harmonics
- Find a solution with lower peak field
- Good mechanical turn configuration (wedges, tilt angle, etc).

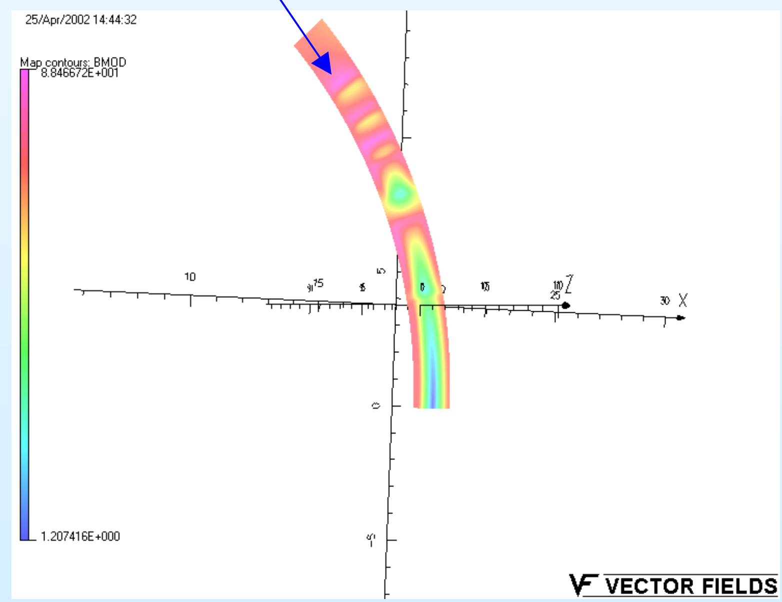
A series of computer programs have been written to carry out the above optimization in an exhaustive and systematic manner.

- New 70 turn configuration has several percent higher margin than the previous 69 turn configuration; primarily because of lower peak field.

Peak Field in the Body of the Magnet

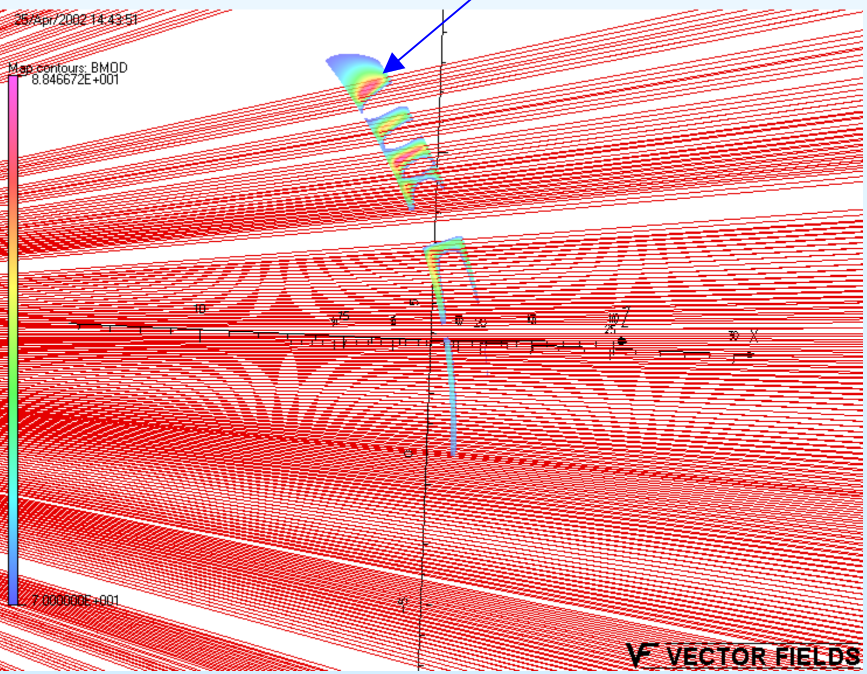
Peak Field Location (pole turn)

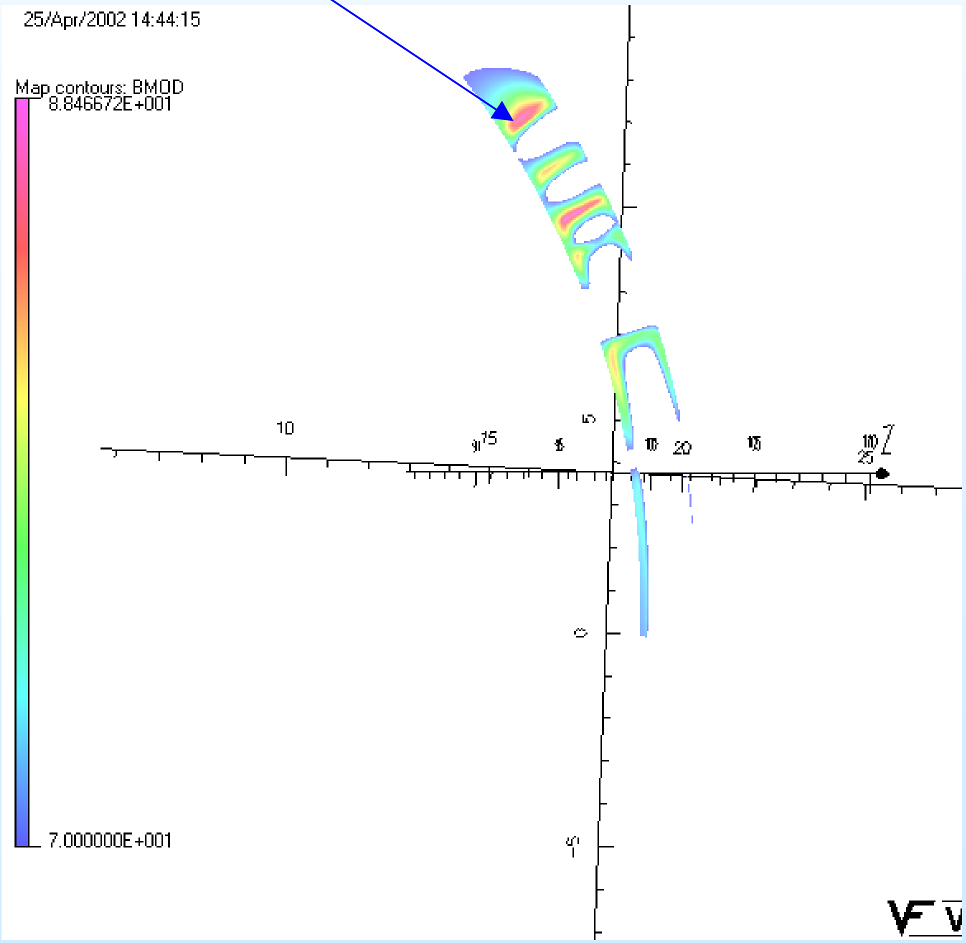




Peak Field in the S.S.

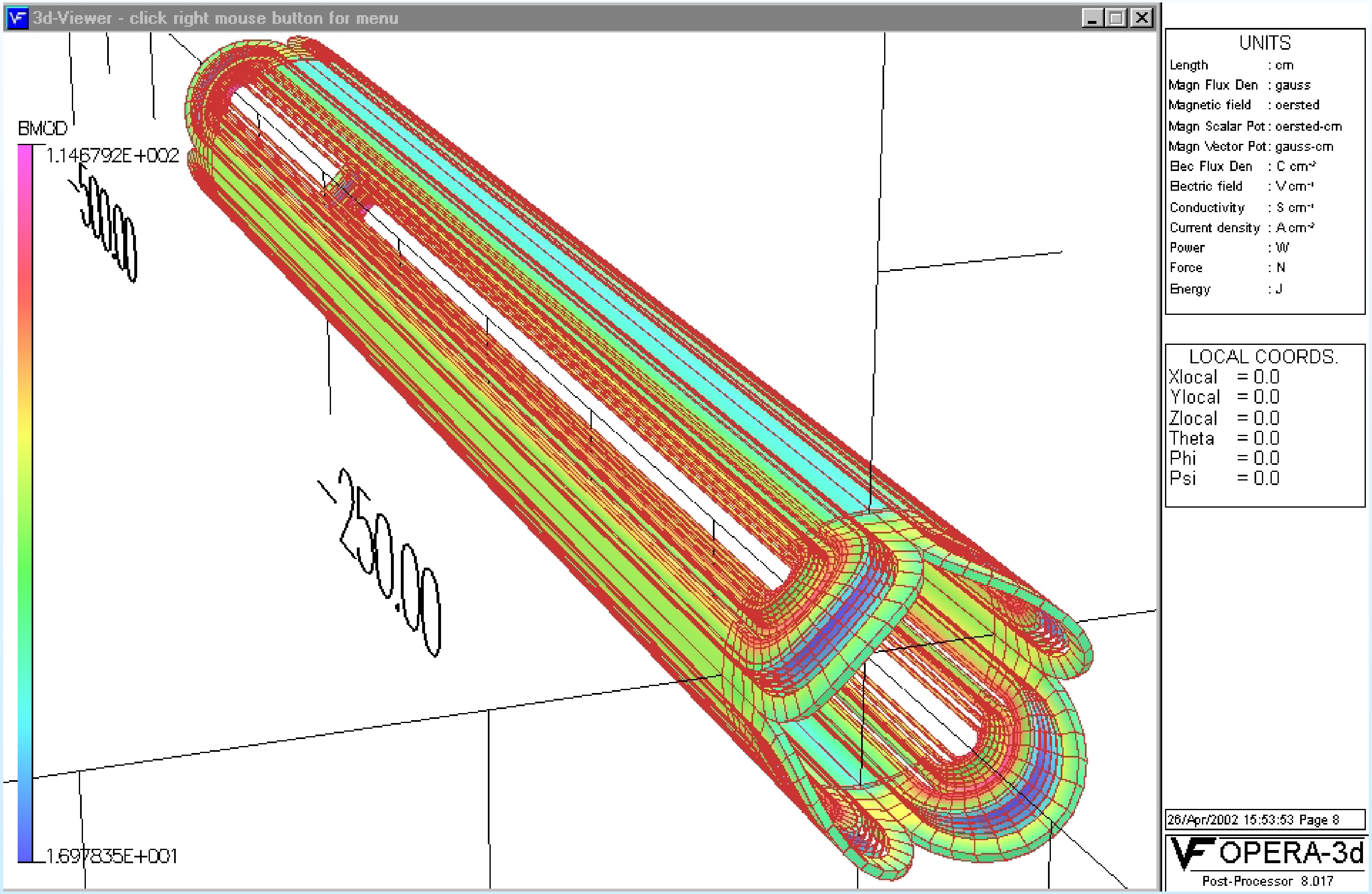
Peak Field Location (pole turn)



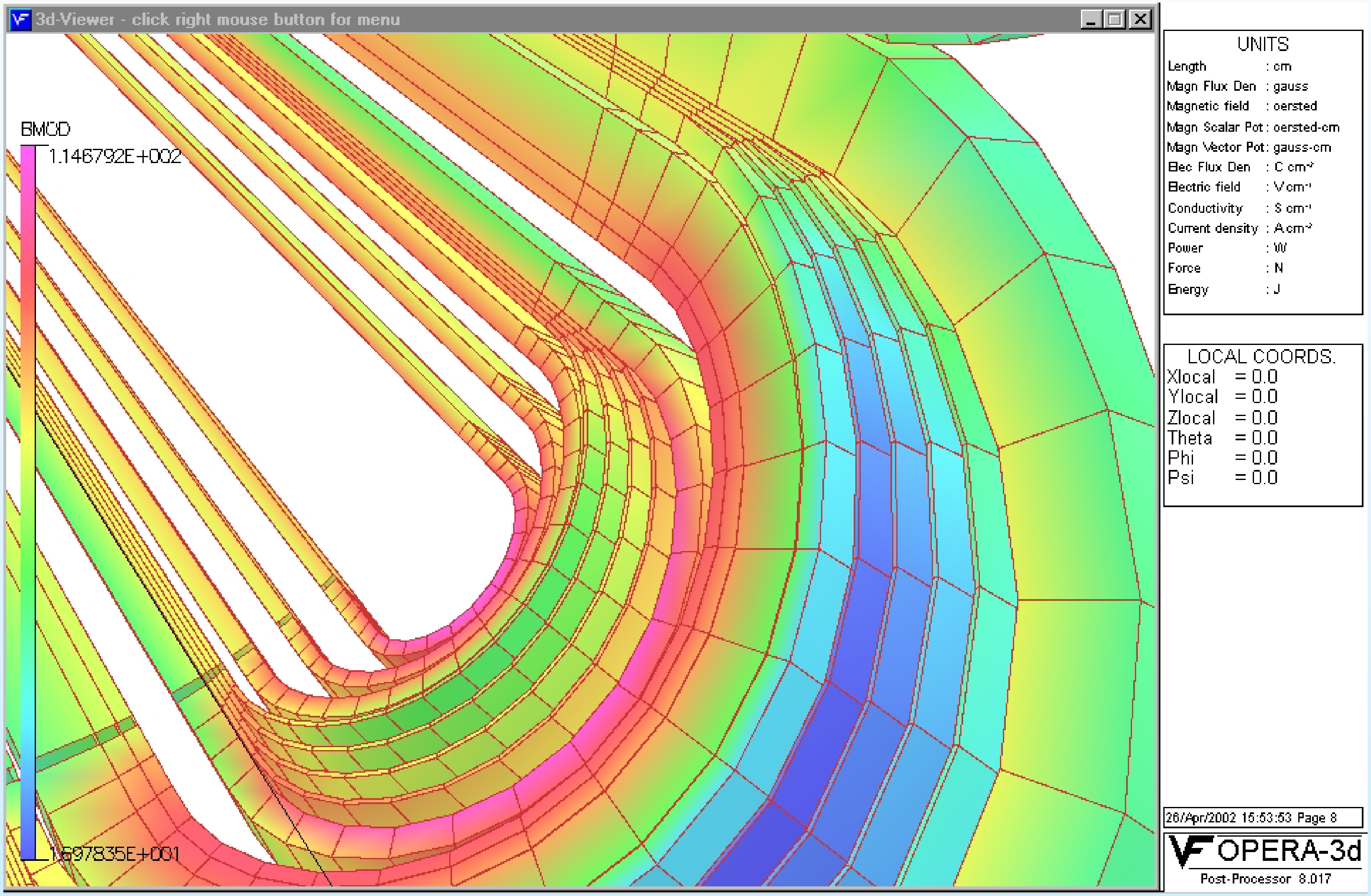


Note: Min/Max range changed

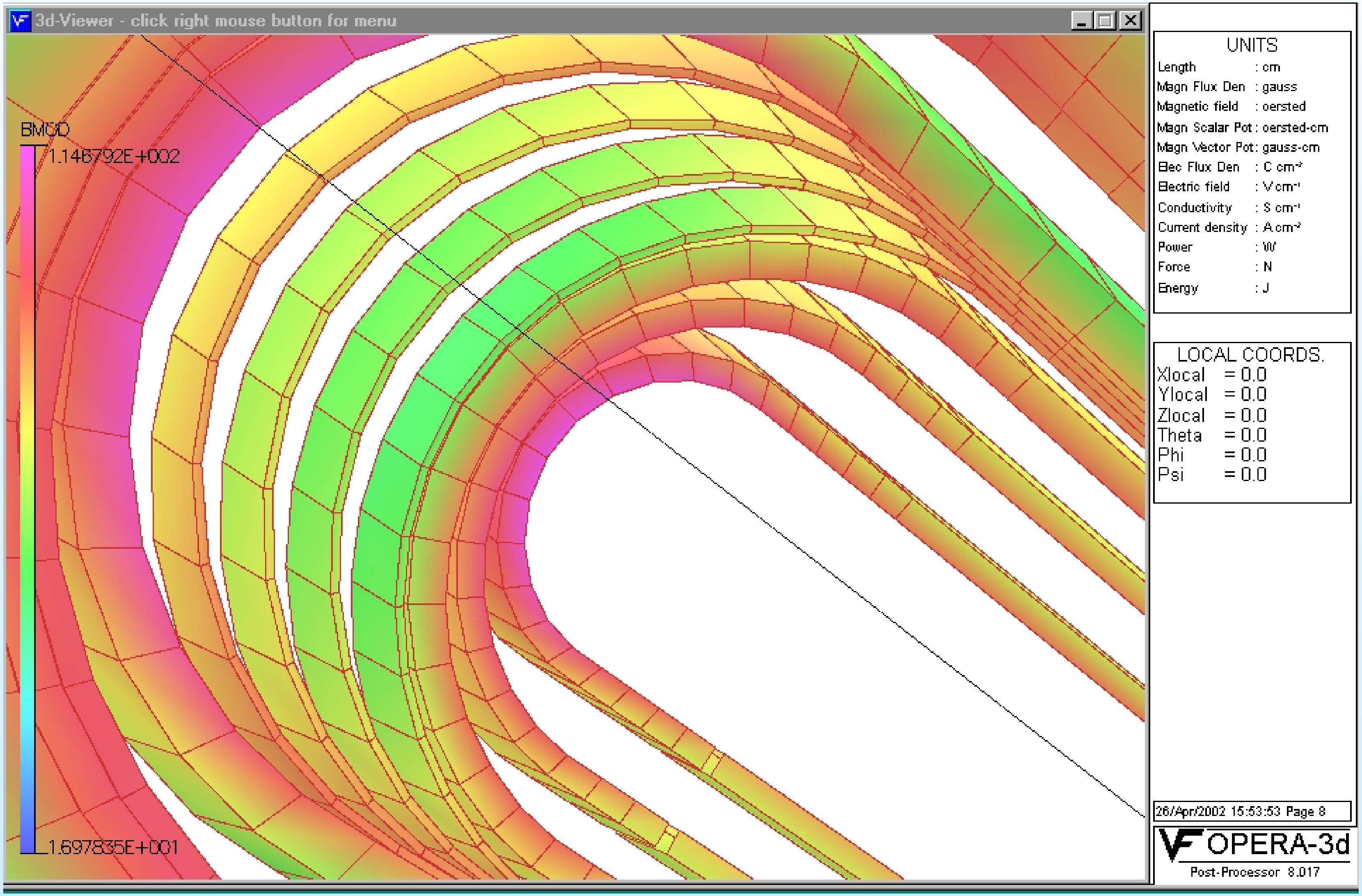
Peak Field in the End



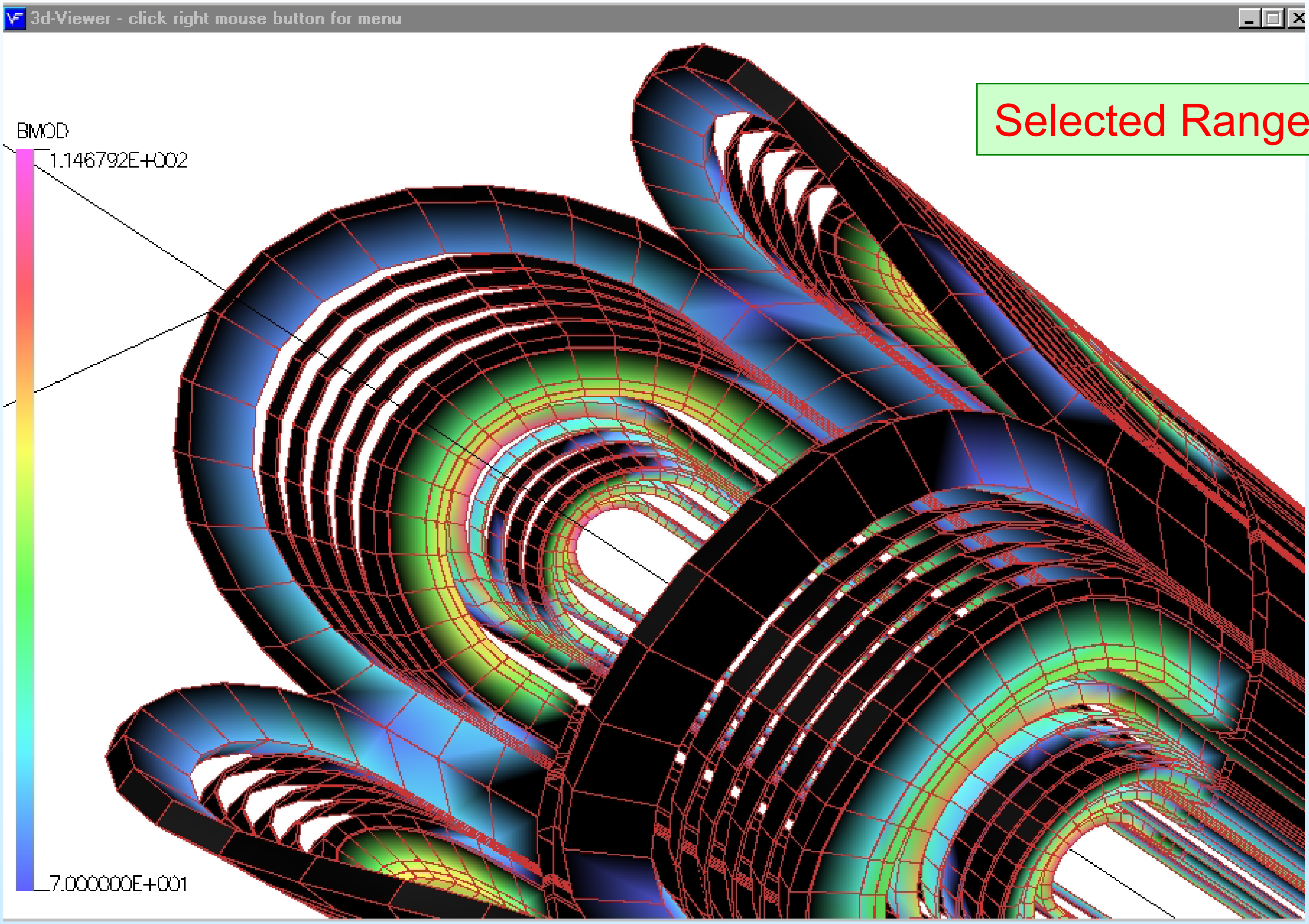
Peak Field in the End



Peak Field in the End



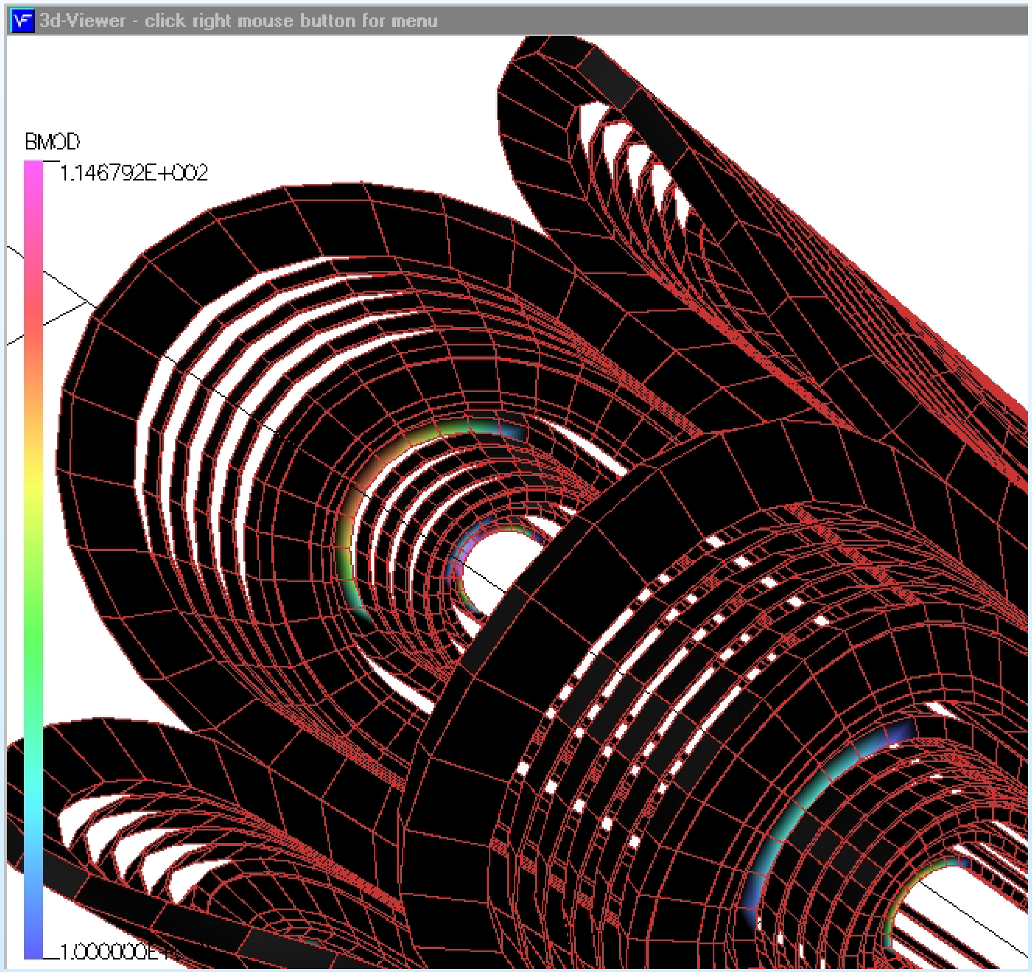
Peak Field in the End

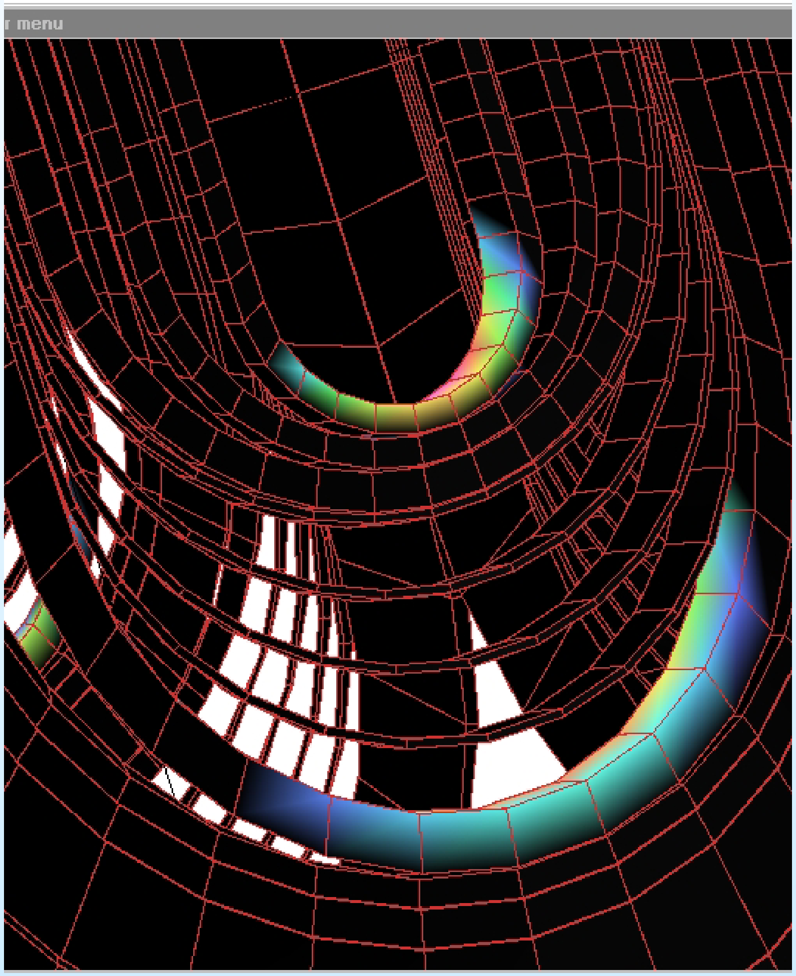


Selected Range

Peak Field in the End

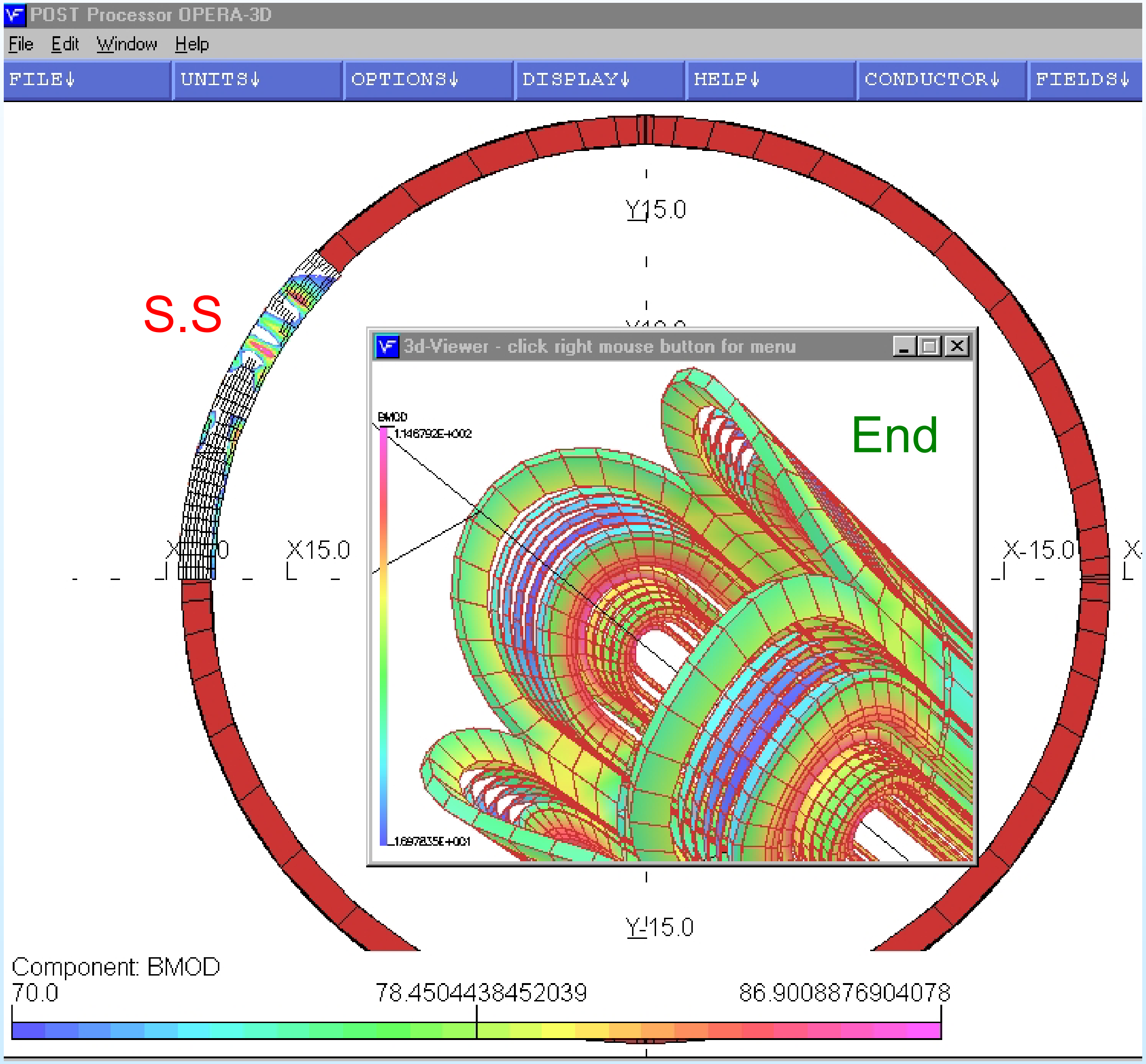
Selected Range





Peak Field in the End

How does it compare to Body?

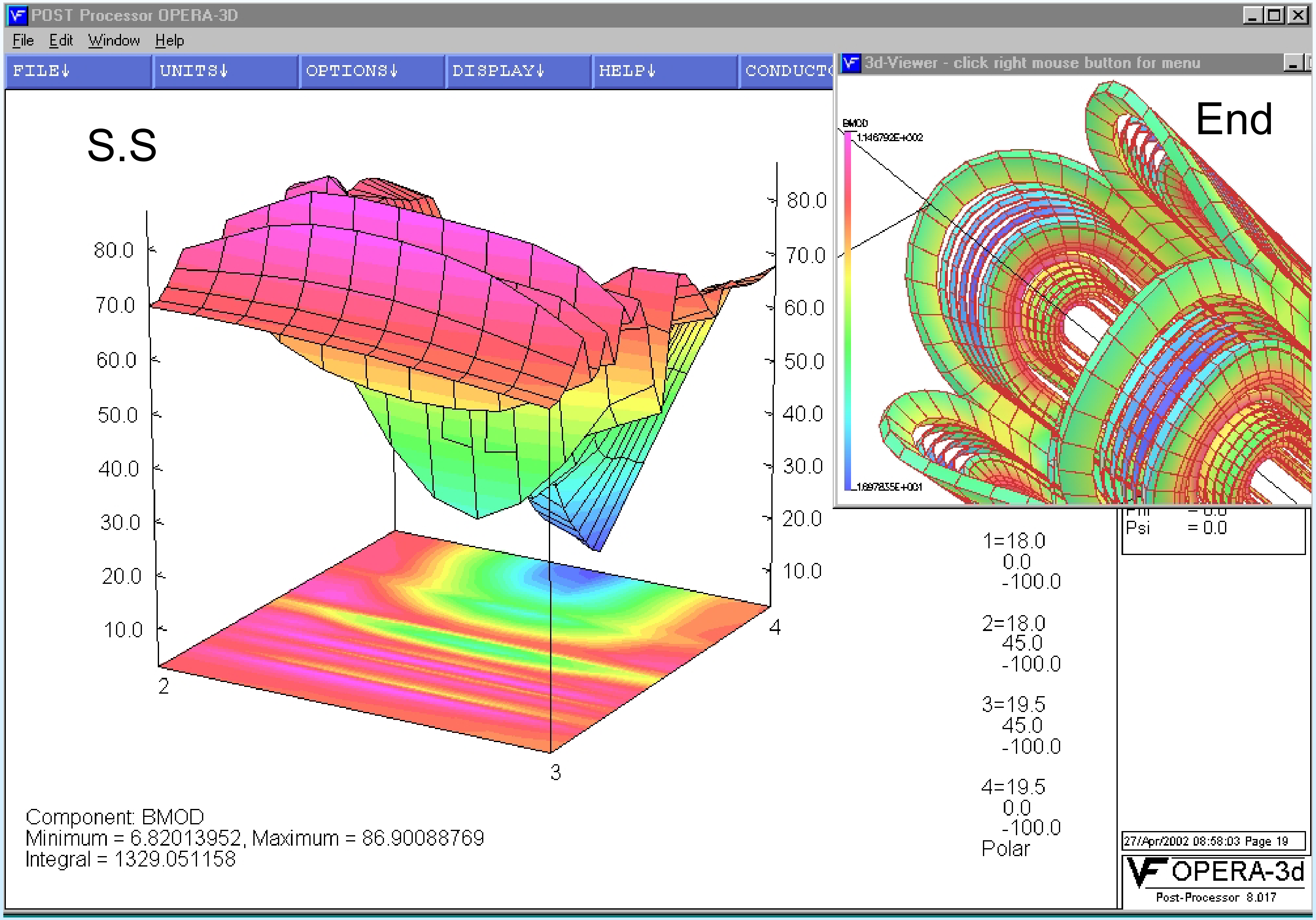


Based on the preliminary calculations, the peak value in Design A is larger in the end.

The peak field in the end will be minimized more in Design B.

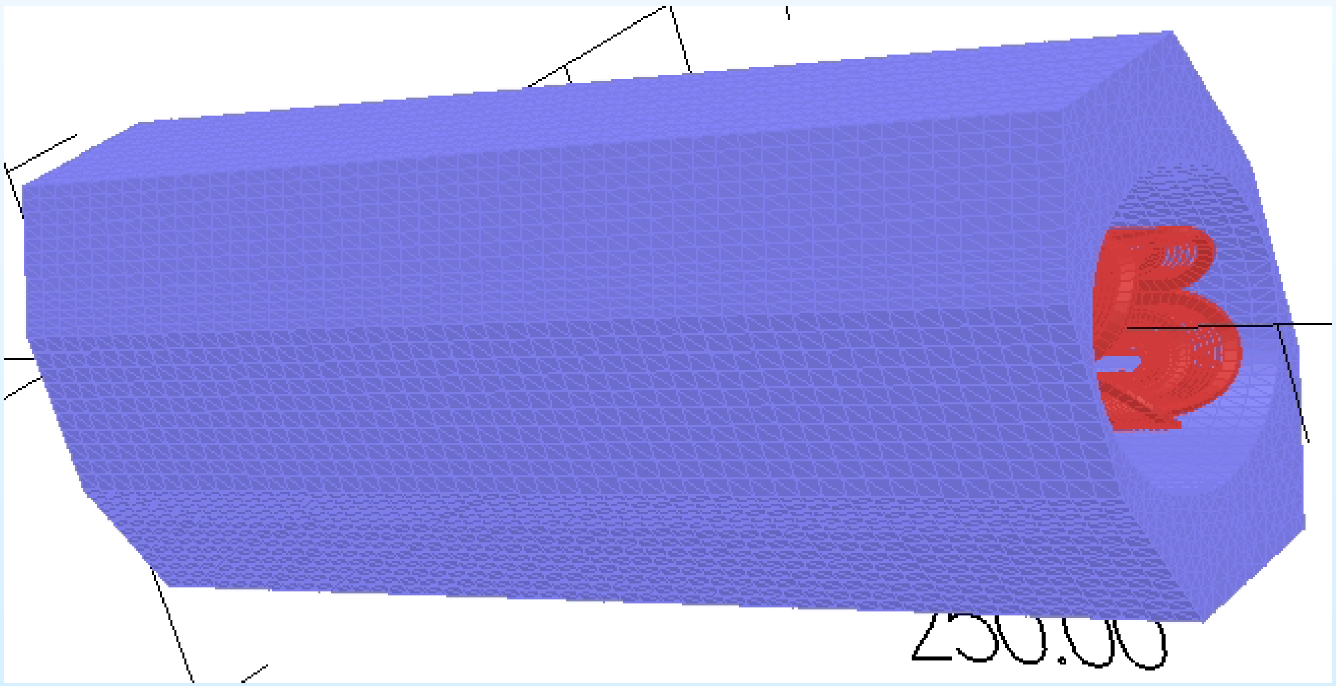
In typical end design, we remove iron (or increase yoke i.d.) to reduce field in the end. That option is not that effective here.

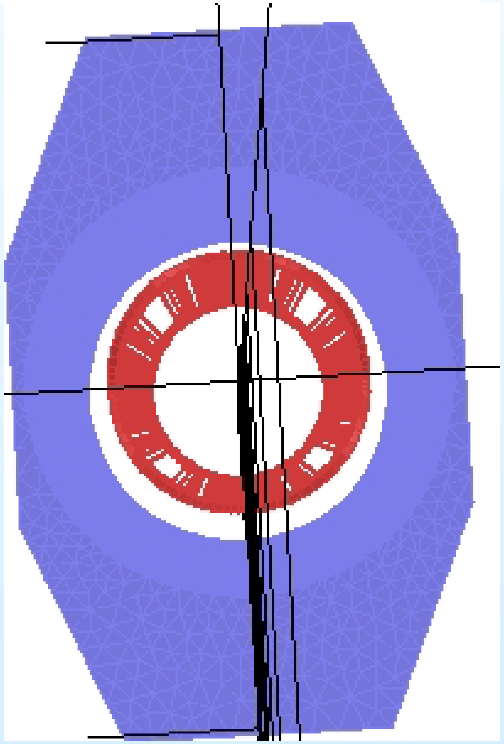
Peak Field in the End



3-d Calculations with Iron (work in progress)

Initial modeling work: Compute cross talk, etc. as the separation changes. The cross talk may be significant if the flux can not be contained in the yoke.





Need only ½ of this model for calculations. Apply boundary conditions on right and left side to simulate various cases. Need only ¼ of the model if boundary condition is the same on the left and right side.

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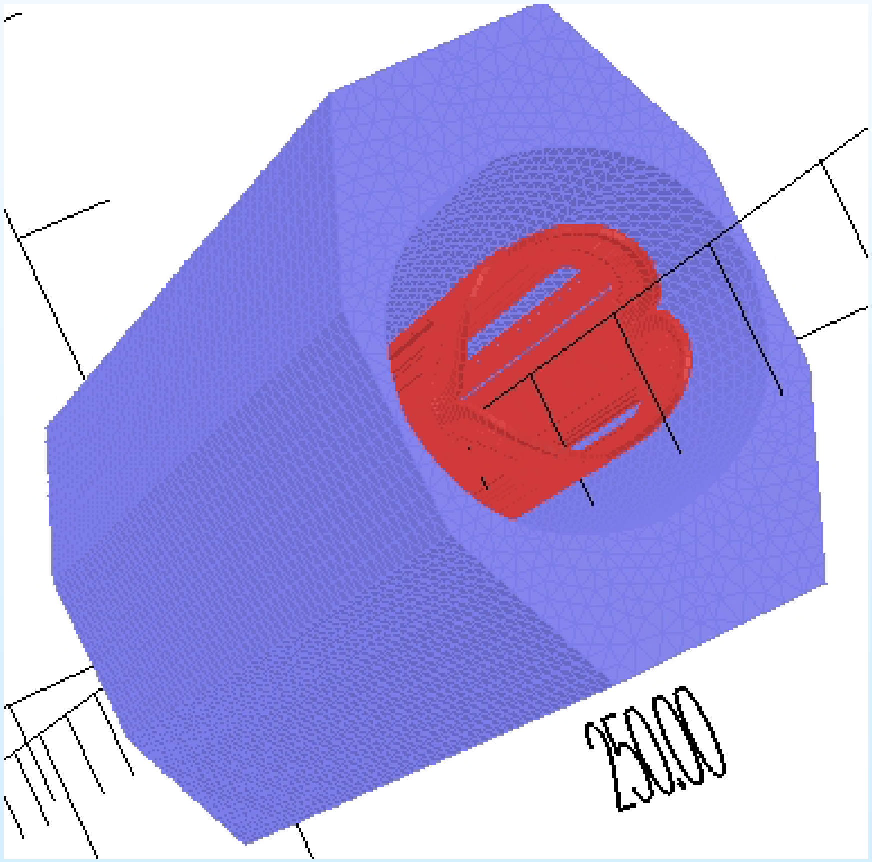
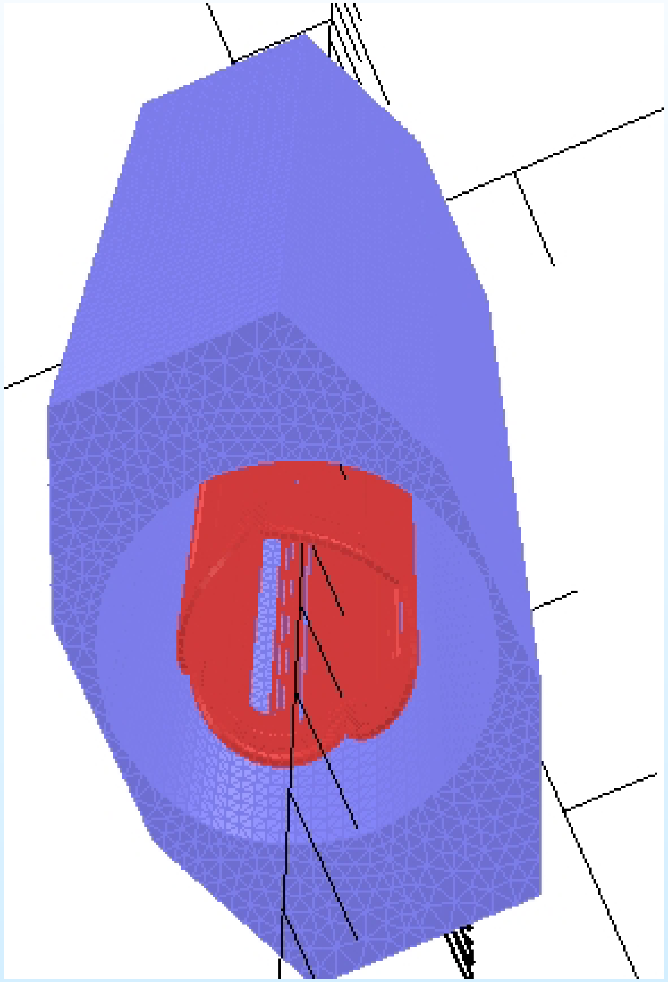
3-d Calculations with Iron (work in progress)

More views of the model



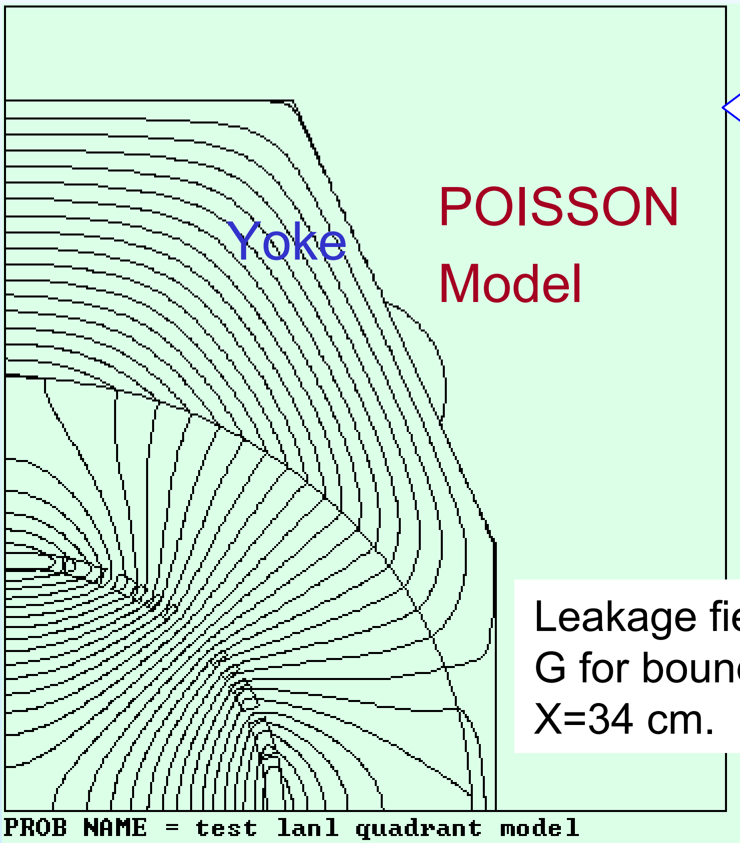


If cross talk is present, it would be maximum when the separation between the two quads is minimum. It should drop rapidly as the separation increases.

Cross Talk Along the Axis
2-d Simulation (Worst case scenario)

Change the location of boundary to simulate the change in separation.

2-d simulation presents a worst case scenario as the flux lines can go to in third dimension (towards the end where field is lower) to reduce the impact.



Boundary Condition

Leakage field ~700 G for boundary at X=34 cm.

The separation becomes quiet large by the time we reach S.S.

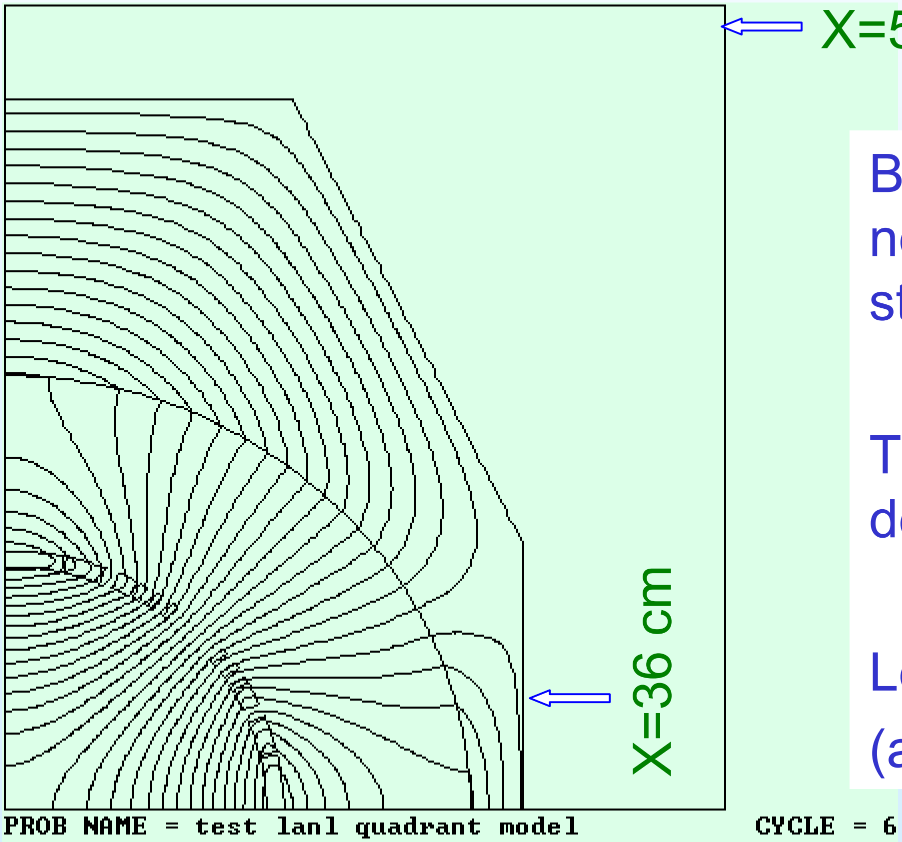
At 3 meter point it is over 78 cm [2*SIN(θ/2)]. For yoke width use [2*TAN(θ/2)] but leave small gap.

However, at the end saddle, the separation becomes over 94 cm and at S.S. over 104 cm.

The problem is not cross talk; it is lack of symmetry!

More POISSON Calculations for 3-d Simulation

For Animesh Jain's new design (yoke to x = 36 cm)



Boundary condition is put at X=50 cm, near the beginning of mechanical straight section.

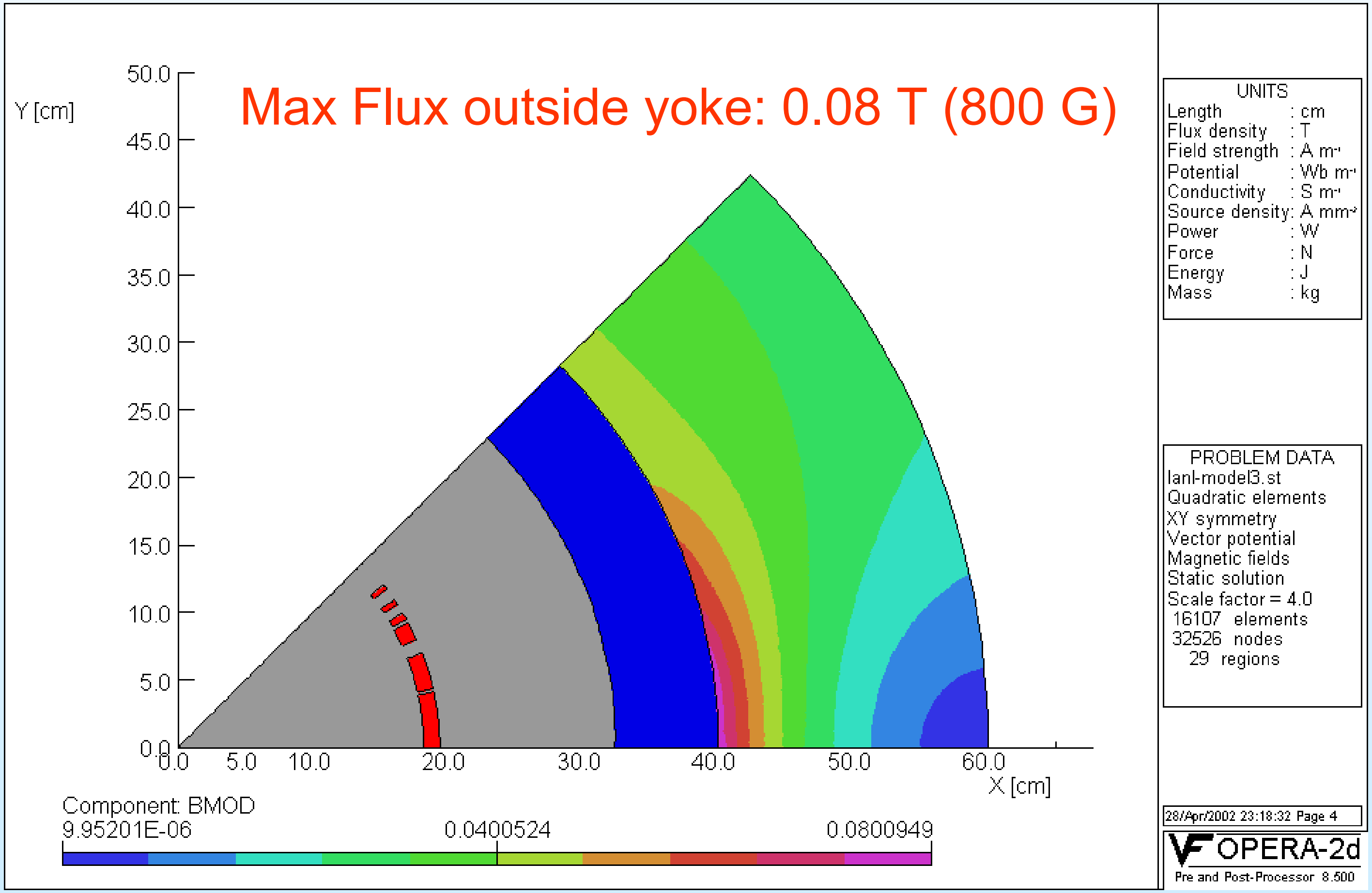
The computation is again done at the design field.

Leakage field ~100 G for X=36 cm (as per Animesh Jain's new design).

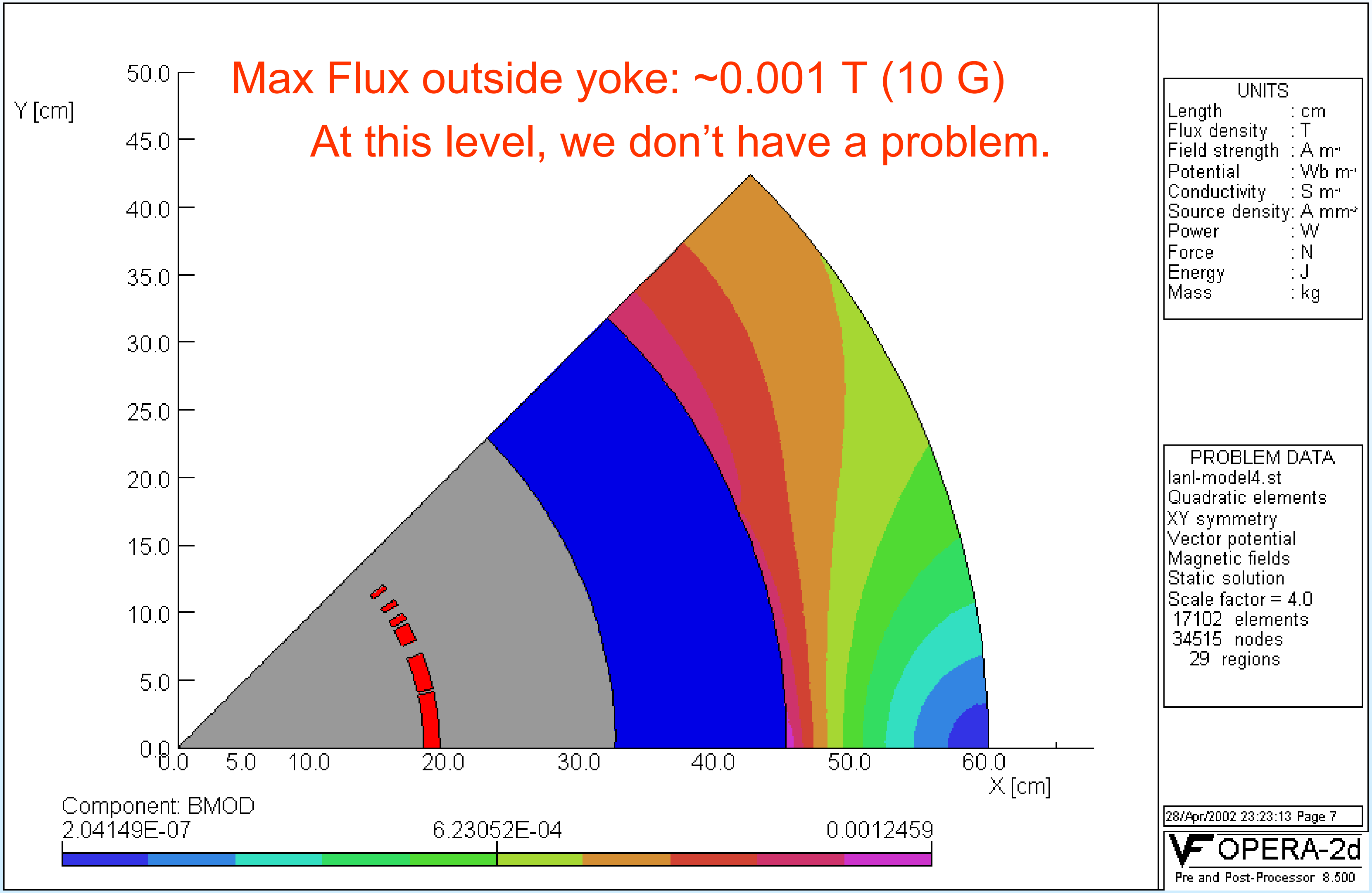
Flux Leakage for 40 cm Yoke Outer Radius

Simple model for quick estimates

See Animesh Jain's talk for detailed and complete calculations



Flux Leakage for 45 cm Yoke Outer Radius



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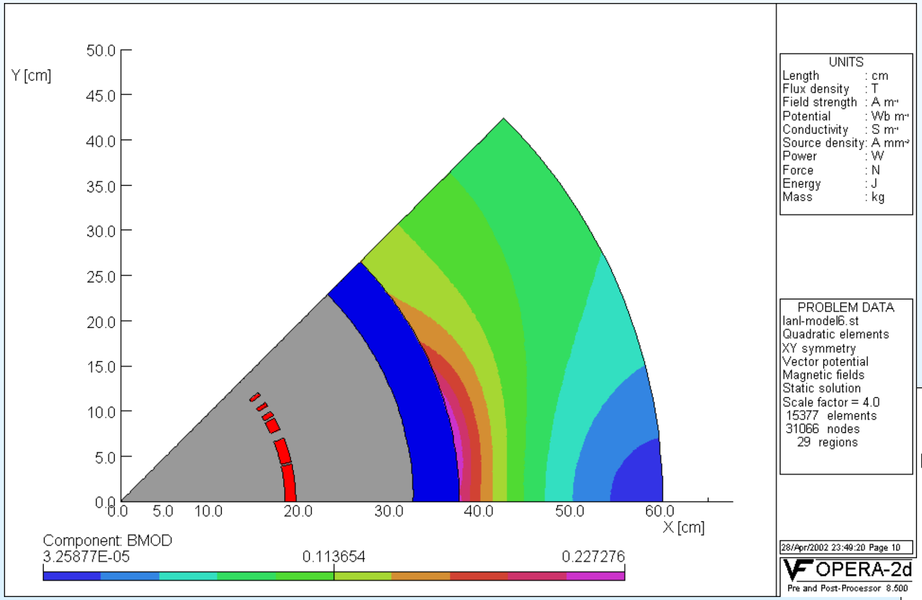
More Cases: Vary Yoke O.D.

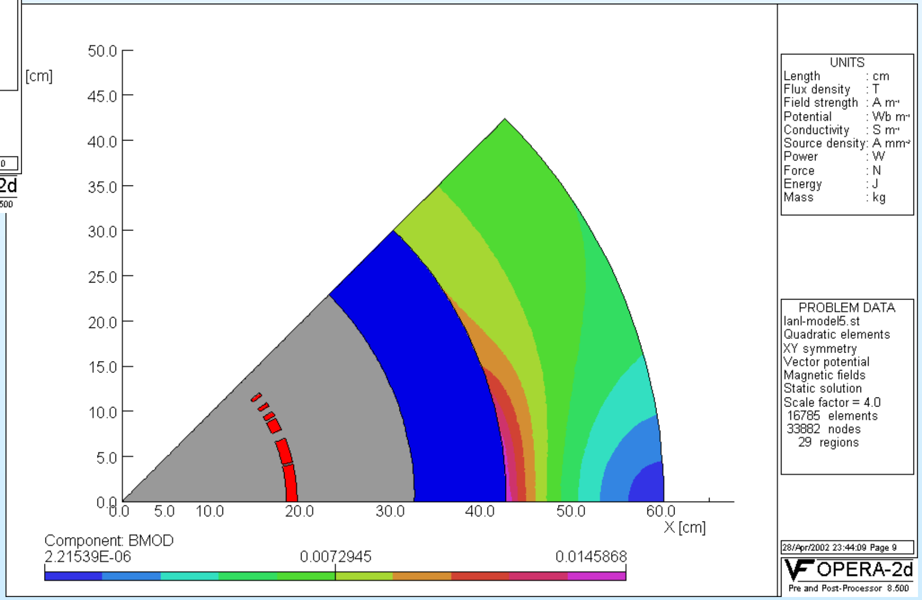
O.R. = 37.5 cm

Max Leakage field 2.3 kG



O.R. = 42.5 cm

Max Leakage field 150 Guass



Benefits of Larger Circular Yoke O.D.

Recall: the problem in harmonics is primarily due asymmetric iron, whose width is not enough on the horizontal axis.

If space, where the magnet end start is not restricted by other reasons, consider higher yoke o.d.

> If space is not available then consider cutting iron only at the entry point where the field (and amount of flux) is lower anyway.
>
> Also the penalty will be small if asymmetry is not large.

Other benefits:

- It would remove non-allowed harmonics due to iron in all cases.
- It would reduce fringe fields.
- Higher field (gradient) option would not be a field quality issue.

End Design Optimization: Design B

Design B

Design philosophy: Let mechanical design drive the ends

Start with a good mechanical lay out of each turn and relationship between the subsequent two

Adjust end spacers to minimize integrated harmonics and peak fields.

This is a magnet where end forces are large!

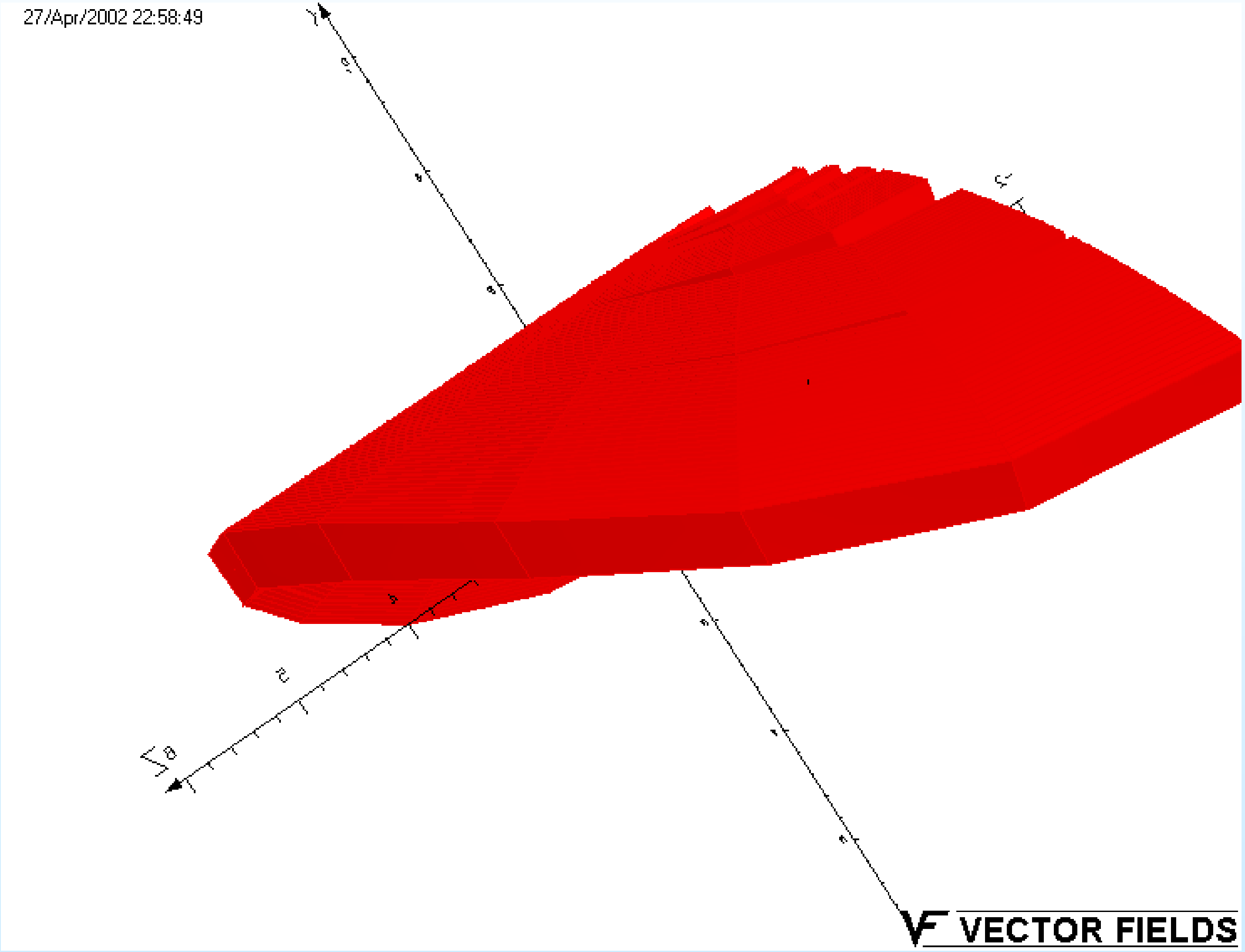
The ends would play a major role on quench performance of the magnet.

Use CAD software to visualize how the cable turns are being developed.

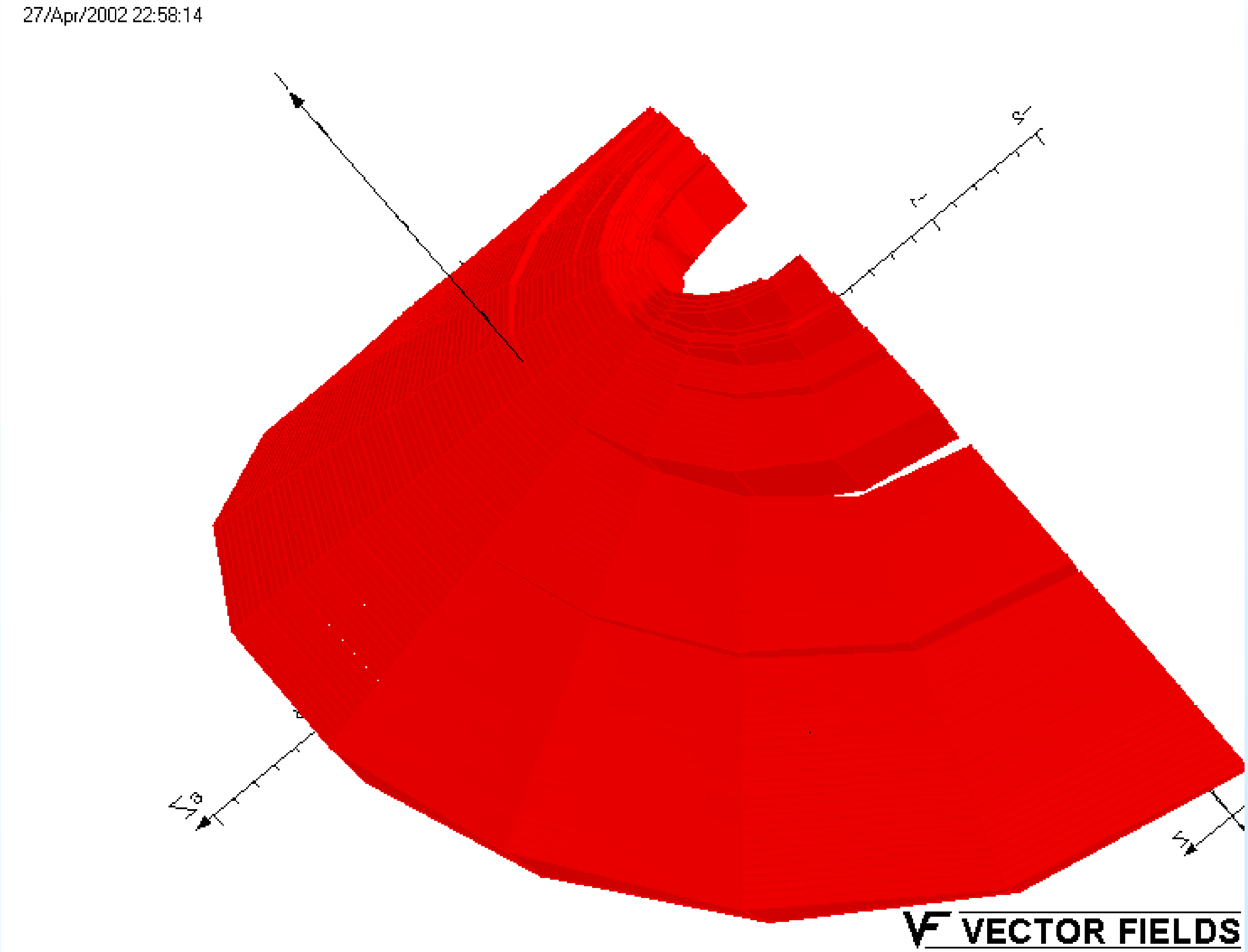
Observe tilt and strain on the cable.

Develop next turn in relation to the previous turn.

Coil Ends: Design B
(Start with a good mechanical layout)



Coil Ends: Design B
(Start with a good mechanical layout)



SUMMARY

- This is work in Progress!
- Issues are large forces and mechanical layout of turns.
- Our initial model and techniques are in place
  - Need to carry out this optimization process further.
- The goal of optimization process is to produce a design that is good both mechanically and magnetically.