Dipole Magnet Design and Innovations

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U.S. DEPARTMENT OF ENERGY

http://www.bnl.gov/magnets/staff/gupta/

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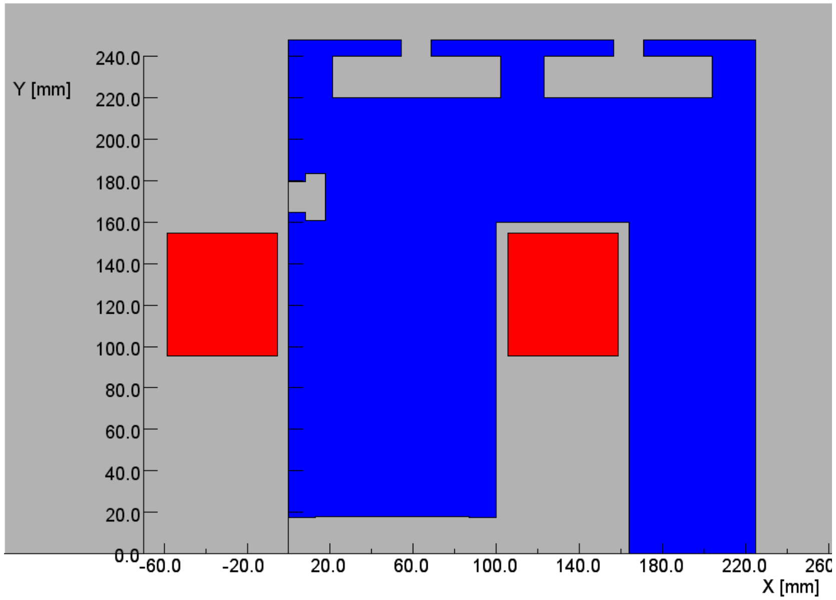
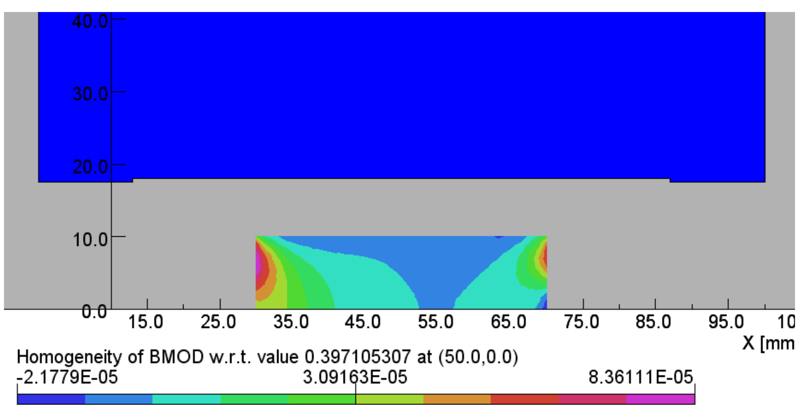
Overview

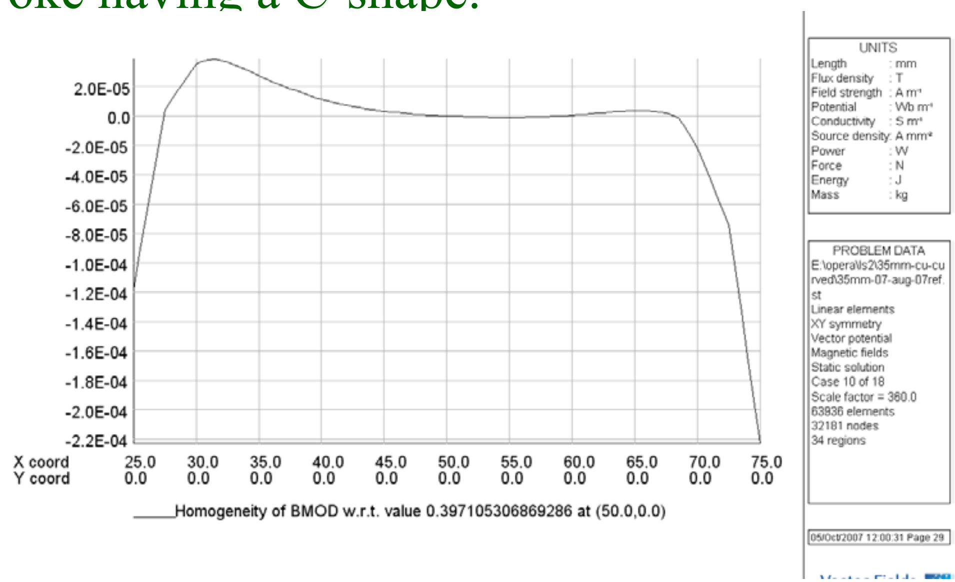
- Brief review of the magnetic designs
  - ➢ Reference, Stangenes and Buckley
- Special features/considerations/innovations:
  - ➢ Extended pole (nose) to save space by increasing the effective magnetic length
  - ➢ Matching between 35 mm and 90 mm aperture dipoles
- Analysis of the measurements
  - ➢ Two 35 mm dipoles have been tested (short length from Stangenes and full length from Buckley)

35 mm Dipole Cross-section (reference design)



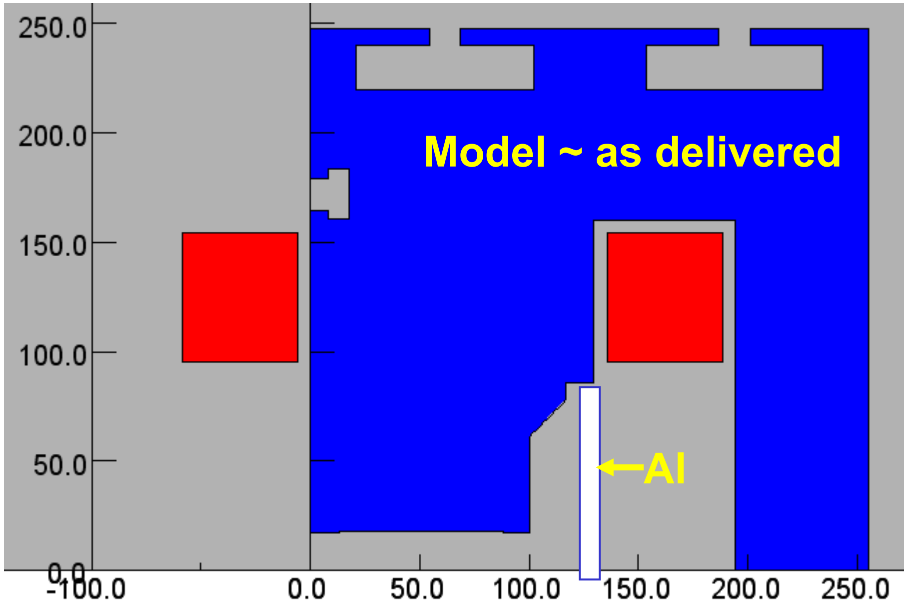


- 16 turns, 13 mm X 13 mm each
With circular cooling water holes.
Overall current density for 0.4 T ~ 1.8 A/mm^2.
- Since coils are sufficiently above midplane, asymmetric pole bumps were not required for removing quadrupole-type terms despite the yoke having a C-shape.



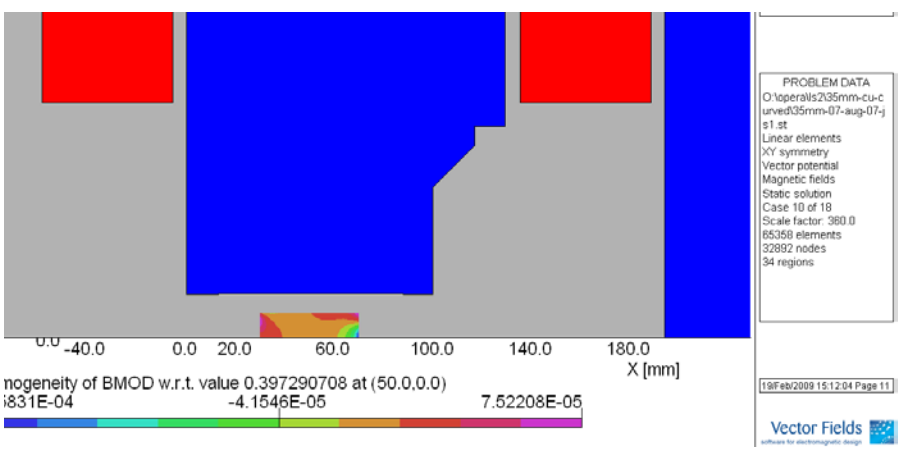
Specified good field quality (a few part in 10^4)
+/-20 mm in horizontal and +/-10 mm in vertical.

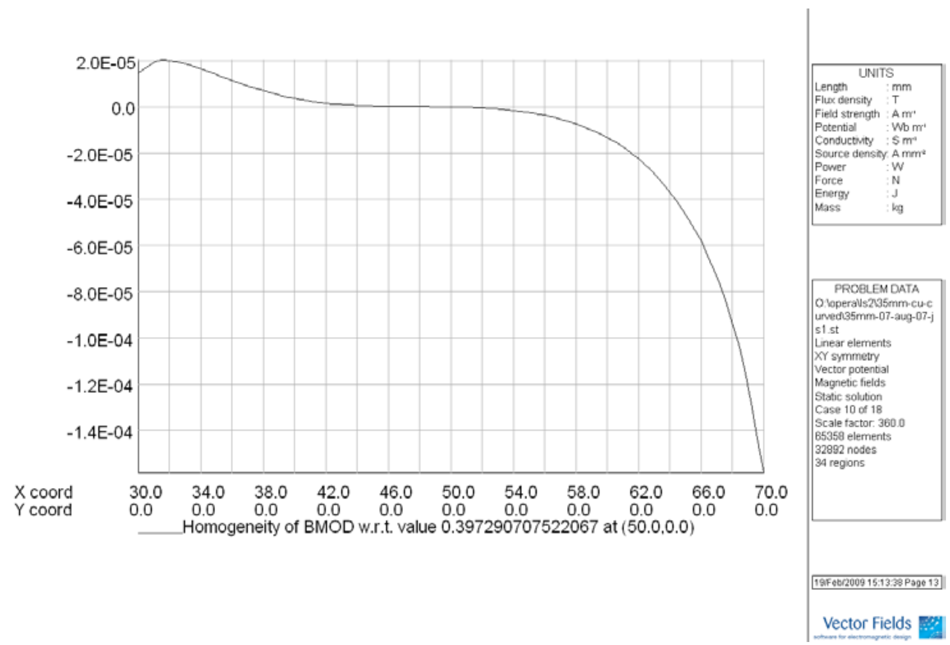
35 mm Dipole Cross-section (Stangenes design)



At that time, asymmetric pole deflection due to Lorentz forces was issue and an Aluminum plate was incorporated to minimize that **(more analysis showed Al plate was not required).**

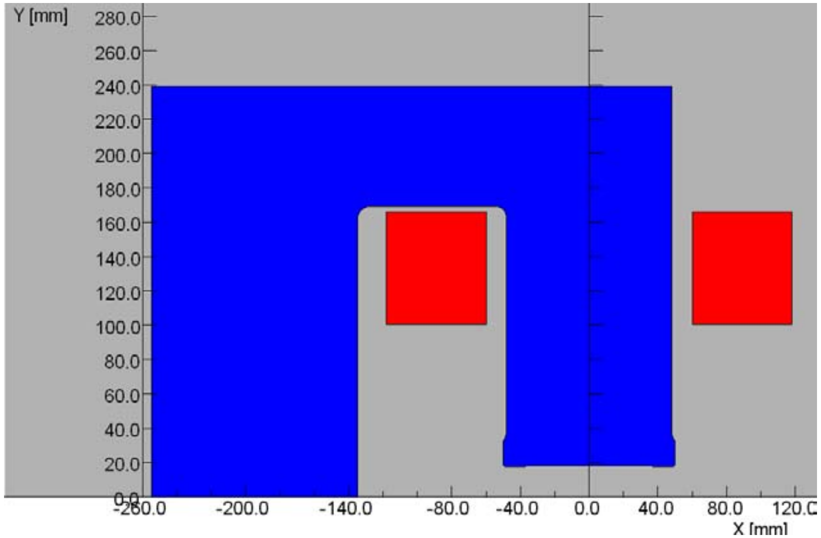
Width of a pole bump (closer to the added yoke) was reduced by 1 mm to keep quad term low.



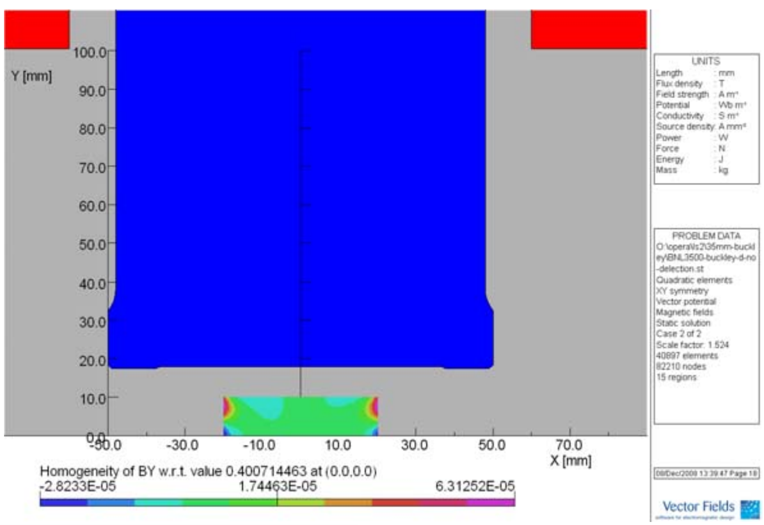


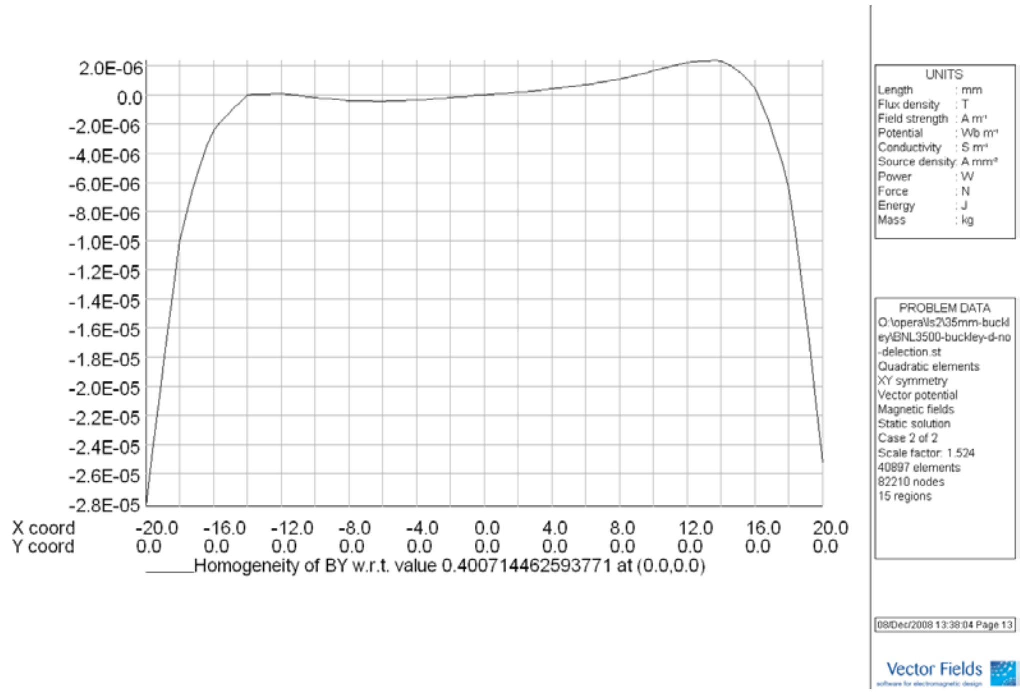
Specified good field quality (a few part in 10^4) +/-20 mm in horizontal and +/-10 mm in vertical.

35 mm Dipole Cross-section (Buckley design)



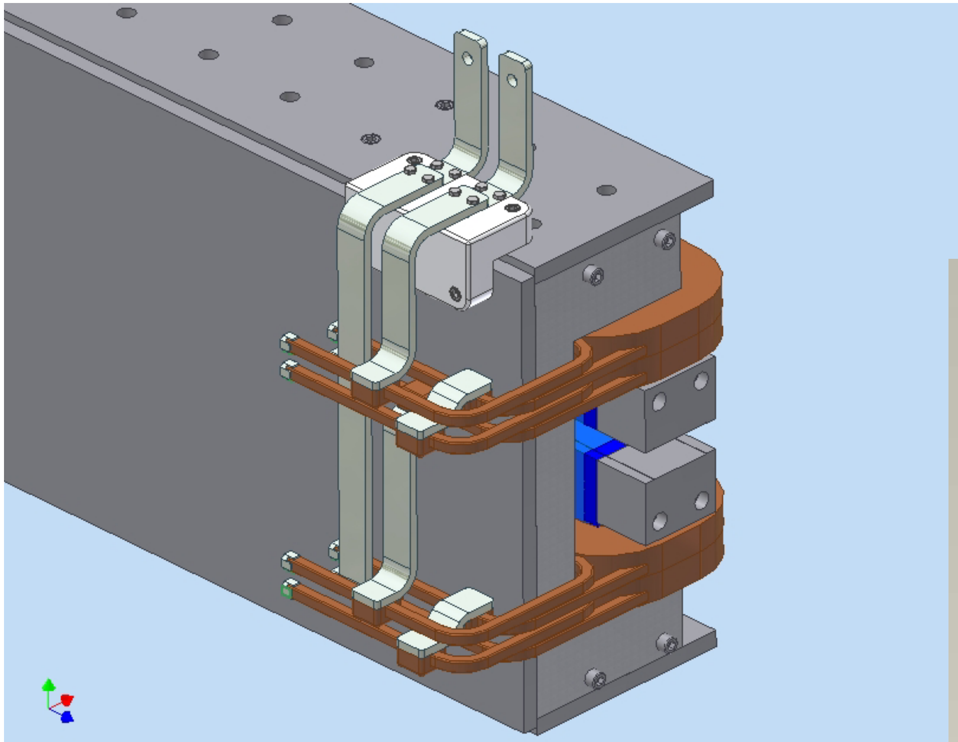
- Pole region was modified to particular construction (coil/yoke interface).
- Pole bumps are almost symmetric again.
- Influence of asymmetric mechanical deflection was examined.



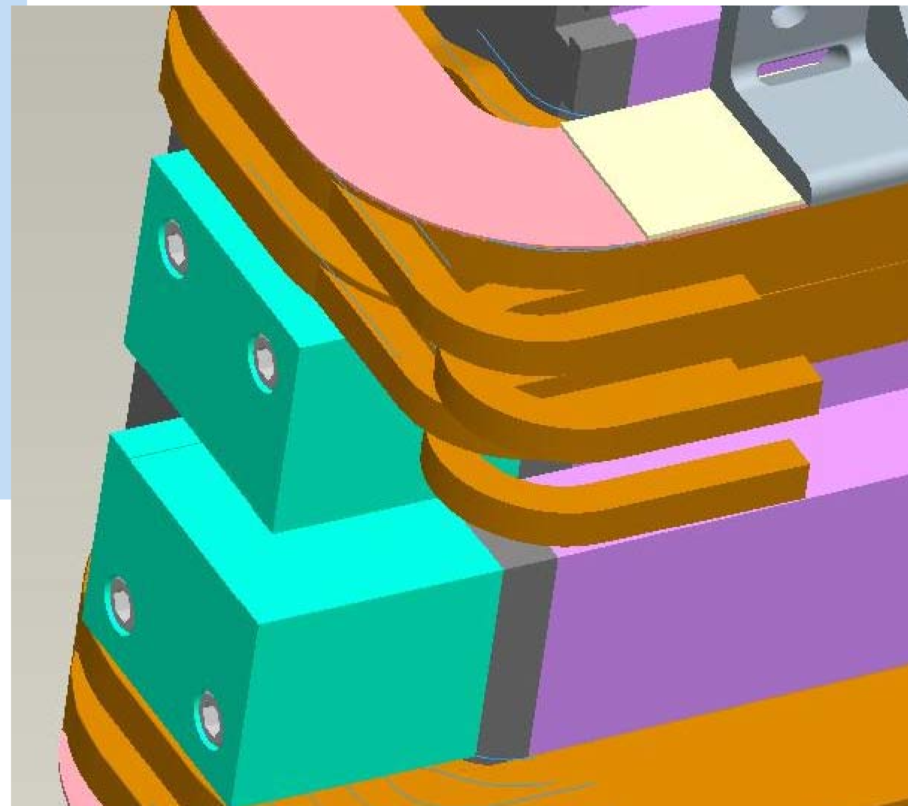


Specified good field quality (a few part in 10^4)
+/-20 mm in horizontal and +/-10 mm in vertical.

Unique Feature : Extended Pole (Nose)



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

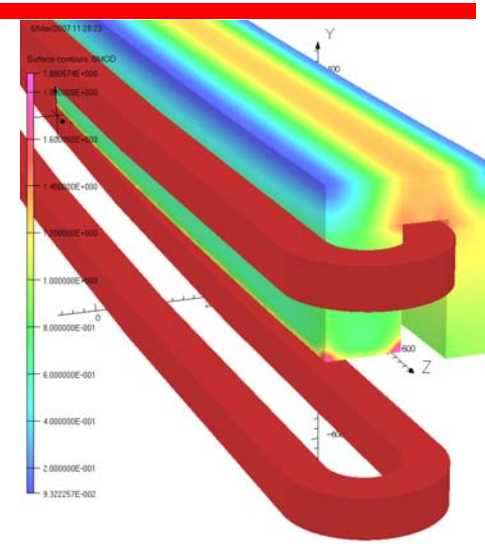


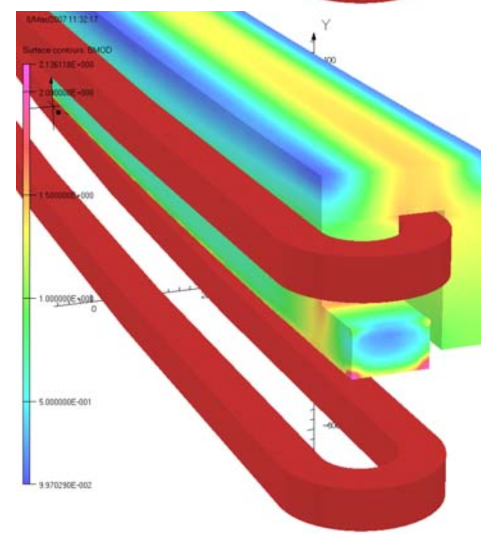
Allows magnetic length > Mechanical length

Length of the nose piece in the Buckley design is about ~10 cm on each side. Thus space made available for other uses in the machine > 10 meters.

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

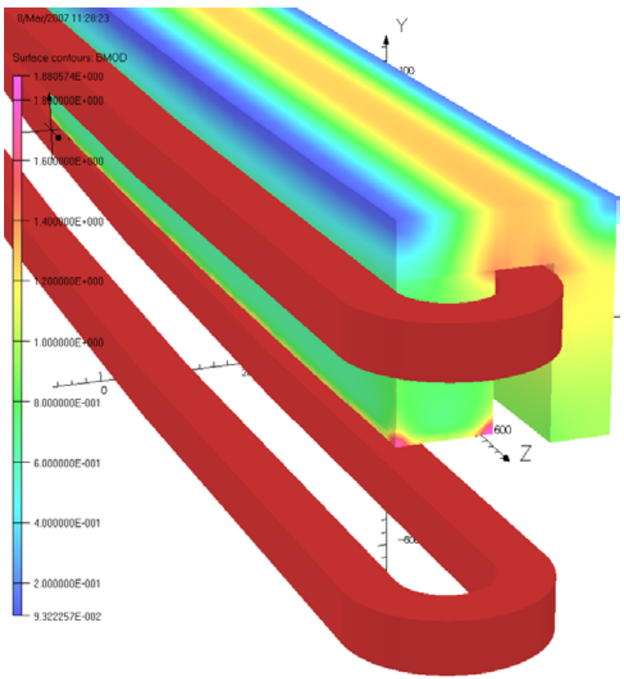
- In most iron dominated magnets, the magnetic length is determined by the length of the yoke and mechanical length by the length of the coil. Thus the mechanical space taken by the coil ends is wasted.
- The proposed *"Pole Extension"* or *"Nose"* essentially eliminates this waste. For all practical 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 almost at the full value (as long as the iron 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 be consisted of one or more pieces. As an added benefit, it allows easy 3-d tuning of the fields (design and machine nose pieces after the first set of magnetic measurements).
- Nose piece also allows us to choose between a sector magnet or ends with parallel face. A ~5.2 mm wedge cut in the nose piece would create a sector bend with end fields perpendicular to the trajectory.



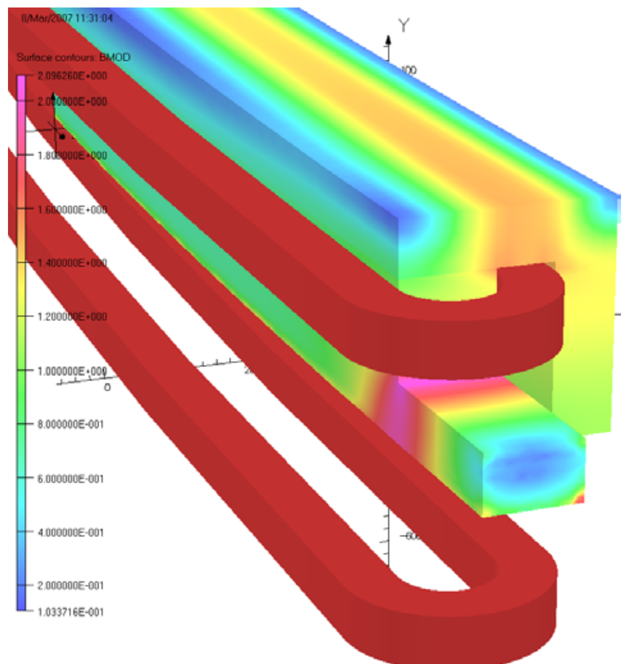


Optimization of Extended Pole (Nose)

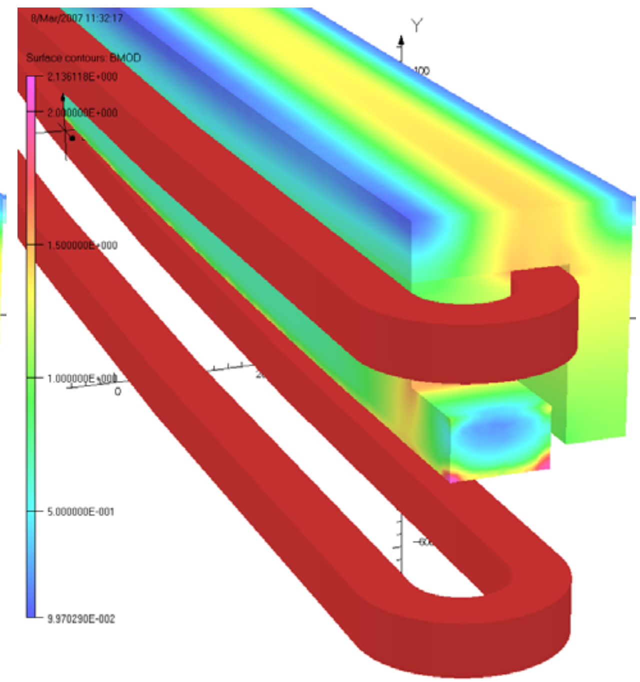
A number of studies were done to optimize axial extension and height of the the extended pole (nose).



No Nose

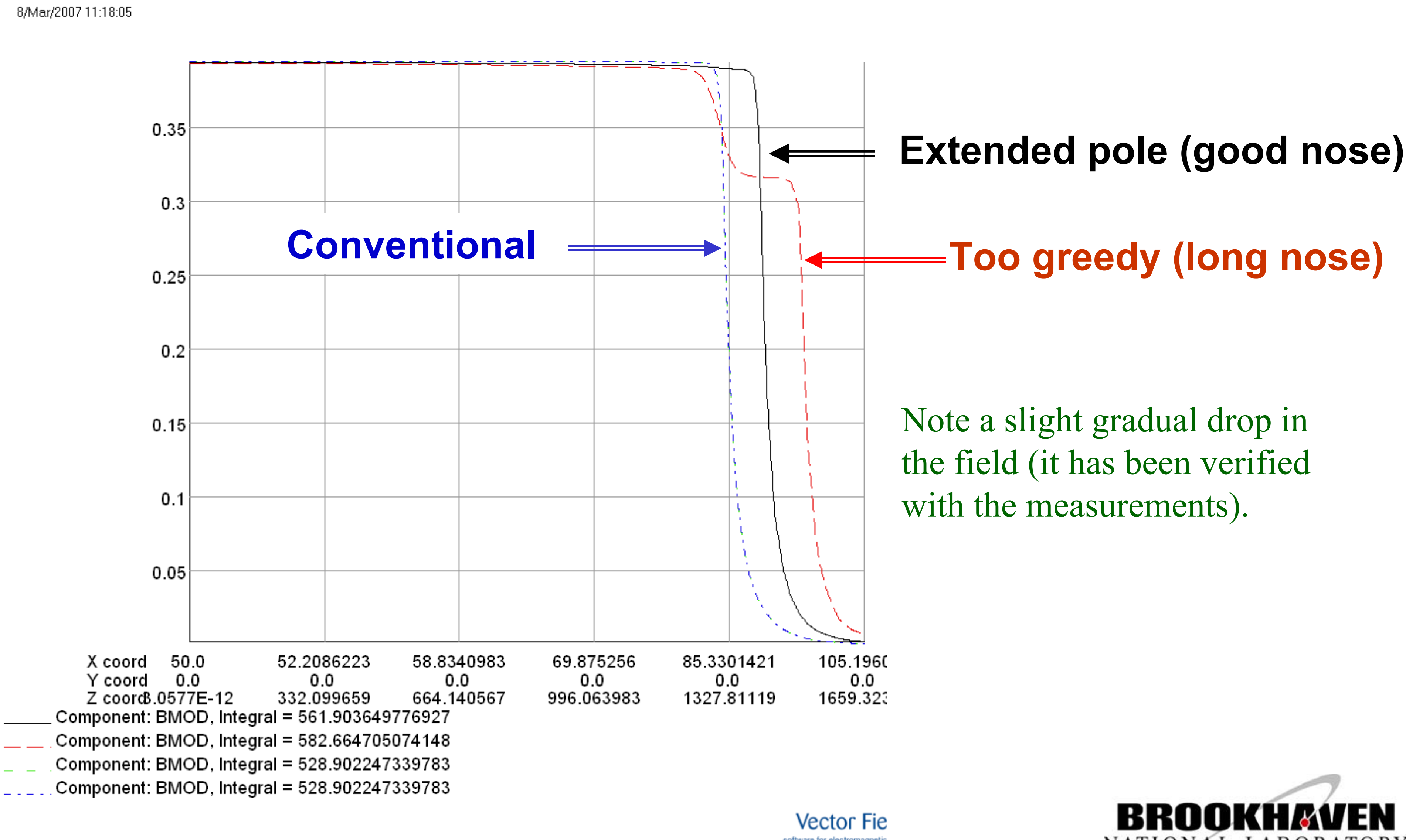


Long Nose (too greedy, note saturating nose)



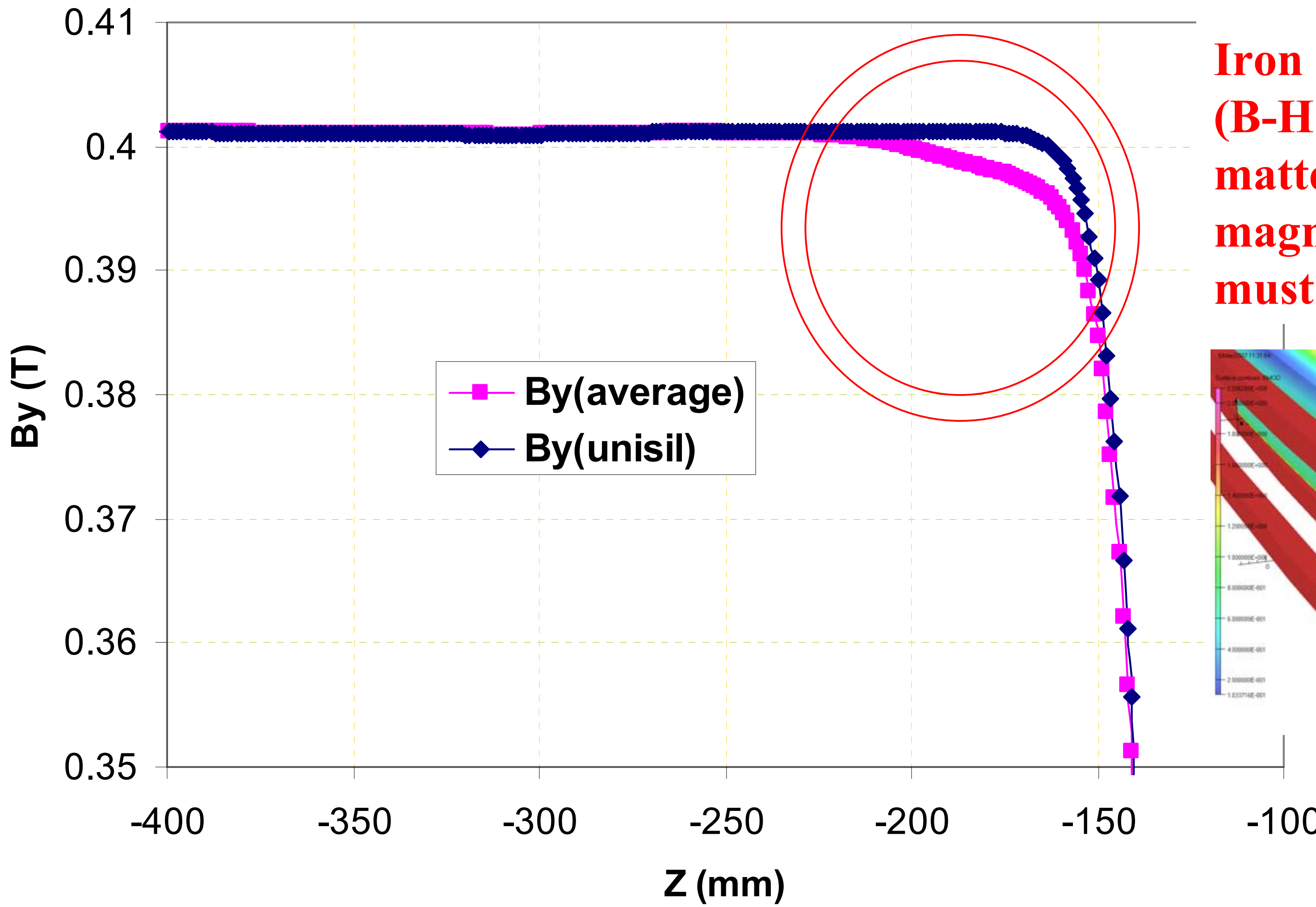
Good Nose (extended pole)

Variation in the Length of Nose Piece

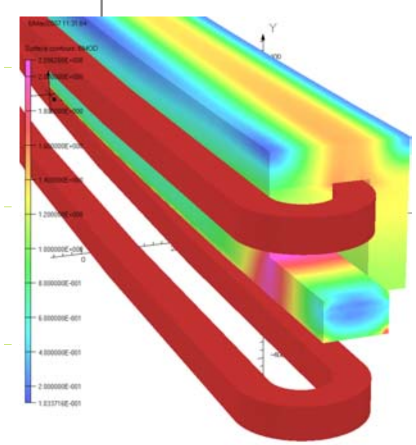


Note a slight gradual drop in the field (it has been verified with the measurements).

Magnetic Properties of the Iron in the Nose Piece



Iron property (B-H curve) matters. A good magnet steel must be used.



Nose Pieces in the R&D Model Magnets

Why are we paying so much attention to the details of nose pieces?

If the nose pieces are not too long and they are made of good material then the length gained won't matter so much on the details.

However, the field measurements (and simulations) indicate that:

a) Choice of magnetic material of nose piece was not good in case of short model from Stangenes

b) Length of the nose piece was increased a bit too much: ~68 mm in Stangenes to ~104 mm in Buckley (the initial design was examined up to 85 mm without any problem for typical iron)

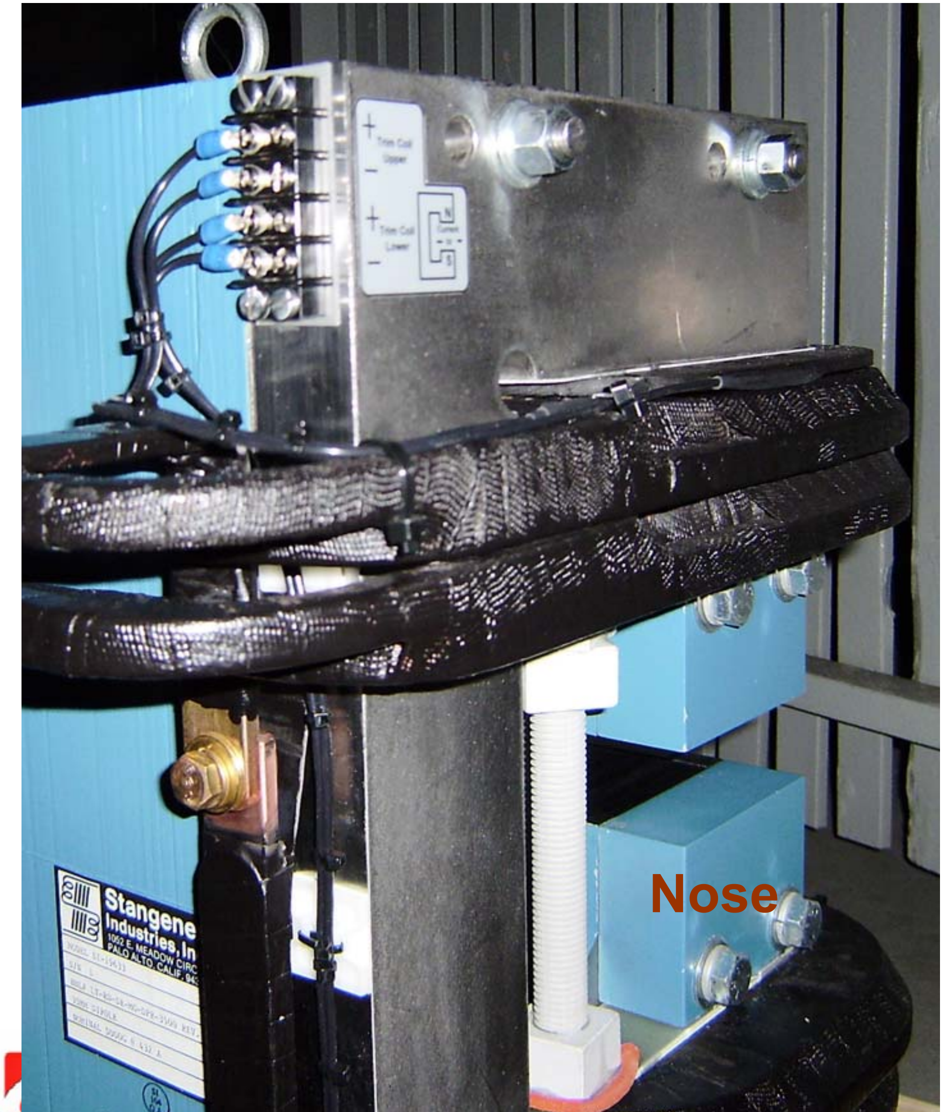
c) This issues is, however, a less of a concern in fixed field magnet as long as the B-H property of nose material does not vary from nose to nose.

Short Model Magnet from Stangenes

Design Parameters for the short model magnet:

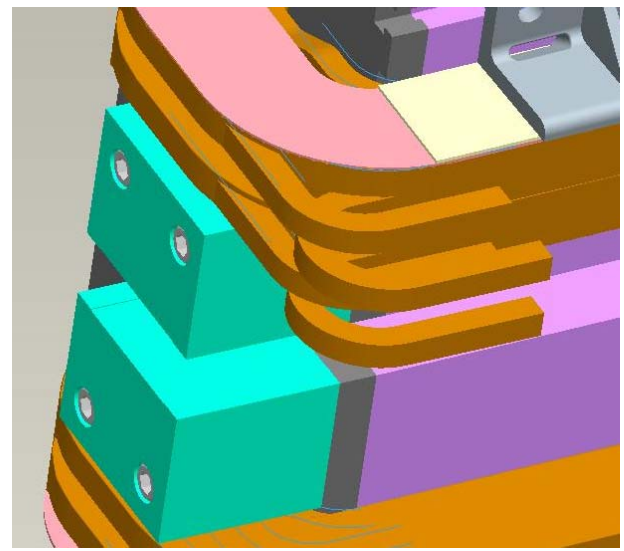
- Yoke-to-yoke length = 0.962 meter
- Nose-to-nose length = 1.137 meter (2 nose pieces, 68.5 mm each)
- Plate-to-plate = 1 meter (plate is non-magnetic)
- Design field = 0.4 T

Nose Piece that was initially delivered had to be replaced



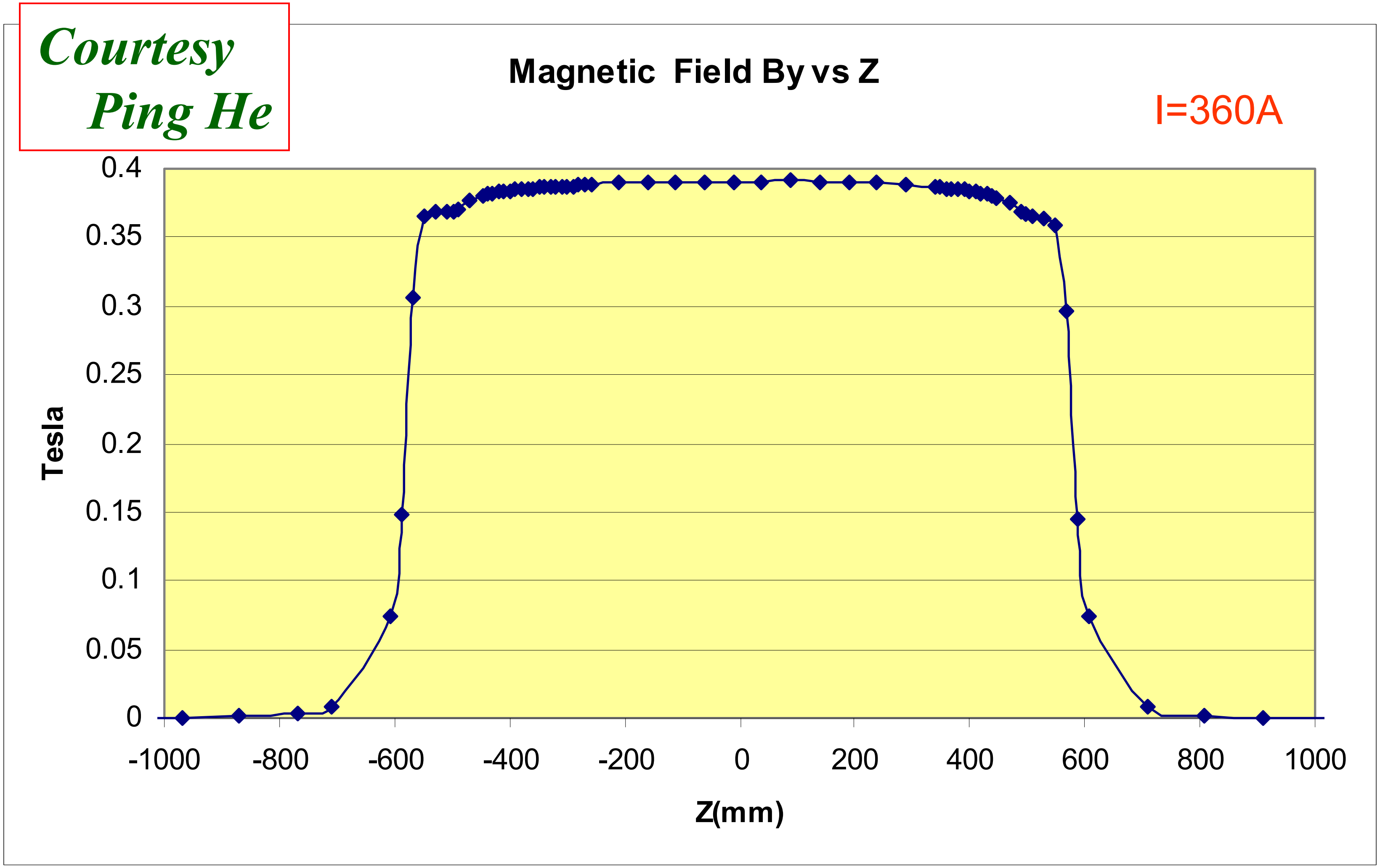
Because:

- Nose piece should have extended to the coil ends
    - ➢ it did not !
- Mounting bolts should not have extended beyond the end of the nose
    - ➢ they did !!



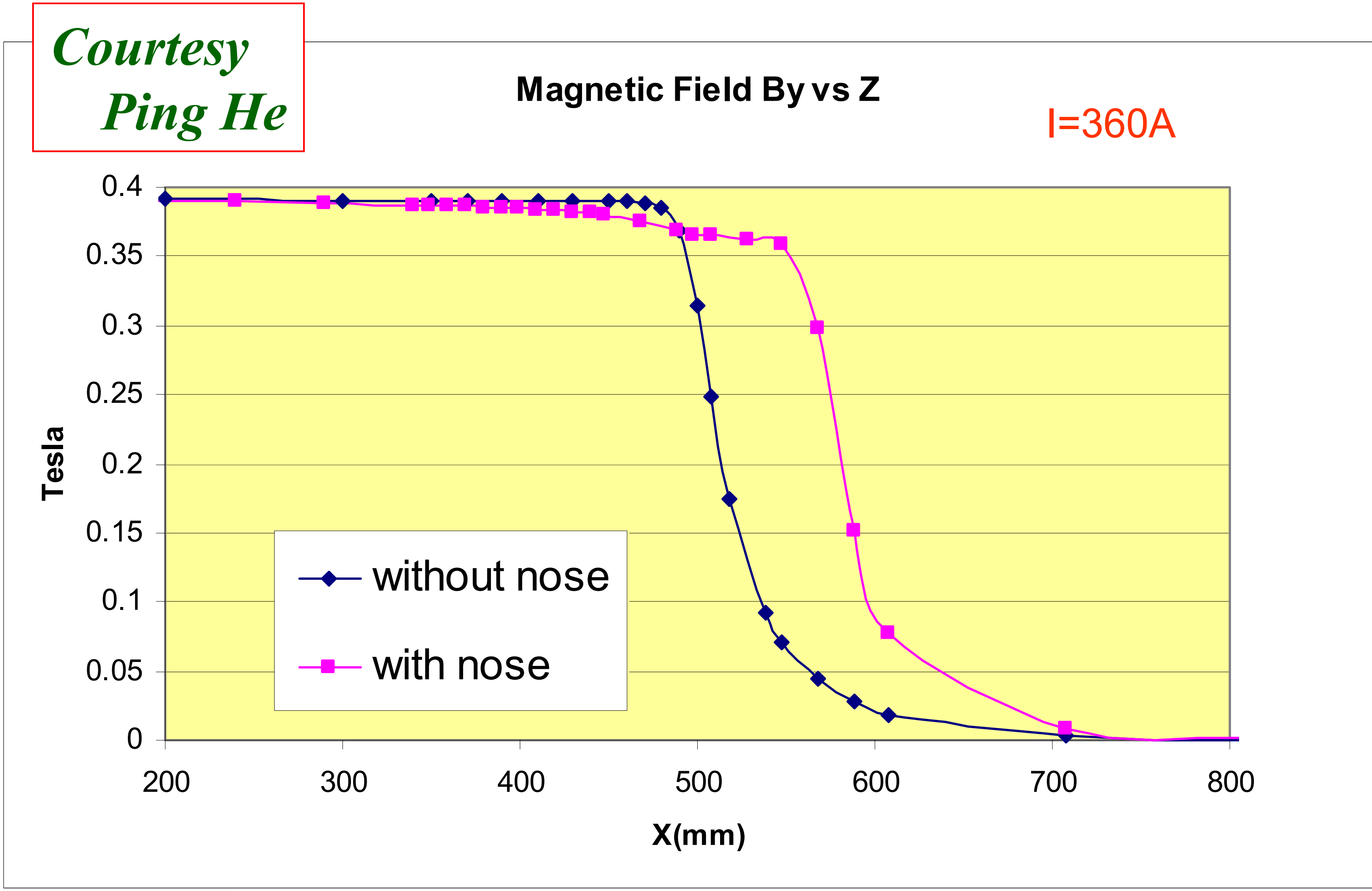
Actual measurements were done with the correct nose piece.

Axial Field Profile of Stangenes Dipole at 0.4 Tesla

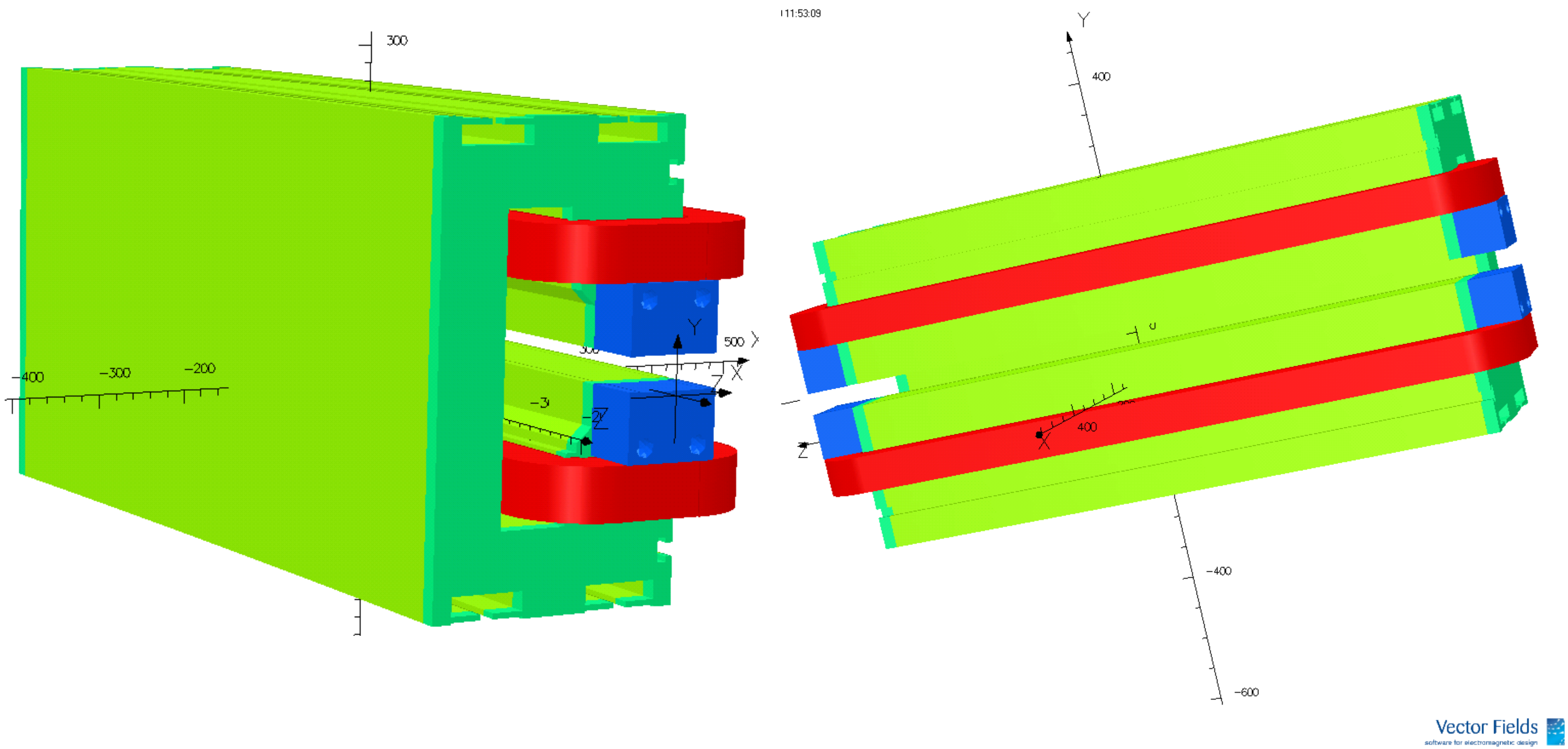


Axial Field Profile at 0.4 Tesla

with/without nose piece

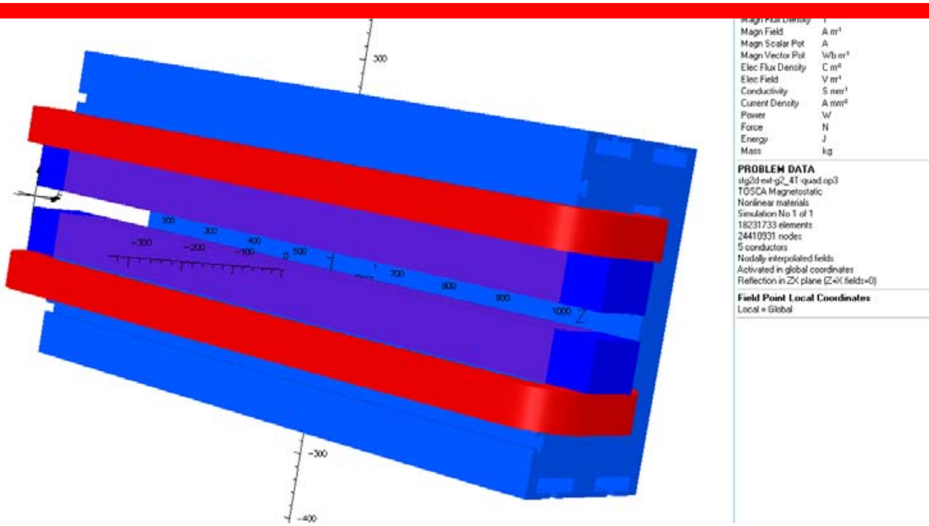


Magnetic Model of Stangenes 35 mm Short Dipole (1)

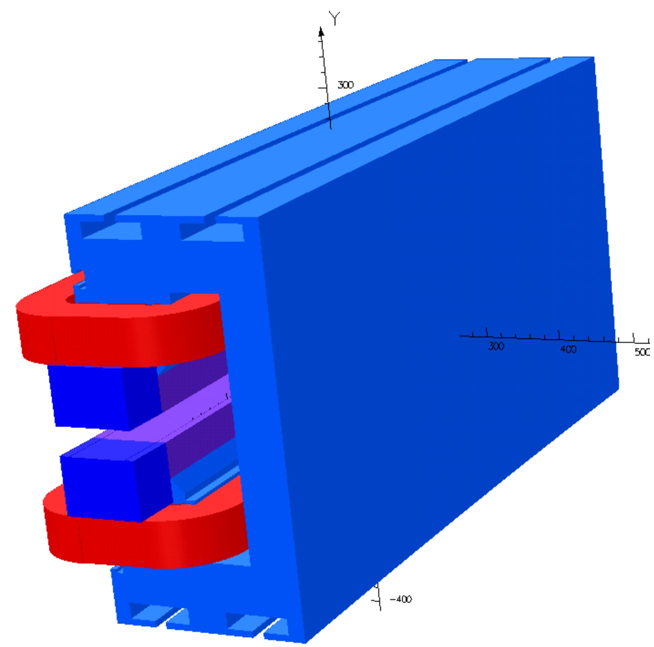


Model made from the CAD model (SAT file) provided by the vendor

Magnetic Model of Stangenes 35 mm Short Dipole (2)



Model made by extruding the optimized OPERA-2d model

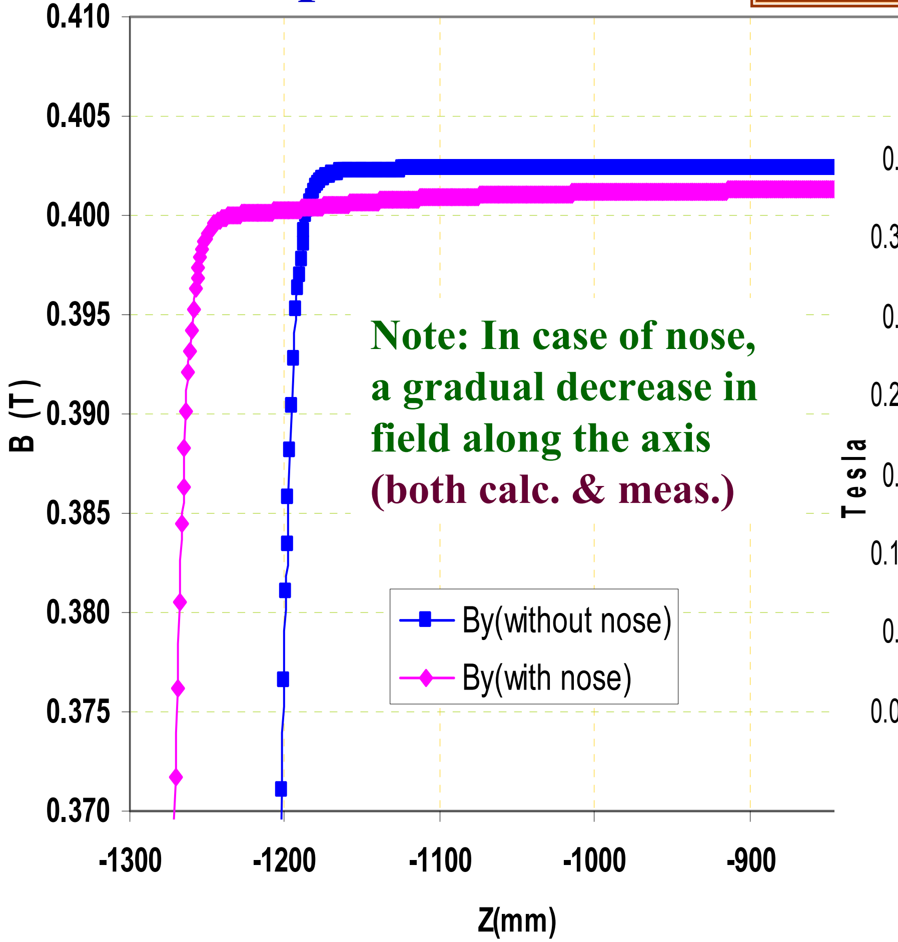


- Using vendor CAD file assures that, in principle, we are make model of the as built magnet.
- However, this may not necessarily produce the best mesh for the most accurate field calculations for the same number of mesh points as more mesh points may go in less critical area.
- Therefore, I generally prefer the method described here is preferred as it gives a better handle on the mesh and hence on the accuracy of field calculations.
- Also sometime CAD model sent by vendor may not match the actual magnet.

Extension of Magnetic Field Region Due to Nose

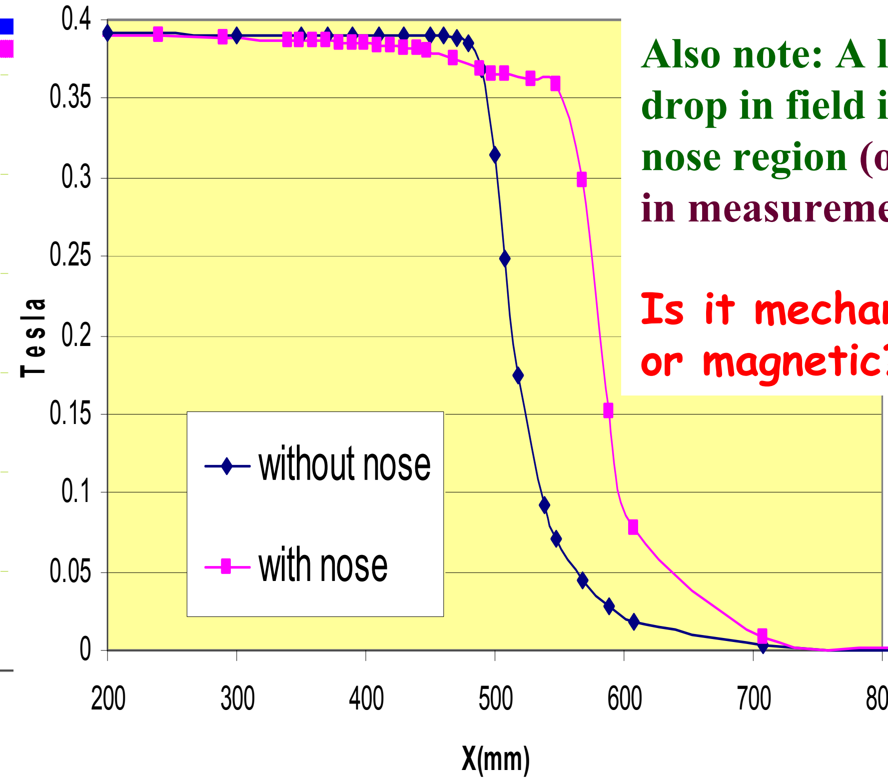
Length of the Nose Piece = 68.5 mm

Computer model



Note: In case of nose, a gradual decrease in field along the axis (both calc. & meas.)

Measurements

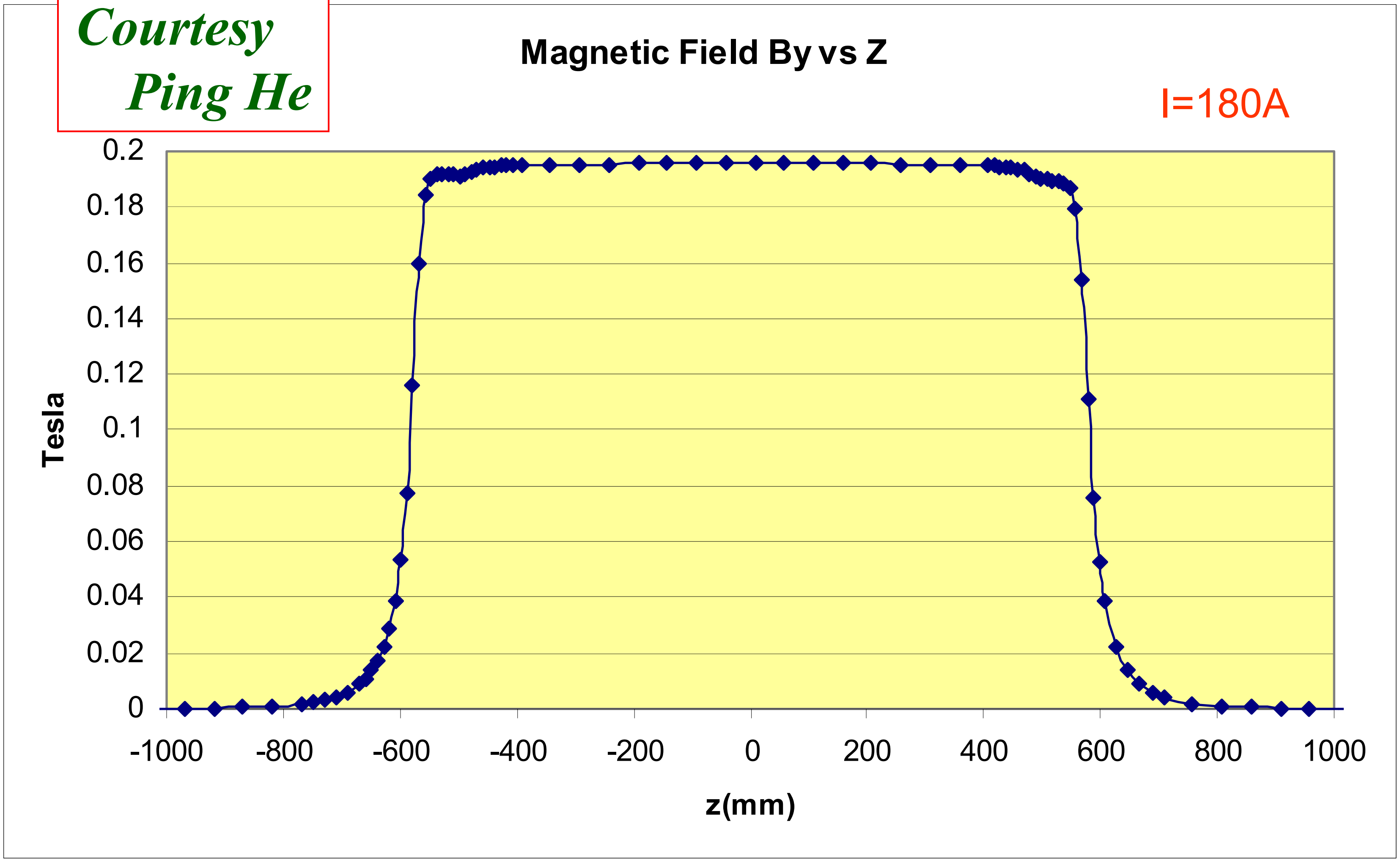


Also note: A large drop in field in nose region (only in measurements).

Is it mechanical or magnetic?

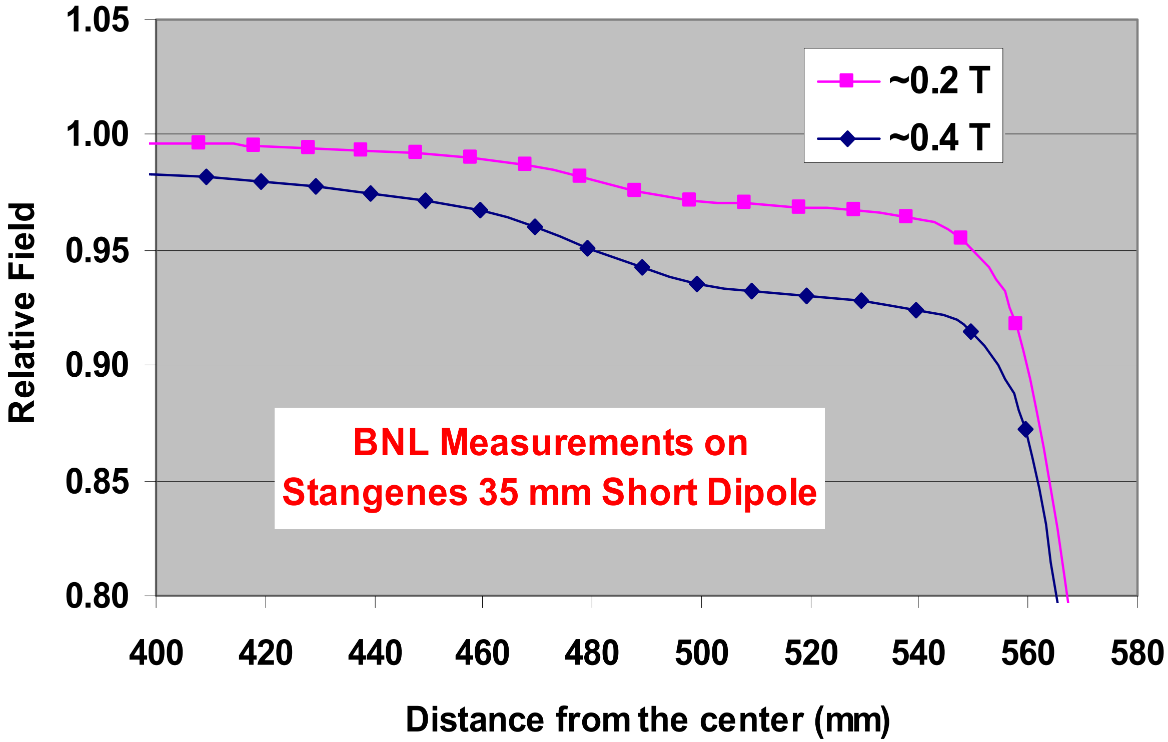
Axial Field Profile at 0.2 Tesla (half the design field)

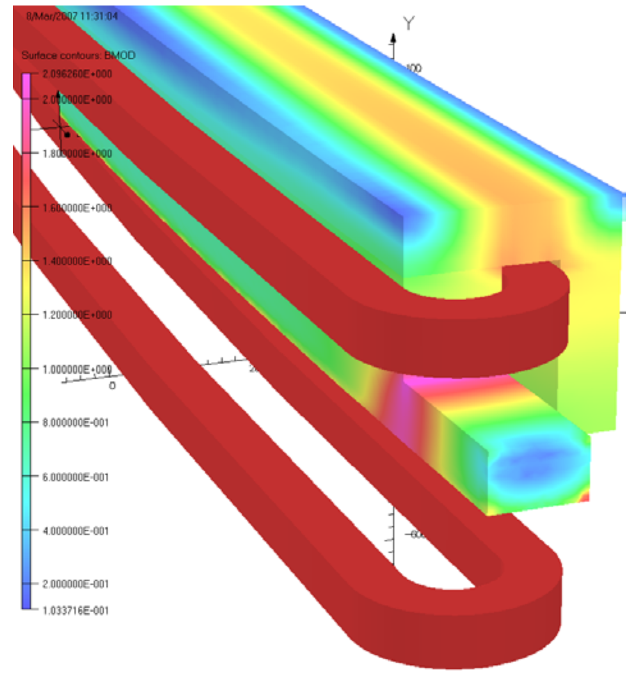
Courtesy Ping He



Verification of Iron Saturation in Nose

If drop in field in nose region is due to mechanical discrepancy, then the relative drop would be independent of excitation

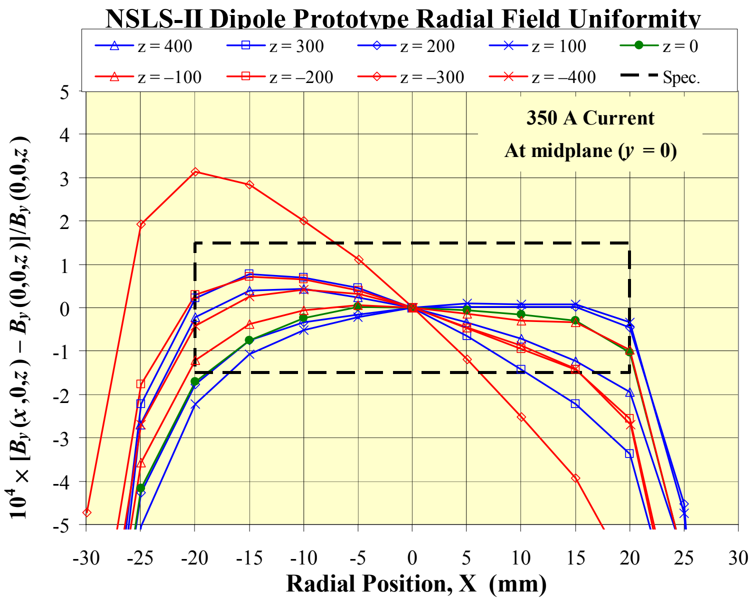


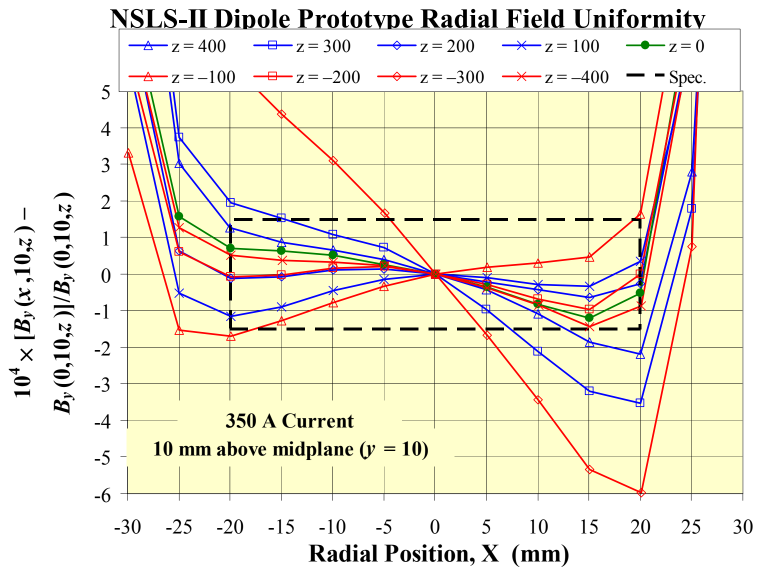


However, if the relative drop is due to iron saturation, then the drop would be lower at lower fields (lower saturation, as here).

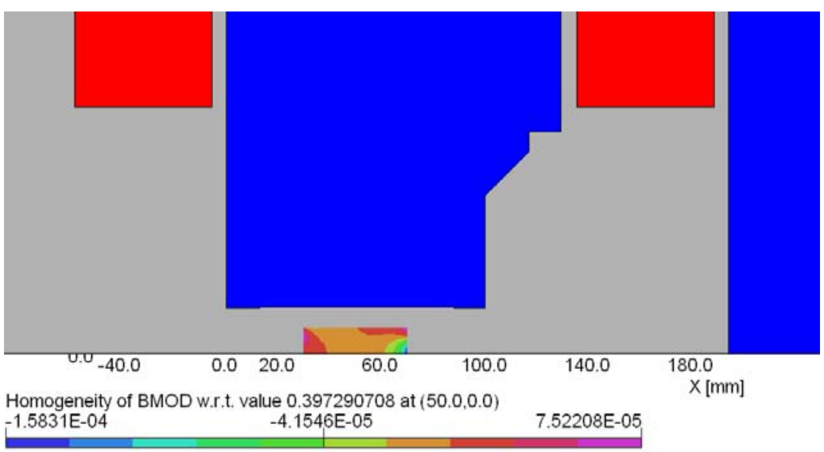
Conclusion: It's magnetic <u>NOT</u> mechanical.

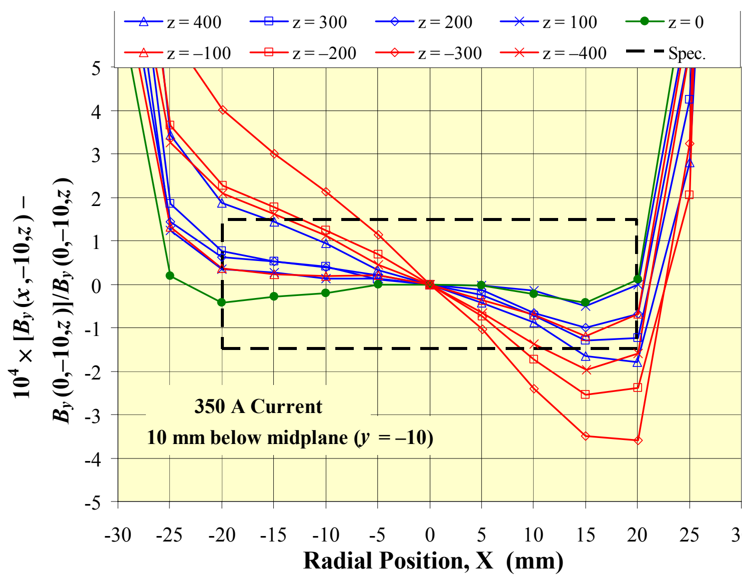
Field Errors in the Aperture





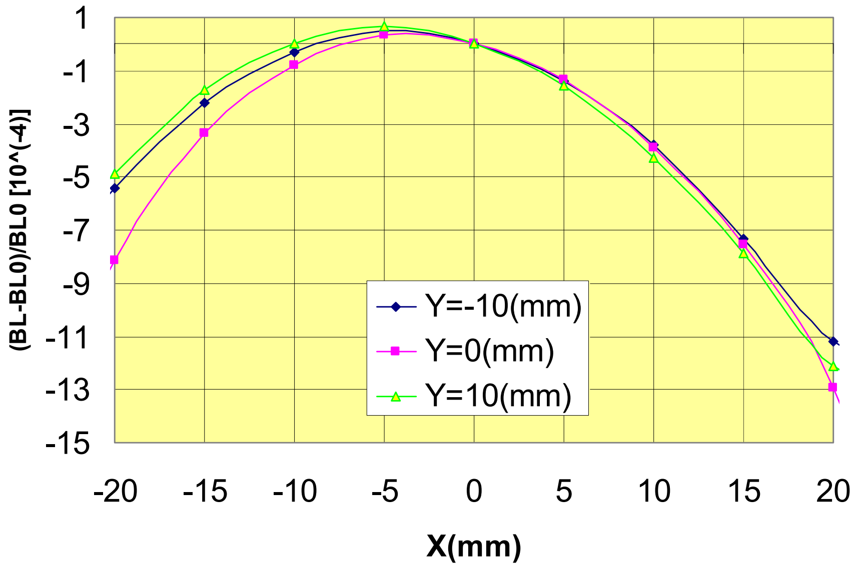
Measurements courtesy: Animesh Jain & Ping He



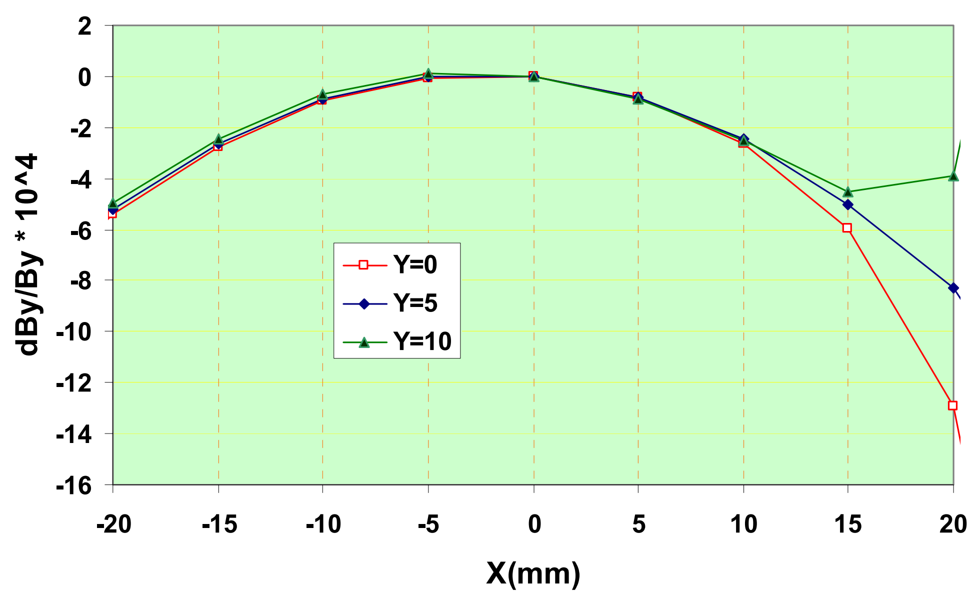


We generally meet the specs. There are always additional errors due to construction, calculations and measurements. The agreement is reasonable.

Comparison Between Calculations and Measurements

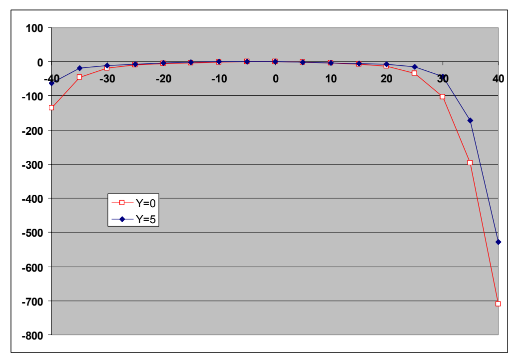


A reasonable agreement between calculations and measurements



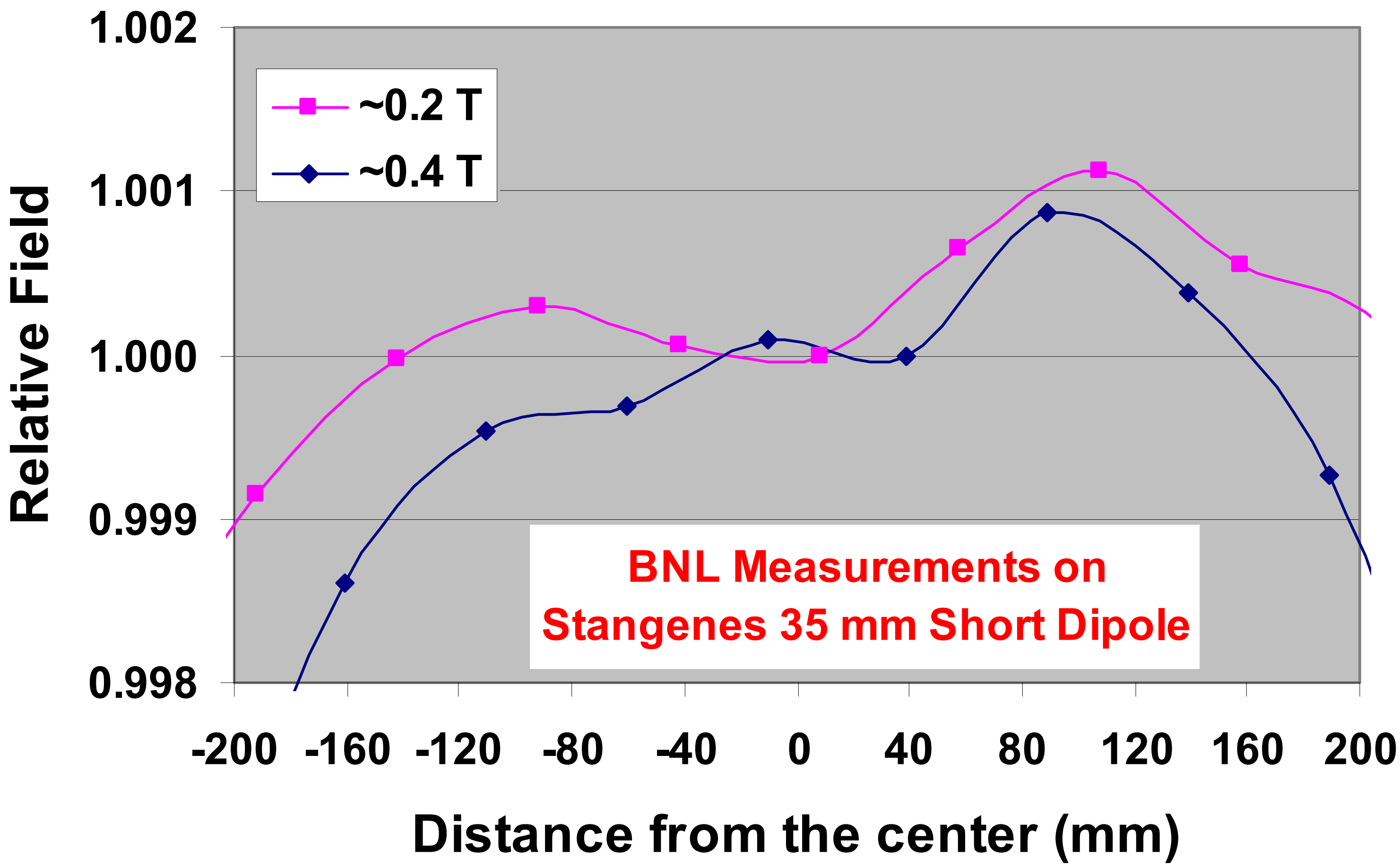
As per plan, the nose will be chamfered to minimize the measured integrated error.

Field quality specs are expected to be met.



Also present small quad and perhaps higher order odd terms

Axial Profile in 35 mm Stangenes Dipole

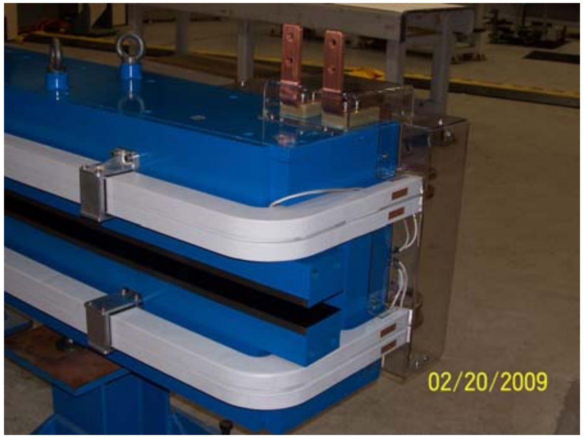


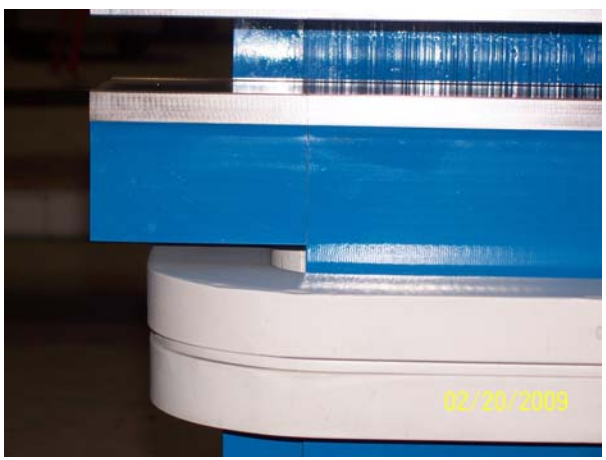
A few part in 1,000 variation has been observed along the magnet length.
Possible cause (mechanical or magnetic) is under investigation.
Is it typical? Is it a machine performance issue?

Full Length 35 mm Dipole R&D Model from Buckley

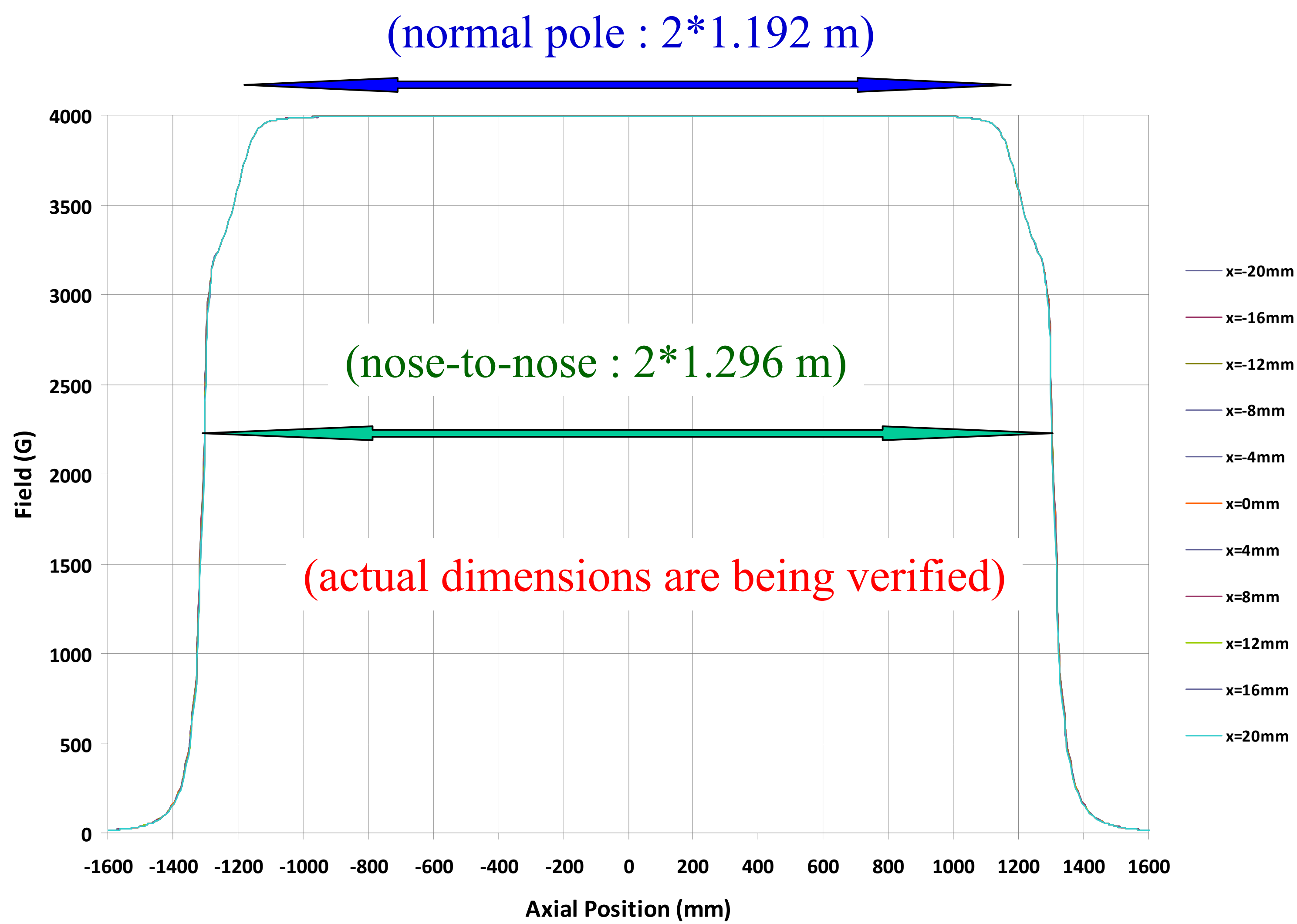
Just Arrived (Friday afternoon)

Nose Area in Buckley 35 mm Dipole

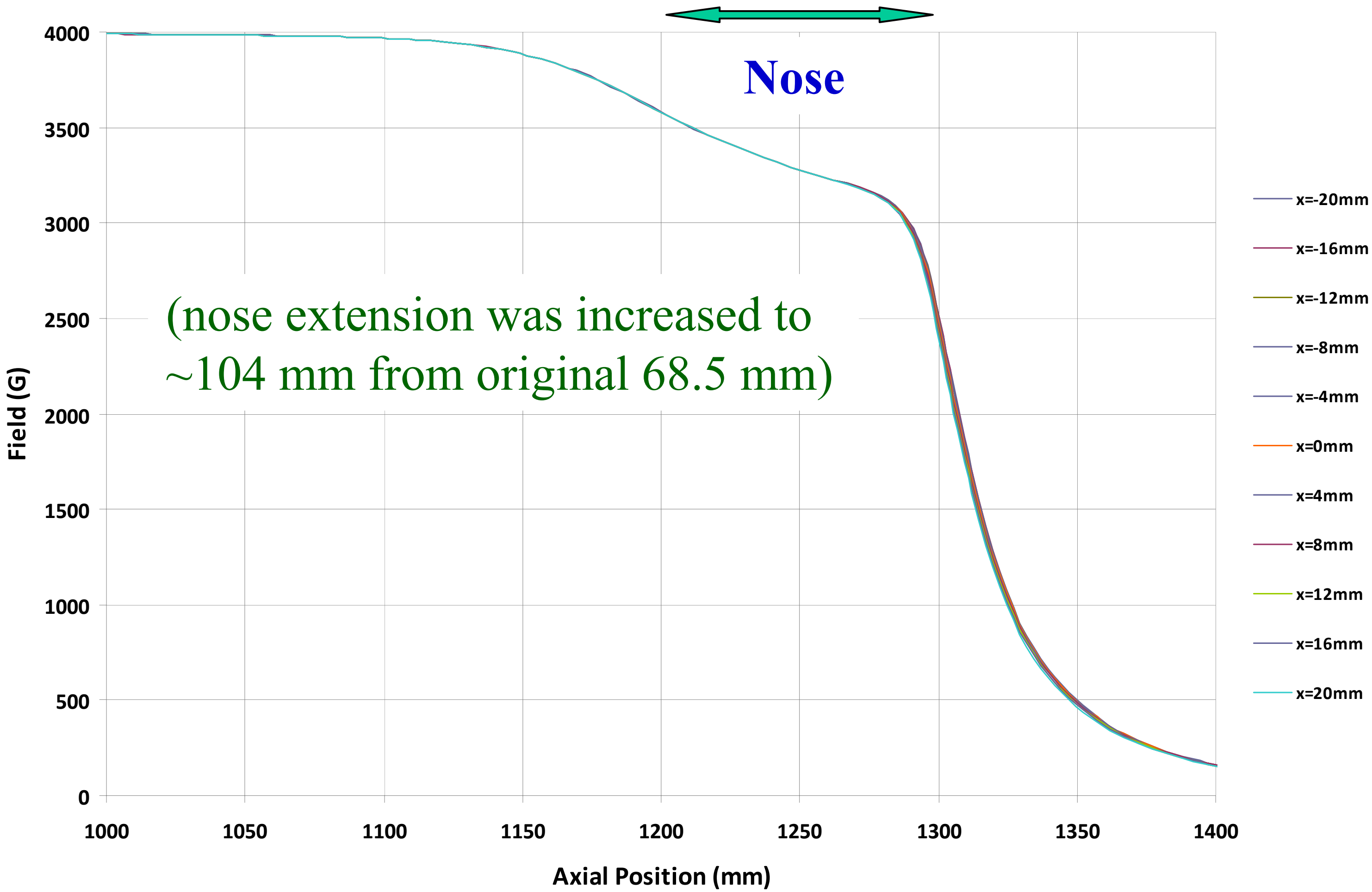




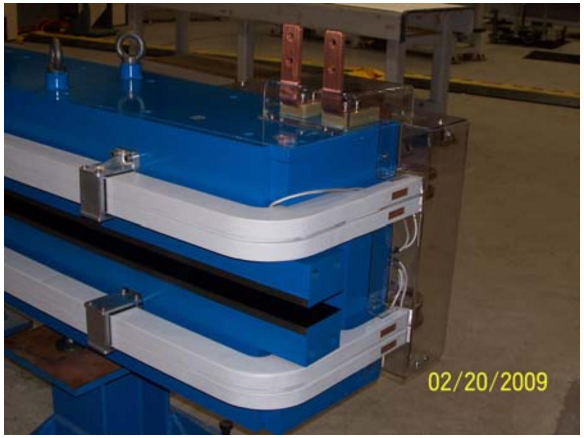
Axial Profile Of 35 mm Buckley Dipole (as measured in New Zealand)

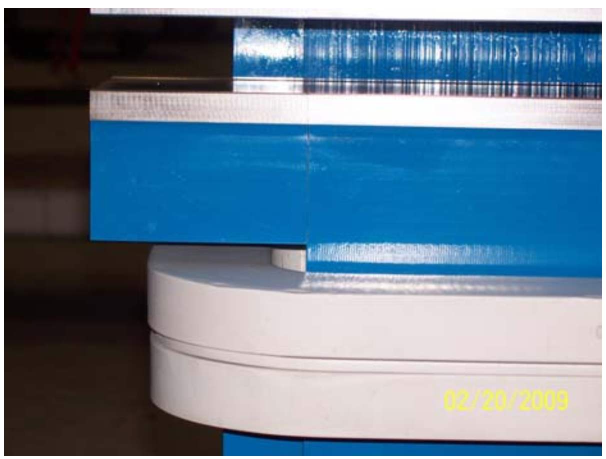


Details of Measurements in End (nose) Region



Nose Area in Buckley 35 mm Dipole

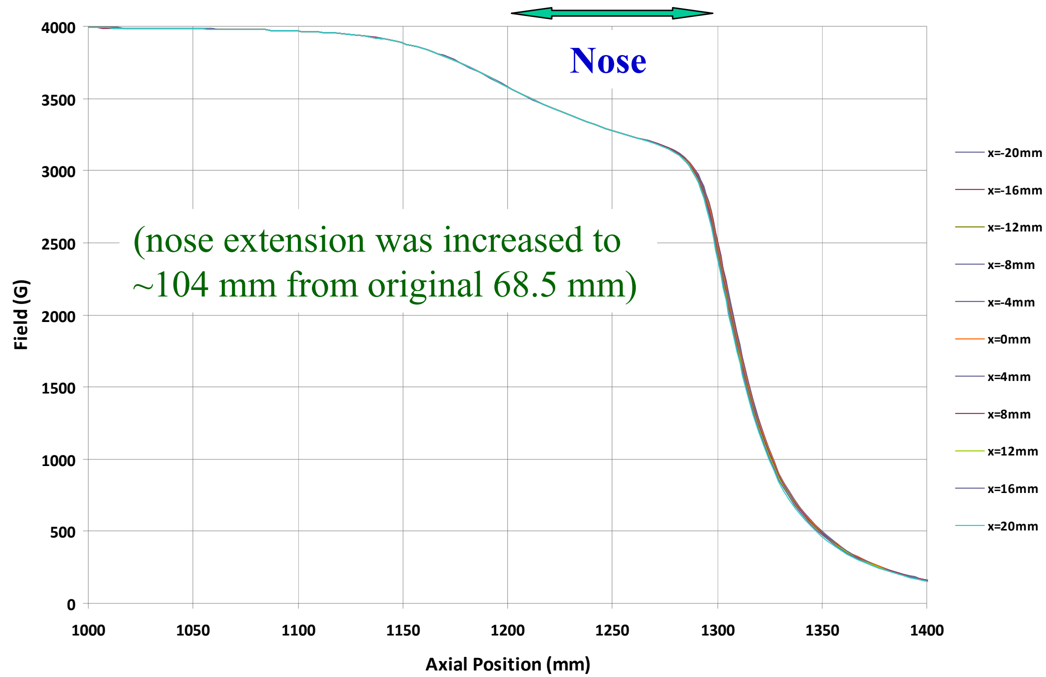


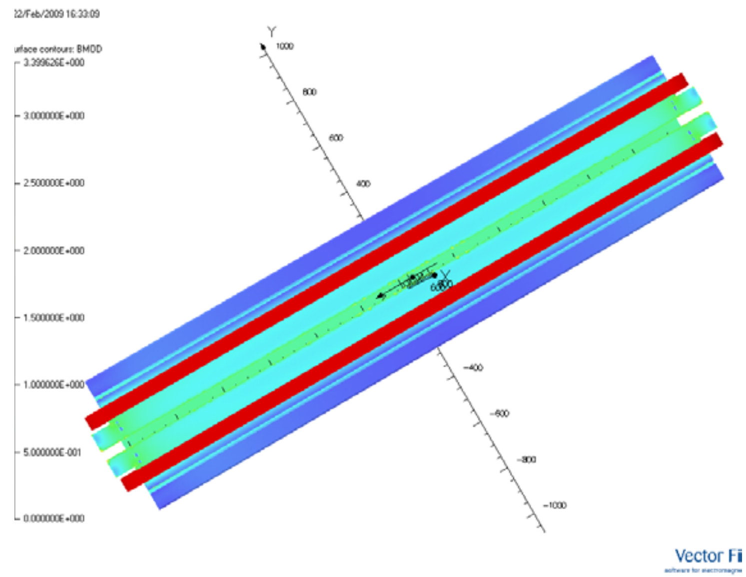


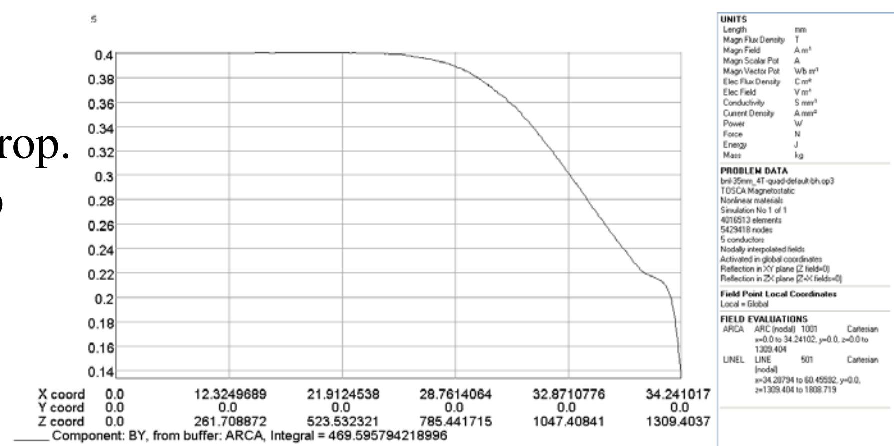
There is a clear opportunity to minimize a small drop in field in nose region

(insert iron, extend normal pole, etc.)

Drop in Field in Nose Region

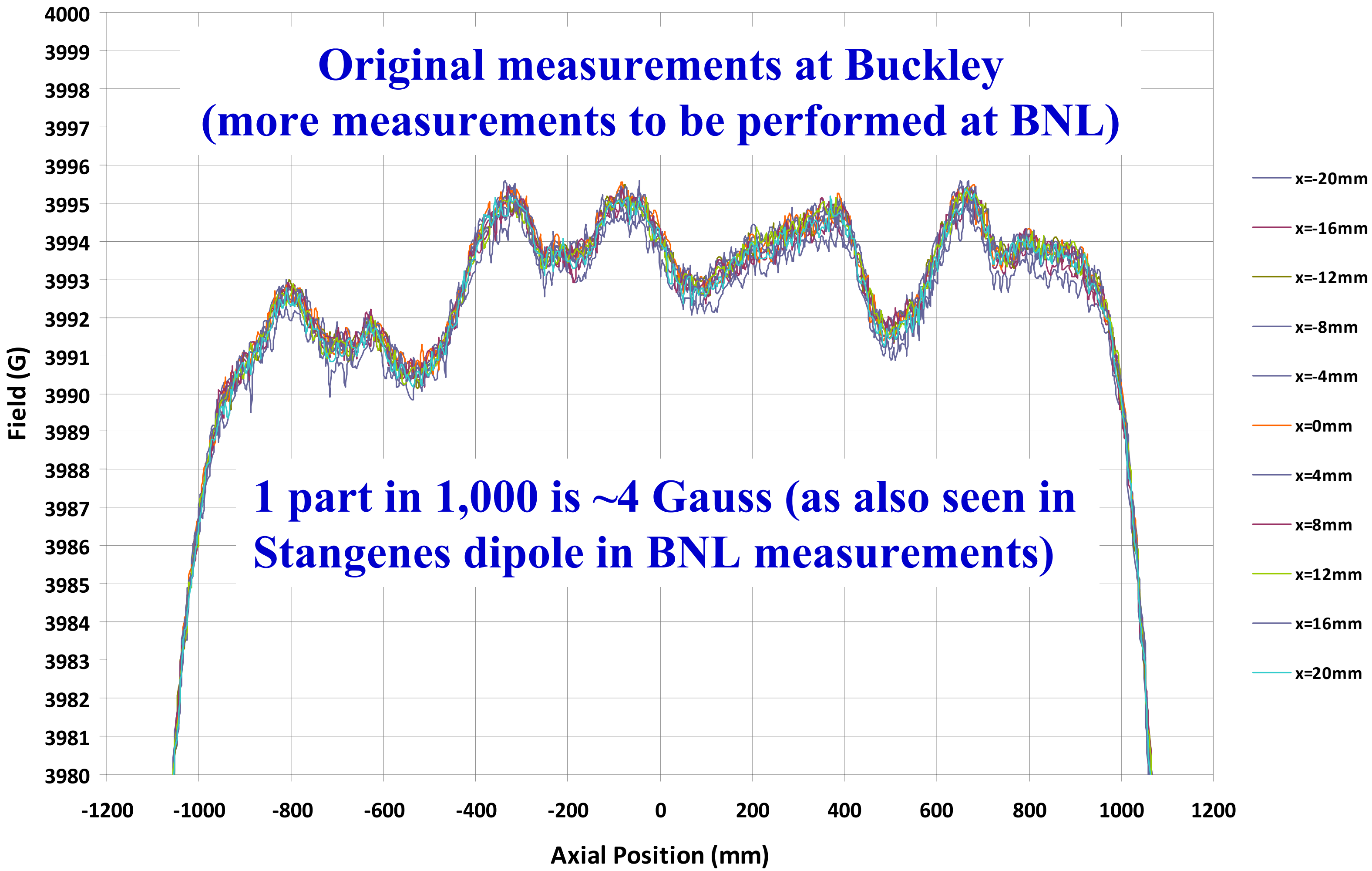




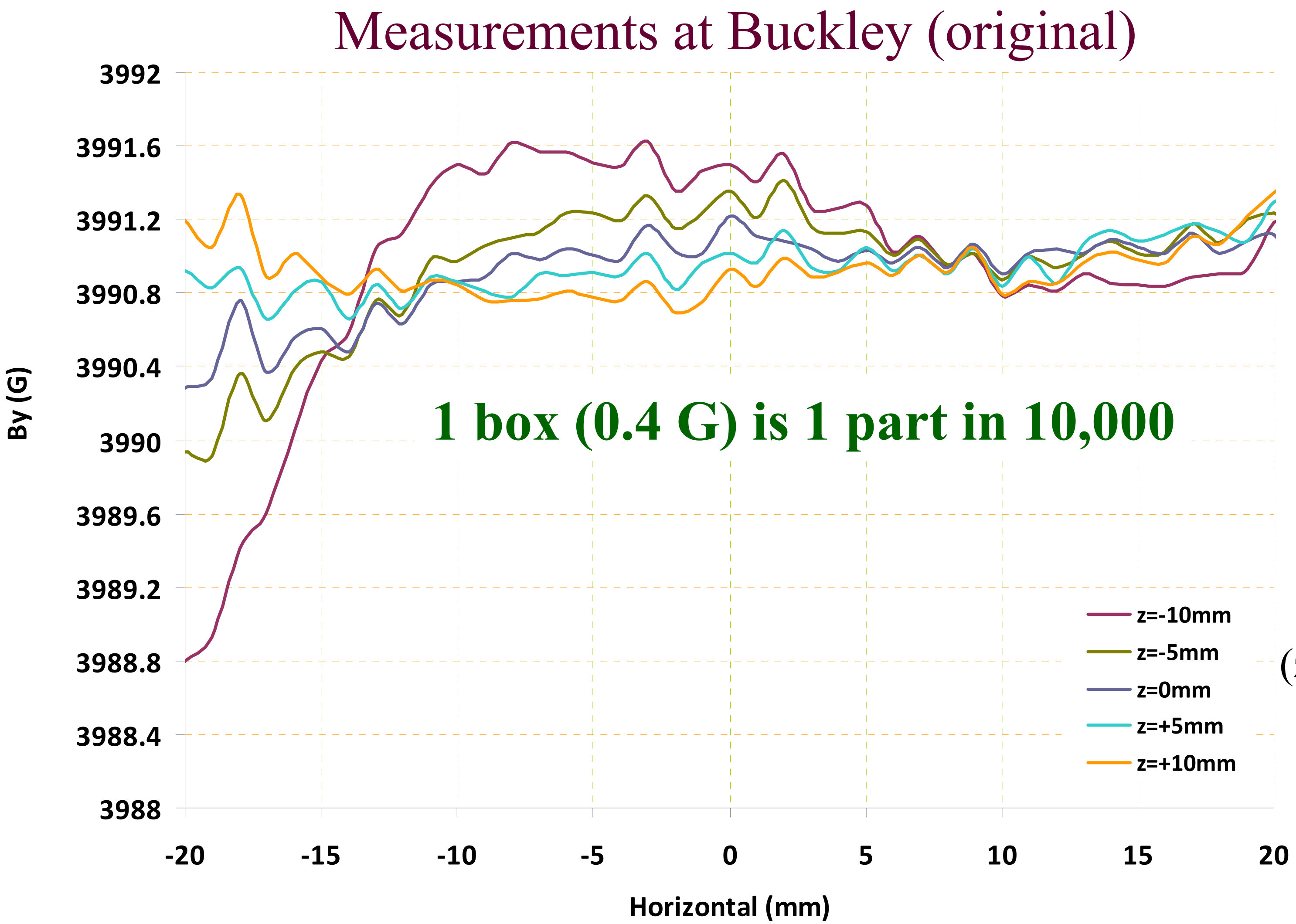


The magnet has just arrived (Friday).
We would do more analysis to explain and fix this drop.
In principle it is possible to create even a larger drop than the one measured (see one simulation on right).
We would do measurements at lower field, etc. to follow-on.

Field Along the Magnet Axis (fine variations)



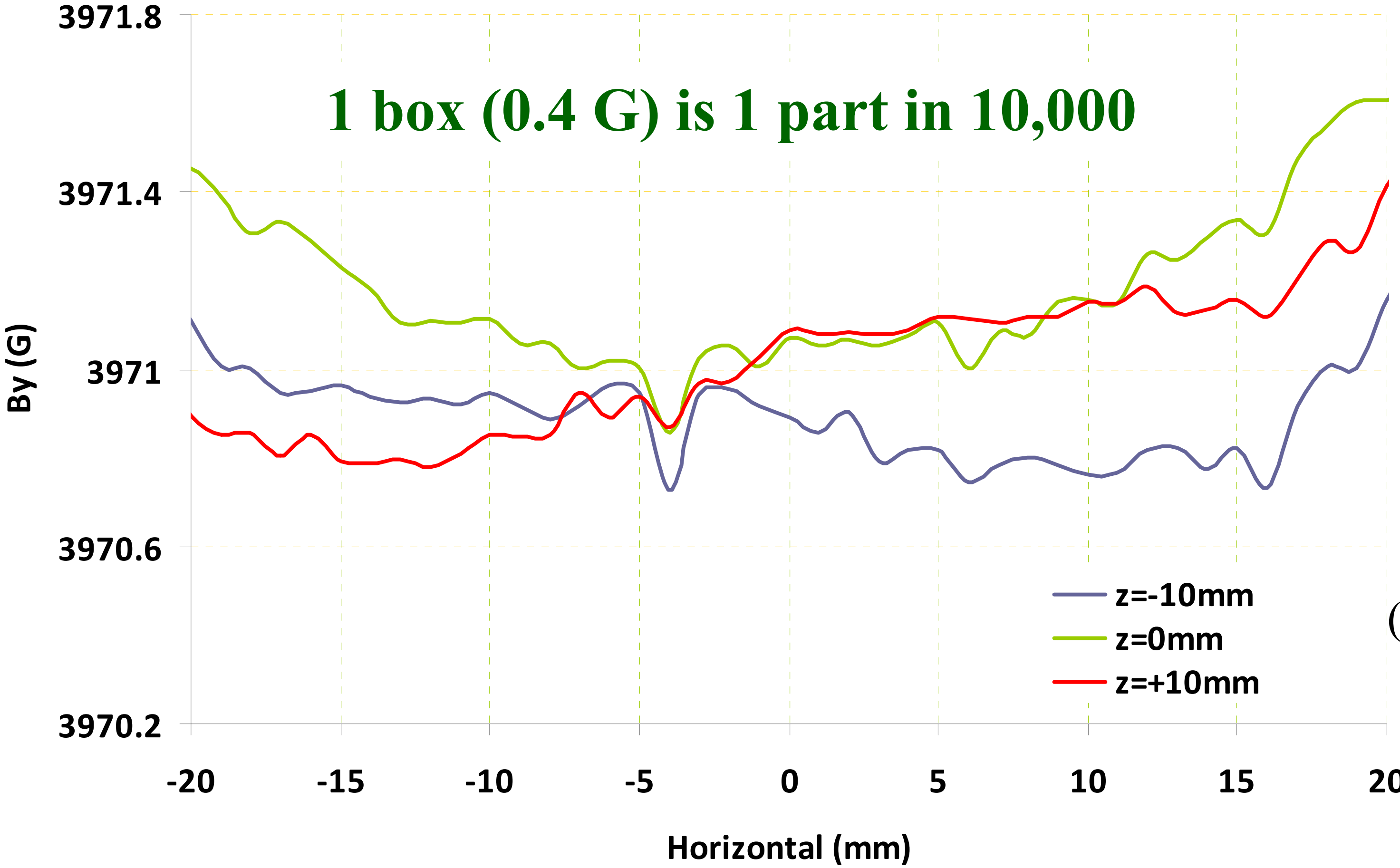
Field Quality in Magnet Aperture



(z is vertical here)

Field Quality in Magnet Aperture

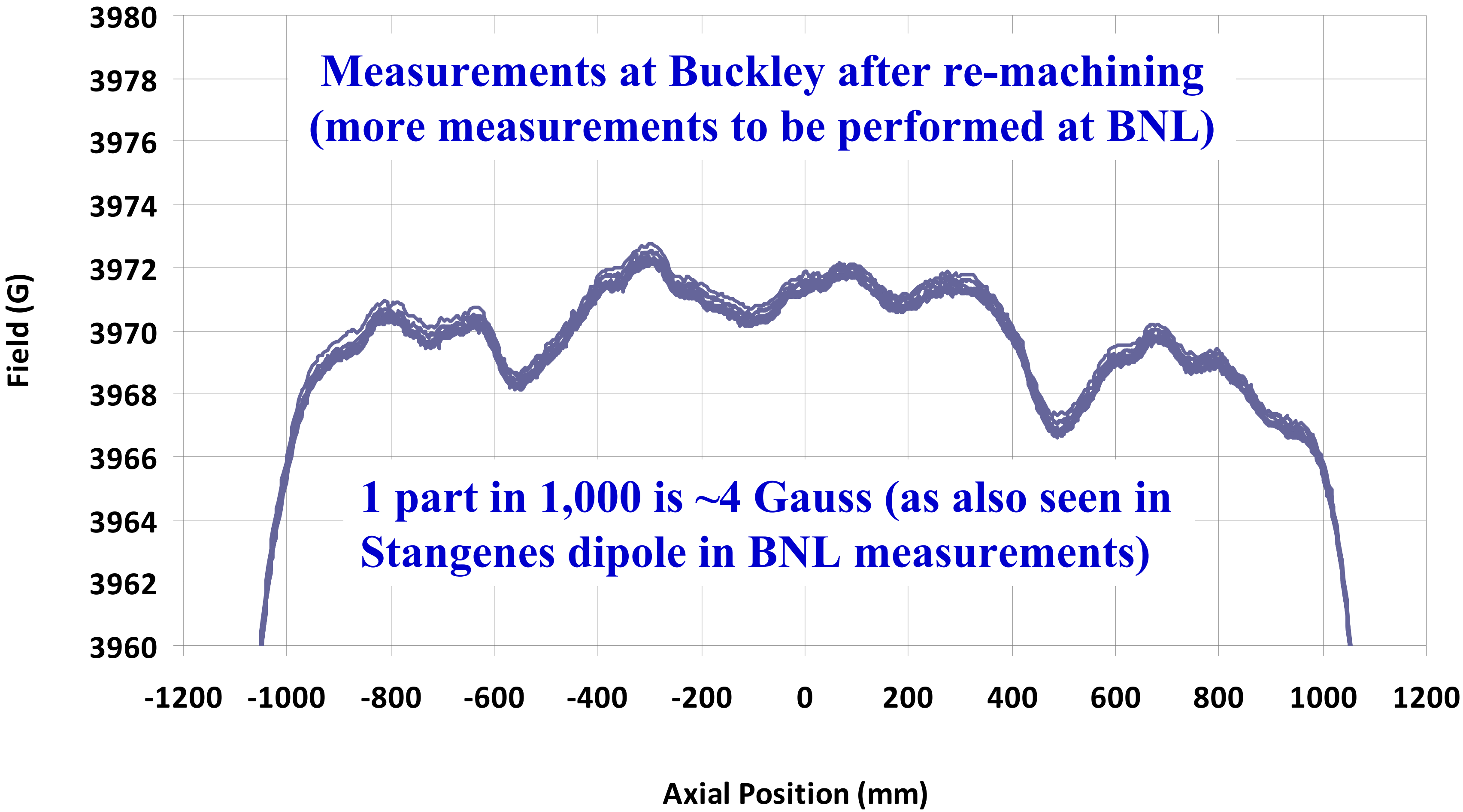
Measurements at Buckley (after re-machining)



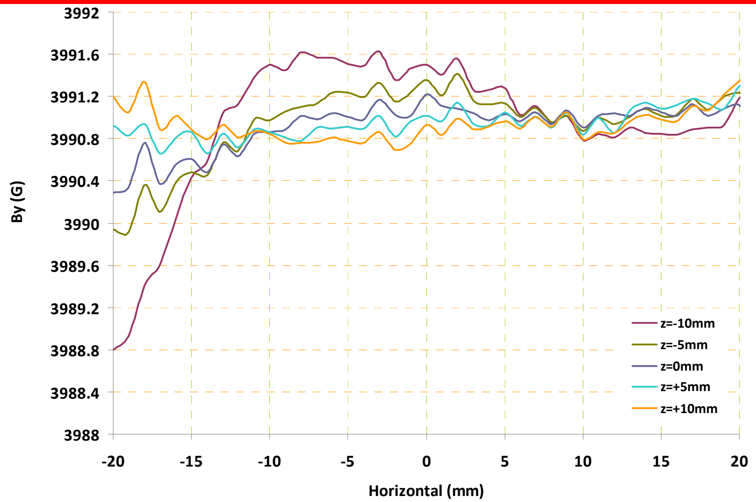
Field quality seems to have improved by re-machining

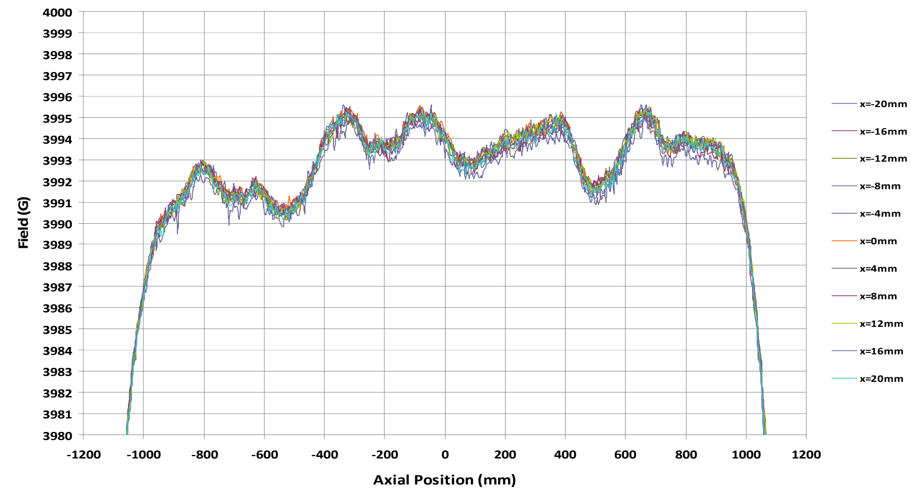
(z is vertical here)

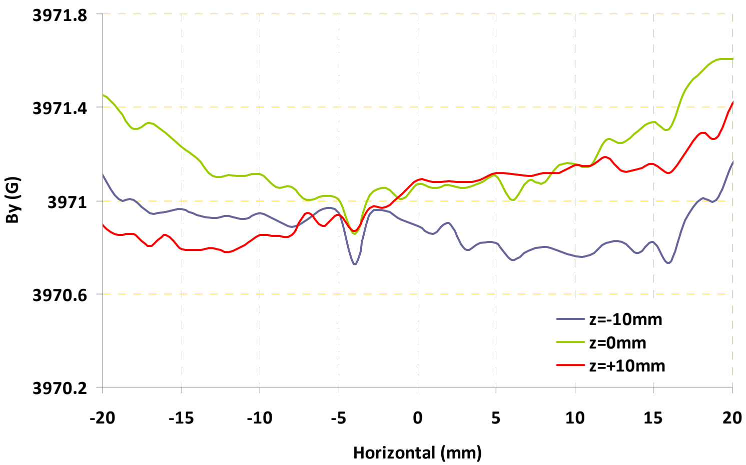
Field Along the Magnet Axis (fine variations)

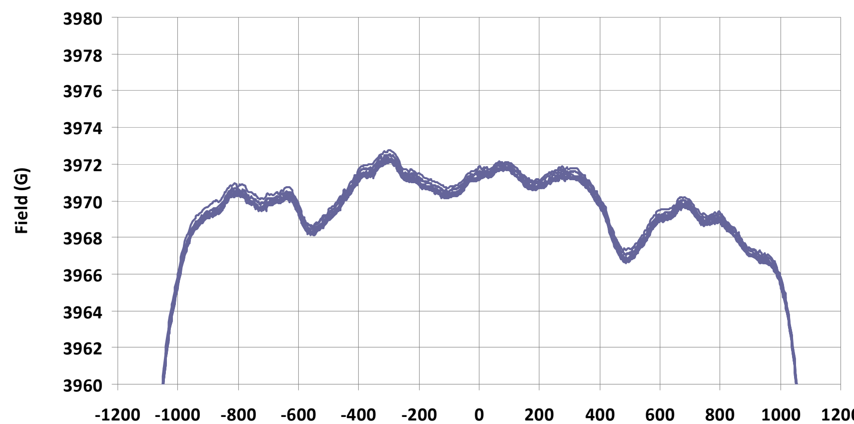


Buckley Dipole (before and after re-machine#2)





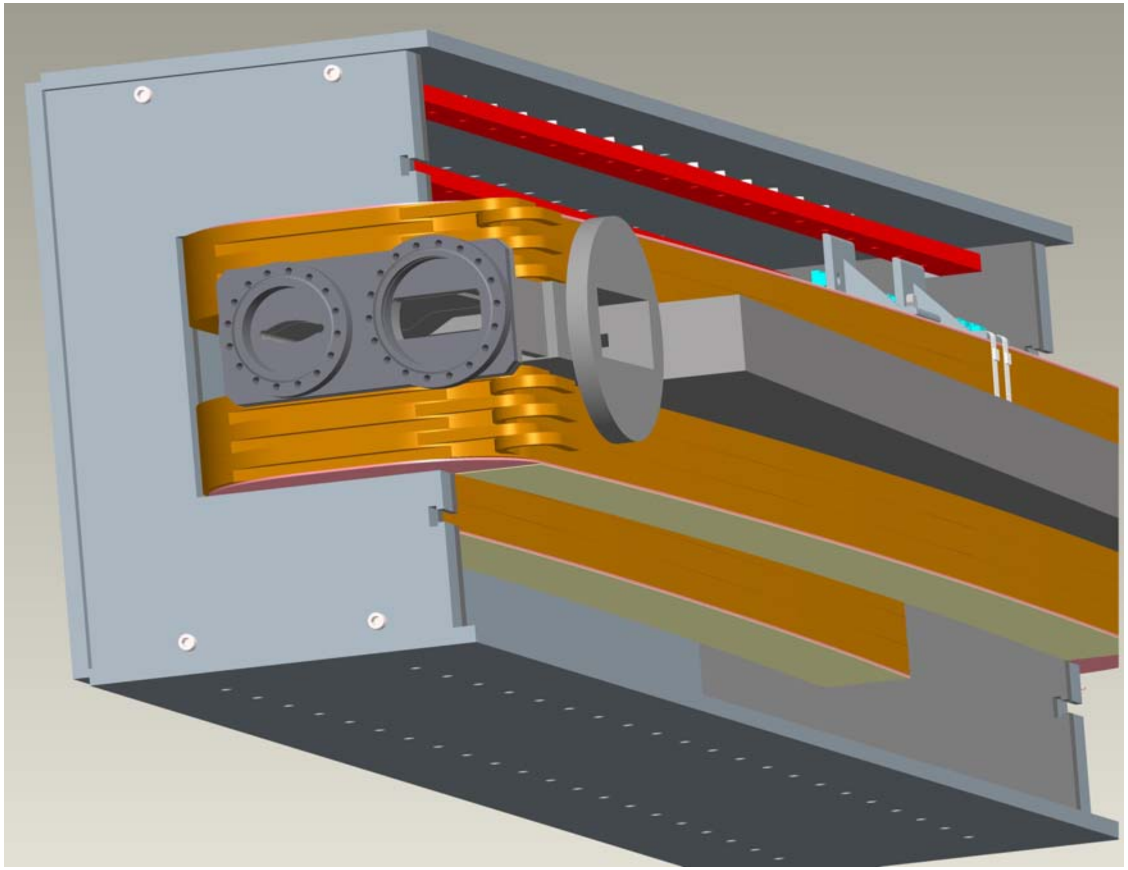




Field quality seems to have improved by re-machining

1 part in 1,000 is ~4 Gauss (as also seen in Stangenes dipole in BNL measurements)

90 mm aperture dipole



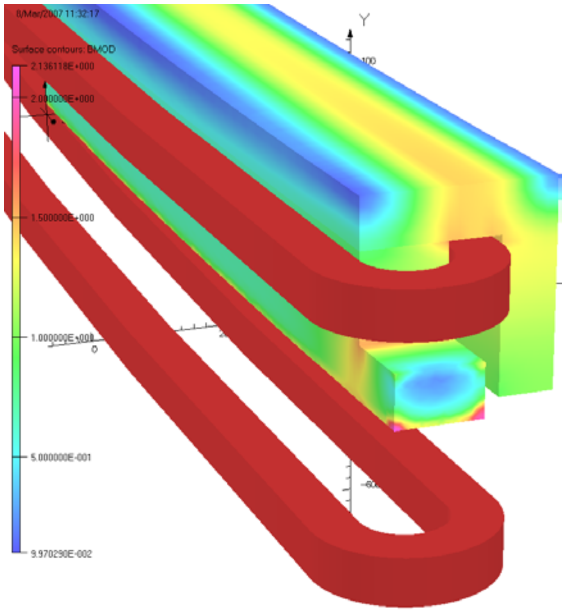
Coils and mechanical features (such as enclosure) are shown.
Yoke is hidden in side this box.

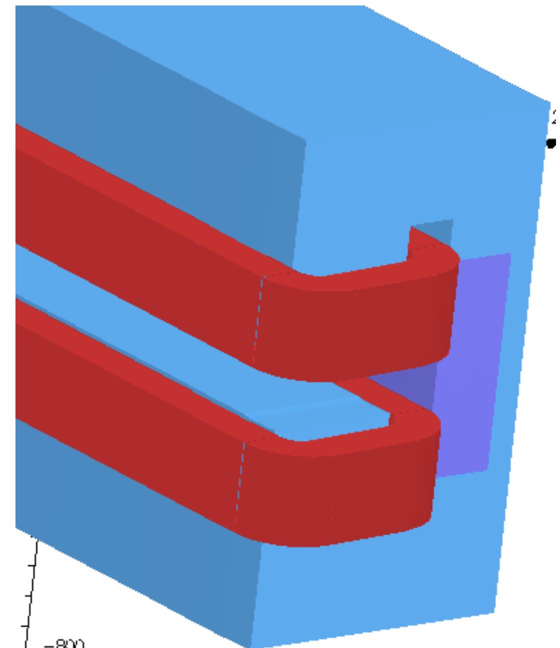
90 mm Aperture Dipole built at Stangenes

Magnet arrived recently.
This is being prepared for magnetic measurements.
No update over last review.

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

Ends of 35 mm Dipole



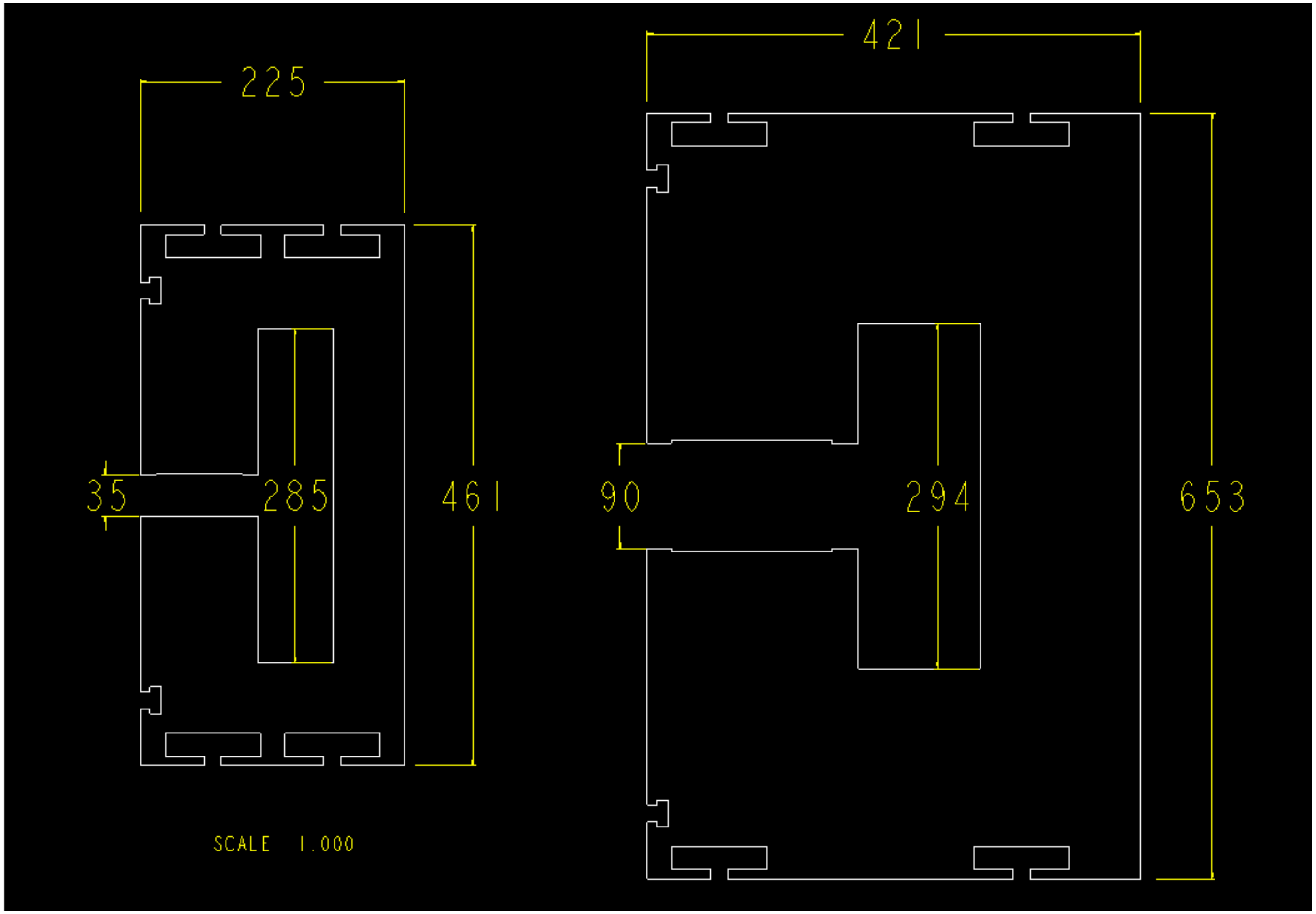


Ends of 90 mm Dipole

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
- Controlled saturation in nose and adjustment in packing factor can be used to better match the field profile, if needed.

Laminations of 35 mm and 90 mm Aperture Dipoles



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

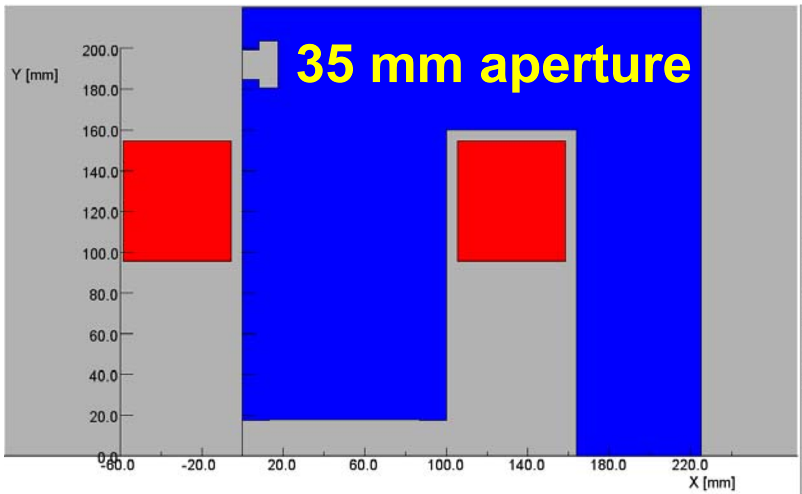
Design Parameters of 90 mm Aperture Dipole

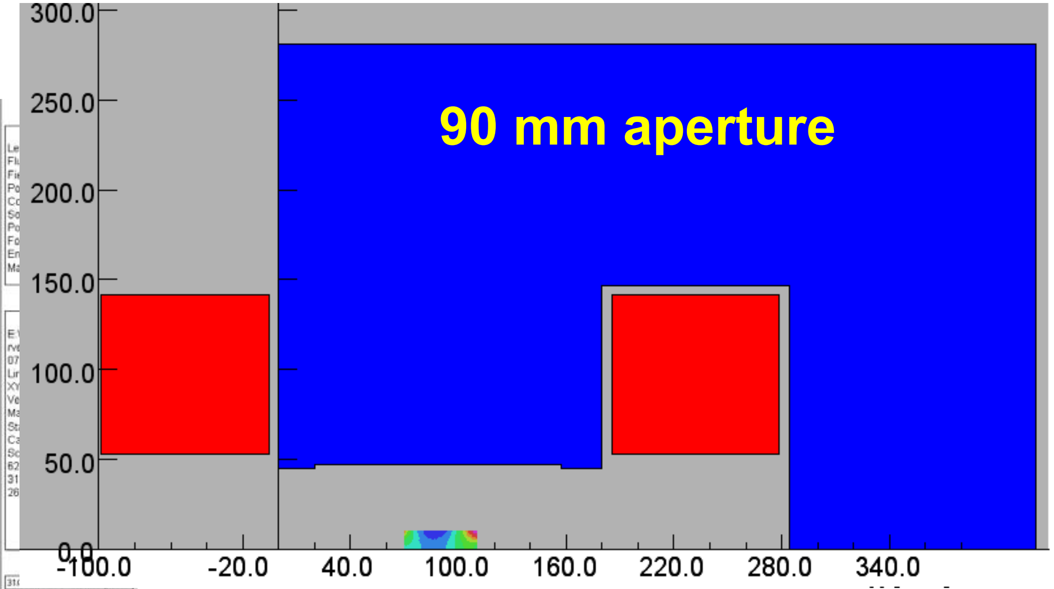
- Magnet Gap – 90 mm (minimum clearance)
- Nominal Field – B_o = 0.40 T (+20%)
- Field Homogeneity in B_X & $B_Y = 1 \times 10^{-4}$
- Good field region B_X : +/- 20mm, B_Y : +/- 10mm
- Magnetic length – 2620 mm
- Nominal Current density in the coil cross section 2 Amps/mm^2
- Maximum allowable temperature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

Comparison of 35 mm and 90 mm Aperture Dipoles

Overall design



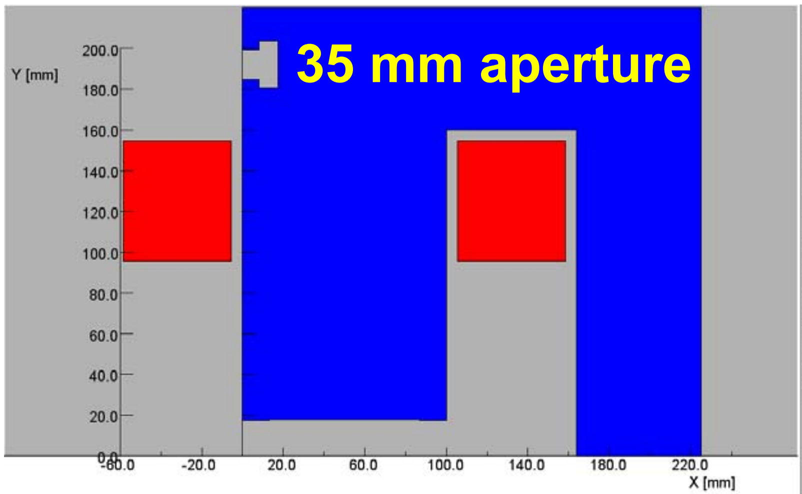


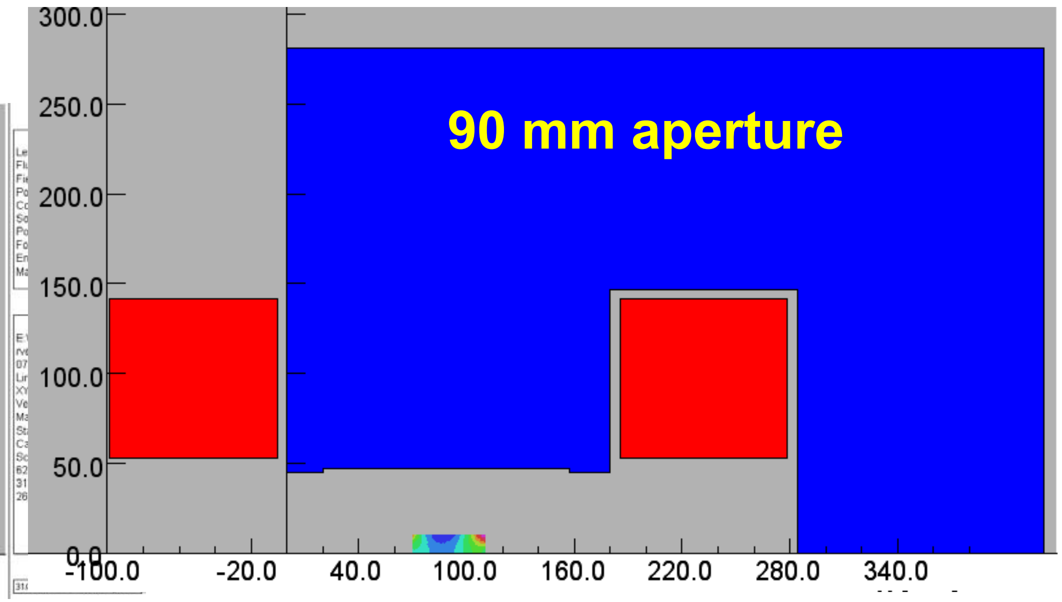
Note: 35 mm and 90 mm are the minimum vertical clearances.
Pole gaps at the magnet center are slightly higher.

• 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% (initially 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) will be carried out by fine tuning the length of the extended pole (nose) in 35 mm aperture dipole.

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).

SUMMARY

• 35 mm dipole program is in advanced stage.

• Field quality specs are being met in the cross-section. End region will be optimized by chamfering the nose piece (as planned).

• The nose piece has extended the magnetic length of the dipole.

• It is important to use good steel in the nose region. This can saturate appreciably particularly since the length of it is significantly increased (68.5 mm to ~104 mm). We would further look to mitigate the saturation.

• 90 mm dipole has been delivered. Field quality measurements will be carried out soon.

• Integral transfer function and integral field harmonics of 35 mm aperture and 90 mm aperture dipoles will be matched with the help of nose piece, etc.