Corrector Designs for Superconducting Solenoid for e-lens

Ramesh Gupta

April 13, 2010

Design Considerations for e-lens correctors

- Short correctors must create a dipole field of 0.02 T and long correctors 0.006+ T (both horizontal and vertical)

- Should have low operating current to minimize heat load (more important for tests when RHIC cryo-system is not on)

- Should have a minimum layers to minimize schedule and cost

Goals - Desired and Possible

- **Last Week's Desired Goal:**
  - **One single layer coil to do the job for each of horizontal corrector and vertical correctors (one each for short length and long length correctors)**

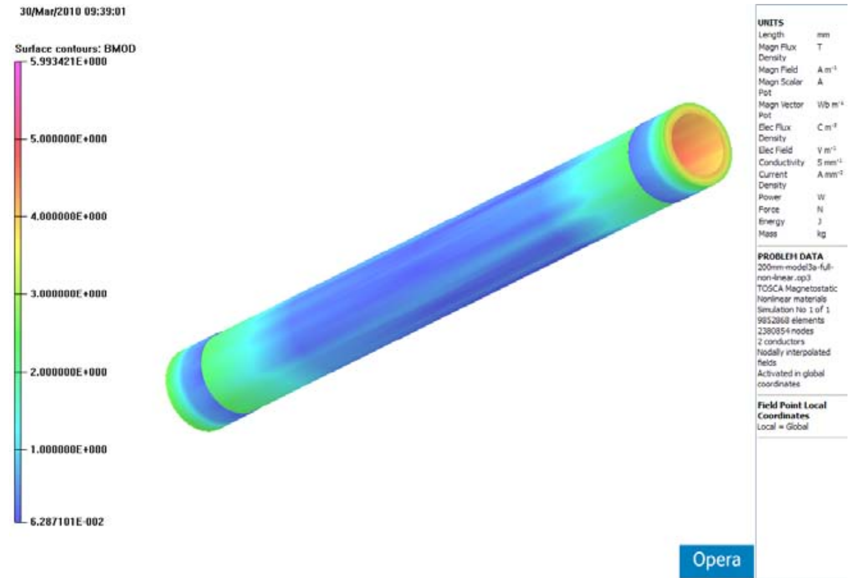
- **It will be shown that we can do that.**

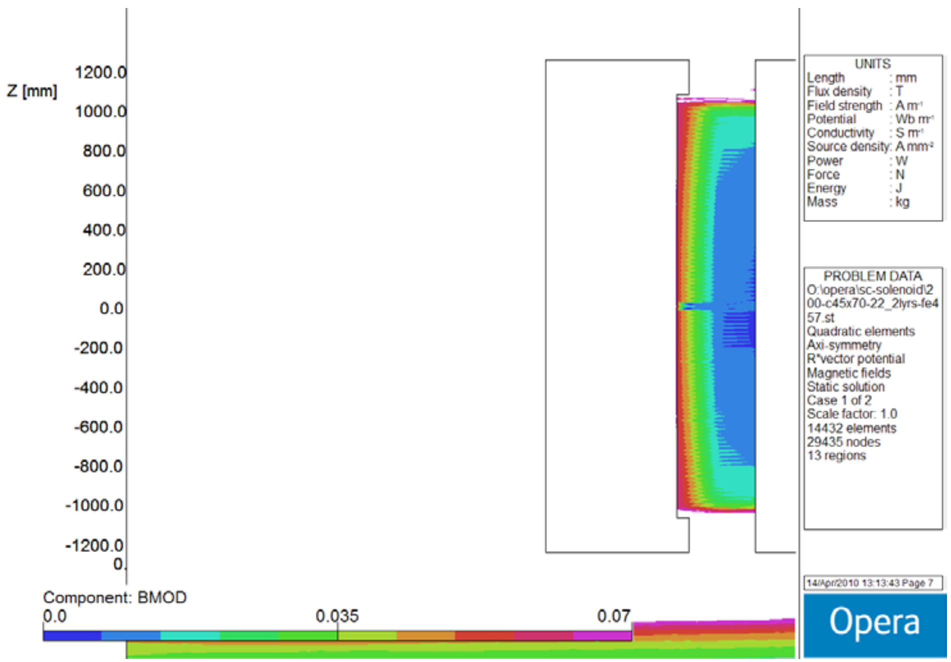
- **In fact, with the designs proposed here, we should be able to do even better.**

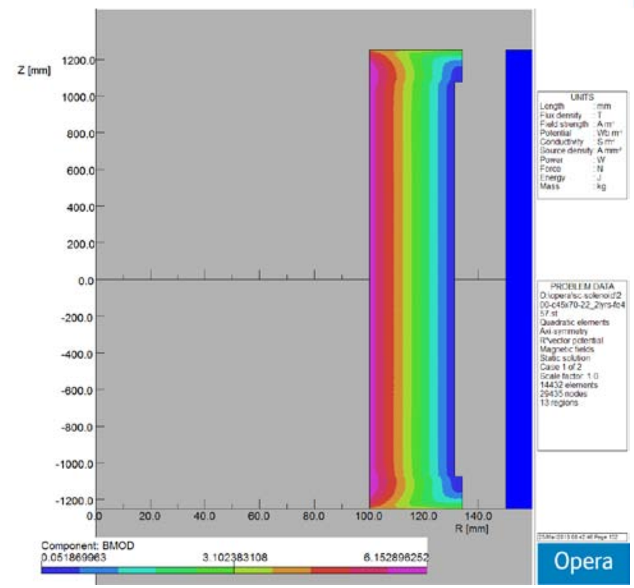
- **That would translate into significant cost and schedule savings.**

Field on the Corrector

- Correctors will be placed outside the solenoid
- They reside in a low field region (<1% of 6T)
- This helps significantly because:
  - ➢ Large margin because of higher Ic
  - ➢ Low Lorentz forces on the conductor
  - ➢ Persistent current concerns due to large solenoid field are reduced







Design Types of Conductor Dominated Correctors

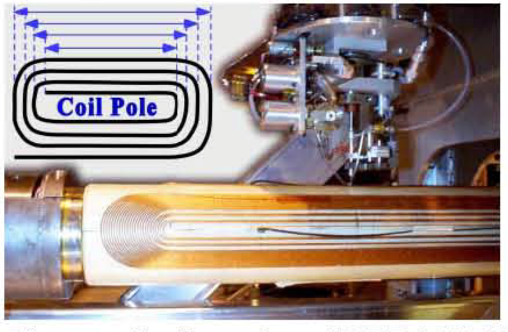
- Design with Conventional Ends
  - Used in earlier magnets (RHIC Correctors)
- Design with Serpentine Ends
  - Used in most current magnets
- Optimum Integral Design
  - Used and developed for AGS Helical magnet

Earlier Design with Conventional Ends

BNL DIRECT WIND HISTORY

RHIC corrector magnets were made by bonding coated conductor in spiraling paths, here identified as "planar patterns," on flat substrate. The flat coil was wrapped around a tube for support and firmly secured in place with a tensioned Kevlar string overwrap[1]. When faced with demanding harmonic goals for the HERA-II Upgrade, we modified this process to lay single-strand round wire and round seven-strand cable, under full computer control, directly on support tubes with substrate already attached in order to improve conductor placement accuracy[2].

But even with direct winding on support tubes, HERA-II patterns were fundamentally planar and suffered from limitations illustrated in Fig.1. The spiral nature of planar patterns has conductor next to the pole trapped by turns further away. This was partially mitigated by winding poles in clockwise/counterclockwise pairs but leads were still trapped and had to be bent sharply to be brought out over the final conductor pack. Leads coming from the pole interfere with later winding and are exposed and vulnerable during subsequent processing steps.



From Parker's PAC 05 paper

Figure 1. Planer coil schematic and HERA-II GO quad.

Conventional Design:

- First optimize cross section for field and field quality
- Then optimize end for field quality
- End takes significant space
- About 1 coil diameter wasted in dipoles

Conductor occupies about 60 degree space. That means it takes $\pi/3$ * Radius or more at each end. Generally generate field only half of that length.

Serpentine Coil Design

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

SERPENTINE COIL TOPOLOGY FOR BNL DIRECT WIND SUPERCONDUCTING MAGNETS*

B. Parker[#] and J. Escallier, BNL, Upton, NY 11973, U.S.A.

Abstract

Serpentine winding, a recent innovation developed at BNL for direct winding superconducting magnets, allows winding a coil layer of arbitrary multipolarity in one continuous winding process and greatly simplifies magnet design and production compared to the planar patterns used before. Serpentine windings were used for the BEPC-II Upgrade and JPARC magnets and are proposed to make compact final focus magnets for the ILC. Serpentine patterns exhibit a direct connection between 2D body harmonics and harmonics derived from the integral fields. Straightforward 2D optimization yields good integral field quality with uniformly spaced (natural) coil ends. This and other surprising features of Serpentine windings are addressed in this paper.

BNL DIRECT WIND HISTORY

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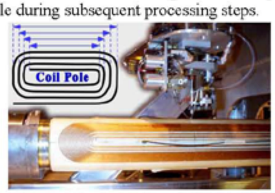

Figure 1. Planer coil schematic and HERA-II GO quad.

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#parker@bnl.gov

Planar patterns also have a subtle design issue with inner turns shorter than outer ones. This correlation of turn length with angle means that for a short magnet integral field harmonics, derived by integration through the magnet, may differ substantially from harmonics based on the 2D cross section. Harmonic correction then involves tricky 3D conductor placement optimization for the coil ends (often requiring insertion of odd-shaped end tuning spacers that complicate final magnet production).

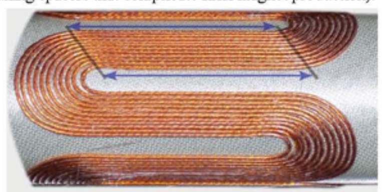


Figure 2. Serpentine style octupole coil pattern wound with five and a half turns per pole.

THE SERPENTINE SOLUTION

Now consider winding a coil if instead of always turning the same direction we make turns in opposite directions at the coil ends as shown in Fig.2. Rather than trapping conductors we can lay in turns for every coil pack of a given layer in one continuous path by snaking back and forth on the support tube. Our trick uses the support tube topology; after going around 360° we come back again and can lay new turns next to ones already down. Such patterns, which cannot be drawn on a flat sheet of paper without lifting, are Serpentine windings.

For winding the BEPC-II quadrupole coils with eight cable layers[3] we were strongly motivated to find an alternative to planar patterns. Using HERA-II style coils would have left an undesirably thick bundle of stabilized leads and solder joints atop the coil pack and eaten up radial space budgeted for the anti-solenoid. Using pseudo-planar patterns of dual-layer spirals, as shown in Fig.3, (pseudo since winding jumps up/down between two different layers) it is possible to bring leads out the end by first spiraling in to the pole, going up a layer and then spiraling back out; however, doing this strongly impacts

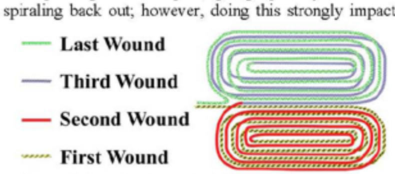


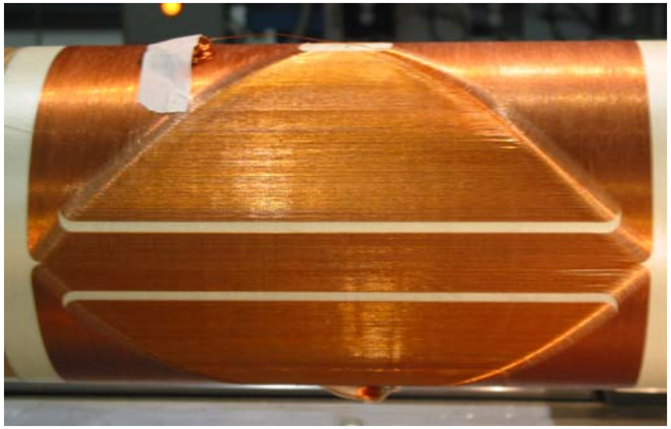
Figure 3. Pseudo-planar dual-layer winding pattern.

<u>Serpentine Design</u> (B. Parker):

- Simple ~2-d design
- Easy to bring leads out
- Used in most magnets (default these days)
- End takes/wastes some space

(a penalty only in short magnets)

Optimum Integral Design



Coil dia: 182 mm, Coil length 300 mm

Presented at the 2004 Applied Superconductivity Conference at Jacksonville, Florida, USA, Oct 3-8, 2004.

Optimum Integral Design
for Maximizing the Field in Short Magnets

Ramesh Gupta

Abstract— An ***Optimum Integral Design*** is introduced for cosine($n\theta$) coils where the entire end-to-end length of the coil generates field with the dilution from ends practically eliminated.

The increase in length comes primarily from the presence of end spacers (see Fig. 1) that must be used to minimize the field harmonics and also to reduce the peak field on the conductor in superconducting magnets. The average field in

TABLE I
COMPUTED INTEGRAL FIELD HARMONICS IN THE AGS CORRECTOR DIPOLE DESIGN AT A REFERENCE RADIUS OF 60 MM. THE COIL RADIUS IS 90.8 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

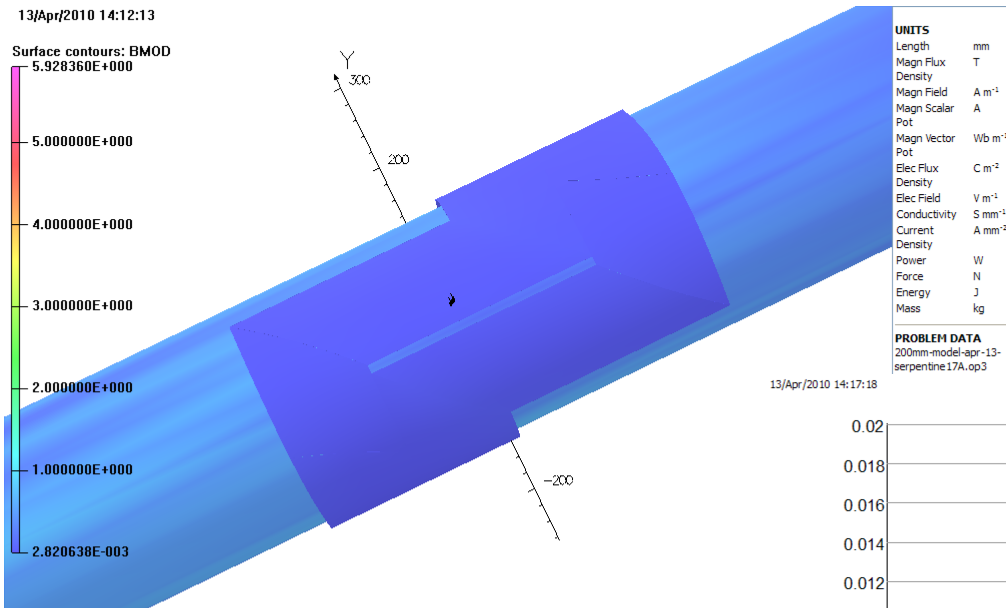
Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4

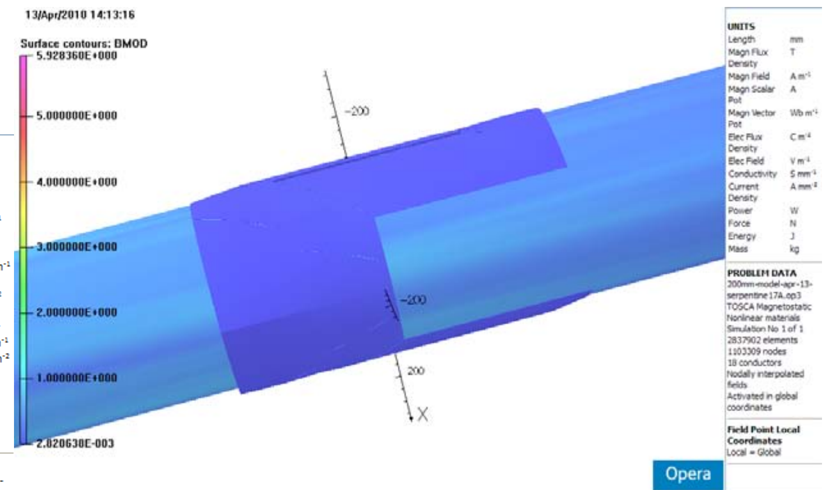
Optimum Integral Design

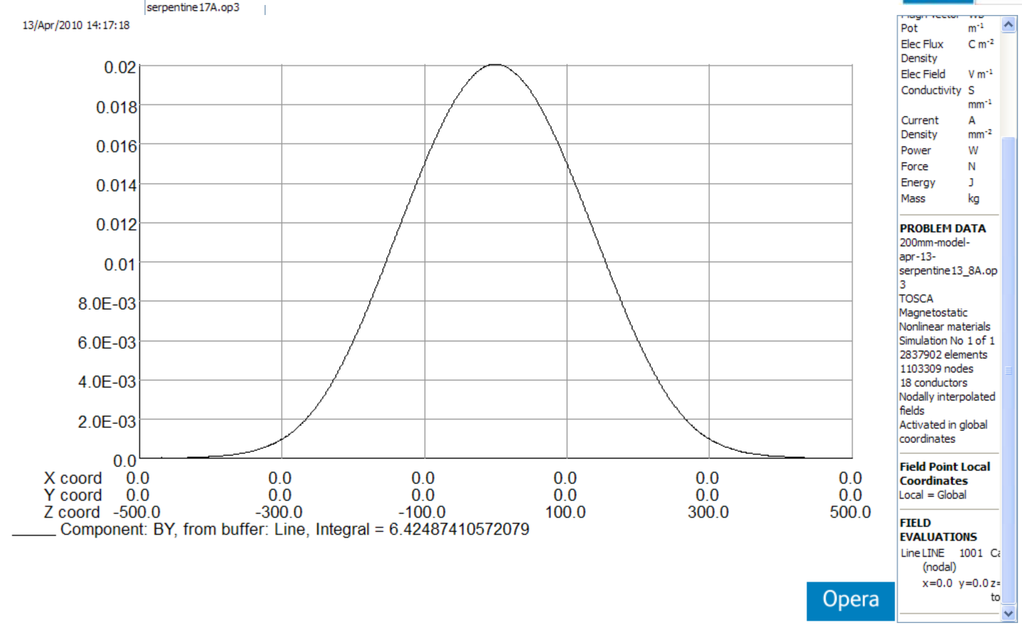
- Most optimum use of space (other dipole end design use one diameter total even with no end spacers).
- Full conductor length used at midplane.
- Spacers in body and ends are modulated to obtain integral cosine theta distribution
- Leads do not come out as easily as in Serpentine design (issue in a single layer coil)
- Developed and used in AGS corrector (in helical magnet)
- Here we have coil dia ~280 mm and coil length ~450 mm (similar ratio as in AGS corrector)

Preliminary Serpentine Design for e-lens corrector

One layer each for horizontal and vertical dipole correctors



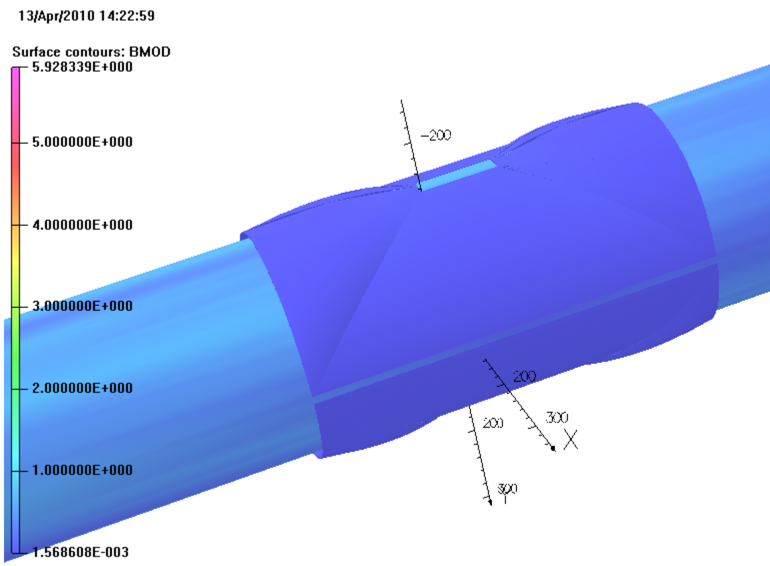


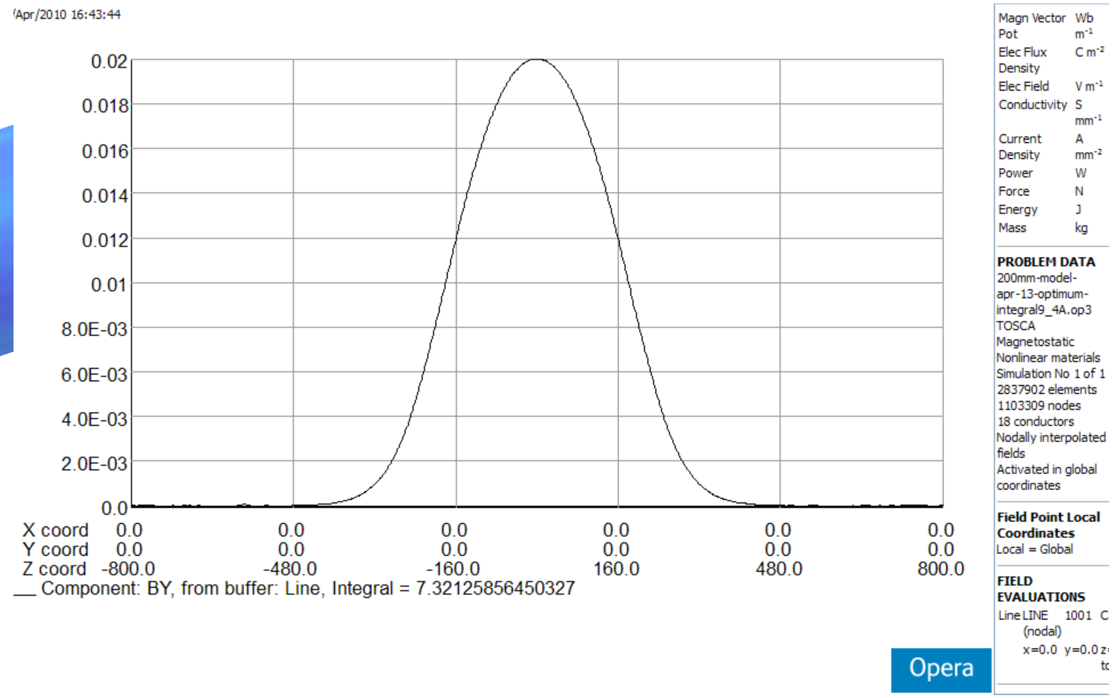


Desired Field is obtained at 13.8 A

Preliminary Optimum Integral Design for e-lens corrector

One layer each for horizontal and vertical dipole correctors



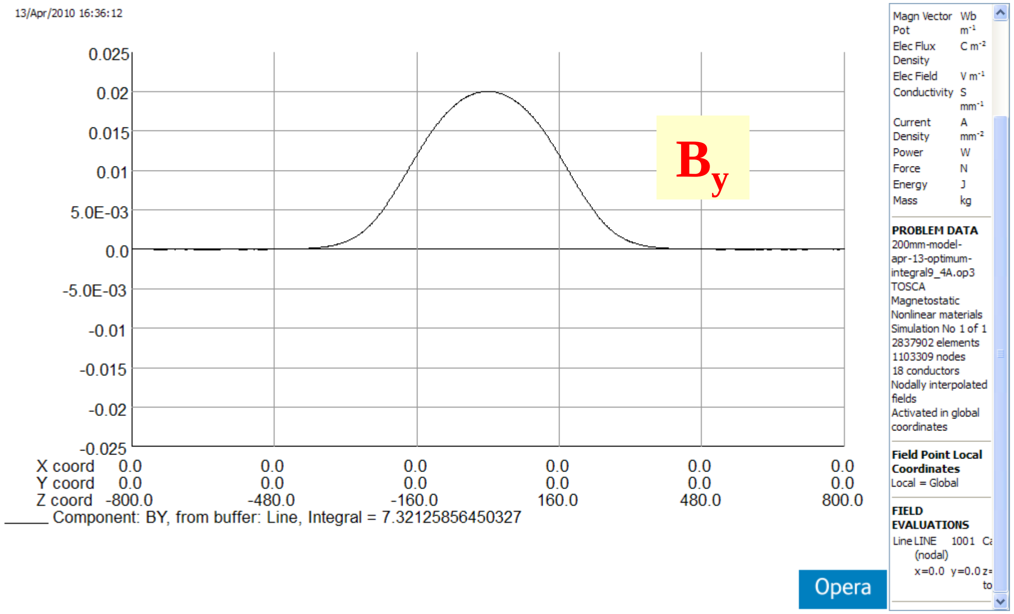


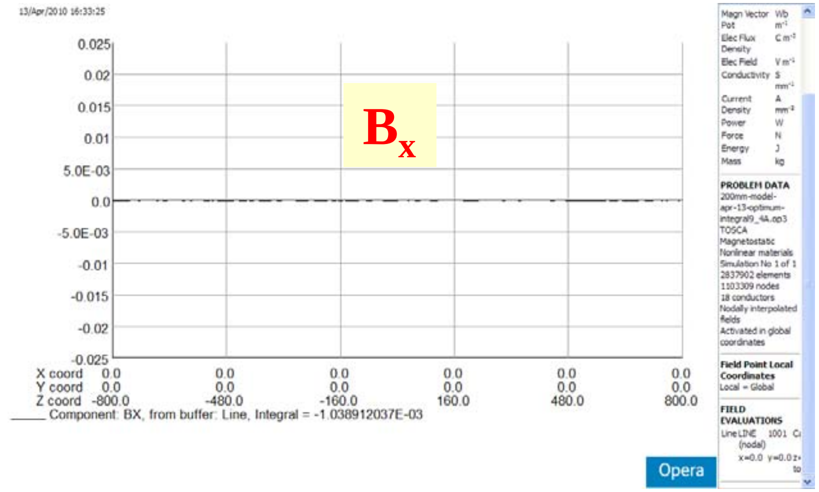
Desired Field of 20 mT (0.02 T) is obtained at 9.4 A

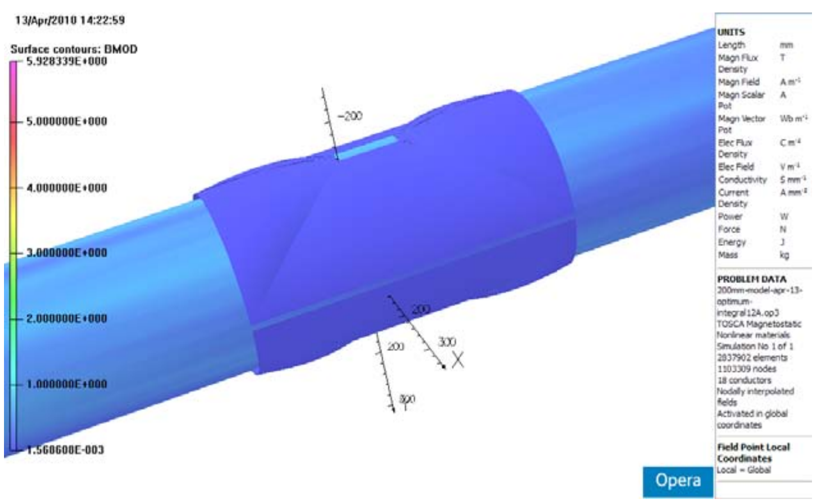
- As compared to this serpentine design needs ~50% more current.

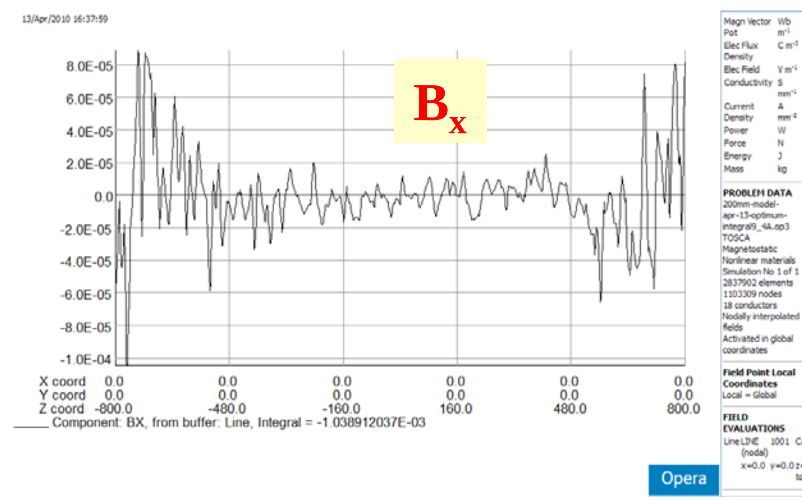
  This implies that optimum integral design should be used.

Cross-talk on other field component in Optimum Integral Design for e-lens Corrector







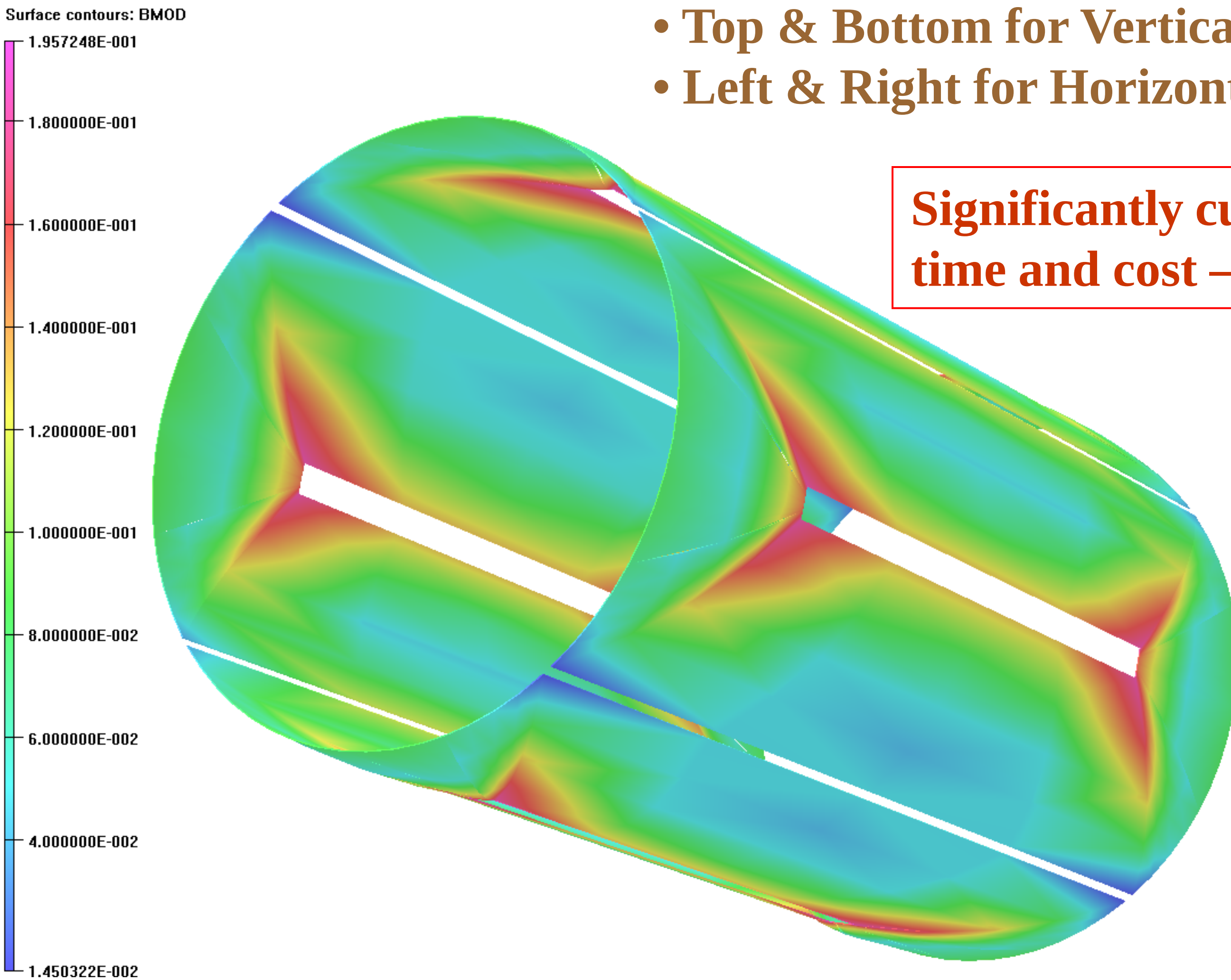


- **So we can easily do it in a single layer.**
- **Can we be creative to do it even better?**

- **That is, can we make horizontal and vertical correcrtors share the same real estate?**
- **Rest of the this talk would present two designs that may allow us to do that.**

Optimum Integral Design (take 2)

Both horizontal and vertical dipole correctors are accommodated in a single layer



- **Top & Bottom for Vertical**
- **Left & Right for Horizontal**

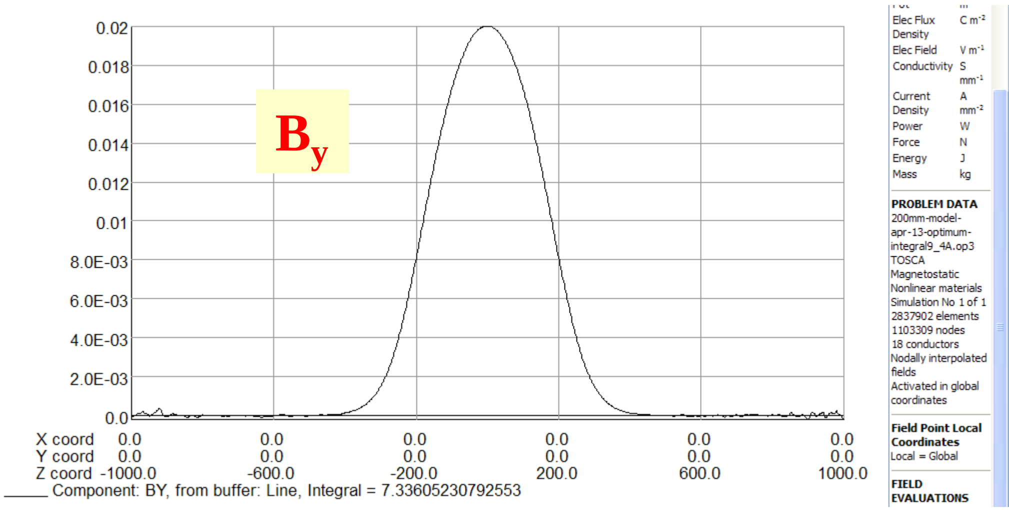
Significantly cuts down on construction time and cost – the main motivation

Down side:

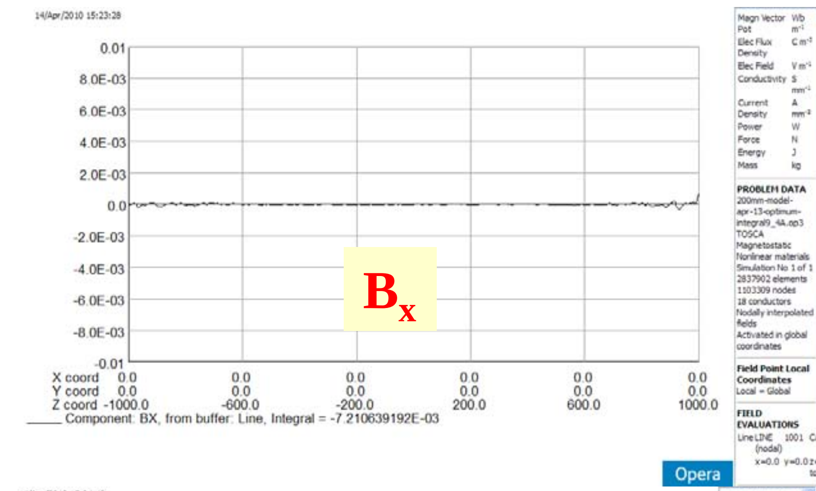
- Higher operating current
  (~30 A, ~5000 Amp-turns)

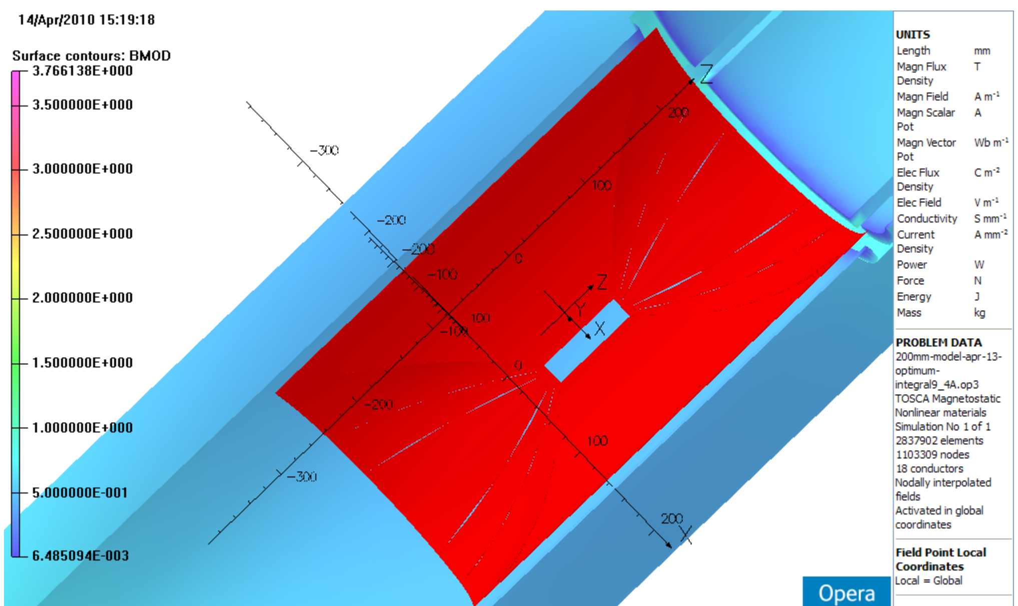
- Field Quality
  (not a major issue)

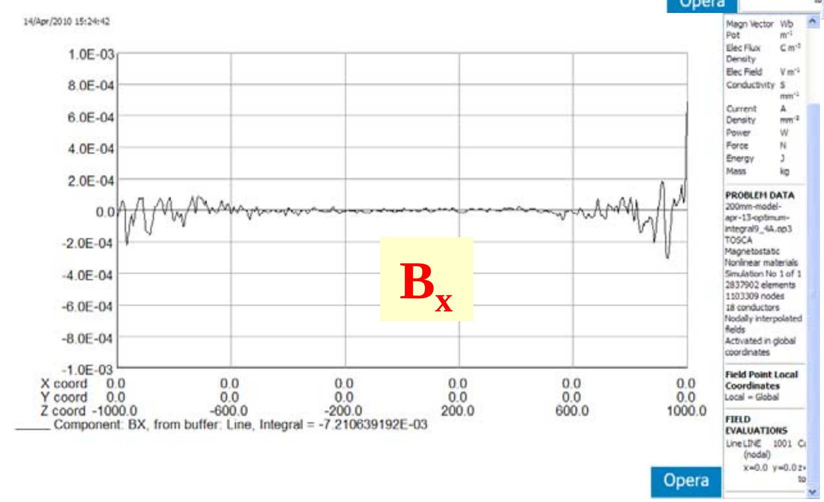
Field in the Optimum Integral Design in One e-lens Corrector (vertical)



0.02 T @ ~30 A
Small cross field

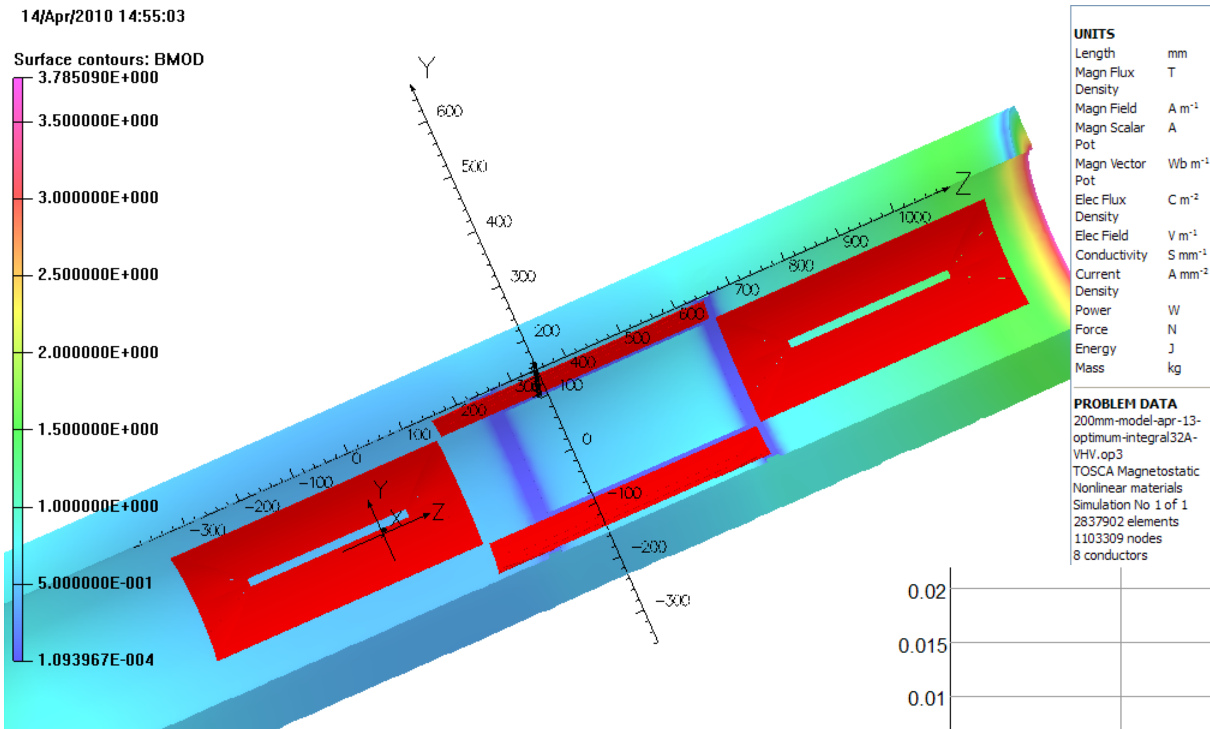




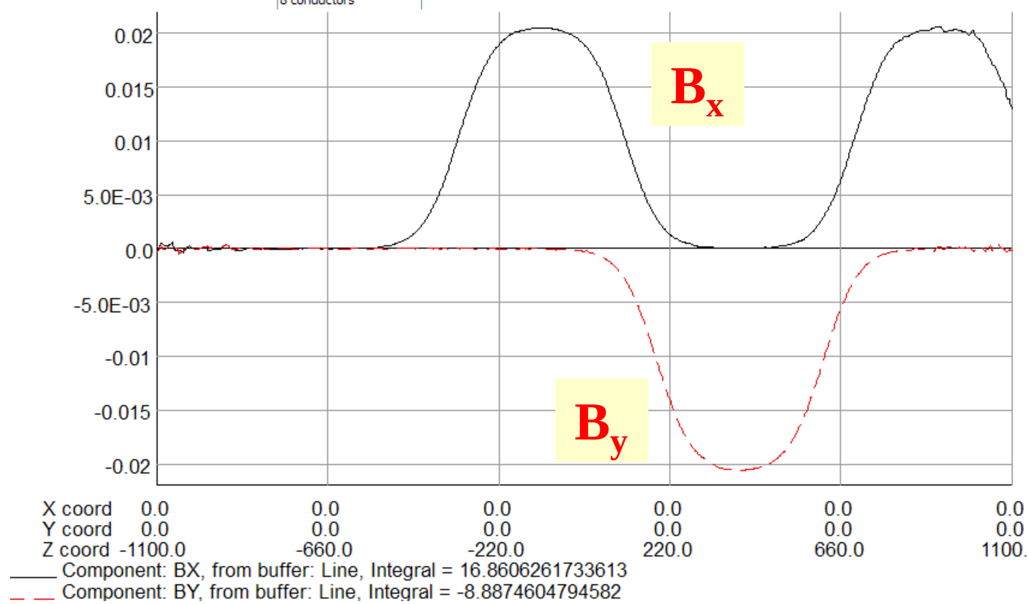


Ramesh Gupta, April 14, 2010

Optimum Integral Design for e-lens Correctors in Series

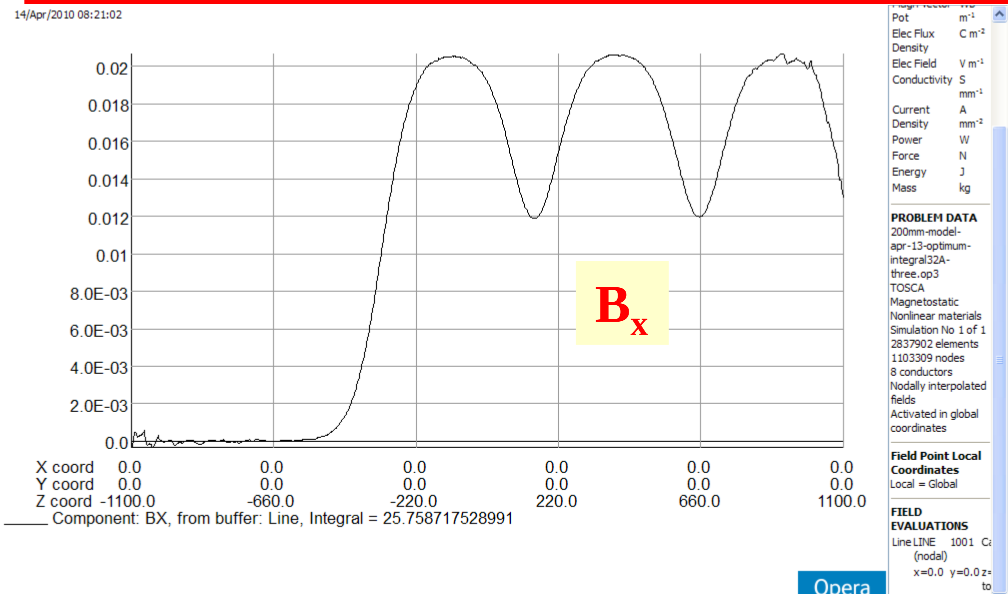


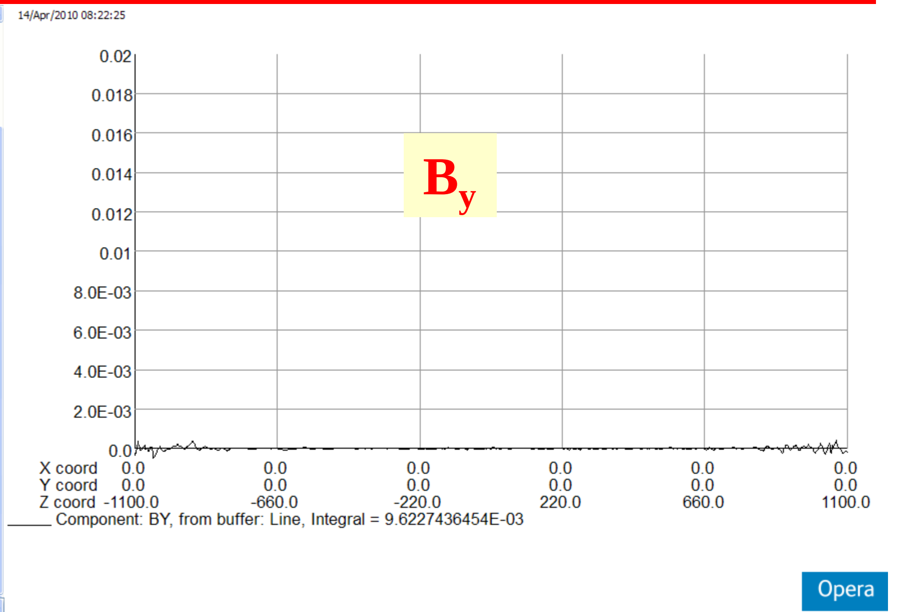
Powered alternately at full horizontal or full vertical field

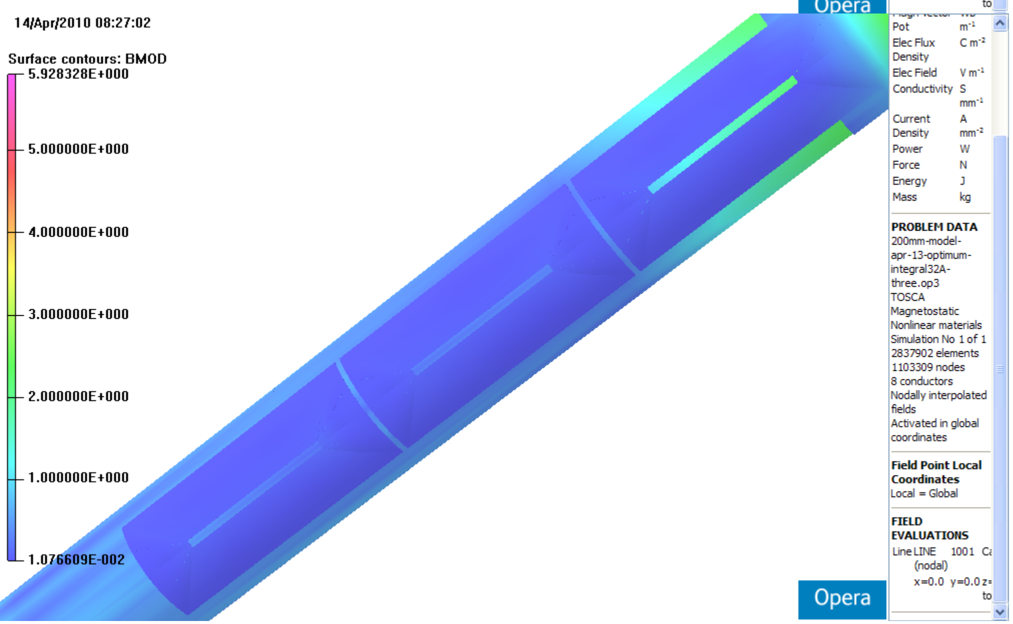


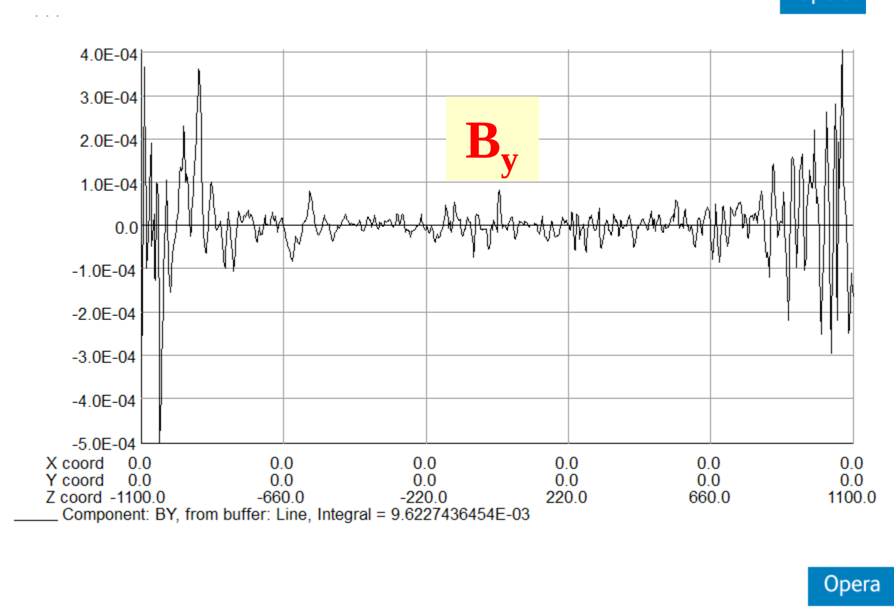
Works well.
Little cross-talk, etc. for transverse field in other direction.

Optimum Integral Design for e-lens Correctors in Series









Intermediate Summary and Discussion

• If we allow 30 Amp operation then, we can place both horizontal and vertical correctors on the same layer.

• This significantly reduces the construction cost and saves significantly on the schedule.

• However, at the penalty of higher helium consumption.

• What is the balance between the two

(a) when RHIC Cryo-system is available and

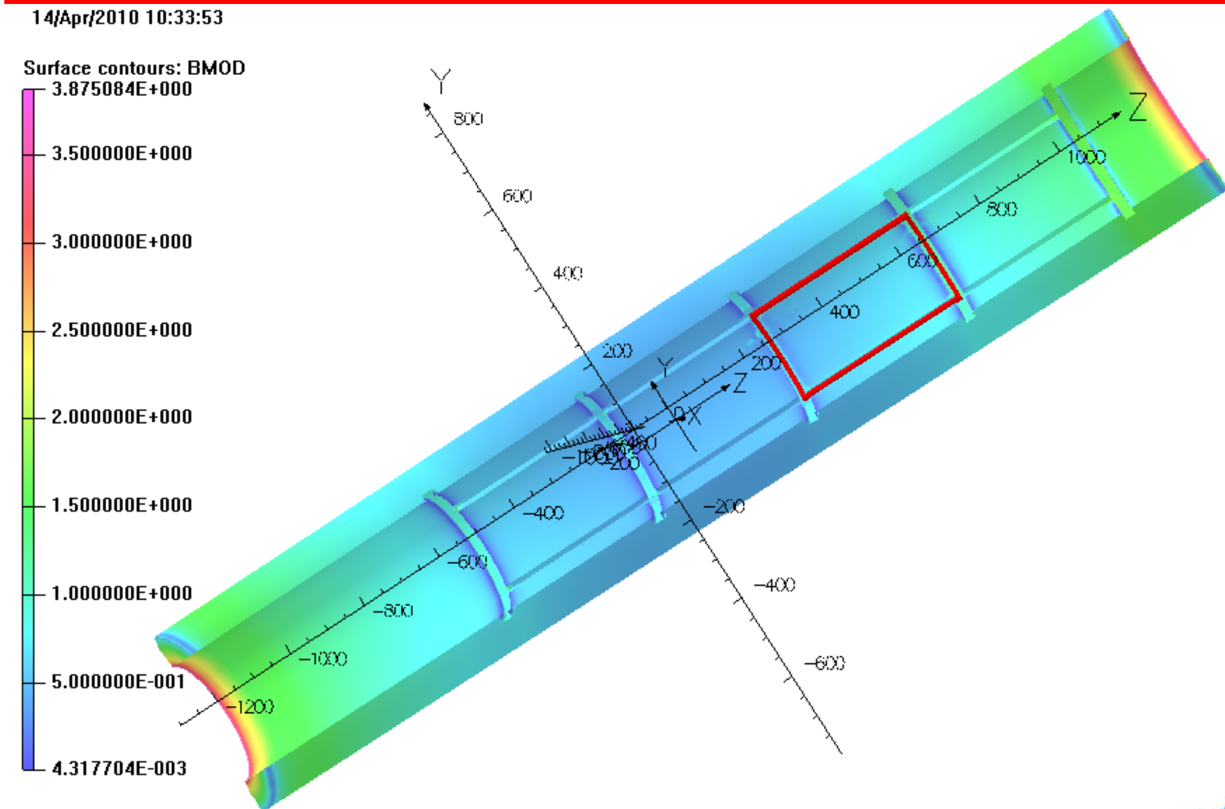
(b) when not (how often are those tests?)

Another Candidate Design

Superferric Design:

When the field is created at the pole, why not use iron?

Another Option: Iron Dominated Corrector Design
(Super-ferric)

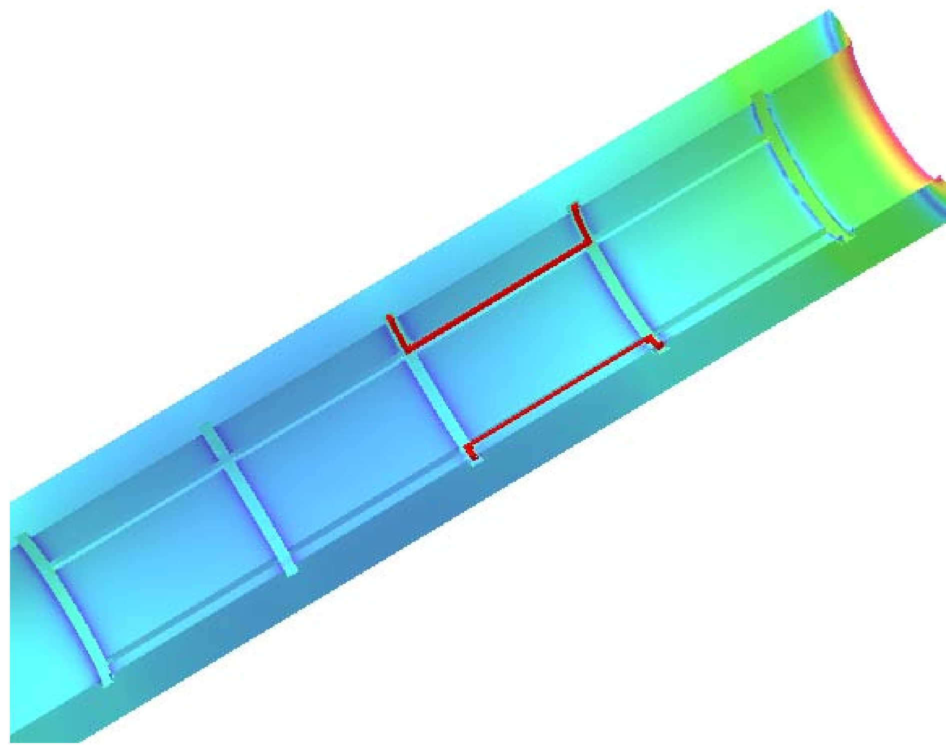


Benefits

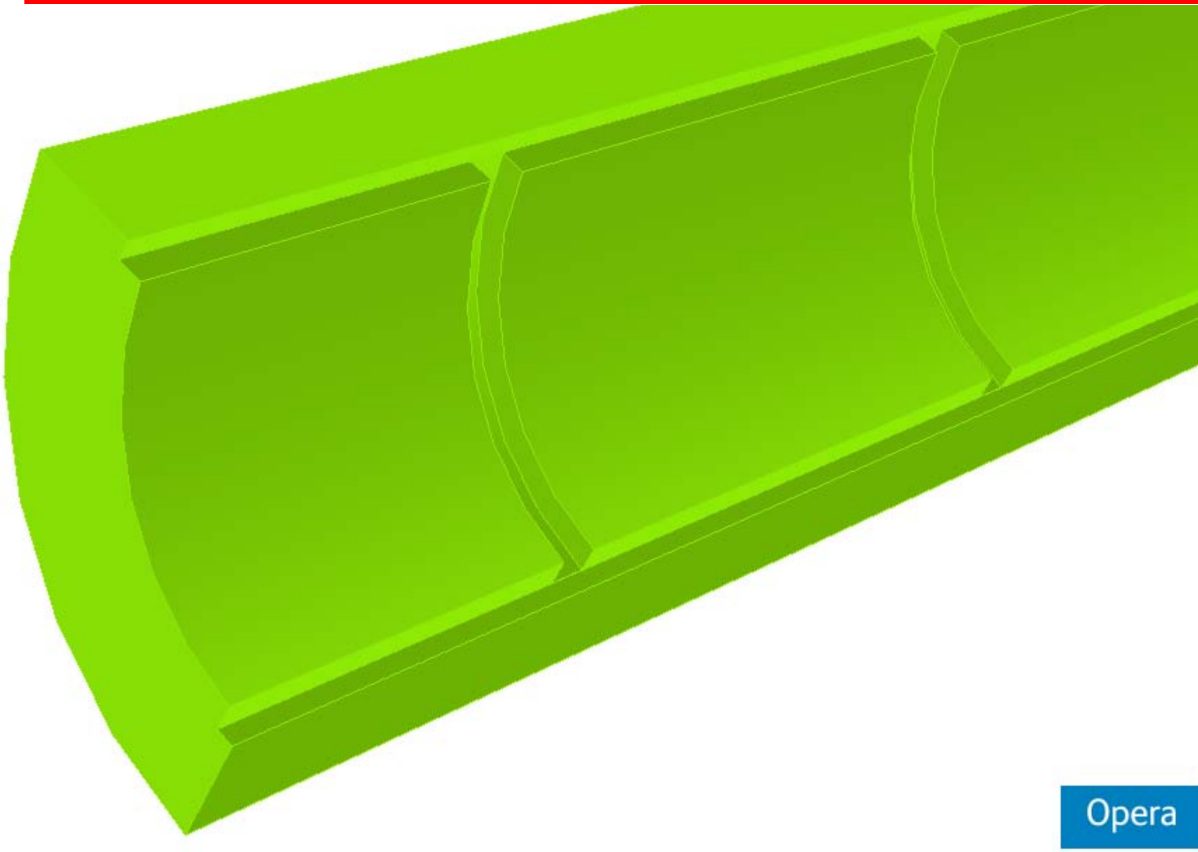
- Lower current operation
- Possibly easier and cheaper to build

- Cut slots in the iron and put superconducting corrector coils there

- There is still enough mu left in the iron to generate 0.02 T magnetic field (a low field, super-ferric design)

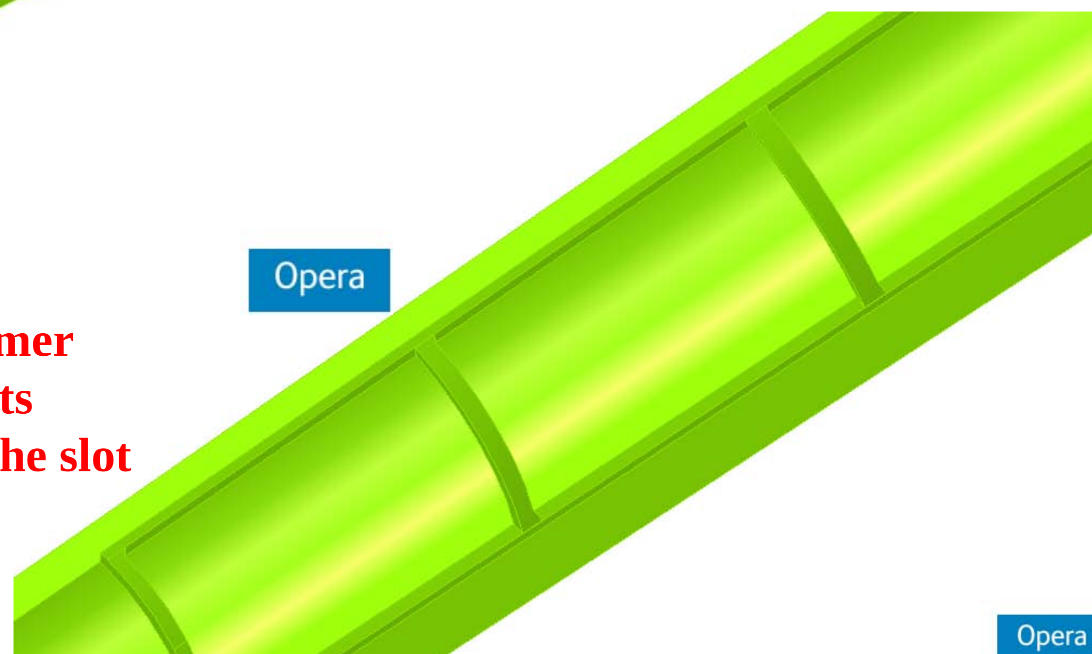


Possible Construction Methods



We still have to work out the possible construction methods. But one may be:

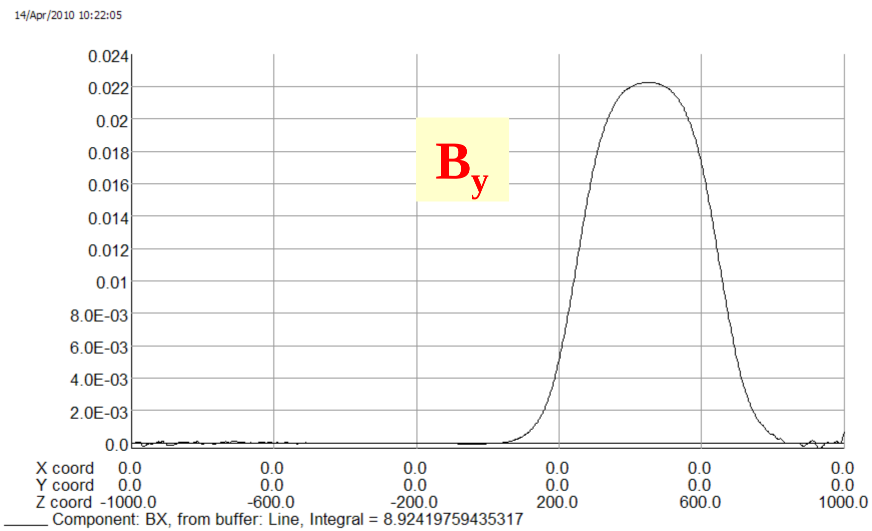
- **Four piece yoke(s)**
- **Slots may be cut by simple machine tools**

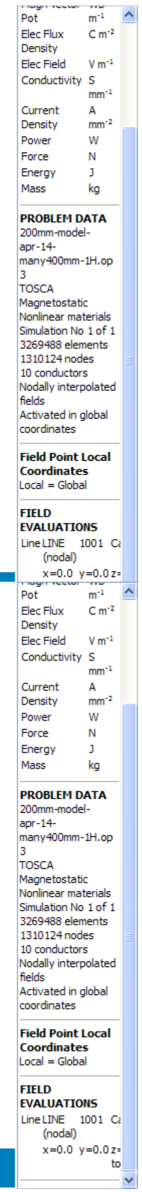


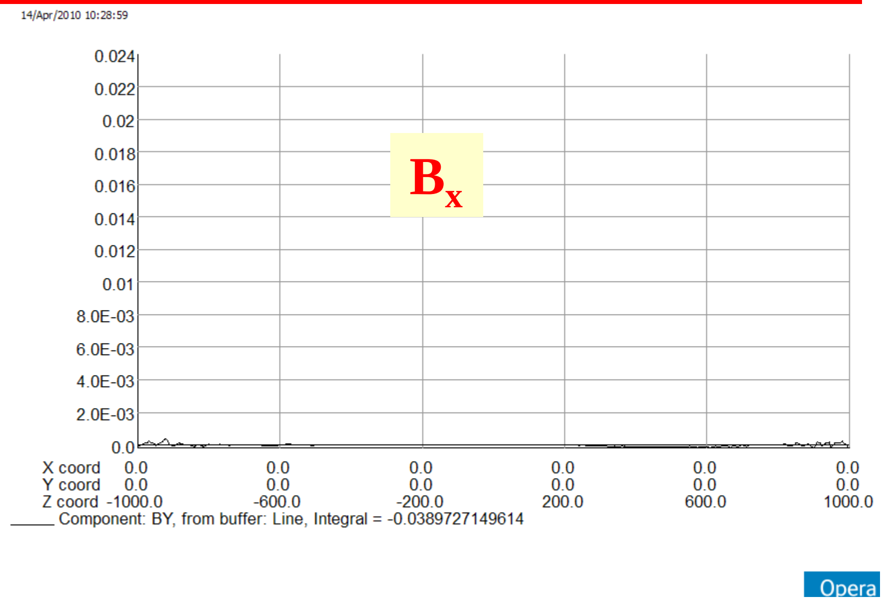
- **Coils may be pre-wound in a 2-d former**
- **Then they may be dropped in the slots**
- **Coils may be secured with epoxy in the slot**

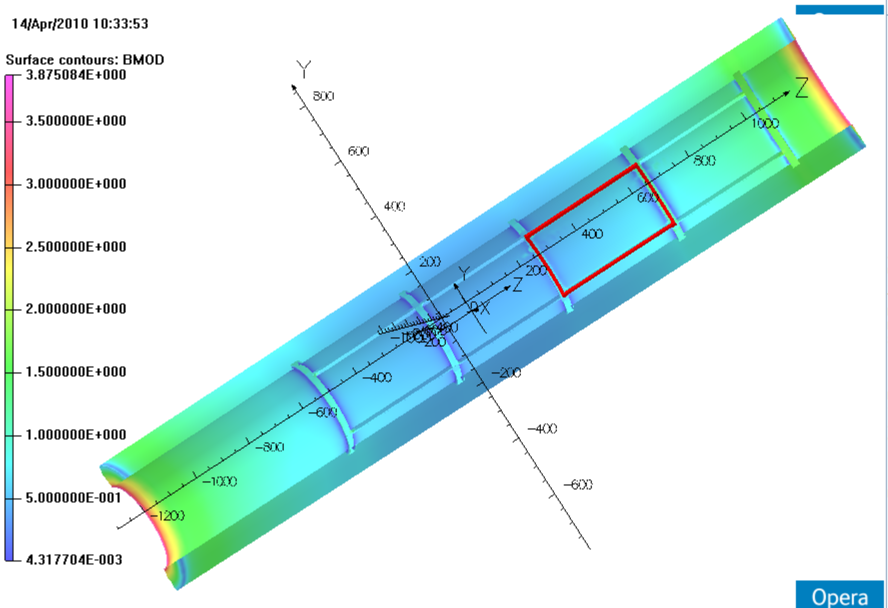
Note: these are very low field magnets with small Lorentz forces

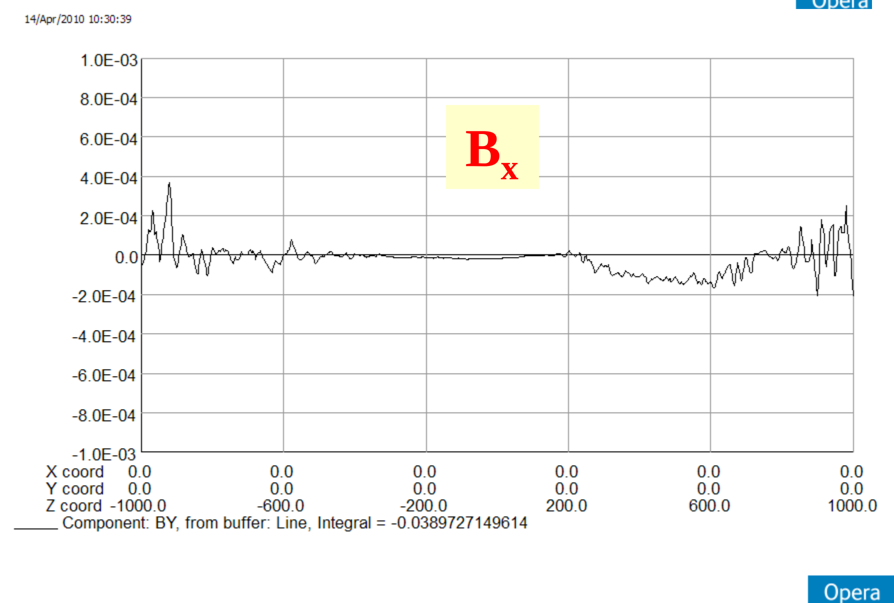
Cross-talk on other field component in Super-ferric Design for e-lens Corrector



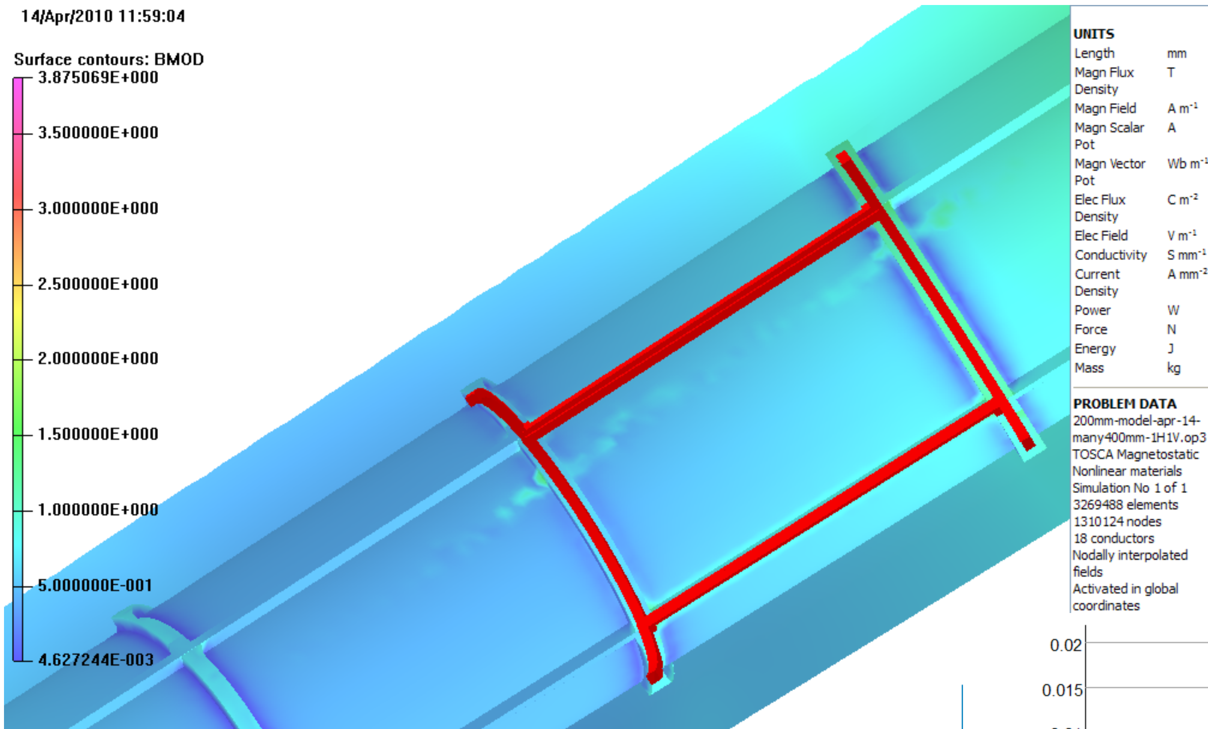


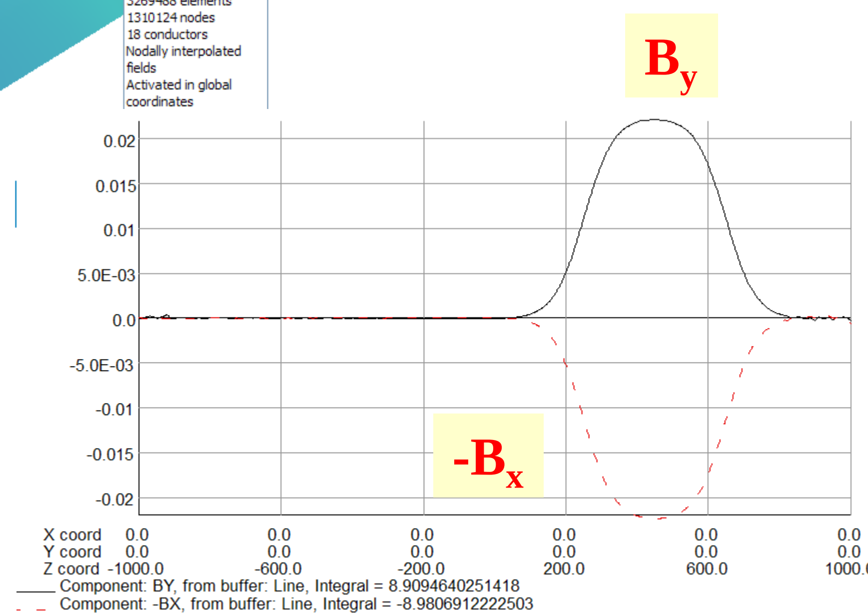






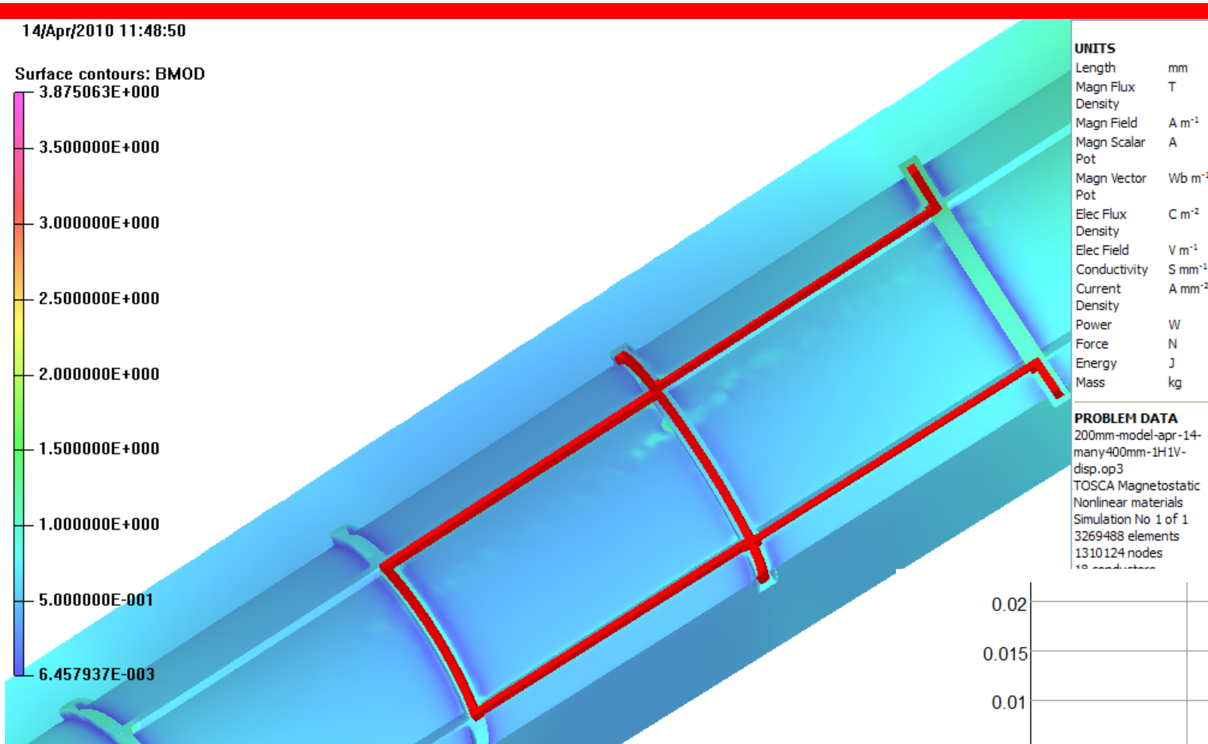
Vertical and Horizontal Corrector Powered
(same axial location)

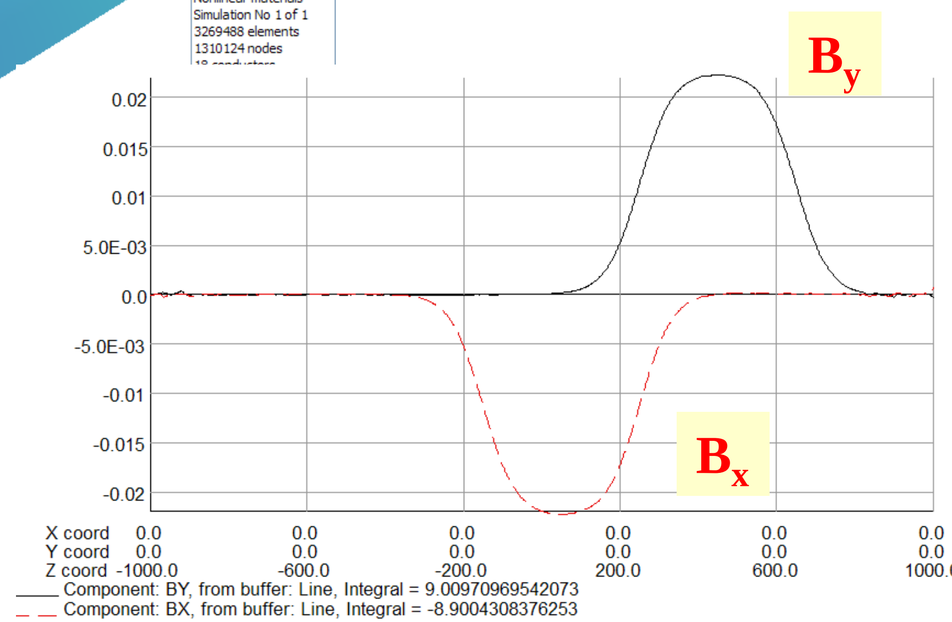




Works well

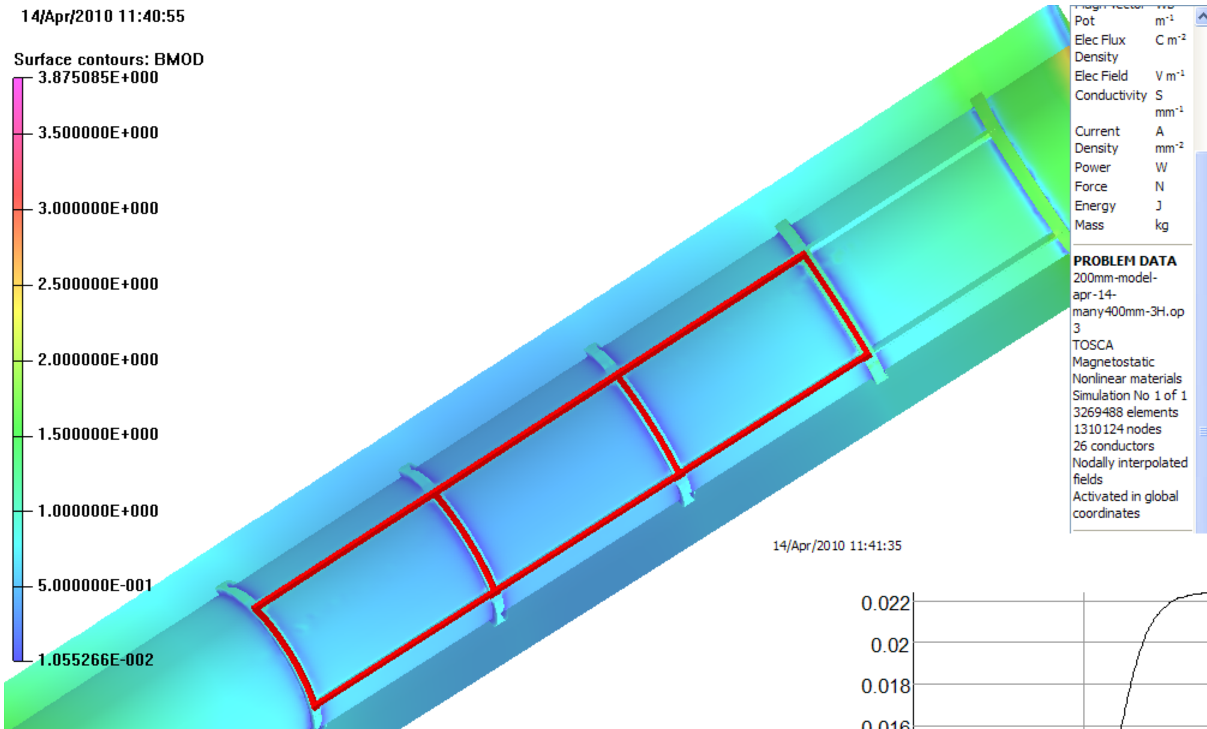
Vertical and Horizontal Corrector Powered
(next to each other)

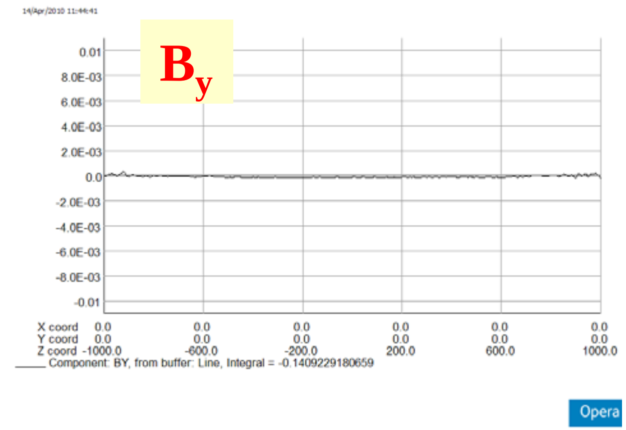


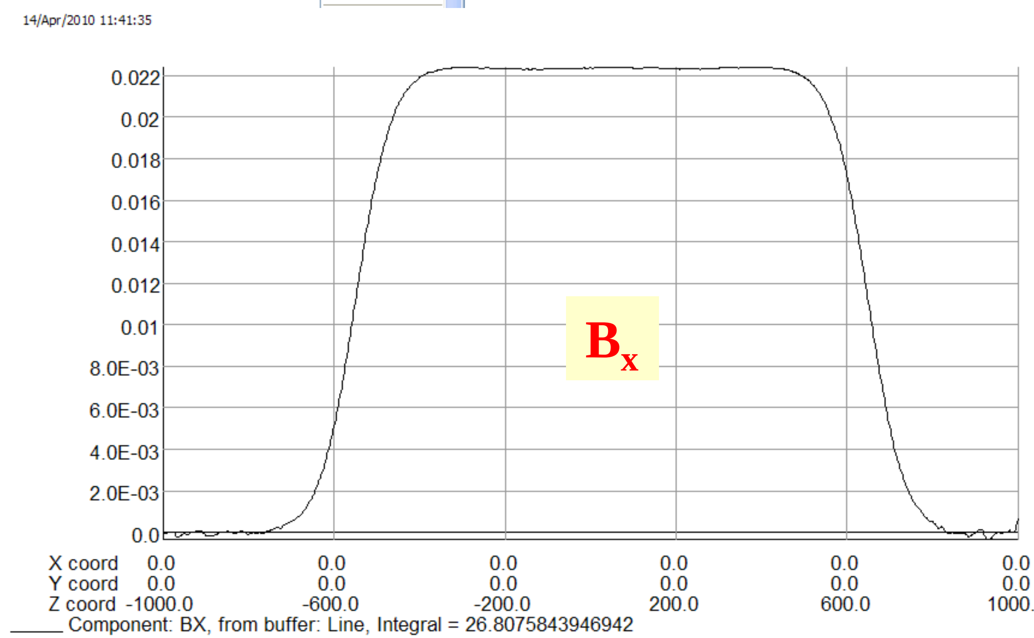


Works well

Three Horizontal Correctors at Full Strength



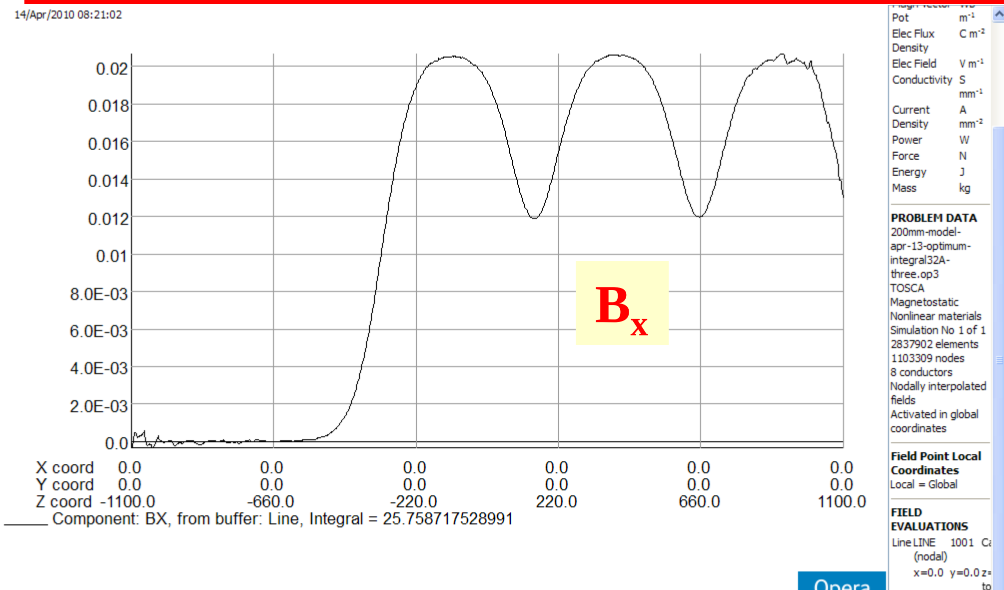


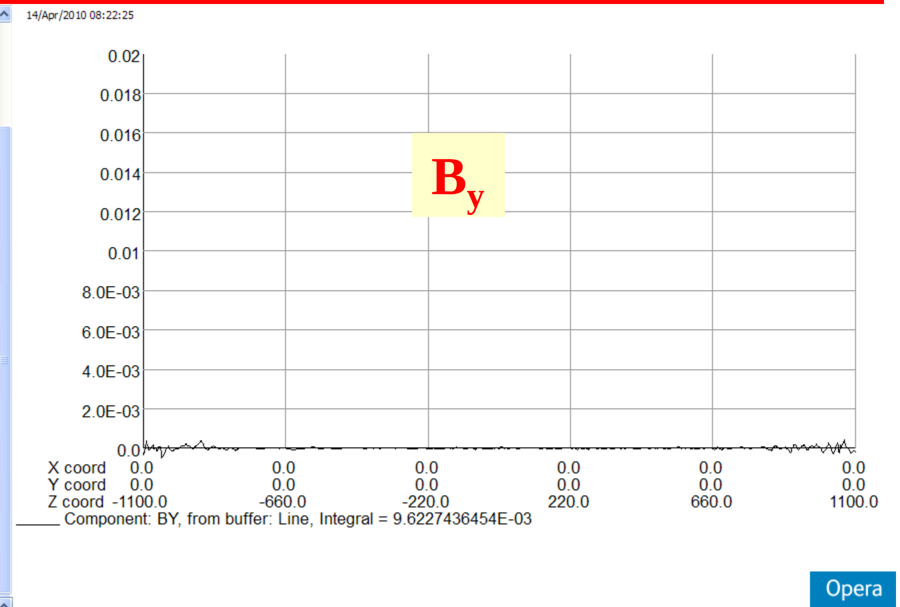


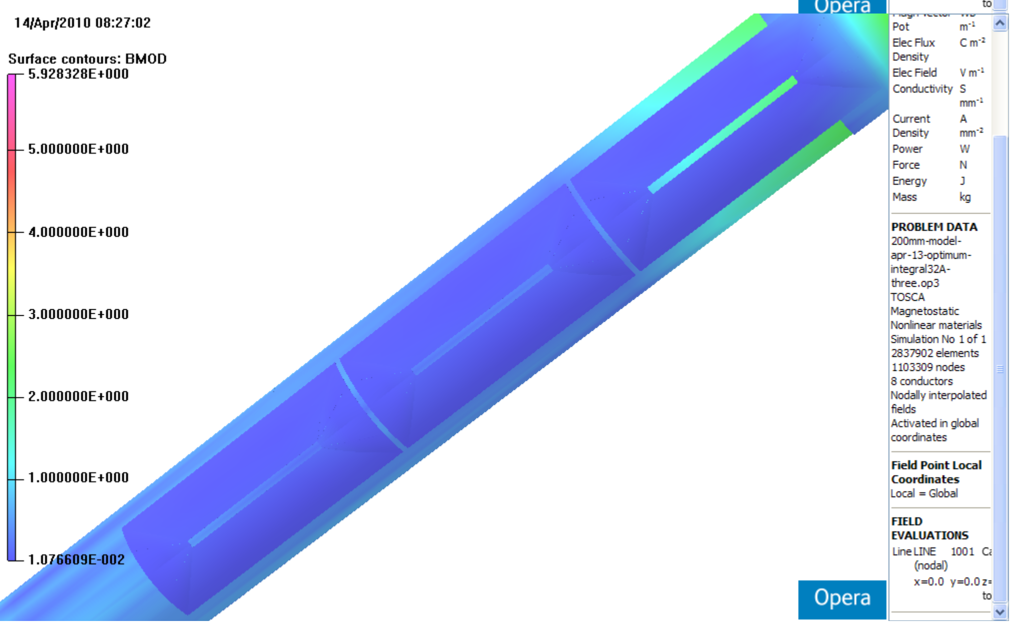
Works really well – even better than optimum integral design (field is very flat in this case).

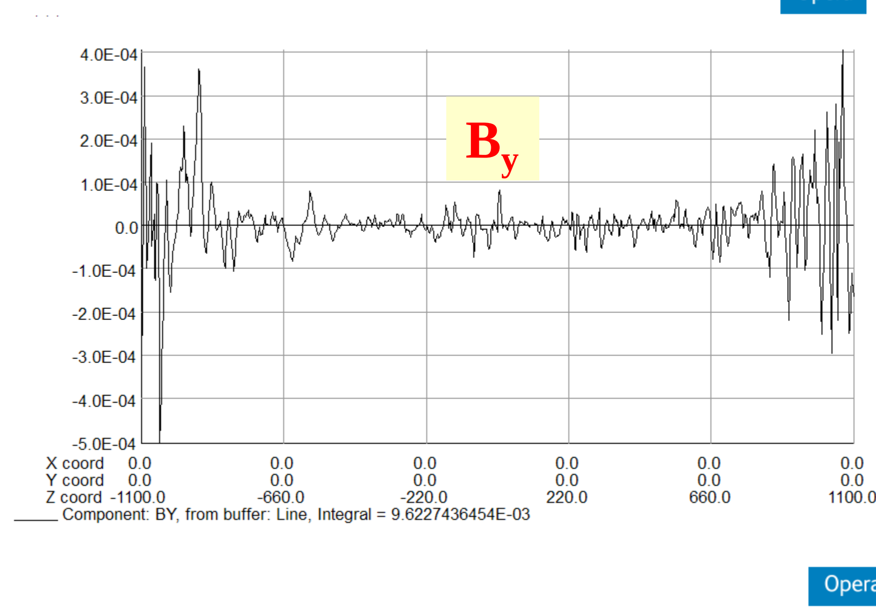
Compare in next slide

Compare with the
Optimum Integral Design for e-lens Correctors in Series









Ramesh Gupta, April 14, 2010

Summary

• **With the design presented here, we can significantly reduce the construction cost and schedule.**

• **We are in the process of comparing the two designs.**

• **We know how to make optimum integral design work. We are looking if we can do better in the super-ferric design.**

• **In discussion with you, a better design (in overall sense) will be adopted.**