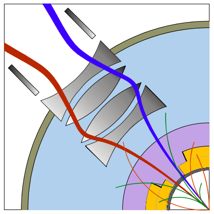


D1 Field Quality

Ramesh Gupta

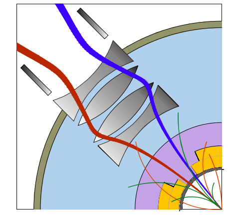
Superconducting Magnet Division

BNL

APUL CD1 Director's Review

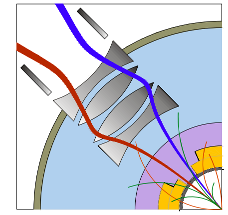
July 16-17, 2009

Issues



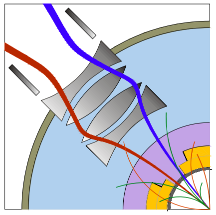
- In terms of field quality expectations in APUL D1 dipoles, we should benefit from the fact that similar 180 mm dipoles have been built and tested before for RHIC insertion region. Field quality in those 13 RHIC DX dipoles has been measured and is generally assumed to be acceptable for LHC upgrade.
- However, when looked in detail, the situation is not so straight forward.
- For good field quality and correct pre-stress, we generally want coil size to be within 50 micron or less of the design. However, for a 71 turn coil it is already exceeded by about an order of magnitude by the cumulative cable tolerances of +/- 6 microns (in RHIC DX, we had to increase number of turns to 71 from original design of 70).
- Since the iron yoke (both geometry and material) is different; saturation-induced allowed harmonics will be different. Moreover, Lorentz force-induced harmonics could be different. In addition, there are skew harmonics because of non-symmetric placement of coldmass in cryostat.
- Good field quality depends on the details. We have our hands full as we try to achieve that without any conventional iteration.

Challenges



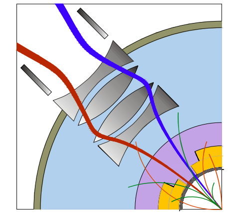
- Magnet iterations, however common they are in this business, take significant time and cost significant money. Eliminating them, if successful, is perhaps the "Value Engineering" at its best.
- Thus the main field quality challenge of the program is the absence of any "*proto-type or pre-production magnet*"
  - The first magnet should be usable in the machine.
  - No change in coil or iron cross-section or in magnet ends is allowed.
  - Only minor adjustments are planned to control field quality in the initial magnets and in the magnets continuing through the production.
- For the success of the program, the challenges (risk) to assuring "a good field quality" needs to be managed carefully.
- The key to "risk mitigation" is incorporating a "flexible design" in the program.
- This presentation will outline our plans based on the past experience in various RHIC magnets. We are confident that it can be done (again)!

Overview of the Plan

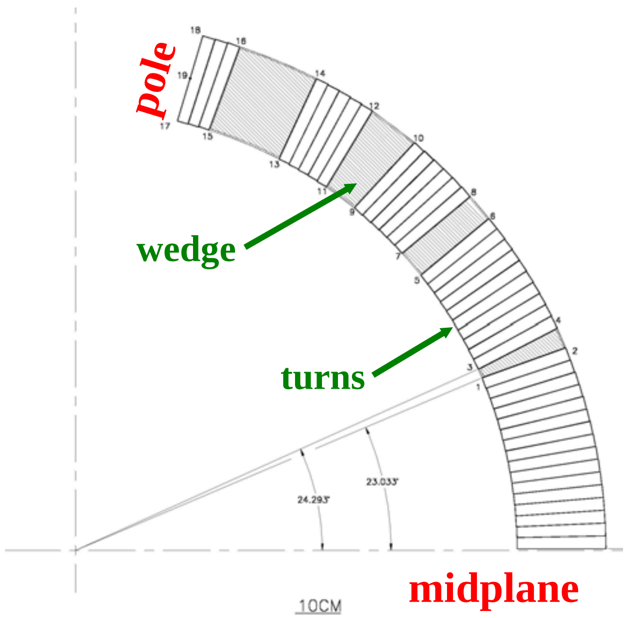


- Assuring geometric field quality and optimizing coil cross section while accommodating variations in cable size and other components of the coil
- Assuring saturation-induced allowed harmonics (due to non-linear iron and Lorentz forces) and iron cross-section.
- Minimizing fringe field and skew quad harmonics due to asymmetric placement of coldmass in the standard size cryostat (“value engineering”, otherwise, one would have used larger coldmass and larger cryostat).
- Study of alternate end design with ROXIE 10.1 using “Differential Geometry” method (similar to the method used in BEND) to examine the possibility of improved mechanical ends.
- Strategy for assuring good field quality in actual magnets (i.e. the rational behind magnetic measurement plan combined with field quality tuning during the initial phase and the production phases of the magnets).

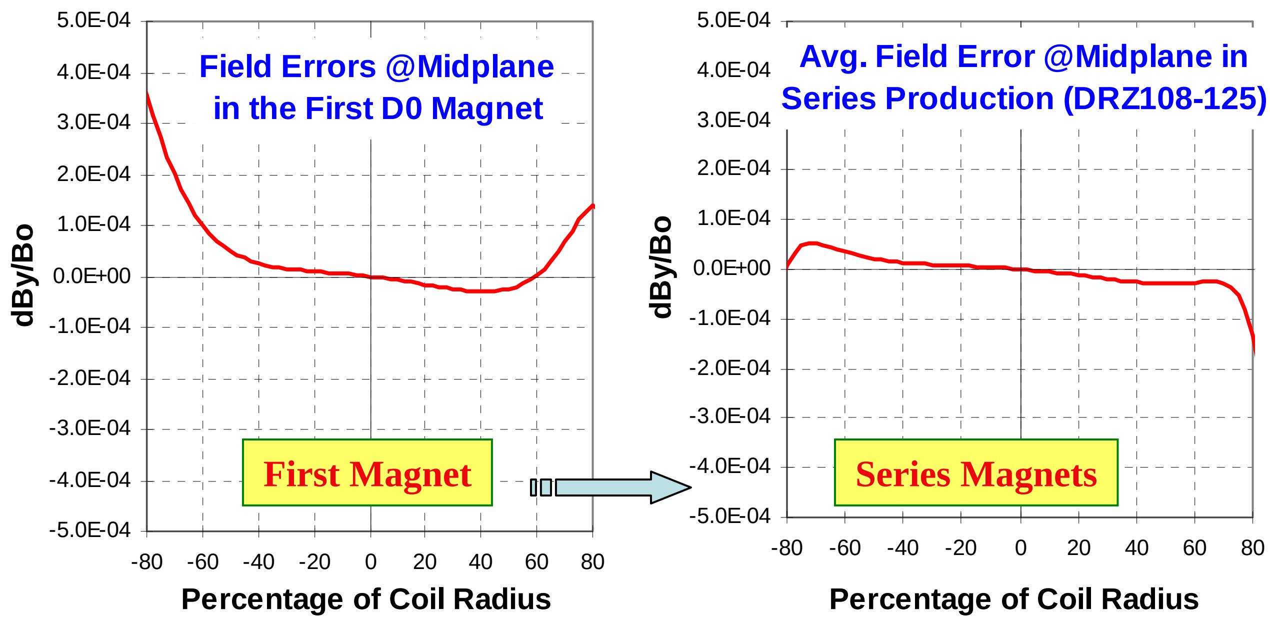
Plan for Flexible Coil Cross-section in APUL D1
(Do the same as done in 100 mm RHIC IR Dipole)



- Usually one needs to build a few magnets to obtain a good field quality.
- These magnet iterations results in a significant time and cost penalties.
- Simple techniques (midplane + pole shims) produced accelerator grade field quality in the very first magnet (field errors ~1 part in 10^4 up to 60% coil radius).
- This flexibility in the design allowed easy harmonic tuning during the production without changing coil or yoke. It resulted in good field quality magnets - average error <1 part in 10^4 up to ~80% of coil radius (almost entire vacuum pipe).

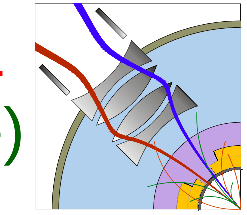


RHIC 100 mm D0

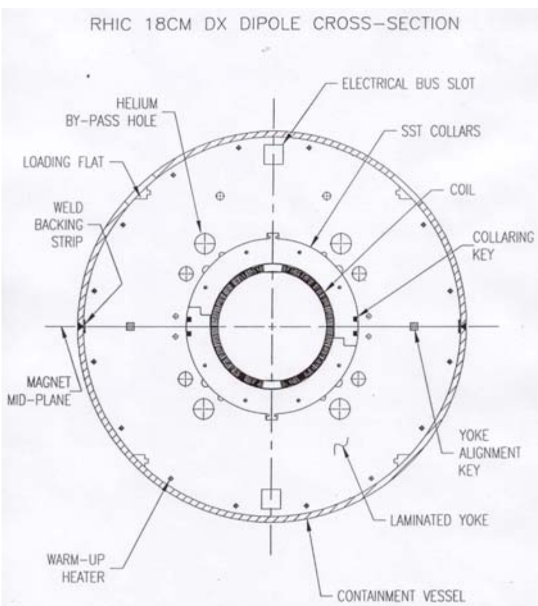


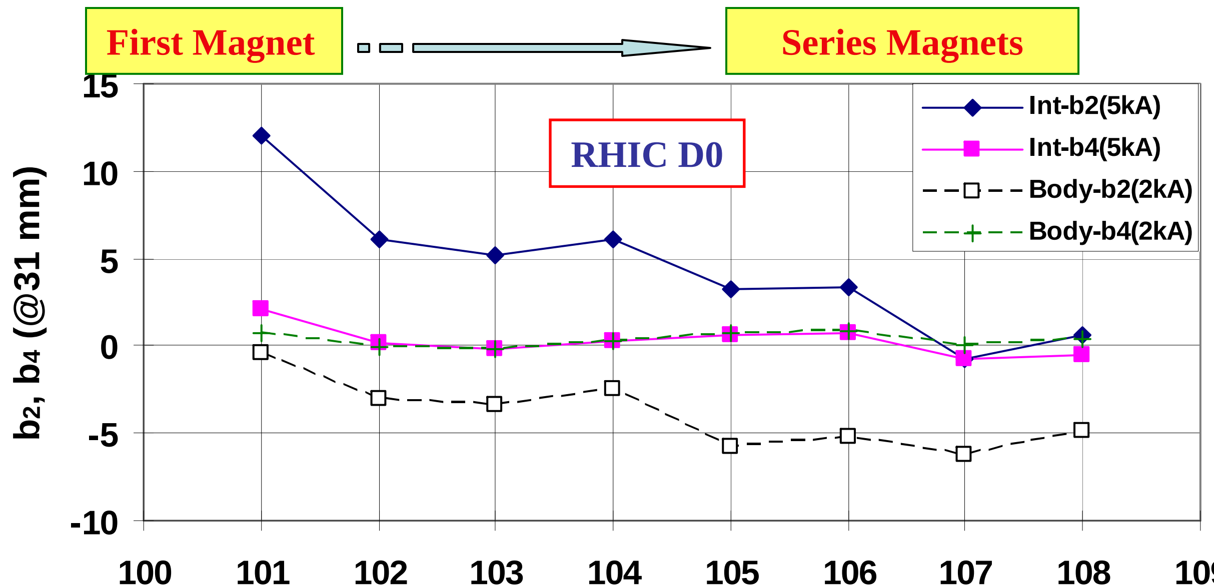
Much faster and much cheaper than conventional iterations

Plan for Flexible Yoke Cross-section in APUL D1
(Do the same as done in 100 mm RHIC IR Dipole)



- Have extra strategically located saturation control holes in the yoke lamination and fill them up with iron rods as needed.
- This takes care of both saturation-induced harmonics (culprit iron) and Lorentz force induced harmonics (culprit coil, particularly if there is a small radial gap of ~50 micron or so between coil & collar, built-up due to normal tolerances in parts).
- Final result of this adjustment is a smaller change in harmonic as a function of current, independent of who the culprit is.





Much faster and much cheaper than conventional iterations

Skew Quad (a_2) Harmonic at High Field

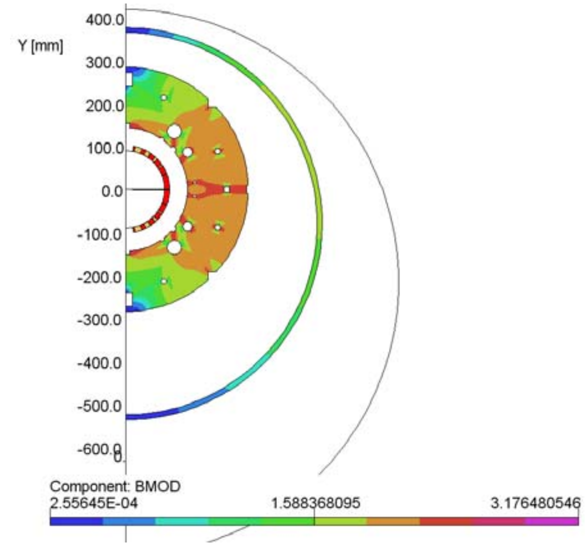
- Non symmetric vertical placement of coldmass inside the cryostat creates skew quadrupole harmonic (a_2) at high fields when the flux leaks out of the yoke.

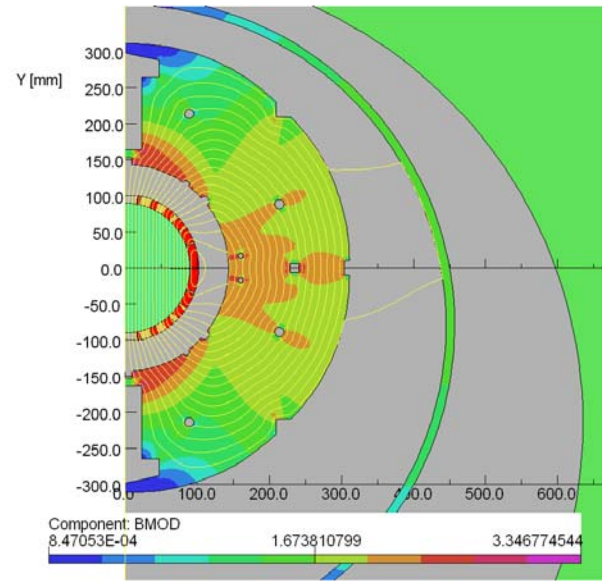
- In RHIC dipoles, this was partly compensated by placing heavier yoke packs on the lower side.

- We could also do similar thing here.

- In addition we can have some strategically located holes in the yoke and fill them in the lower half and not in the upper half to compensate for the proximity of the cryostat to the upper half.

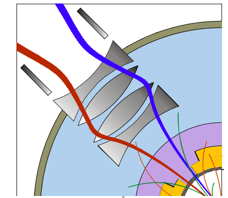
- Filling holes with iron rods technique can also be used for fine tuning of this skew quad harmonic.



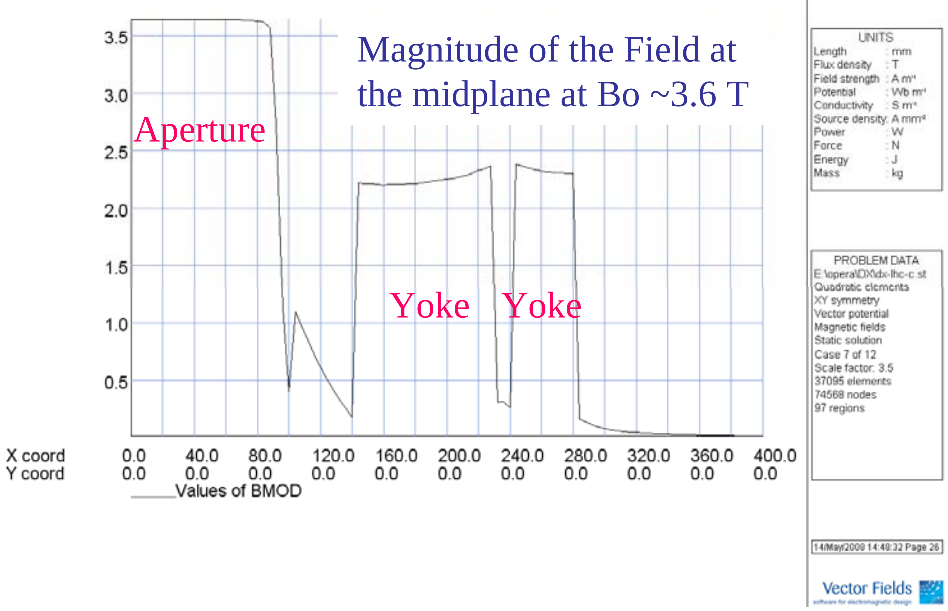


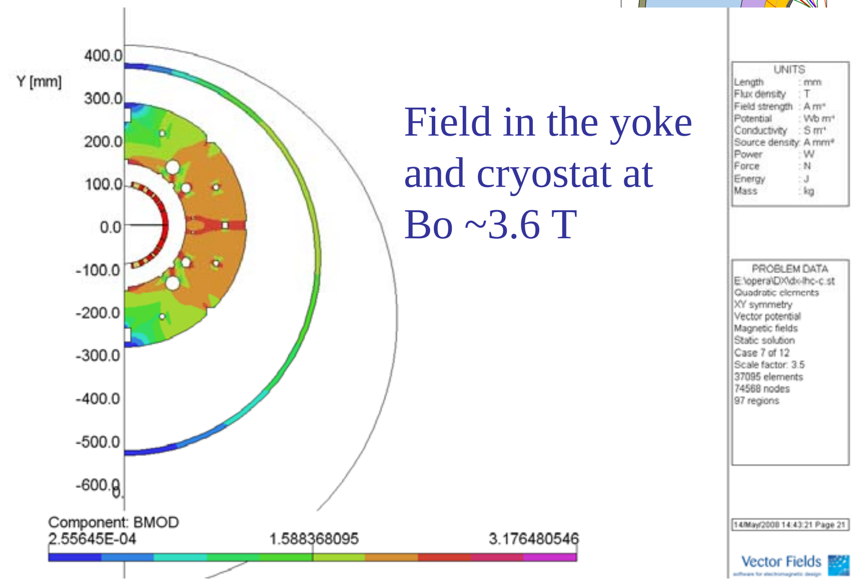
Circular Vs. Oblate Yoke in APUL D1

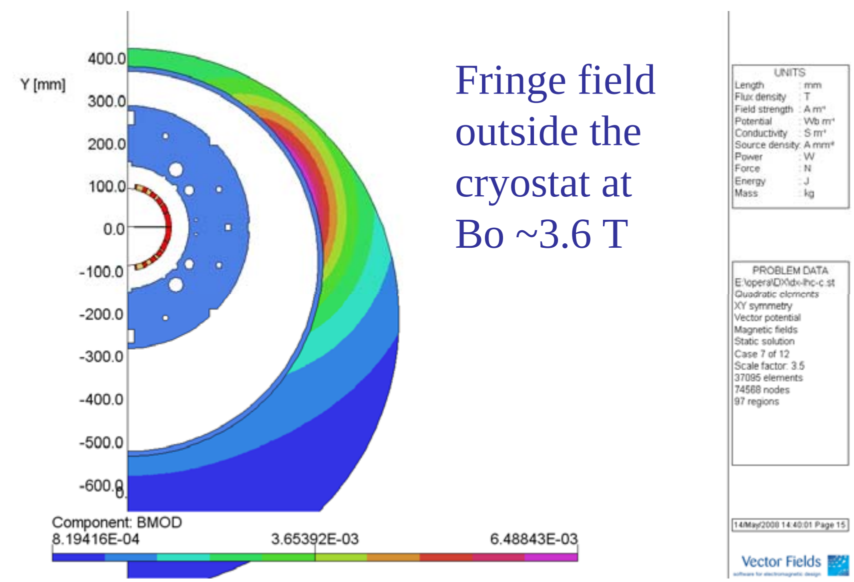
Option #1 : Circular Yoke as in RHIC DX



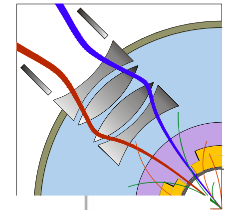
- Representative circular yoke with 570 mm o.d.
- Coil cross section and the collars are similar to RHIC 180 mm DX
- Design central field is ~ 3.6 T (with a later request for 4.06 T for 30 Tesla.meter bend strength)
- Note : Circular yoke has ~ 6.5 mT fringe field outside cryostat and ~2.4 T in yoke at midplane.
- Sextupole saturation is ~8 unit at 2/3 radius



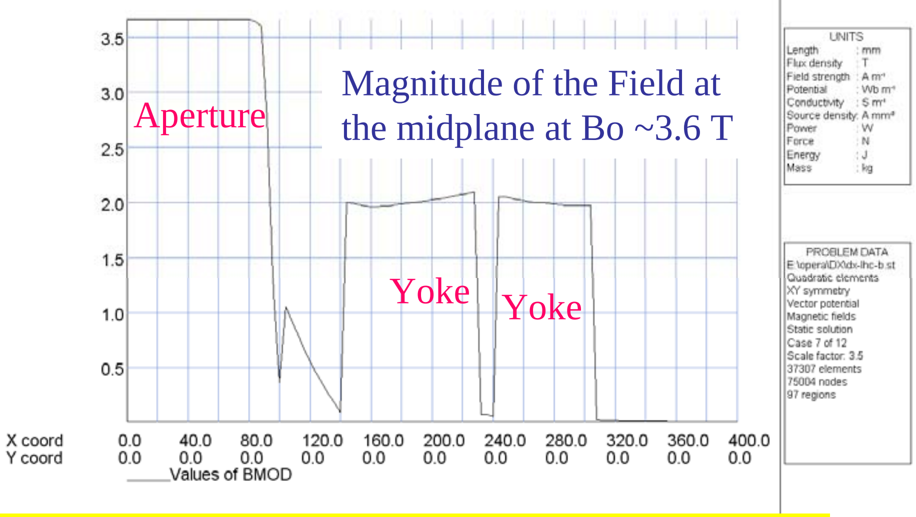


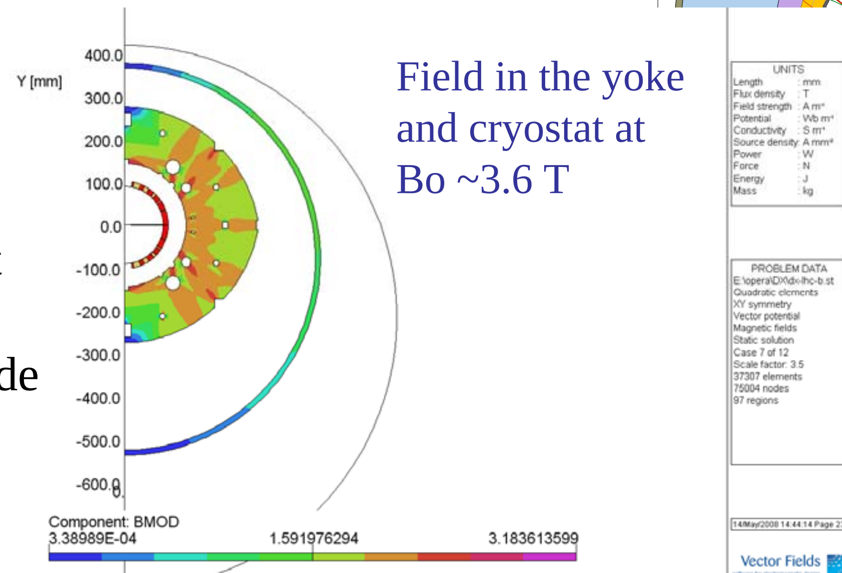


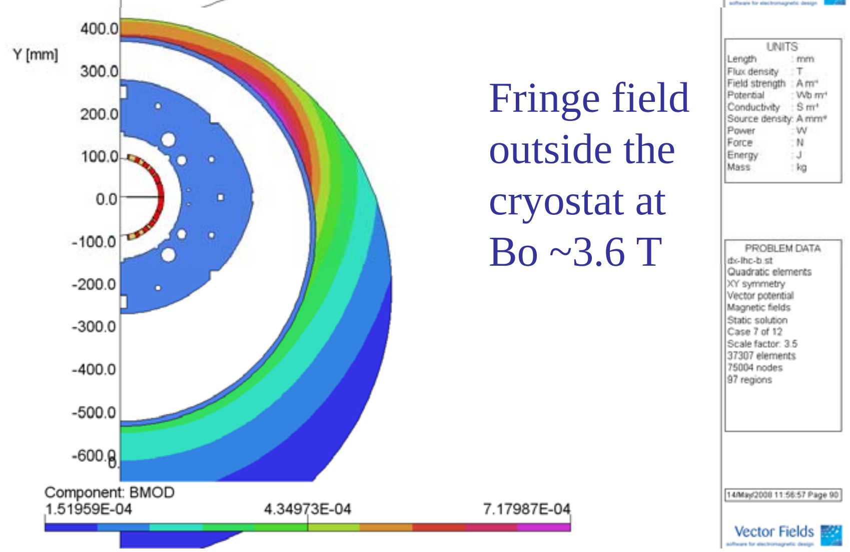
Option #2 : Oblate Yoke



- Representative oblate yoke as in LHC D2/D4
- Coil cross section and the collars are similar to identical to RHIC 180 mm DX
- Design central field is ~ 3.6 T (with a later request for 4.06 T for 30 Tesla.meter bend strength)
- Note : Oblate yoke has ~ 0.7 mT fringe field outside cryostat and ~2 T in yoke at midplane. Sextupole saturation is ~3 unit at 2/3 radius







Saturation control is yet to be optimized

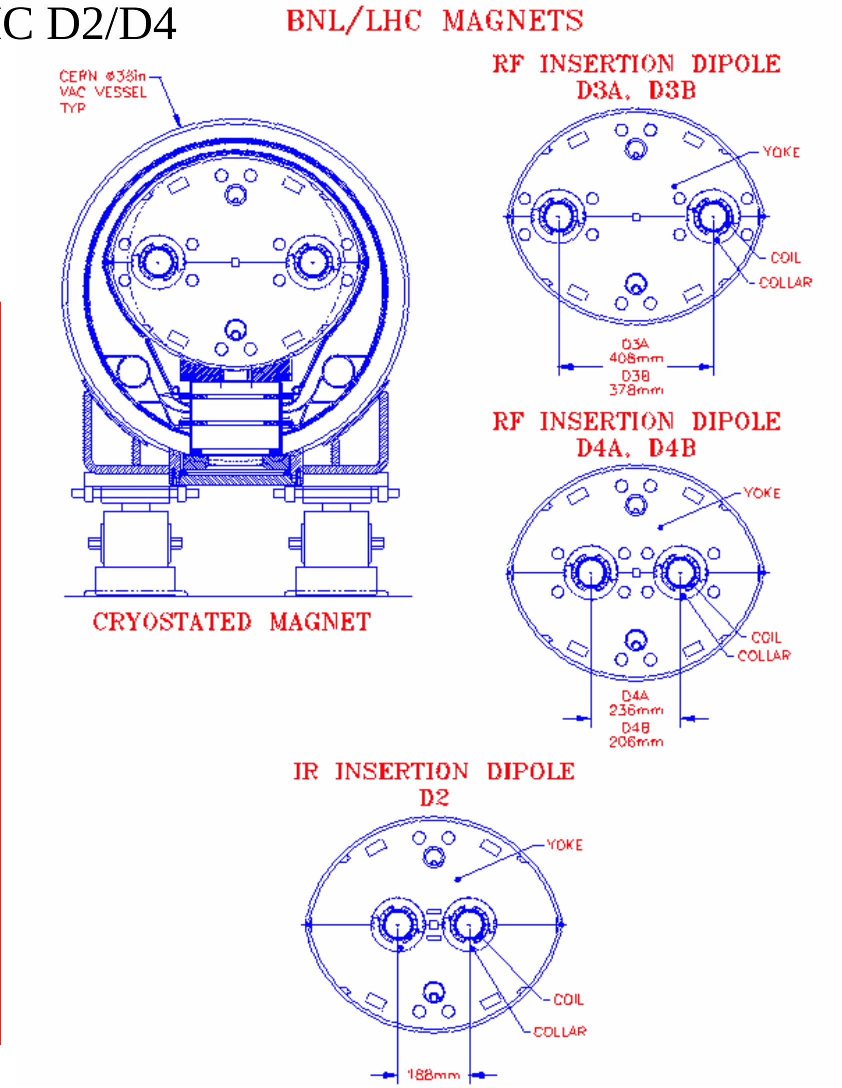
Background on Oblate Yoke Option

- Oblate yoke has now been successfully used in LHC D2/D4

- This saved significant effort and money by allowing us to use standard LHC cryostat and posts.

From MT15 Paper

The proposed oblate-shaped yoke also offers a way to reduce the overall cryostat size in future magnets. In most magnets, the horizontal size is determined by the magnetic and mechanical designs and the vertical size is determined by the heat leak budget and post design. The two are then added to determine the overall size. In modifying the circular yoke shape to an oblate shape, yoke iron is removed from the vertical plane, as this material does not contribute to the magnetic and mechanical design. The vertical space, thus saved, can be utilized by the post and thermal shielding, reducing the overall size. The validity of this design will be tested in the first model magnet to be built at BNL prior to the production run of the LHC insertion magnets.

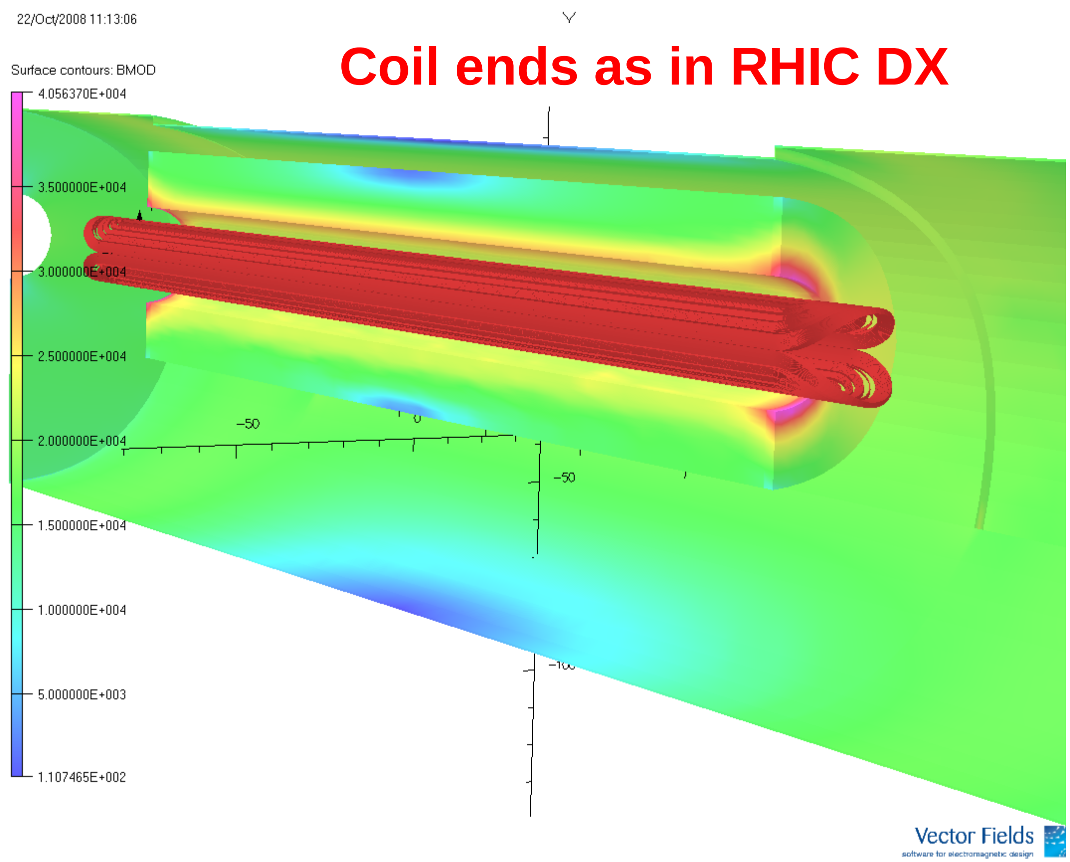


Coil Ends

Present guideline is to develop an alternate end design to determine/compare by computer modeling the new improved ends with the original RHIC DX coil ends (Mike Anerella).

- **The layout of the blocks and individual turns in coil ends will be optimized using "differential geometry" method of ROXIE 10.1 (similar to the method used in program BEND) to improve the mechanical design of the turns.**
- **The size and location of the end spacers will be optimized with ROXIE to obtain a good magnetic design (low end harmonics) that is consistent with the improved mechanical design of new ends.**

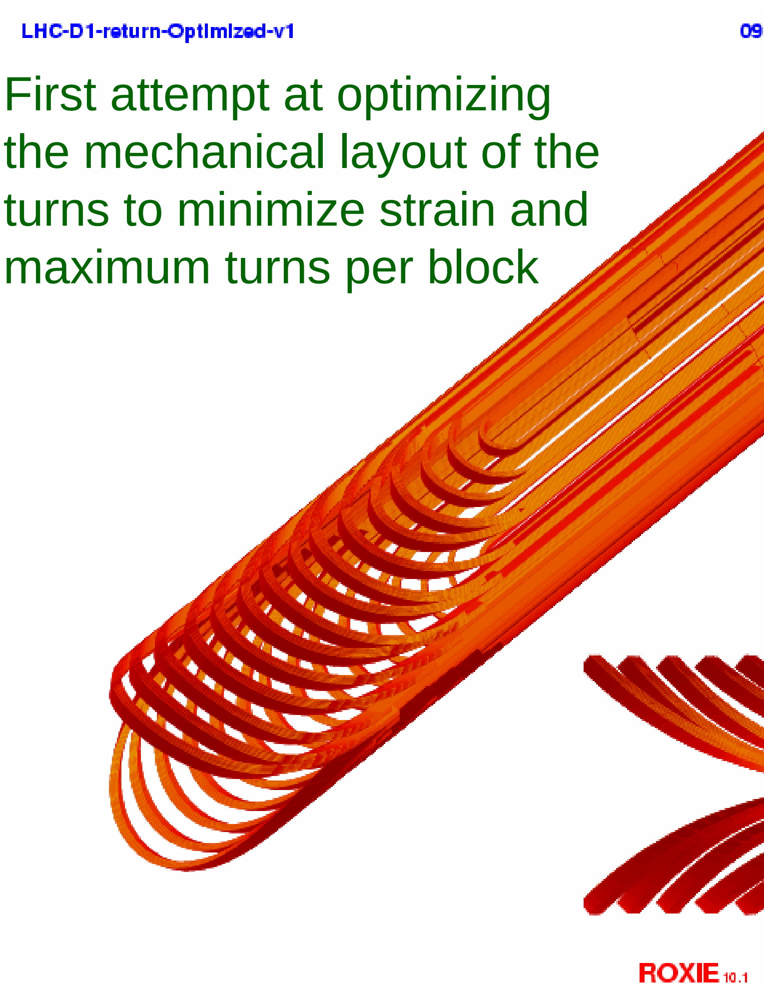
Coil ends as in RHIC DX

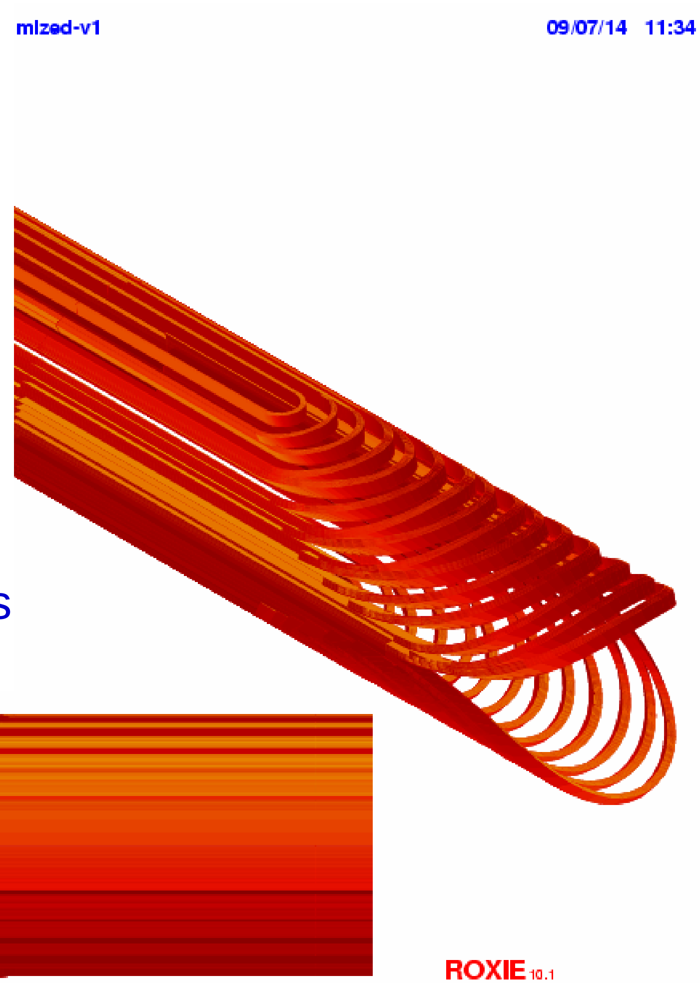


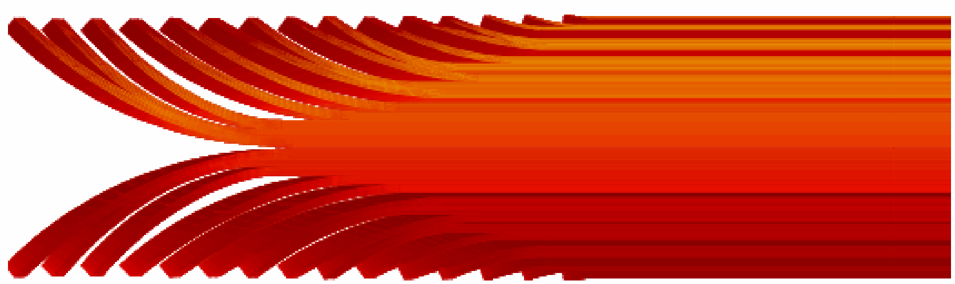
OPERA3d Model of RHIC DX

Work in Progress in Optimizing Ends with ROXIE

First attempt at optimizing the mechanical layout of the turns to minimize strain and maximum turns per block

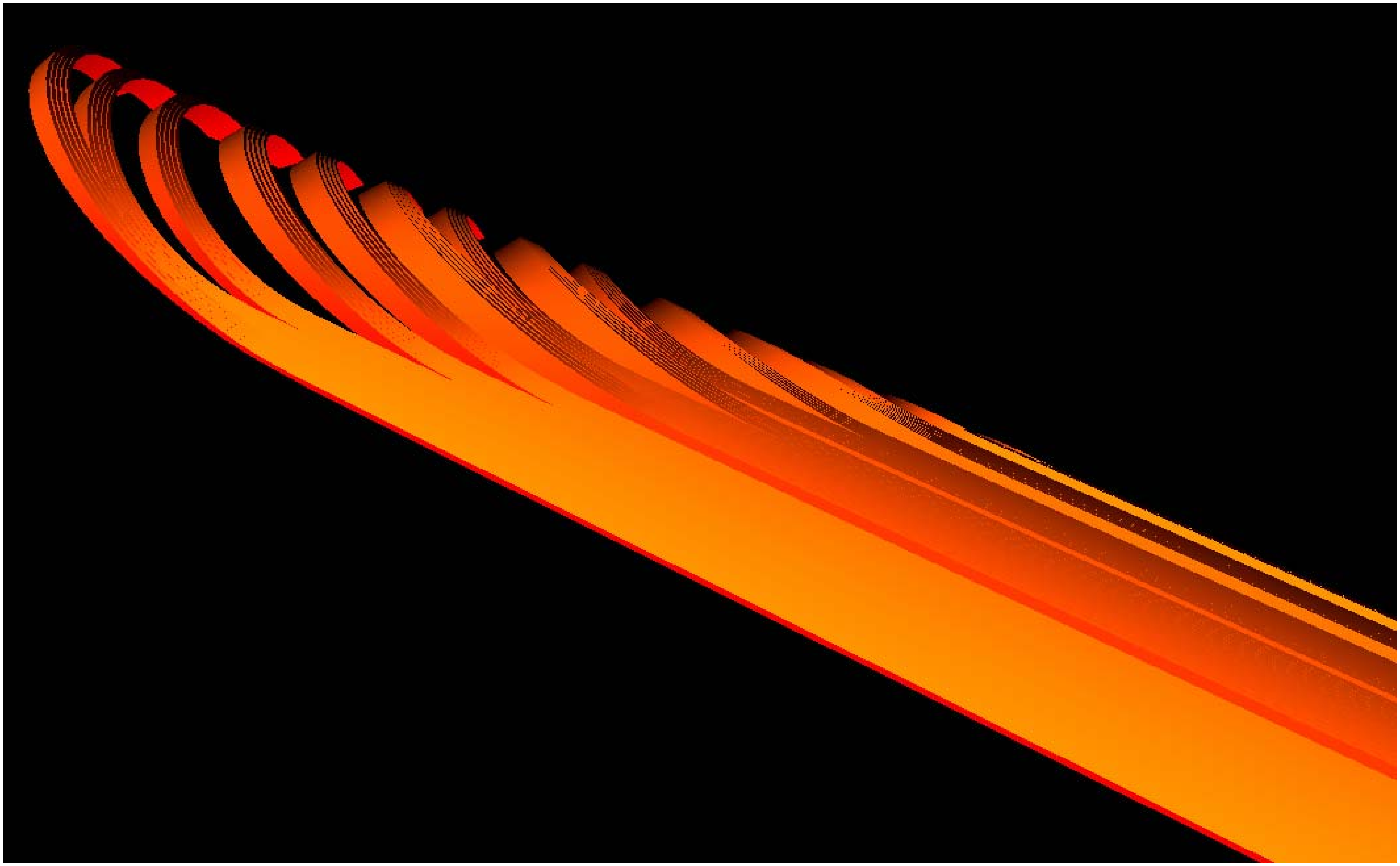




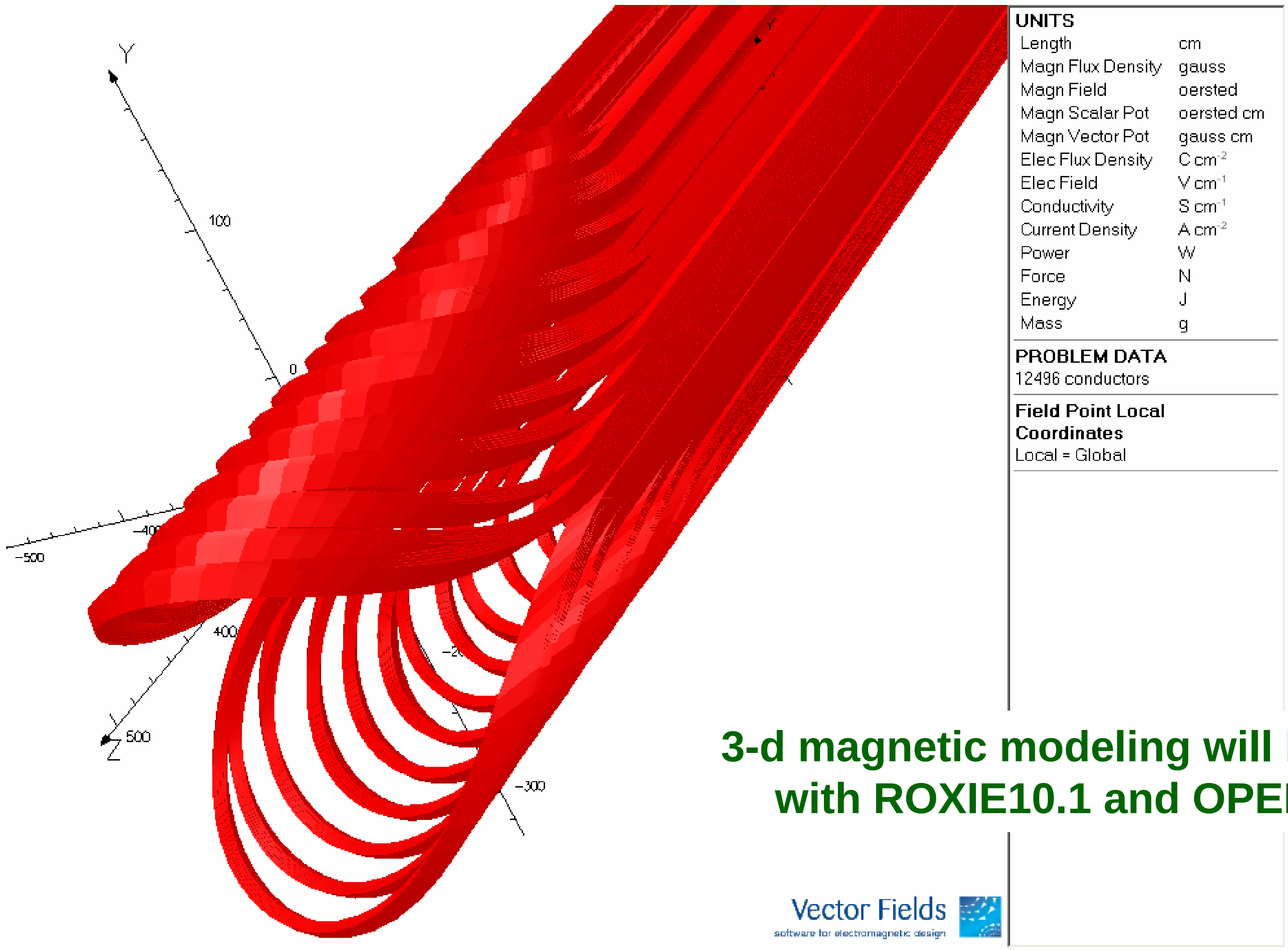


Different views

ROXIE Ends thru Virtual Reality

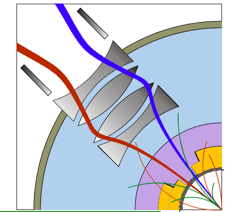


ROXIE Ends Exported to OPERA3d



3-d magnetic modeling will be done with ROXIE10.1 and OPERA3d

Expected harmonics for APUL D1
(consisted of 2 cold-masses)



LE + Body + NLE + space + NLE + Body + LE

LHC/BNL/D1 Version (1c)

Expected values of integral harmonics at 2000 A in
180 mm aperture D1 dipoles (consisted of two LDX):

(assumes one LDX coldmass with 2 warm and 2 cold measurements to be used for tuning of INTEGRAL geometric and saturation harmonics)

***** Reference Radius is 40 mm *****

Harmonics in units (European notation; n=3 is sextpole)

[<bn> = mean, d(bn) = uncertainty in mean]

[sig(bn) = sigma for bn, sig(an) = sigma for an]

n	<bn>	d(bn)	sig(bn)	<an>	d(an)	sig(an)
2	0.0	0.5	0.6	0	2	2
3	0	2	1	-1	2	0.3
4	0.0	0.2	0.1	0.0	0.3	0.4
5	0.0	1.0	0.1	0.0	0.1	0.05
6	0.0	0.05	0.02	0.0	0.10	0.05
7	-0.2	0.3	0.02	0.0	0.02	0.02
8	0.000	0.002	0.003	0.0	0.02	0.01
9	-0.05	0.100	0.003	0.0	0.01	0.001
10	0.00	0.001	0.001	0.0	0.005	0.001
11	-0.02	0.020	0.0003	0.0	0.0003	0.0002
12	0.00	0.0001	0.0001	0.0	0.0002	0.0002
13	0.01	0.010	0.0001	0.0	0.0001	0.0001
14	0.00	0.0001	0.0001	0.0	0.0001	0.0001
n	<bn>	d(bn)	sig(bn)	<an>	d(an)	sig(an)

Reference Radius is only 40 mm for a coil Radius of 90 mm.

- **Expect smaller higher order harmonics**

Maximum Design field is ~3.6 T @5.5 kA or ~4.06 T at 6.3 kA.

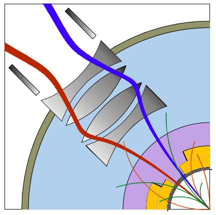
Following harmonics may show significant variation as a function of current
(as compared to the uncertainty in mean)
Persistant current changes are incorporated in <b3> and saturation in d(b3) and d(a2)

I (A)	<b3>	d(b3)	sig(b3)	<a2>	d(a2)	sig(a2)
360	-5	2.5	1.1	0	2	2
1000	-1	2	1	0	2	2
2000	0	2	1	0	2	2
4000	0	2	1	0	2.5	2.2
5600	0	2	1	0	2.5	2.5
6500	0	2.5	1.0	0	3.0	3.0
7500	0	3.0	1.1	0	3.0	3.5

LHC/BNL/D1 Version (1c)

Ramesh Gupta, July 6, 2009

Strategy for Assuring Good Field Quality
(while retaining proper pre-stress on coils)

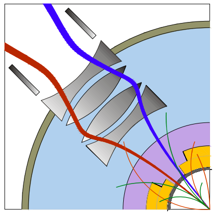


- Adjust number of turns, if necessary (by about 1 of 71 per quadrant).
- If coil size and pre-stress are significantly off, then another option could be to adjust the insulated wedge sizes (significant change). The goal and expectation of the program is that no such change will be necessary.
- Perform warm magnetic measurements and adjust midplane and pole shims to tune geometric harmonics with correct pre-stress. Do iterations, as necessary.
- Perform detailed cold measurements (with ~1 m coil) to obtain body and end harmonics as a function of current in one magnet.
- Fill holes, re-measure with integral coil, as necessary, to tune (minimize) saturation induced harmonics (primarily b_3, may be b_5). For this iteration, integral harmonic measurements are sufficient.
- Do complete set of measurements with both magnets inside the cryostat in a structure that will be delivered to CERN.
- Adjust/iterate midplane shims (midplane caps), pole shims, and filling-up of holes with rods during the production, as and if necessary.

Risk and risk mitigation:

If harmonics are out-of-spec then "consult with CERN" if magnets are acceptable or may be acceptable by increase in corrector strength, etc. If not then add more tuning/iterations and measurements to assure good field quality in the magnets.

Summary



- We are adopting a ***value engineering*** approach to save on budget and schedule by eliminating customary iterations.
- Main field quality challenge of the program is to assure a good field quality in production despite "**NO** *proto-type or pre-production magnets*".
- With a ***flexible design***, past experience and proper planning, we are confident to be able to do it again.
- Flexible design minimizes schedule-slippage even when certain components are somewhat out-of-spec and minimizes the associate cost.
- These strategies are not new and all of them have been successfully employed during various RHIC production magnets
  - Minimize geometric harmonics with proper pre-stress in the coil
  - Minimize saturation induced harmonics (normal odd and skew even)
  - Minimize integral harmonics to absorb residual end harmonics