D1 Field Quality

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APUL D1 Dipole Internal Review

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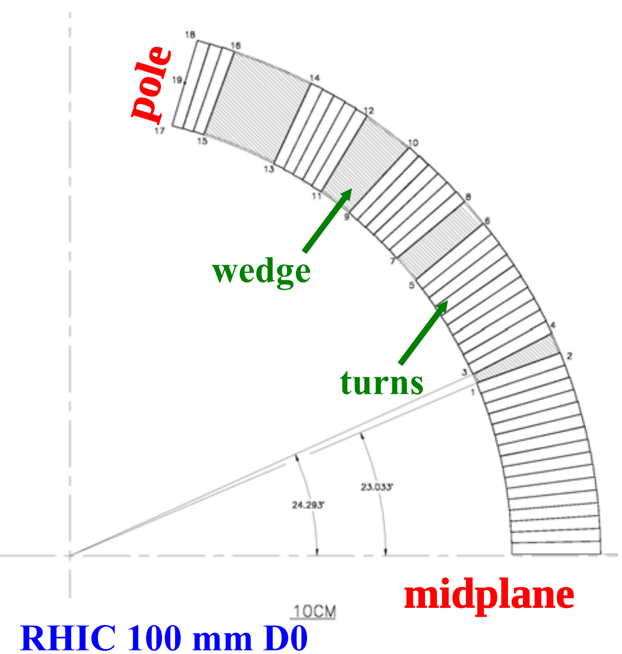
Overview and Issues

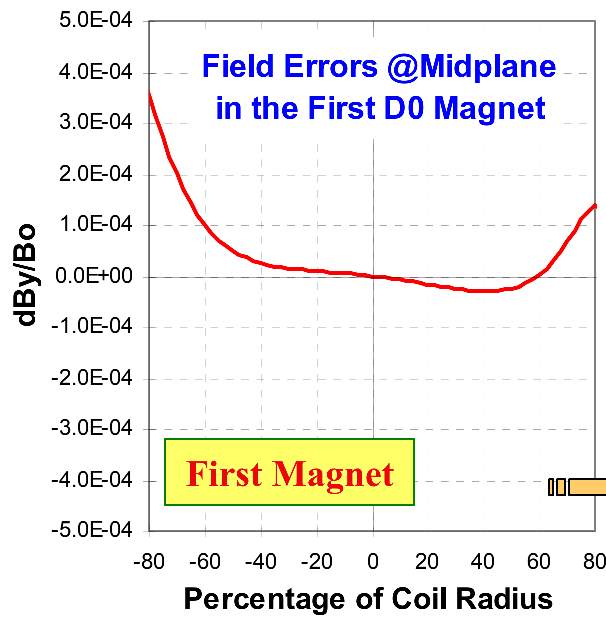
- Main field quality challenge of the program is that there will be "**NO** *proto-type or pre-production magnets*". The first magnet must be usable. Minor iterations may, however, continue through the initial part of the production.
- We have been through this situation before, successfully, in RHIC 100 mm aperture dipole program. With a flexible design and proper planning, which is the subject of this review, we are confident to be able to do it again.
- Apart from the usual considerations of geometric and saturation-induced harmonics, we must also deal with the skew quad harmonic, etc. due to top-bottom asymmetry and the oblate yoke (both dealt with before).
- Other challenge is that in a coil with ~71 turns the usual tolerance in cable thickness and pre-stress could mean that the actual number of turns in coil may change by one or so (happened in RHIC DX). The resulting influence in field quality needs to be accommodated (also done before).
- Alternate coil end design will also be examined.
- This presentation will give our initial thoughts and not the final design.

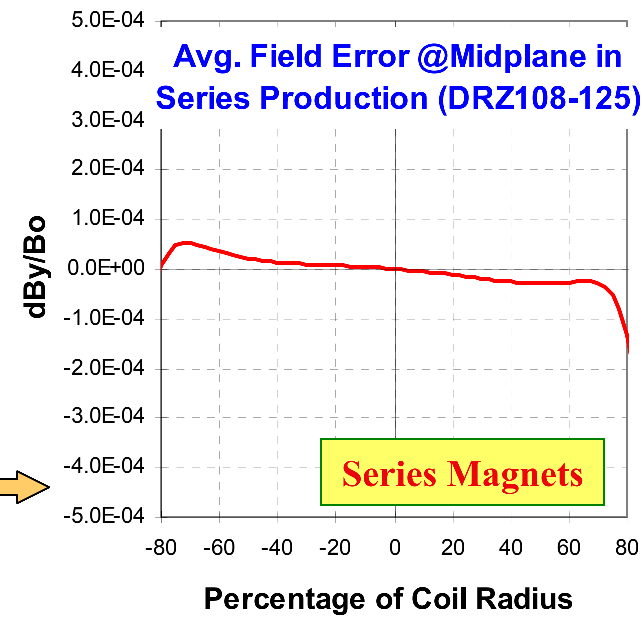
Plan for Flexible Coil Cross-section in APUL D1 (Do the same as done in 100 mm RHIC IR Dipole)

- 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

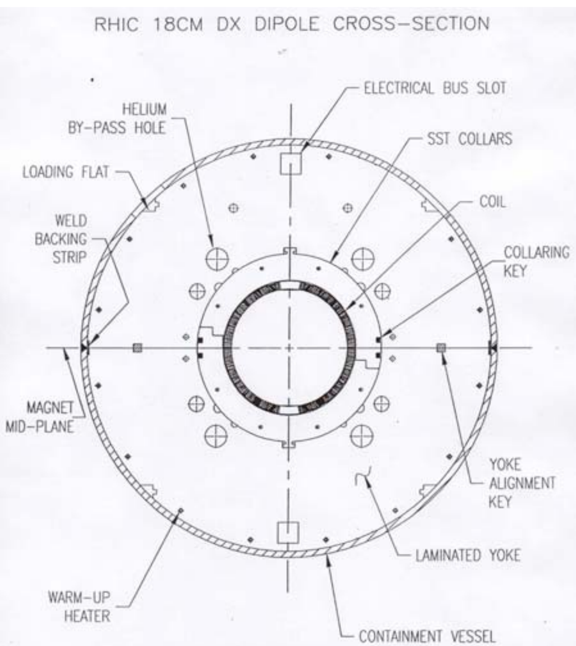


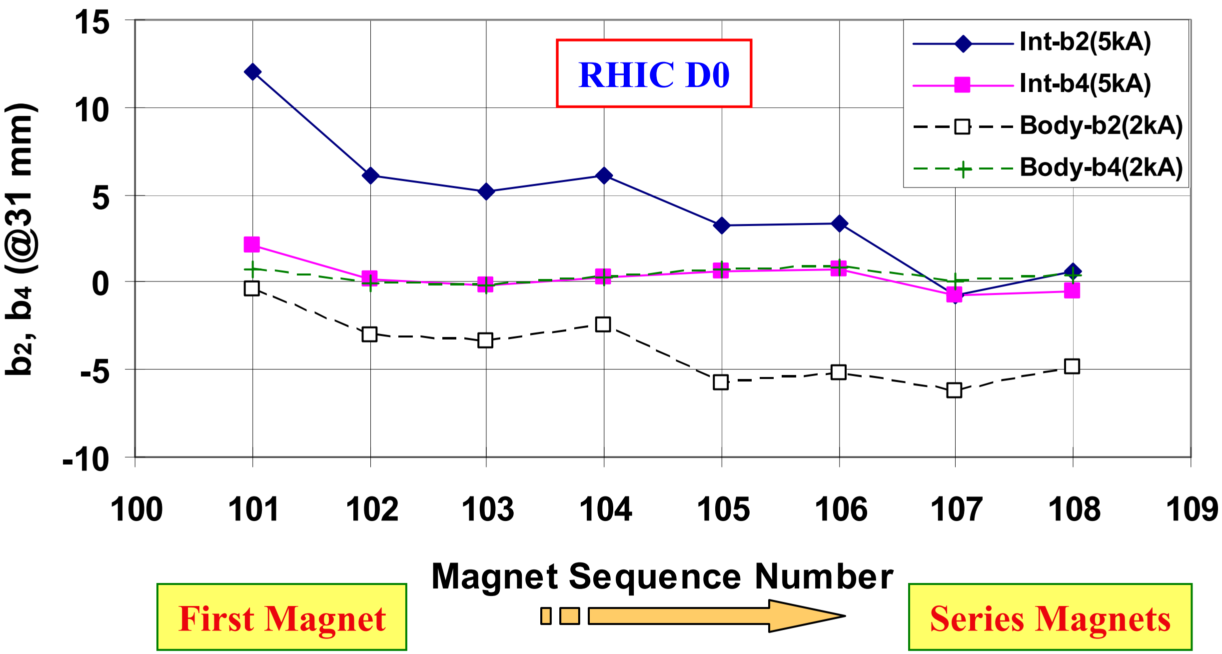


Plan for Flexible Yoke Cross-section in APUL D1 (Do the same as done in 100 mm RHIC IR Dipole)

APUL

- 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.





Skew Quad (a_2) Harmonic at High Field

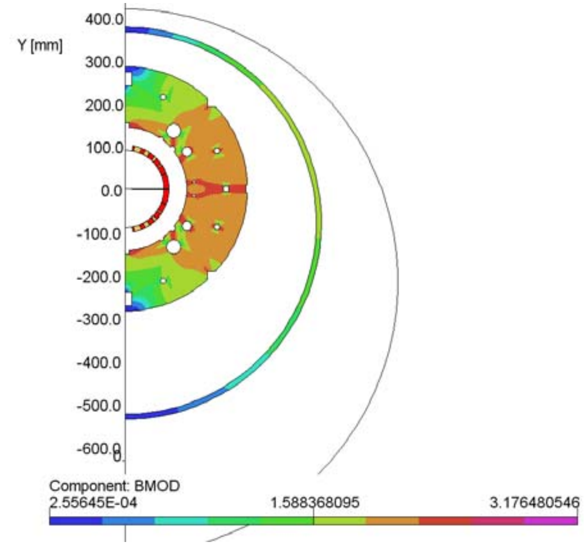
• Non symmetric vertical placement of coldmass inside the cryostat creates skew quadrupole harmonic (a_2) at high fields when the flux leaks out of the yoke.

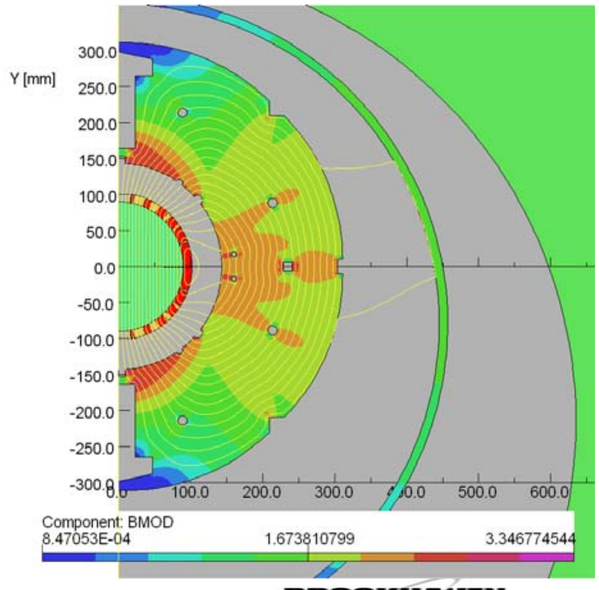
• In RHIC dipoles, this was partly compensated by placing heavier yoke packs on the lower side.

• We could also do similar thing here.

• We can also take advantage of the fact that the helium and bus holes in APUL D1 are not top-bottom symmetric in the yoke. The size and location of these holes can be tuned to minimized a_2 saturation.

• Filling holes with iron rods technique can also be used for tuning skew quad harmonic as well.

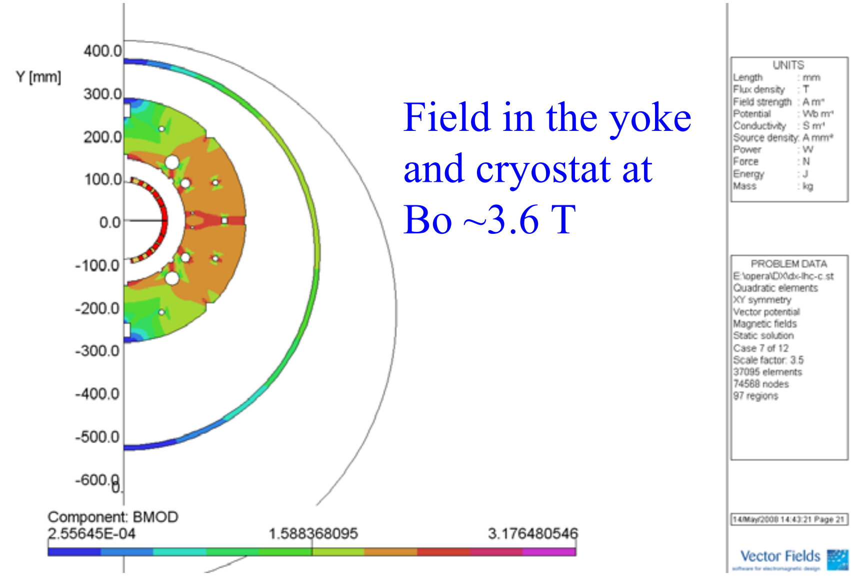


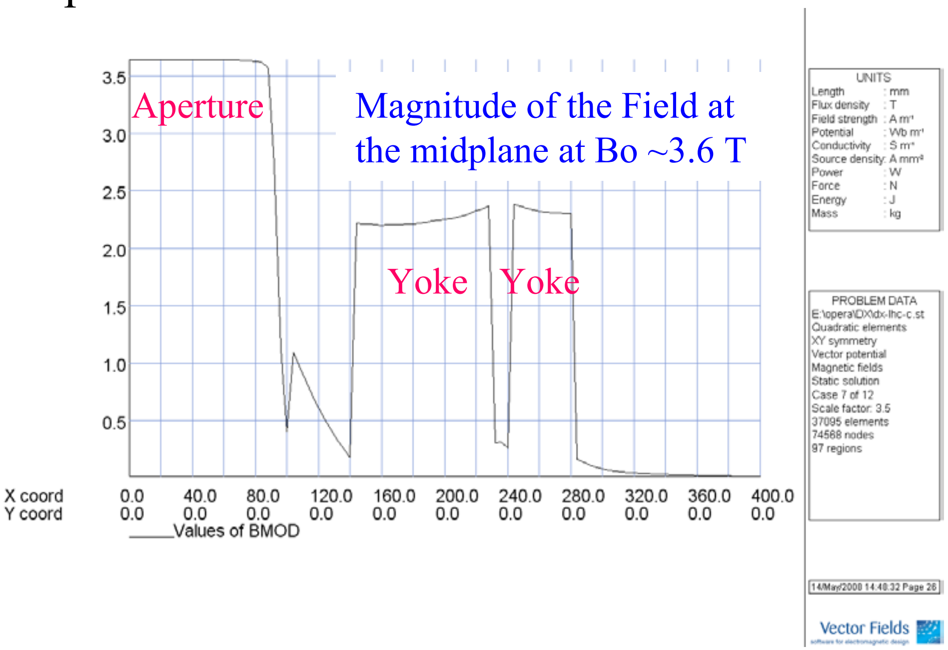


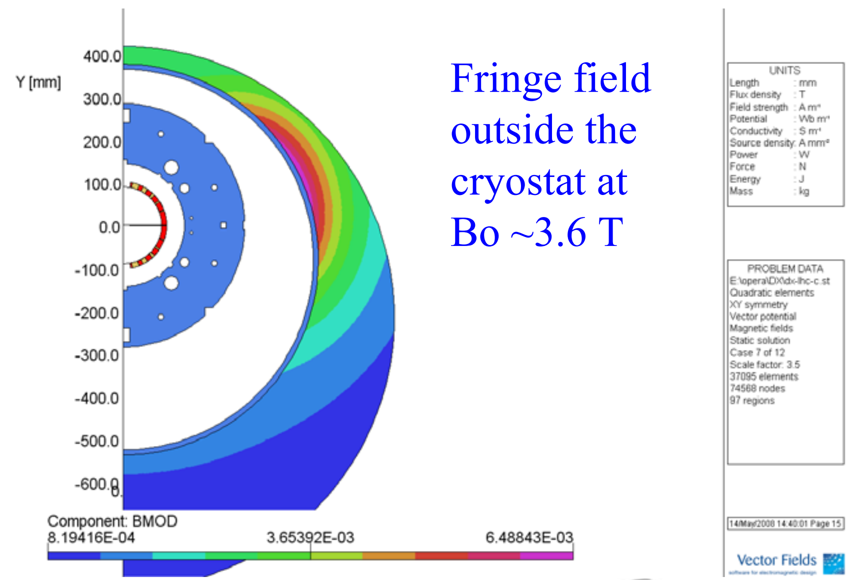
Circular Vs. Oblate Yoke in APUL D1

Circular Yoke Option for LHC D1 from RHIC DX

- Representative circular yoke with 570 mm o.d.
- Coil cross section and the colloars are identical to RHIC 180 mm DX
- Coil ends would be improved for better mechanical support (improved quench performance)
- Design field ~ 3.6 T (magnet has large margin)
- 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.



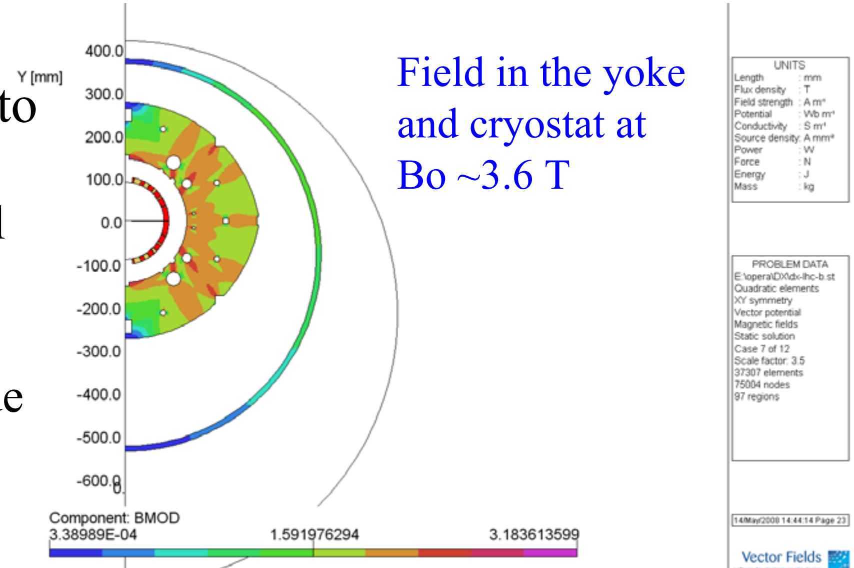


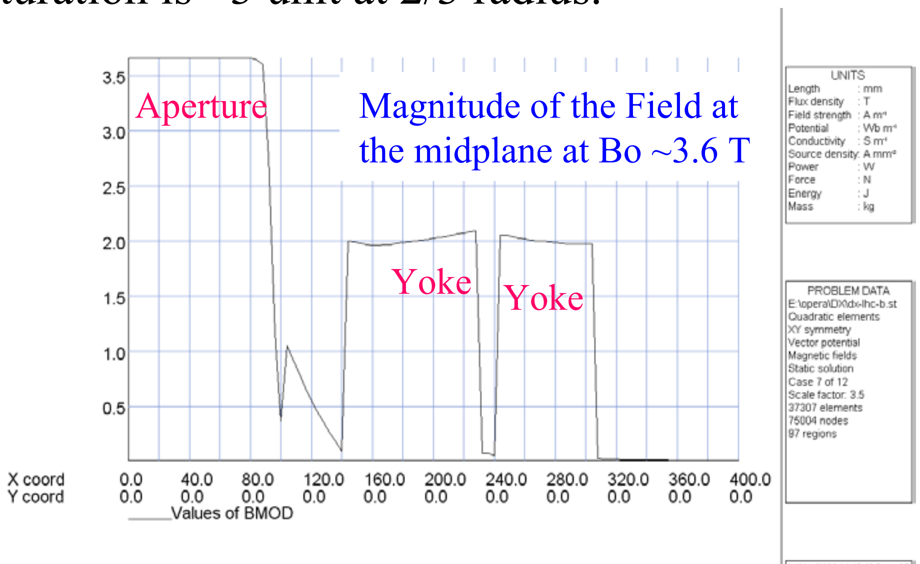


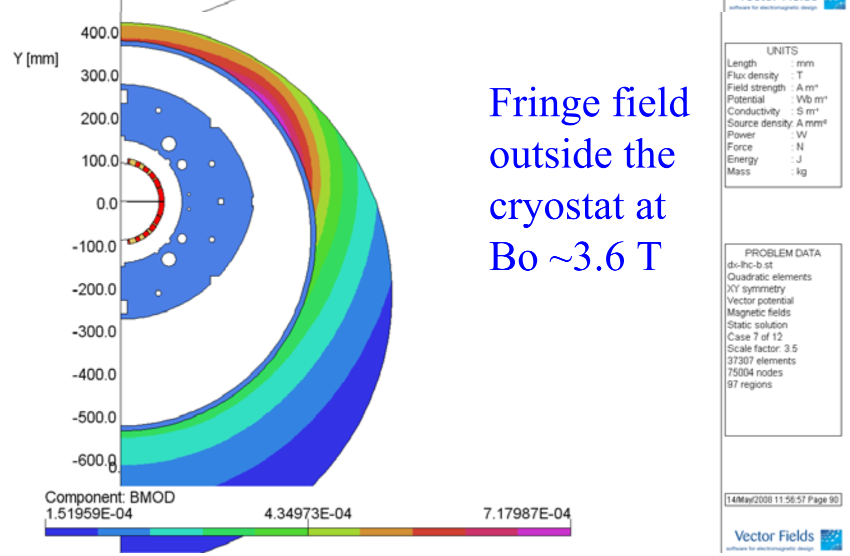
Oblate Yoke Option for LHC D1 from RHIC DX

APUL

- Representative oblate yoke as in LHC D2/D4
- Coil cross section and the colloars are identical to identical to RHIC 180 mm DX
- Coil ends would be improved for better mechanical support (improved quench performance)
- Design field ~ 3.6 T (magnet has large margin)
- 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.



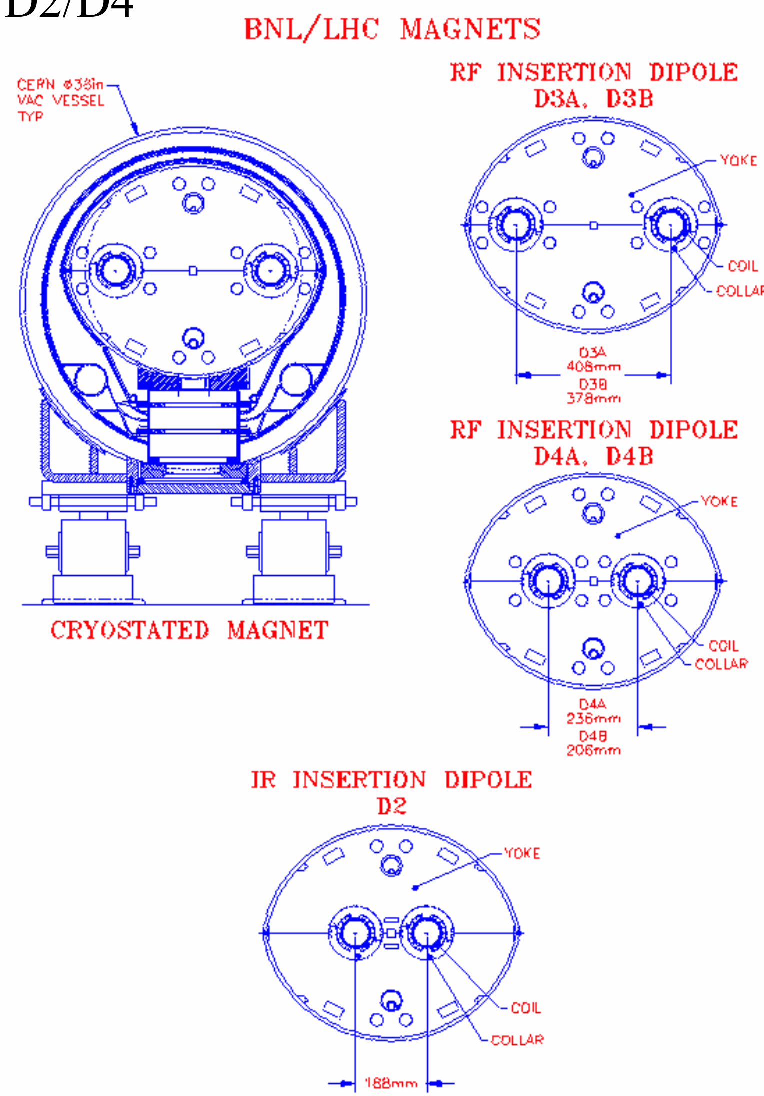




Saturation control is yet to be optimized.

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.



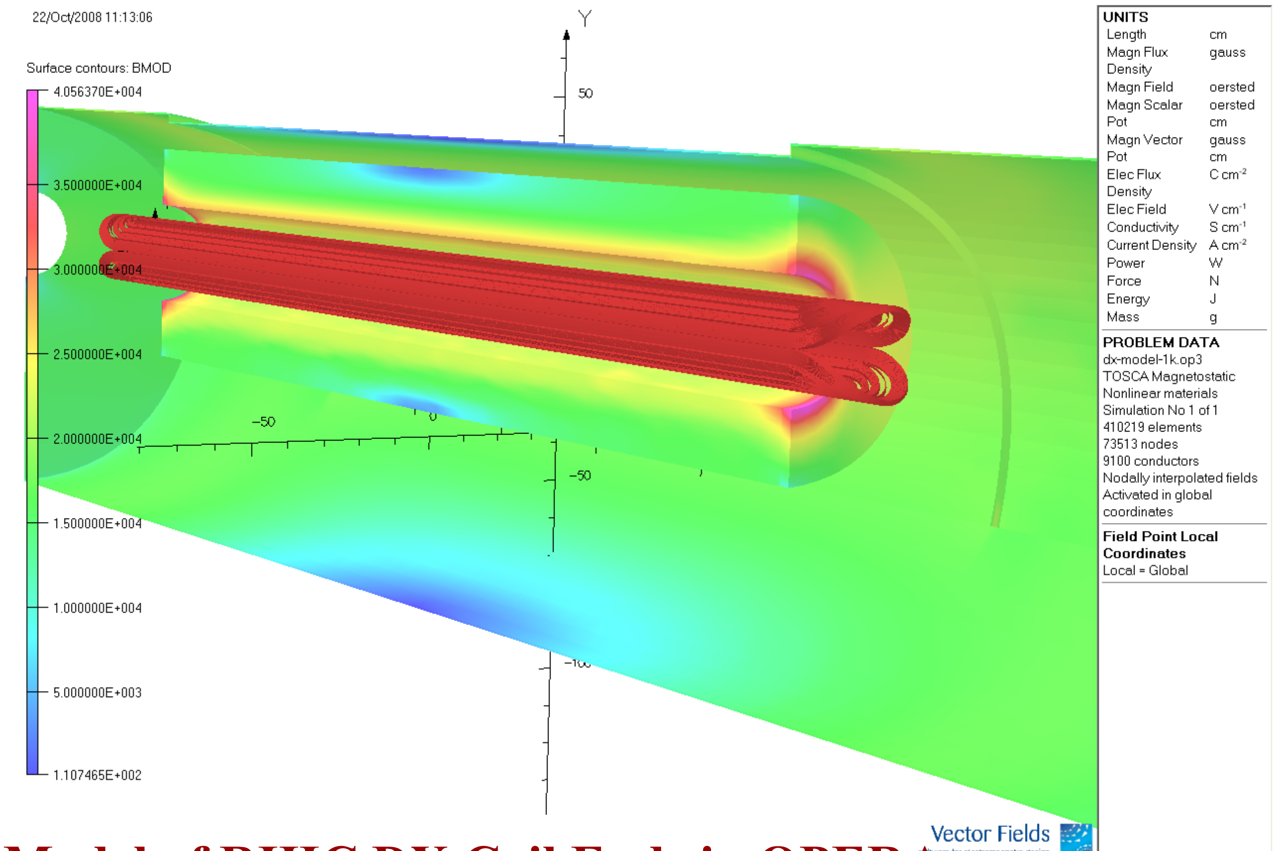
From MT15 Paper

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

The plan is to obtain significant mechanical improvements in RHIC DX coil ends when this design is adapted for APUL D1 (Mike Anerella)

The coil end spacers will be optimized to support that effort. The size and location of those will be optimized with ROXIE to obtain a good magnetic design that is consistent with the improved mechanical design for APUL D1



Model of RHIC DX Coil Ends in OPERA

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

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

LHC/BNL/D1 Version (1b)

Expected values of integral harmonics at 2000 A in
180 mm aperture D1 dipoles for LHC (consisted of two RHIC DX):

(assumes one 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. Smaller higher order harmonics

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 (1b)

Ramesh Gupta, 12/2/2008

Strategy

- Adjust number of turns, if necessary (by about 1 of 71 per quadrant).
- If coil size and pre-stress are significantly off then another drastic course will be to adjust the insulated wedge size. The goal and expectation of the program is that no major 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, pole shims, and filling-up of holes with rods during the production, as and if necessary.

Summary

- Main field quality challenge of the program is that there will be "**NO** *proto-type or pre-production magnets*". The first magnet must be usable.
- Minor iterations may, however, continue through the initial part of the production.
- With a flexible design and proper planning, we are confident to be able to do it again.
- These strategies are not new and all of them have been successfully employed during various RHIC production magnets.
  - Geometric harmonics
  - Saturation induced harmonics (normal odd and skew even)
  - End harmonics