Common Coil Dipoles for Future High Energy Colliders

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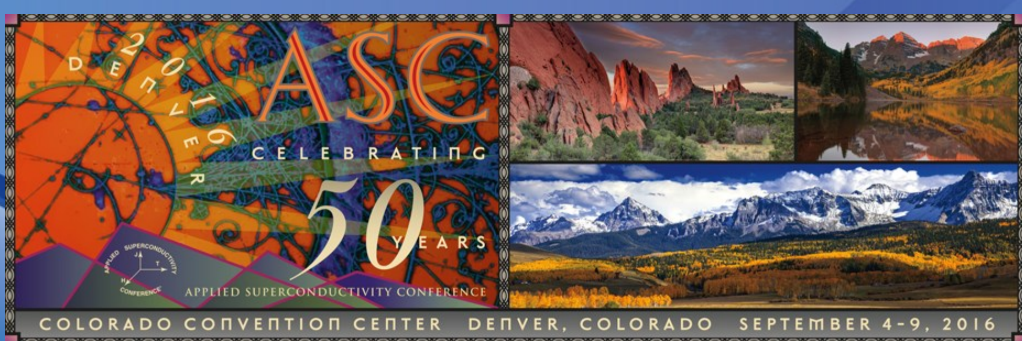

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Purpose of this Exercise

Examine if a common coil cross-section is possible that satisfies the key FCC 50 mm, 16 T design requirements

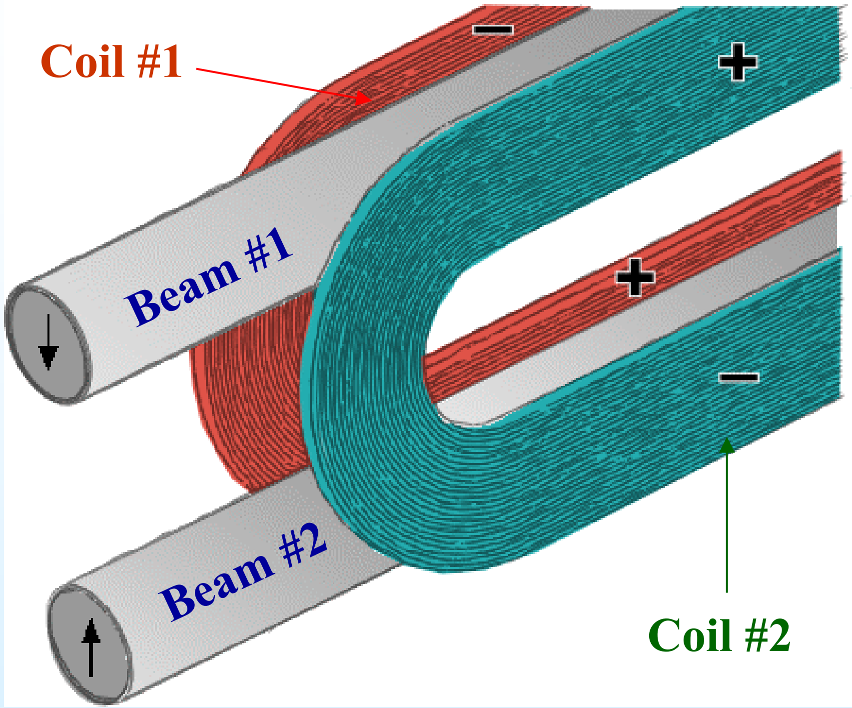
- **Harmonics (geometric & saturation): less than the specified**
- **Conductor usage: similar or less than in the other designs**
- **Stored energy: similar or less than in the other designs**
- **Inductance: much less than in the other designs (*NEW*)**
- **Standard intra-beam spacing: 250 mm**
- **Standard yoke outer diameter: 700 mm**
- **Structure able to hold pole (auxiliary) coils**

If so, then one can take several inherent advantages of the common coil in making high field collider dipoles cheaper and more reliable

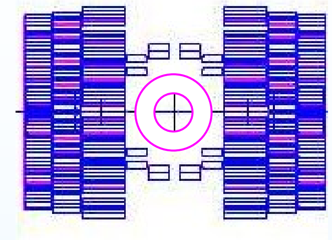
Basic design presented here satisfies above requirements

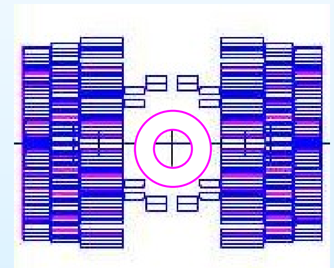
Common Coil Design

Main Coils of the *Common Coil Design*



Bend radius is determined by the aperture spacing (large), not by the aperture (small)





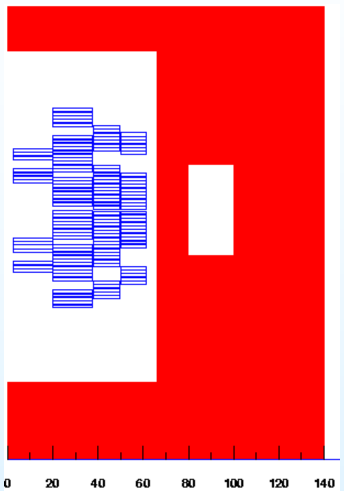
Good Field Quality *Common Coil Design*

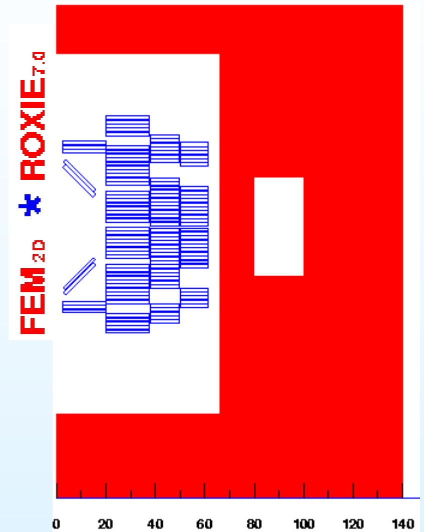
- **Simple coil geometry with large bend radii: reliability & lower cost expected; suitable for both "Wind & React" and "React & Wind"**
- **Same coil for two aperture: Manufacturing cost should be lower as the number of coils required for 2-in-1 magnet is half**
- **Rapid turn-around for systematic and innovative magnet R&D**
- **Used in the initial designs of VLHC and SppC. How about in FCC?**

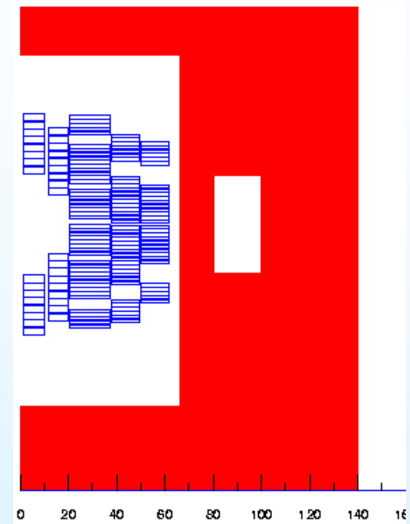
Need of the Hour for the FCC Study
Present a Competitive Design

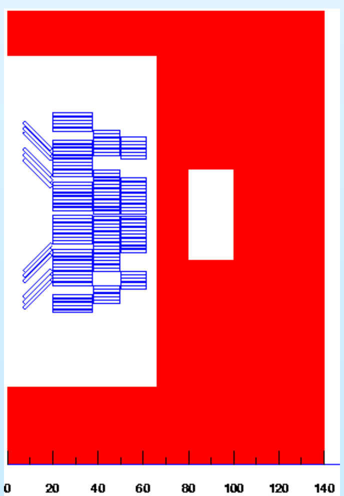
- Pole coil adds to the complication but must be used

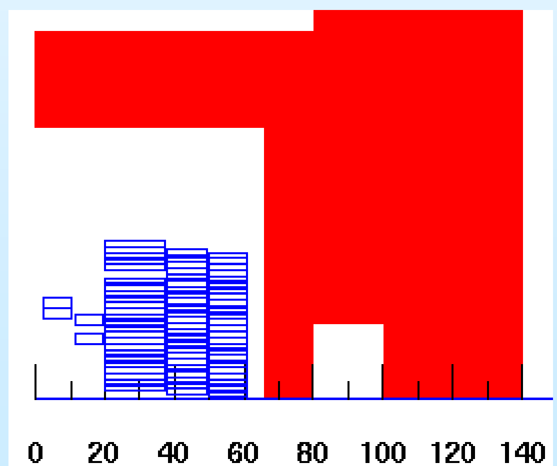
Start by choosing one style from the previously examined

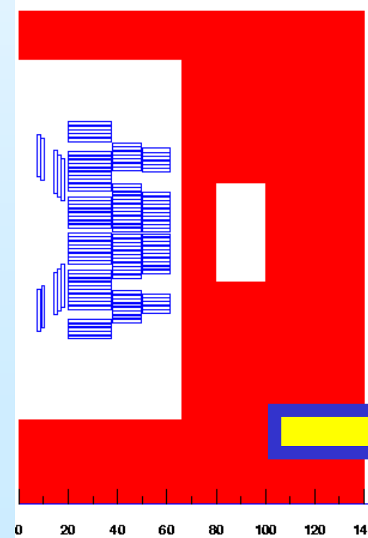








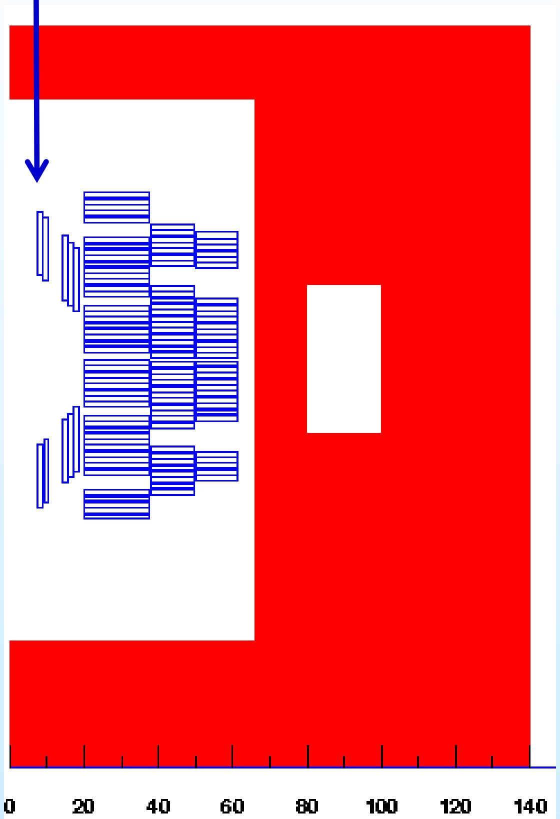




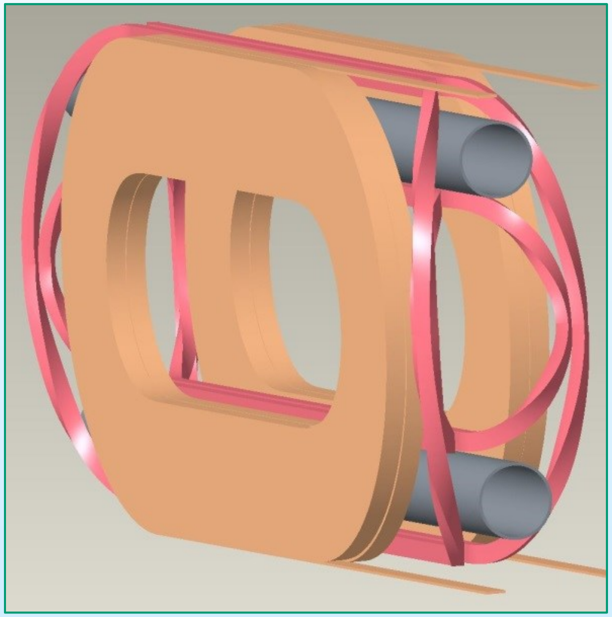
Only this one examined

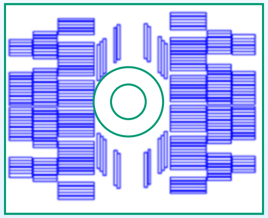
Design Examined

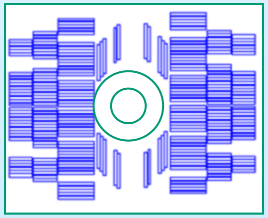
➤ **Pole (auxiliary coils) must clear the beam tubes in the ends**



In this design, the pole coils are like midplane coils of cosine theta dipoles (first easy bend then large radii bend)







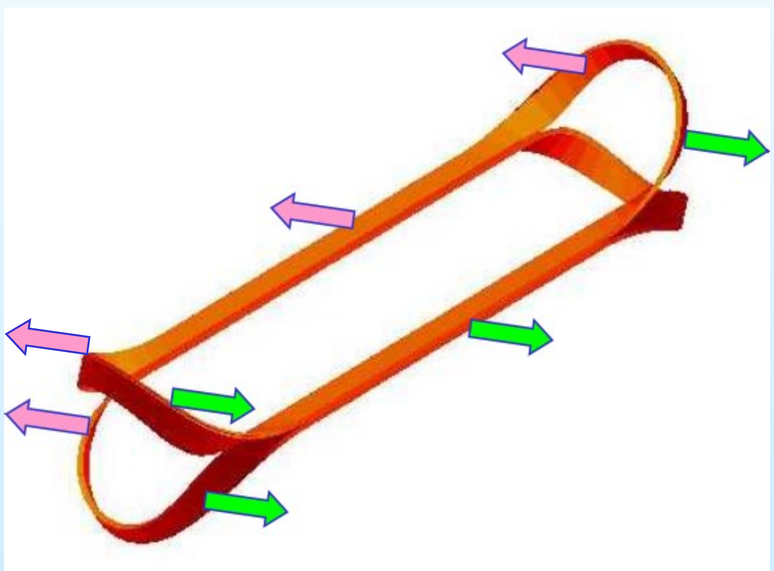
Try at home with Rutherford cable – easy to do

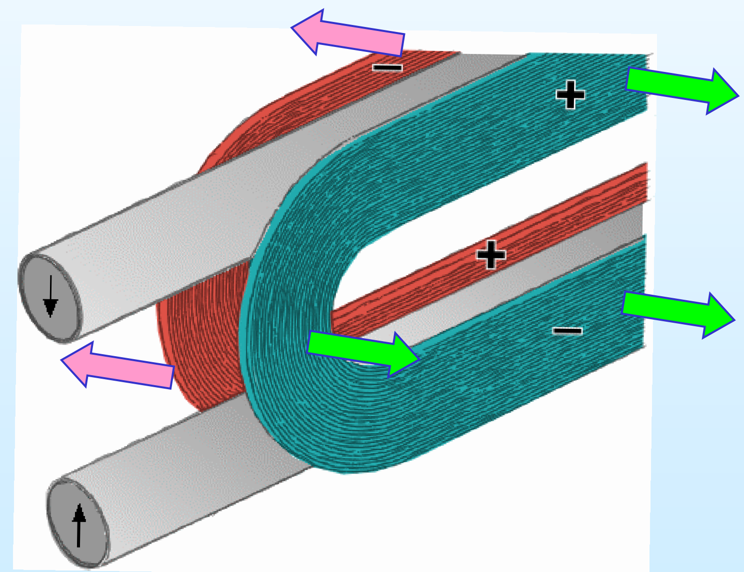
Common Coil Magnet Structure

A key technical and cost issue in high field magnets is structure

In cosine theta and block designs, large forces put excessive strain on the conductor in the end region

In a common coil design, coils move as a whole - much smaller strain on the conductor in the end region





BNL common coil dipole tolerated ~200 µm (typical ~50 µm)

Acknowledgements

- Susana Izquierdo Bermudez (CERN) : ROXIE
- Fernando Toral (CIEMAT) : Common Coil Design
- Luca Bottura (CERN) : Request to work with
- Lucio Rossi (CERN): Asking challenging questions

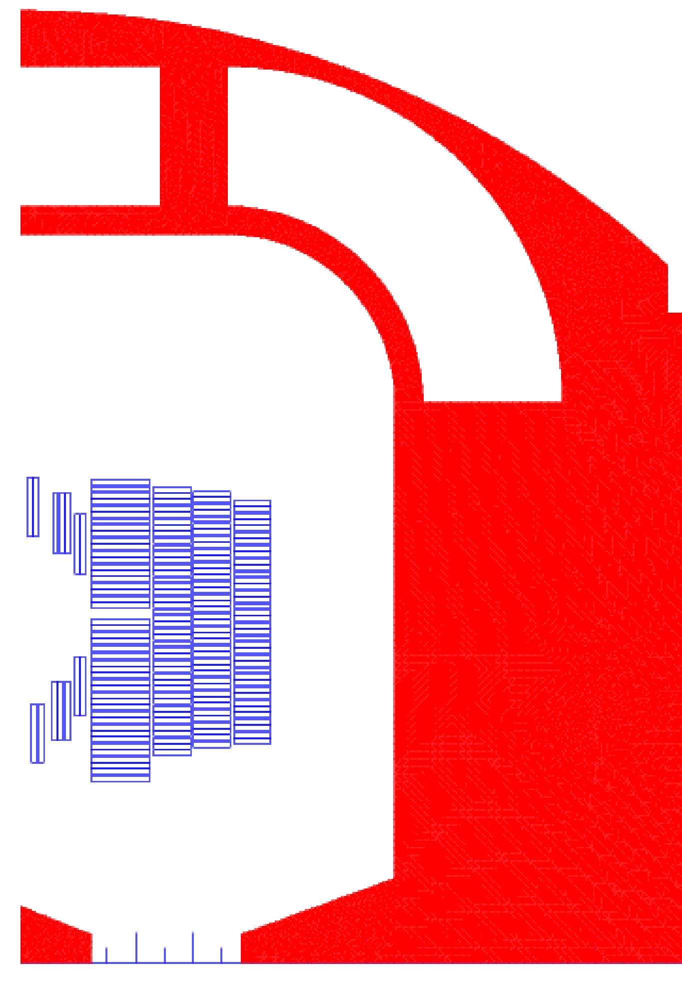
Choice of Cable/Conductor

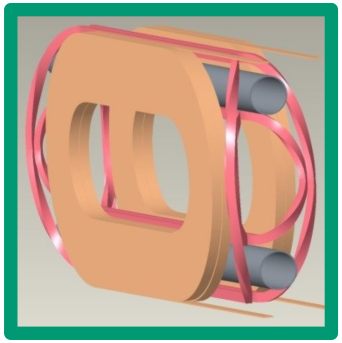
- Filament : Same as in EuroCirCol Common Coil
- Strand : Same as in EuroCirCol Common Coil
- Cable: Wider (reach 16 T @~16 kA)

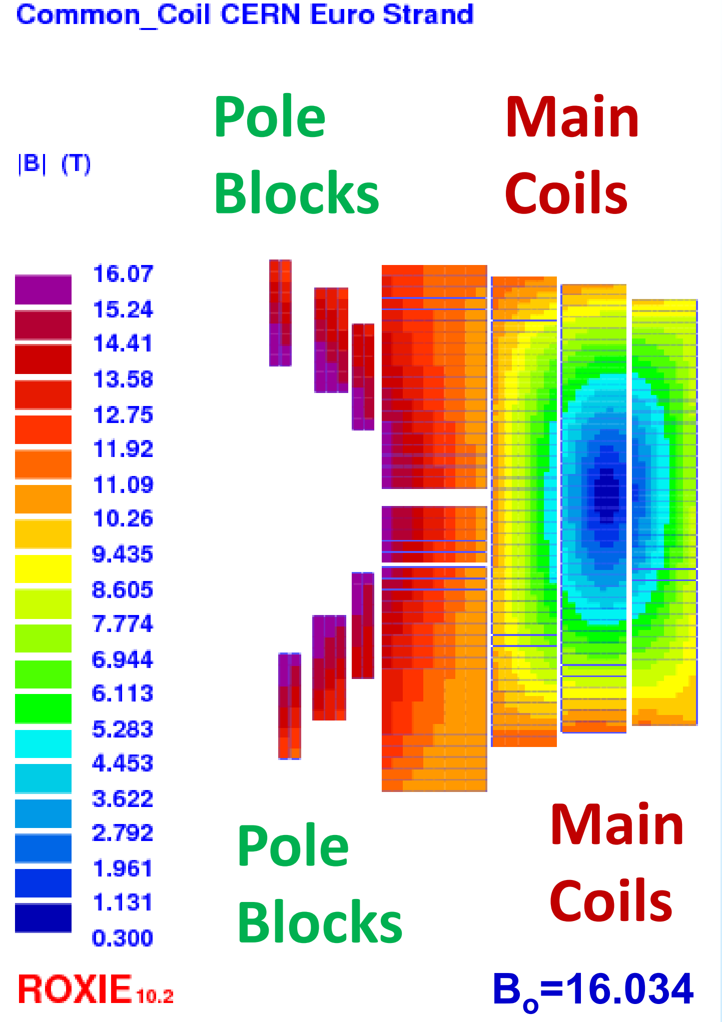
  OK in conductor friendly common coil design

  - Reduces inductance (helps quench protection)
  - Fewer coils (helps in reducing cost)

Magnet Cross-section (design #1)







¼ of a 2-in-1 magnet, ½ of one aperture

Intra-beam spacing = 250 mm; yoke od =700 mm; wider cable

Geometric Harmonics

SKEW AND NORMAL HARMONICS AT 17 MM RADIUS AT 16 T IN DESIGN #1

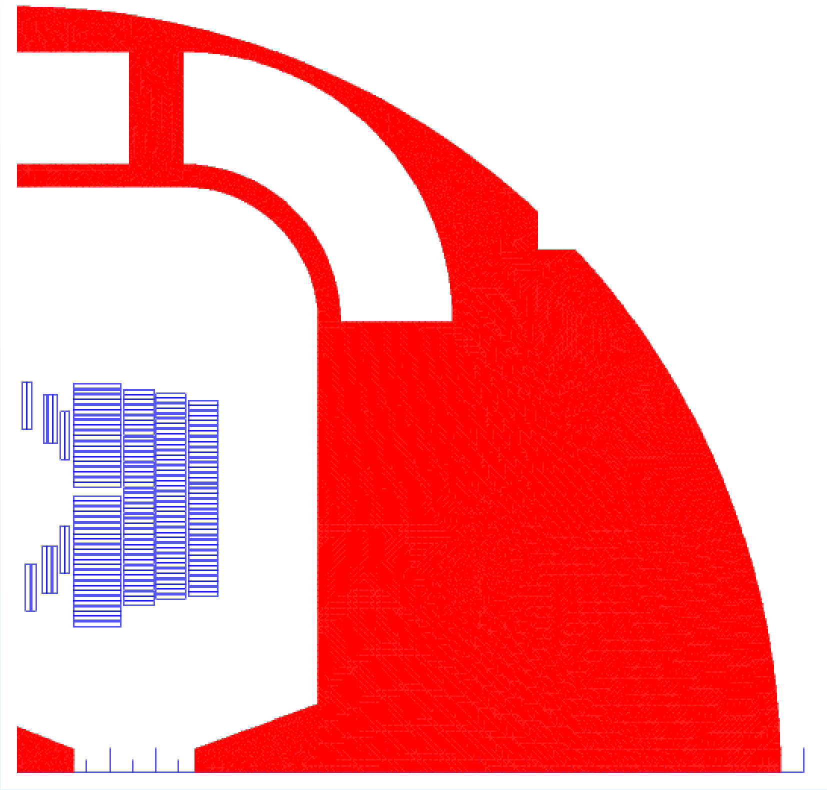
a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.00	0.27	0.21	-0.07	-0.31	0.07
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.01	-0.16	-0.10	-0.35	-0.32	0.03

Specifications < 3 unit

- We obtained about an order of magnitude better
- Errors to be determined by magnet construction

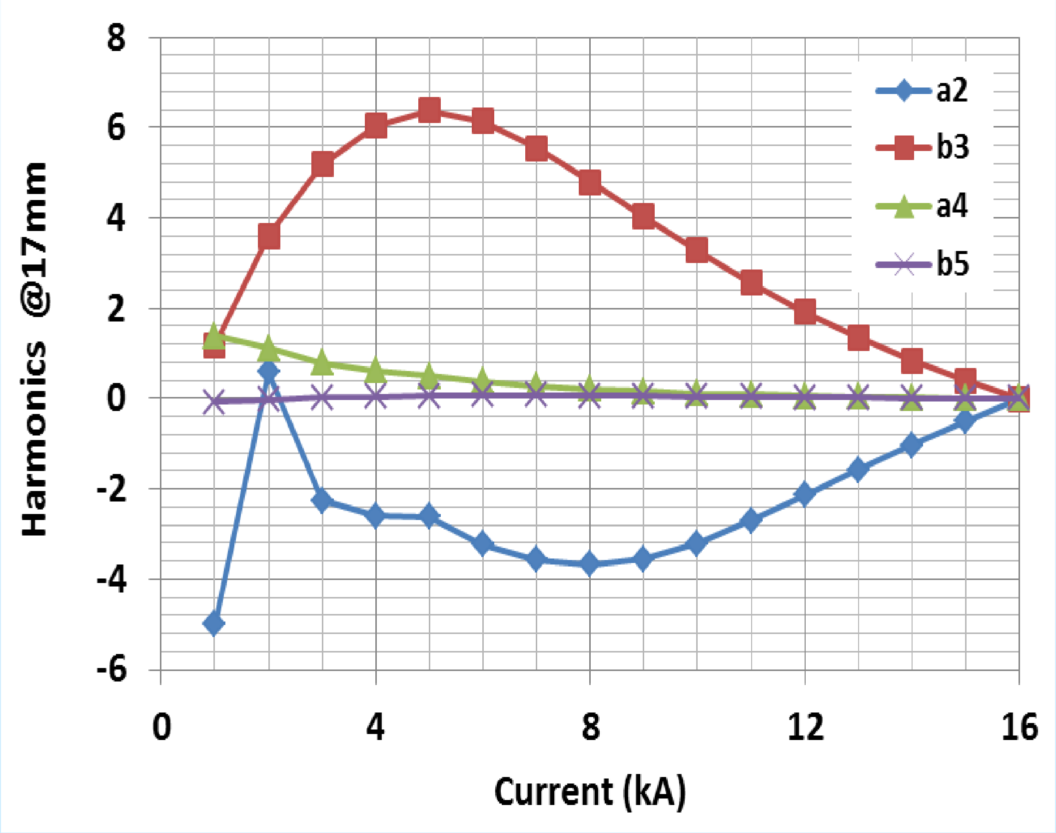
Iron Saturation

Yoke od = 700 mm
Intra-beam = 250 mm



Well below specification:

- ❑ b_3 < 7 units (spec <10 units)
- ❑ a_2 < 6 units (spec < 20 units)

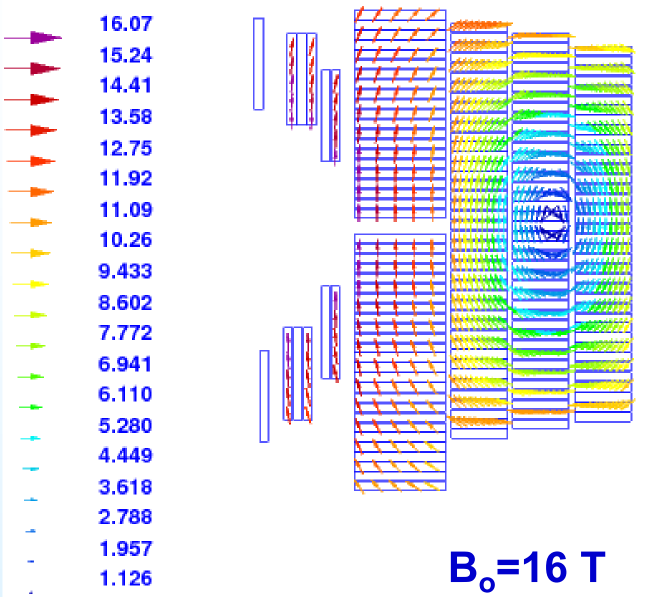


Optimized by : Nick Maineri
2^{nd} year undergrad student
6 week DOE SULI program

Basic Design Parameters

Operating current	(kA)	15.96
Field in the aperture	(T)	16.0
Margin at 4.2 K	%	8.5
Intra-beam spacing	(mm)	250
Yoke outer diameter	(mm)	700
Stored energy per unit length/aperture	(MJ/m)	1.7
Inductance/aperture	(mH/m)	13
Strand diameter (inner and pole layer)	(mm)	1.1
Strands/cable (inner and pole layer)	-	36
Cu/Non-Cu (inner and pole layer)	-	1.0
Strand diameter (outer layers)	(mm)	1.1
Strands/cable (outer layers)	-	22
Cu/Non-Cu (outer layers)	-	1.5
Total number of turns per aperture		179
Total area of Cu/aperture	(mm^2)	5029
Total area of Non-Cu/aperture	(mm^2)	4026

Design #2 (same cable as in #1)

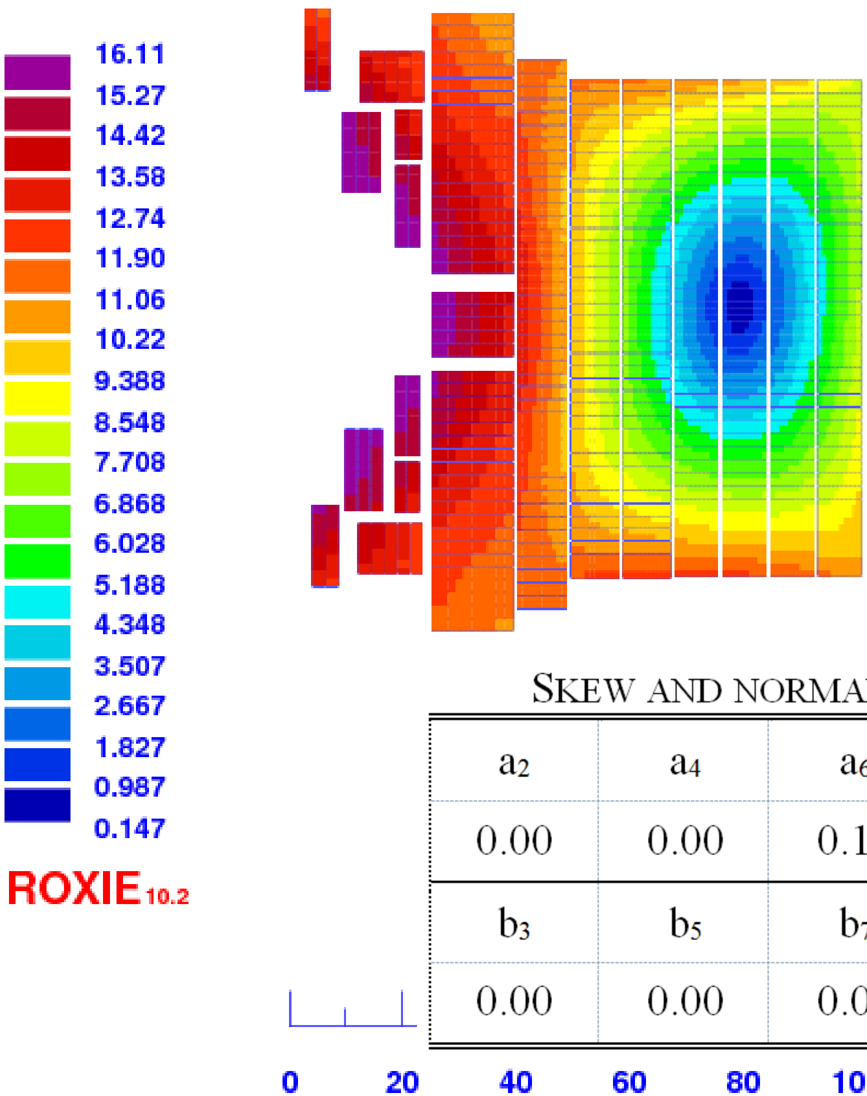


- 3 mm gap between pole coils and main coils for support structure to deal with the vertical forces
- 1 turn each from upper and lower pole blocks moved to the main coils to create space for that
- Only a limited number of cases were examined. Still field quality specs are met
- No change in iron saturation and inductance

Skew and normal harmonics at 17 mm at 16 T in Design #2

a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.00	0.00	0.04	-0.89	-0.30	0.19
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.37	2.01	0.10	-1.06	-0.30	0.16

Design #3 with EuroCirCol Cables



- **Operating current : 8.67 kA**
- **Stored Energy : 1.8 MJ/m/aperture**
- **Inductance : ~50 mH/m/aperture (was ~13 in design #1 & 2)**

A few ROXIE optimization run only (b_{11} = 4.2 instead of <3)

SKEW AND NORMAL HARMONICS AT 17 MM AT 16 T IN DESIGN #3

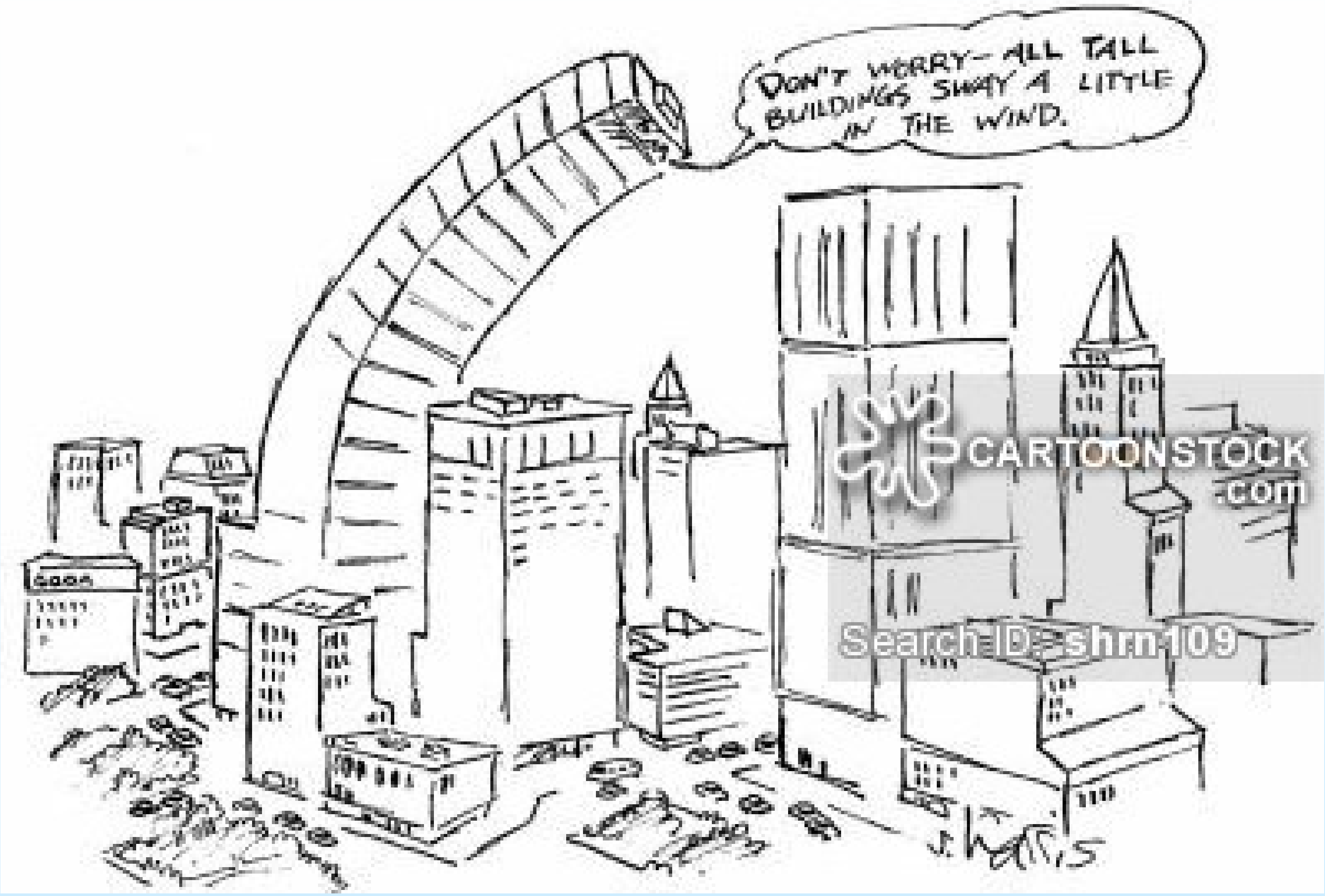
a_2	a_4	a_6	a_8	a_{10}	a_{12}	a_{14}	a_{16}
0.00	0.00	0.18	0.82	-0.05	0.15	0.27	0.03
b_3	b_5	b_7	b_9	b_{11}	b_{13}	b_{15}	b_{17}
0.00	0.00	0.06	-0.02	4.21	0.26	-0.59	-0.08

Common Coil Design
A Breathing Structure Concept

- Allow the coils to move as a whole against the Lorentz forces (just as we do for tall buildings against earthquakes and winds).
- Only requirement is to keep strain on the conductor within acceptable limit.
- Field harmonics will change due to the coil motion. Compute the changes and include them in the design optimization, along with the iron saturation as a function of current.

Just imagine how massive structure would have been if a bit of swaying was not allowed?
Would there have been a practical, affordable structure?

A Cartoon from Internet



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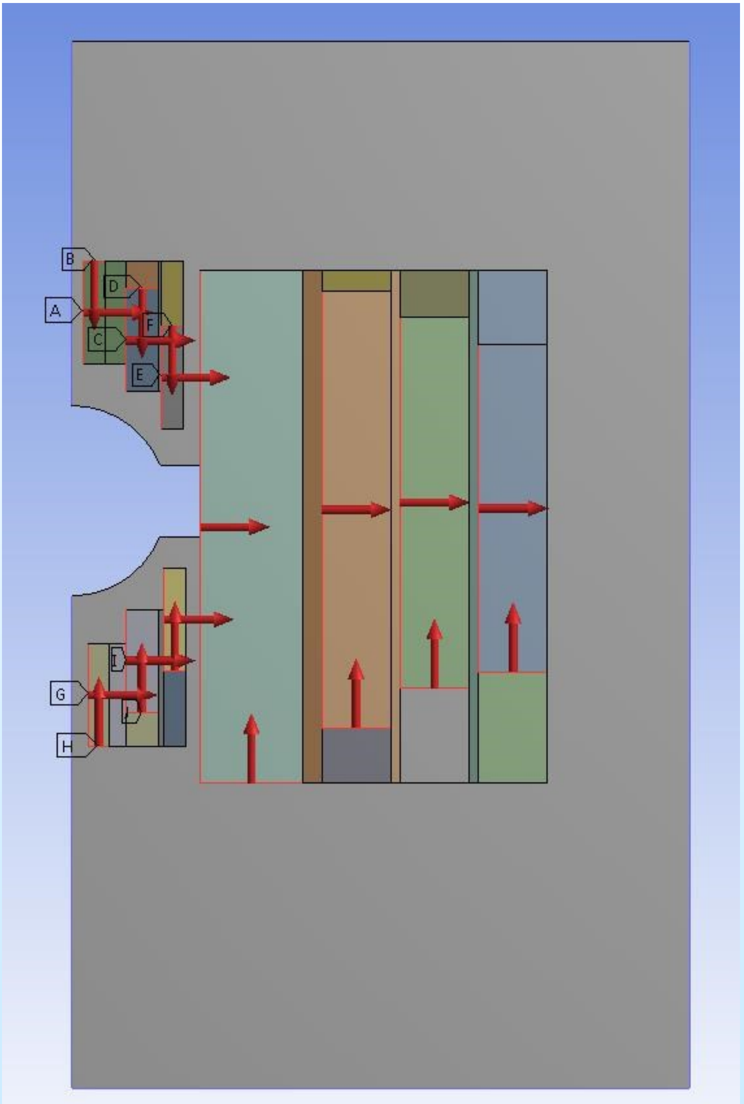
Initial Mechanical Design and Analysis



Preliminary analysis with simplified ANSYS workbench (Schmalzle, Anerella)

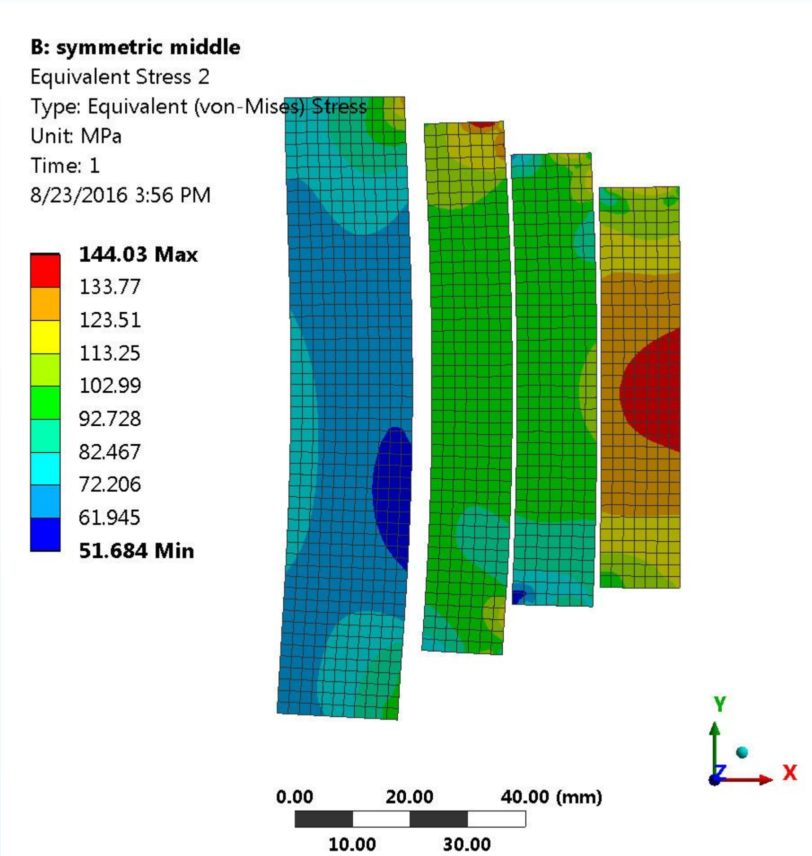
Goal: Get a quick initial evaluation of the structure (particularly for vertical forces)

Assumptions:

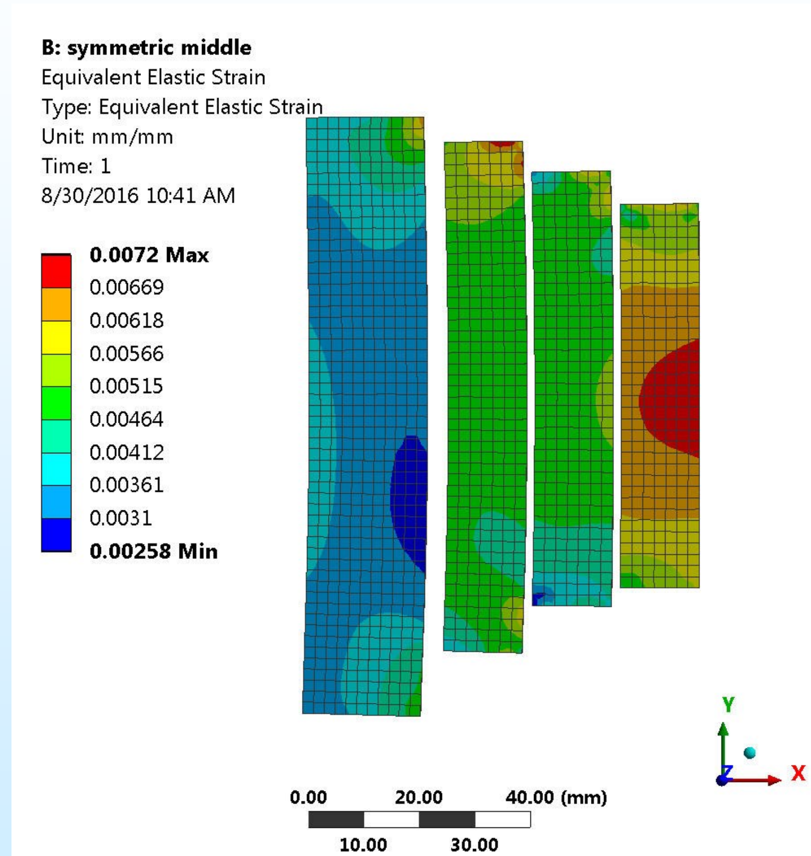
- **3 mm SS support between pole coils and main coils (none at midplane)**
- **Coil modulus: 20 GPA**
- **Simplified, single piece collar (no joints)**
- **Frictionless symmetry at horizontal & vertical split line**
- **Frictionless support on right edge**

Stress and Strain on the Main Coils

Stress: 144MPa @16T



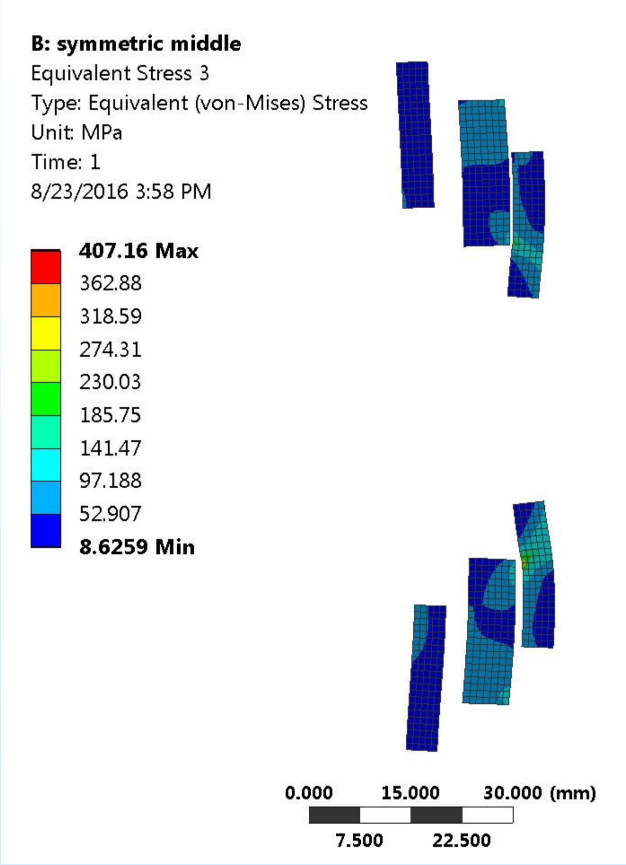
Strain: 007 mm/mm@16T



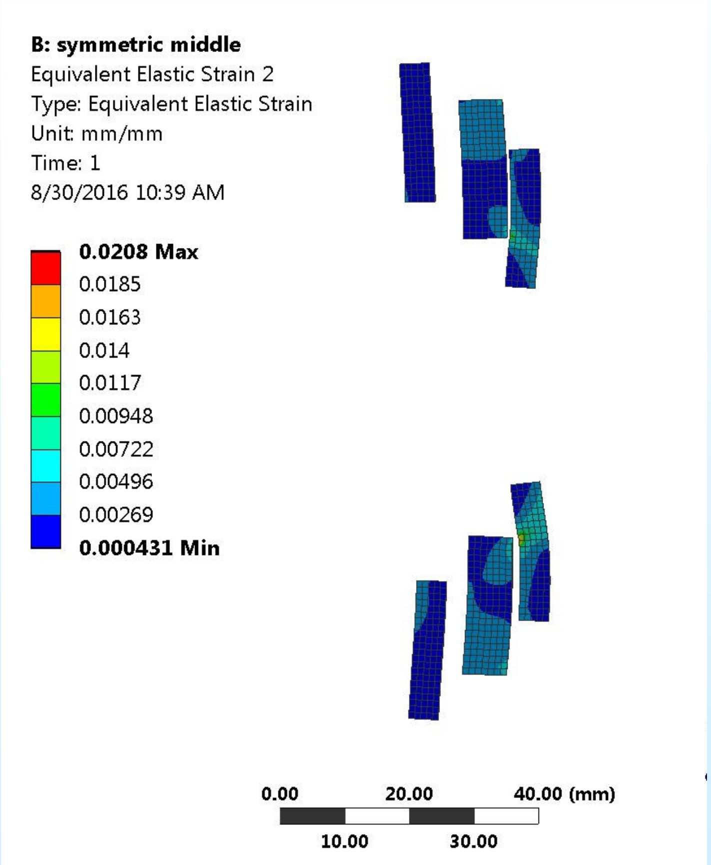
- Coil move as a whole (a major benefit of the common coil design)
- Future work : intermediate structure elements

Stress and Strain on the Pole Coils

Stress: mostly <150 MPa



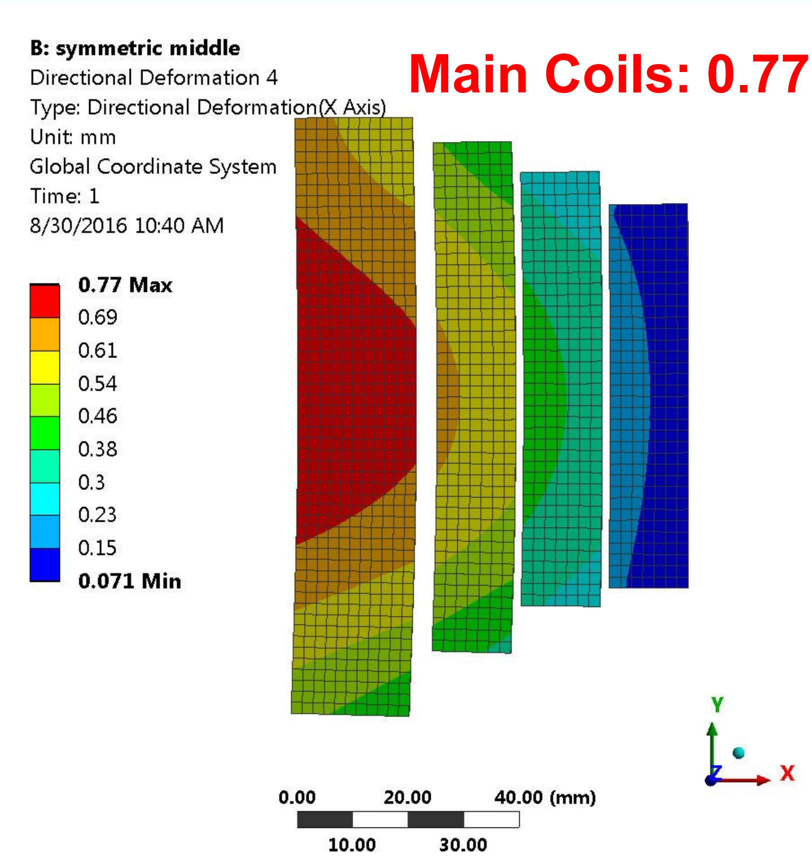
Strain: mostly < 0.007 mm/mm



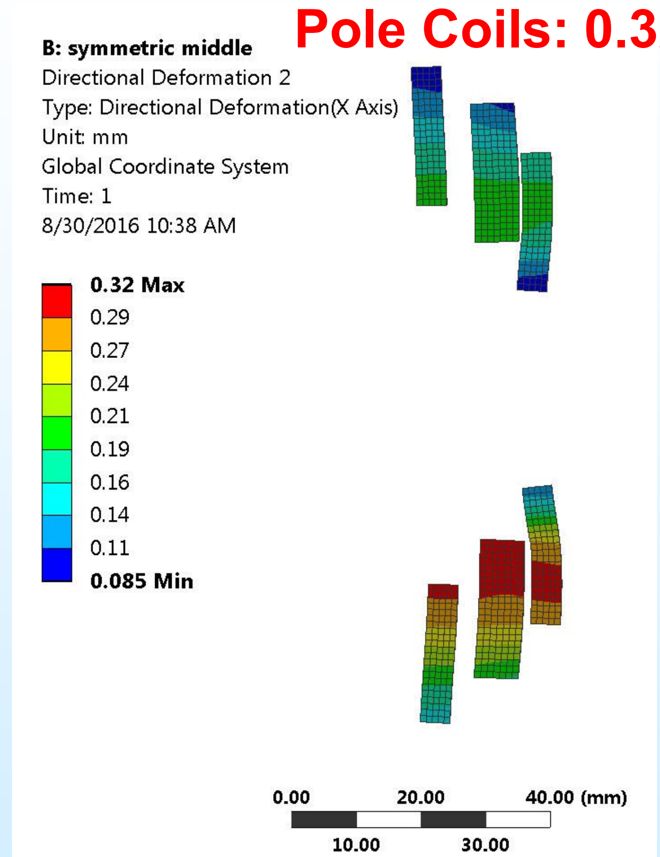
Local pinching at one location (model?) to be reduced in future iterations of magnetic and mechanical design and analysis

Deflections - Horizontal

Main Coils: 0.77 mm



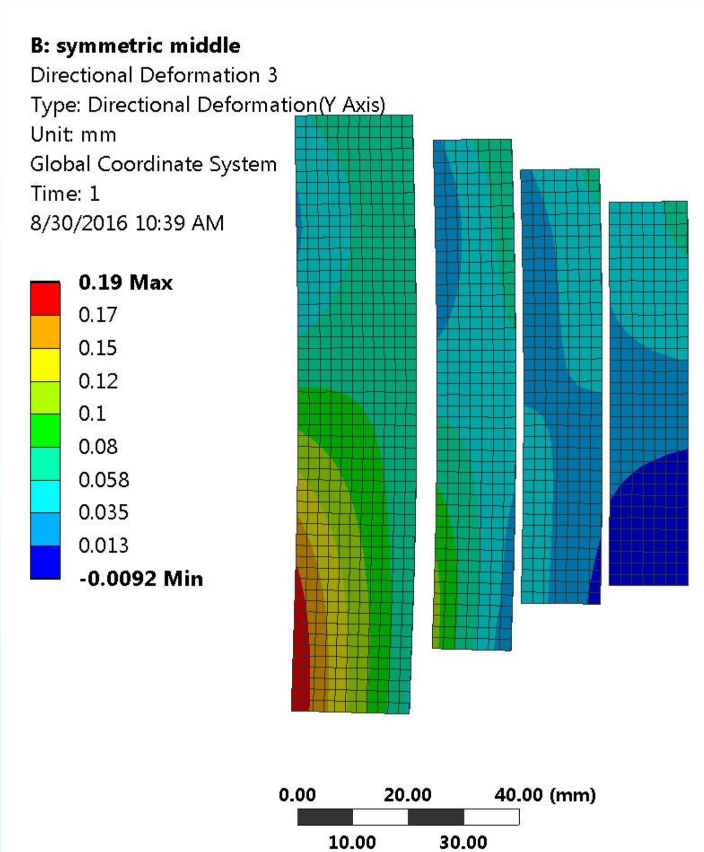
Pole Coils: 0.32 mm

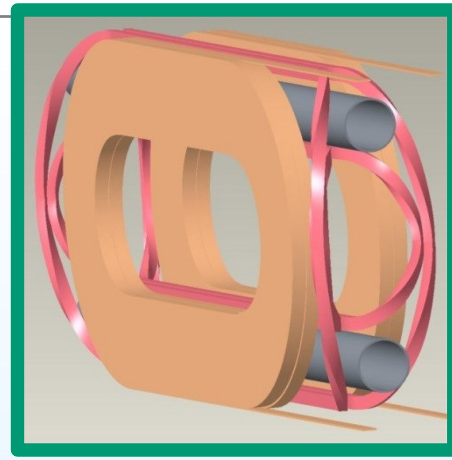


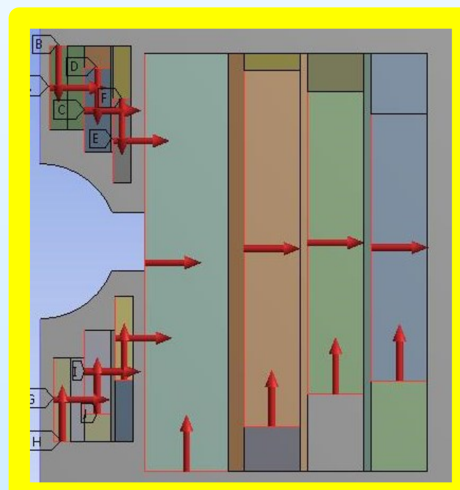
- Coil move as a whole (common coil)
- Further reduce relative bending

Deflections - Vertical

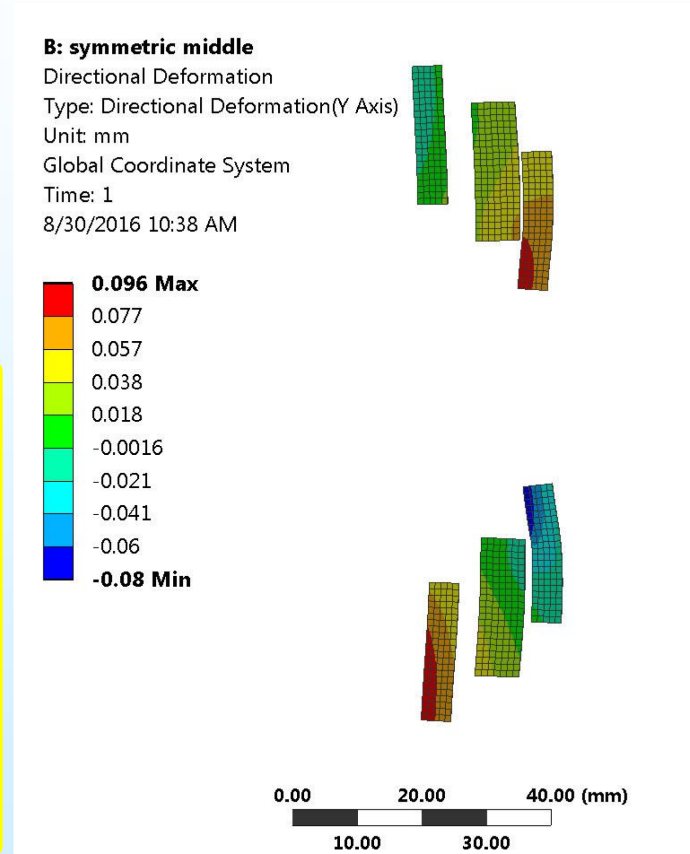
Main Coils: <0.2 mm







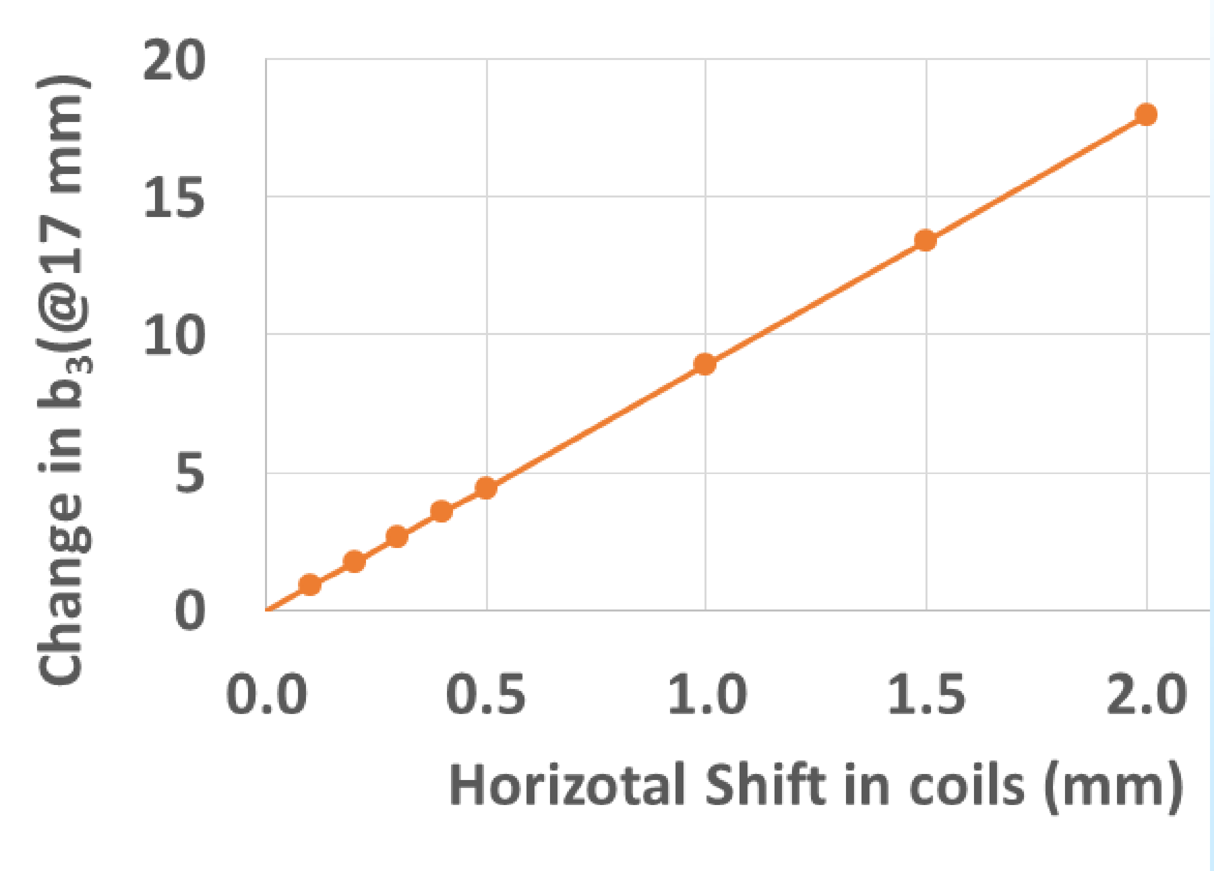
Pole coils: <0.1 mm



Structure seems to be able to hold the pole coils against vertical forces with no structure at the midplane (details to be worked out)

Influence of Coil Deflections due to Lorentz Forces on the Field Quality

- Major deflections found in horizontal direction
- Major change in harmonics found in b_3 only



Change in b_3 at 16 T < 7 units (0.77 mm)

(this can be easily accommodated or re-optimized with iron saturation)

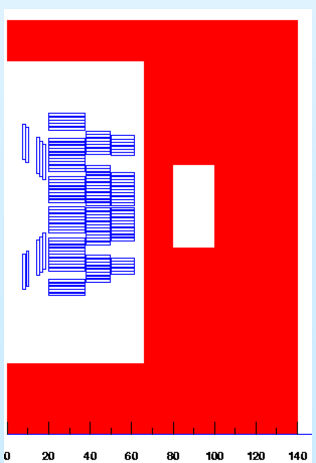
Work to be Performed on Structure

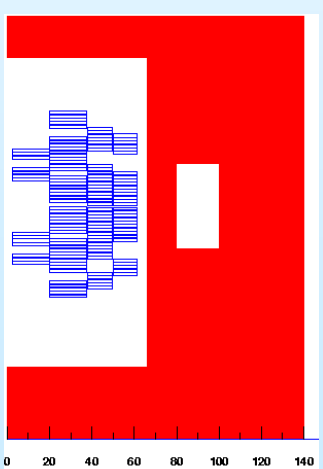
Initial results are encouraging but more remains to be done

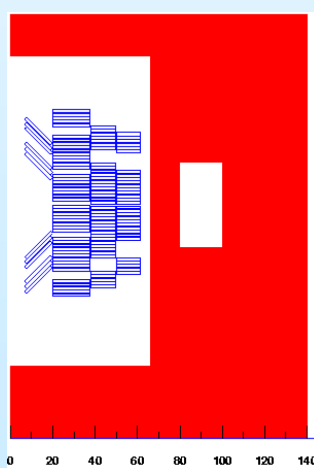
- Full mechanical analysis with real structure
- Magnet Assembly

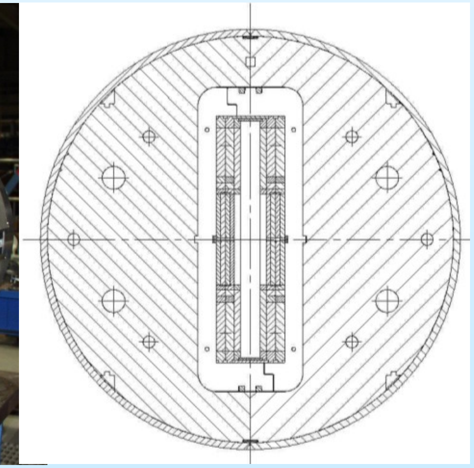
Common Coil Magnet with Pole Coils

- Several main coils common coil magnets have been built and tested with impressive performance at various laboratories
- However, pole coils with proper structure are yet to be demonstrated
- PBL/BNL SBIR on going Phase I (Ron Scanlan, PI) is performing model studies (including this paper) and would perform some practice windings
- Phase II (if funded) will do construction and 4K test of a few Nb_3Sn pole coils in a unique Nb_3Sn common coil BNL magnet with a large open space
- That will be an important proof-of-principle demonstration of Nb_3Sn common coil magnet - hard to believe it can be done with the SBIR funding







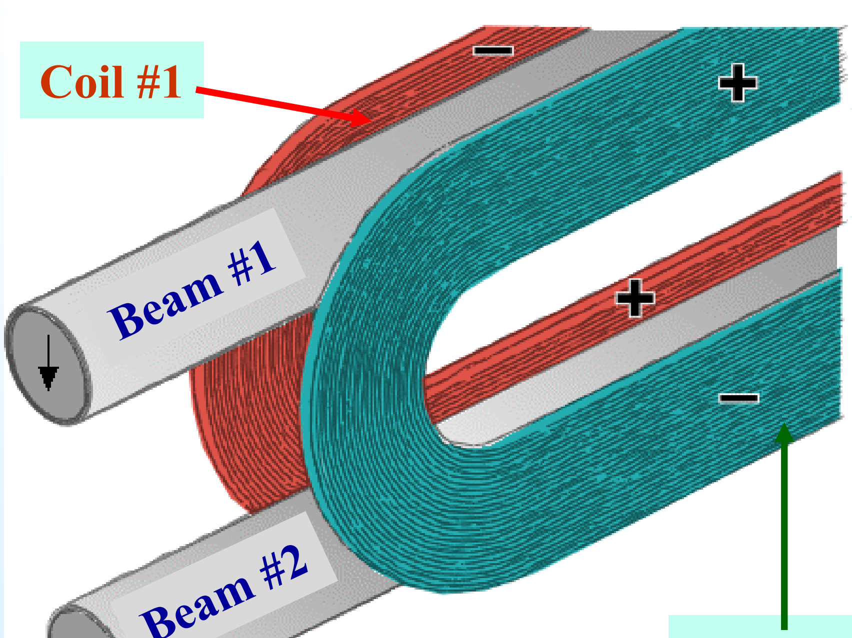



CONCLUSIONS

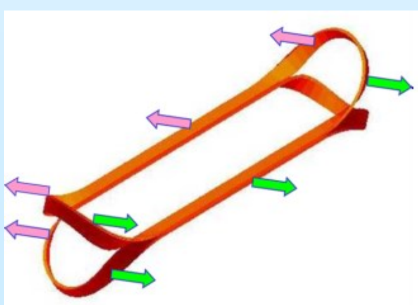
- **The basic common coil design presented here satisfies the key design requirements of a 50 mm, 16 T dipole:**
  - ✓ **Harmonics (geometric & saturation): less than the specified**
  - ✓ **Conductor usage: similar or less than in the other designs**
  - ✓ **Stored energy: similar or less than in the other designs**
  - ✓ **Inductance: much less than in the other designs**
  - ✓ **Standard intra-beam spacing: 250 mm**
  - ✓ **Standard yoke outer diameter: 700 mm**
  - ✓ **Structure able to hold pole (auxiliary) coils**
- **Given several inherent advantages of the common coil design in building high field collider dipoles cheaper and more reliable, it should now be one of the leading candidates**
- **BNL is interested in contributing and collaborating with others using its unique US experience in building reliable and low cost magnets for colliders in large production**

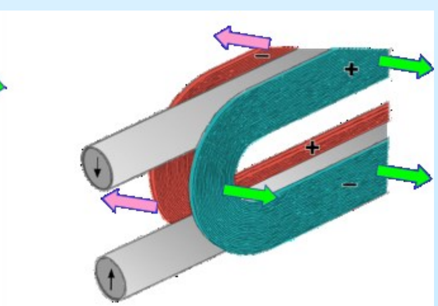
Extra Slides

Common Coil Design (Summary of Benefits)



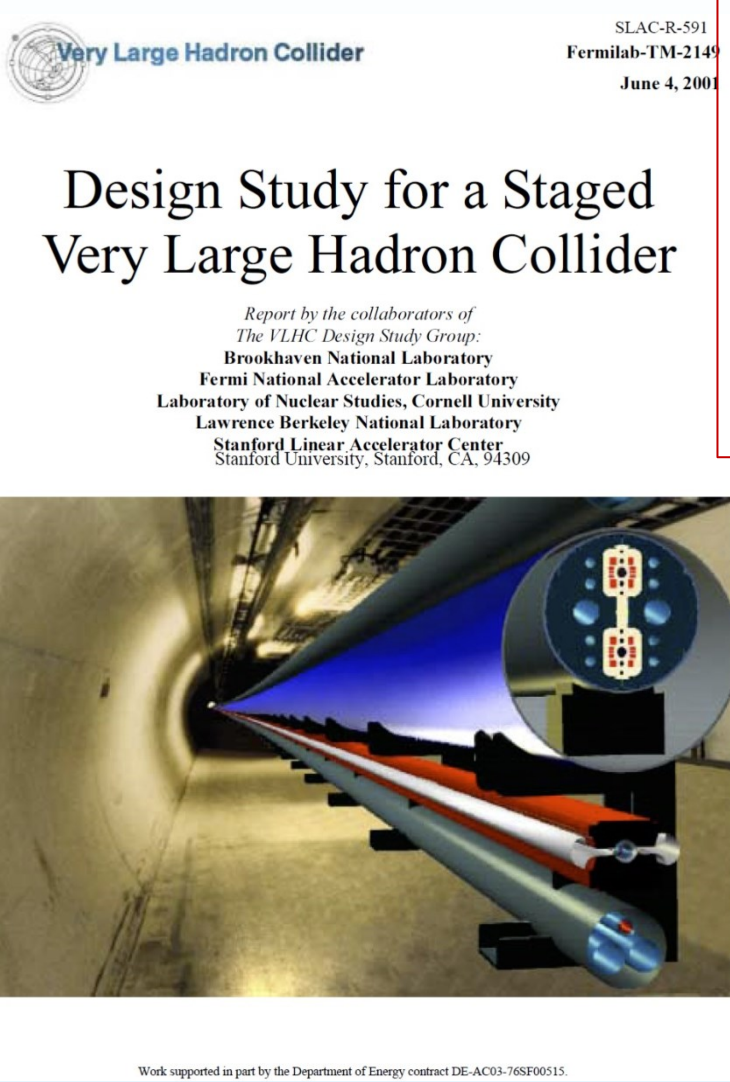
Main Coils of the *Common Coil Design*





- Simple 2-d coil geometry for colliders
- Fewer coils (about half) as the same coils are common between the two apertures (2-in-1 geometry for both iron and coils)
- Conductor friendly - large bend radii with simpler ends allowing many new options
- Block design with lower internal strain on the conductor under Lorentz forces
- Savings from less support structure
- Easier segmentation for hybrid designs (Nb_3Sn & NbTi and possible HTS?)
- Minimum requirements on big expensive tooling and labor
- Potential for producing lower cost, more reliable (less margin) high field magnets
- Efficient and rapid turn around magnet R&D due to simpler and modular design

Brief History of Common Coil


Very Large Hadron Collider

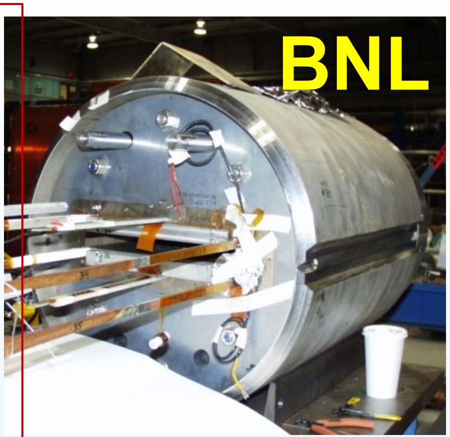
SLAC-R-591
Fermilab-TM-2149
June 4, 2001

Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
Stanford University, Stanford, CA, 94309

Work supported in part by the Department of Energy contract DE-AC03-76SF00515.

- R&D magnets built at LBL, BNL and FNAL
- Started the culture of fast turn-around R&D
- Base line design for VLHC; also for SppC



Work stopped after a few years for reasons other than the failure of the design