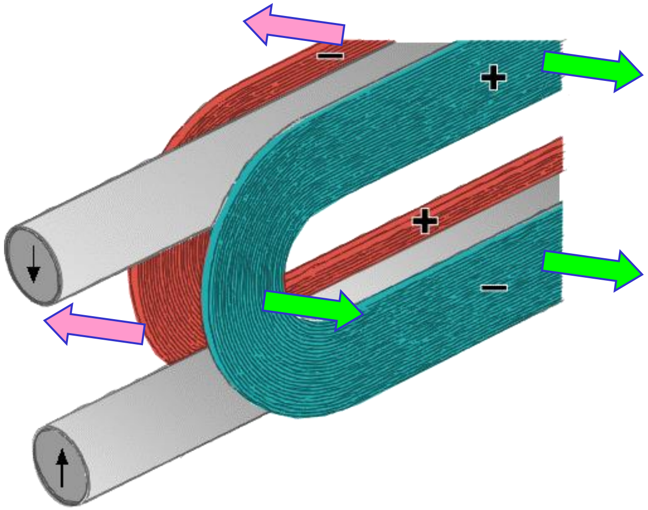
Review and Potential of 16 T (or more) Common Coil Dipole

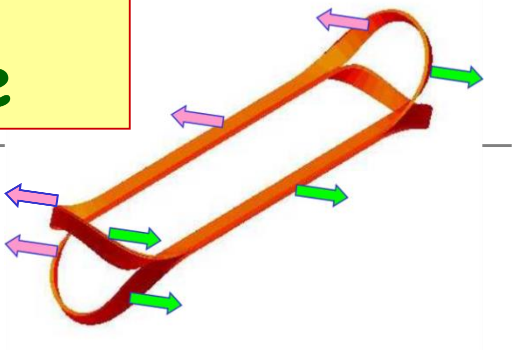
Ramesh Gupta
Brookhaven National Laboratory
April 13, 2016

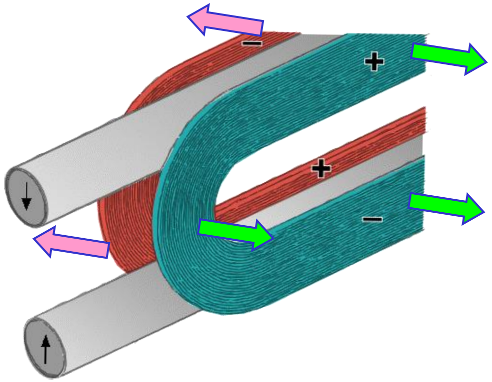
Overview



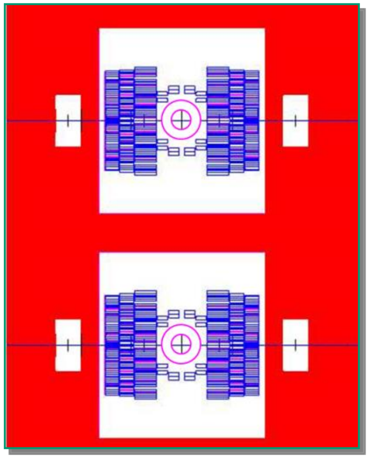
- Strategies to take advantage of the simple common coil geometry
- Status and proposed plans at BNL on common coil design
- HTS to test new superconducting magnet geometries rapidly and HTS for added field/margin
- Summary

Strategy
Mechanical Structure



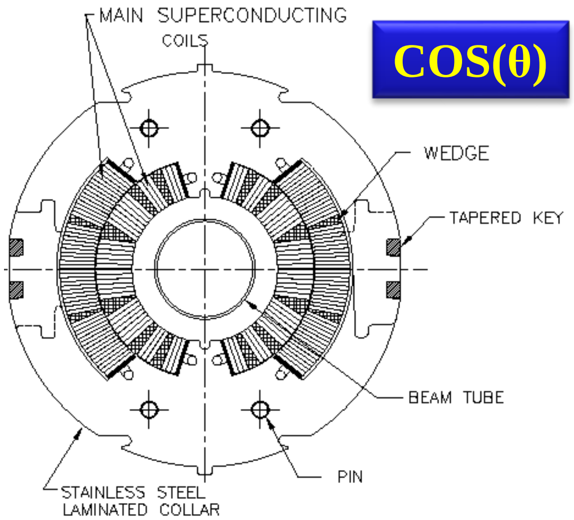


- Common coil design is a block coil design with simpler ends. Simpler coils usually perform better, particularly for Nb_3Sn magnets.
- Common coil geometry puts low strain on the conductor. Compare the impact of horizontal Lorentz forces: conventional designs put large strain on the conductors in the end region; common coil doesn't since the coil moves as a whole. Large deflections don't create large strains (BNL magnet tolerated over 200 μm).
- Therefore structure can be much less expensive. Examine strain on the conductor not deflections.
- When separation between two apertures is large, use of two separate collars in SS (rather than one common to both) may significantly reduce the amount of structure.



Strategy
Magnetic Structure

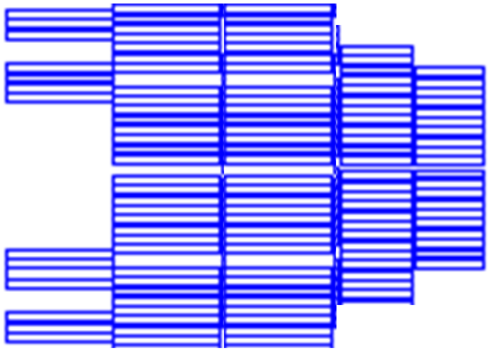
- Block coil geometry gives more freedom on coil optimization than the conventional cosine(θ). Increase horizontal size (rather than the vertical size) to increase efficiency.


COS(θ)

- Good field quality coils don’t have to look like cosine(θ). Intersecting ellipse may be more efficient with more conductor horizontally.

- Coil deflections (previous slide) could cause field errors. Impact of the radial/horizontal deflections is generally much less than the azimuthal/vertical deflections. Include this in design calculations together with the iron saturation in computing current dependence.

More Efficient Design



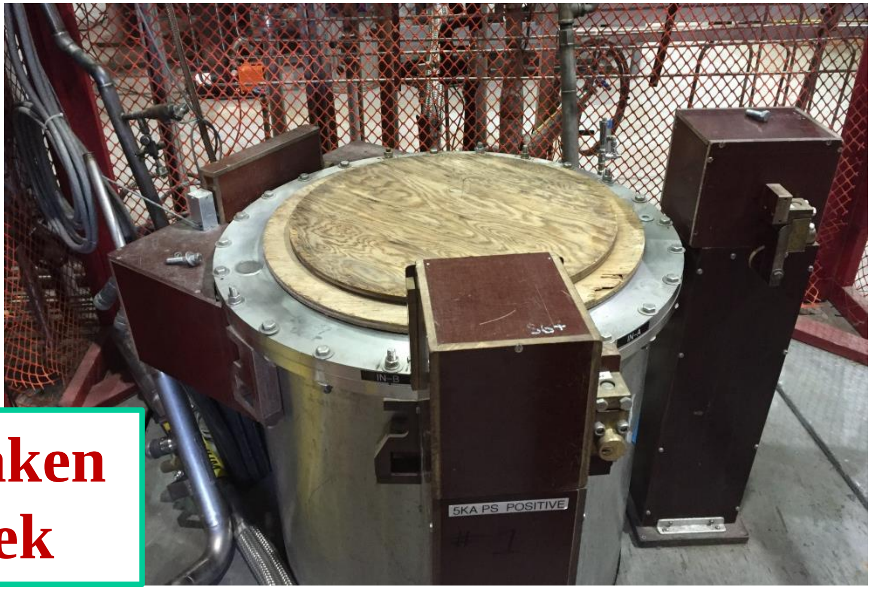
Strategy : Alternate Options
R&D, Technology, Material and Manufacturing

- **Common coil design is based on simple racetrack coils with cheaper and faster R&D. Modular nature of the design makes it more adaptable to variations and high field insert coil testing.**
- **Large bend radii and conductor friendly features of common coil offers the possibility of both “Wind & React” and “React & Wind” technologies. Don’t exclude “React & Wind” approach.**
- **Since in the “React & Wind” technology, coils and associated structures are not subjected to the high temperature reaction, a wide range of insulation and other materials may be used.**
- **Simpler geometry should allow lower cost and more reliable manufacturing. Moreover, for 2-in-1 dipoles, the number of coils to be manufactured is reduced by a factor of 2 in common coil.**

Status and Plans at BNL

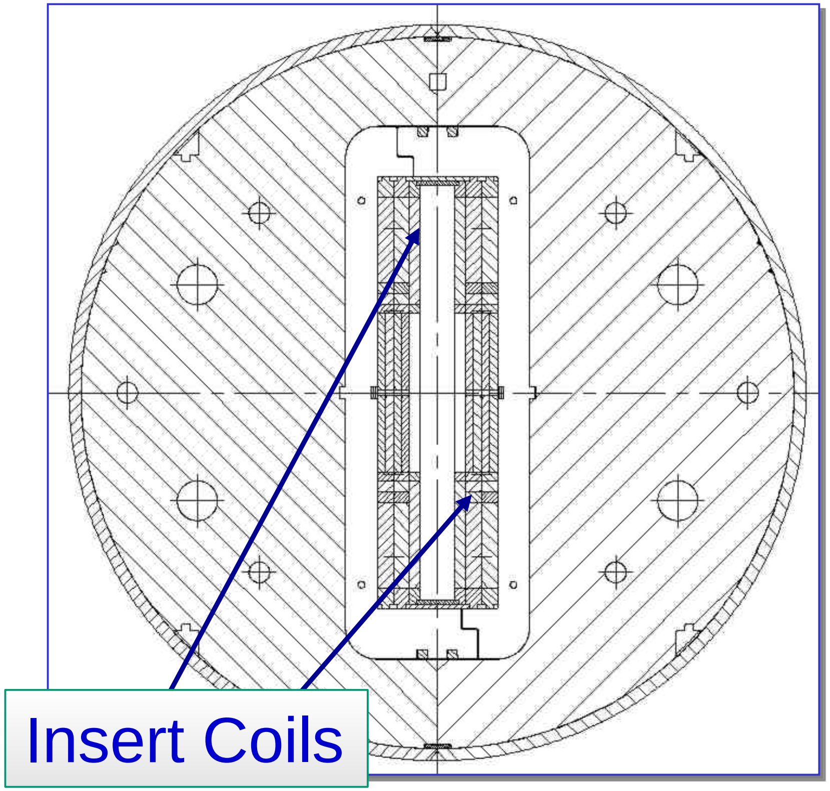
Partially funded and/or expected to be funded by
LDRD (internal lab funding), SBIR & GARD

Commissioning of Common Coil Magnet as a Unique Facility for Testing Insert Coils in 10 T Background Field



Photos taken last week

A New Way of Coil and Magnet R&D



Unique feature: large open space for testing “coils” in high fields without any disassembly (fast turn around, low cost)

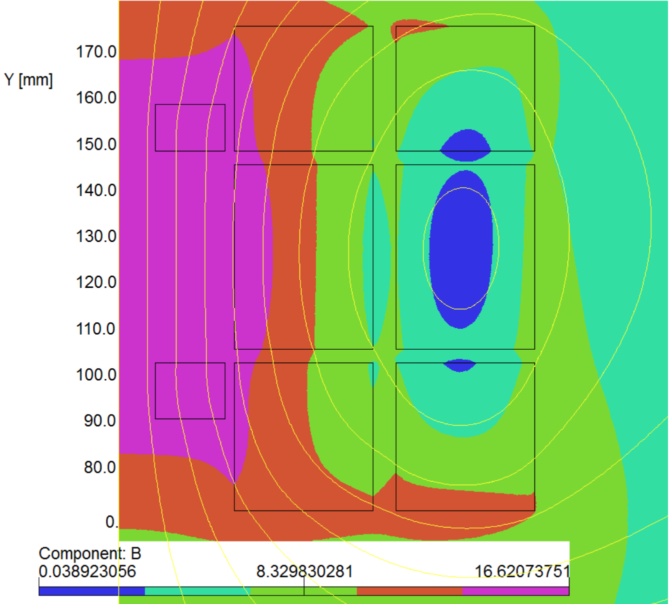
- **Build/Insert/Replace coils, not the entire magnet**
- **Expect operation and test results soon (~Oct 2016)**

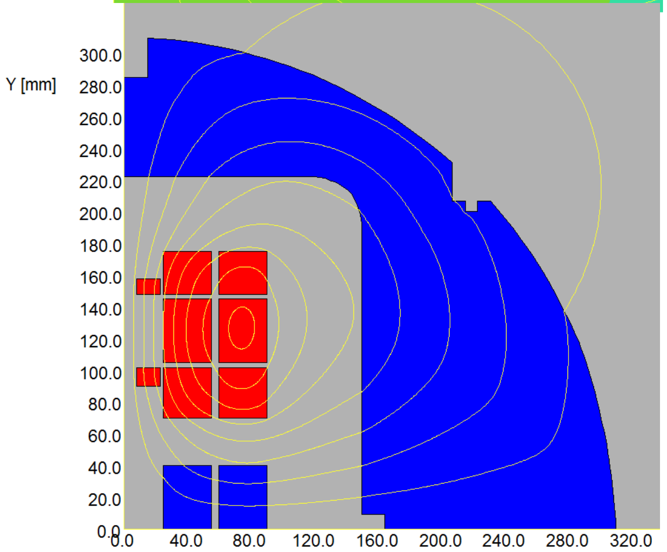
Proof-of-Principle 16 T R&D Design

- Goal: Demonstrate essential features and benefits of the common coil design in a 16 T, 50 mm aperture 2-in-1 dipole
- Build and test a “Proof-of-Principle (PoP)” common coil dipole using as much existing hardware as possible to keep cost low
- Reduce spacing between two apertures to fit test Dewar to be used
- Use the same cable as proposed for FNAL 15.6 T, 60 mm dipole
- Initial zeroth order design creates 16 T in 50 mm aperture with low peak field enhancement. Mechanical analysis & design work is starting, coil to be optimized from 10^{-3} to 10^{-4} field quality

In parallel, carry out design of a 16 T, 50 mm aperture “Common Coil Dipole” in cryostat for FCC parameters (larger spacing) with reasonable engineering of structure & assembly (paper@ASC2016)

A Few Parameters of Preliminary 16 T Common Coil PoP Dipole





Aperture : 50 mm

Bore Field: 16.05 T

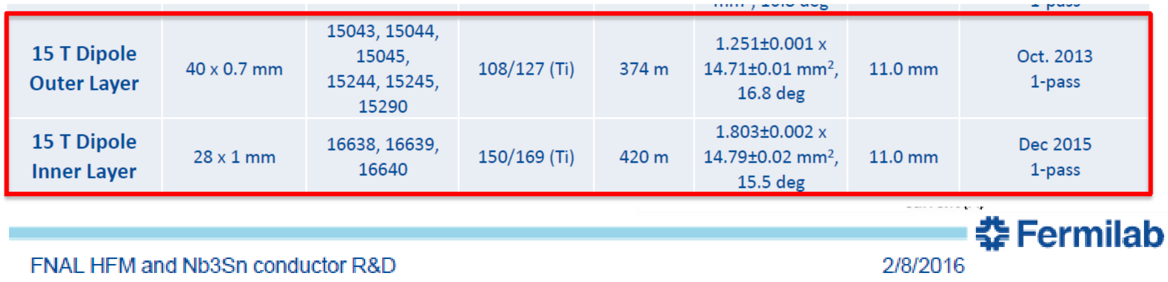
Current: 10. 6 kA

Stored Energy
(per aperture) : 1.8 MJ/m

Peak field : 16. 62 T

Peak Enhancement = 3.6%

Conductor: Same as used in FNAL design



15 T Dipole Outer Layer	40 x 0.7 mm	15043, 15044, 15045, 15244, 15245, 15290	108/127 (Ti)	374 m	1.251±0.001 x 14.71±0.01 mm², 16.8 deg	11.0 mm	Oct. 2013 1-pass
15 T Dipole Inner Layer	28 x 1 mm	16638, 16639, 16640	150/169 (Ti)	420 m	1.803±0.002 x 14.79±0.02 mm², 15.5 deg	11.0 mm	Dec 2015 1-pass

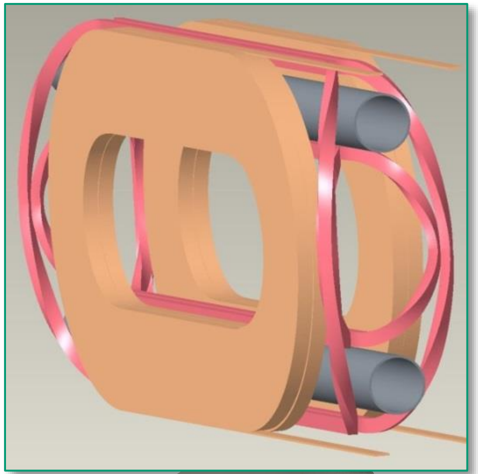
FNAL HFM and Nb3Sn conductor R&D 2/8/2016 Fermilab

Benefits of R&D with HTS Coils

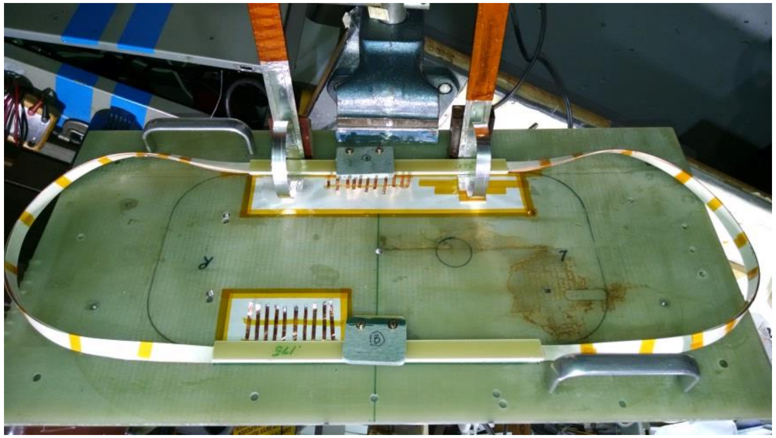
- Faster and cheaper way to make some early examinations of a new design since the material comes pre-reacted, coils can be tested in LN_2
- Sometime in future, HTS might also provide added field/margin

Pole/Insert Coils in Common Coil

- **BNL common coil magnet needs the pole coils for field shaping to show accelerator type dipole.**
- **Due to large bend radii, conductor can be easily bent without much strain (see attempt on Roebel cable at CERN). This also aligns field parallel to the wide face of the HTS tape in common coil.**
- **As a part of PBL/BNL SBIR, HTS coils made with 12 mm tape carried over 360A at 77 K.**

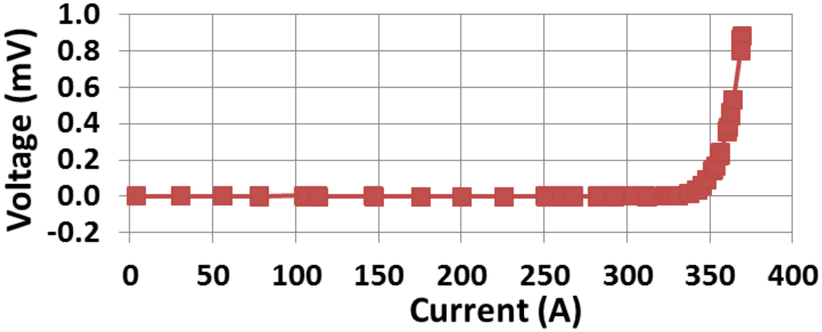


Courtesy CERN



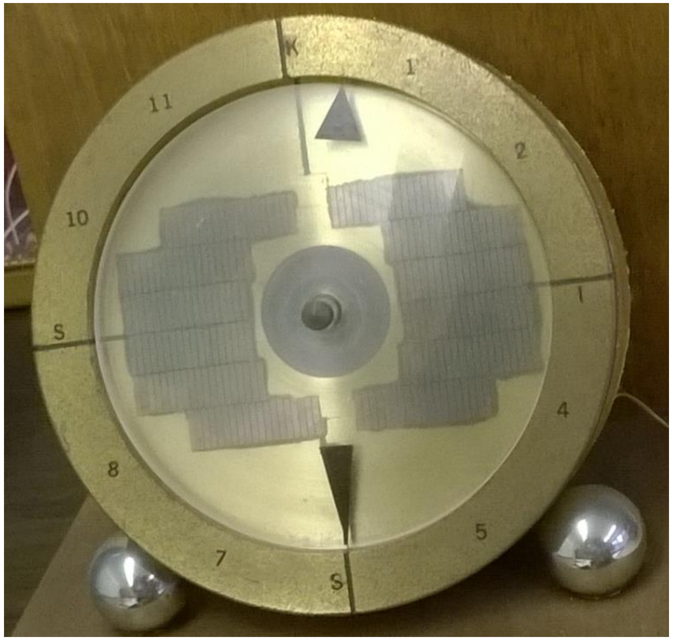
Test of HTS coil in background field

~10/16 PBL/ BNL SBIR

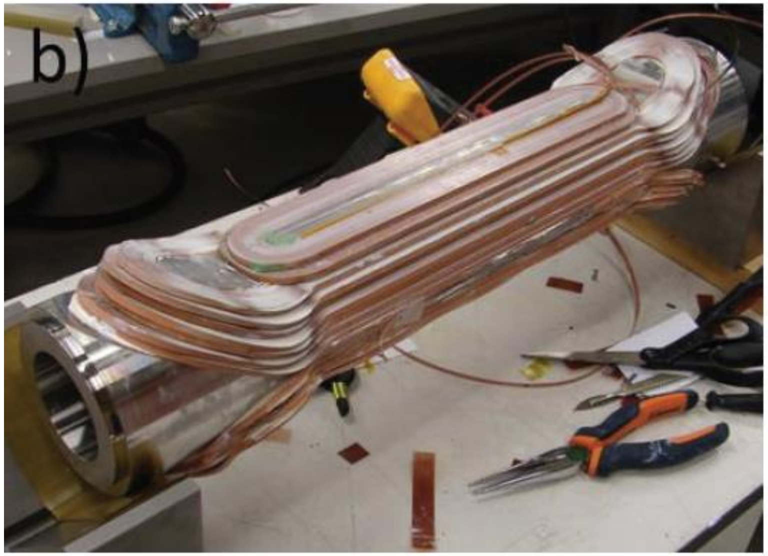


Test of a New End Design with HTS Coils (for a single aperture block coil dipole)

- Simple cross-section of block coil design gets complicated in the end region with bend in hard direction – lifted ends to clear the tube - long length, reverse bend
- Efficiency and performance of such magnets is often limited by the ends



Bill Sampson, BNL

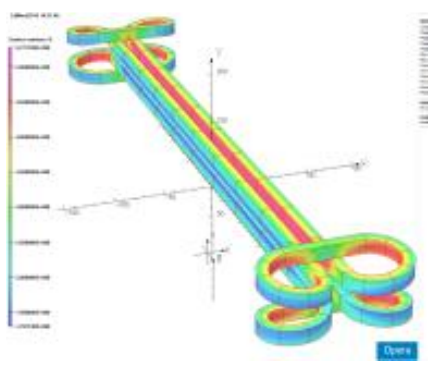


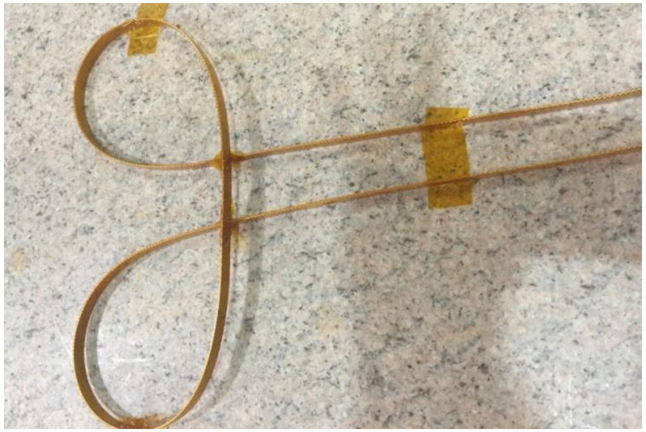
Danfysik HTS Dipole

New Overpass/UnderPass End Design

To visualize, imagine driving on a highway when you have to go back

- **No reverse or hard way bend**
- **Conductor friendly design – less strain**
- **Less axial length of ends**
- **Useful for block designs (both for Nb_3Sn and HTS coils)**

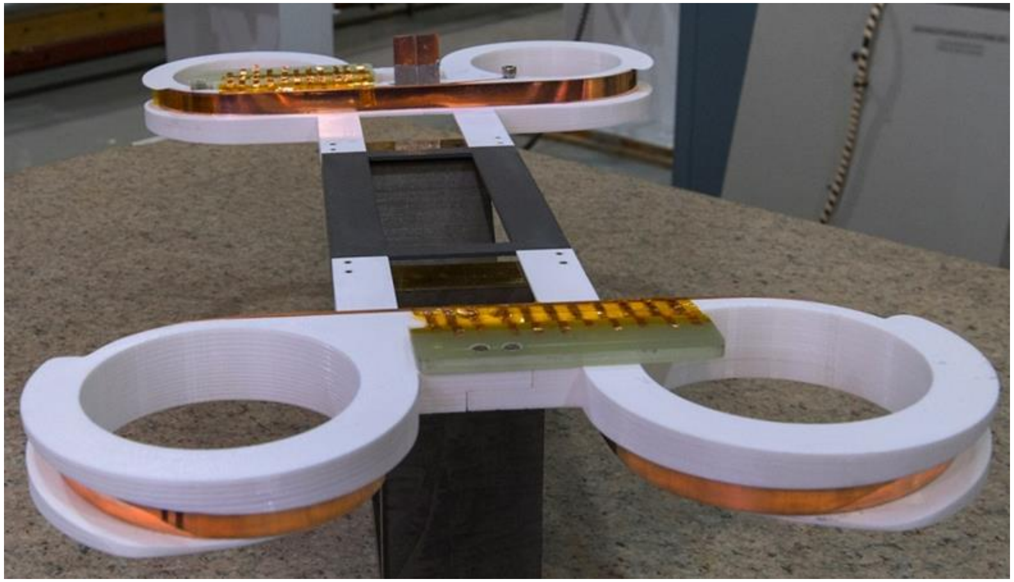


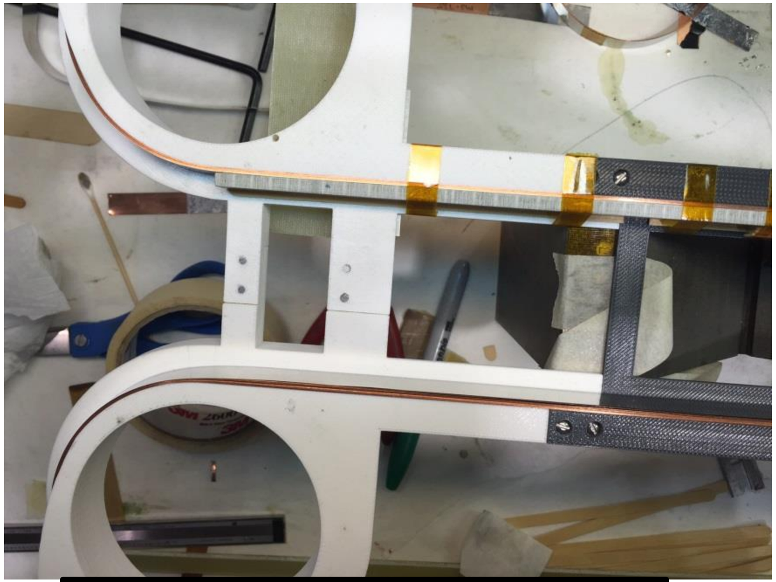


Courtesy:

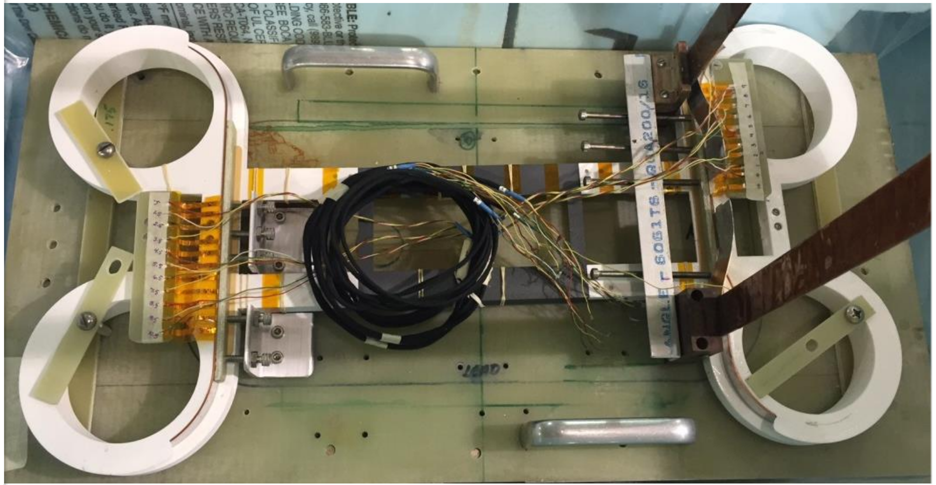
Glyn Kirby, CERN

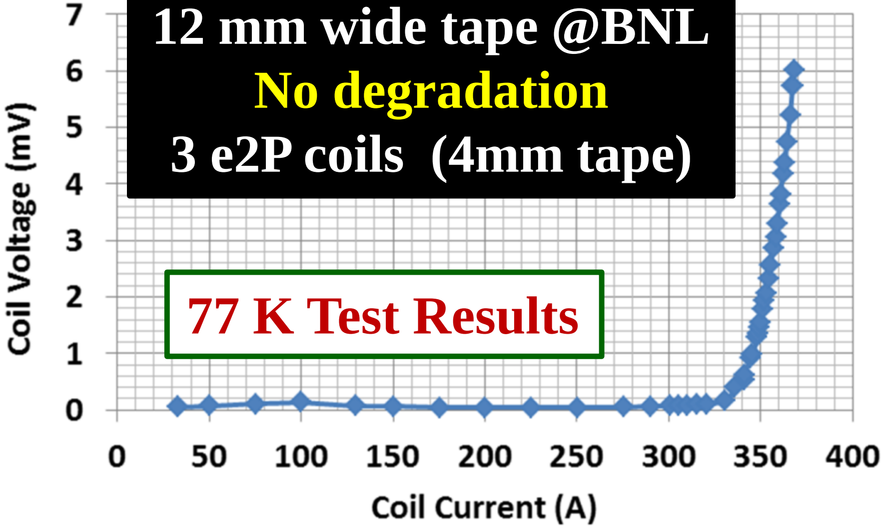
Demonstration with HTS Coils (e2P/BNL SBIR Phase I: 77K tests)





Courtesy 3d printer

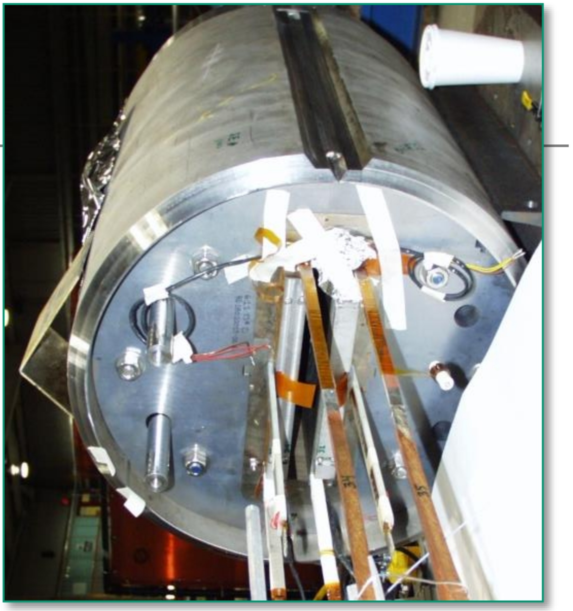




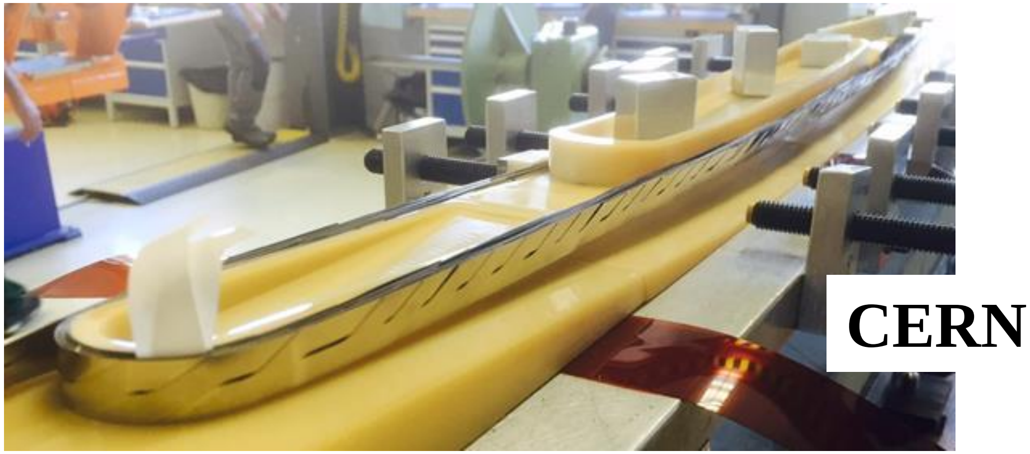
12 mm wide tape @BNL
No degradation
3 e2P coils (4mm tape)

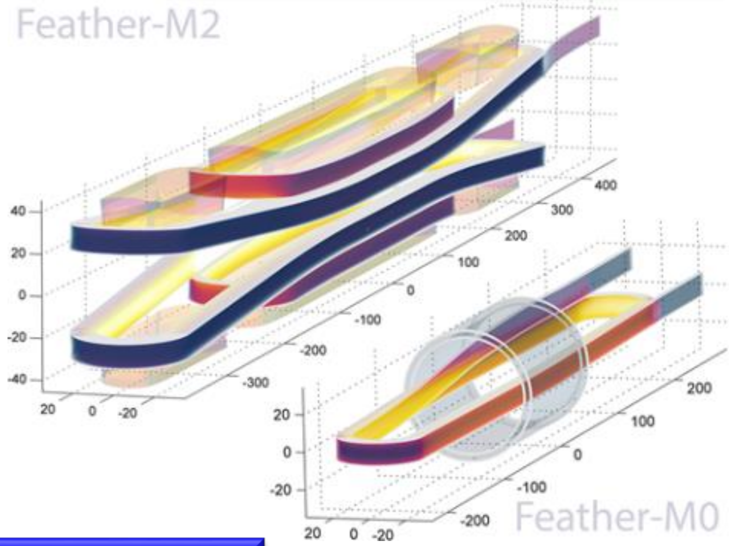
77 K Test Results

Future Possibilities



- A successful demonstration of this technology will open the door for new possibilities
- For example, it might be considered for Roebel with field in right direction – now a late option for CERN's Fresca II or "Feather design"
- Phase II SBIR proposal to examine HTS coil in the background field of BNL common coil magnet

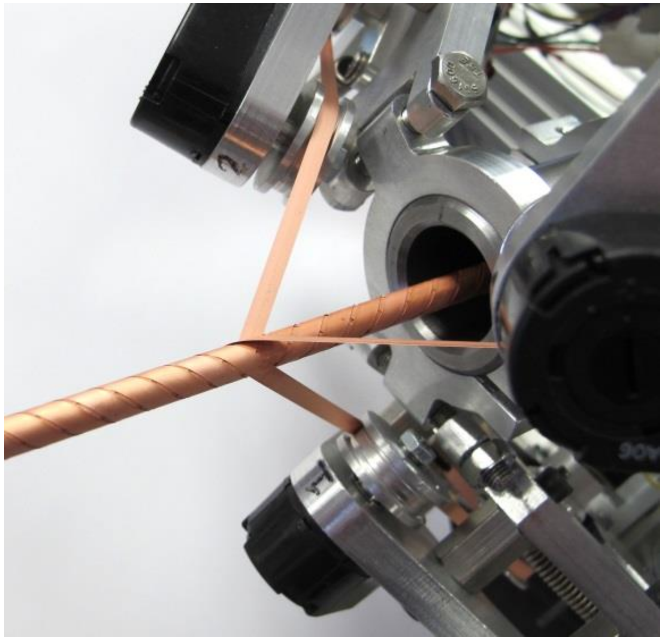




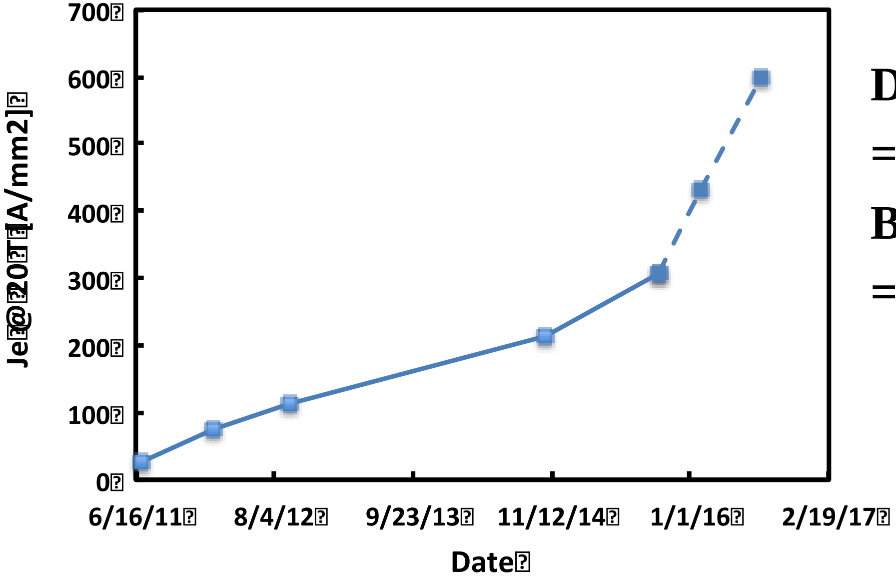
New R&D Approach: HTS coils to pre-test a new geometry rapidly before the high field test in background field magnet

CORC® Cable for Accelerator Dipoles
High J_e, High I_c

- J_e of >600 A/mm^2 at 20 T for 10 kA cable next year
- J_o of ~1000 A/mm^2 at 20 T for 20 kA cable in a few years



Aren't we almost there?



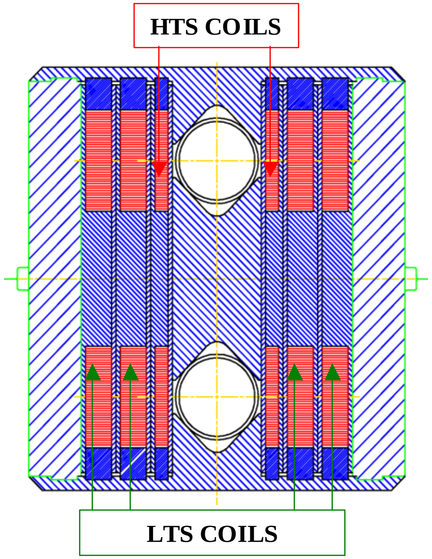
Diameter =6-7 mm

Bend diameter =100-150 mm

CORC can be made in smaller diameter also. But J_e goes down rapidly (as much as by an order of magnitude).

Hybrid Common Coil Dipole Design with High Current CORC® Cable

- High I_c, High J_e CORC® cable requires large bend radii – "common coil design" allows that
- Consider HTS CORC® cable coil powered in series with the LTS Rutherford cable coil
- Easier operation, easier protection – reasonable inductance (high current)
- Partially transposed CORC® cable also helps in reducing magnetization-induced field errors associated with the high strength ReBCO tape
- Proof-of-principle proposed with HTS insert running in series with Nb_3Sn BNL Common coil dipole within the budget of Phase II SBIR



SUMMARY

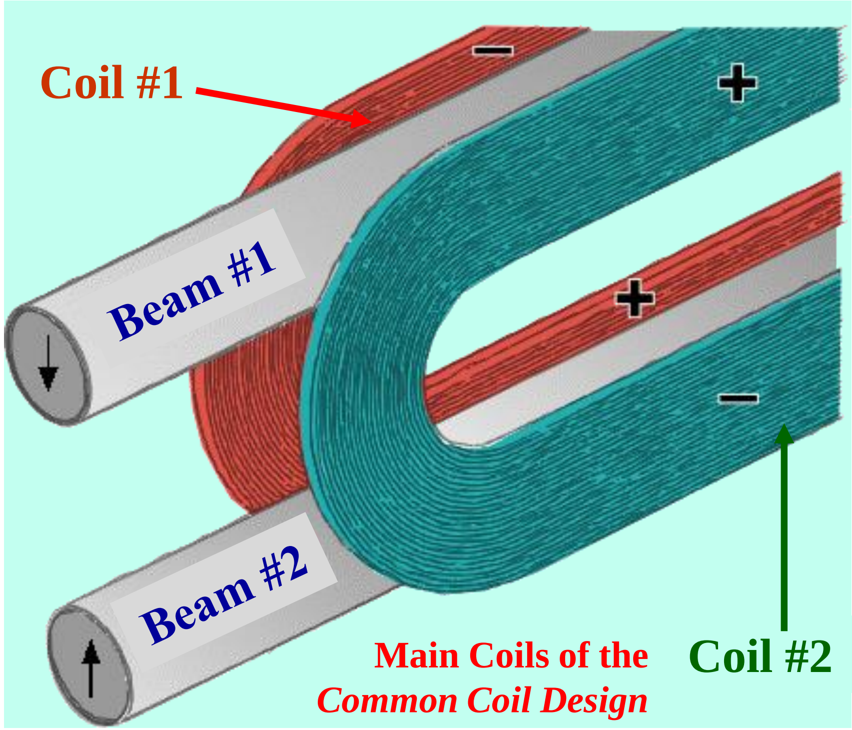
- Common coil geometry is a block coil design with simpler ends.
- In this design, coil moves as a whole under large horizontal forces in high field magnets. This reduces the amount of strain on the conductor and the amount of expensive support structure required.
- Common coil design has a potential to produce reliable lower cost magnets.

- High field insert coil test facility, where coils can be tested rapidly in a cost effective way (somewhat similar to the conductor test facility), could change the way we do magnet R&D. We could be more bold and more systematic.
- BNL test facility should be operational soon.

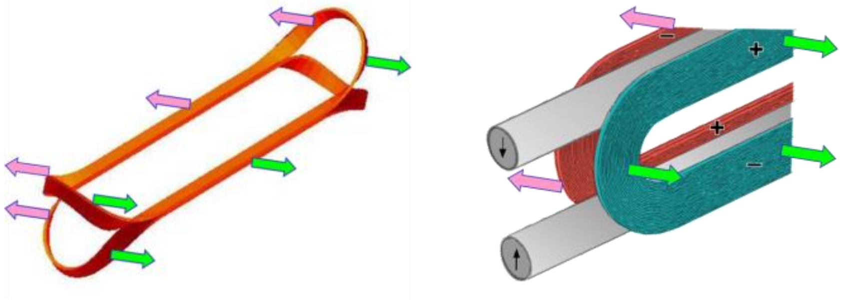
- HTS provides a test vehicle for experimentally evaluating new geometries.
- HTS also provides extra margin/field. HTS may become attractive if cost goes down and we learn how to use these material in accelerator magnets.

Extra Slides

Common Coil Design (Summary of Benefits)

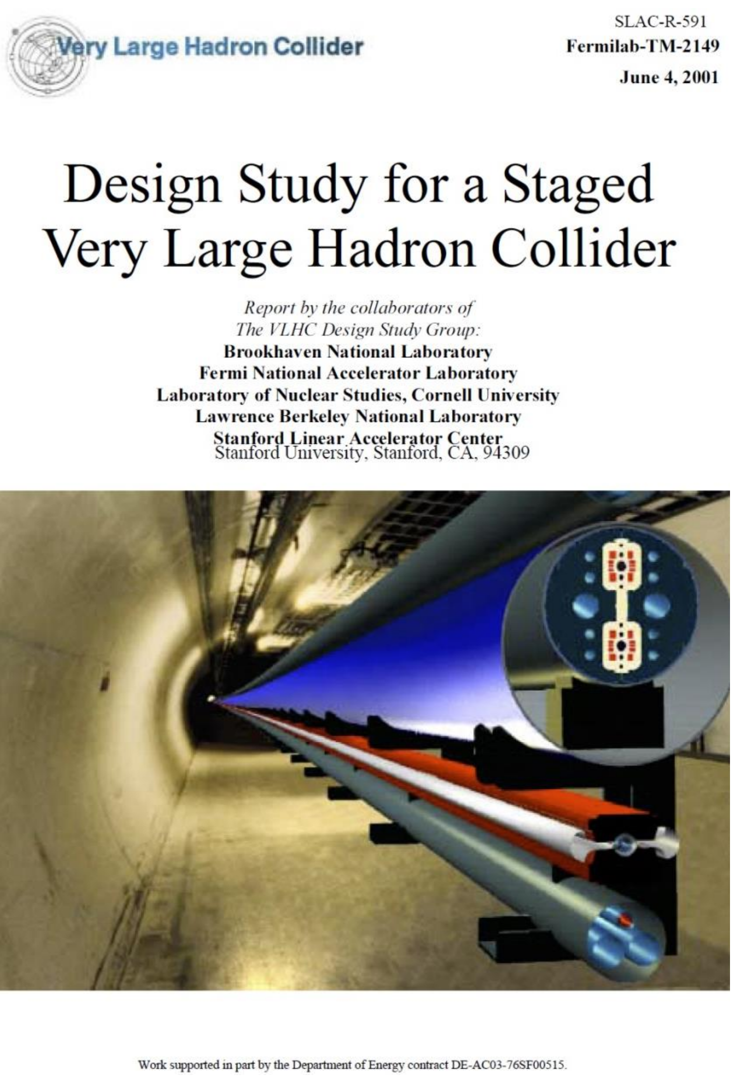


Main Coils of the *Common Coil Design*



- 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

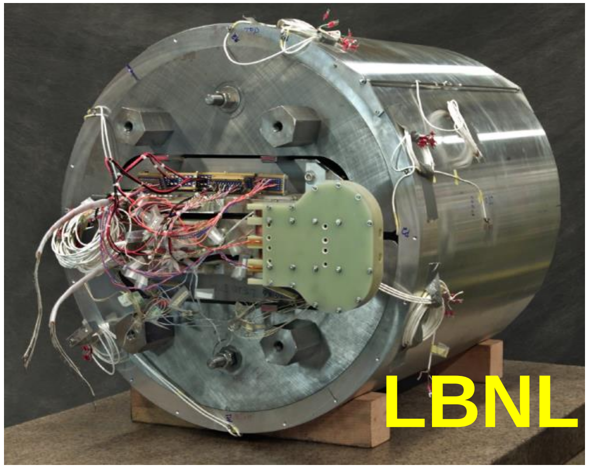
Design Study for a Staged Very Large Hadron Collider

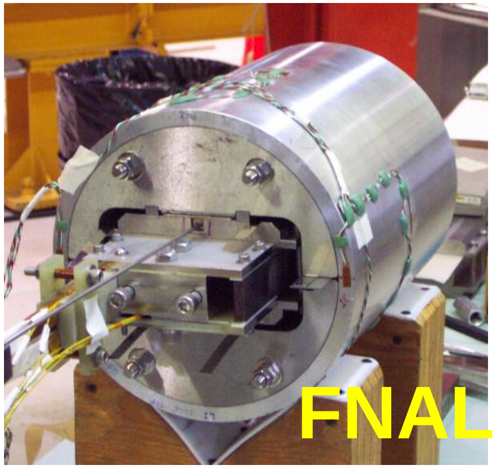
Report by the collaborators of
The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
Stanford University, Stanford, CA, 94309

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





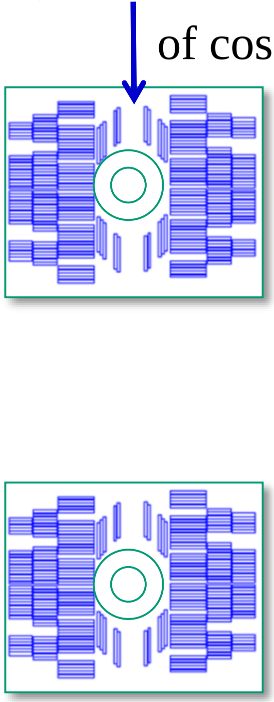
Remains to be Demonstrated Accelerator-type Field Quality

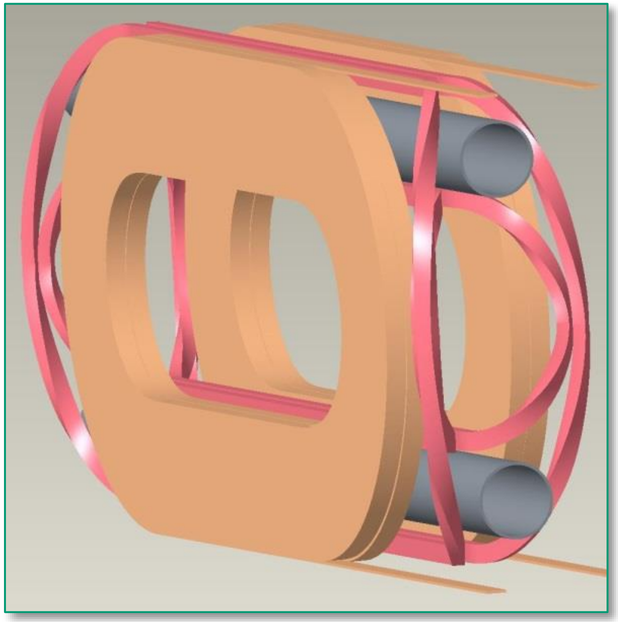
- **Require "pole coils" which must clear the beam tubes in the ends**

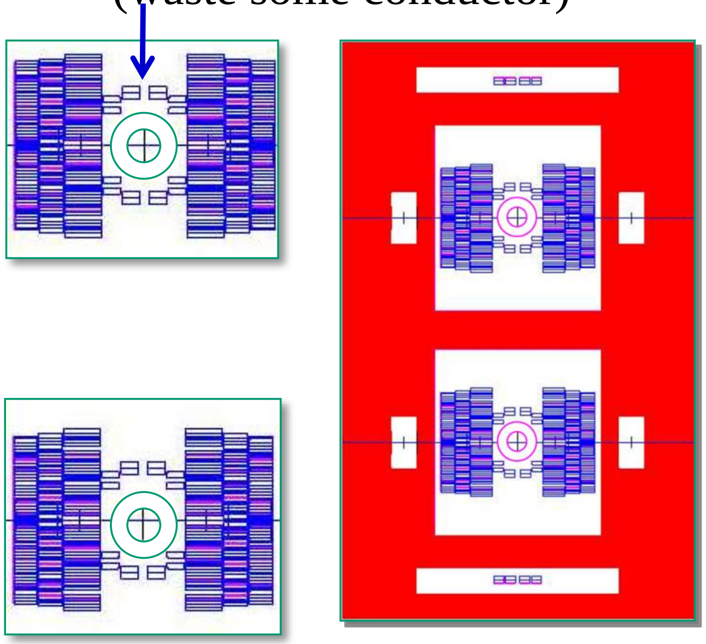
(a) Pole coils like midplane coils of cosine theta dipoles (easy bend)

OR

(b) Simpler configuration of pole coils (waste some conductor)



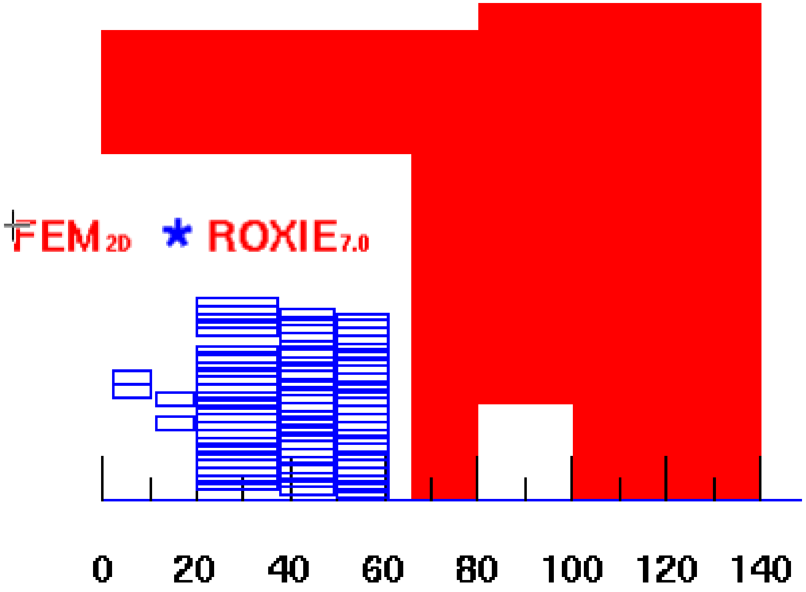


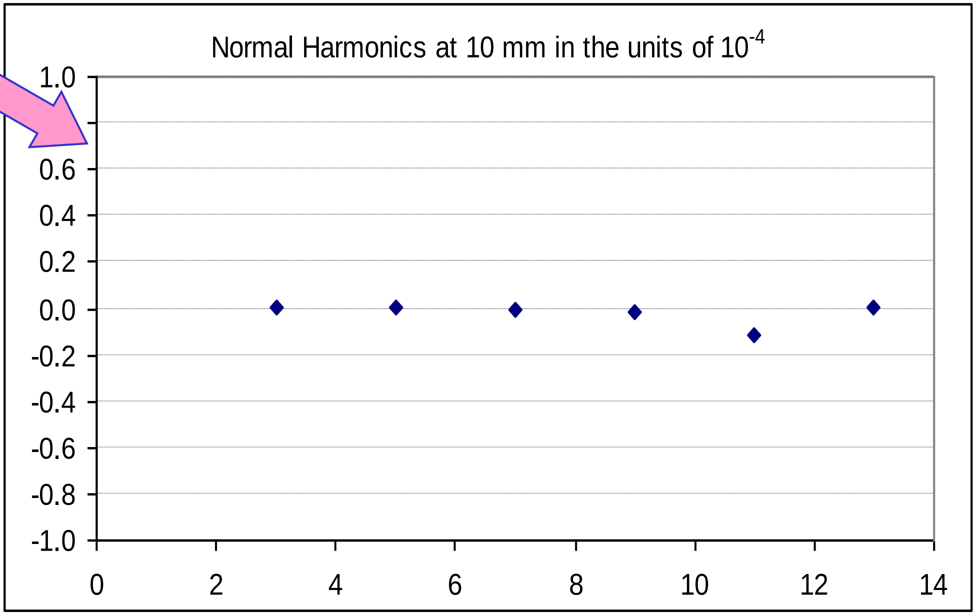


Good field quality have been shown in computer models but not yet demonstrated in a model magnet with added (minor) complication

Demonstration of Good Field Quality (Geometric Harmonics)

Typical Requirements:
~ part in 10^4, we have part in 10^5





(from 1/4 model)

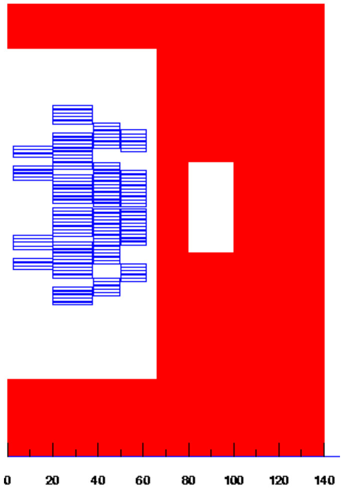
MAIN FIELD: -1.86463 (IRON AND AIR):

b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

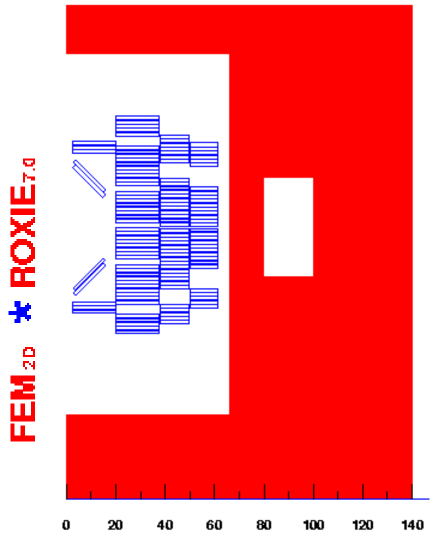
Horizontal coil aperture:

40 mm

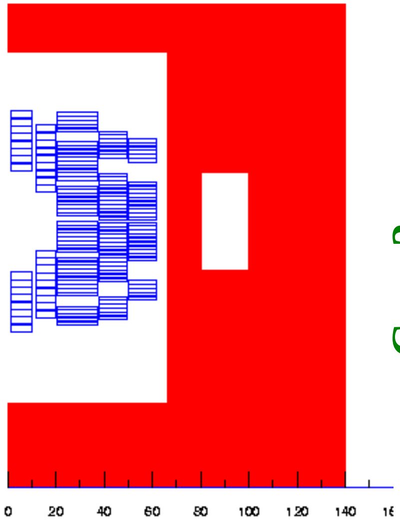
A Few Good Field Quality Configurations



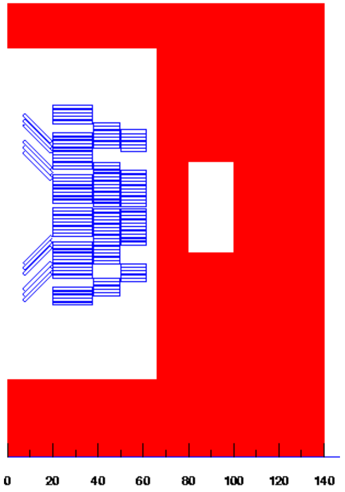
Case 1a



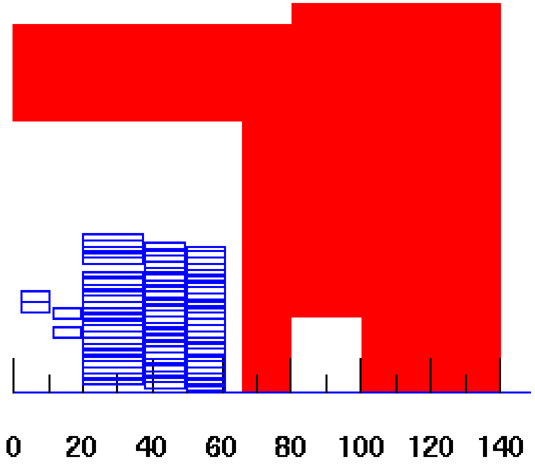
Case 1c

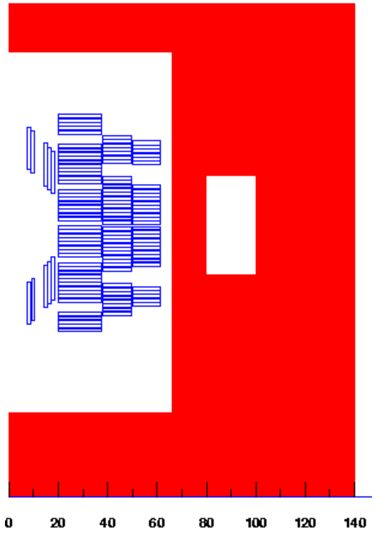


Case 2



Case 1b

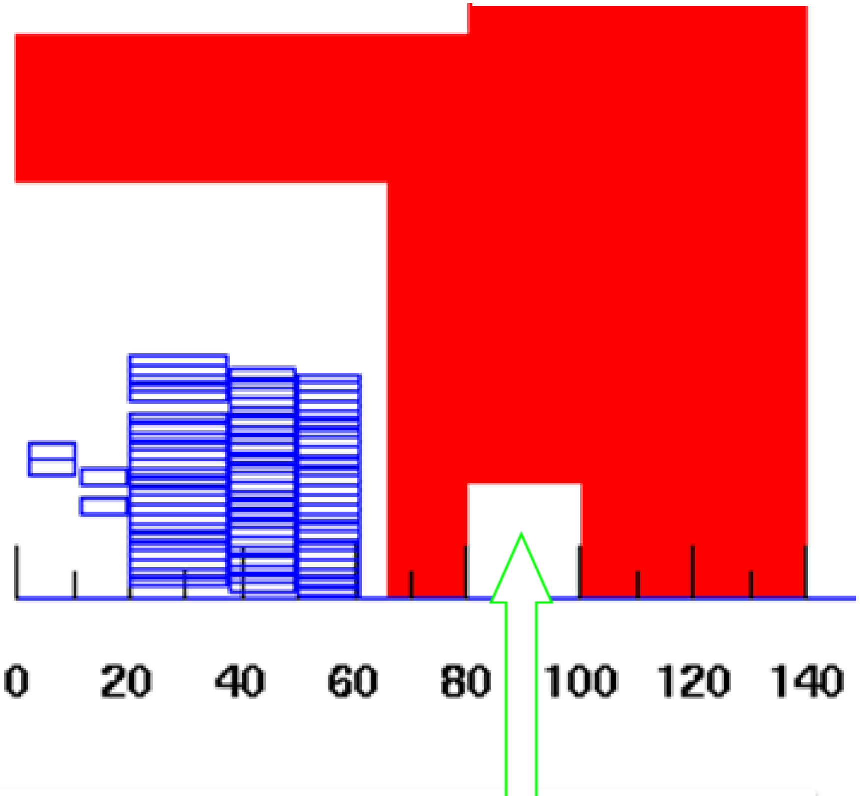


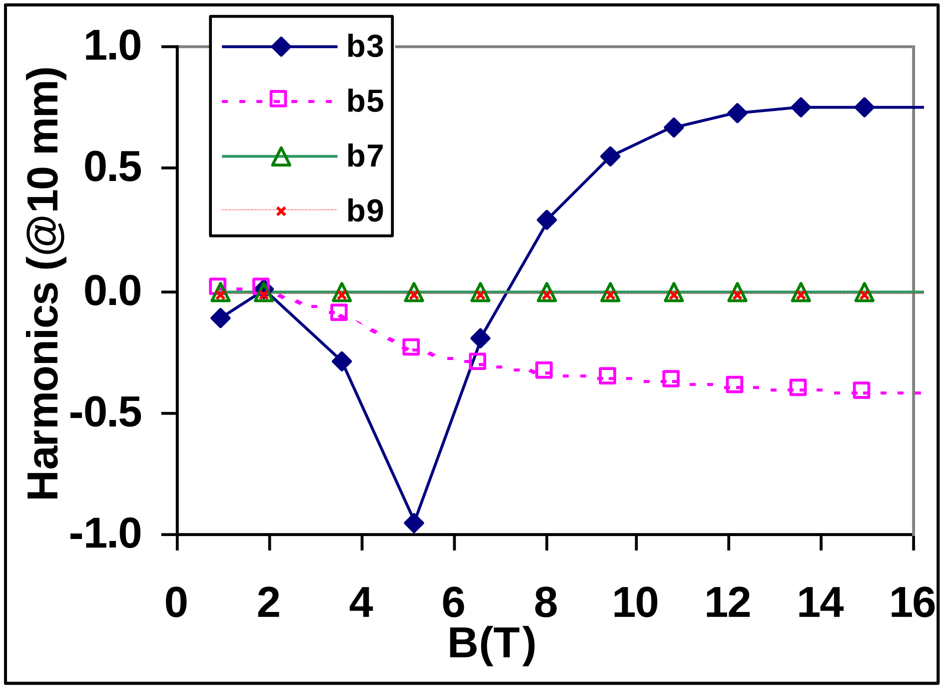


Case 3

Demonstration of Good Field Quality (Saturation-induced Harmonics)

Maximum change in entire range: ~ part in 10^4 (satisfies general accelerator requirement)





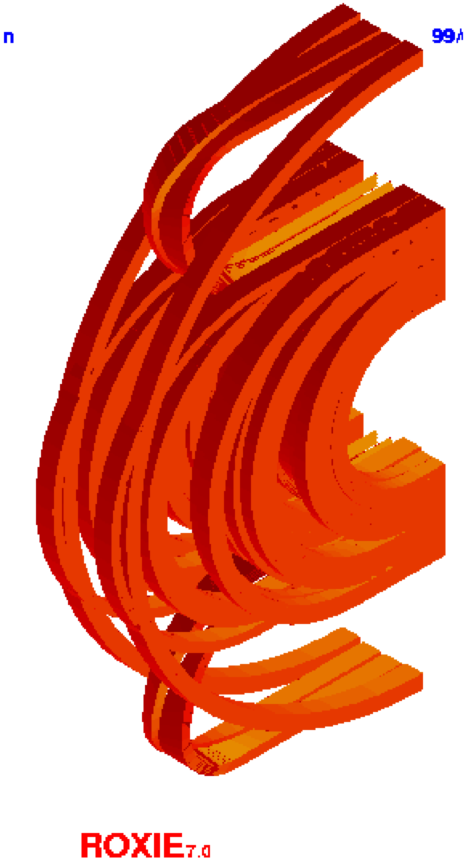
Use cutouts at strategic places in yoke iron to control the saturation

Low saturation-induced harmonics (within 1 unit)

Demonstration of Good Field Quality (End Harmonics)

End harmonics can be made small in a common coil design.

(Very small)



End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Contribution to integral (a_n,b_n) in a 14 m long dipole (<10^{-6})

n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000