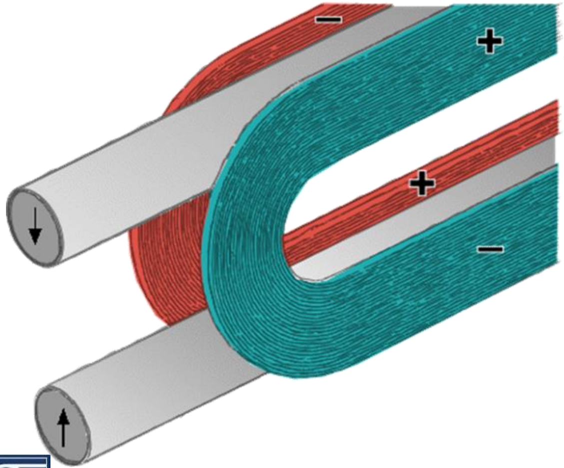
Common Coil Magnet Design for High Energy Colliders

Ramesh Gupta
Brookhaven National Laboratory
Upton, NY 11973 USA



September 15, 2015

Contents

- Introduction to Common Coil Design
  - Simple geometry, custom made for colliders
  - Suitable for high fields, lower cost magnets expected
- Status of Common Coil Dipoles
  - R&D magnets built at LBL, BNL and FNAL
- Single Aperture and Dual Aperture Block Designs
  - Single aperture - Flared ends - a necessity
  - Dual aperture – simpler common coil ends – a possibility

Contents (contd.)

- **Modular design - cost-effective and rapid turn around**
  - **Encourages innovations and systematic studies**
- **Field Quality**
- **Summary**

Present Magnet Design and Technology

Tevatron Dipole

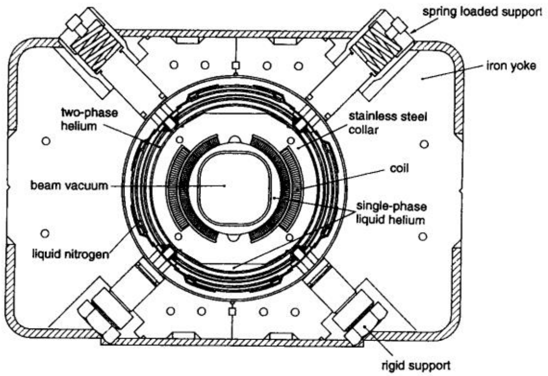
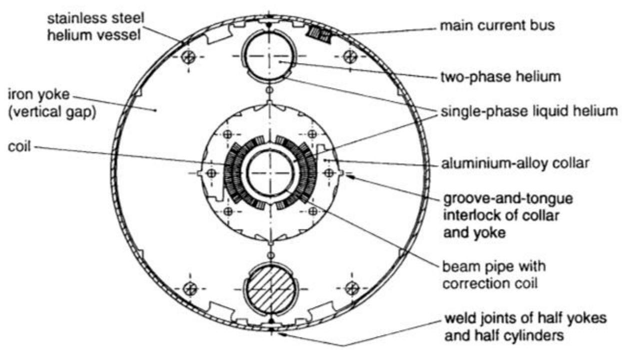
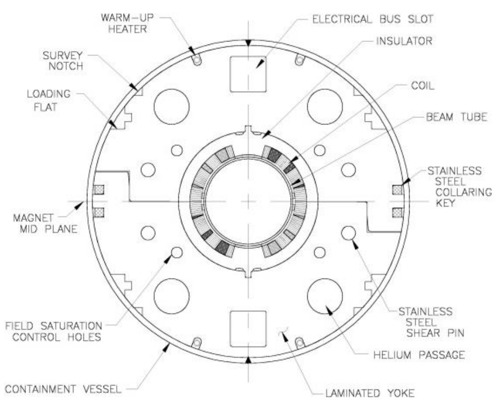


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

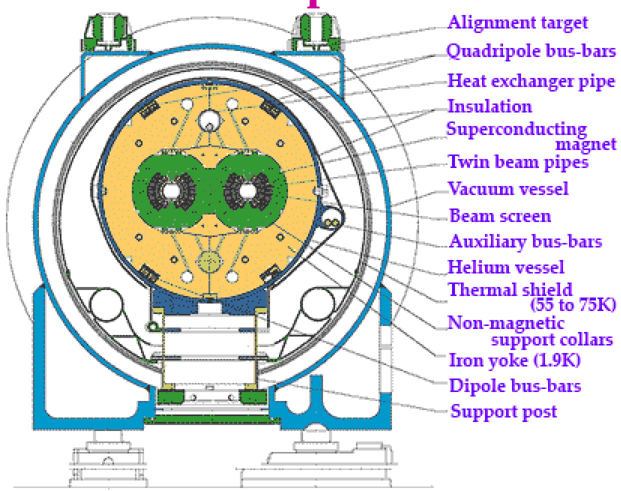
HERA Dipole



RHIC Dipole



LHC Dipole

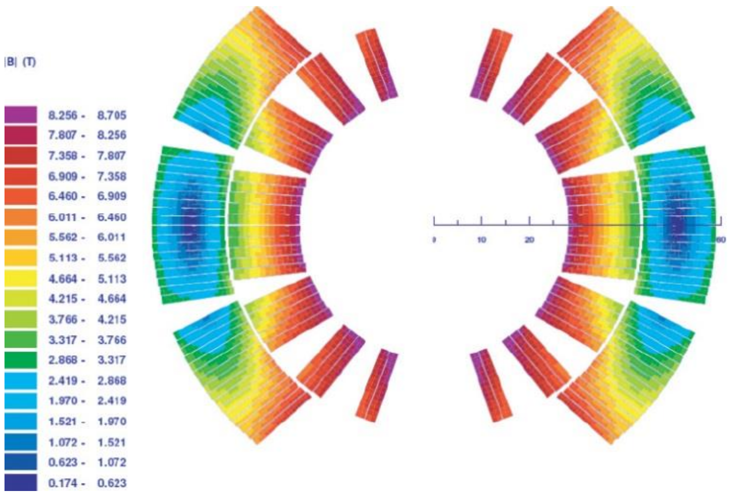


- **All magnets use Nb-Ti Superconductor**
- **All designs use cosine theta coil geometry**
- **The technology has been in use and mastered for decades**
- **Significant improvements in performance and/or reduction in cost are unlikely to come now**

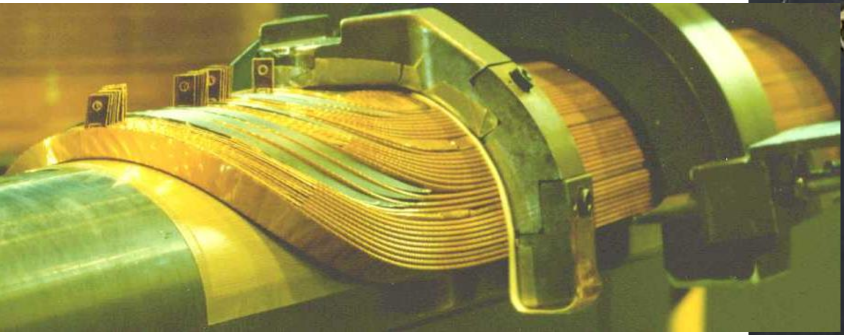
➢ **For the stated requirements of ~16 T for FCC, need new materials/technology**

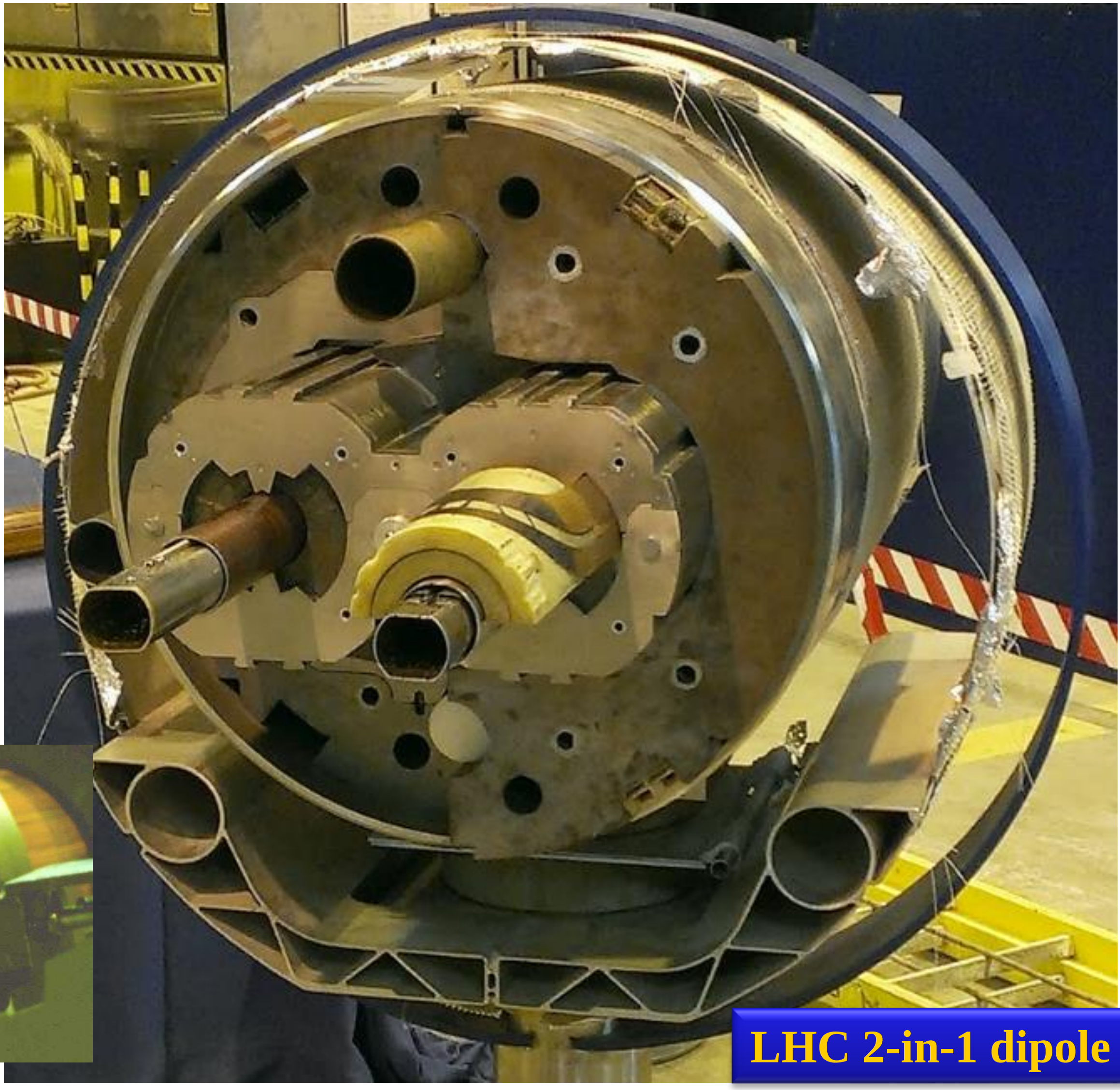
Cosine Theta Magnets

Cosine(θ) current distribution



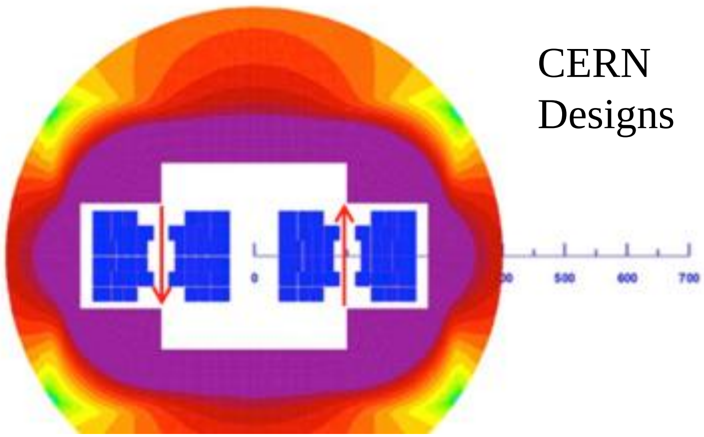
complex ends



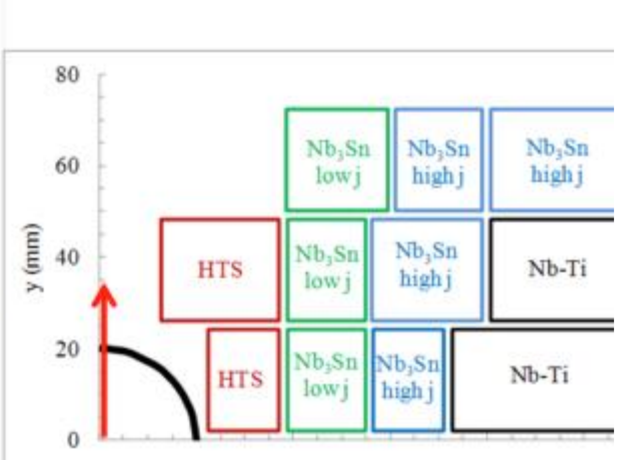


LHC 2-in-1 dipole

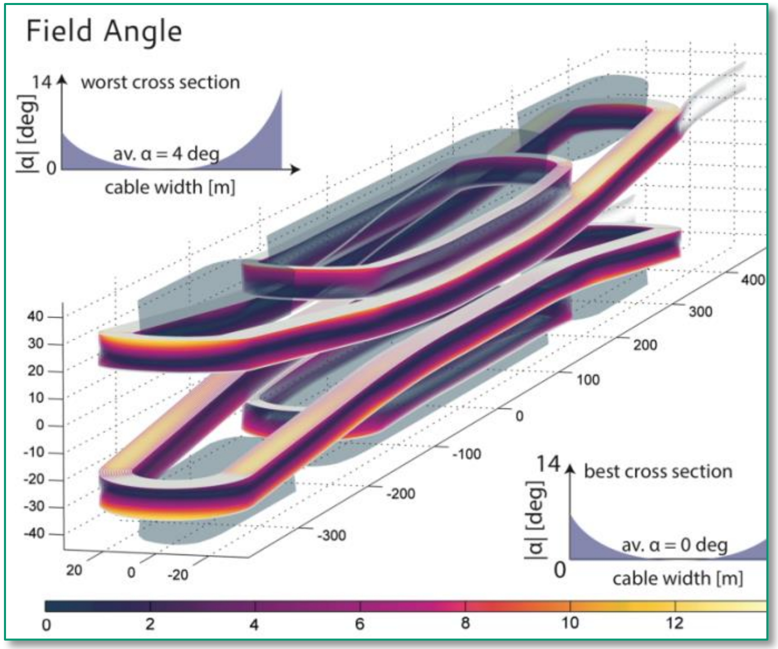
Block Dipole Designs



CERN Designs

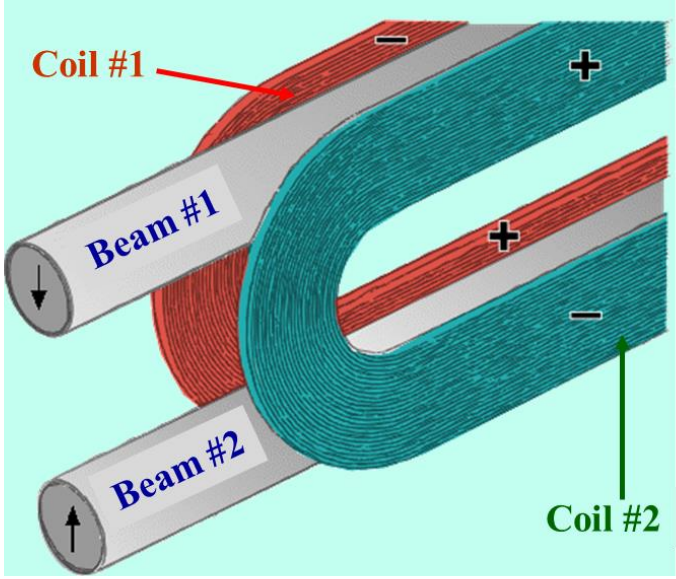


Block coil type dipole designs are attractive for high field magnets

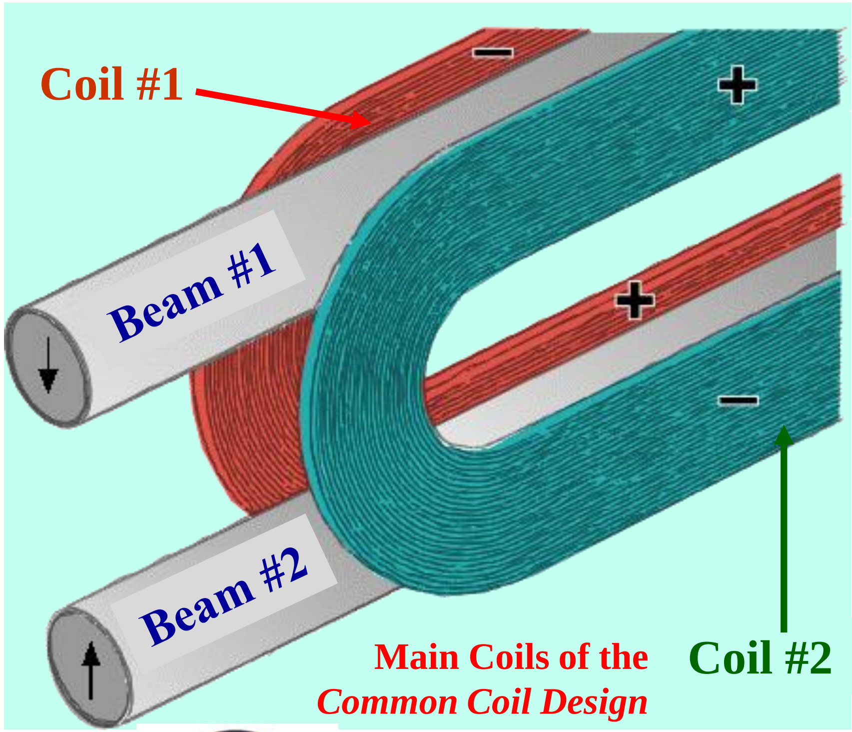


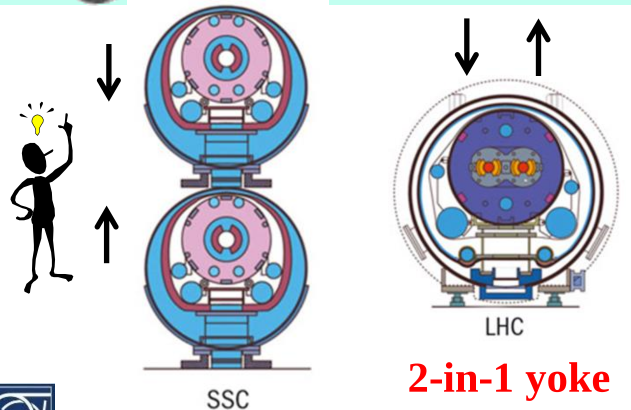
Common coil design is a block coil type design, but with simpler ends

Common Coil Design



Common Coil Design (The Basic Concept)



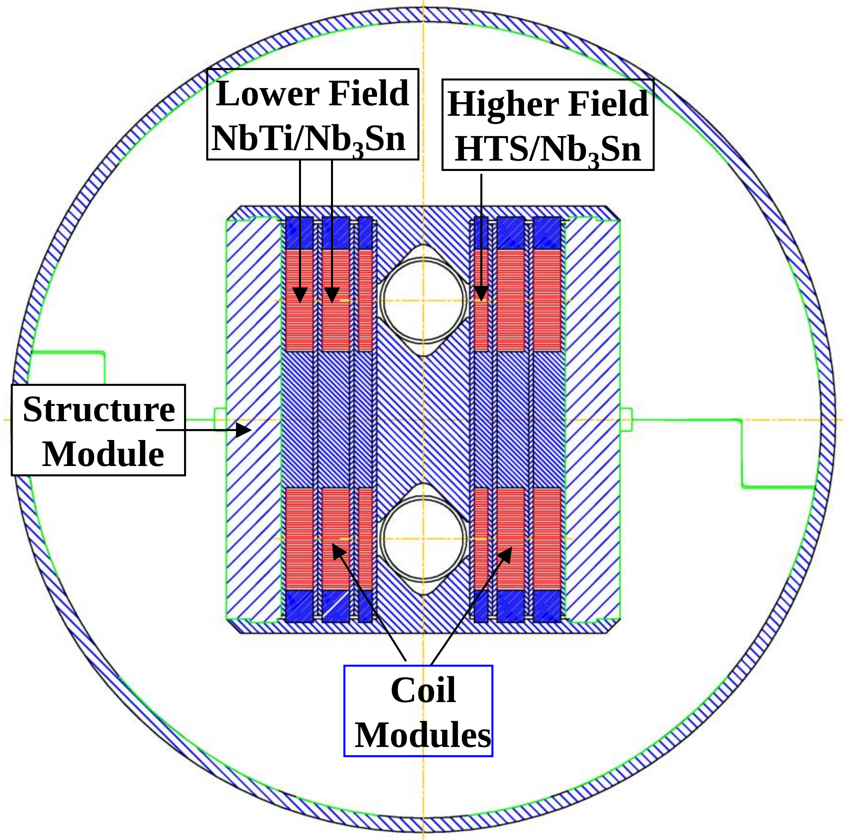


2-in-1 yoke

- **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** with large bend radii (determined by the spacing between two apertures) without complex 3-d ends
- **Block design** with lower internal strain on the conductor under Lorentz forces
- **Easier segmentation** for hybrid designs (Nb_3Sn and NbTi + HTS?)
- **Minimum** requirements on big expensive **tooling and labor**
- **Potential for** producing low cost, more reliable (**less margin**) high field magnets
- **Efficient** and rapid turn around magnet R&D due to simpler and **modular design**

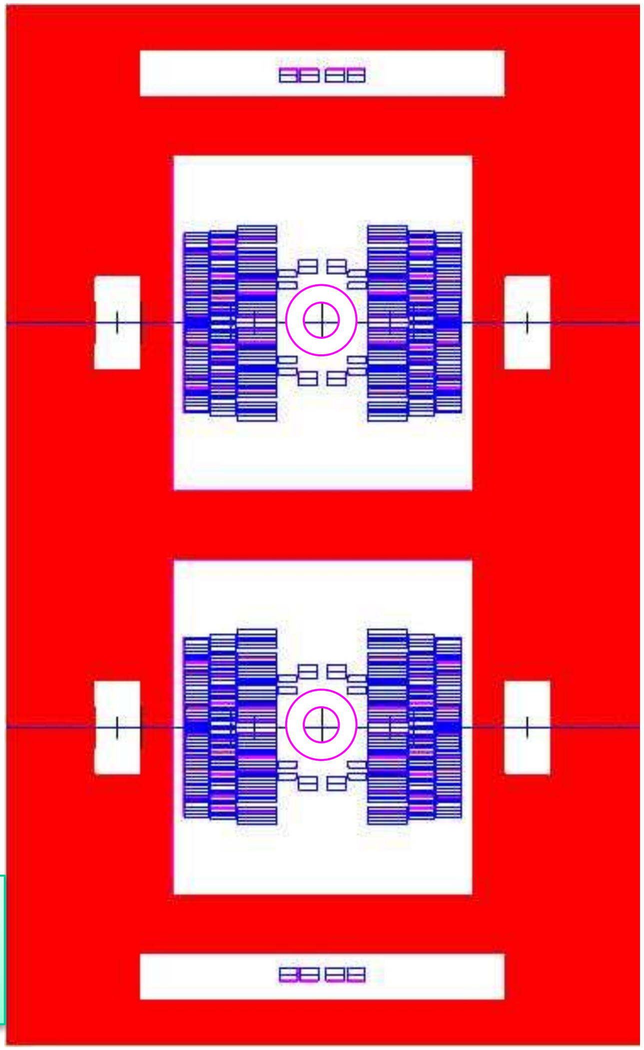
Layout of High Field Common Coil Design

Coil layers/modules



Vertical coil modules allow better conductor segmentations with fields

15 T Field Quality Magnet



Field quality design also needs pole coil modules

15 T design is based on Nb_3Sn conductor with J_c = 2200 A/mm^2 @(12T, 4.2K)

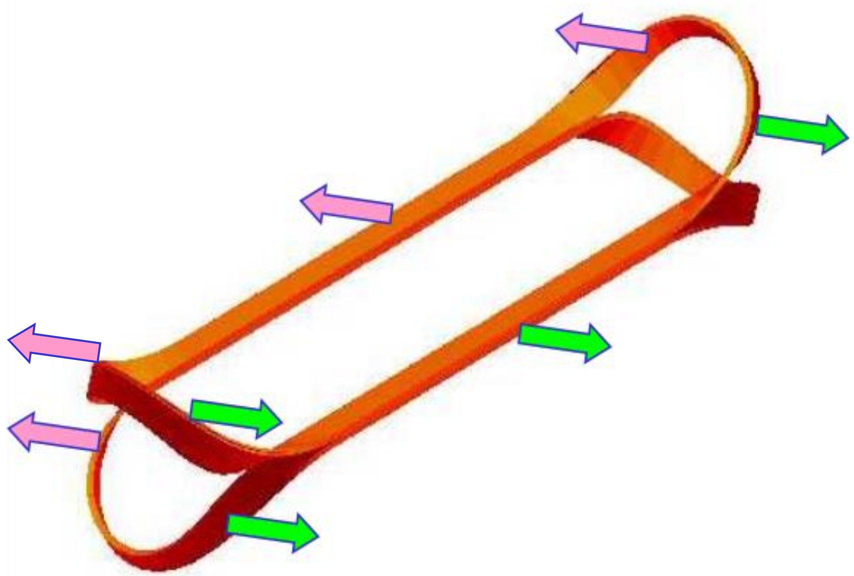
More horizontal space for structure will need a minor iteration in magnetic design

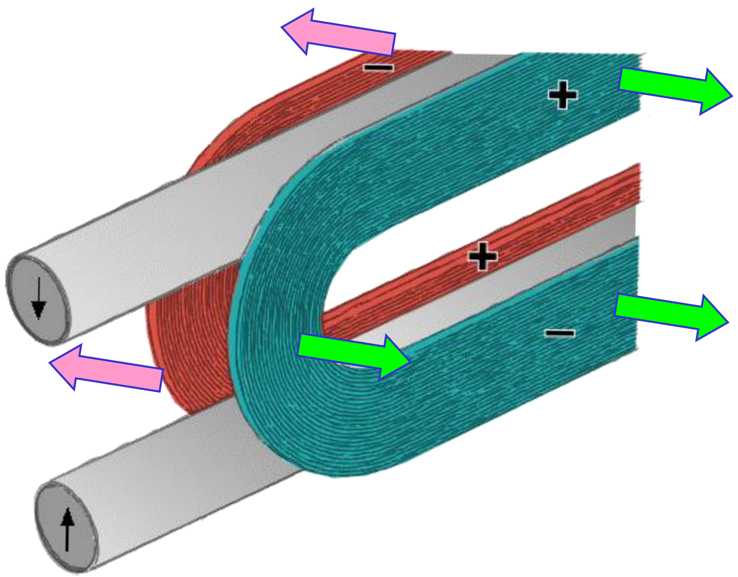
Advantage of Common Coil Design in High Field Magnet Structure

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

In cosine theta (and also in block designs), large forces put excessive stress/strain on the conductor in the end region

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



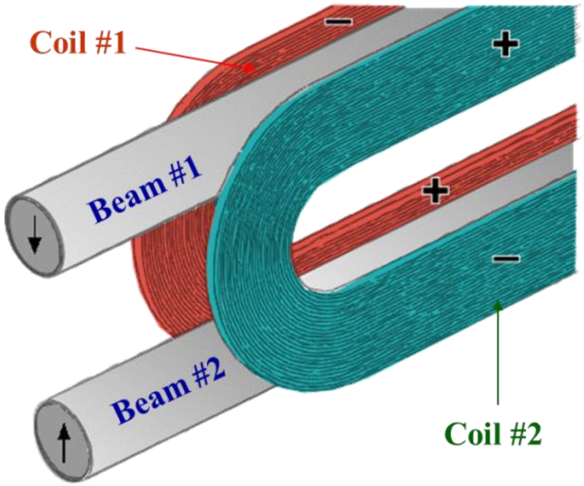


BNL common coil dipole tolerated ~200 microns motion (typical ~25-50 μm)

Expect lower cost due to less structure and better performance due to less strain

Common Coil Design and React and Wind Technology

- 16 T needs Nb_3Sn, which must be reacted at high temperature (~650 C) to make it superconducting. Unfortunately Nb_3Sn turns brittle after reaction
- Most magnets to date are based on “Wind & React” technology where the entire coil module is reacted to avoid degradation or damage
- Common coil design adds another safe option - “React & Wind” approach with pre-reacted cable, thanks to large bend radii and simple geometry
- “React & Wind” approach opens door to another option for coil manufacturing
- It also allows several more material options for insulation, conductor and other coil components, as the coil doesn’t have to go through the high temperature reaction cycle

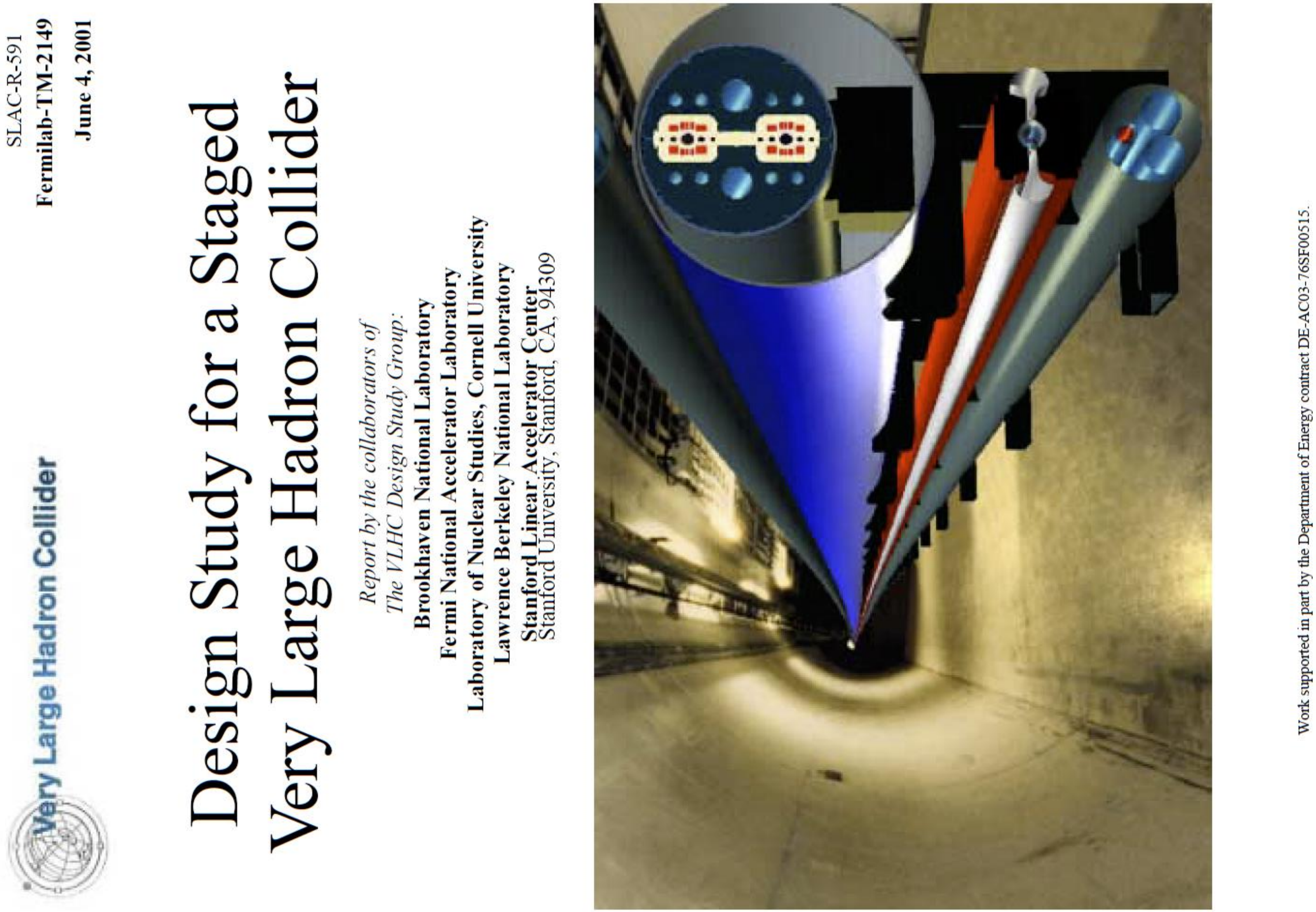


Status of
Common Coil Magnet

BROOKHAVEN
NATIONAL LABORATORY

Superc
Magne

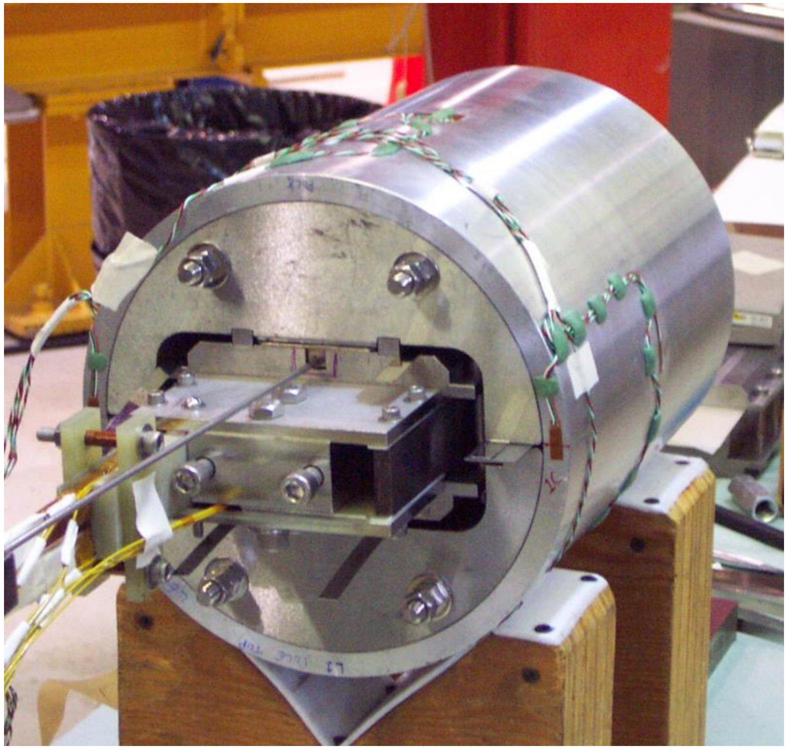
Common Coil Design for VLHC



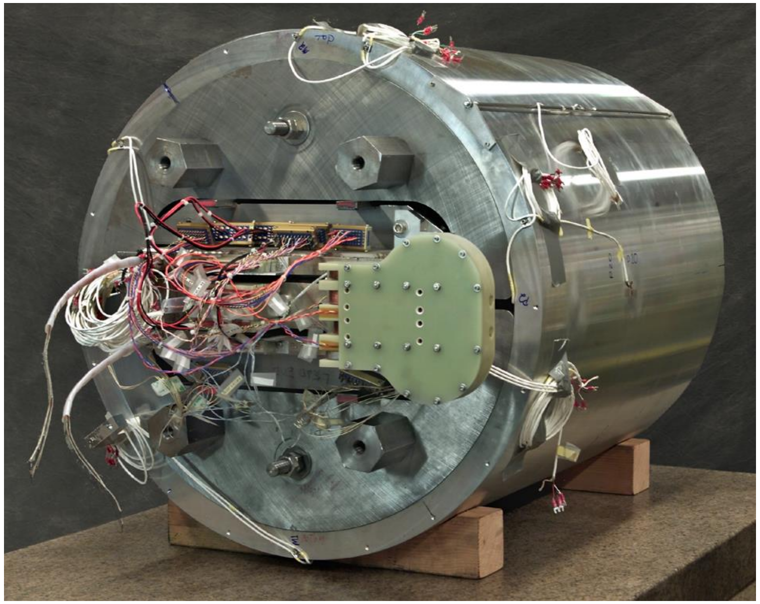
Common Coil Magnets Built at BNL, FNAL, LBNL

BNL

FNAL



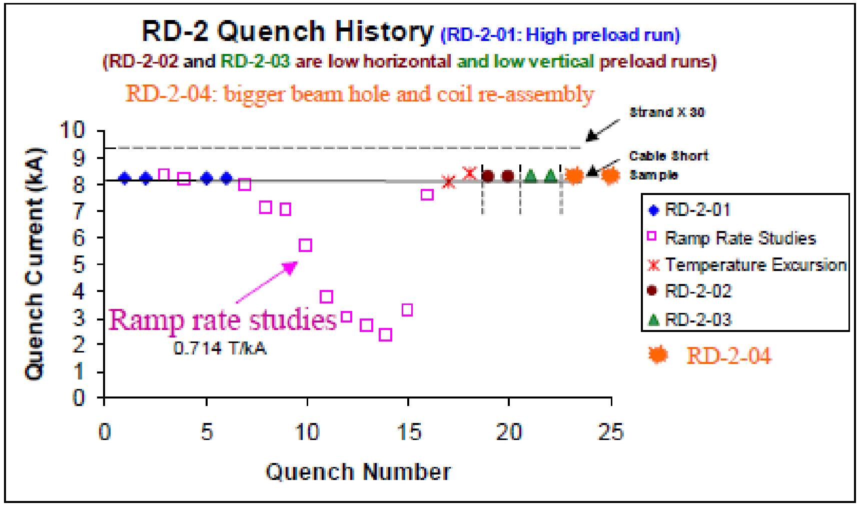
LBNL

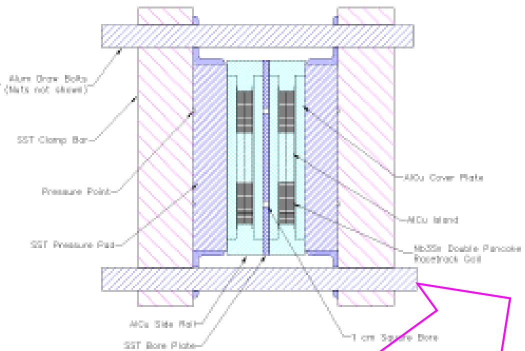


Experimental Investigations for support structure design in ultimate magnet

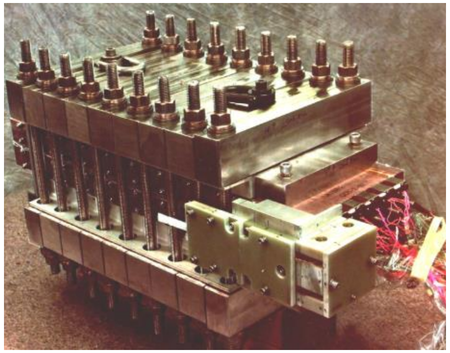
- Common Coil design invented at BNL;
- First magnet built at LBNL
- First to be used in the machine at ???

Support structure is expansive and the cost grows rapidly in high field magnets. The cost may be lowered and the magnet may be made simpler if we can prove that full pre-stress is not essential. (LHC magnet experiments).





1. The magnet reached plateau performance right away (plateau seems to be on the cable short sample, not wire short sample).
2. Didn't degrade for a low horizontal pre-load (must for this design).
3. Didn't degrade for a low vertical pre-load (highly desirable).
4. Didn't degrade for a bigger hole (real magnets).



Magnet System Designs for A Lower Cost Hadron Collider — AFRD Division Review, June 15-16, 1999
BERKELEY LAB
Superconducting Magnet Program — Ramesh Gupta, Slide No. 20/23

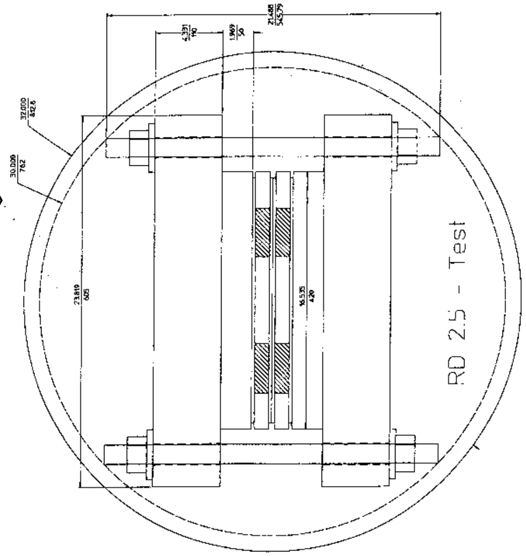
○ Important Results

LBL SM program is perhaps an evolution of this

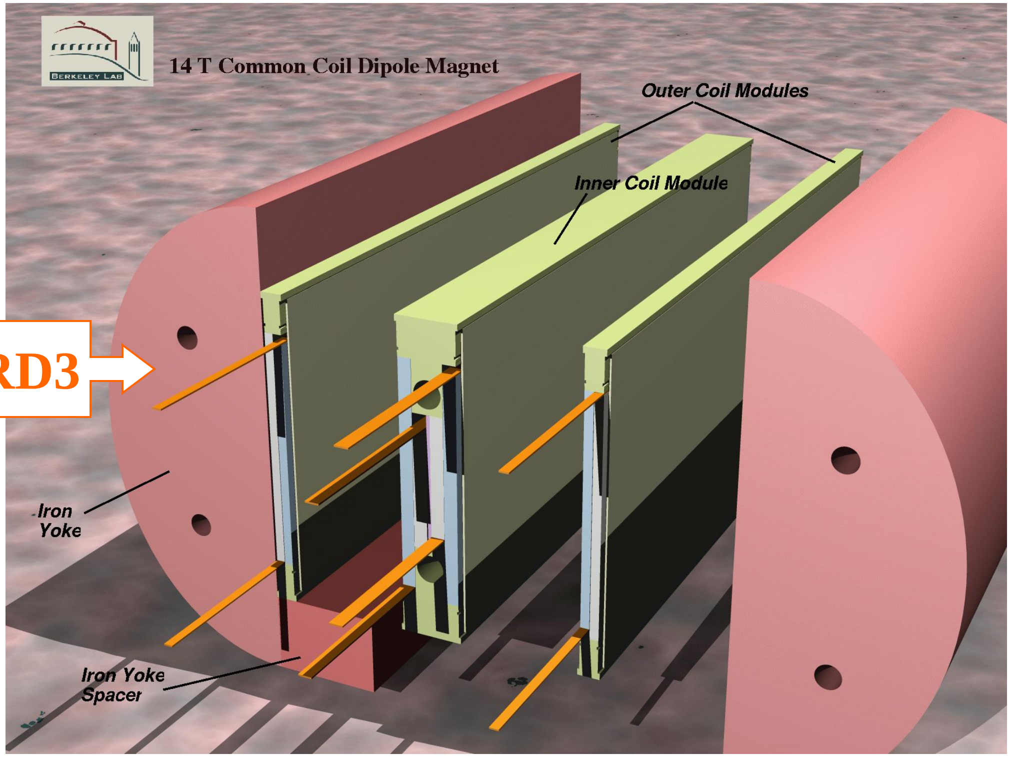
On To A Higher Field Common Coil Magnet

The first step towards high field common coil magnet: test outer coils with minimum gap.

RT1



RD3



Bss ~12.3 T

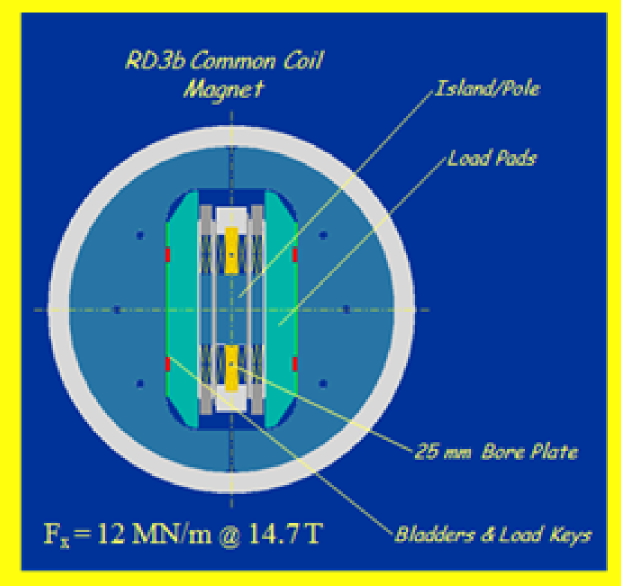
RT1 reached the short sample field (~12.3 T) with only a few quenches.

RD Series: Conductor Limits

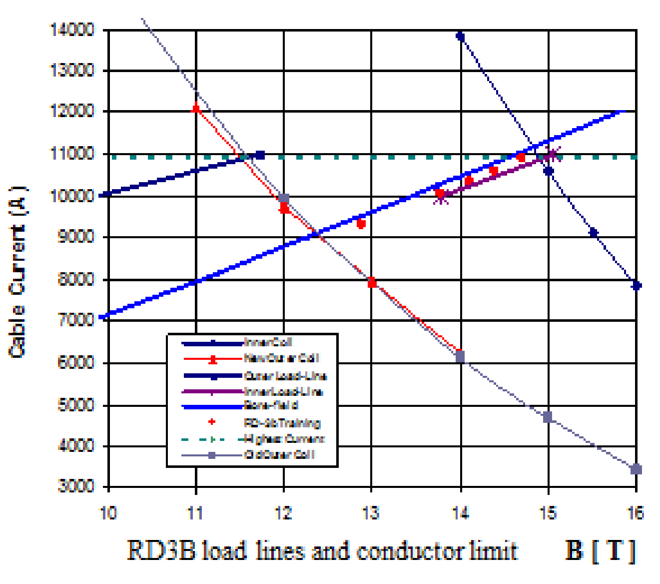
RD3

14.7 T

RT-1, RD3B – No performance degradation up to 14.7 T, 120 MPa



F_x = 12 MN/m @ 14.7 T



RD3B load lines and conductor limit

March 17-18, 2003 — *Superconducting Magnet Program* — Gian Luca Sabbi

BERKELEY LAB

Slightly doctored slide

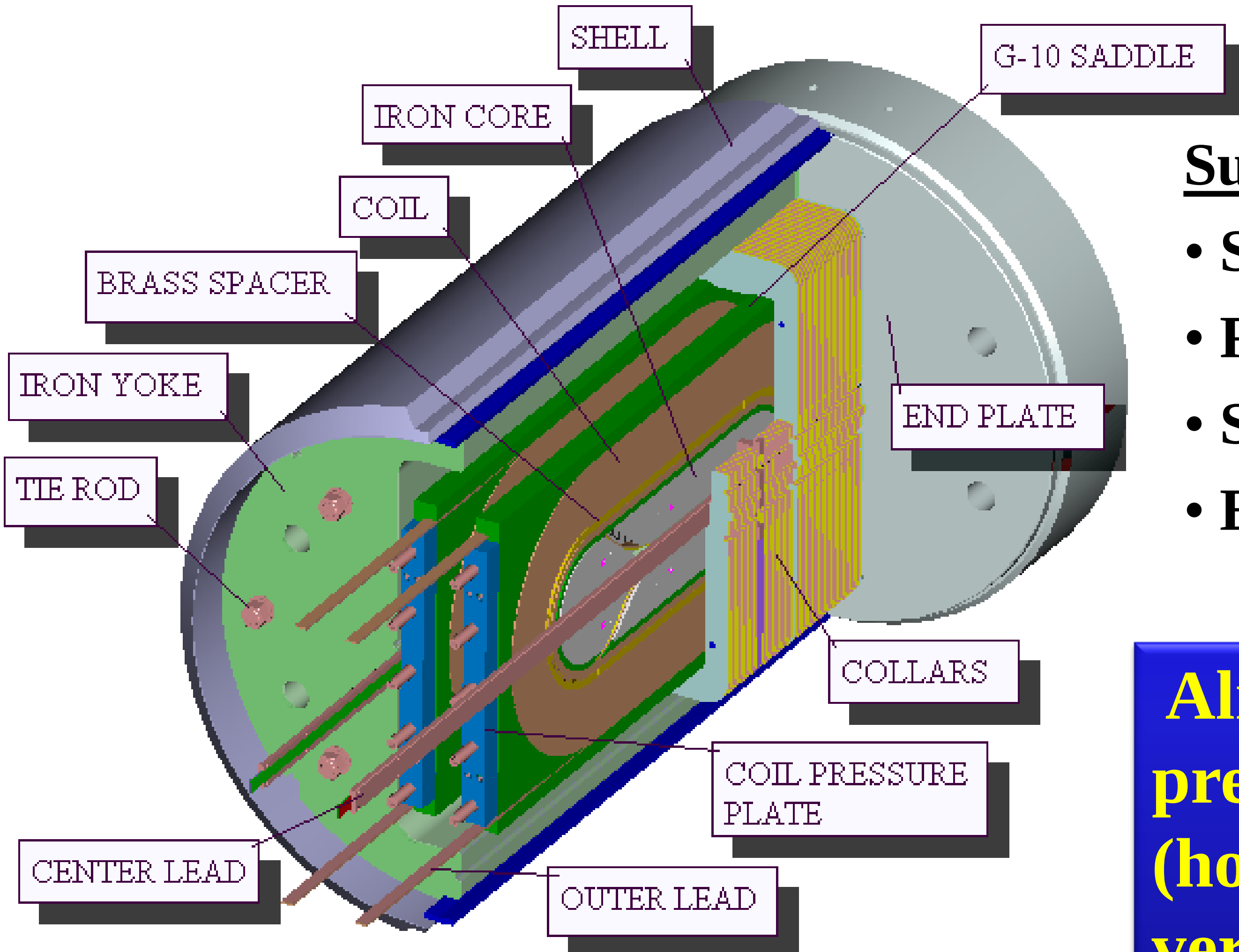
Common coil magnets approaching short sample

BNL Nb_3Sn Common Coil Dipole DCC017 (React and Wind Approach)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Mechanical Design Features

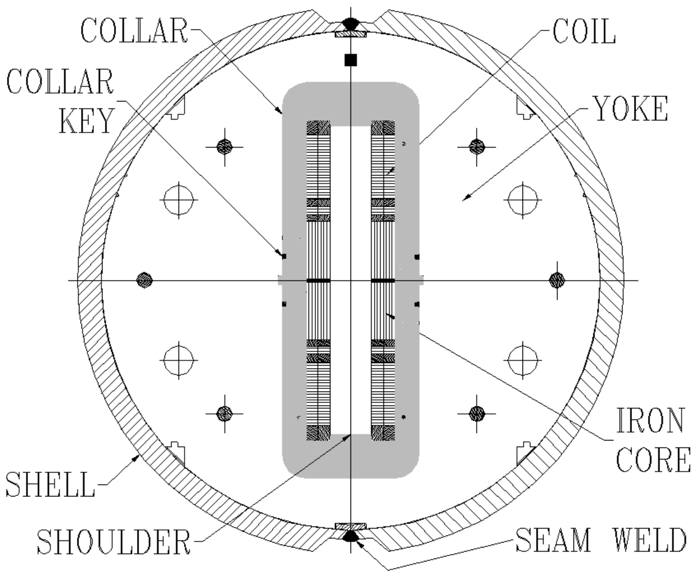


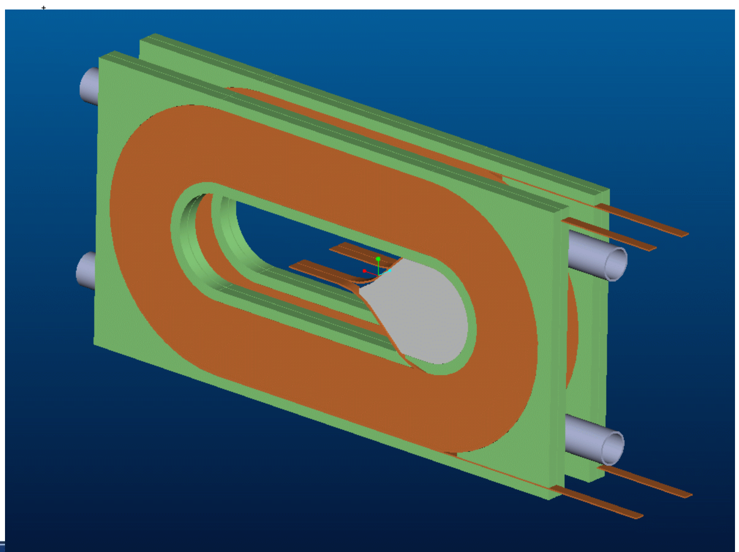
<u>Support structure:</u>

- Stainless steel collar
- Rigid yoke
- Stainless steel shell
- End plate

Almost no cold pre-stress (horizontal, vertical or axial)

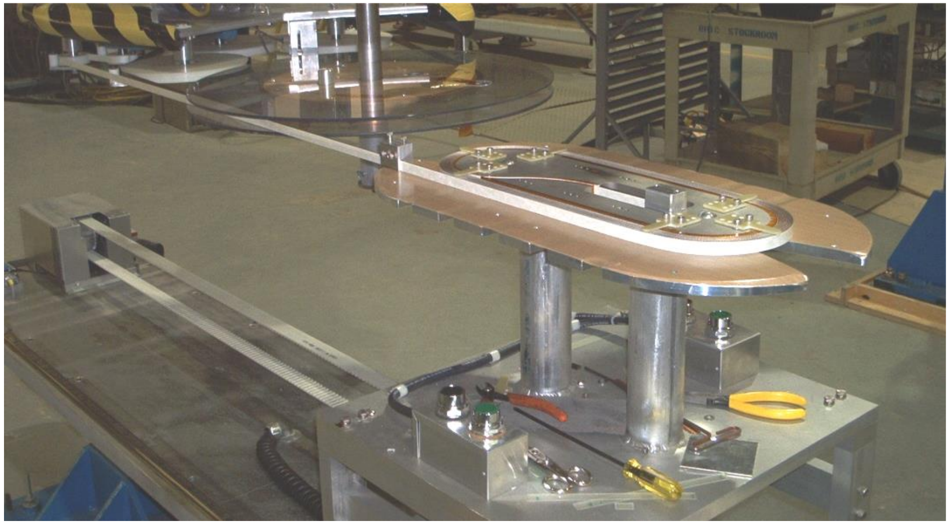
Basic Features of BNL Nb_3Sn 10^+ T React & Wind Common Coil Dipole

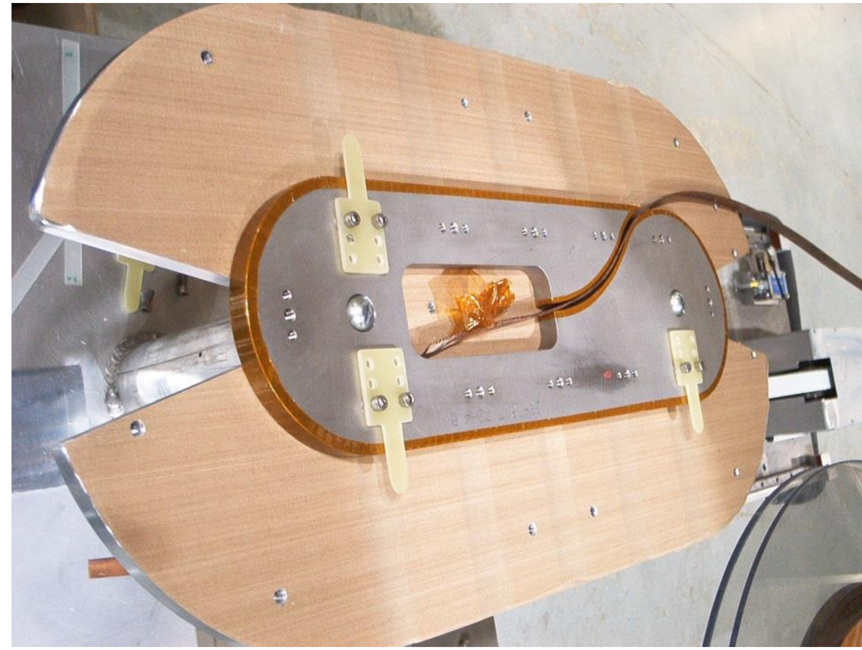


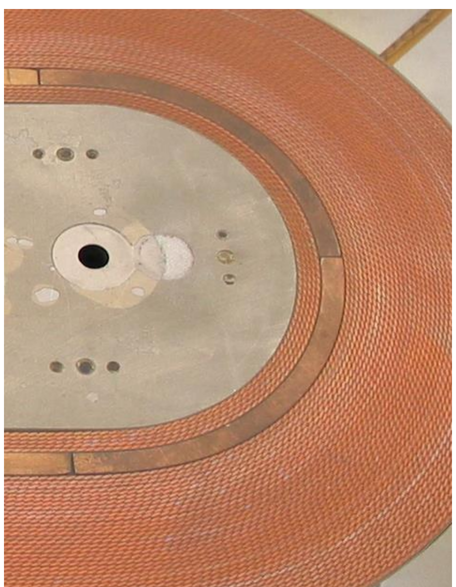


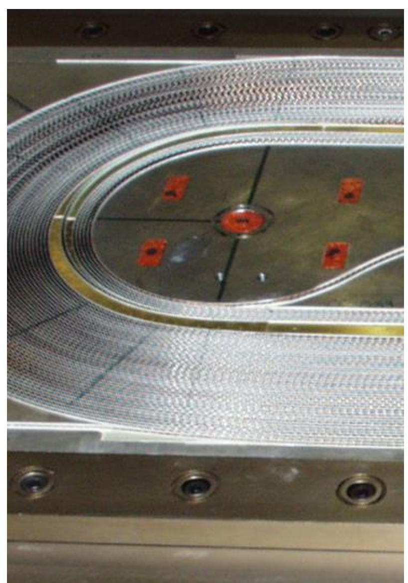
- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- 31 mm horizontal aperture
- Large (338 mm) vertical aperture
  - » A unique feature for coil testing
- Dynamic grading by electrical shunt
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum bend radius
- 620 mm overall coil length
- Coil wound on magnetic steel bobbin
- One spacer in body and one in ends
- Iron over ends
- Iron bobbin
- Stored Energy@Quench ~0.2 MJ

Racetrack Coil (with brittle pre-reacted Nb_3Sn)



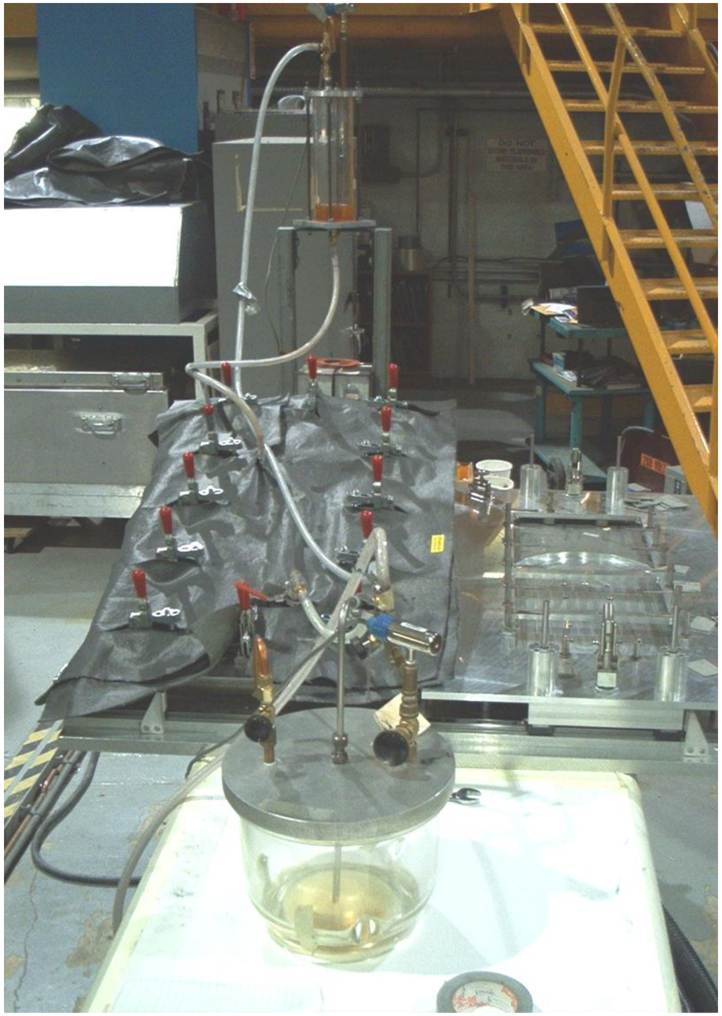


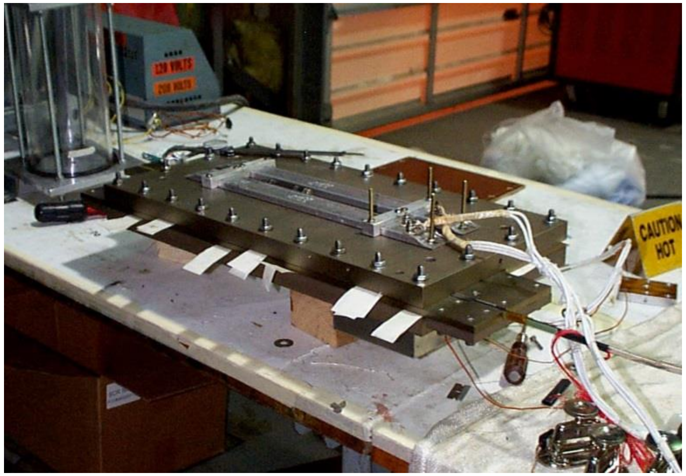




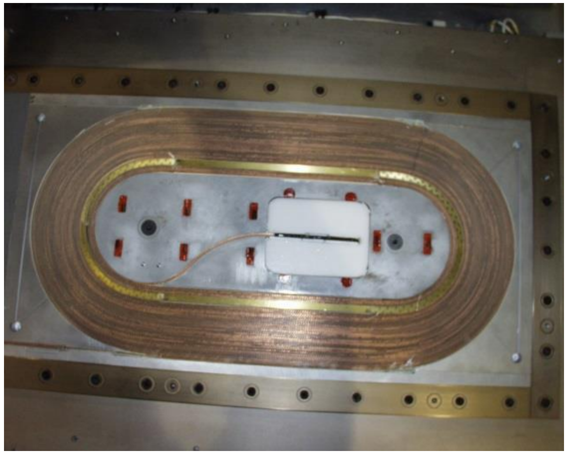
Simplicity and a reasonable care contribute to lower cost and success

Racetrack Coil Modules and Vacuum Impregnation


Coil impregnation fixture



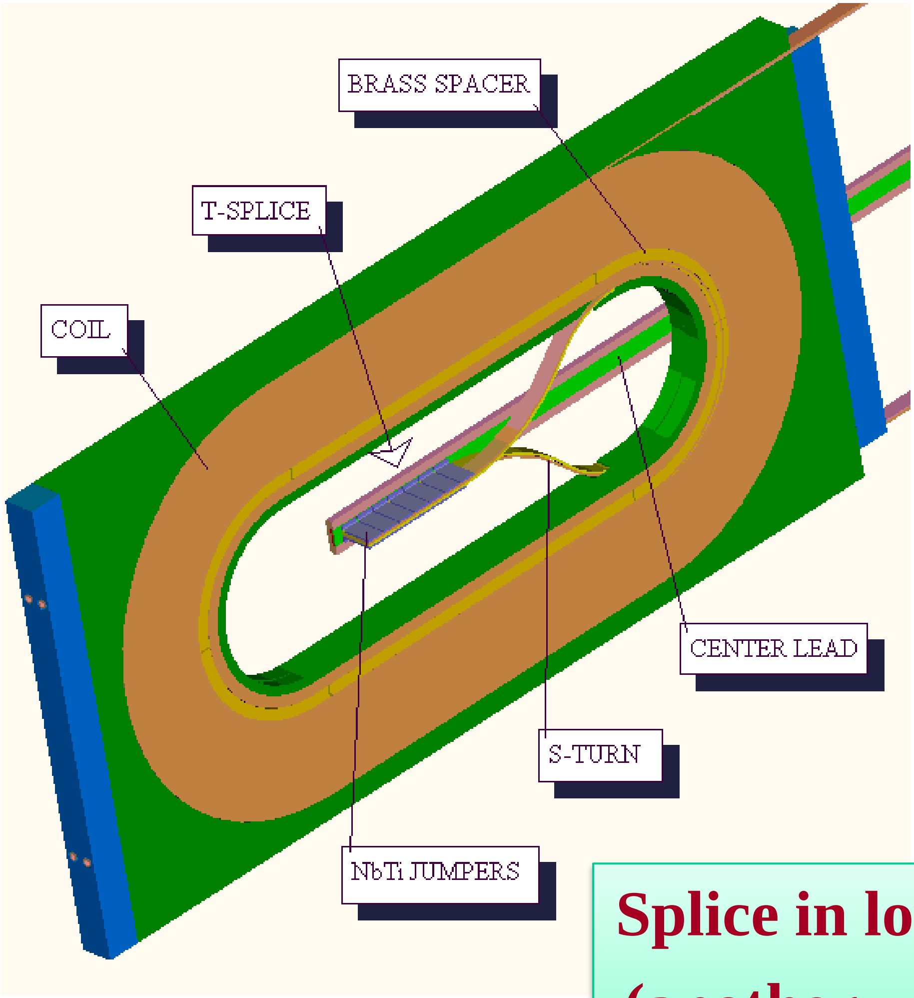

Before Impregnation

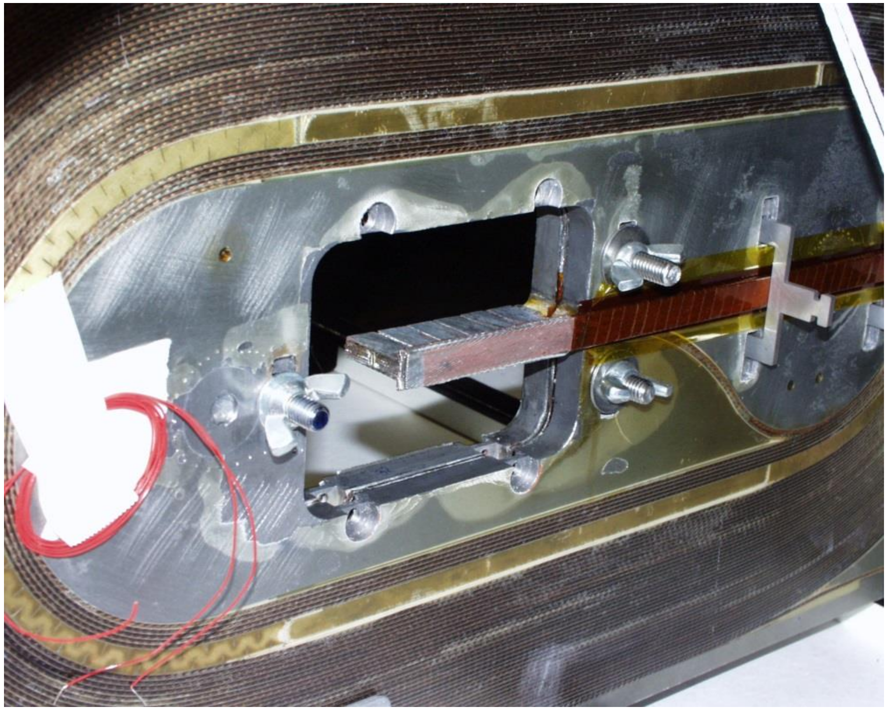

After Impregnation

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

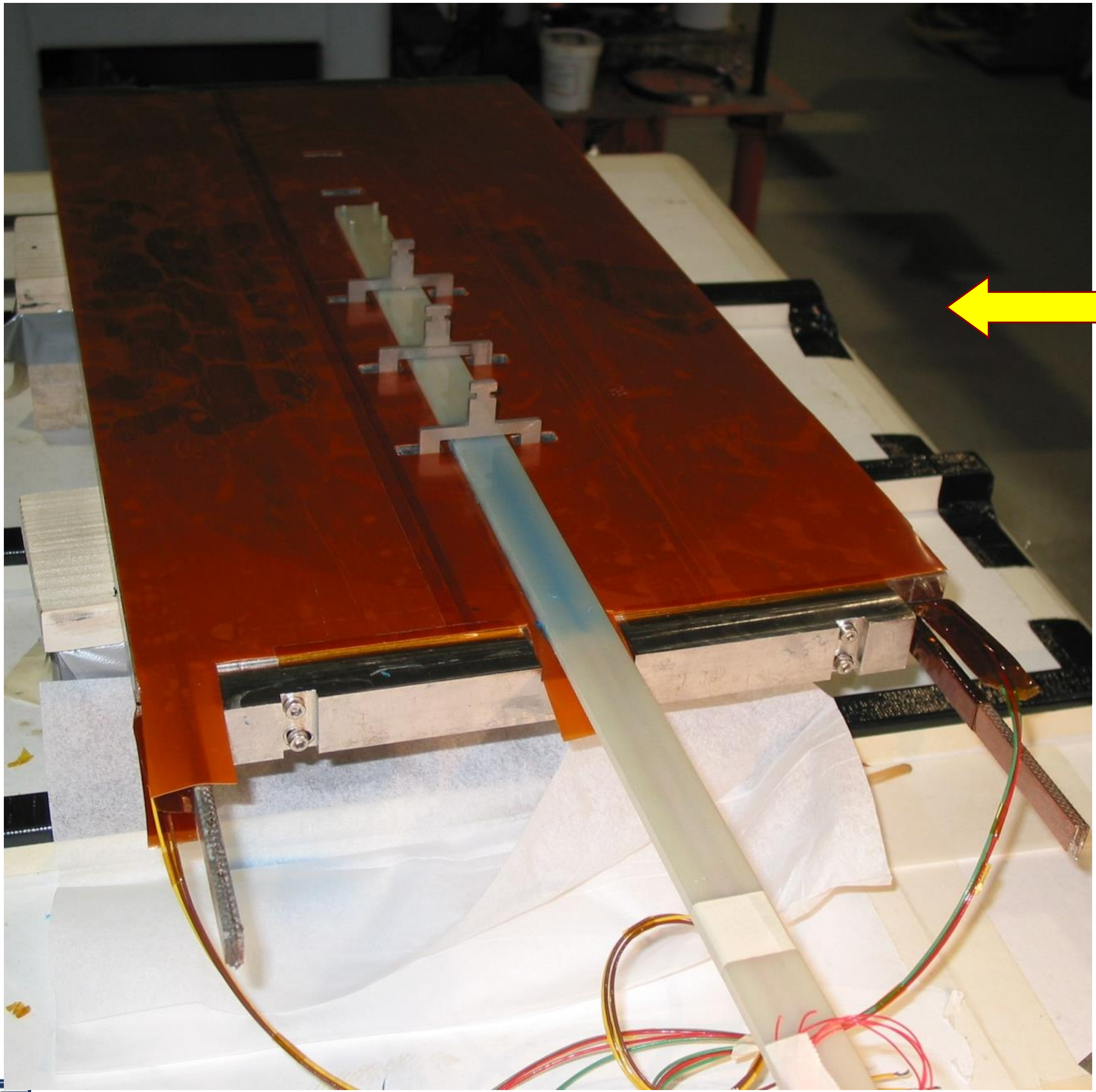
Splice Between a Pair of Coils



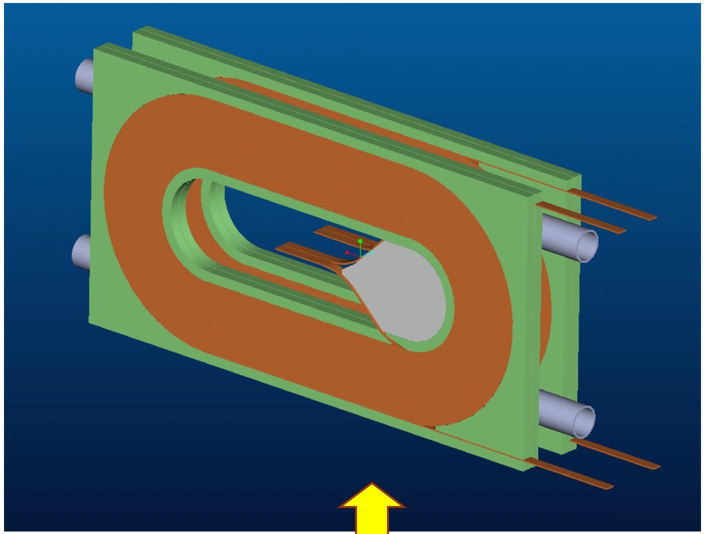


Splice in low field region having ample space (another unique feature of the common coil)

Complete Module for One Side

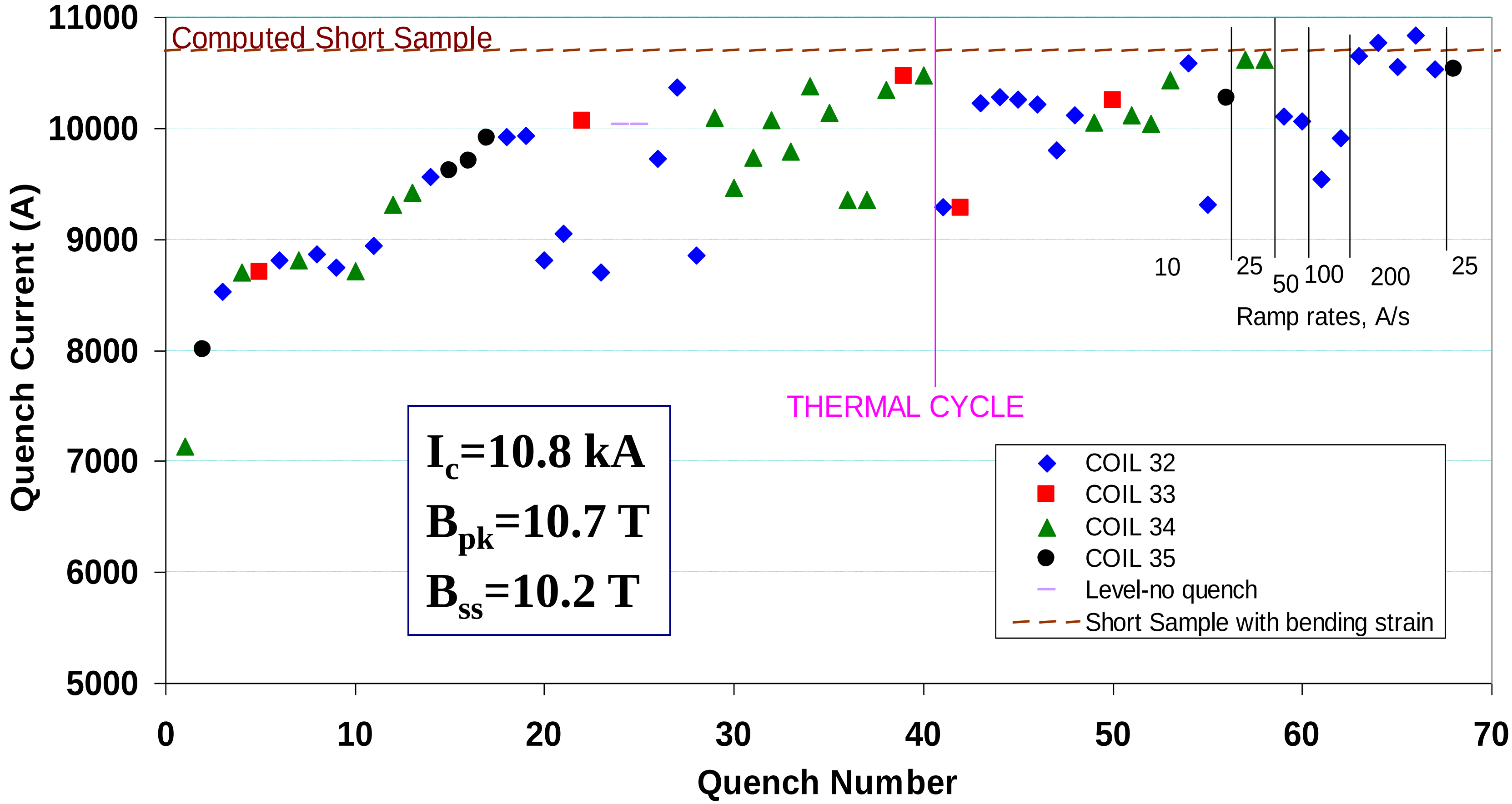


A completed simple coil module consisted of two coils, shunt lead, quench heaters, etc.



Two Pairs of Coil Modules in Common Coil Configuration

Quench Plot of BNL React & Wind Common Coil Dipole DCC017



- **Magnet slightly exceeded short sample after a number of quenches**
- **A record field (still) for "React & Wind" technology**

Single Aperture and Dual Aperture

"Block Designs"

Nb_3Sn Magnet Performance of Cosine theta and Block Designs

- **A significant number of Nb_3Sn magnets have been built**
- **Most are based on cosine theta designs but some on racetrack coil block design**
- **Compare the performance of cosine theta and block designs**
  - **Statistically speaking, generally block designs are reaching short sampler closer and faster**

Is there something inherently favorable in block designs (as compared to cosine theta designs) for high field Nb_3Sn magnets?

Differences between Single Aperture and Dual Aperture Block Designs

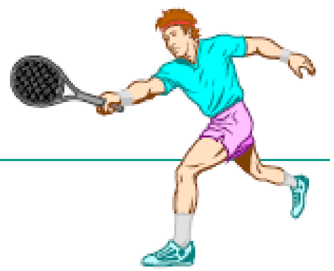
- **In single aperture block designs, flared ends is a necessity**
- **In dual aperture 2-in-1 collider magnets, common coil design is an option**
- **Common coil ends are simpler and shorter than the flared ends**

Why not flared ends for single aperture dipoles and simpler common coil for dual aperture collider dipoles?

Magnet R&D based on Common Coil Design

BERKELEY LAB

The Game Plan/Philosophy



Where we are?

- We are 10-15 years to the next machine
- We have 5-10 years to advance the supporting technologies to make a genuine impact on the cost or design of the future machine
- Magnets are the single most costly and critical technology component of the large hadron colliders

BERKELEY LAB

What should we do? Our Response

•Magnet design should have a longer term outlook (vision)

•This is the time to explore different approaches

Be innovative

Not only in the geometry, but the way we do magnet R&D

Develop an approach to give faster turn-around on R&D

Build "A Magnet R&D Factory"

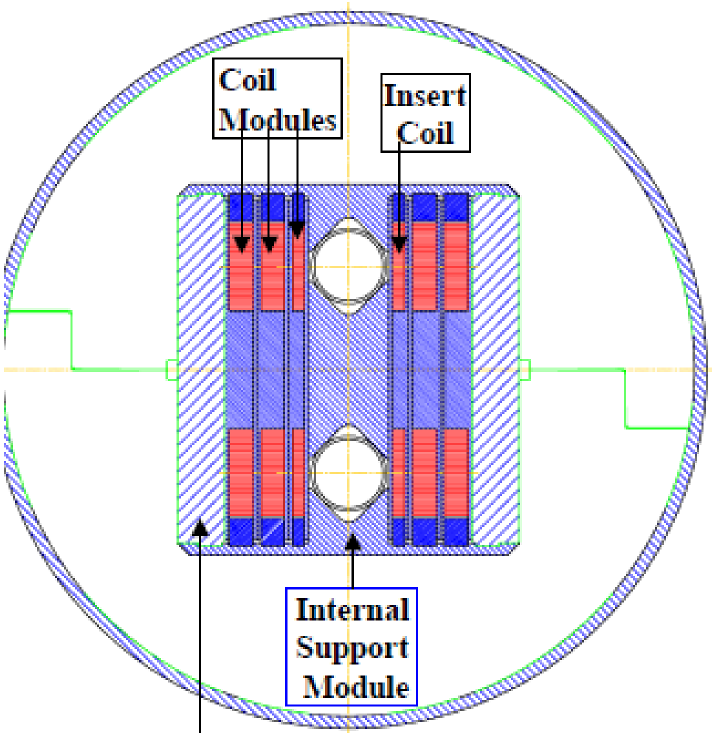
•Don't just build magnets - develop technology and build magnets to demonstrate the technology. Build "The Technology Magnets"

•Think that how this R&D will lead to accelerator-quality magnets (and demonstrate parts of it, whenever possible)

Lower cost, long magnets and large volume production

Accelerator and Fusion Research Division
Superconducting Magnet Program
BERKELEY LAB
Slide No. 4
A New Approach to Accelerator Magnet Design
Ramesh Gupta; June 2, 1998

A Modular Design for a New R&D Approach



- Replaceable coil module
- Change cable width or type
- Combined function magnets
- Vary magnet aperture
- Study support structure

Traditionally such changes required building a new magnet

Also can test modules off-line

This is our Magnet R&D Factory

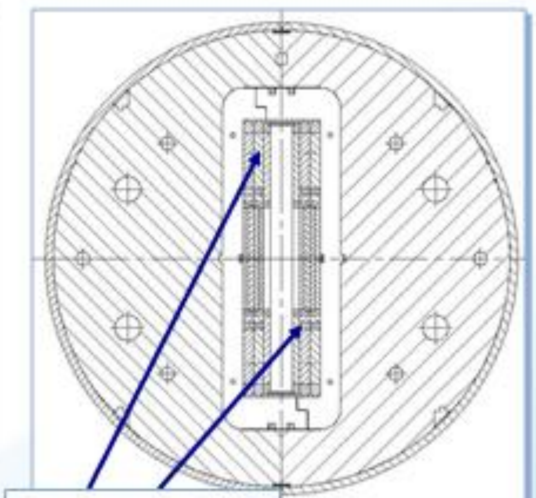
Fast Forward – After 17 Years

A New Way of Coil and Magnet R&D

Unique features of BNL's common coil dipole: large open space for inserting & testing "coils" without any disassembly (fast turn around, low cost)

- Build/Replace a coil, not the entire magnet for developing technology

Examples: (a) Pole coils for initial demo of accelerator type dipole
(b) New conductor, new insulation, variation in techniques
(c) HTS coil for high field HTS/LTS hybrid dipole



Insert Coils

Modular design allows coils of different width, etc.

Magnetic Design Optimization

1. Field Quality
2. Conductor Requirements

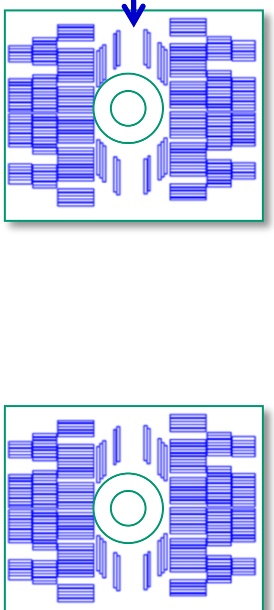
Obtaining Accelerator-type Field Quality Block Dipole Designs

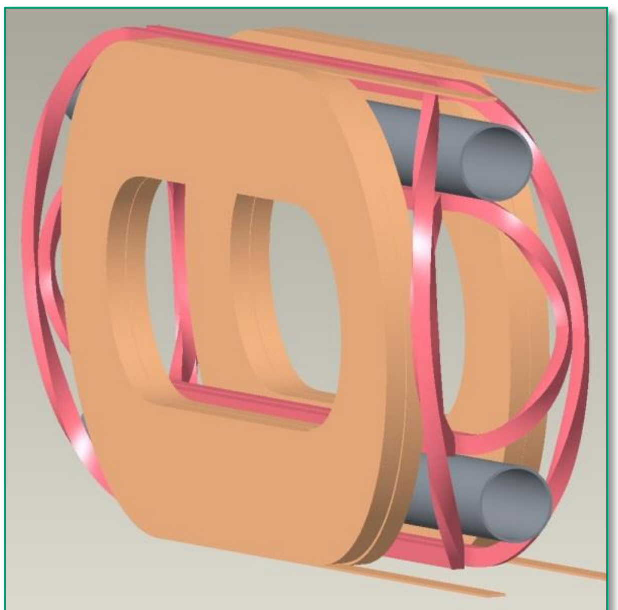
- **Require "pole coils" which must clear beam tube in the ends**

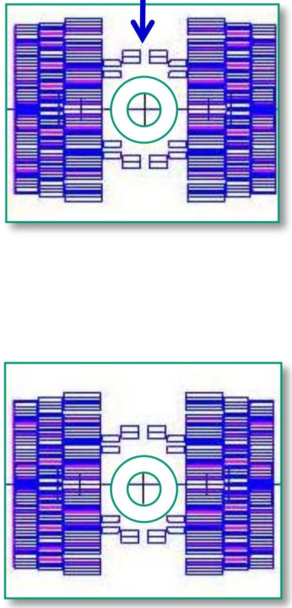
(a) Pole coils like midplane coils of cosine theta dipoles (easy bend)

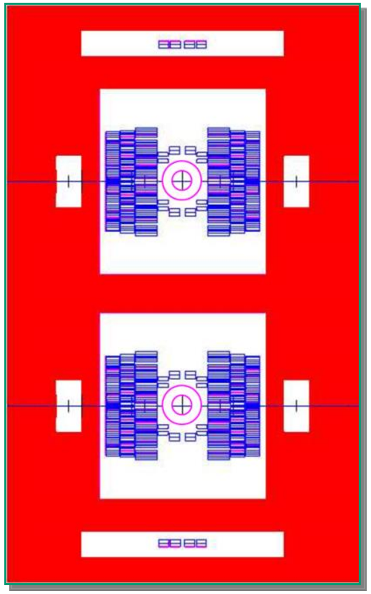
OR

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



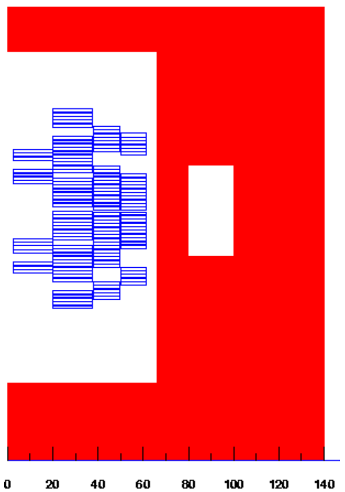




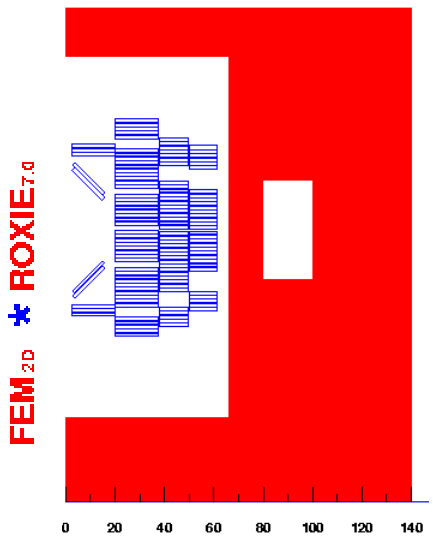


Slightly more complicated, but still much simpler and shorter than flared ends

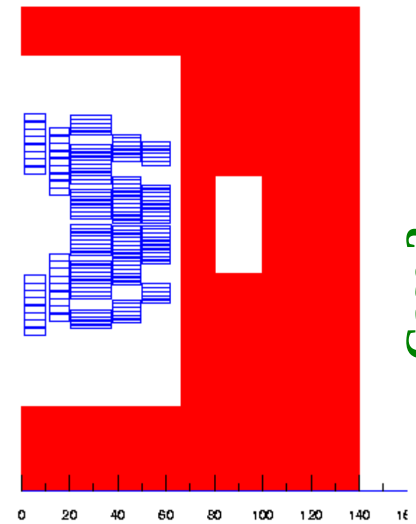
A Few Options for Good Field Quality Configurations



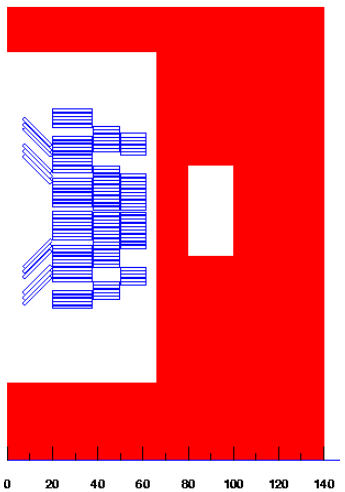
Case 1a



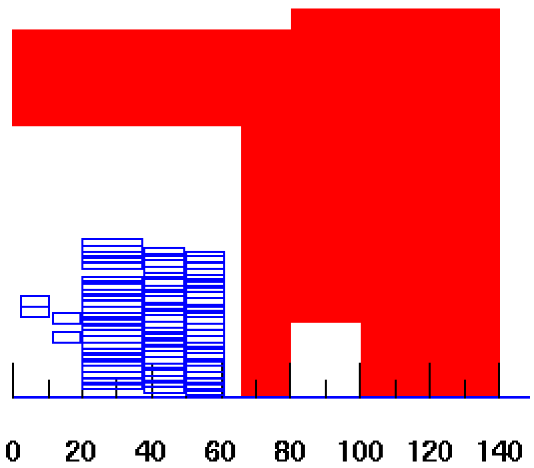
Case 1c

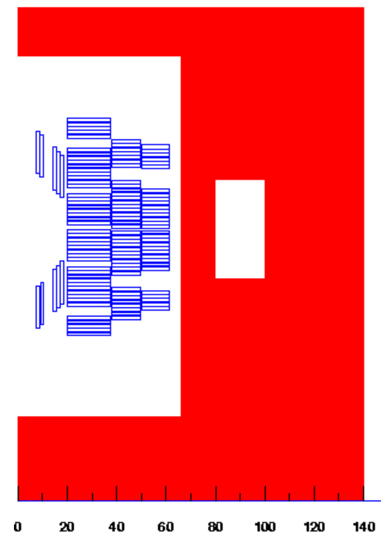


Case 2



Case 1b





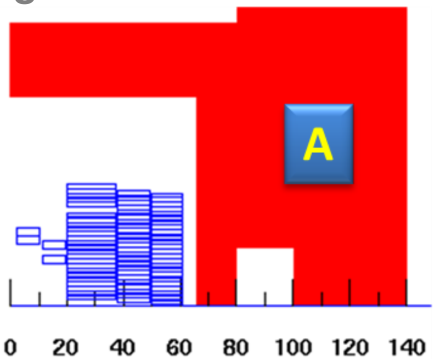
Case 3

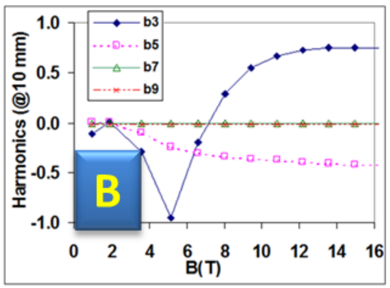
All cases optimized for 10^{-4}

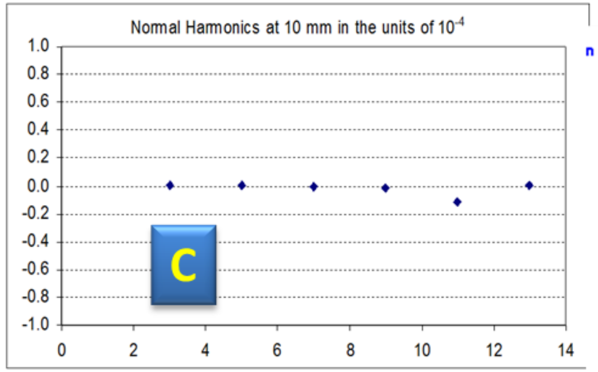
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Good Field Quality (few parts in 10^{-4}) in Common Coil Designs





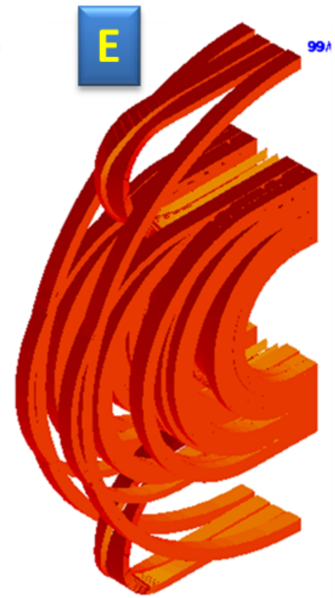


(from 1/4 model)

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
b13:	0.00932	b14:	0.00000	b15:	0
b16:	0.00000	b17:	-0.00049	b18:	0

D



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	0.0	0.00
15	0.0	0.00
16	0.0	0.00
17	0.00	0.00
18	0.00	0.00

F

(a) 1/4 cross section in one aperture
(b) saturation induced-harmonics
(c) plot of geometric harmonics
(d) values of geometric harmonics
(e) optimized end geometry
(f) end harmonics

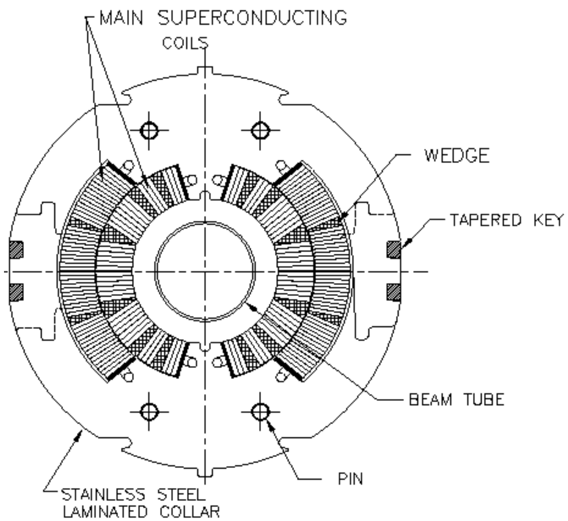
Optimization for good field quality in a 15 T Nb_3Sn common coil design (coil aperture 40 mm, reference radius 10 mm).

More details in extra slides

Coil Optimization in Block Designs (including in common coil)

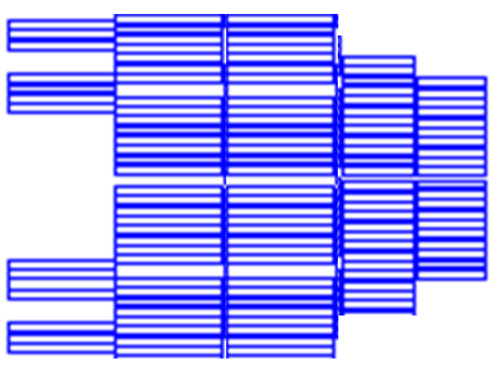
- **In cosine theta design, the amount of conductor that can be put is constrained between 0 degree to 90 degree of cylinder between coil radii a_1 and a_2**
  - **Thus for a typical magnetic design, it limits how good or bad one can be**
- **Multi-layer block designs (including common coil design) gives a designer more freedom to expand independently horizontally or vertically**

COS(θ)

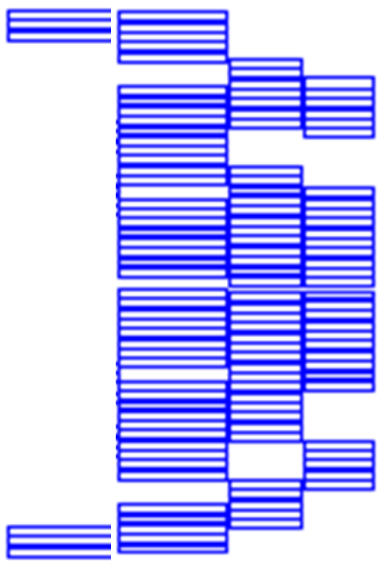


SSC 50 mm X-section

More Efficient Design



Less Efficient Design

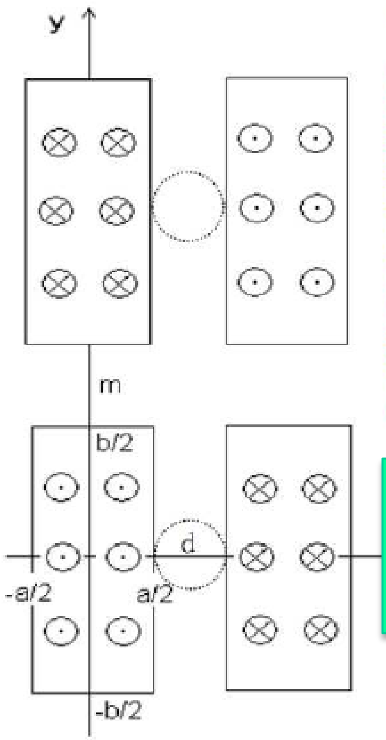


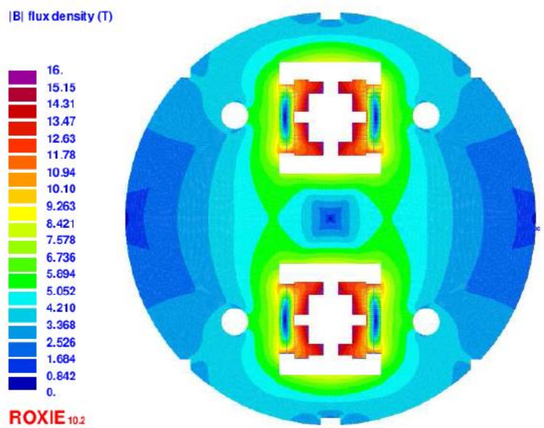
Some Analytical Tool/Guidance for Optimizing Common Coil Design

Magnetic Design Study of the High Field Common Coil Dipole for High Energy Accelerators

Qingjin Xu

ASC2014





50 mm, 15 T Nb_3Sn design for IHEP

Courtesy: Qingjin Xu

Fig. 1 Analytical modeling of the common coil configuration: The four current-carrying blocks represent the two racetrack coils with opposite current directions. The coil width and height are a and b respectively. The bore diameter is d and the bending radius of the coil is $m/2$.

$$B_x = \frac{\mu_0 I}{2\pi}\frac{y-y_0}{(x-x_0)^2+(y-y_0)^2} \qquad (1)$$

$$B_y = \frac{\mu_0 I}{2\pi}\frac{x-x_0}{(x-x_0)^2+(y-y_0)^2} \qquad (2)$$

By integrating the equation (1) and (2) in the four current-carrying blocks in Fig. 1, the magnetic field in the twin-aperture of the common coil configuration can be derived as

$$B_x = \frac{\mu_0 I}{4\pi}\Bigg[\int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(x-x_0)^2+(y+\frac{b}{2})^2}{(x-x_0)^2+(y-\frac{b}{2})^2}dx_0 - \int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(a+d-x-x_0)^2+(y+\frac{b}{2})^2}{(a+d-x-x_0)^2+(y-\frac{b}{2})^2}dx_0 + \int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(x-x_0)^2+(m+b-y+\frac{b}{2})^2}{(x-x_0)^2+(m+b-y-\frac{b}{2})^2}dx_0 - \int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(a+d-x-x_0)^2+(m+b-y+\frac{b}{2})^2}{(a+d-x-x_0)^2+(m+b-y-\frac{b}{2})^2}dx_0\Bigg] \qquad (3)$$

and

$$B_y = \frac{\mu_0 I}{4\pi}\Bigg[\int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(x+\frac{a}{2})^2+(y-y_0)^2}{(x-\frac{a}{2})^2+(y-y_0)^2}dy_0 + \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(\frac{3a}{2}+d-x)^2+(y-y_0)^2}{(\frac{a}{2}+d-x)^2+(y-y_0)^2}dy_0 - \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(x+\frac{a}{2})^2+(m+b-y-y_0)^2}{(x-\frac{a}{2})^2+(m+b-y-y_0)^2}dy_0 - \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(\frac{3a}{2}+d-x)^2+(m+b-y-y_0)^2}{(\frac{a}{2}+d-x)^2+(m+b-y-y_0)^2}dy_0\Bigg] \qquad (4)$$

Assume the bending radius of the racetrack coil is large enough that the cross-talk of the magnetic field between the two apertures are negligible, by replacing the x with $(a+d)/2$ and y with 0 in equation (4), we get the main dipole field of the common coil configuration as

$$B_y = \frac{\mu_0 I}{2\pi}\int_{-\frac{b}{2}}^{\frac{b}{2}} ln\left(\frac{(a+\frac{d}{2})^2+{y_0}^2}{(\frac{d}{2})^2+{y_0}^2} + \frac{\left(\frac{d}{2}\right)^2+(m+b-y_0)^2}{\left(a+\frac{d}{2}\right)^2+(m+b-y_0)^2}\right)dy_0 \qquad (5)$$

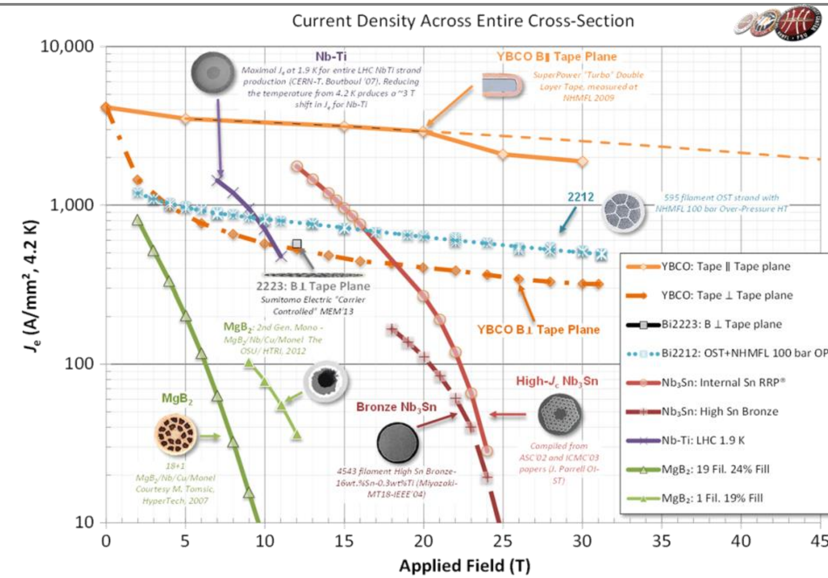
High Field Hybrid Designs (with ReBCO)

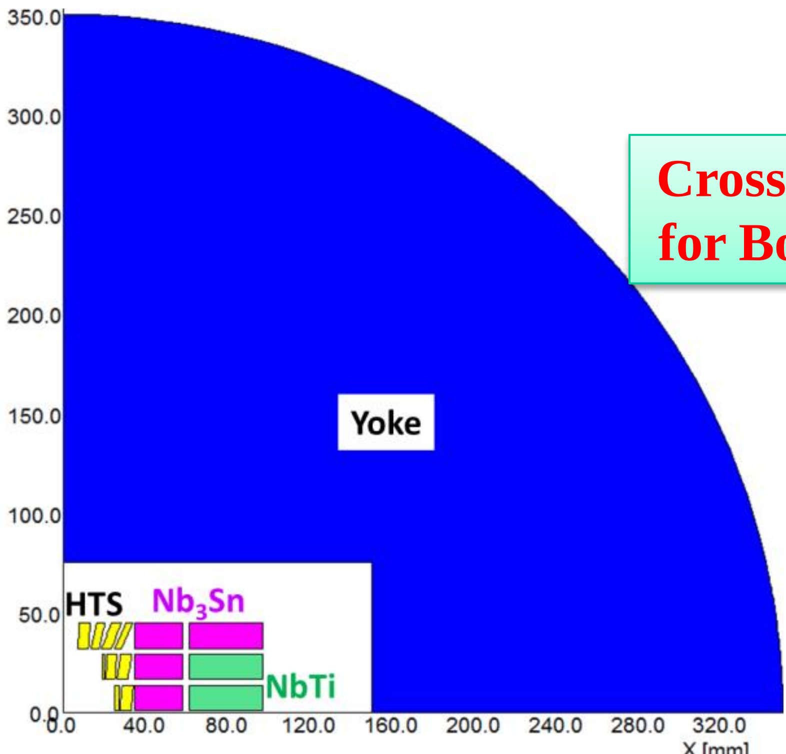
Bi2212 in extra slides

HTS/LTS High Field (>20 T) Hybrid Dipole

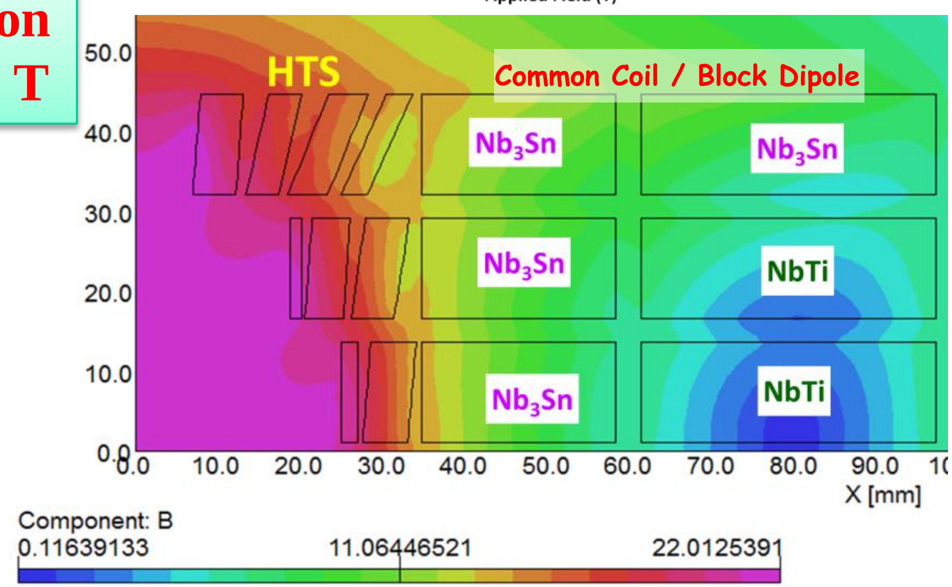
Hybrid Design:

- HTS in high field region
  - contributing the final 4-8 T field
- LTS (Nb_3Sn/NbTi) in lower field region
  - to reduce overall magnet cost





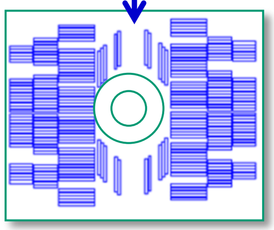
Cross-section for Bo = 21 T

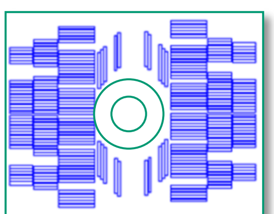


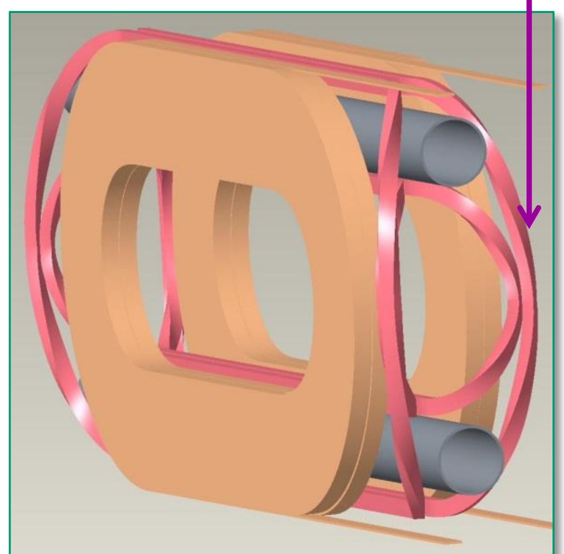
Windings for Lower Magnetization

Narrow side of the HTS tape aligned perpendicular to the field produces lower magnetization (proportional to the width) and higher critical current

In 2-in-1 common coil design, conductor in HTS coils bends in easy direction





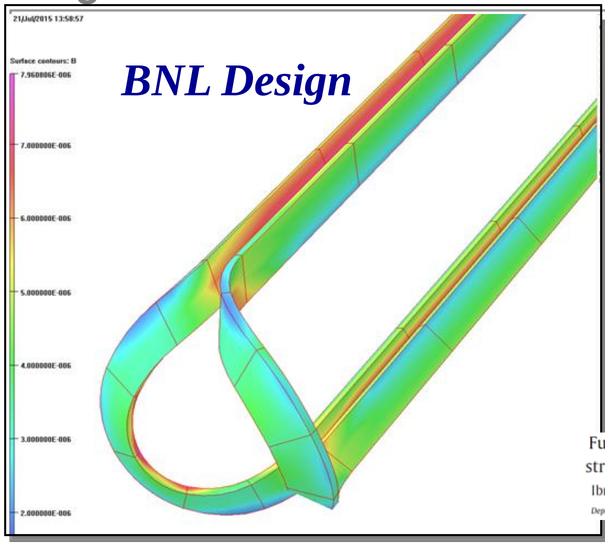


Common coil design provides easy segmentation between HTS & LTS

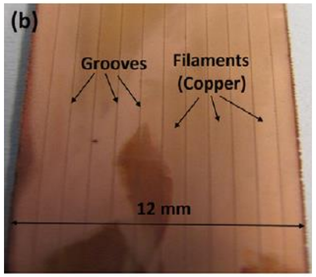
Complementary Nature of BNL and CERN HTS Magnet Programs

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division



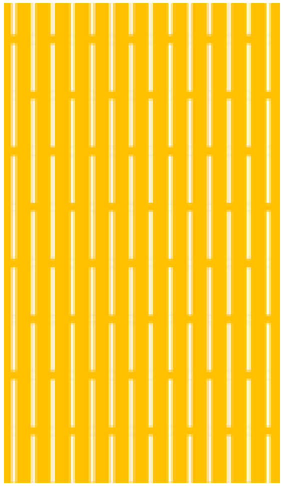
Cable options



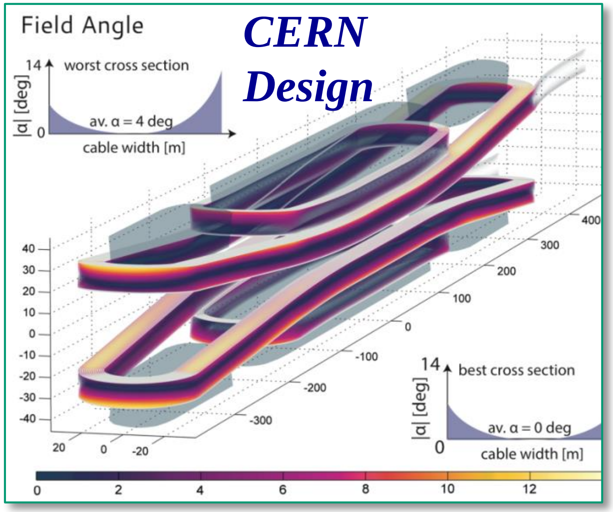
Fully filamentized HTS coated conductor via striation and selective electroplating

Ibrahim Kesgin, Goran Majkic, Venkat Selvamanickam*

Department of Mechanical Engineering and Texas Center for Superconductivity, University of Houston, Houston, TX 77204, USA

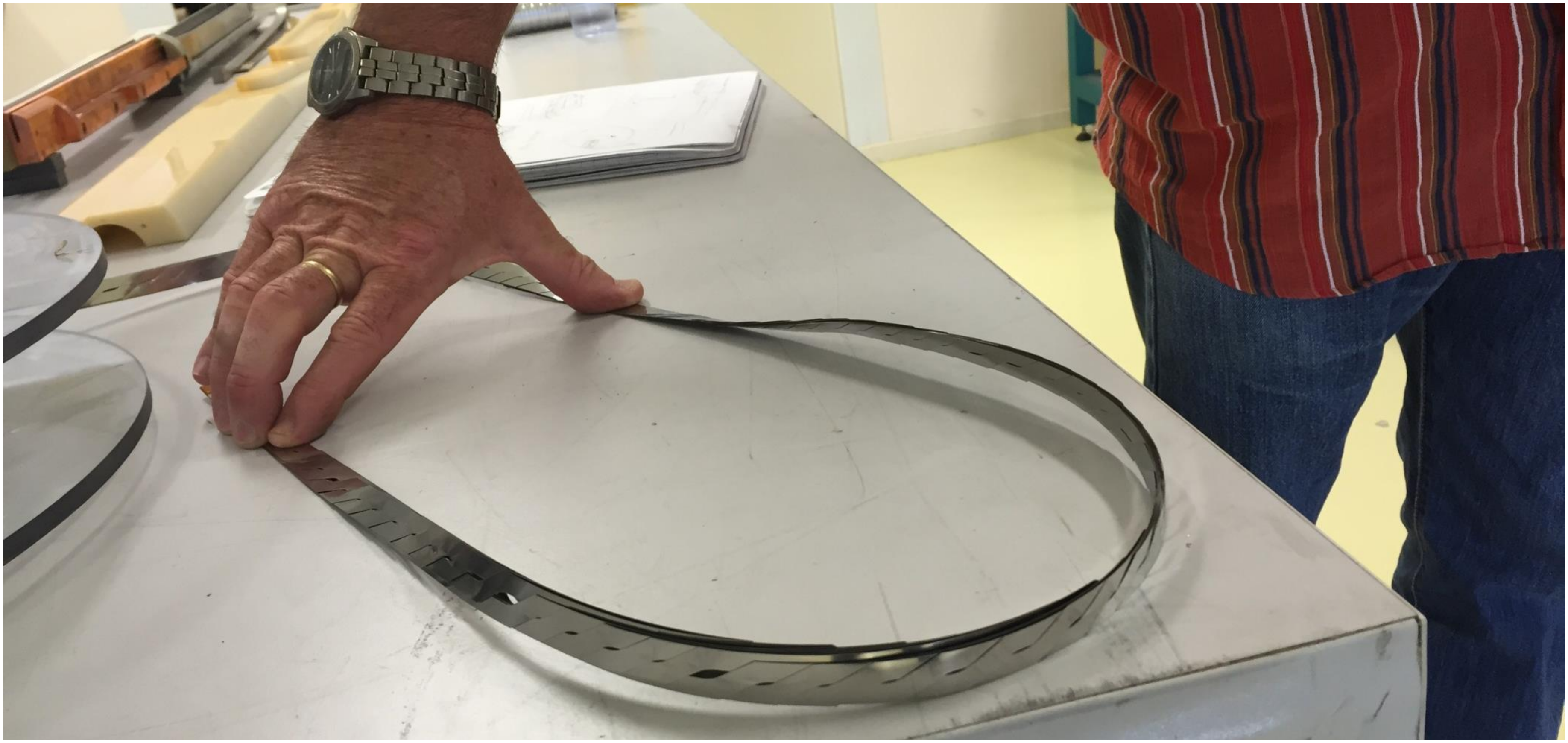


Bonded wire production line



- **BNL and CERN are both pursuing ReBCO technology, but presently with different designs**
- **BNL bends tape in easy direction in ends (allowed by common coil design); CERN bends in hard direction**
- **For >10 kA, BNL is exploring simple multi-tape (multi-tape for higher current and reliability) and striation to further reduce magnetization) or CORC cable (since large radii allowed in common coil); CERN is focusing on Roebel cable**

Common Coil Ends for Aligned Roebel Cable



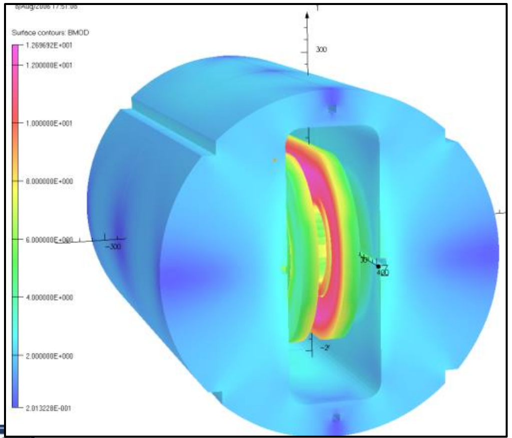
Time needed to try the idea: <5 minutes (Yesterday @CERN)

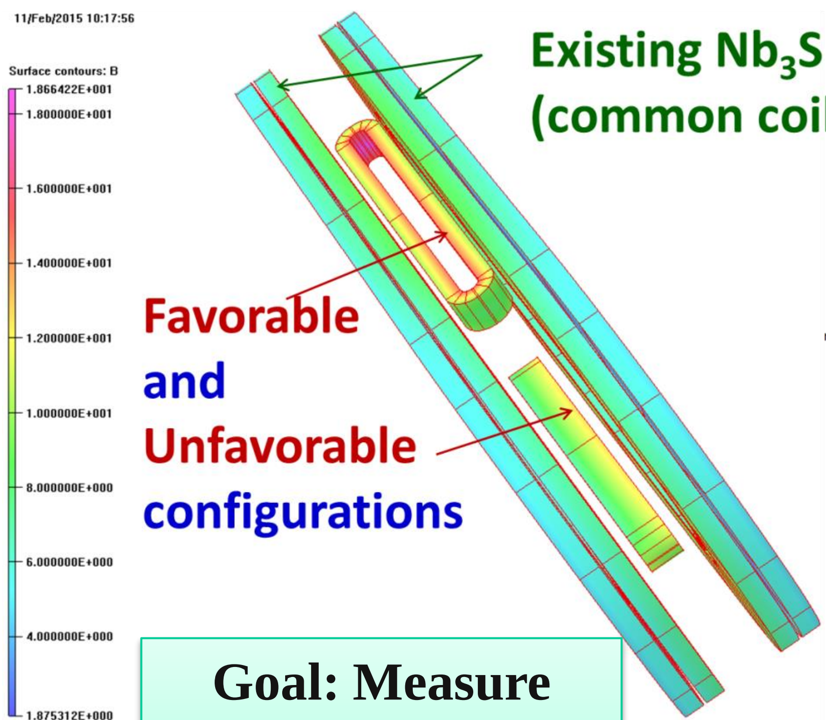
Test of Principle in A Real Magnet

(measure and compare magnetization in two configurations)

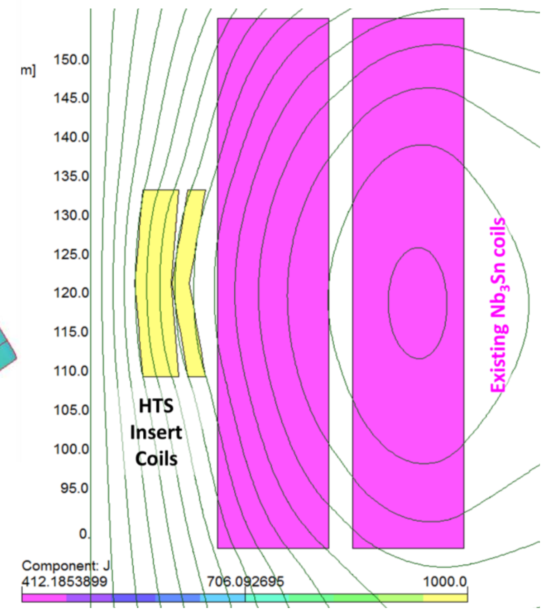
BNL Common Coil Dipole with a large open space

- HTS coils can be inserted without opening the magnet





PBL/BNL
Phase II
STTR



Goal: Measure magnetization due to HTS coils in two configurations

SUMMARY

- For dual aperture block dipoles, 2-in-1 "Common Coil Design" offers an attractive possibility for high field collider magnets.

- R&D block dipole magnets have generally produced Nb_3Sn magnets closer to the short samples. Test results at BNL, LBL and elsewhere supports that. Common coil is likely to produce magnets closer to short sample and hopefully having higher reliability.

- Thanks to simpler geometry, fewer coils (half), need for less support structure, etc., common coil design is also likely to produce lower cost magnets.

- Common coil modular design also offers an opportunity to perform, lower-cost, fast turn-around R&D. Such R&D is needed at this stage to carry out systematic and innovative R&D.

Extra Slides

Field Quality

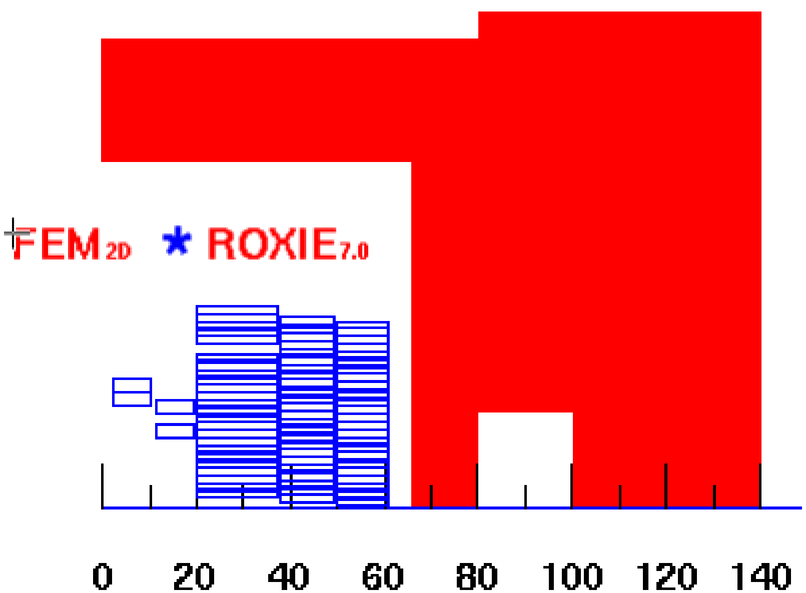
Optimization of Magnetic Design

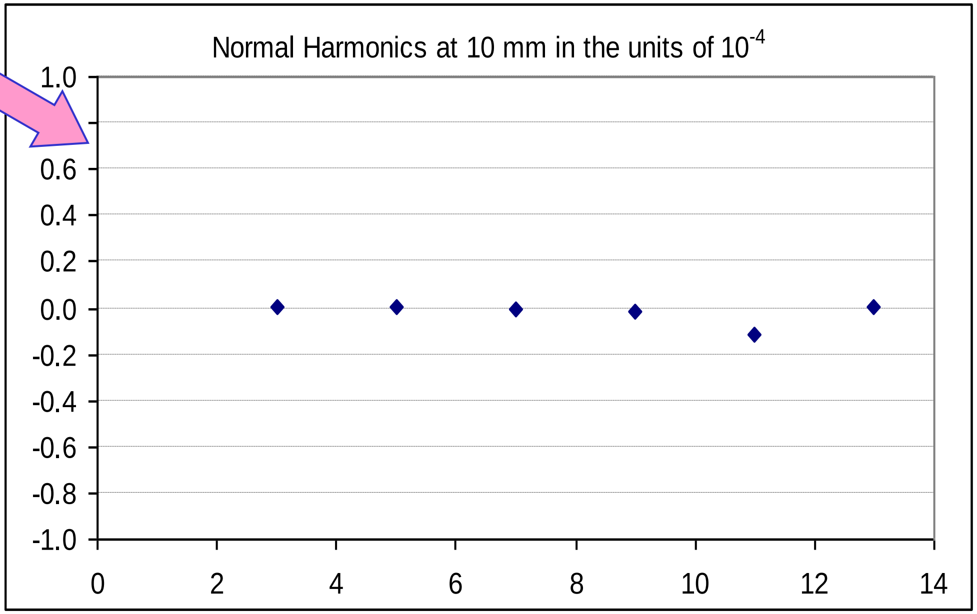
Good field quality design developed for:

- **Geometric harmonics**
- **Saturation-induced harmonics**
- **End harmonics**

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):

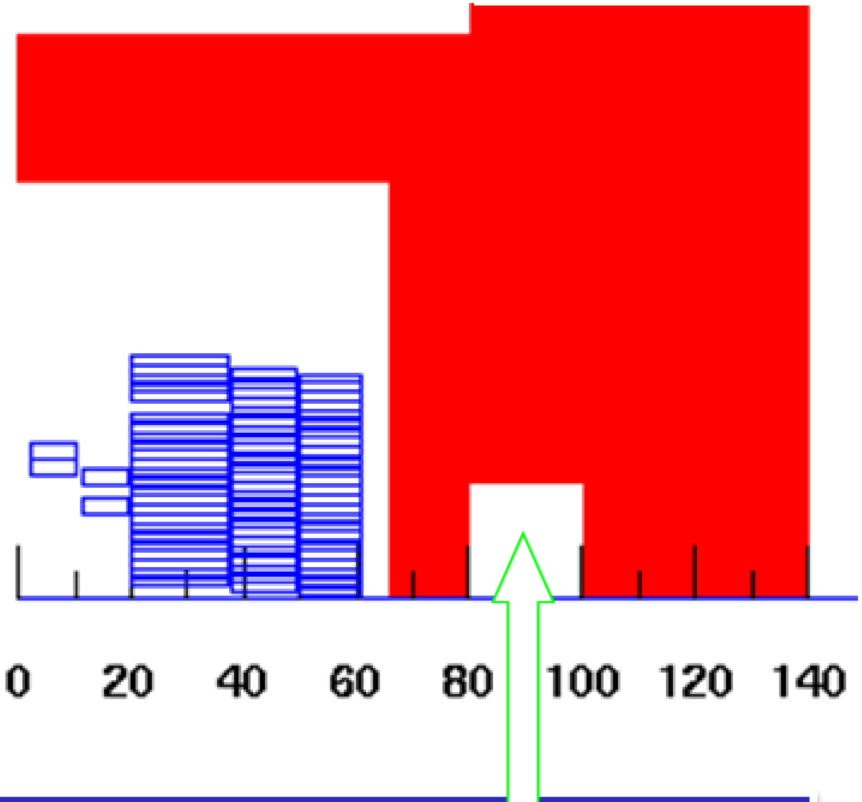
b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

Horizontal coil aperture:

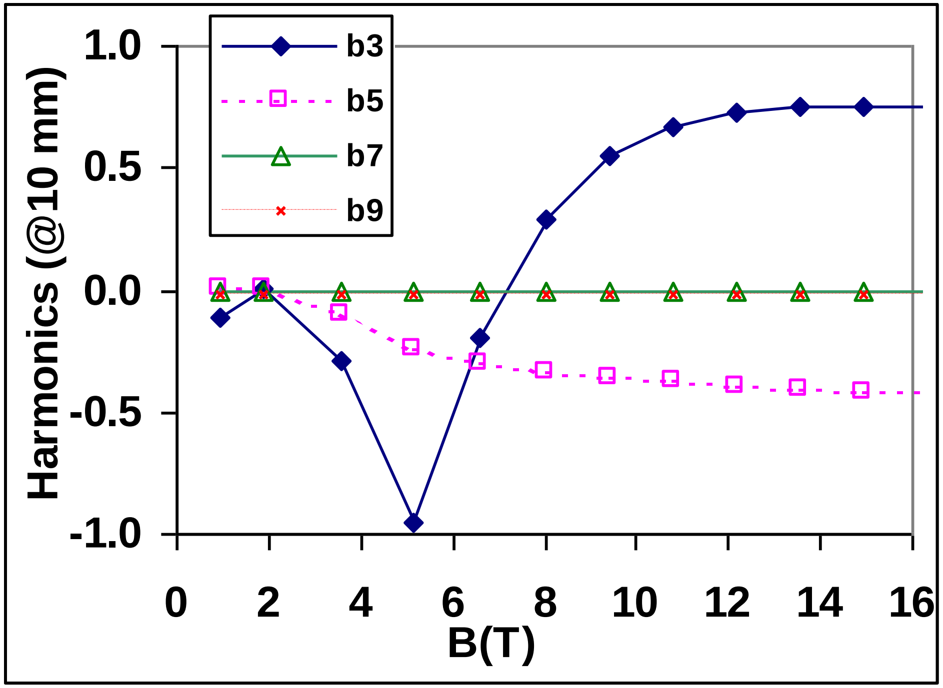
40 mm

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

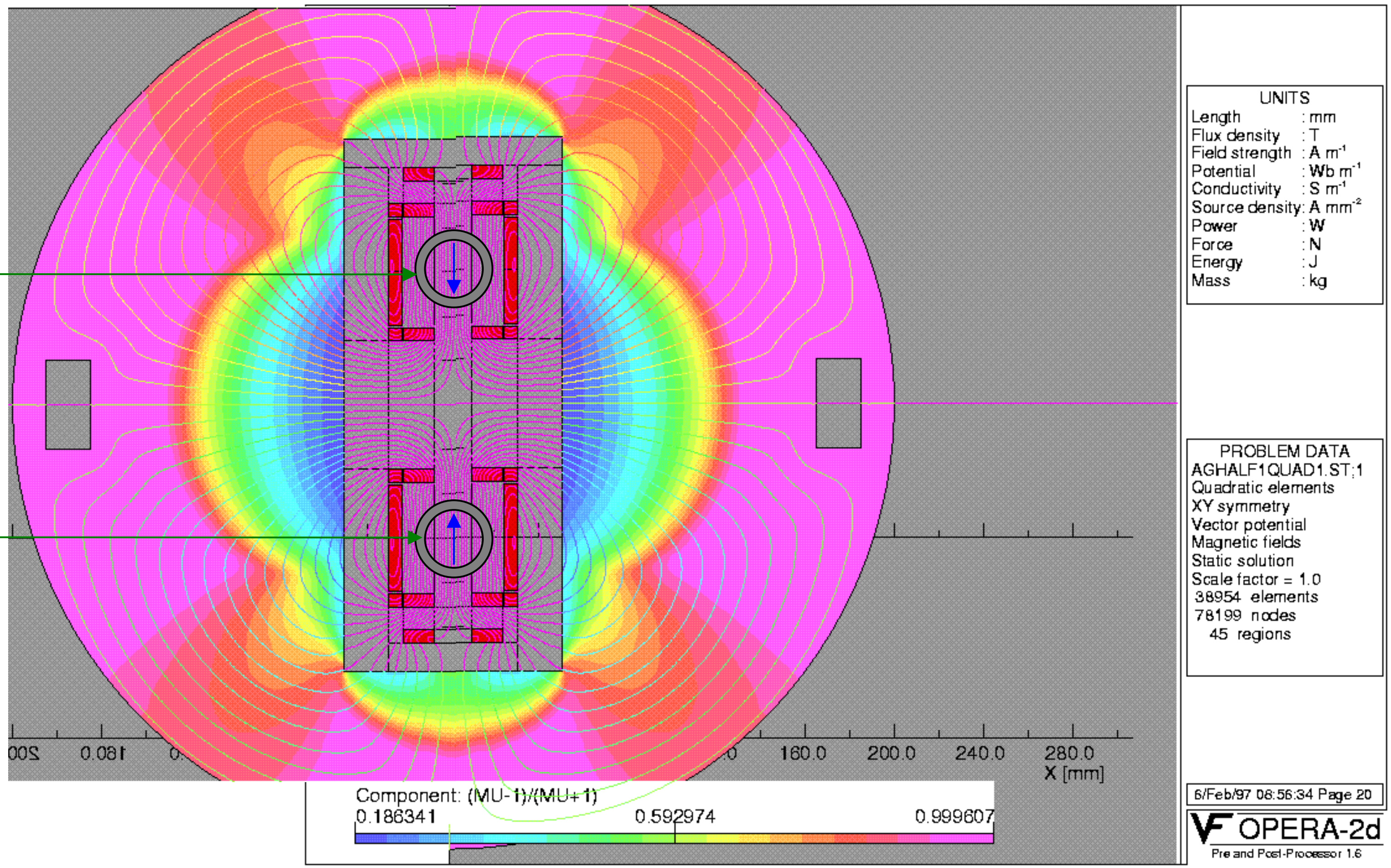


Low saturation-induced harmonics (within 1 unit)

Field Lines at 15 T in a Common Coil Magnet Design

Aperture #1

Aperture #2

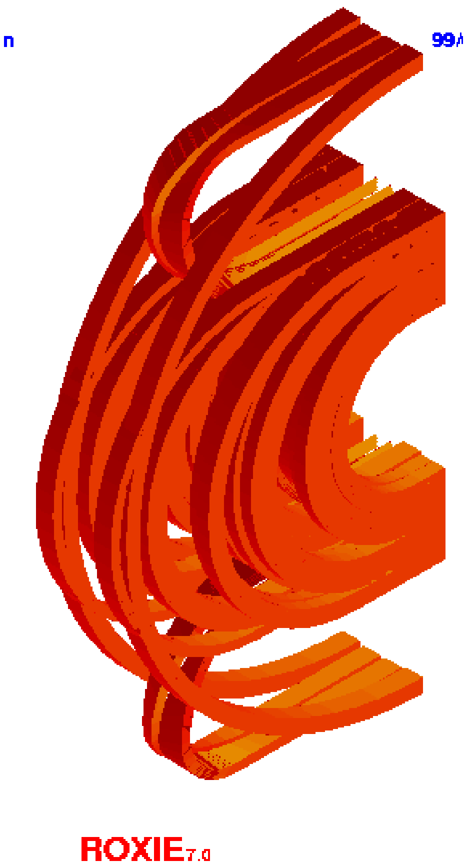


For most optimization, ¼ of coil X-section is sufficient

Demonstration of Good Field Quality (End Harmonics)

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

(Very small)

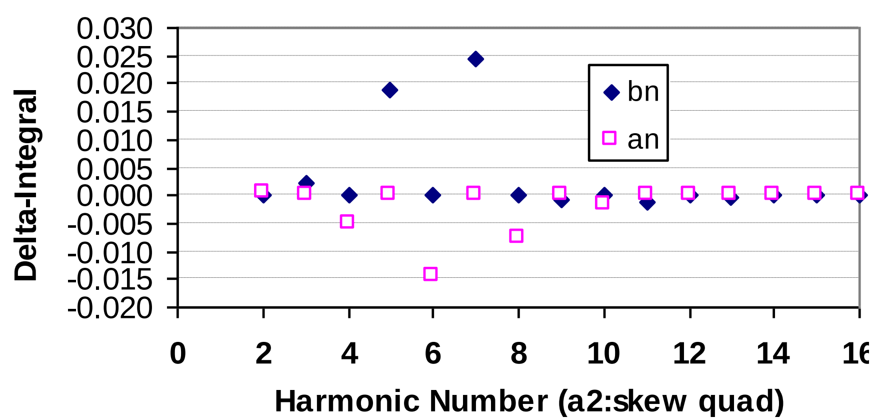


End harmonics in Unit-m

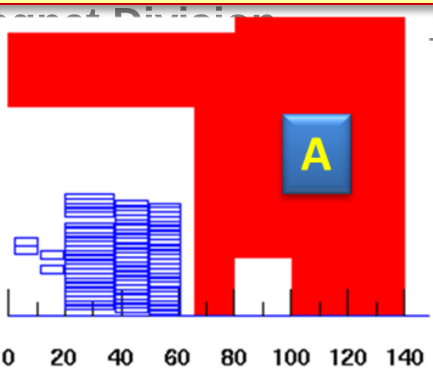
n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

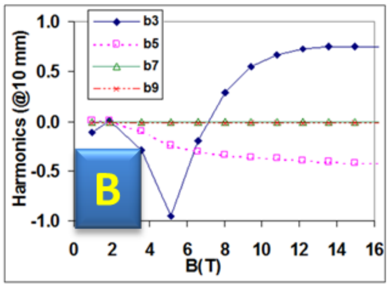
Contribution to integral (a_n,b_n) in a 14 m long dipole (<10^{-6})

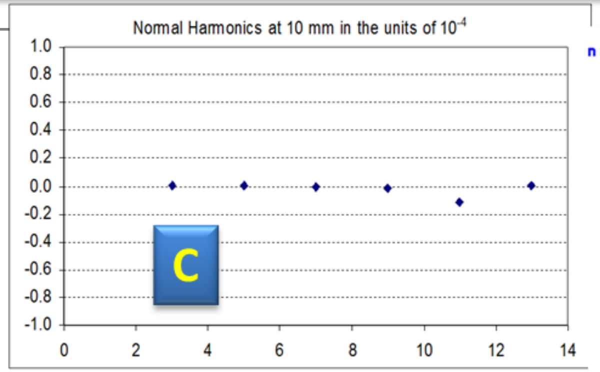
n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000



Good Field Quality Common Coil Designs







(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
b13:	0.00932	b14:	0.00000	b15:	0
b16:	0.00000	b17:	-0.00049	b18:	0

D

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	0.0[illegible]	0.00
15	0.0[illegible]	0.00
16	0.0[illegible]	0.00
17	0.00	0.00
18	0.00	0.00

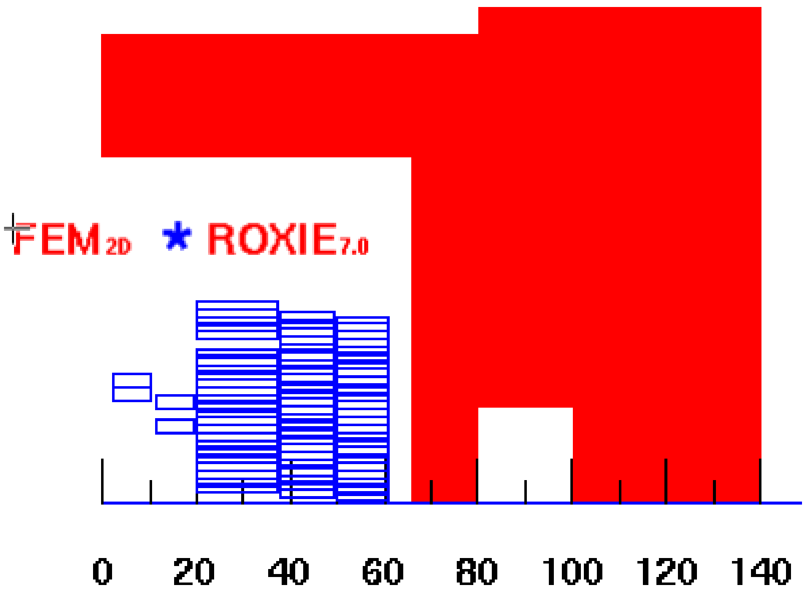
F

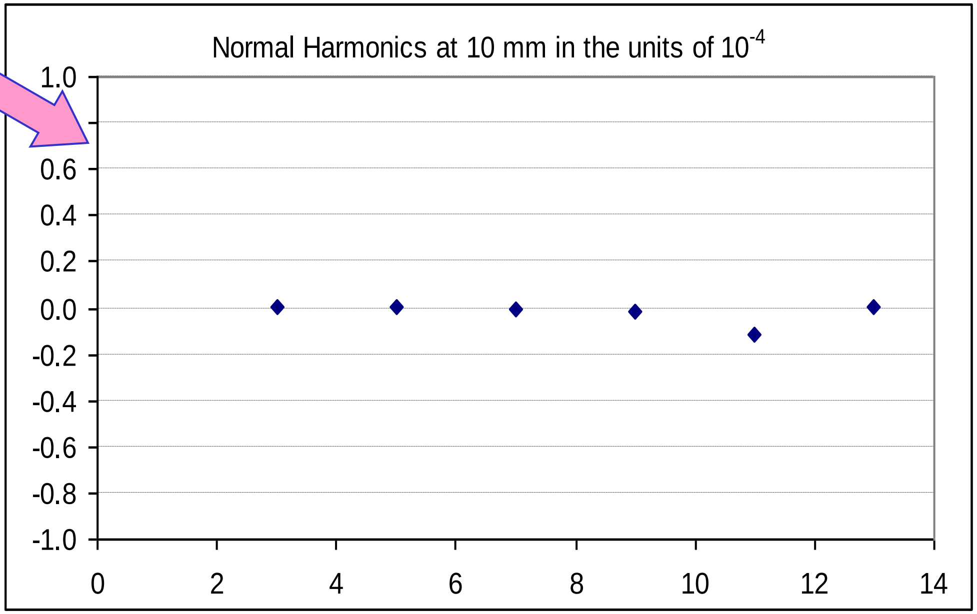
Optimization for good field quality in a 15 T Nb_3Sn common coil design (coil aperture 40 mm, reference radius 10 mm).

(a)1/4 of magnet cross section in one aperture, (b) normal saturation induced-harmonics, (c) plot of geometric harmonics, (d) values of geometric harmonics, (e)optimized end geometry, and (f) end harmonics.

A Good Field Quality Design for Geometric Harmonics

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





Horizontal coil aperture:
40 mm

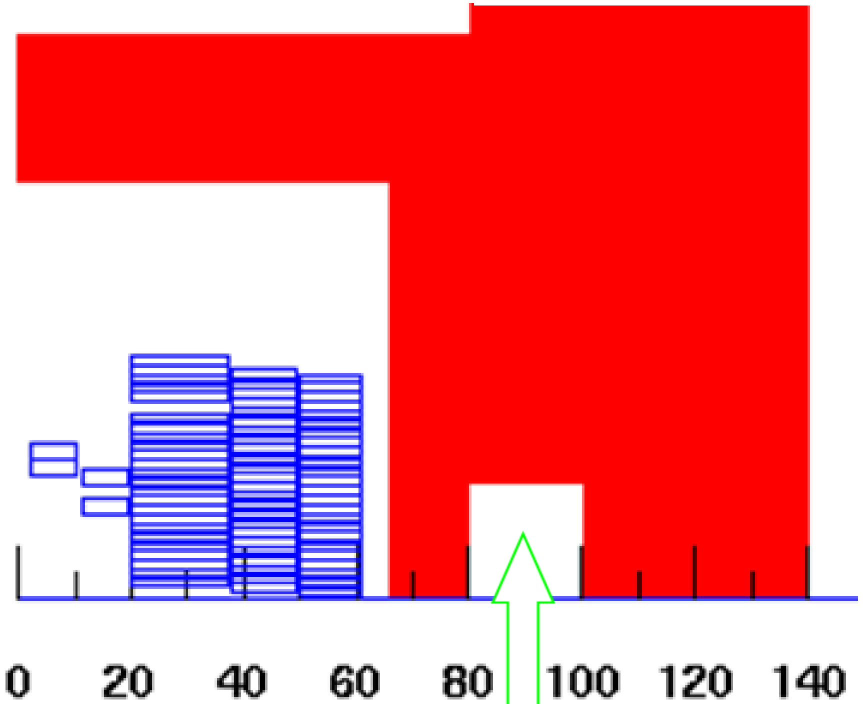
(from 1/4 model)

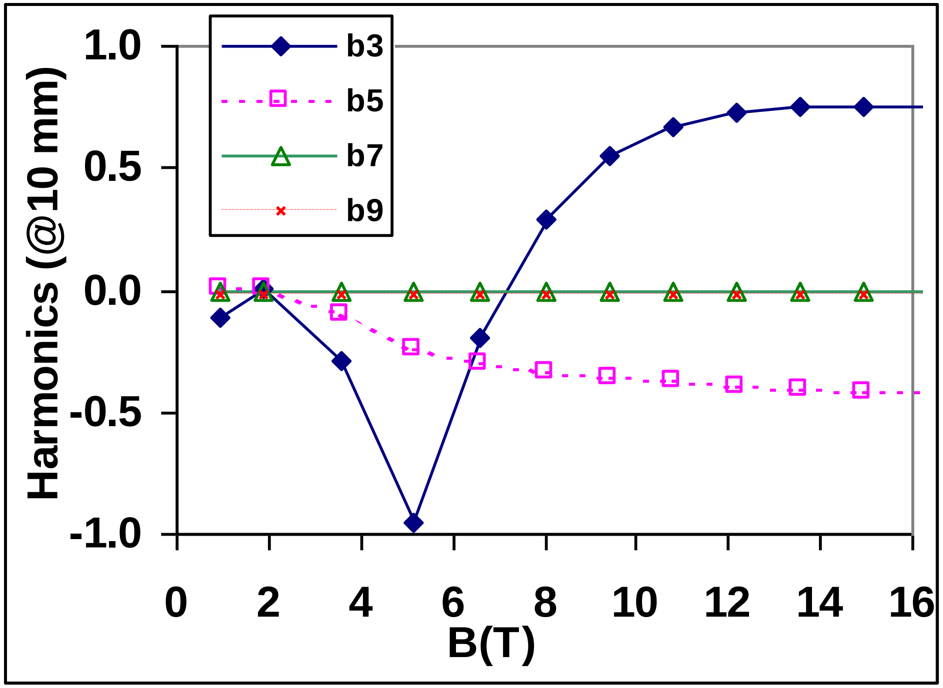
MAIN FIELD: -1.86463 (IRON AND AIR):

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

A Good Field Quality Design for 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)

A Good Field Quality for End Harmonics

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

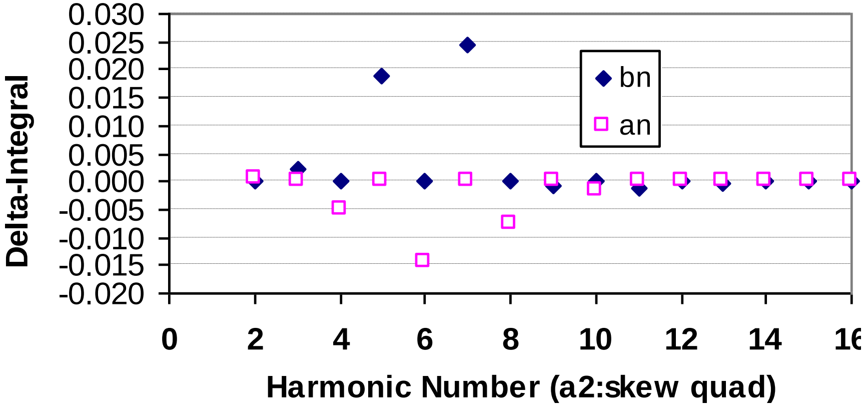
(Very small)

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 ($<10^{-6}$)

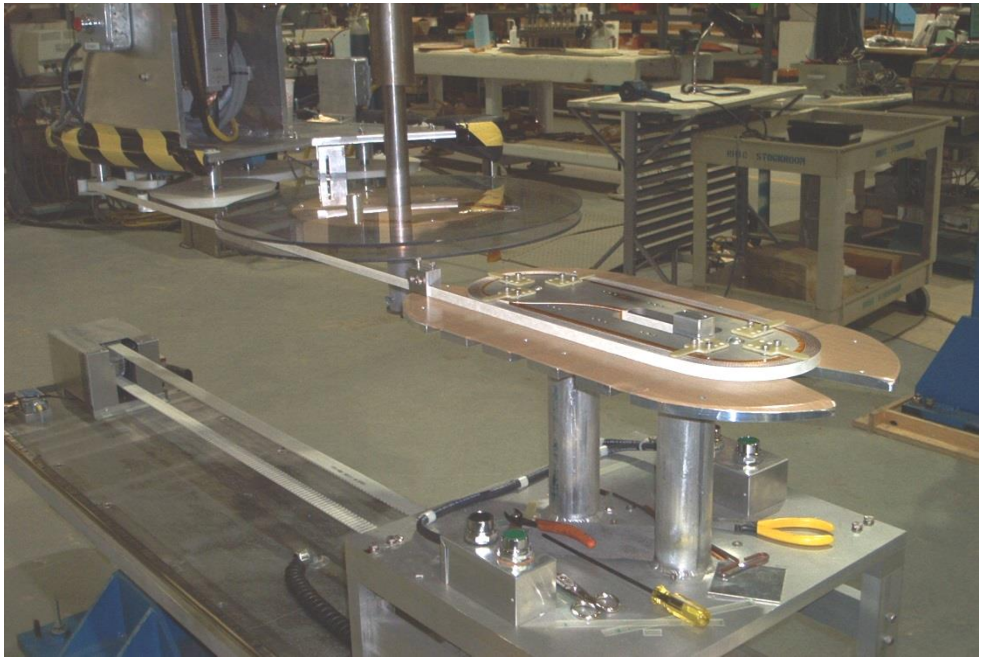
n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000



High Field Hybrid Designs

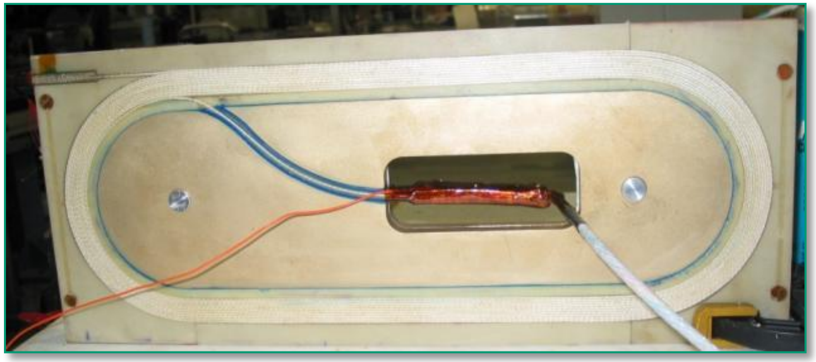
(with Bi2212)

Automatic Coil Winder : A Key Component in Developing "React & Wind" Technology



Each part and step in this new automatic coil winder is carefully designed to minimize the potential of bending degradation to brittle superconductors during the winding process. The machine is fully automated and computer controlled to minimize uncontrolled errors (human handling). All steps are recorded to carefully debug the process, as and if required.

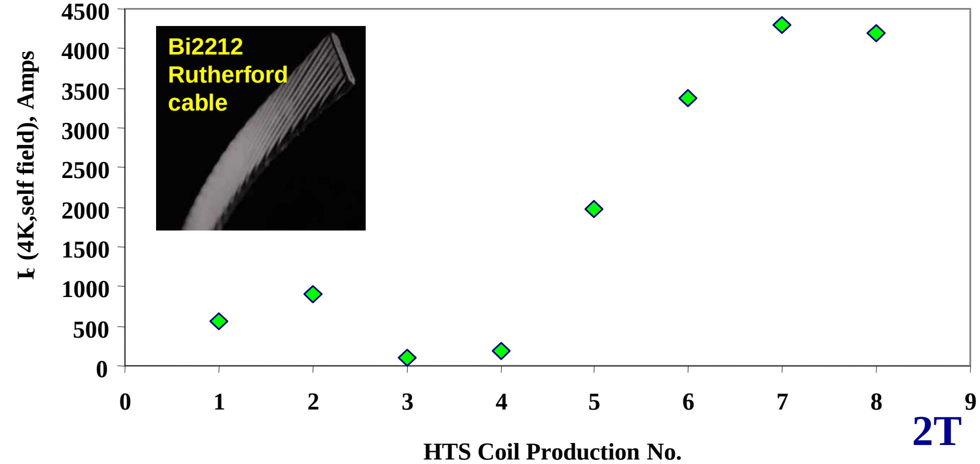
Bi2212 Common Coil Dipole at BNL
(with React & Wind Bi2212 Rutherford Cable)



Bi2212 "React & Wind" coils
(8 coils, 5 magnets)

Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)



Initial goal was to insert these HTS coils in Nb_3Sn common coil dipole for a demo of hybrid high field dipole.

Funding & work stopped ~2005

Bi2212 HTS Coils and Magnets @ BNL

TABLE II

COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand)	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag	74 mm spacing Common coil	182	177 [80]	0.045
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370	215 [143]	0.95
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands	2 HTS, 4 Nb_3Sn coils (total 6 coils)	4200	272 [212]	1.84

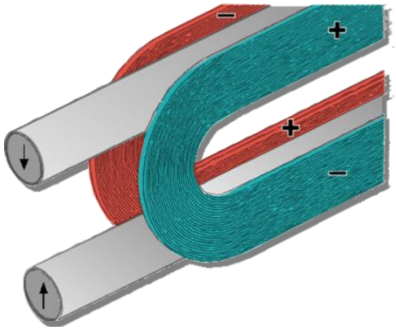
BNL pursued "React & Wind" technology for Bi2212

Eight coils and five magnets were built at BNL with Rutherford Bi2212 Cable (Showa/LBNL)

Slides on Developing Higher Field, Lower Cost Collider Magnets

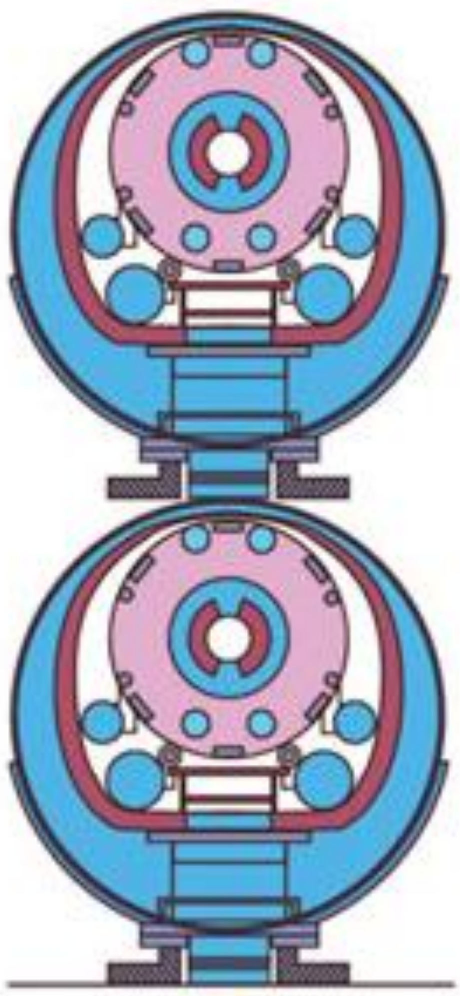
Overview of BNL Program Vision

- Develop a common coil design with the dual goal of improving performance and reducing cost
- Demonstrate 16 T Nb_3Sn accelerator quality dipole; build ReBCO HTS coils and integrate them with Nb_3Sn coils for ~20 T hybrid dipole
- Use a unique BNL magnet for testing coils at high fields – fast turn around, lower cost – ideal for advancing technology both for systematic optimization & for high risk, high reward R&D

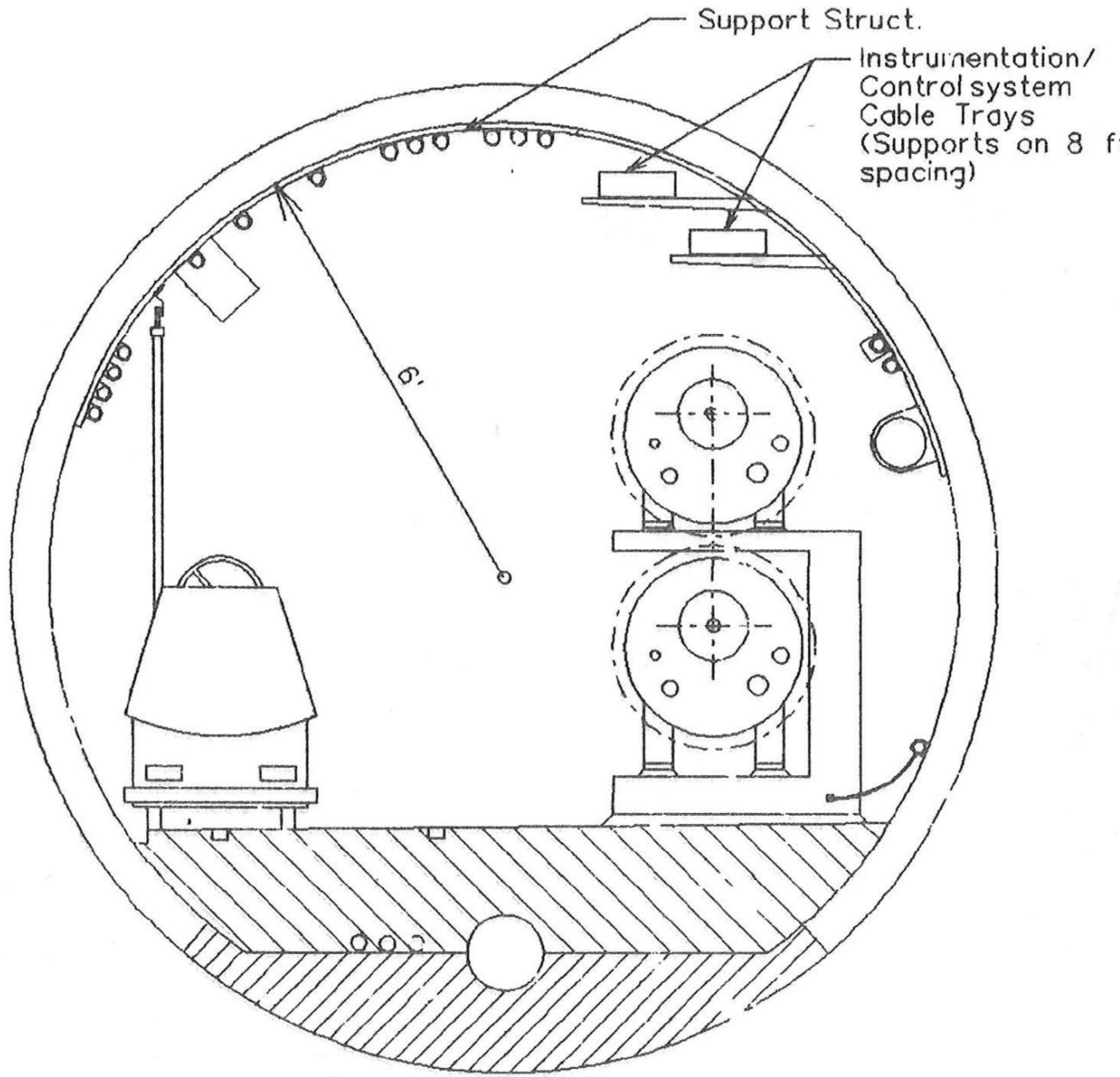


BNL's magnet program is naturally aligned with HEPAP Subpanel Recommendations

SSC Design
Dipoles “over-under” in Tunnel



SSC



A Common Coil Magnet System

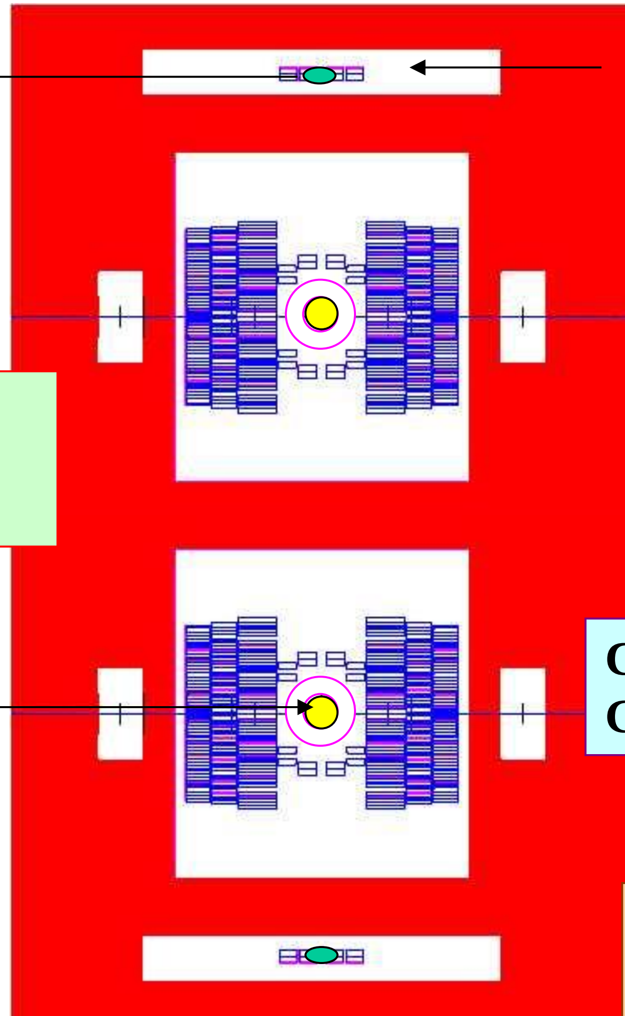
A Solution to the Persistent Current Problem

A 4-in-1 magnet for a 2-in-1 machine

Inject in the iron dominated aperture at low field and accelerate to medium field

Injection at low field in iron dominated aperture should solve the large persistent current problem associated with Nb3Sn

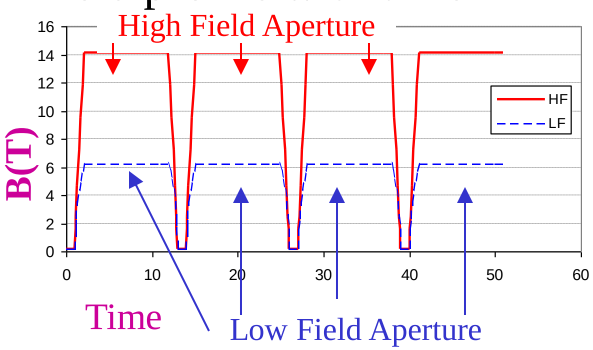
Transfer to conductor dominated aperture at medium field and then accelerate to high field



Conductor dominated aperture Good at high field (1.5-15T)

Iron dominated aperture Good at low field (0.1-1.5T)

Field profile with time



Compact size

AP issues? Compare with the Low Field Design.

Preliminary Design Study
of the High Field Dipole Magnets for
CEPC-SppC

Qingjin XU
On behalf of the SppC magnet working group

Institute of High Energy Physics (IHEP)
Chinese Academy of Sciences (CAS)
Beijing, China

2015.3.26

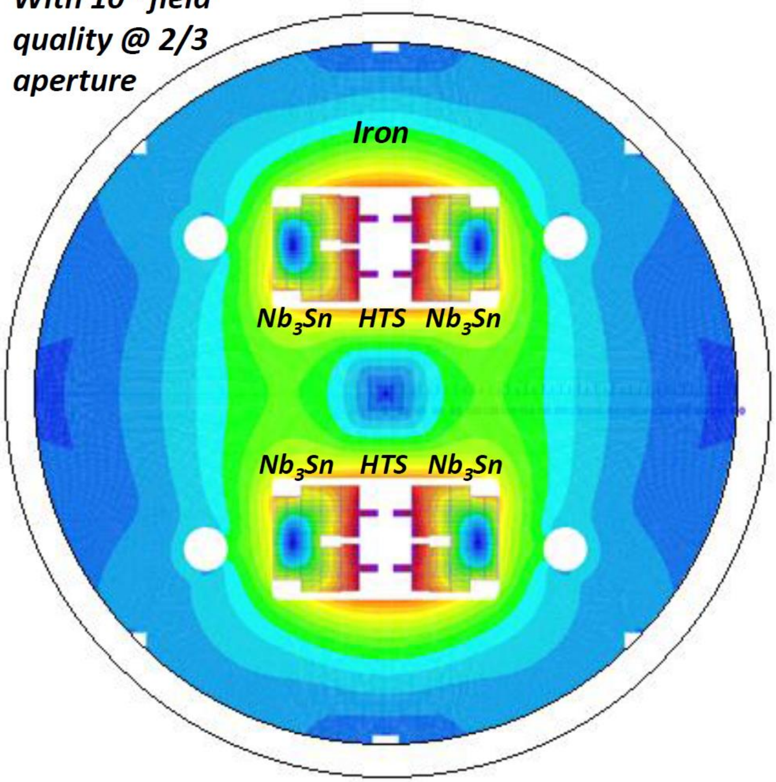
Common Coil in SppC Proposal

Preliminary Design study of a 20-T dipole

20-T Nb_3Sn + HTS common coil dipole for SppC

*Space for beam pipes: 2 * Φ50 mm, with the load line ratio of ~80% @ 1.9 K and the yoke diameter of 800 mm*

With 10^{-4} field quality @ 2/3 aperture



Main Design Parameters

Number of apertures	(-)	2
Aperture diameter	(mm)	50
Inter-aperture spacing	(mm)	330
Operating current	(A)	14700
Operating temperature	(K)	1.9
Operating field	(T)	20
Peak field	(T)	20.4
Margin along the loadline	(%)	~20
Stored magnetic energy	(MJ/m)	7.8
Inductance (magnet)	(mH/m)	72.1
Yoke ID	(mm)	260
Yoke OD	**(mm)**	**800**
Weight per unit length	(kg/m)	3200
Energy density (coil volume)	(MJ/m^3)	738
Winding pack current density	(A/mm^2)	400
Force per aperture – X/Y	**(MN/m)**	**23.4/2.4**
Peak stress in coil	**(MPa)**	**240**
Fringe Field @ r = 750 mm	(T)	0.02

Recap on Cost Saving Possibilities for VLHC

A multi-pronged approach:

- Lower cost magnets expected from a simpler geometry.
- Possibilities of applying new construction techniques in reducing magnet manufacturing costs.
- Possibilities of reducing aperture due to more favorable injection scenario in the proposed common coil magnet system design.
- Possibility of removing the high energy booster (the second largest machine) in the proposed system.
- Possibility of removing main quadrupoles (the second most expansive magnet order) in the proposed combined function magnet design.

Need to examine the viability of these proposals further, need to continue the process of exploring more new ideas and re-examine old ones (as they may be attractive now due to advances in technology, etc.), need to keep focus on the bigger picture...

A significant progress is being made elsewhere also that would help reduce vlhc cost, for example, progress in reducing tunneling cost for low field proposal, etc.

Advantages of React & Wind Approach

- In the "React & Wind" approach, the coil and associated structures are not subjected to the high temperature reaction. This allows one to use a variety of insulation and other materials in coil modules.
  - » In "Wind & React", one is limited in choosing insulating material, etc. since the entire coil package goes through reaction.
- The "React & Wind" approach appears to be more adaptable for building production magnets in industry by extending most of present manufacturing techniques. Once the proper tooling is developed and the cable is reacted, most remaining steps in industrial production of magnets remain nearly the same in both Nb-Ti and Nb_3Sn magnets.
- Since no specific component of "React & Wind" approach appears to be length dependent, demonstration of a particular design and/or technique in a short magnet, should be applicable in a long magnet in most cases.

Common Coil Design allows both "Wind & React" and "React & Wind"

Because of large bend radius, common coil open doors to various technologies that are prevented by "Wind & React". For example, "React & Wind" and CORC

Mandatory for small coils
Electrical insulation issue

Suitable for large coils
Low thermal strain
Cheaper tooling cost

Wind & React	Wind-React-Transfer	React & Wind
Complete Conductor Assembly	Complete Conductor Assembly	Pre-assemble Cable (no steel)
Apply dry Insulation	Apply temp. Spacers	Coil on av. Diameter
Wind in Final Shape	Wind in Final Shape	Heat Treat
Heat Treat	Heat Treat	Uncoil to complete conductor assembly
Pot by VPI	Un-spring to apply dry insulation	Apply dry insulation
	Re-compose the coil	Wind in Final Shape
	Pot by VPI	Pot by VPI

Mandatory for use of Incoloy (SAGBO issue)
Suitable for large coils, High tooling cost

CRPP

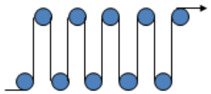
Pierluigi Bruzzone ITER Conductors FCC, Washington March 2015

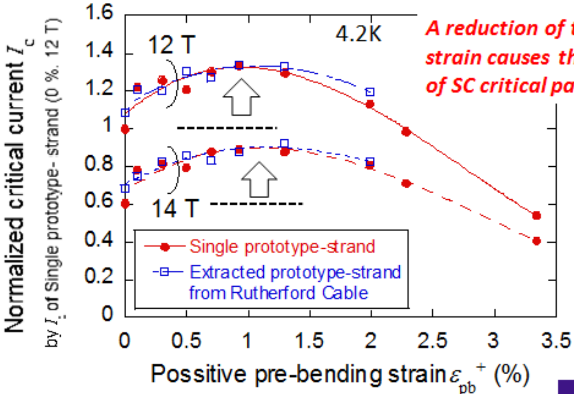
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ic Improvement by Process

FURUKAWA ELECTRIC

Useful pre-bending (pre-strain) effect for enhancing Ic suggests a reality of *React & Wind* Nb_3Sn magnet.



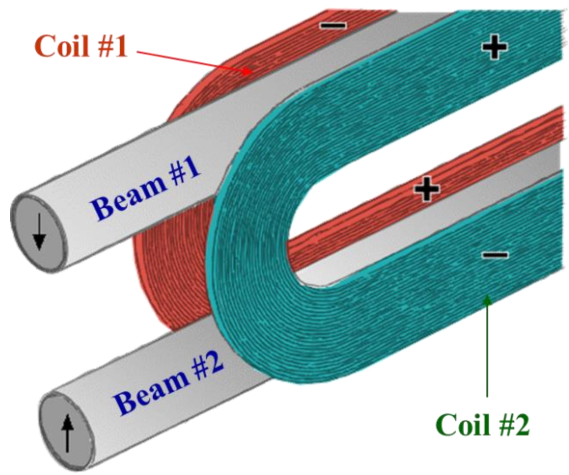


A reduction of the residual strain causes the improvement of SC critical parameters!

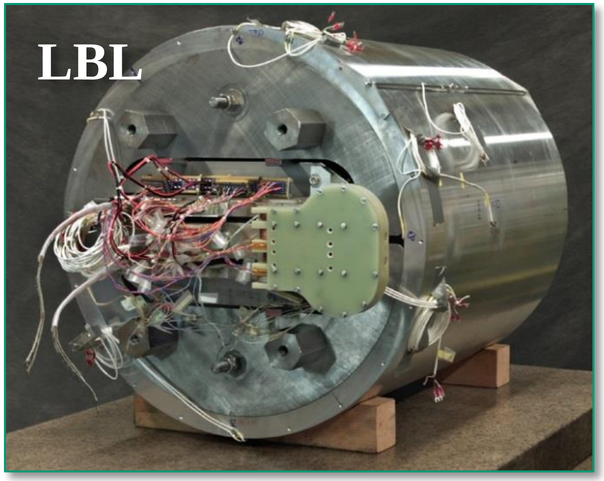
This work was performed under collaboration with HFLSM, IMR, Tohoku University.

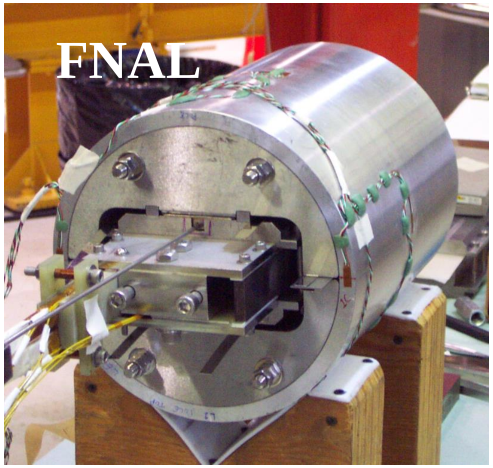
March 25, 2015 T. Nakamoto, FCC Week 2015 at Washington, DC 10

TOHOKU



Common Coil 2-in-1 PoP Dipoles





- R&D common coil Proof-of-Principle (PoP) dipoles built at BNL/LBL/FNAL
- LBL's first common coil dipole reached quench plateau right away and reduction in pre-stress (structure study) had no impact on performance
- BNL's ~30 mm aperture 10+ T (record for "React & Wind" technology) reached short sample (slightly exceeded)

- Despite a good start, the work didn't continue, partially because the design was specifically for a 2-in-1 dipole (required twice the conductor for a single R&D unit) and also LARP required single aperture quadrupole.

BERKELEY LAB

In Conclusion, A Personal Opinion:

The "Common Coil Geometry" provides a unique and flexible *"Test Facility*"* for conductor and magnet development.

*a.k.a.:
Magnet R&D Factory