BROOKHAVEN
NATIONAL LABORATORY

Superconducting
Magnet Division

High Field Hybrid Design

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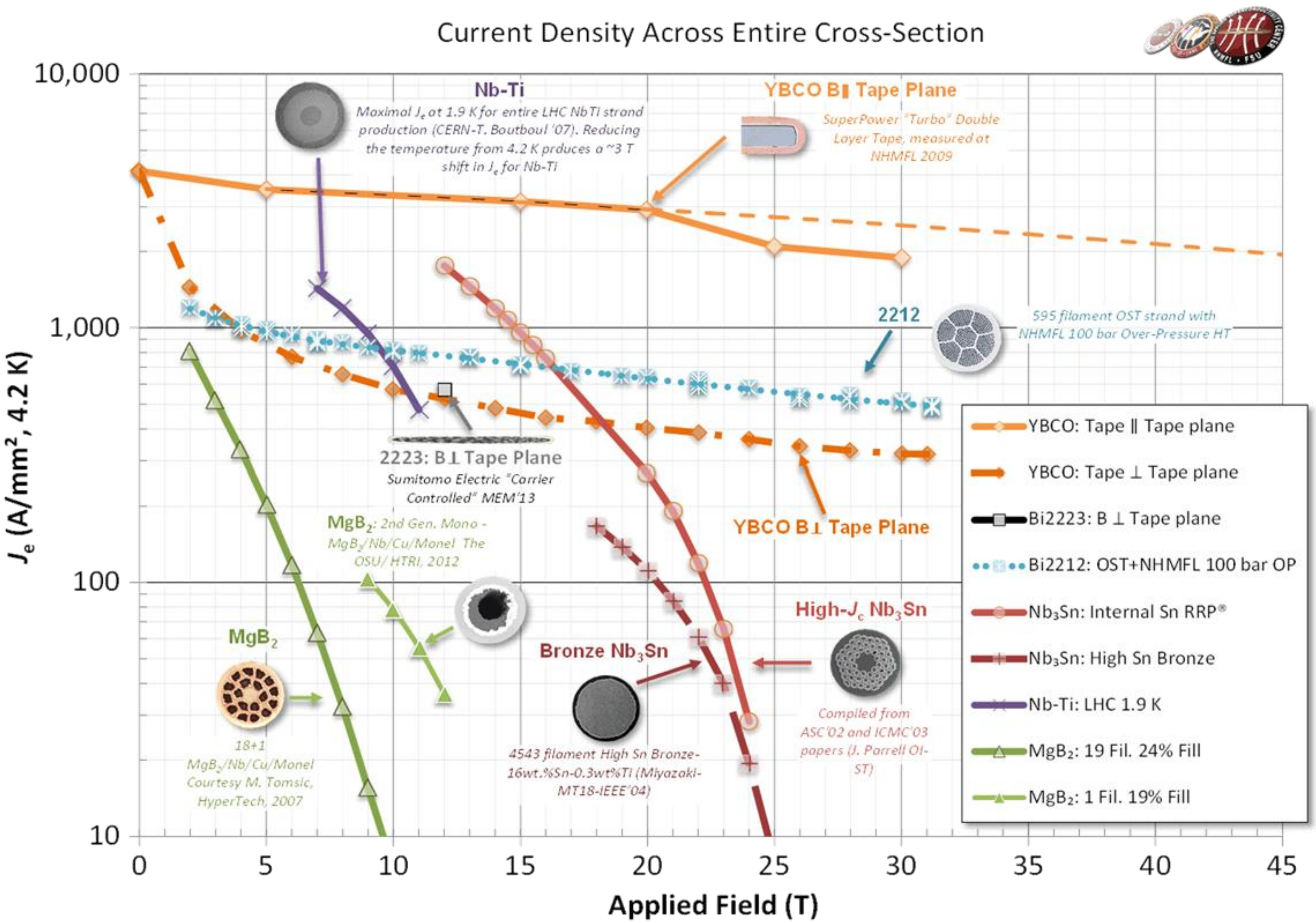
June 15, 2015

Overview

- **HTS/LTS hybrid designs for high field (>20 T) dipole**
- **Techniques for obtaining a good field quality in hybrid dipoles built with HTS tape**
- **HTS coil and hybrid magnet R&D at BNL**
- **Summary**

Superconductors for High Field Magnets



Data compiled by P. Lee NHMFL

What will it be in 20-30 years from now?

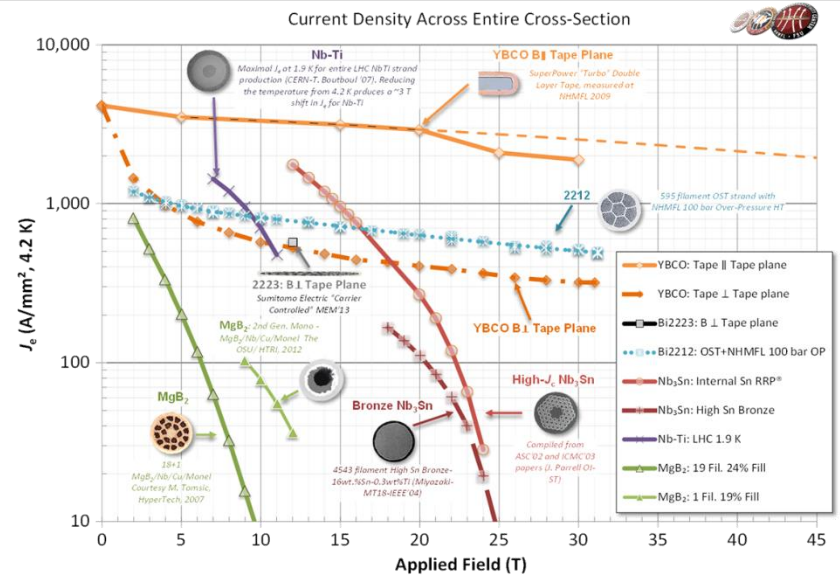
Superconductor & Magnet Technologies for 15 T and 20 T Dipole Designs

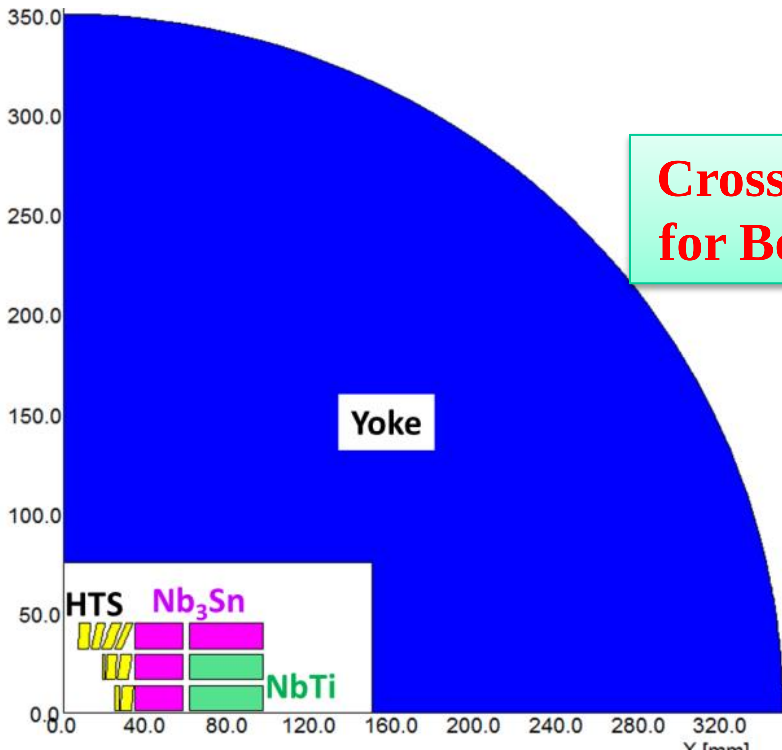
- **A 15 T central field means >16 T peak field on the conductor and a 20 T central field means ~22 T peak field on the conductor.**
- **For ~15% margin, this translates to ~19 T peak field on the conductor for 15 T and ~25 T for a 20 T machine dipole.**
- **This means "*Nb_3Sn only" option* is good to 15-16 T maximum.**
- **For a 20 T design, use of HTS as High Field Superconductor (HFS) is necessary, at least in the high field regions.**

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

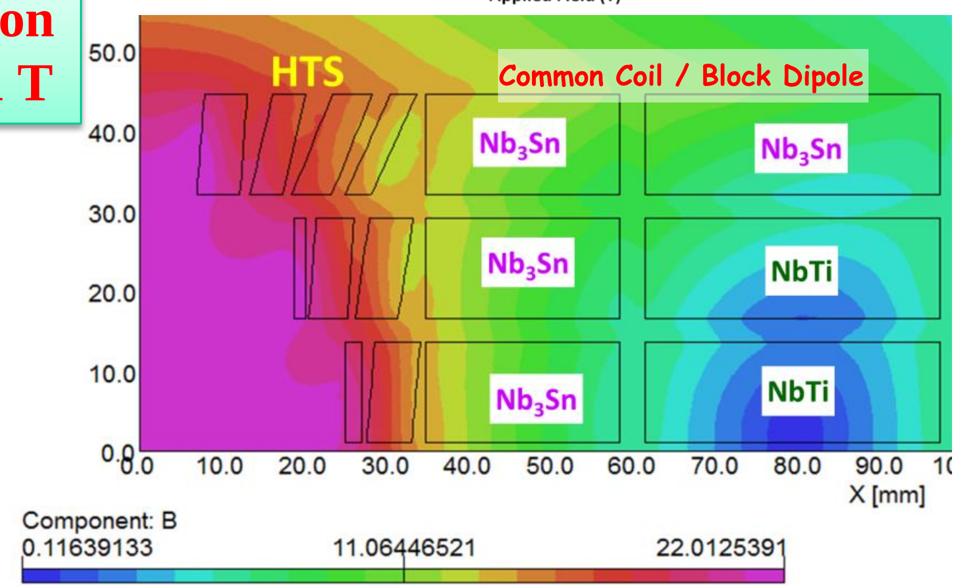
Hybrid Design:

- ❑ 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



HTS Conductor Options in a High Field (>20 T) Hybrid Dipole

Bi2212

- Advantages: Round wire, Rutherford cable
- Challenges: Limited production & long term economic viability,
  Degradation in performance under large stresses

ReBCO

- Advantages: Larger production from multiple vendors,
  - Can tolerate large stresses as in high field magnets
- Challenges: Tape form could cause large magnetization,
  Lower current without new or complex cable

Focus of this presentation:

Possibility of making ReBCO based hybrid magnets more attractive

- ➢ Both in performance, and in cost …
- ➢ As such magnet designs allow both "React & Wind" and "Wind & React"

Magnet Design and Technology

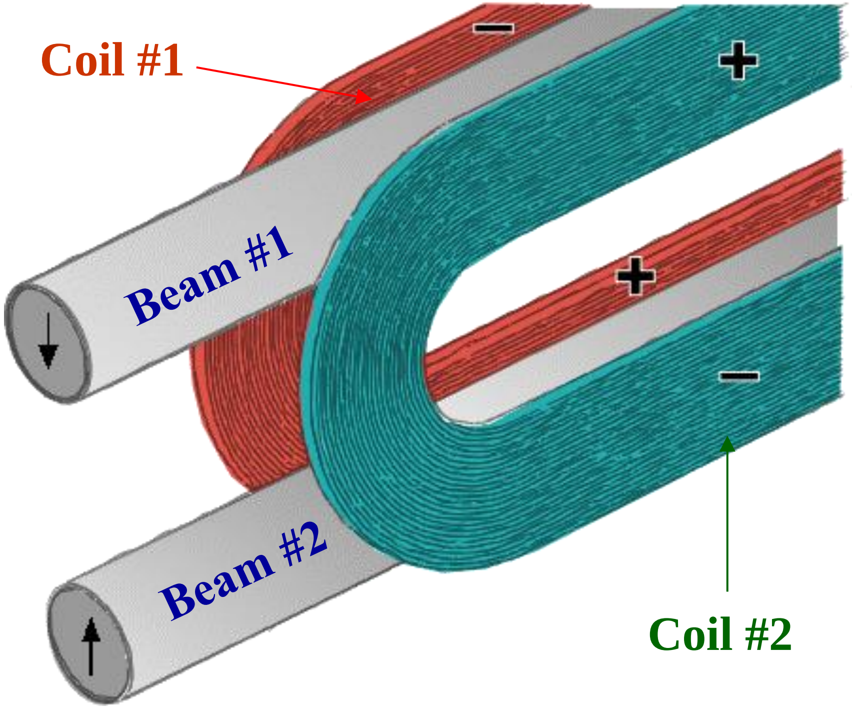
- **Simple racetrack design coil designs are chosen for lower cost and superior technical performance**
- **Conductor friendly designs are chosen to allow use of both "React & Wind" and "Wind & React" technologies**
- **React & Wind technology is preferred to allow more choices on coil components and magnet construction**

Advantages of React & Wind Approach

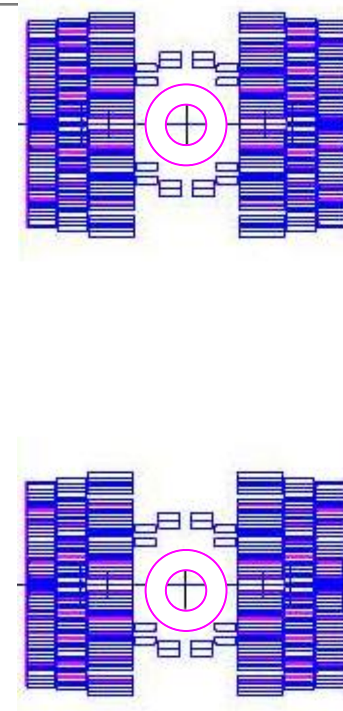
- In the "React & Wind" approach, the coil and associated structures are not subjected to the high temperature reaction. This allows one to use a variety of insulation and other materials in coil modules.
  - » In "Wind & React", one is limited in choosing insulating material, etc. since the entire coil 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

Main Coils of the *Common Coil Design*



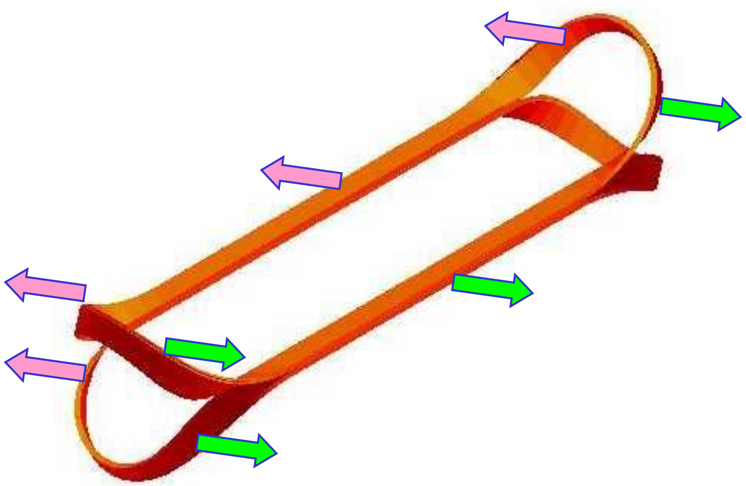
Bend radius is determined by the aperture spacing (large), not by the aperture (small)



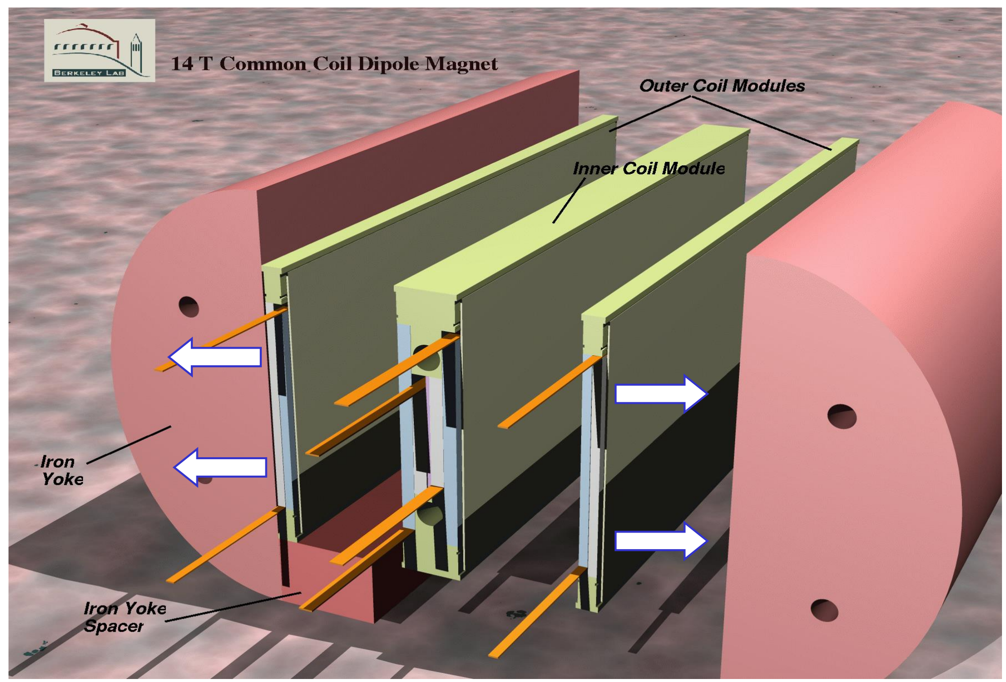
Good Field Quality *Common Coil Design*

- **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
- **Coil aperture can be changed during the R&D** without much loss
- **Used in the initial design of VLHC and now of SppC**

Common Coil Under Lorentz Forces



In common coil design, the coil moves as a whole, without straining the conductor in the ends. This is particularly important in high field magnets where forces are large and this may minimize quench or damage.



In cosine theta or conventional block coil designs, the coil module cannot move as a block. Therefore, Lorentz forces put strain on the conductor at the ends which may cause premature quench.

Optimized Magnetic Design

Good field quality designs developed for:

- Geometric harmonics
- Saturation-induced harmonics
- End harmonics

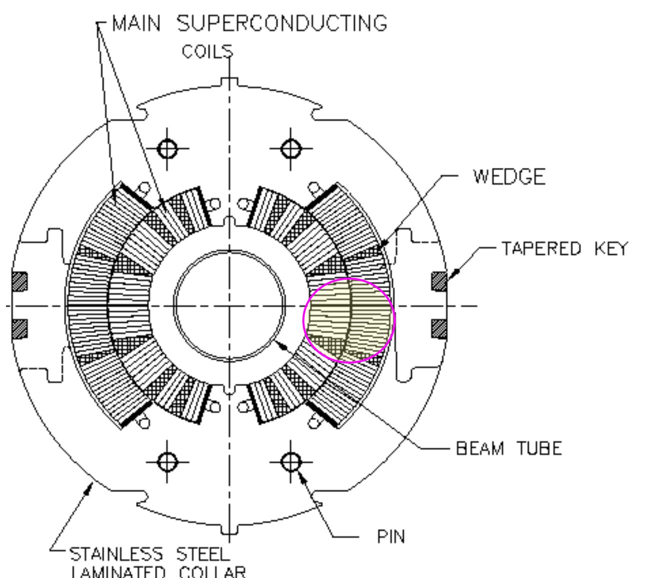
Optimized design included in backup slides
(work presented earlier at Magnet Technology and Applied Superconducting Conference)

- Persistent current-induced harmonics: next few slides

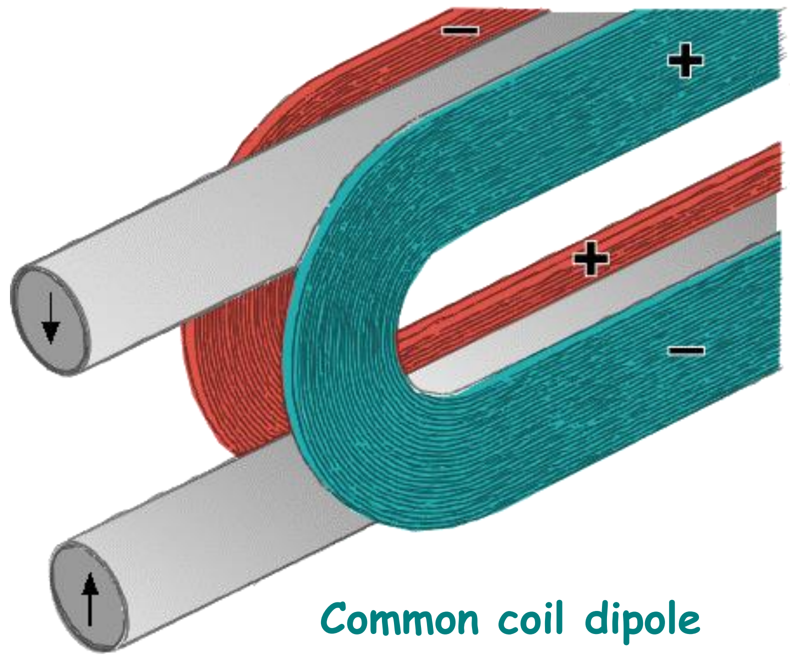
Conductor Magnetization and Persistent-current Induced Harmonics

Conductor magnetization and hence the persistent-current induced harmonics are related to the width of the conductor

- In most Nb-Ti magnets, the filament size is ~ 6 μm
  - higher in Nb_3Sn, but usually <100 μm
- In ReBCO it is ~12 mm for high current tapes



SSC 50 mm dipole



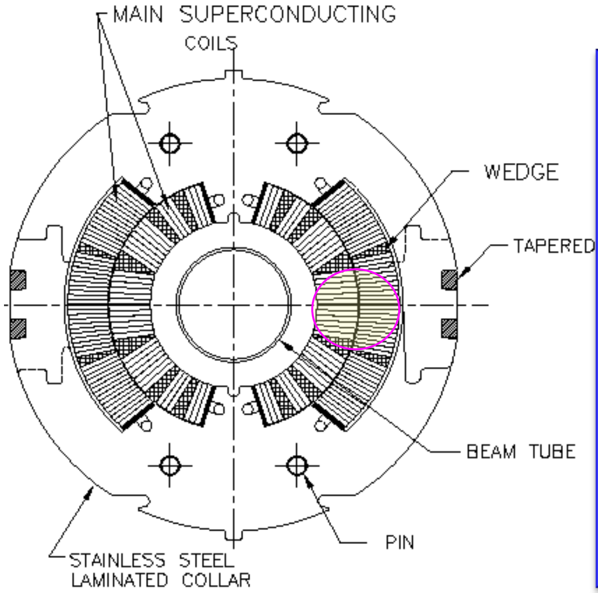
Common coil dipole

Conductor Magnetization and Persistent-current Induced Harmonics

Conductor magnetization (***more accurately***) and hence harmonics are related to the width of the conductor (filament) subtended

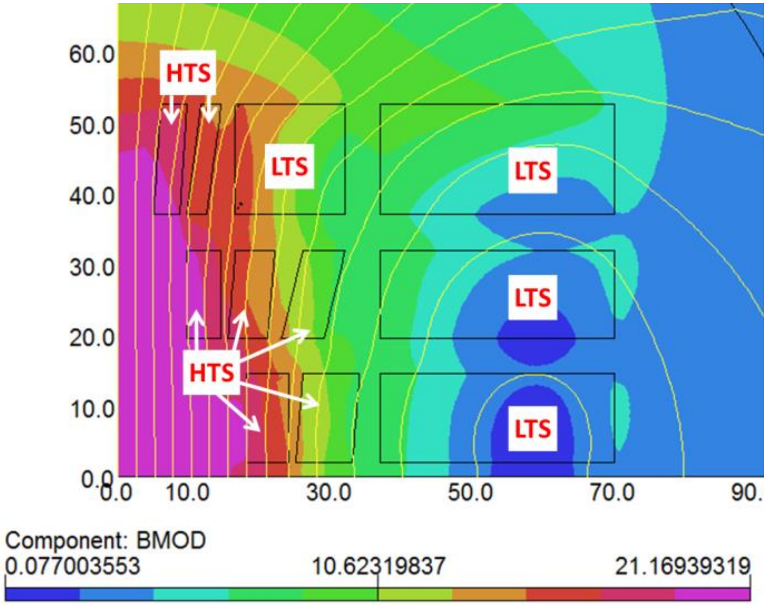
"***perpendicular to the field***"

Wide side of the HTS Tape Perpendicular to Field



Larger magnetization (BAD DESIGN)

Narrow side of the HTS Tape Perpendicular to Field



Smaller magnetization (GOOD GESIGN)

Design Technique to Reduce Magnetization

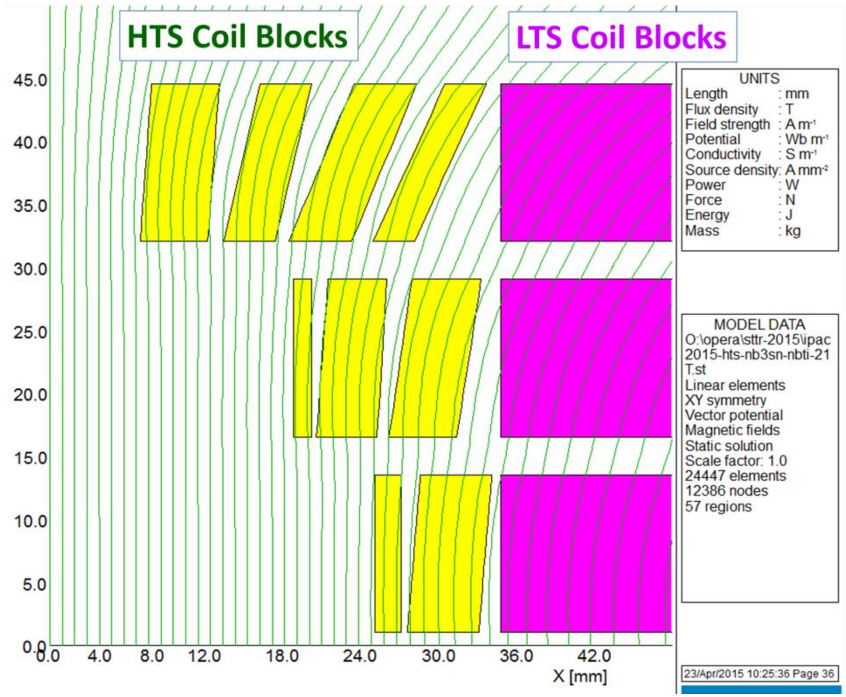
Design Technique to Reduce Magnetization Effects:

- Align the tape conductor (thickness few μm) such that primarily the

  "narrow side sees the perpendicular field"

- It is possible to align HTS tape to a good extent in HTS/LTS **hybrid designs**

  "by carefully designing the coil"



Effective filament size of 12 mm reduces

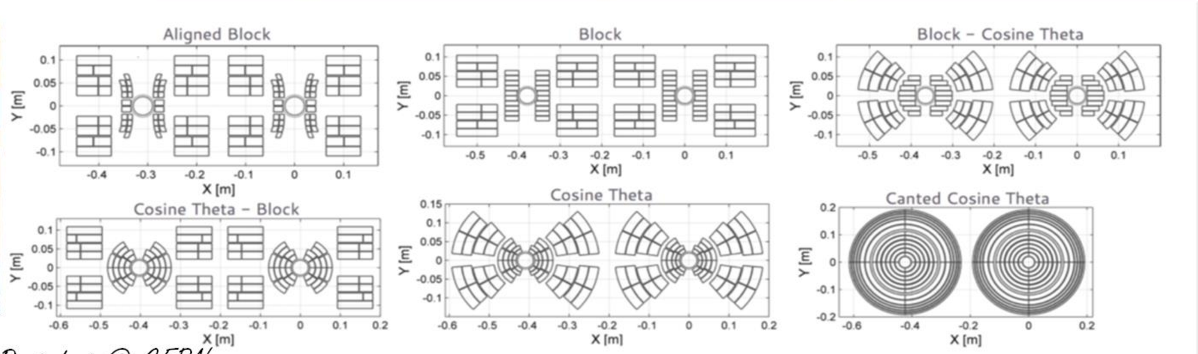
⇨ **to a few mm in an ideal design**

Magnetization in an actual magnet will depend on the level of optimization and on how things work in real world (beyond computations)

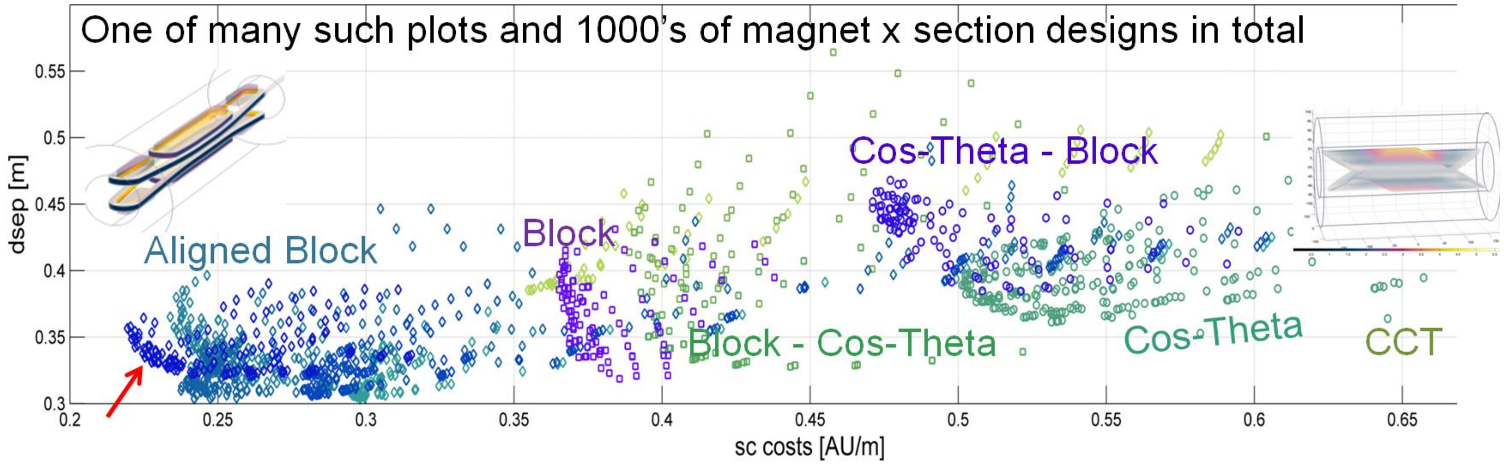
Other Benefits of Aligned Tape Design (conductor efficiency)

5 **Survey of 20 T Magnet design possibilities**

Courtesy:
J. Van Nugteren
CERN



Jeroen Van Nugteren PhD student @ CERN

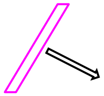


UNIVERSITY OF TWENTE.

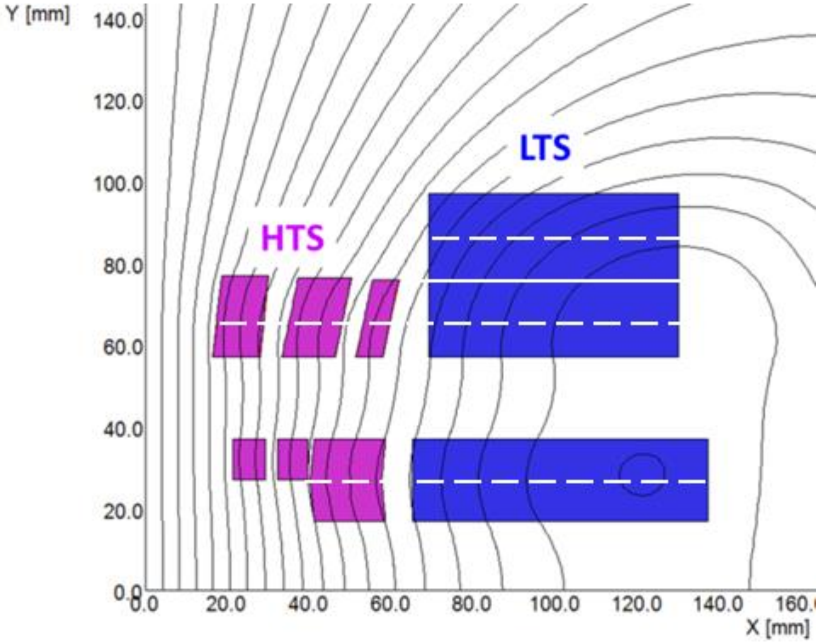
Other Benefits of Such Designs (2)

- **Lorentz forces are primarily on the wide face of the conductor**

I × B



➢ ReBCO can tolerate large stresses on the wide side

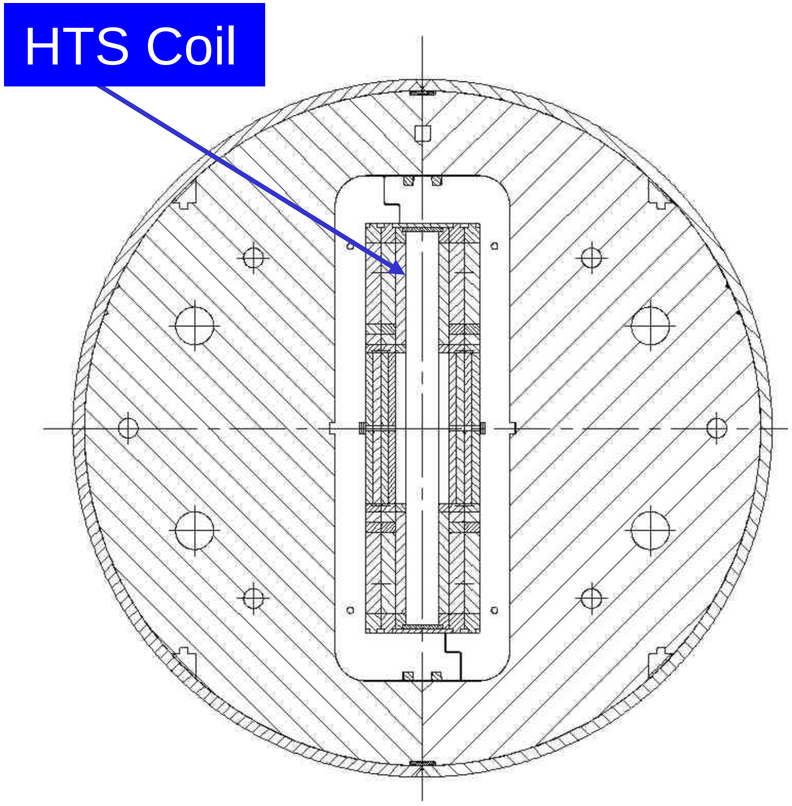


- **Blocks are easy to segment**
  - ➢ Between HTS and LTS
  - ➢ For stress management

Proof-of-Principle Magnet

A unique feature of the BNL common coil magnet is a large vertical open space for testing HTS insert coils without disassembling the magnet.

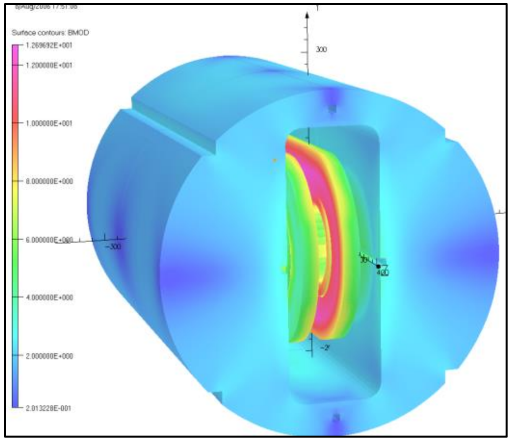
Large vertical space for insert coil testing

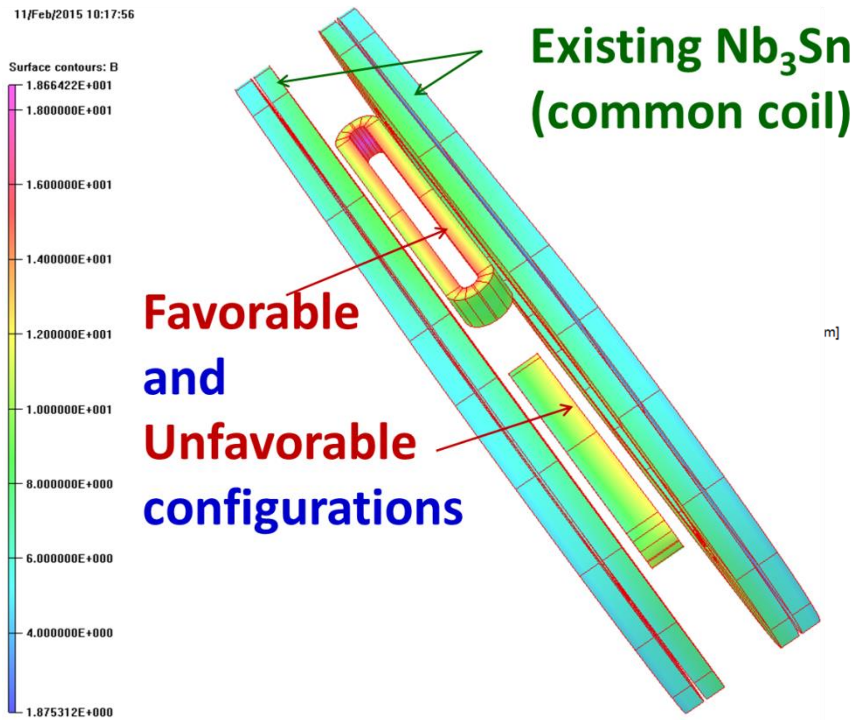


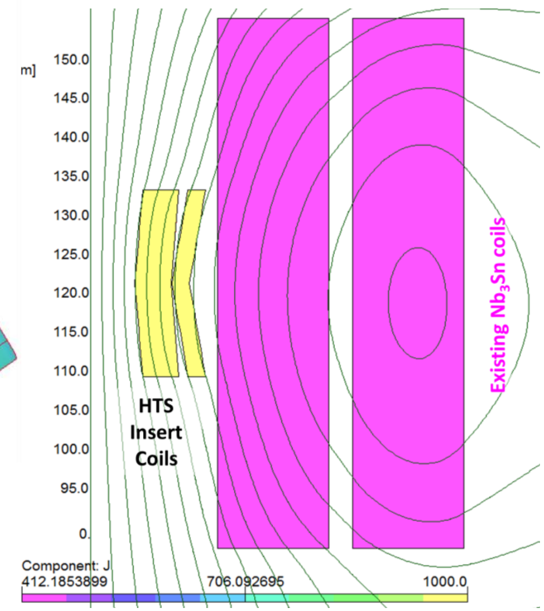
HTS insert coil test configuration (HTS/Nb_3Sn Hybrid magnet)

Test of Principle in A Real Magnet
(measure and compare magnetization in two configurations)

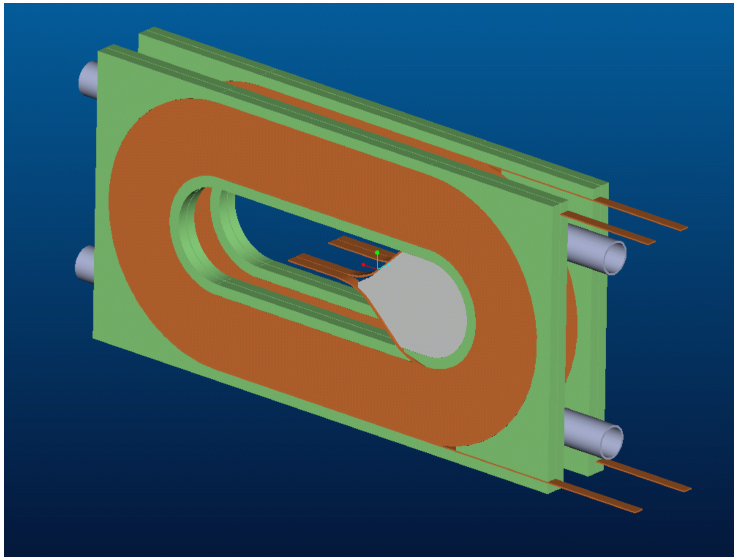
Common Coil Dipole with a large open space
- Coils can be inserted without opening the magnet

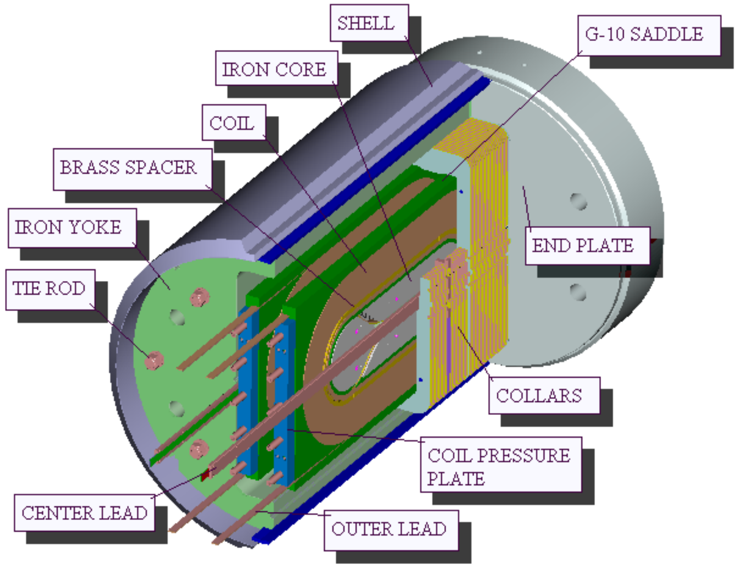






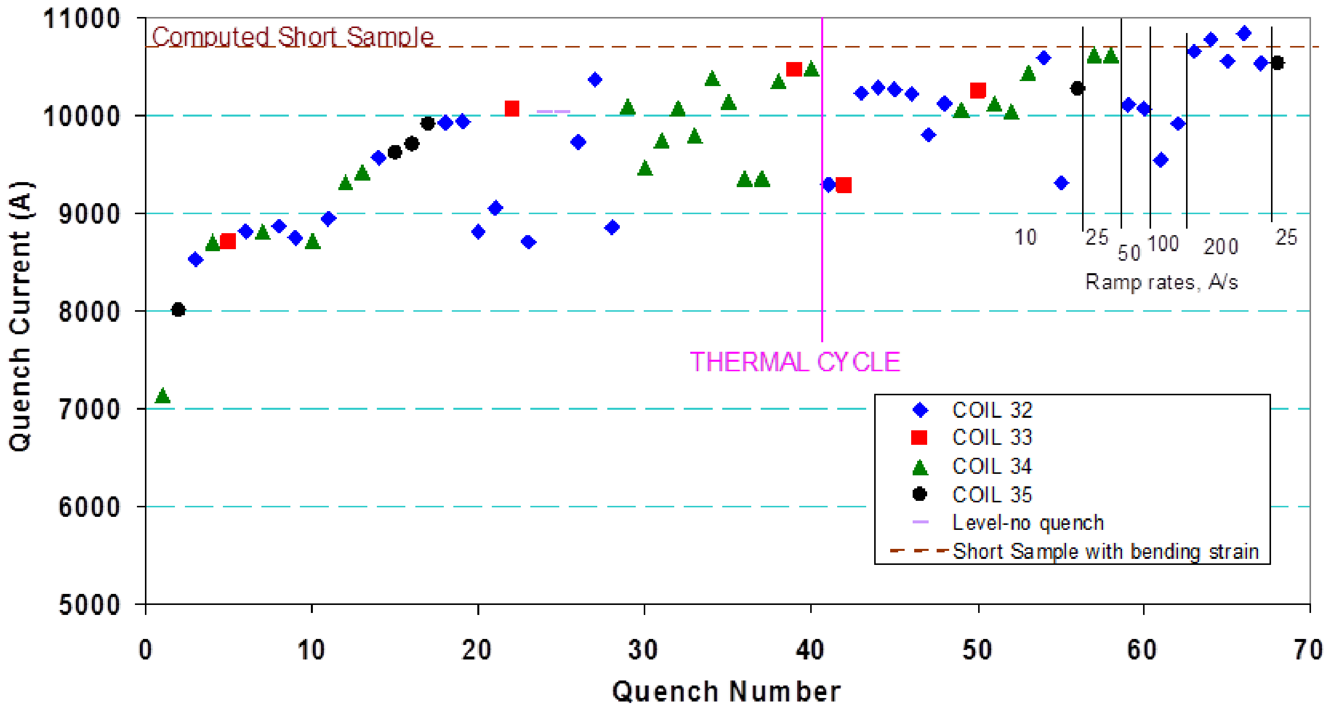
Basic Features of BNL Nb_3Sn 10^+ T React & Wind Common Coil Dipole





- 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

Performance of React & Wind Dipole (despite large deflections)



I_c=10.8 kA
B_{pk}=10.7 T
B_{ss}=10.2 T

- Slightly exceeded the computed short sample
- Practically no vertical or horizontal pre-load

- Magnet reached short sample after a number of quenches
  - ➢ Reasonable for the first technology magnet
- The geometry can tolerate large horizontal forces and deflections
  - ➢ important for high field magnets as it can reduce/simplify structure
  - ➢ computed horizontal deflection/movement of the coil as a whole ~200 μm

SUMMARY

- **Initial/conceptual designs of high field hybrid magnet presented. React & Wind technology is attractive for ReBCO/Nb_3Sn/NbTi hybrid magnegts.**

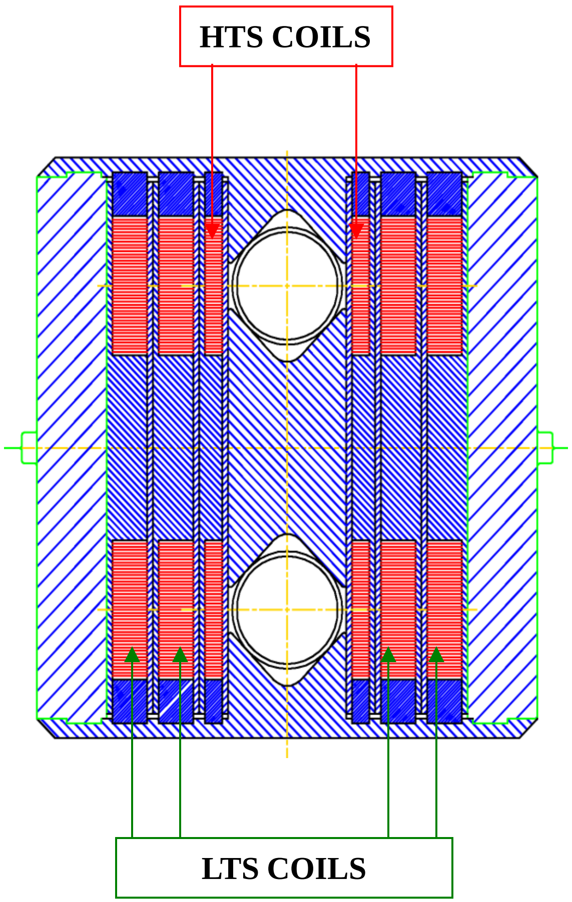
- **It is possible develop high field hybrid magnet designs such that the persistent current-induced harmonics become manageable, overcoming a major technical issue with the ReBCO tape. Proof-of-Principle magnet is being built.**

- **Requirements of expensive conductor are significantly reduced because of the field orientation (previous design work at CERN).**

- **Conductor (HTS) cost may determine the viability of 20 T dipoles for high energy proton-proton collider. Fraction of the field from HTS will depend on the relative cost of conductor.**

Backup Slides

HTS Magnet R&D in a Common Coil Hybrid Design



- Perfect for R&D magnets now.

  HTS is subjected to the similar forces that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.

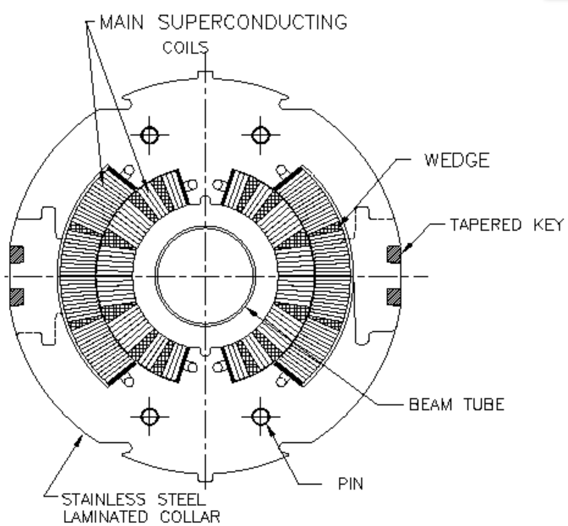
- Also a good design for specialty magnets where the performance, not the cost is an issue. Also future possibilities for main dipoles.

- Field in outer layers is ~2/3 of that in the 1st layer. Use HTS in the 1st layer (high field region) and LTS in the other layers (low field regions).

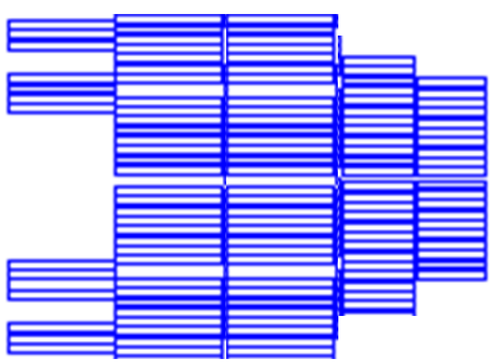
Coil Optimization in Block Designs (including in common coil)

- 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 one freedom to either create sort of cos(θ) or expand independently horizontally or vertically
  - One can take advantage of this to create a more efficient design

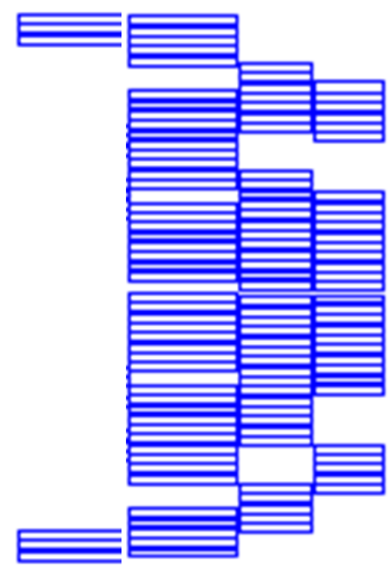
COS(θ)



More Efficient Design



Less Efficient Design

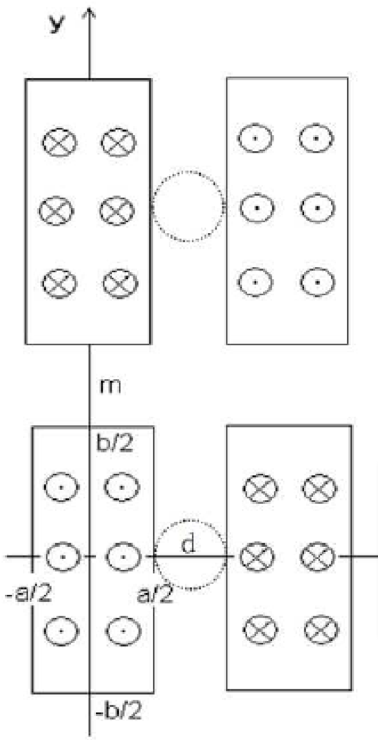


Analytical Tool/Guidance for Optimizing Common Coil Design

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

Qingjin Xu

ASC2014



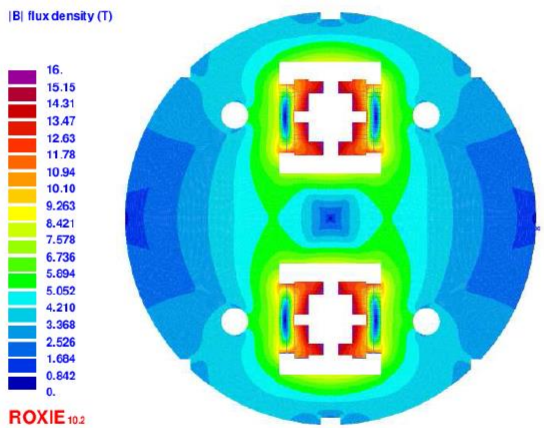


Fig. 1 Analytical modeling of the common coil configuration: The four current-carrying blocks represent the two racetrack coils with opposite current directions. The coil width and height are *a* and *b* respectively. The bore diameter is *d* and the bending radius of the coil is *m/2*.

Courtesy: Qingjin Xu

50 mm, 15 T Nb_3Sn design for IHEP

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

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

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

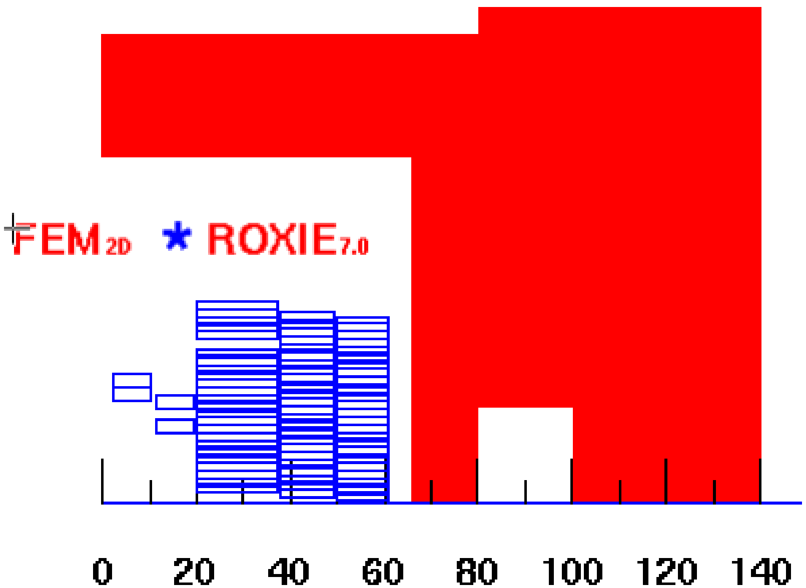
$$B_y = \frac{\mu_0 I}{4\pi}\Bigg[\int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(x+\frac{a}{2})^2+(y-y_0)^2}{(x-\frac{a}{2})^2+(y-y_0)^2}dy_0 + \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(\frac{3a}{2}+d-x)^2+(y-y_0)^2}{(\frac{a}{2}+d-x)^2+(y-y_0)^2}dy_0 - \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(x+\frac{a}{2})^2+(m+b-y-y_0)^2}{(x-\frac{a}{2})^2+(m+b-y-y_0)^2}dy_0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

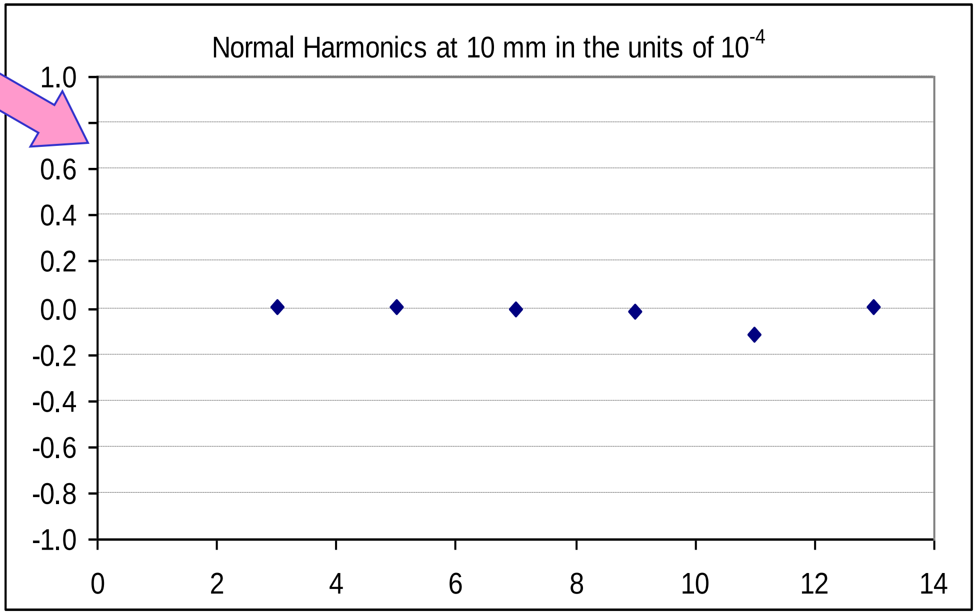
Assume the bending radius of the racetrack coil is large enough that the cross-talk of the magnetic field between the two apertures are negligible, by replacing the *x* with *(a+d)/2* and *y* with *0* in equation (4), we get the main dipole field of the common coil configuration as

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

Demonstration of Good Field Quality (Geometric Harmonics)

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





(from 1/4 model)

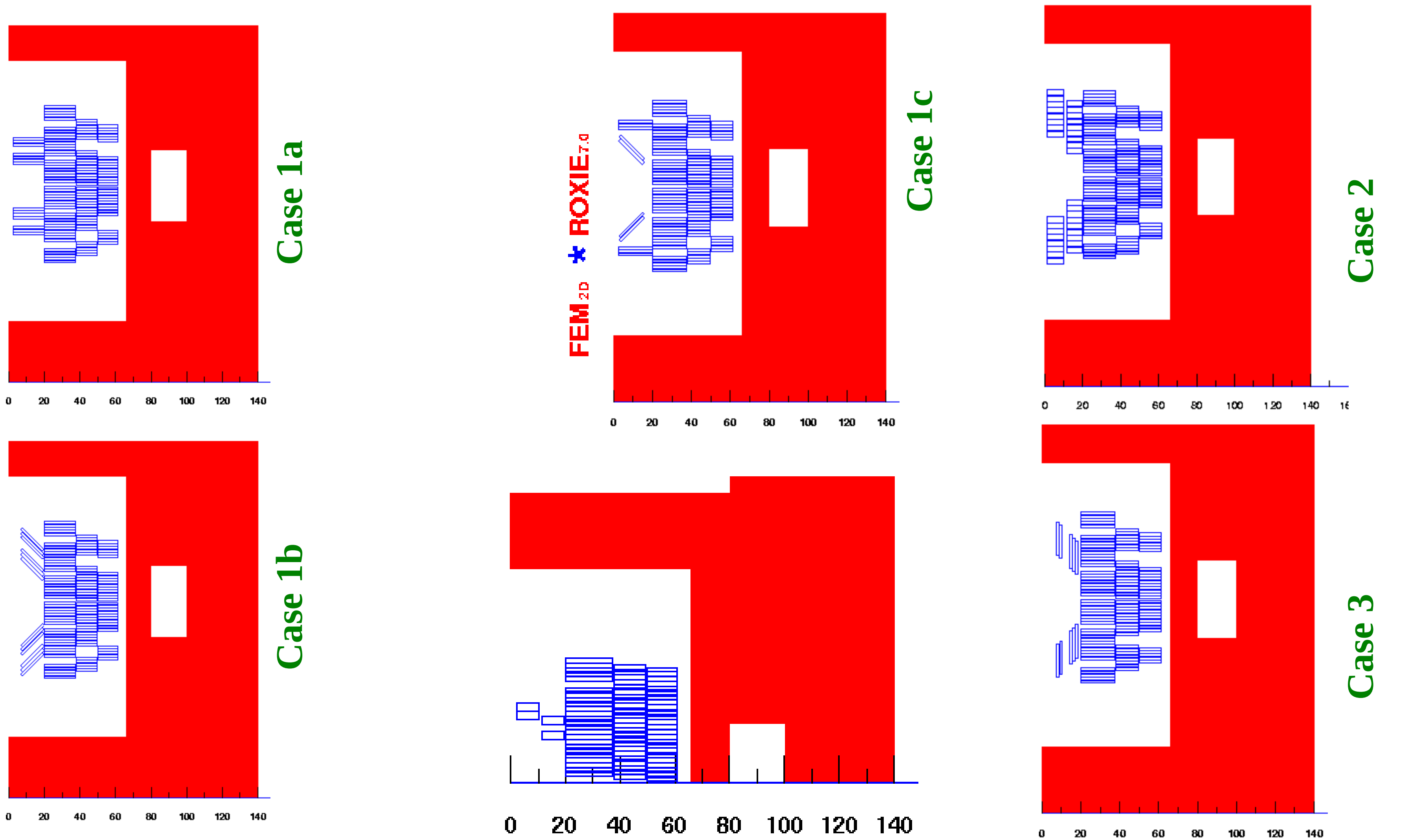
MAIN FIELD: -1.86463 (IRON AND AIR):

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:

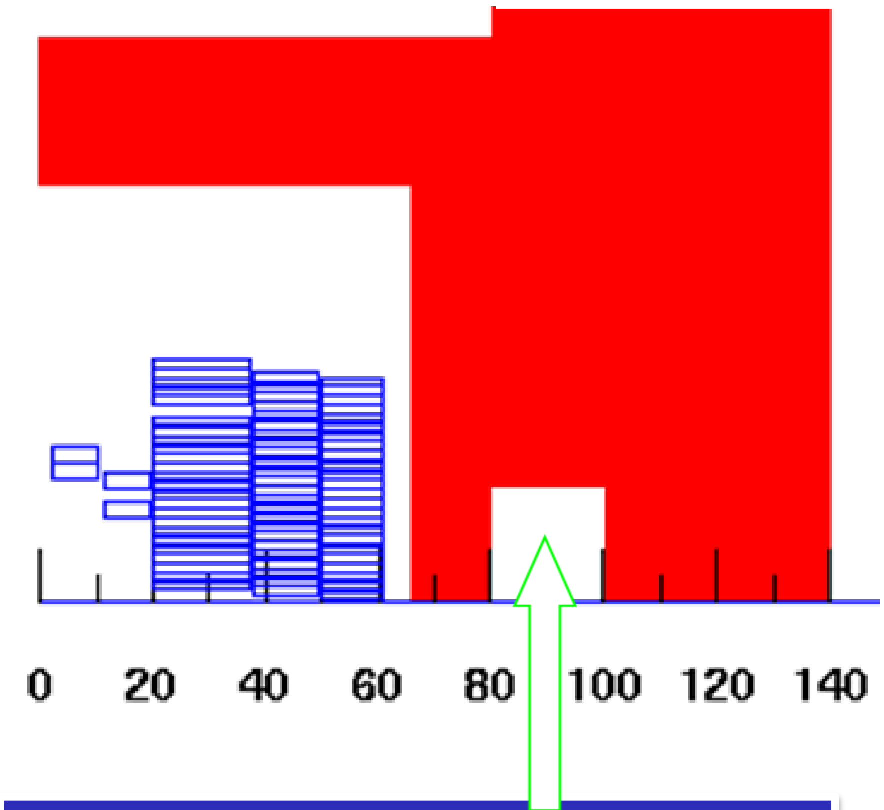
40 mm

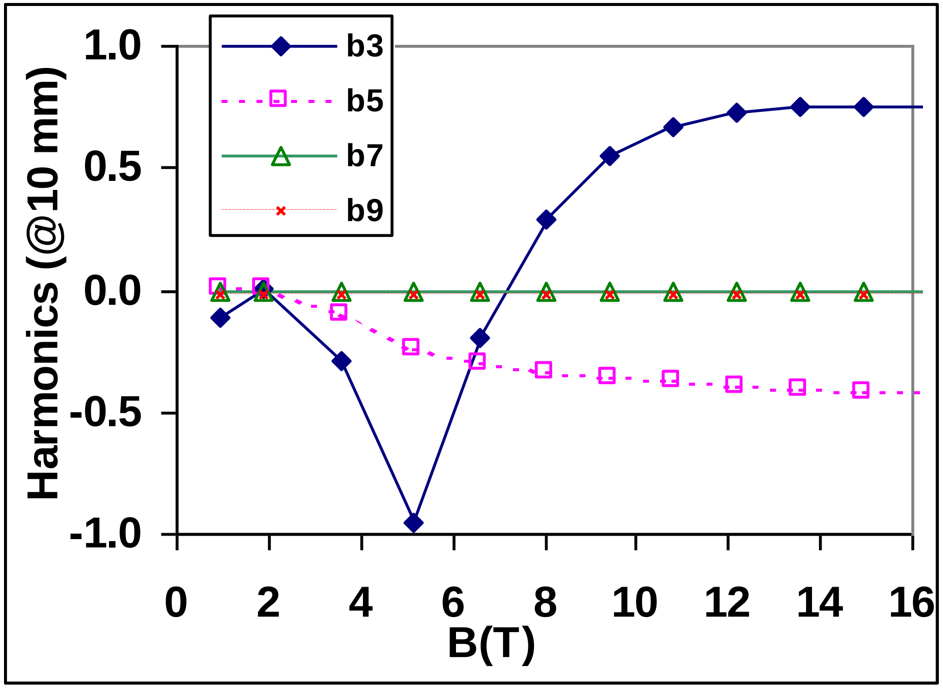
A Few Good Field Quality Configurations



Demonstration of Good Field Quality (Saturation-induced Harmonics)

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





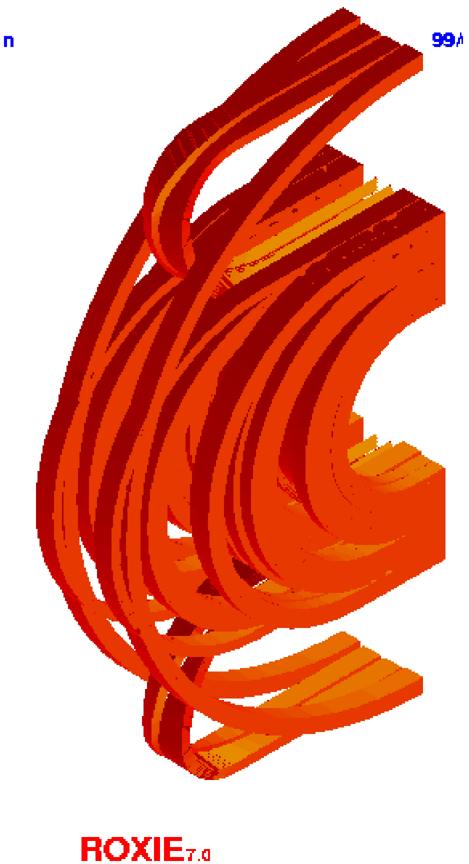
Use cutouts at strategic places in yoke iron to control the saturation

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)

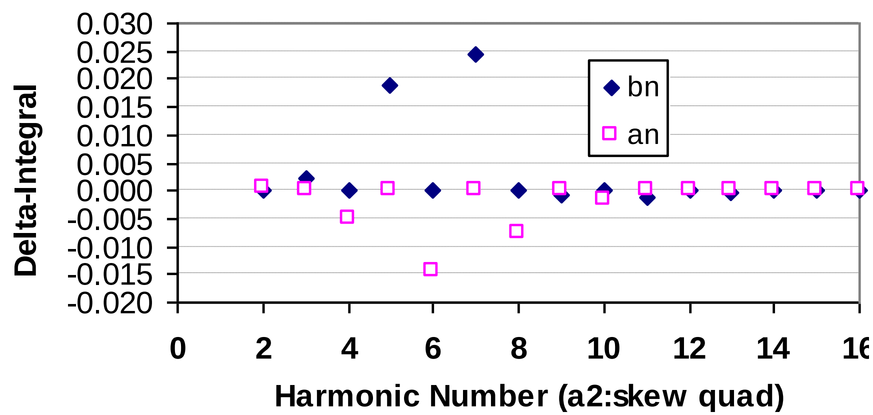


End harmonics in Unit-m

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

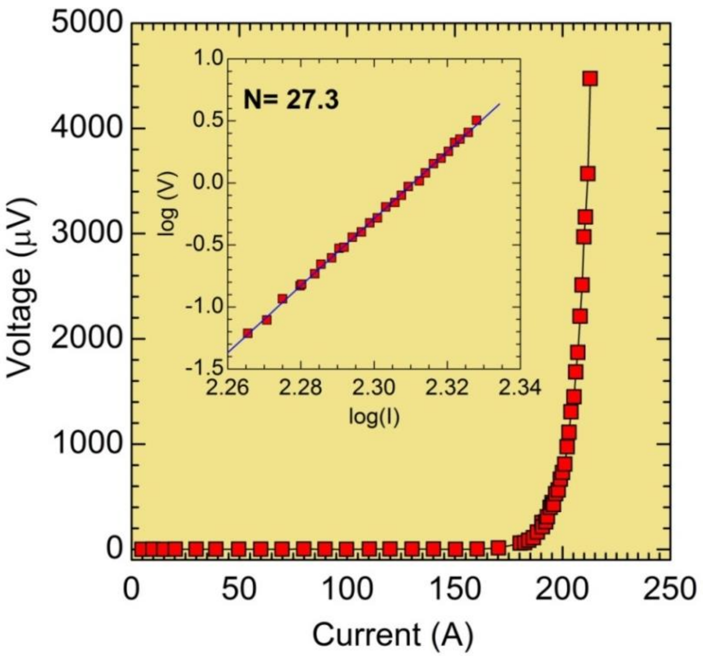
Contribution to integral (a_n,b_n) in a 14 m long dipole ($<10^{-6}$)

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



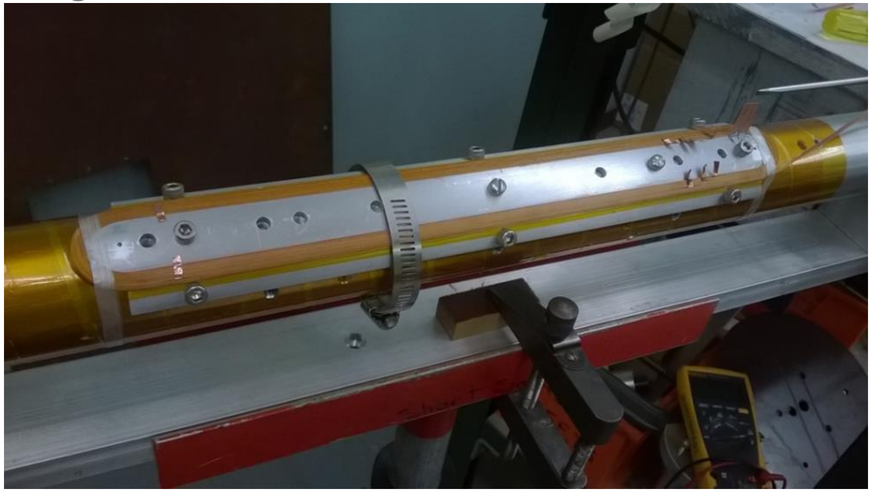
Cos (θ) Coil - PBL/BNL STTR (Willen) (12 mm, one block, 77 K)

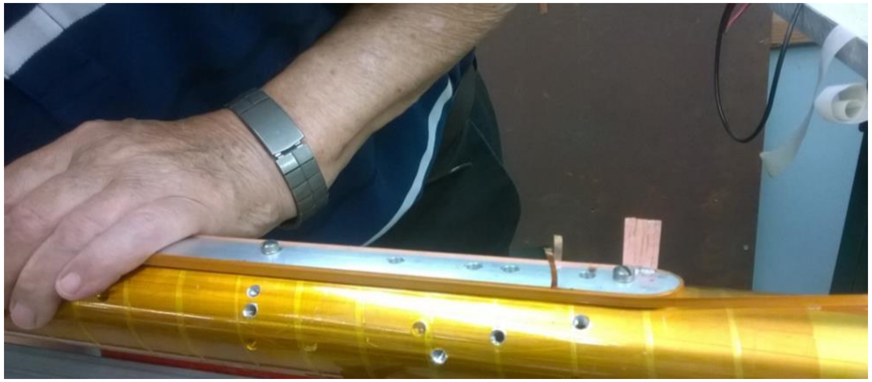
The coil block made here is similar to what would be needed for testing reduction in magnetization



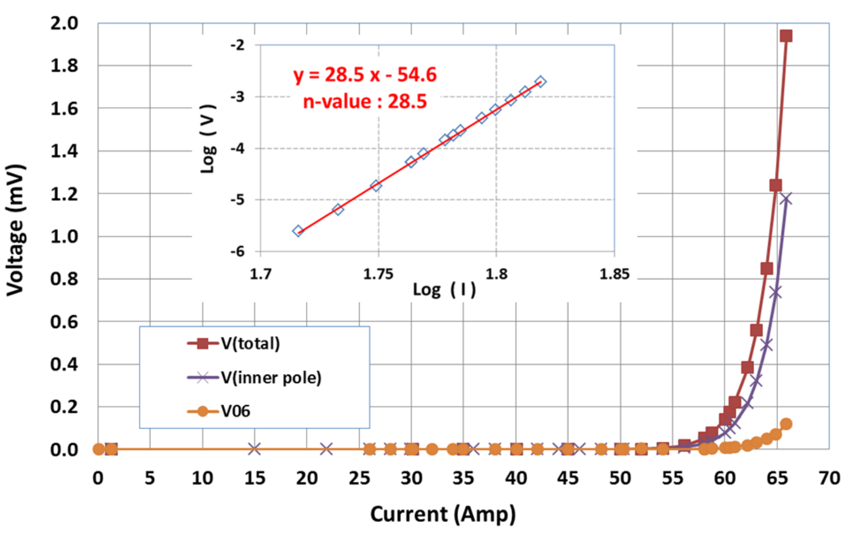
No measurable degradation@77 K

Cos (θ) Coil - PBL/BNL STTR (Scanlan)





Also investigated "bonded" or "clad" 12 mm tape from SuperPower



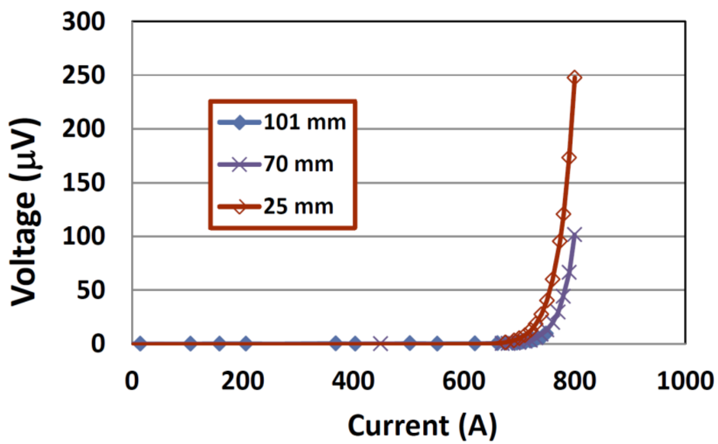


Fig. 17. Bend test results for bonded tape with the YBCO layer oriented toward the central Cu strip. Degradation in I_c begins between a bending diameter of 75 mm and 25 mm.

No measurable degradation@77 K