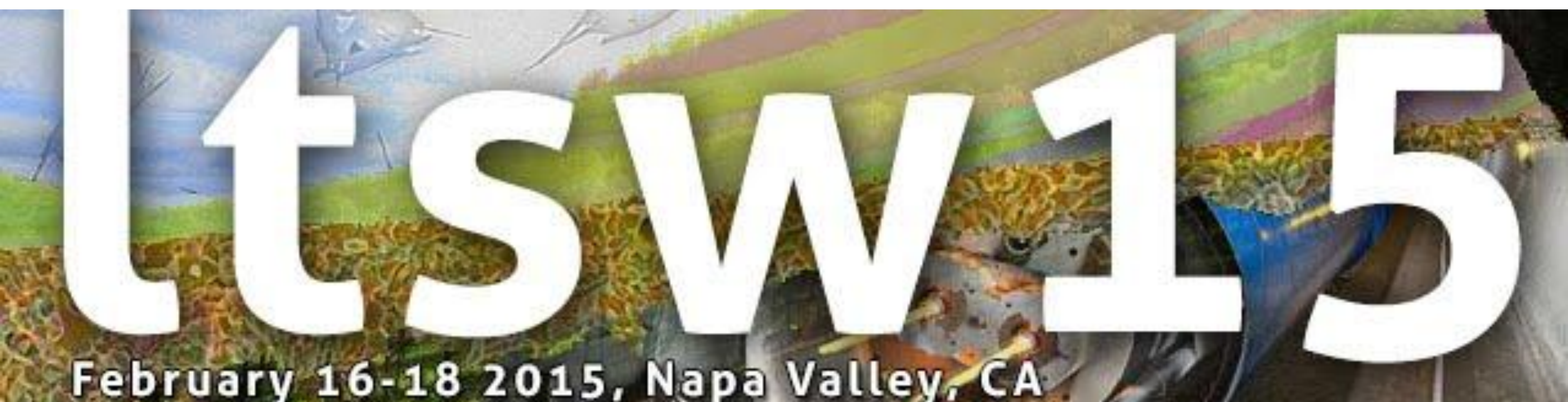
High Field Hybrid Dipoles for FCC

Ramesh Gupta

Brookhaven National Laboratory



Overview

- **Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes**
  - **This could be a game changer for ReBCO**

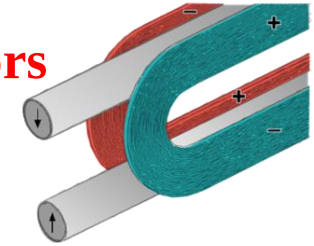
- **Common Coil Dipole (Nb_3Sn and hybrid)**
  - **Additional options and requirements related to Nb_3Sn**

- **Open Midplane Dipole (Nb_3Sn and hybrid)**
  - **Relaxation in temperature margin and PoP model**

Racetrack coil designs

Magnetization in ReBCO Magnets

- **Issue:**
  - **ReBCO is primarily available in tape form**
  - **Magnetization is large in cosine theta or common coil designs**
    - ➢ **related to tape width: 12 mm for high current conductors**



- **Solution #1 : conductor design**
  - **Round wire**
  - **Striated tape**
- **Solution #2 : coil design**
  - **See what we can do to use and <u>enhance</u> the strengths of the conductor**

Next few slides on the technique

Design Technique to Reduce Magnetization

- Conductor magnetization and hence the persistent-current induced harmonics are related to the width of the conductor (wire or tape)

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

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

Design Technique to Reduce Magnetization Effects:

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

  "***narrow side sees the perpendicular field*** "

- It's possible to align HTS tape to a good extent in **hybrid magnets**

  by carefully designing the coil

Part of PBL/BNL Provisional Patent Application

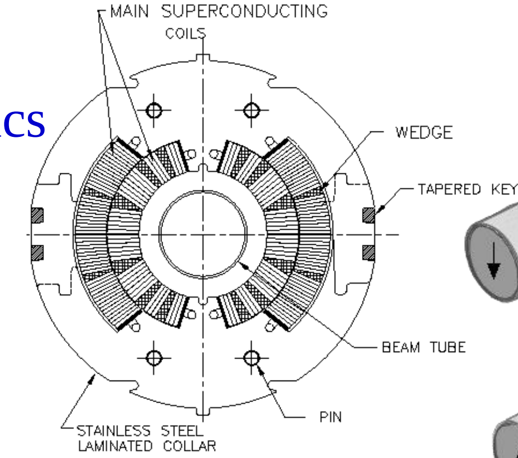
Effective filament size 12 mm → a few μm in an ideal design
- small in a real design, depending on the optimization

Comparing Designs for Magnetization

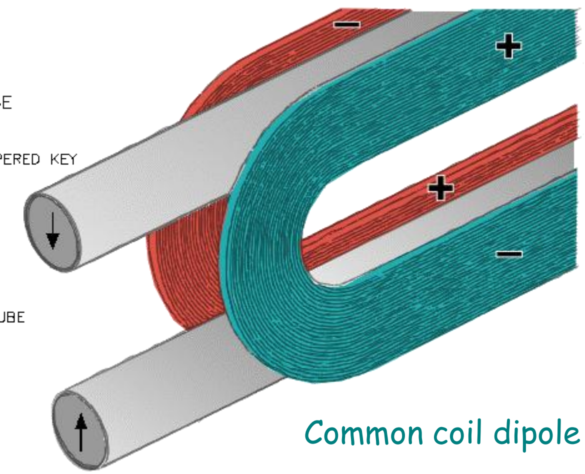
For Single Figure of Merit:

- ❑ Persistent current induced harmonics

➢ **Bad designs for HTS tape**
  large area covered by the perpendicular component of the field



SSC 50 mm dipole



Common coil dipole

➢ **Good designs for tape (small area curved by the perpendicular component of the field)**

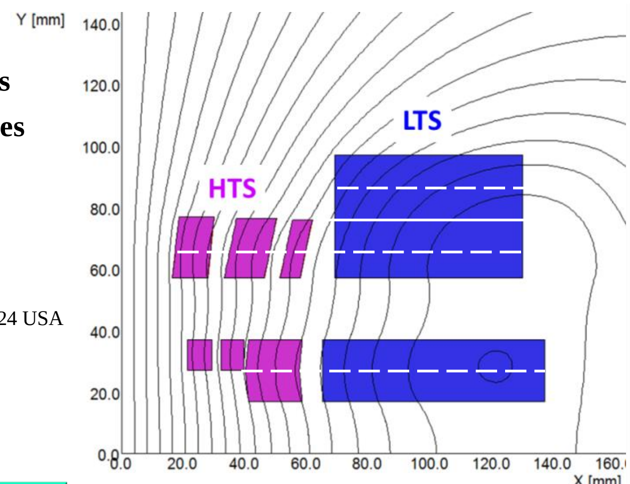
Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes

R. Gupta[1], A. Ghosh[1], R. Scanlan[2] and R. Weggel[2]

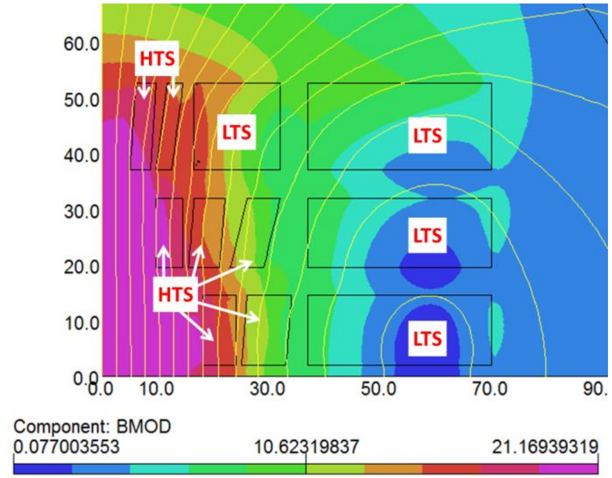
[1]Brookhaven National Laboratory, Upton, NY 11973 USA
[2]Particle Beam Lasers, Inc., 18925 Dearborn Street, Northridge, CA 91324 USA

BNL Magnet Division Note: MDN-676-41

Part of PBL/BNL Provisional Patent Application



Open midplane dipole



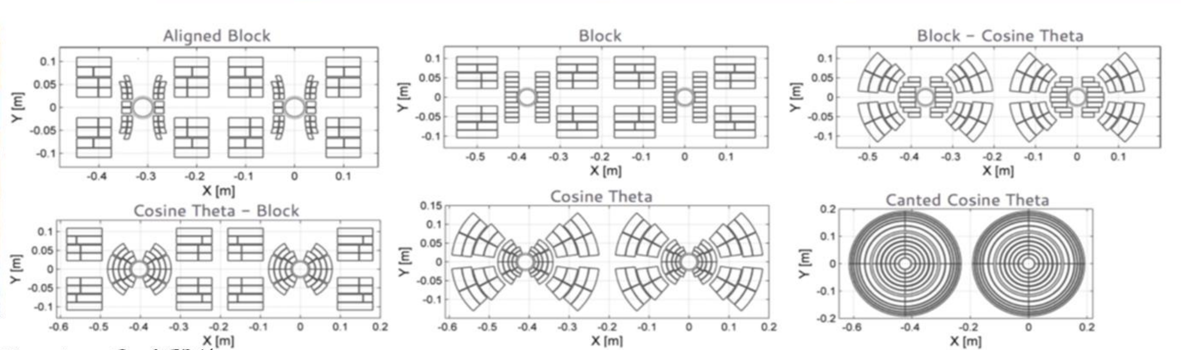
FCC dipole

Other Benefits of Aligned Tape Design (conductor efficiency)

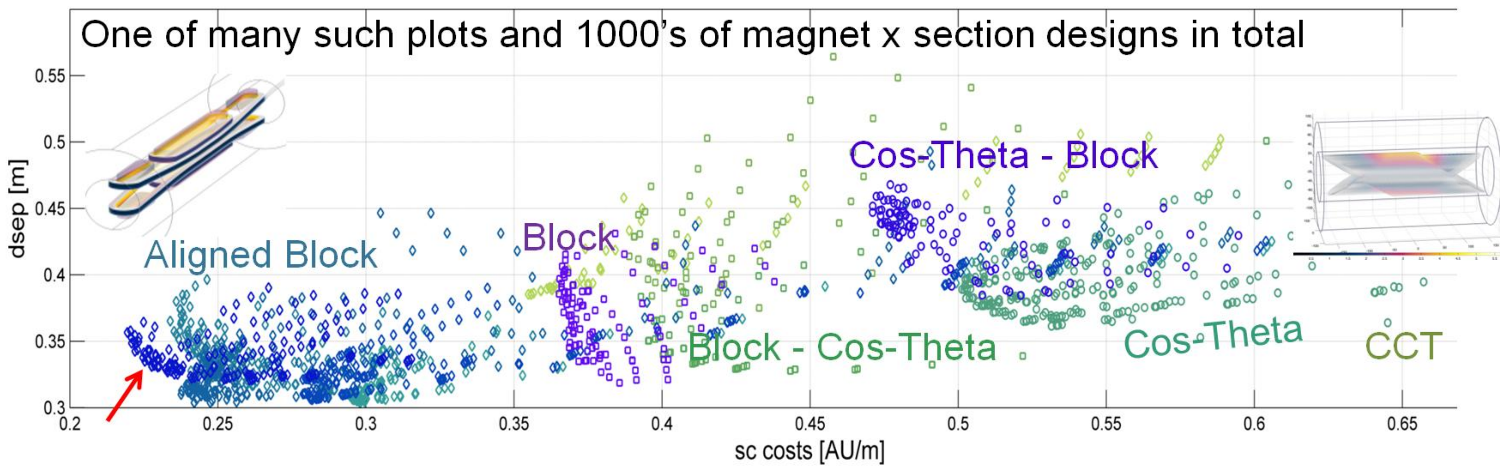
5

Survey of 20 T Magnet design possibilities

Courtesy:
J. Van Nugteren

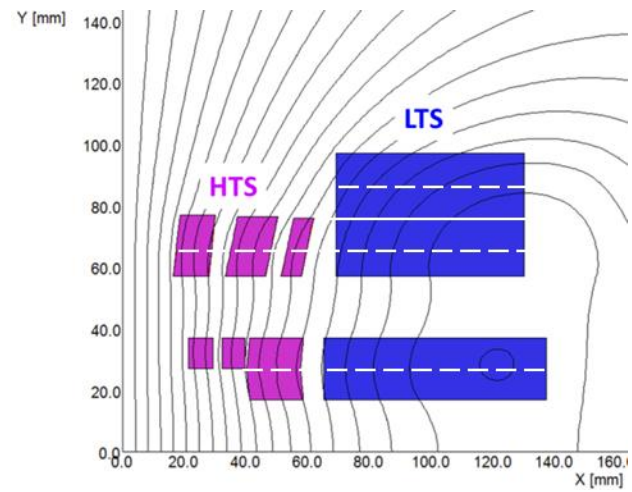


Jeroen Van Nugteren PhD student @ CERN



Other Benefits of Such Designs

- Lorentz forces are primarily on the wide face of conductor
  - ➢ ReBCO can tolerate large stresses on wide side
- Blocks are easy to segment
  - ➢ Between HTS and LTS
  - ➢ Stress management



Part of PBL/BNL Provisional Patent Application

High Current Conductor/Cable

Success of this approach may impact the conductor optimization:

- Attempt to increase isotropy should not sacrifice field parallel I_c
  - However, a broader peak (5-10 degrees) would simplify the magnet design
- Attempt to increase field parallel I_c rather than field perpendicular I_c
- Present value of field parallel I_c is over 3 kA for single tape
  - This is likely to increase as ReBCO thickness becomes ~1 μm to several μm
- Develop simple multi-tape (bonded, multi-ply, …) conductor
  - This increases kA value of conductor
  - This should make conductor more robust as current may bypass from one tape to another (as in "no-insulation") in case of local defect or variation
- Develop wide multi-tape (say four, or more) with copper laminations on either side
  - Perform experiments on how effective such conductor is in magnet coils

A dream conductor may be an optimized multi-tape configuration : 10-20 kA @ design

Test of Principle in A Real Magnet

(measure and compare magnetization in two configurations)

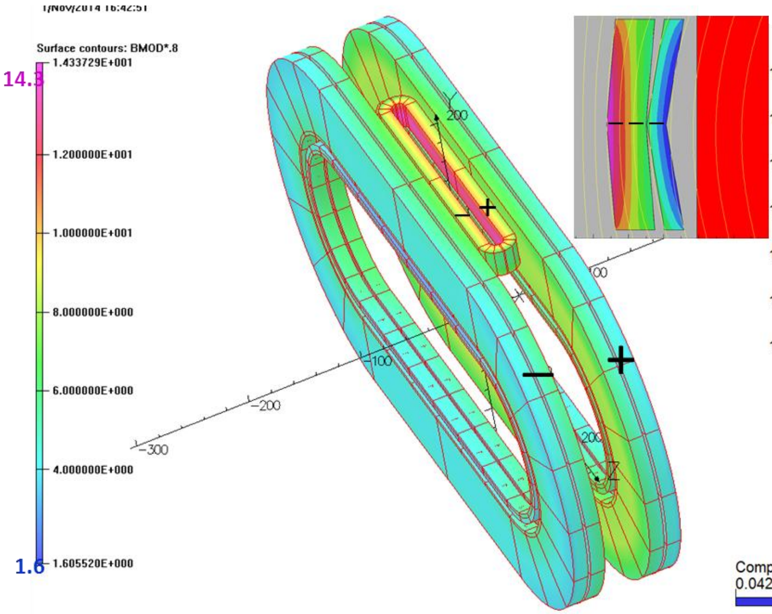
Common Coil Dipole with a large open space

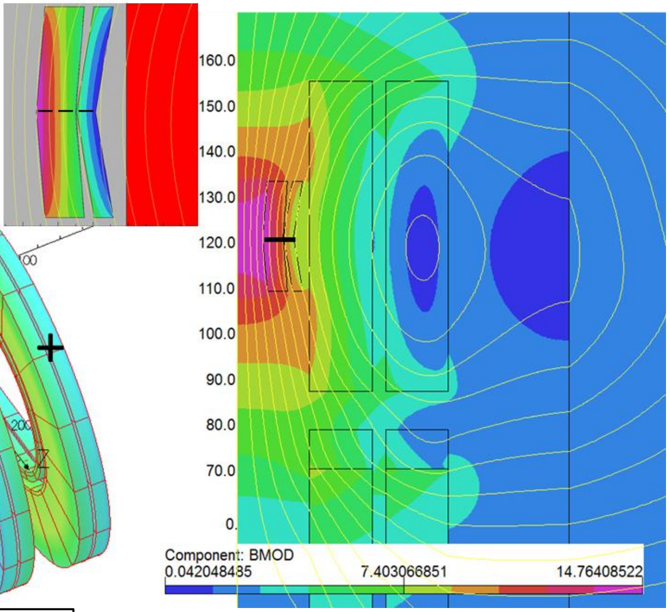
- Coils can be inserted without opening the magnet

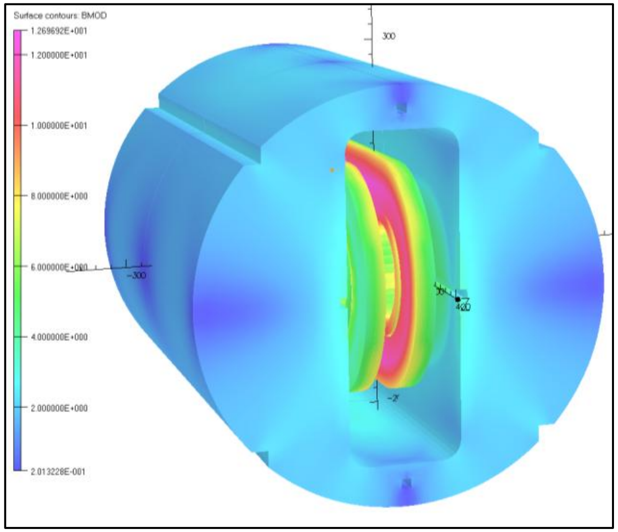
A Hybrid HTS/LTS …High-Field Accelerator Magnets

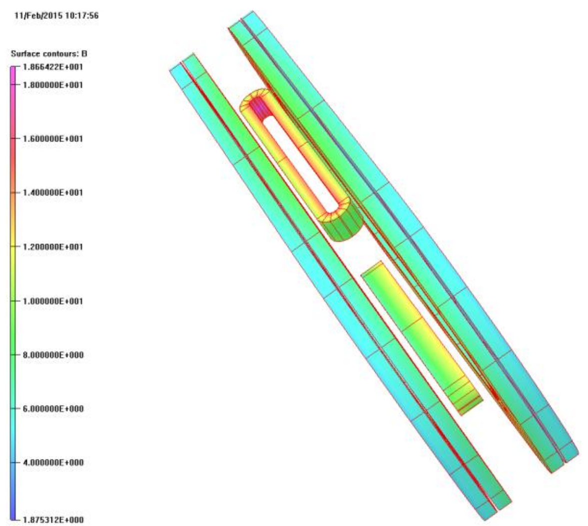
- Pending Phase II PBL/BNL STTR Application

Part of PBL/BNL Provisional Patent Application







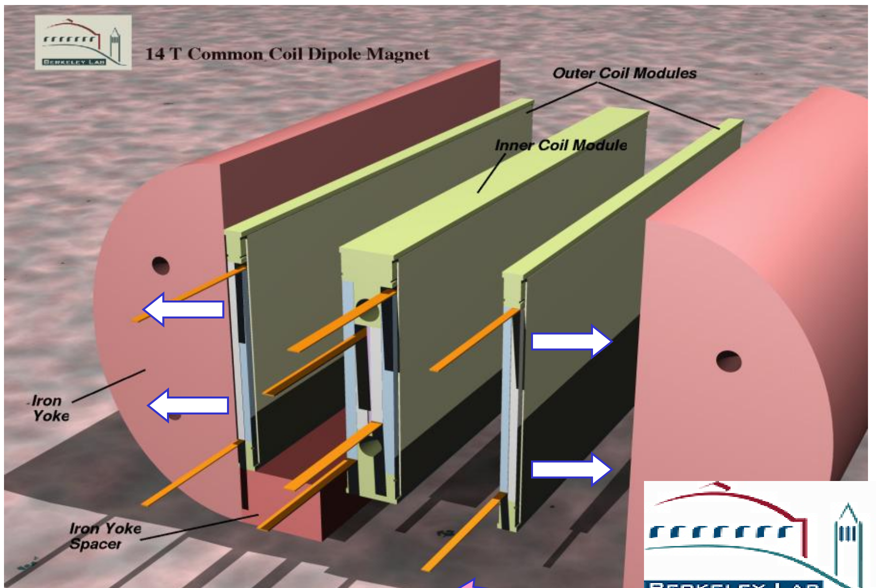


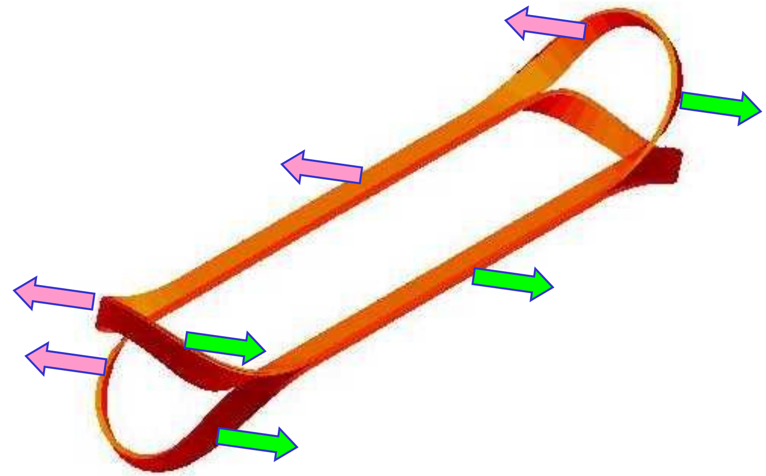
Common Coil Dipole

- **15 T Design : Nb_3Sn or Nb_3Sn/NbTi (LTS only)**
- **20 T Design : HTS/LTS Hybrid**

Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

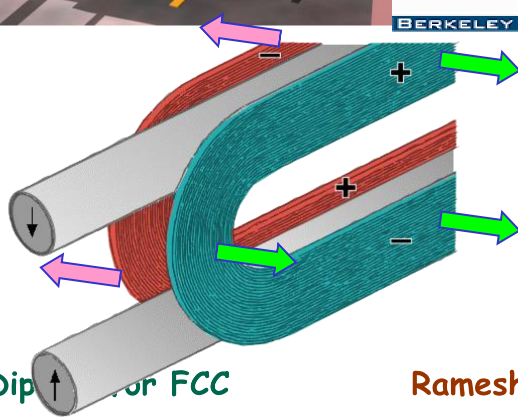
In common coil design, a racetrack coil can move as a block, without straining the conductor in the ends and thus minimize quench or damage.





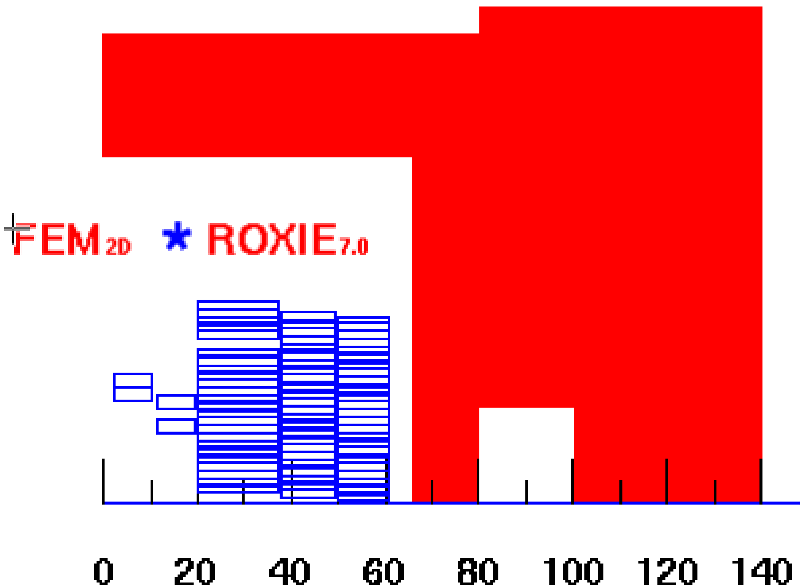
In cosine theta or conventional block coil designs, the coil module cannot move as a block. Therefore, Lorentz forces put strain on the conductor at the ends which may cause premature quench.

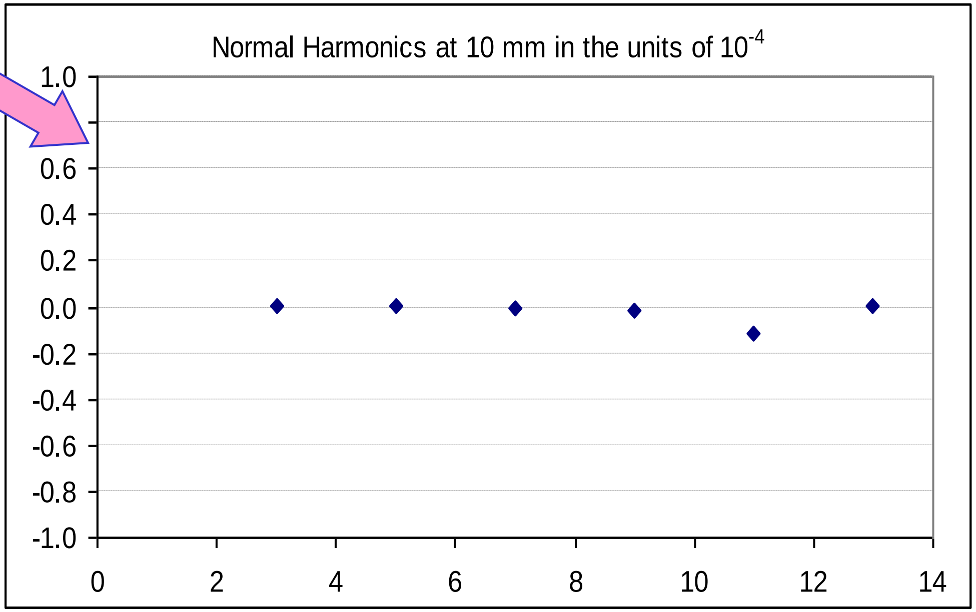
Horizontal forces are larger



Demonstration of Good Field Quality (Geometric Harmonics)

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





(from 1/4 model)

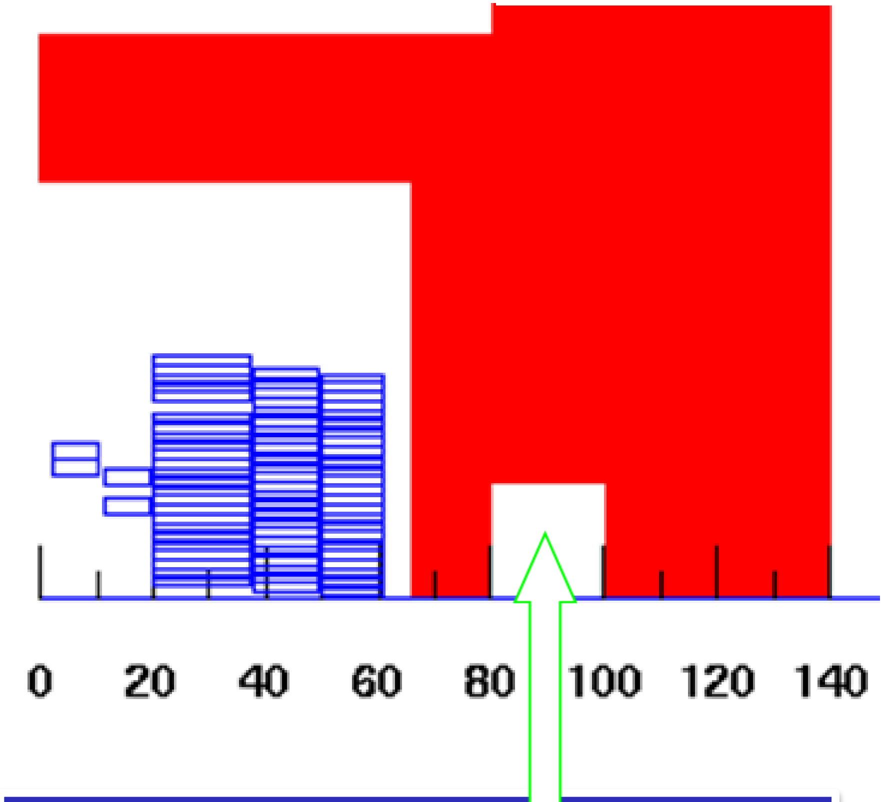
MAIN FIELD: -1.86463 (IRON AND AIR):

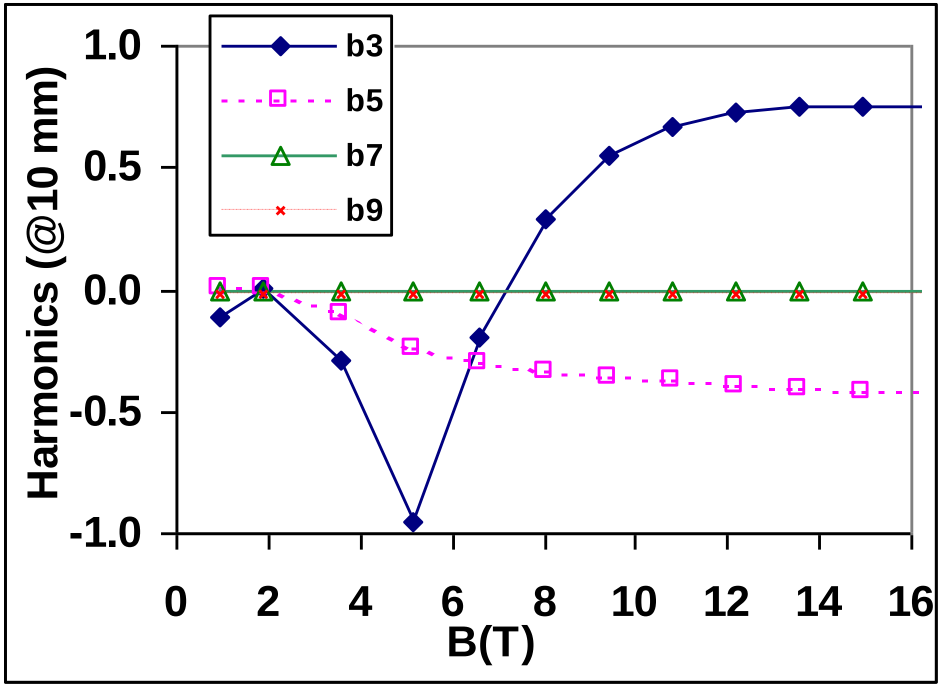
b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

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)





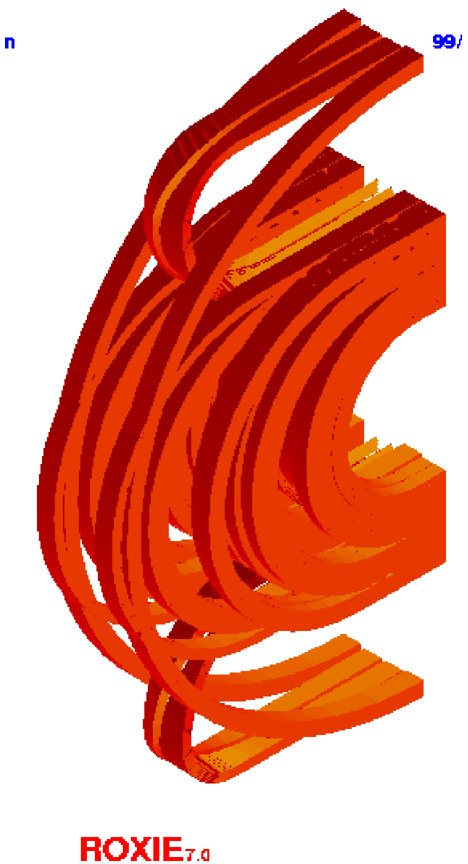
Use cutouts at strategic places in yoke iron to control the saturation

Low saturation-induced harmonics (within 1 unit)

Demonstration of Good Field Quality (End Harmonics)

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

(Very small)

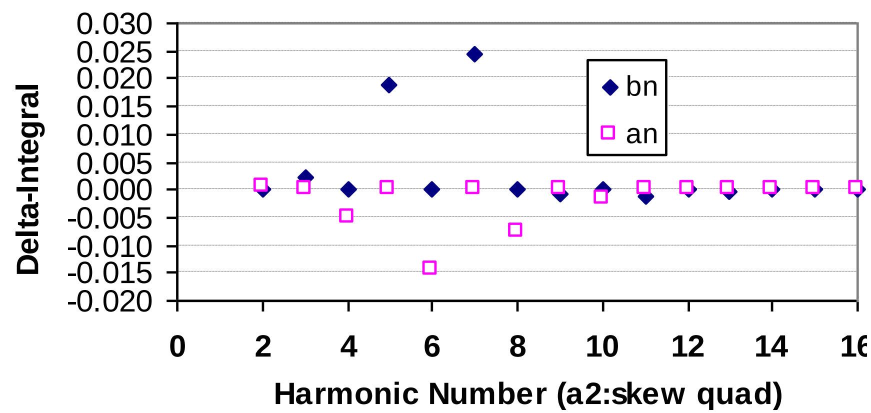


End harmonics in Unit-m

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



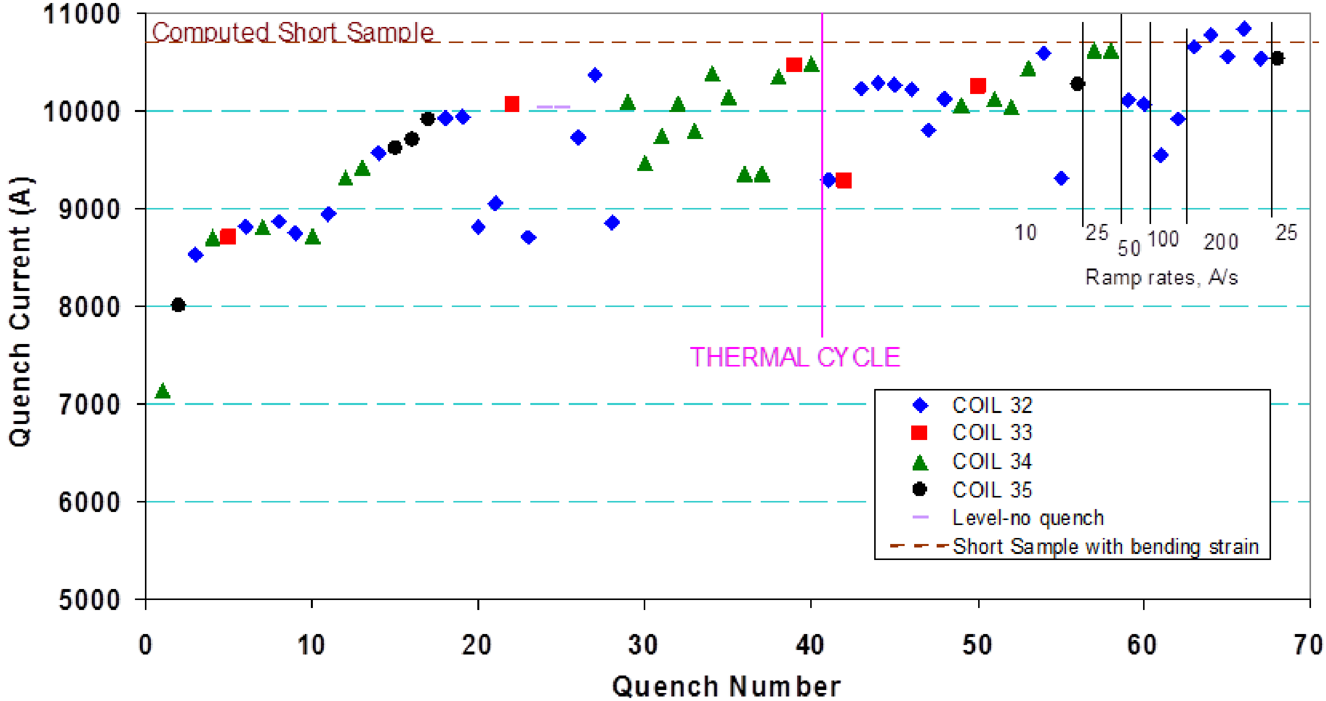
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

BNL Nb_3Sn React & Wind Common Coil Dipole DCC017

Large vertical open space for insert coil testing

Performance of React & Wind Common Coil 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
  - ➢ computed horizontal deflection/movement of the coil as a whole ~200 μm

Relevance to Nb3Sn Conductor, etc.

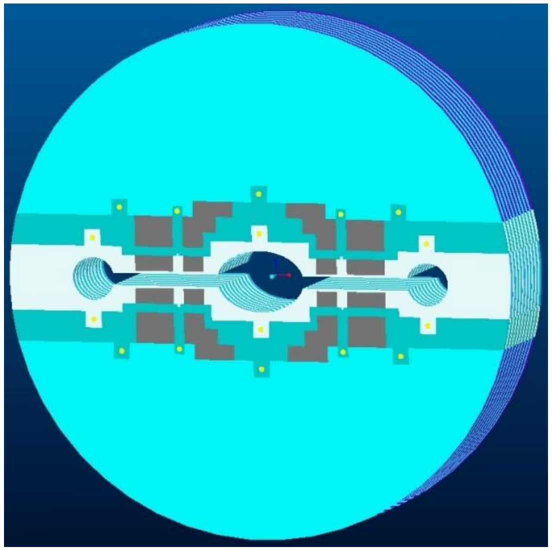
Large bend radius in common coil design also allows the alternate "React & Wind" Approach. "React & Wind" offers the following:

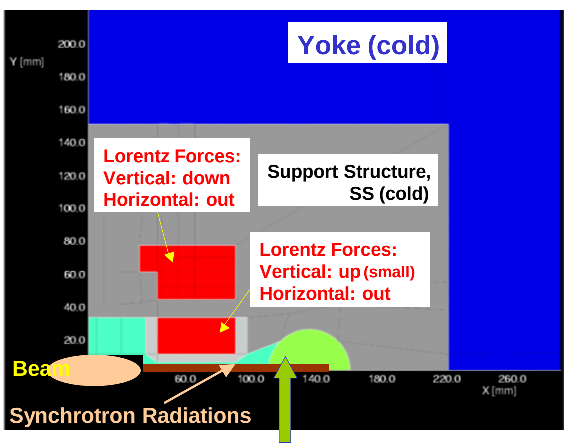
- Allows a larger choices for insulation and other coil material as the coil doesn't have to go through the high temperature reaction process.
- Surprises during scale-up to longer length should be much less of a concern than that in the "Wind & React" approach
- Another minor advantage (though only for a short time scale) that it requires much less expensive tooling to start the R&D magnet production (short or long) as many steps and care involved in coil reaction process are not applicable.
- The "React & Wind" design puts extra consideration on the conductor development. Even though common coil design allows a larger bending radius, the strain dependence degradation should be minimized for high field applications.

Open Midplane Dipole

- **15 T Design : Nb_3Sn or Nb_3Sn/NbTi (LTS only)**
- **20 T Design : HTS/LTS Hybrid**

A True Open Midplane Design Design (no structure at the midplane)





Synchrotron radiations deposit energy in a warm absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

• In a true open midplane dipole, synchrotron radiations deposit most energy in a warm absorber that is sufficiently away from the superconducting coils or cold structure.

• In a "partial open midplane design", although there are "no conductors" at the midplane, there is "structure" between the upper and lower coils. That structure helps in dealing with the Lorentz forces but it also absorbs energy at 4 K and creates secondary showers which then deposit additional energy at 4 K.

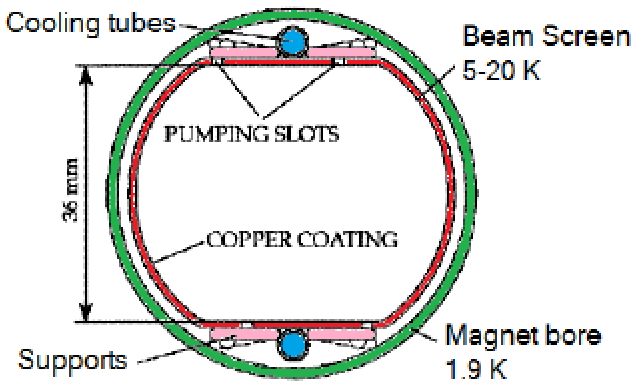
• Therefore, a "true open midplane dipole" is preferred, provided a viable design can be proven.

Open Midplane Dipole for FCC (as championed by Bob Palmer)

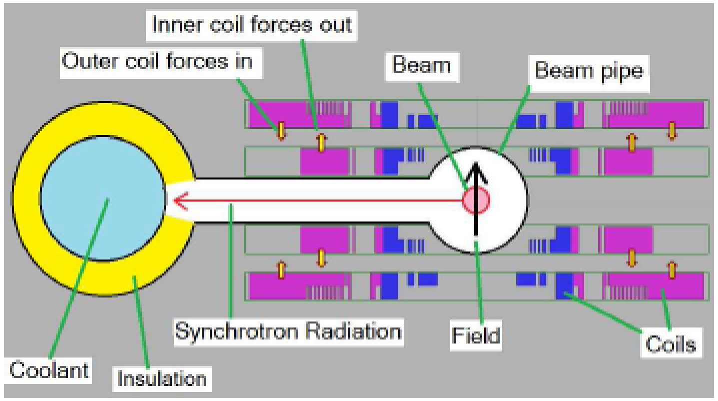
SYNCHROTRON RADIATION

In 100TeV p-p collider (CERN FCC-hh) 0.5 amp 16 T:

- Total SR power = 4.8 MW
- If on magnet bore: wall power to cool is crazy
- Requires beam screen at 50 K
- If screen inside beam pipe: uses valuable space
- If screen in beam tube: Emits electrons ⟶ electron cloud
- If deposited away from beam tube, as in e+e- ring colliders, BOTH PROBLEMS SOLVED



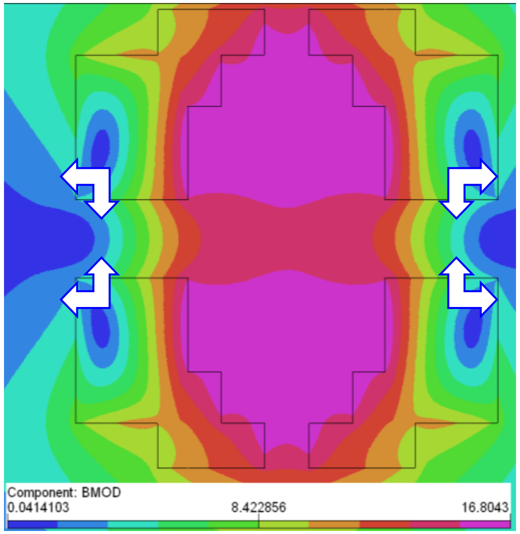
CERN Beam Screen

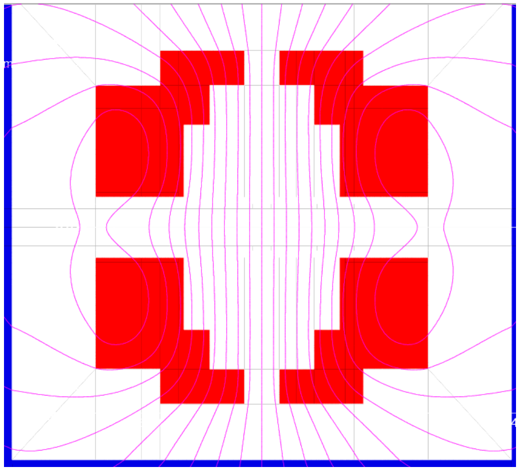


With Open-Plane Magnet

Courtesy: Bob Palmer, BNL

Challenges associated with the "Ideal" or "True" Open Midplane Dipole Design





#1 In usual cosine theta or block coil designs, there are large attractive forces between upper and lower coils. How can these coils hang in air with no structure in between?

#2 The ratio of peak field in the coil to the design field appears to become large for large midplane gaps.

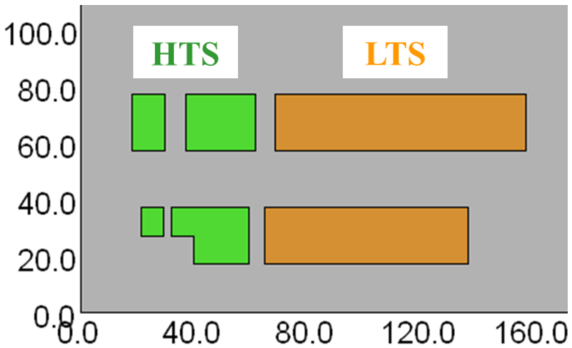
#3 The large gap at midplane appears to make obtaining good field quality a challenging task. Gap requirements are such that a significant portion of the cosine theta, which normally plays a major role in generating field and field quality, must be taken out from the coil structure.

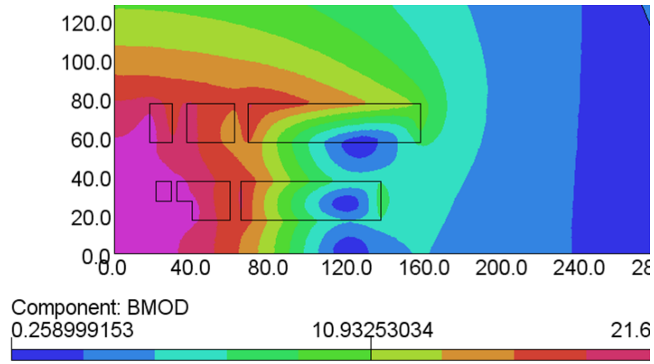
⇨ Several innovative design solutions were developed to overcome above challenges (please see extra slides) with significant funding from LARP. The R&D was terminated before those solutions could be demonstrated.

We get another chance now – either through SBIR and/or direct funding

A Proof of Principle Demonstration of A True Open Midplane Dipole

A 20 T Hybrid Design (HTS & LTS well separated)





Can one have coils energized with no structure between upper and lower halves at midplane?

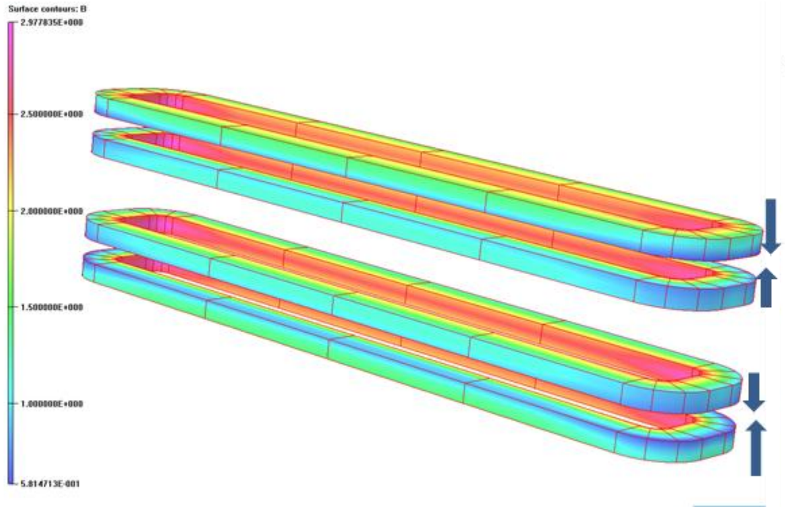
Proof of Principle Demonstration with HTS Coils at 77 K (proposed in Phase I itself)

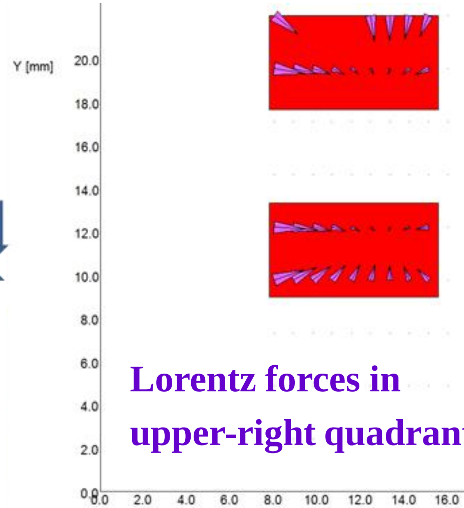
(HTS demo magnets can be cheap to build and test – custom made for graduate research)

e2P Energy to Power Solutions

Novel High Field Hybrid Open Mid-Plane Dipole Coil

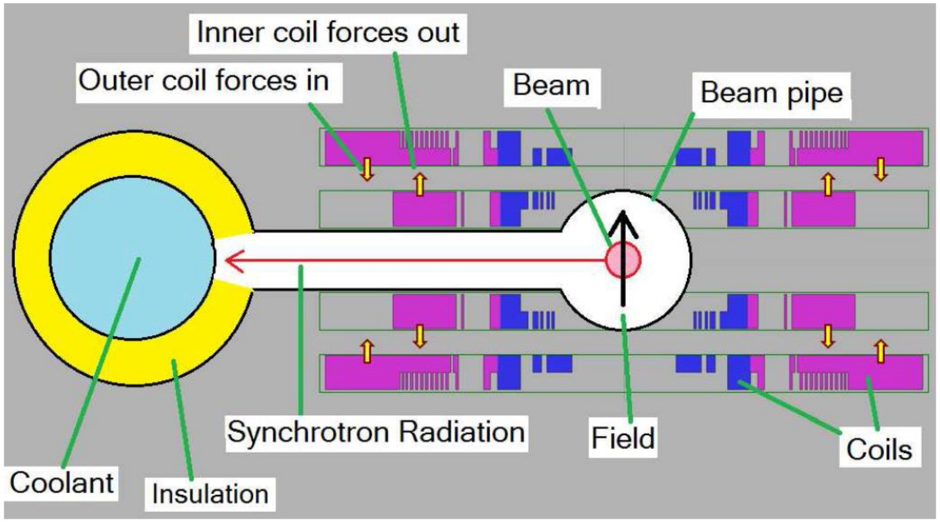
- Phase I E2P/BNL SBIR Application

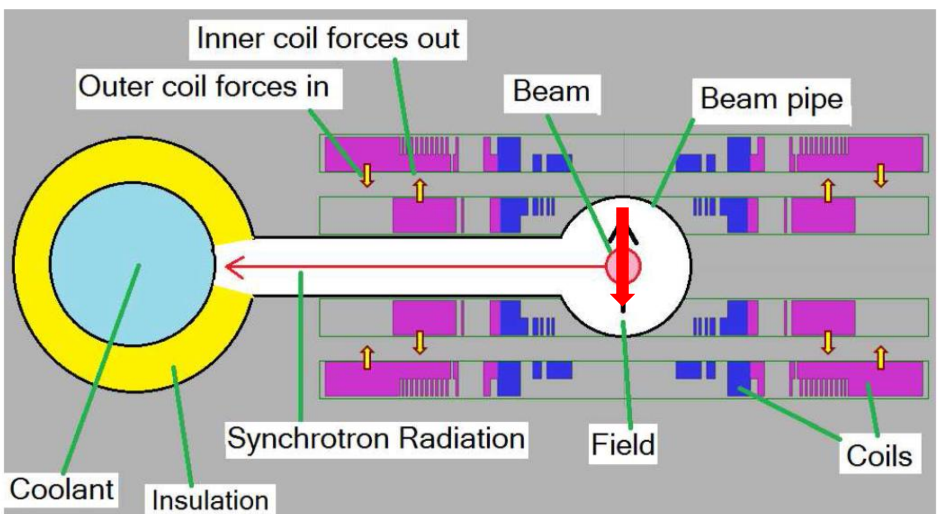




Lorentz forces in upper-right quadrant

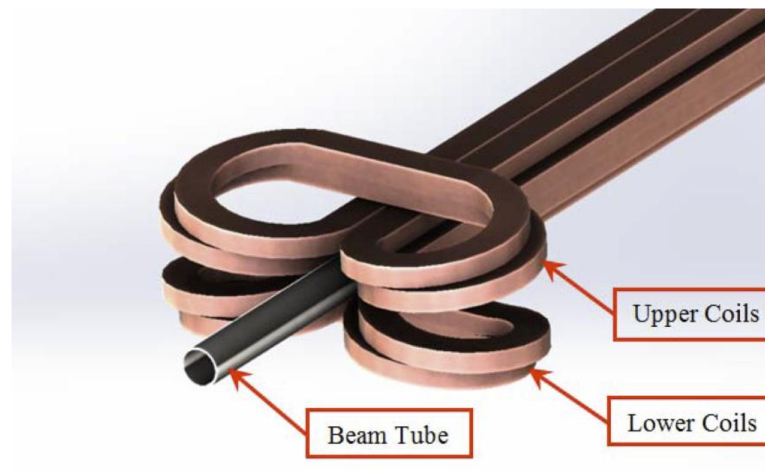
Common Coil Open Midplane Dipole?





Tolerate some perturbation in the ends where turns go from one aperture to another

- Nb_3Sn coil go from upper aperture to lower aperture (as in common coil) but HTS coil within the same while clearing the bore (developed for LHC magnets - ASC2002).
- Such windings allows wide side of the HTS tape align parallel to the field.



From Phase I proposal

Novel High Field Hybrid

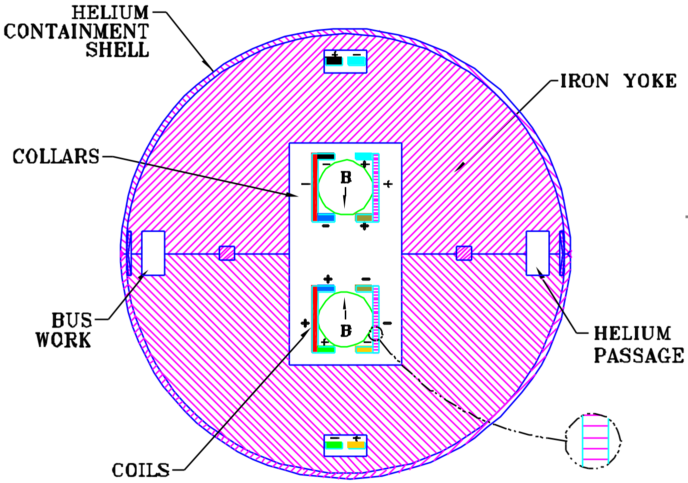
Open Mid-Plane Dipole Coil

Energy to Power Solutions

SUMMARY

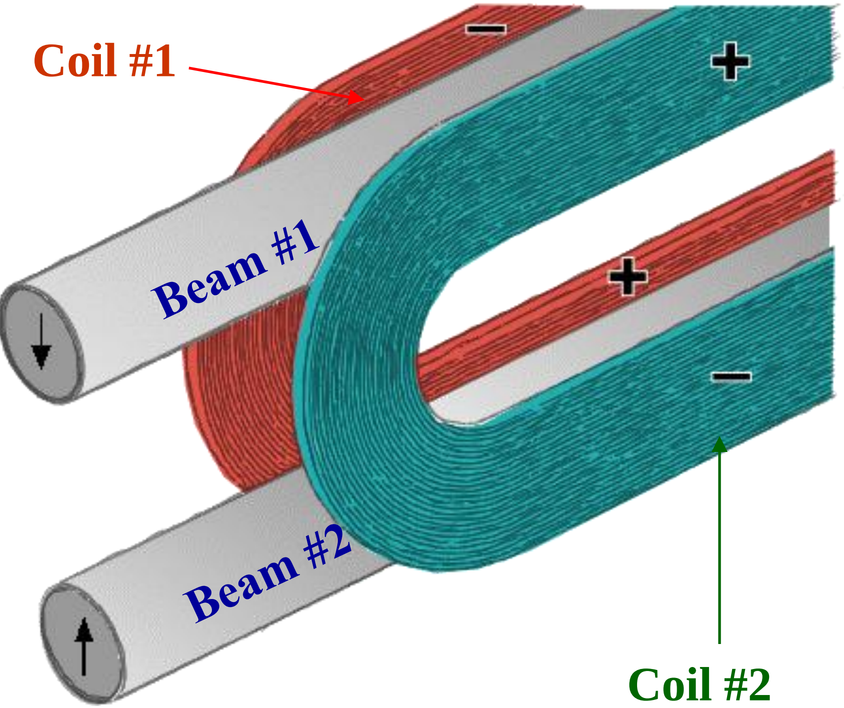
- High field hybrid magnet designs can be developed in such a way that the conductor magnetization (persistent current induced harmonics) become significantly less, overcoming a major technical issue associated with the tape.
- It may be possible to design the high field hybrid magnets with ReBCO tape configuration carrying over 10 kA current.
- Such designs can handle large stresses, as present in high field magnets, as they are against the wider side of the tape.
- Requirements of expensive conductor are significantly reduced because of the field orientation (previous design work at CERN).
- Degree of above benefits need to be determined by model calculations and demonstration. A cost effective systematic R&D could be carried out with a unique background field common coil magnet available for testing at BNL.
- Common coil dipole (either "Nb_3Sn" or "Hybrid" and either "React & Wind" or "Wind & React") could handle large forces.
- Open midplane dipole allows the significant reduction of the heat load on the superconducting coils and on cryogenic system.

Extra Slides



Common Coil Design

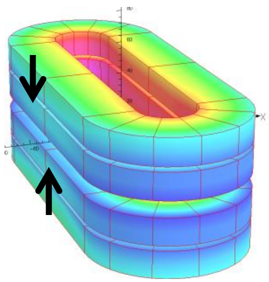
- **Simple 2-d geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly (suitable for brittle materials – can do both Wind & React and React & Wind with LTS and HTS)**
- **Compact (compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)**
- **Special coil geometry (suitable for large Lorentz forces at high fields)**
- **Efficient and methodical R&D due to simple & modular design**
- **Minimum requirements on expensive tooling and labor**
- **Successfully built at LBL, BNL & FNAL**
- **Lower cost magnets expected**



Main Coils of the *Common Coil Design*

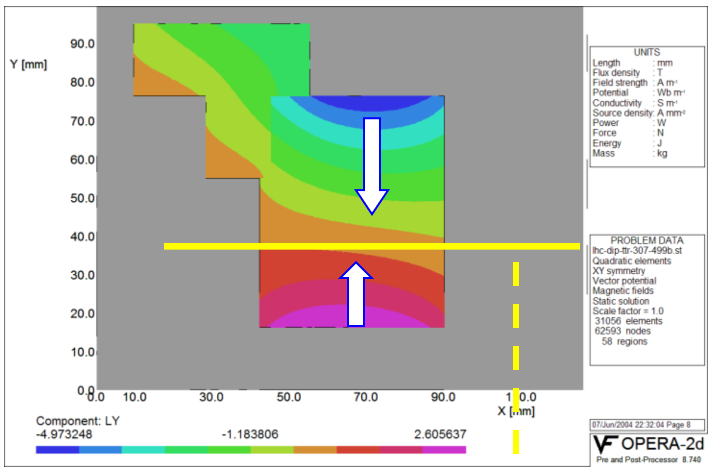
Challenge #1: Lorentz Forces between coils

A new and major consideration in design optimization



In conventional designs the upper and lower coils rest (react) against each other. In a truly open midplane design, the target is to have no structure between upper and lower coils. Structure generates large heat loads and the goal is to minimize them.

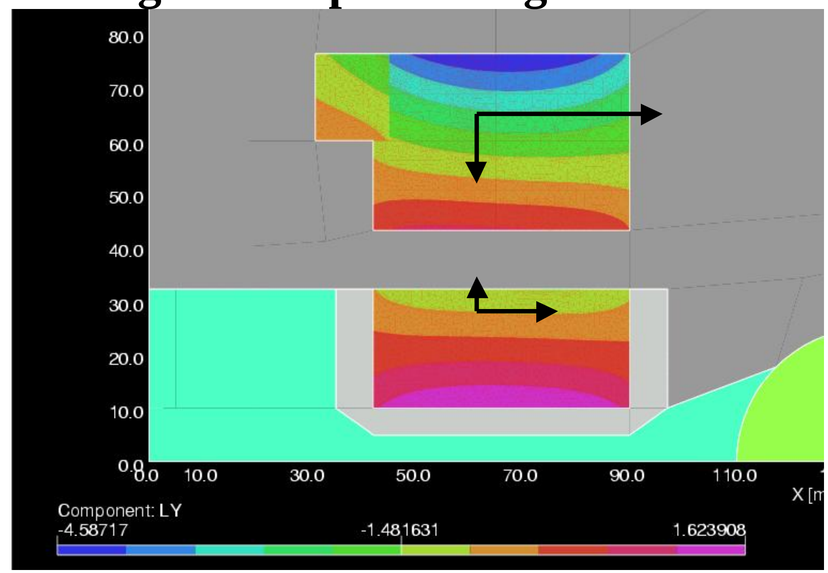
Original Design



Zero vertical force line

Lorentz force density (Vertical)

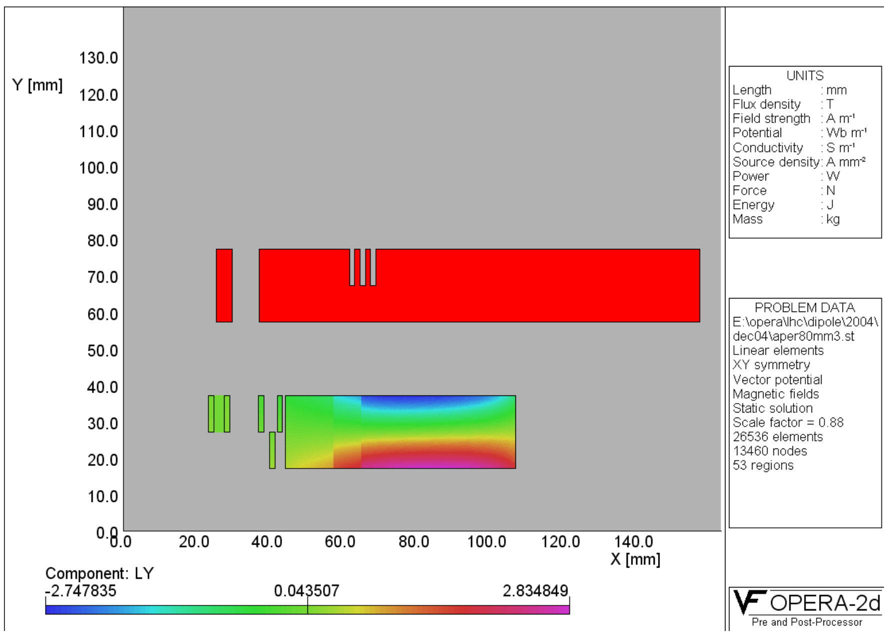
New Design Concept to navigate Lorentz forces



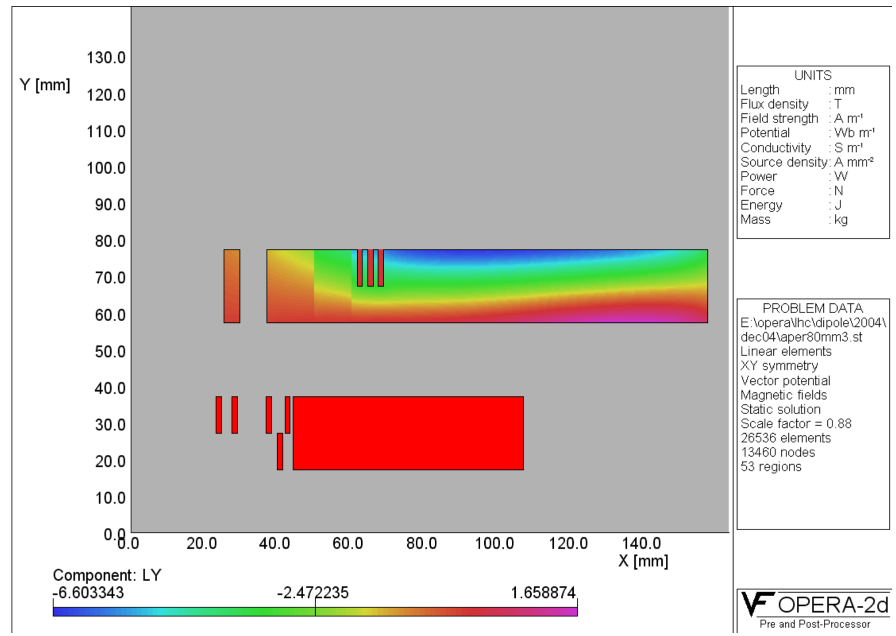
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

Vertical Forces at 15 T
(design optimized to first order)

Net upward vertical force on lower double pancake coil



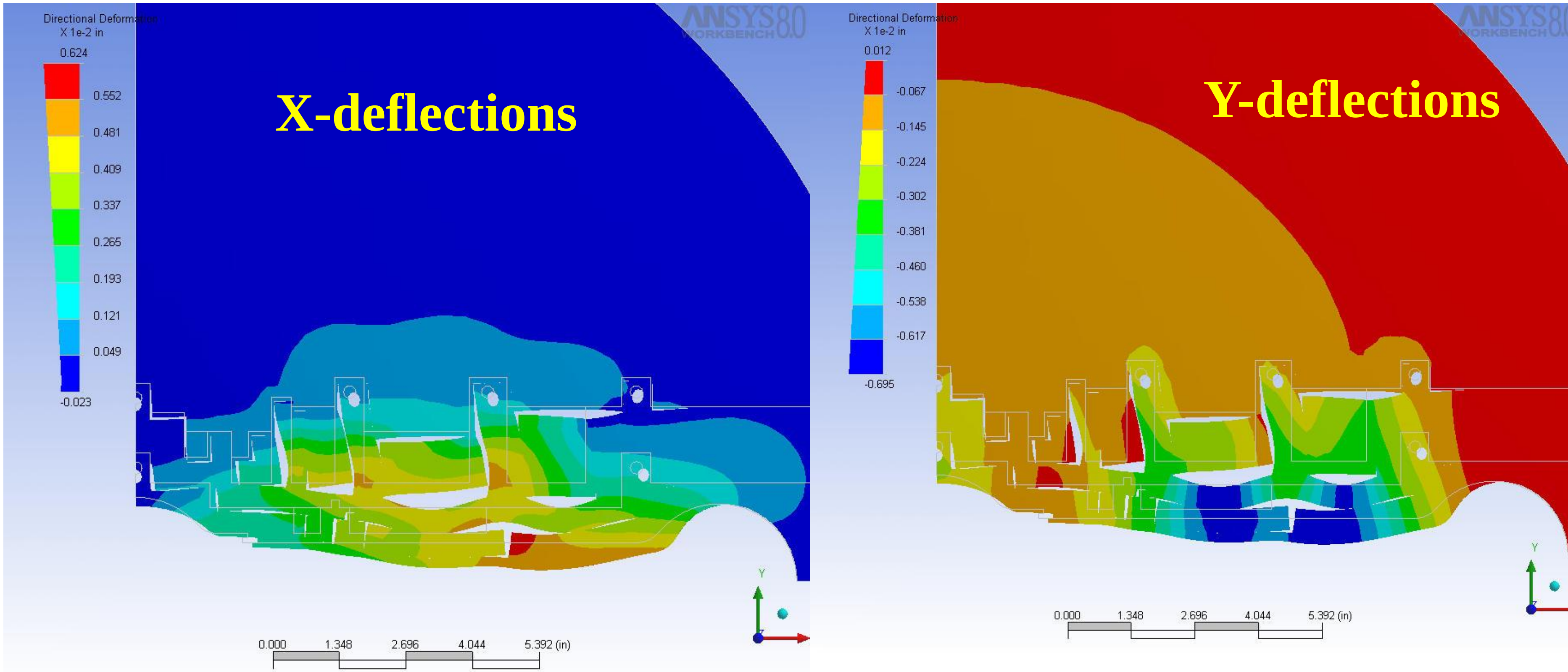
Downward vertical force on upper double pancake coil is taken by the support structure between two double pancake coils



Net Force per quadrant:

Horizontal = 11 MN/m; Vertical –5.4 MN/m

Mechanical Analysis (J. Schmalzle)



In a more optimized design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron)

Above deflections are at design field (13.6 T). They are ~1-2 mil higher at 15 T.

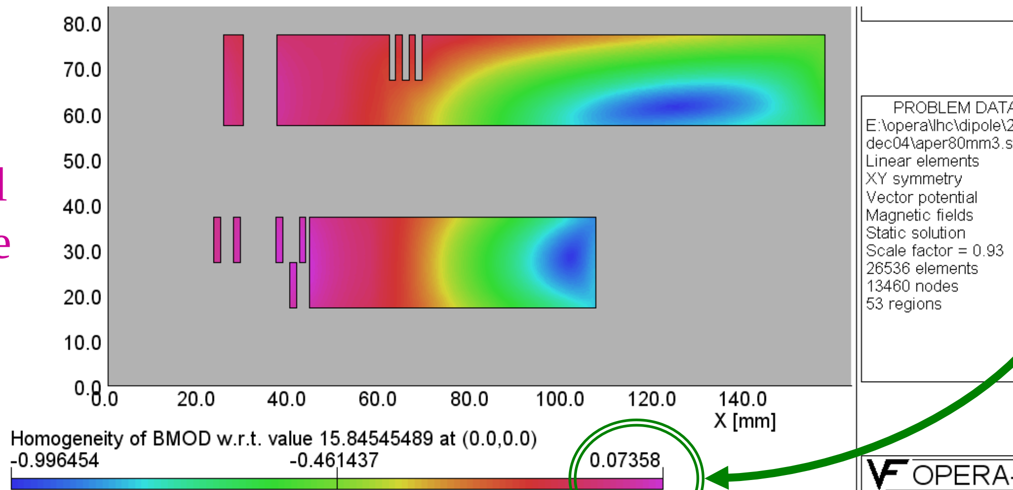
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

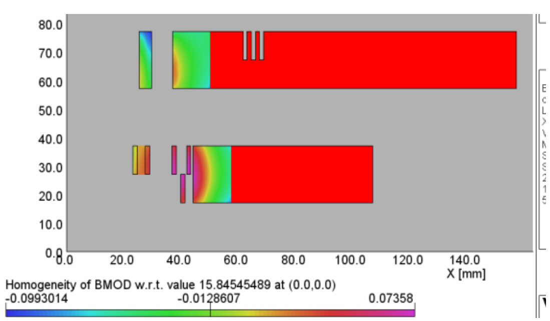
Challenge #2: Peak Field

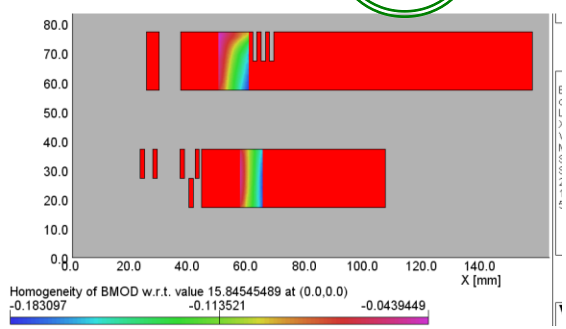
Several designs have been optimized with a small peak enhancement: ~7% over B_o

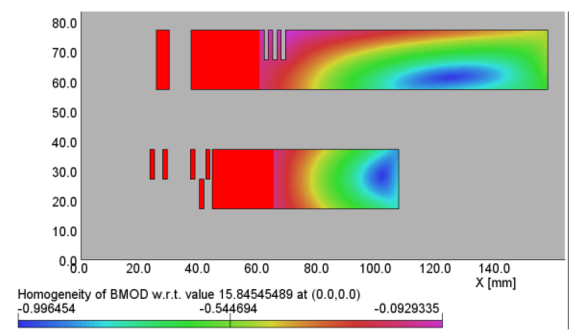
Relative field enhancement in coil (peak field) over the central field



Similar to that in an optimized cosine theta designs







Quench Field: ~16 T with J_c = 3000 A/mm^2, Cu/Non-cu = 0.85

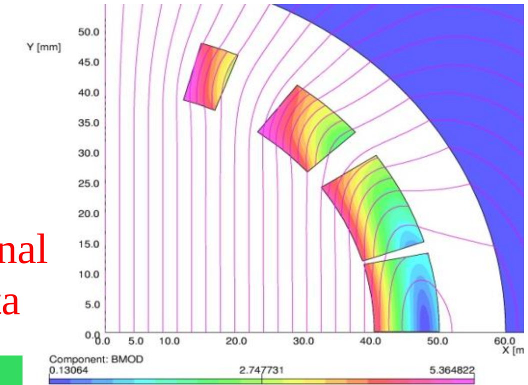
Quench Field: ~15.8 T with J_c = 3000 A/mm^2, Cu/Non-cu = 1.0

Challenge #3: Field Quality

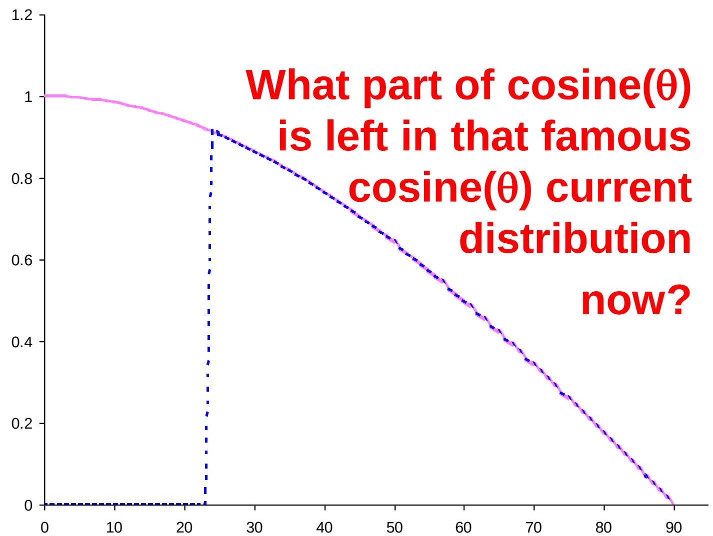
Coil-to-coil gap in this design = 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

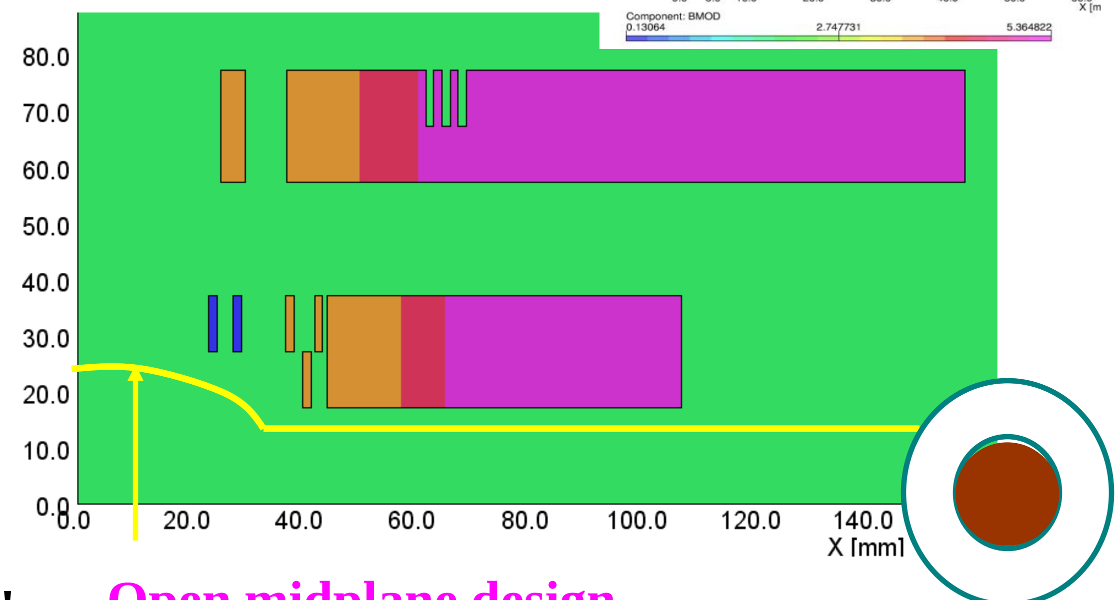
⇒ Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)



Conventional cosine theta



What part of cosine(θ) is left in that famous cosine(θ) current distribution now?



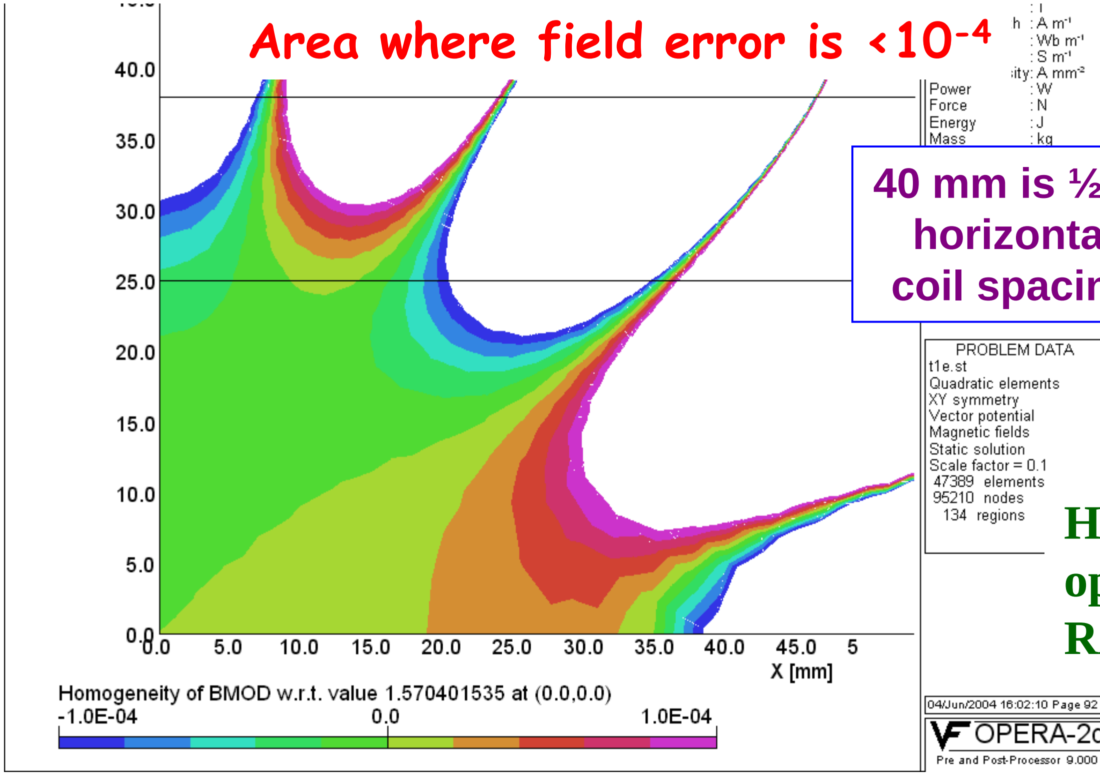
This makes obtaining high field and high field quality a challenging task !

Open midplane design

We did not let prejudices come in our way of optimizing coil - e.g. that the coil must create some thing like cosine theta current distribution !

Field Harmonics and Relative Field Errors in an Optimized Design

Proof: Good field quality design can be obtained in such a challenging design:



(Beam @ x=+/- 36 mm at far end)

(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

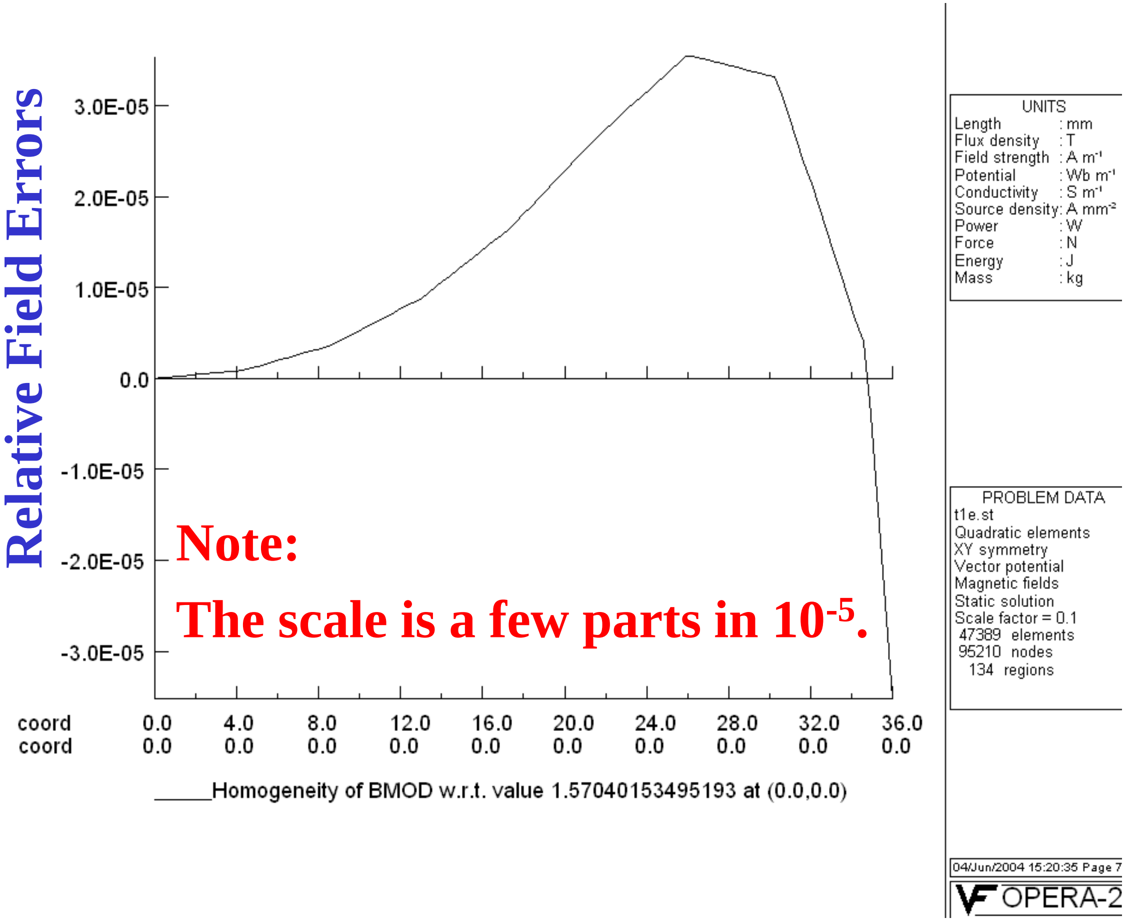
	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
16	0.00	0.00
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

Harmonics optimized by RACE2dOPT

Field errors should be minimized for actual beam trajectory & beam size.
It was sort of done when the design concept was being optimized by hand.
Optimization programs are being modified to include various scenarios.
Waiting for feed back from Beam Physicists on how best to optimize.
However, the design as such looks good and should be adequate.

Field Uniformity in an Optimized 15 T Open Midplane Dipole Design

Proof that good field quality can be obtained in such a wide open midplane dipole design:



The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

The actual field errors in these magnets will now be determined by construction, persistent currents, etc.; i.e., they are not limited by the design geometry.