16 T Dipole Magnet Design Options

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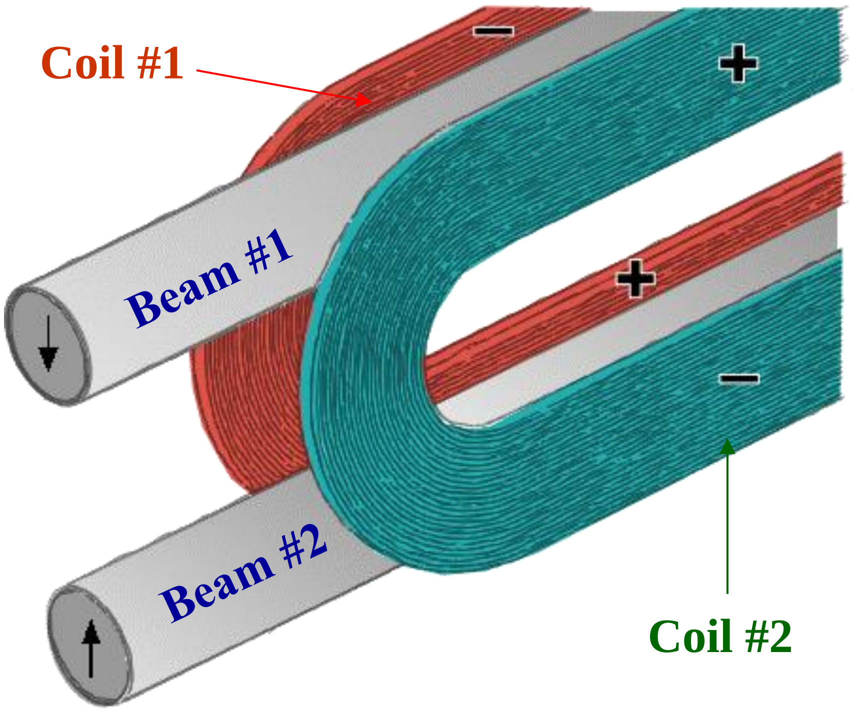
Overview

16 T Racetrack Coil Designs with Nb_3Sn

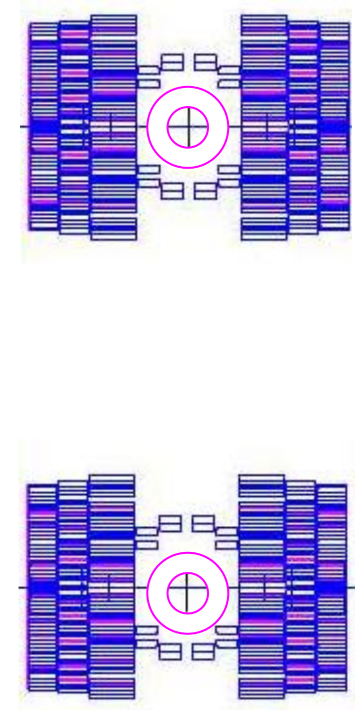
- **Common Coil Dipole**
  - **Simpler geometry and less number of coils**
  - **Design particularly attractive for high field 2-in-1 dipoles**
  - **Allows both "Wind & React" and "React & Wind"**
- **Open Midplane Dipole**
  - **Can tolerate larger synchrotron radiation**
  - **Relaxation in temperature margin**

Common Coil Design

Main Coils of the Common Coil Design



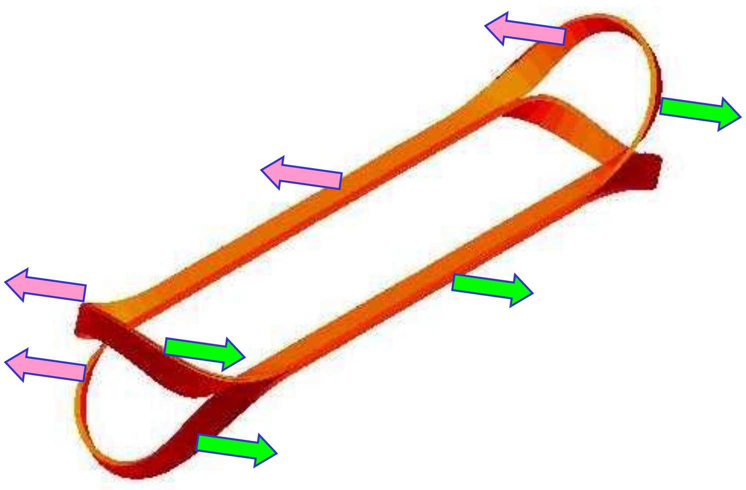
Bend radius is determined by the aperture spacing (large), not by the aperture (small)



Good Field Quality Common Coil Design

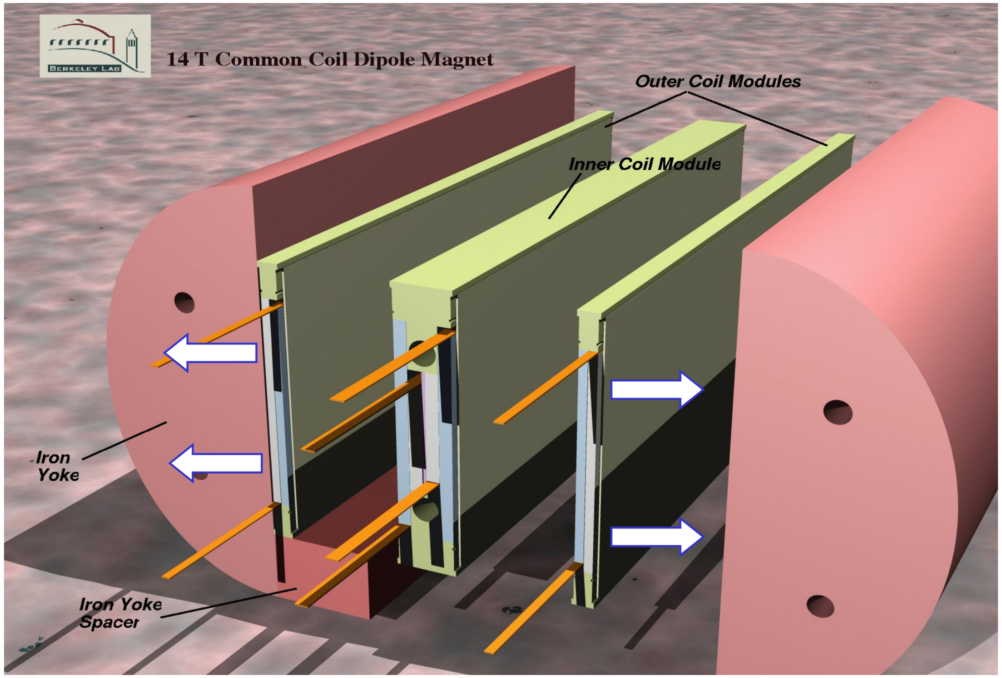
- **Simple coil geometry with large bend radii:** reliability & lower cost expected; suitable for both "Wind & React" and "React & Wind"
- **Same coil for two aperture:** Manufacturing cost should be lower as the number of coils required for 2-in-1 magnet is half
- **Coil aperture can be changed during the R&D** without much loss

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.

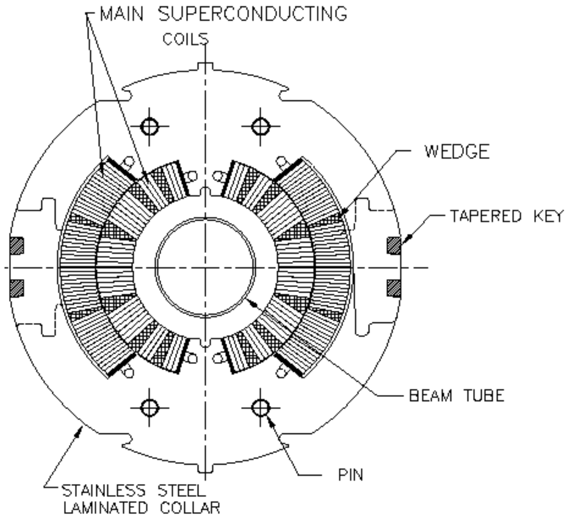
In cosine theta or conventional block coil designs, the coil module cannot move as a block. Therefore, Lorentz forces put strain on the conductor at the ends which may cause premature quench.



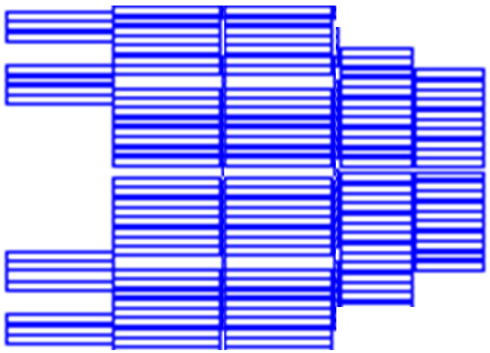
Coil Optimization in Block Designs (including in common coil)

- 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

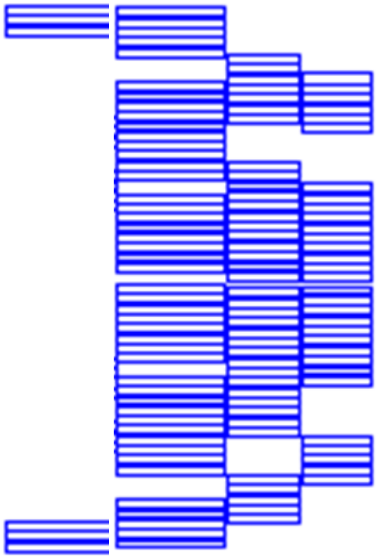
COS(θ)



More Efficient Design



Less Efficient Design

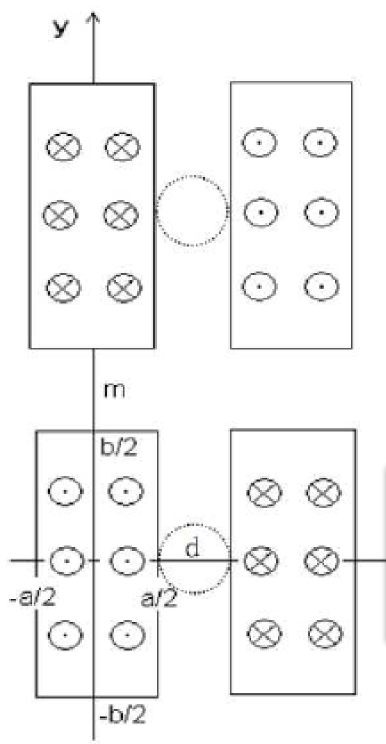


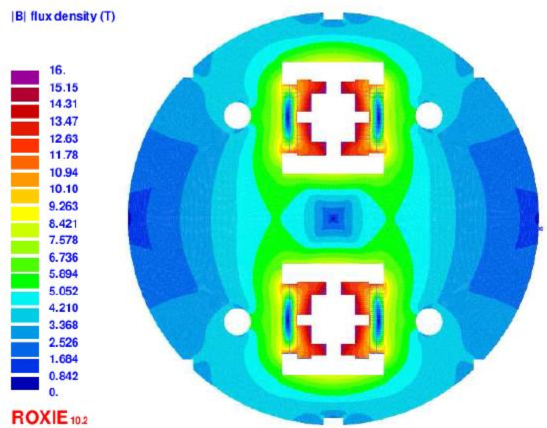
Analytical Tool/Guidance for Optimizing Common Coil Design

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

ASC2014

Qingjin Xu





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 $m/2$.

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

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

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

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

and

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

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

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

Optimized Magnetic Design

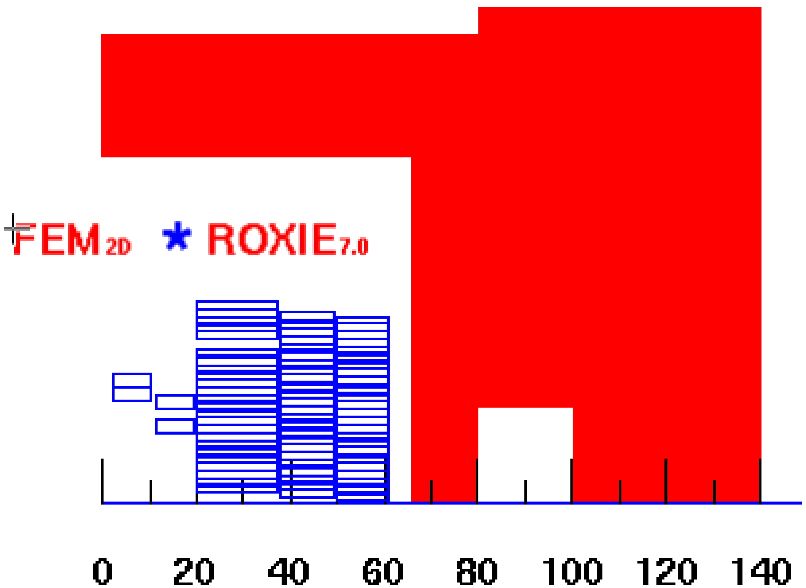
Good field quality design developed for:

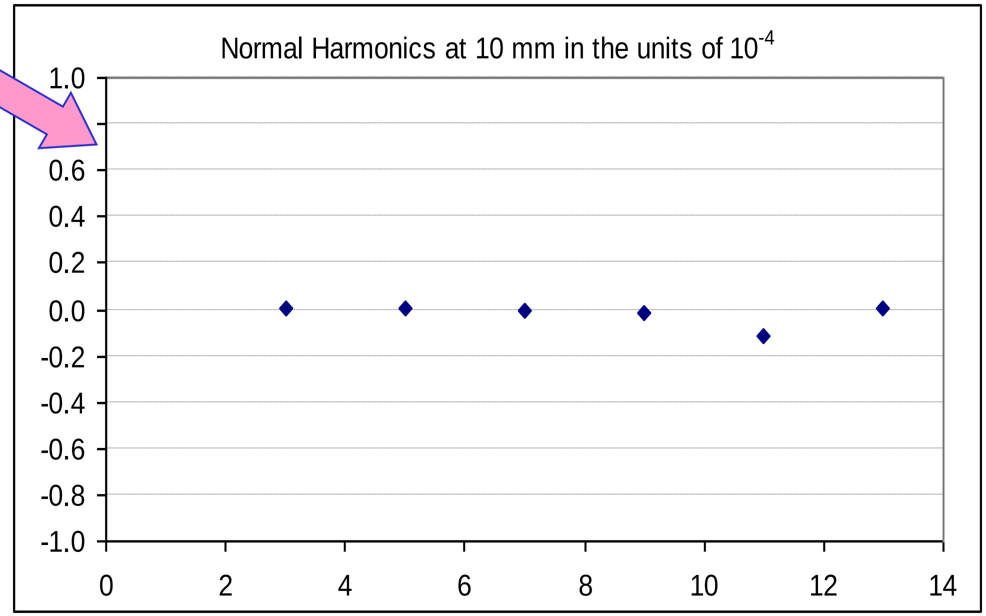
- Geometric harmonics
- Saturation-induced harmonics
- End harmonics

Fast-forward next several slides (presented earlier at MT and ASC)

Demonstration of Good Field Quality (Geometric Harmonics)

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





(from 1/4 model)

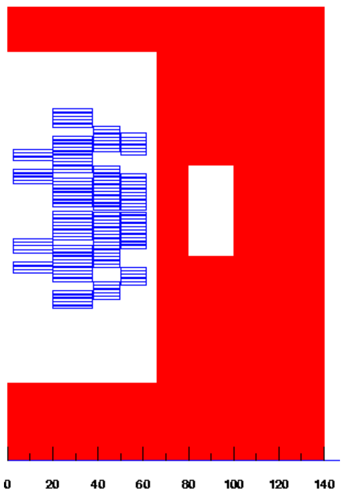
MAIN FIELD: -1.86463 (IRON AND AIR):

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

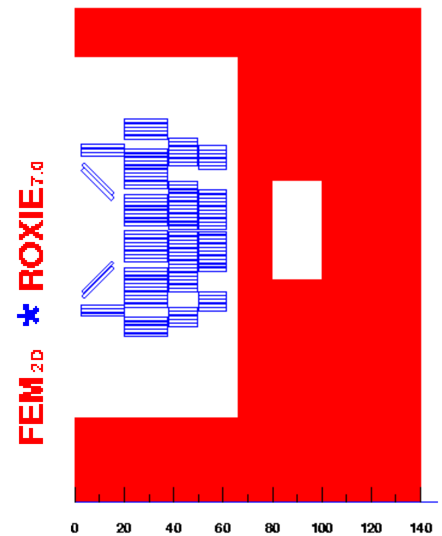
Horizontal coil aperture:

40 mm

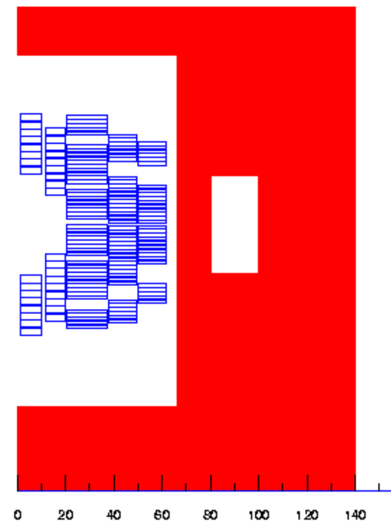
A Few Good Field Quality Configurations



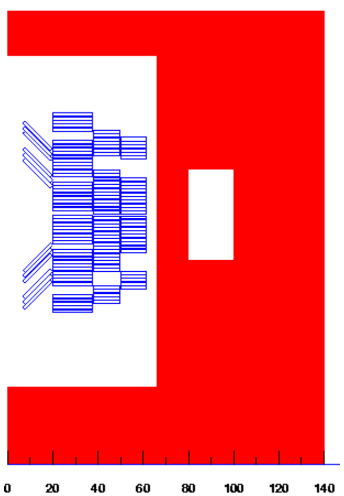
Case 1a



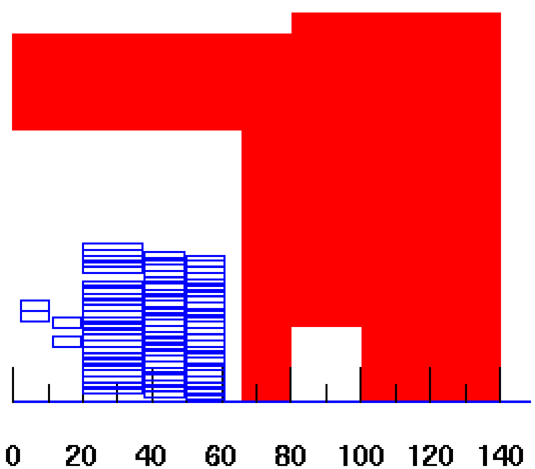
Case 1c

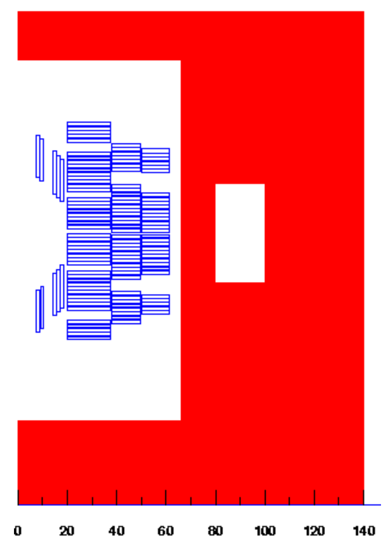


Case 2



Case 1b

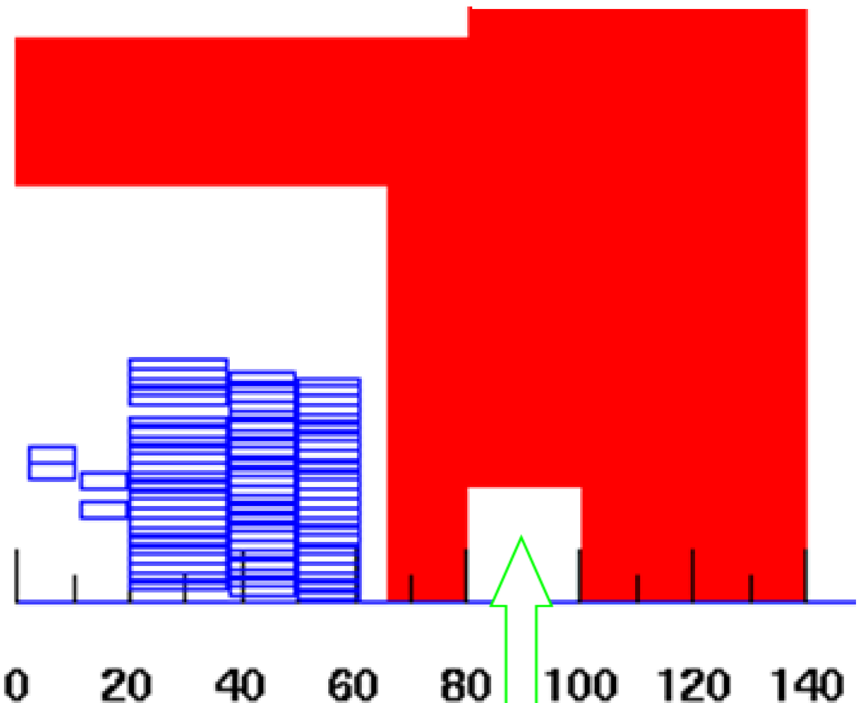




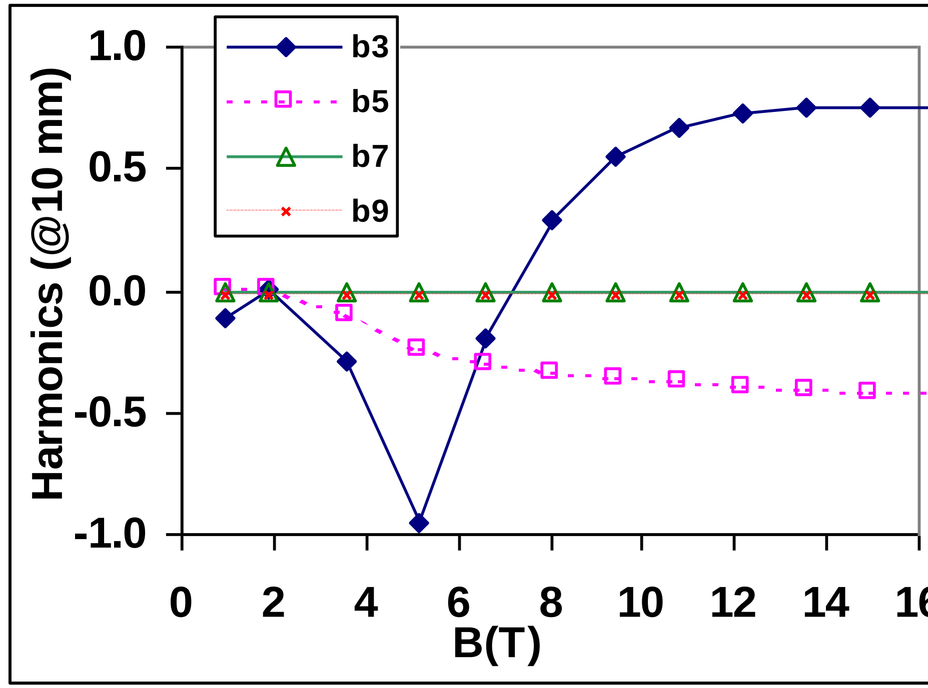
Case 3

Demonstration of Good Field Quality (Saturation-induced Harmonics)

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



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

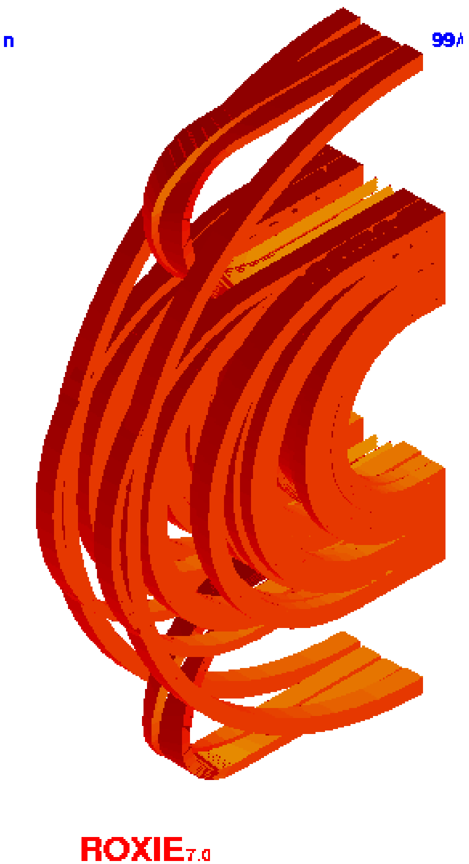


Low saturation-induced harmonics (within 1 unit)

Demonstration of Good Field Quality (End Harmonics)

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

(Very small)

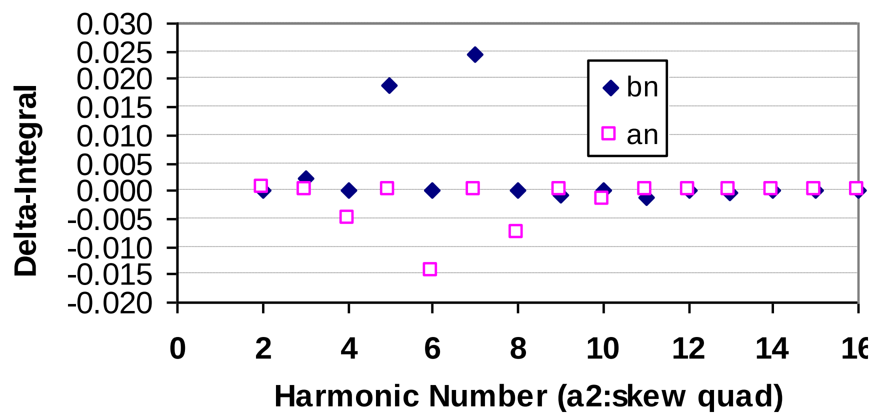


End harmonics in Unit-m

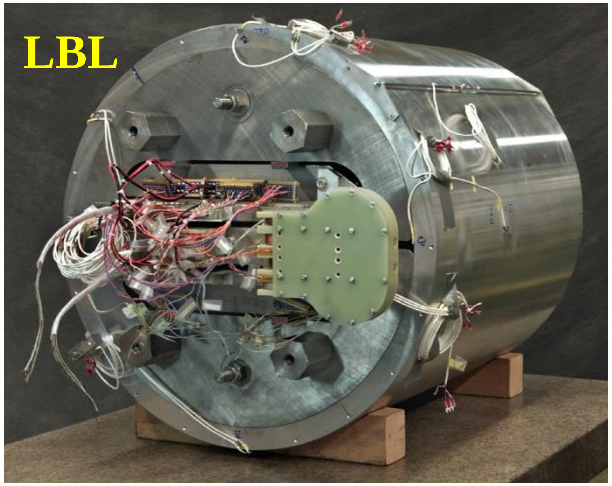
n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

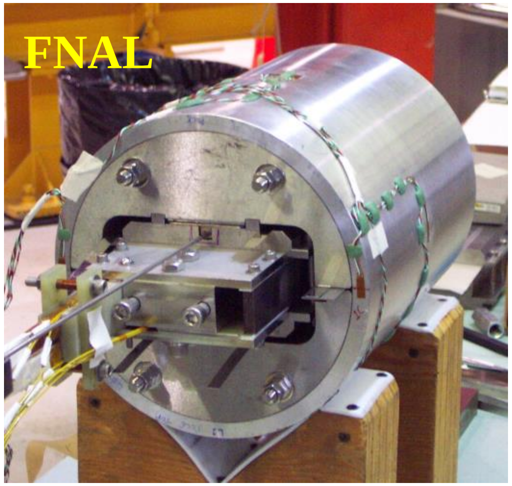
Contribution to integral (a_n,b_n) in a 14 m long dipole ($<10^{-6}$)

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



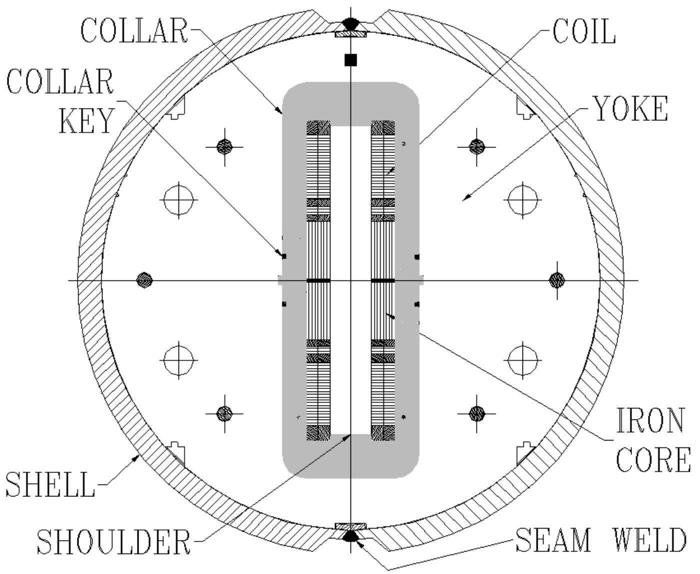
Common Coil R&D Magnets

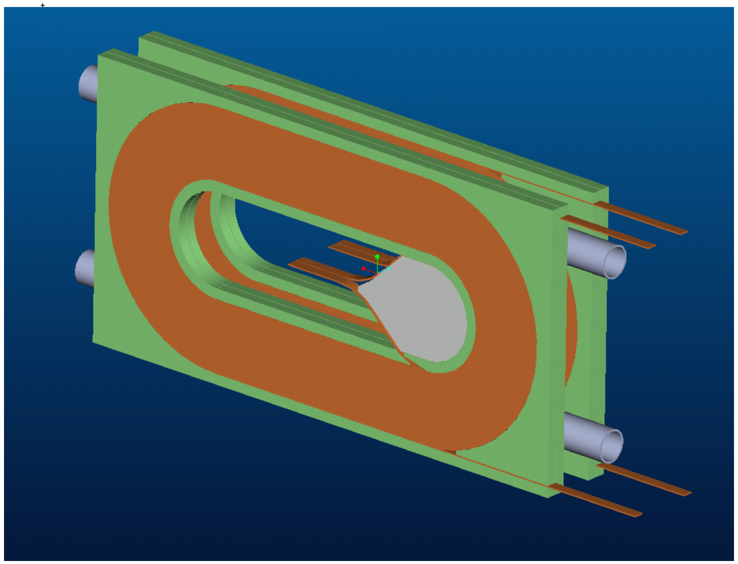




- **Several R&D common coil magnets have been built at BNL, Fermilab and LBNL using both "Wind & React" and "React & Wind" technologies.**
- **For simplicity, some of them didn't have pole or auxiliary coils.**
- **In BNL magnet that coil (or other insert coil), could be added without opening the magnet. Not having that small coil doesn't impact the proof-of-principle demonstration.**

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



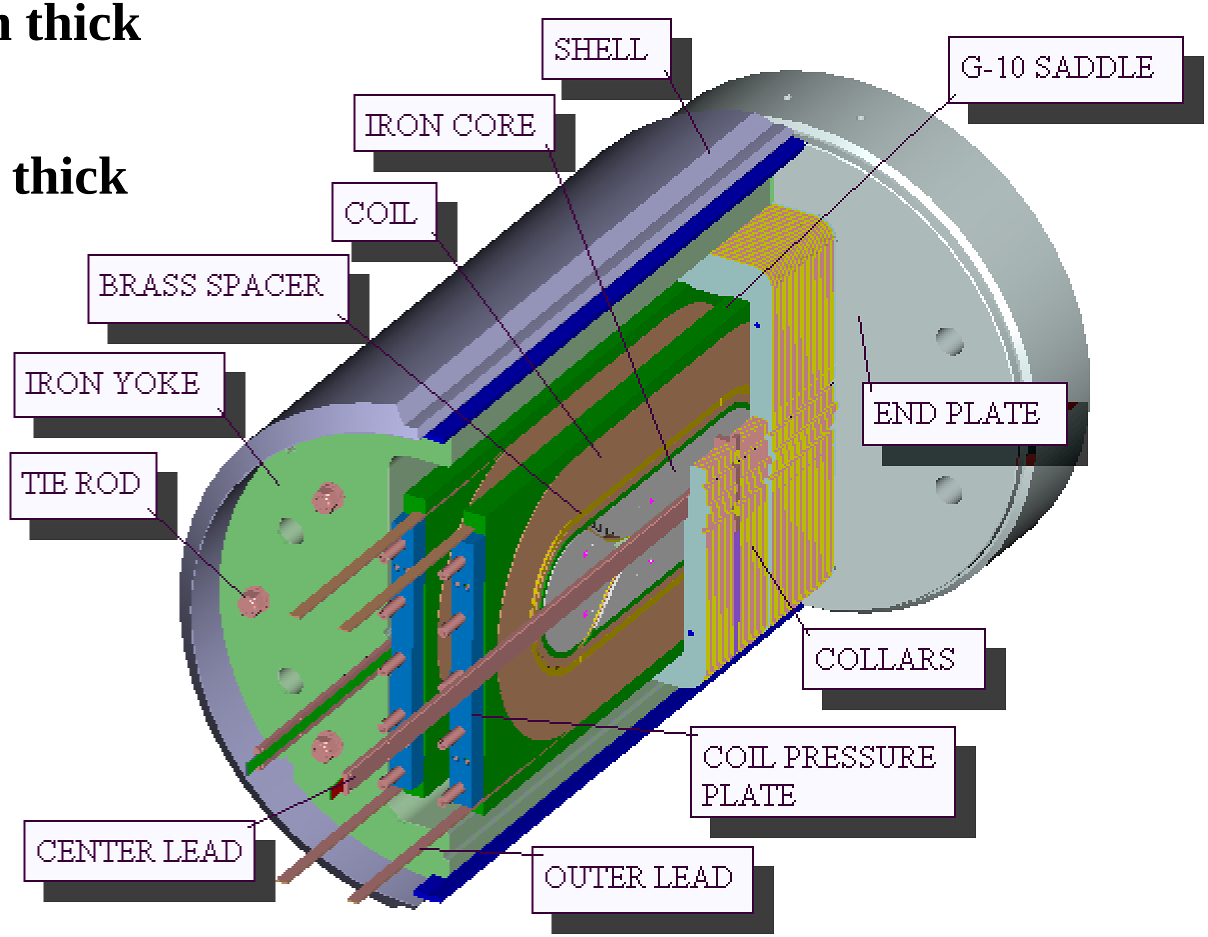


- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- 31 mm horizontal aperture
- Large (338 mm) vertical aperture
  - » A unique feature for coil testing
- Dynamic grading by electrical shunt
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum 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

Mechanical Design Features

Main components of the structure:

- **Stainless steel collar: 13 mm thick**
- **Rigid yoke: 534 mm o.d.**
- **Stainless steel shell : 25 mm thick**
- **End plate: 127 mm thick**



- ➢ **Simple structure**
- ➢ **Almost no cold pre-stress**
- ➢ **Larger deflections (several hundreds of μm)**

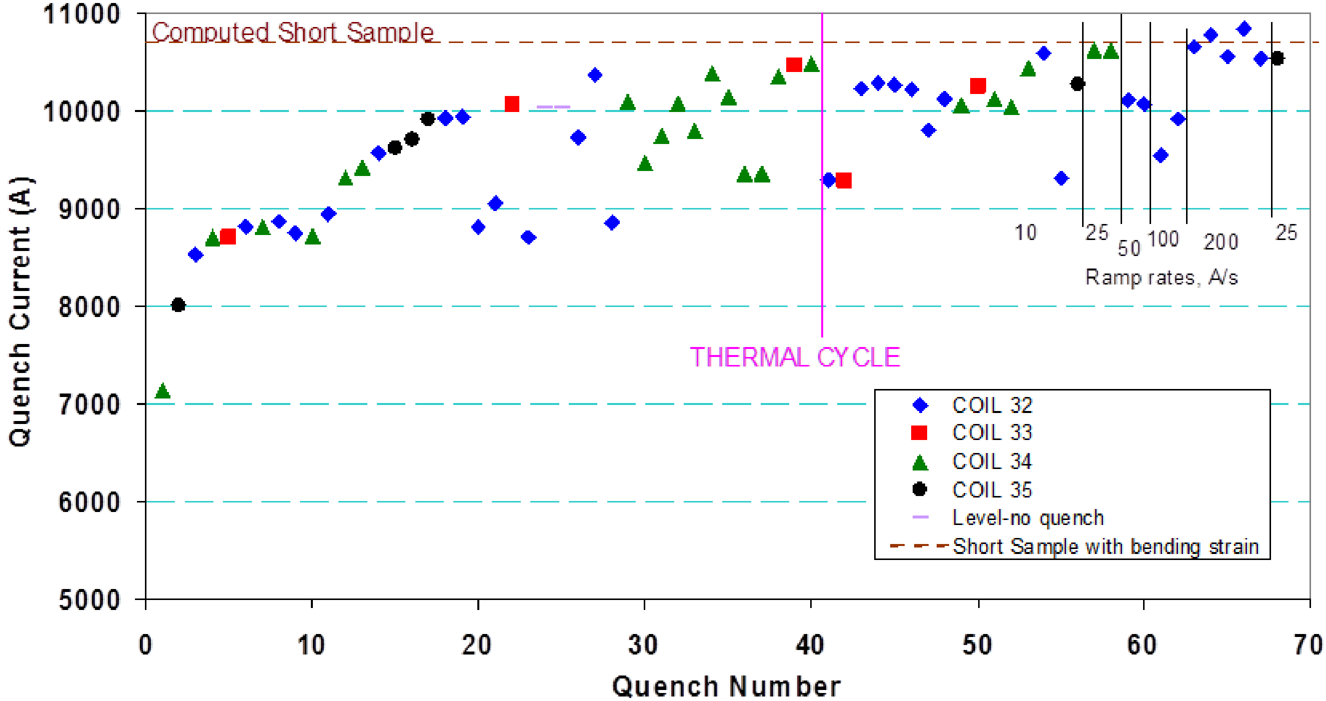
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

BNL Nb_3Sn React & Wind Common Coil Dipole DCC017

Large vertical open space for insert coil testing

Performance of 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 as it can reduce/simplify structure
  - ➢ computed horizontal deflection/movement of the coil as a whole ~200 μm

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

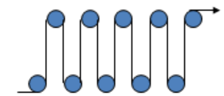
Mandatory for use of Incoloy (SAGBO issue)
Suitable for large coils, High tooling cost

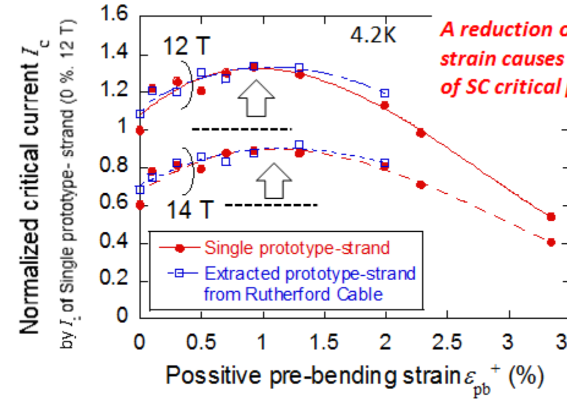
CRPP Pierluigi Bruzzone ITER Conductors FCC, Washington March 2015 EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ic Improvement by Process

FURUKAWA ELECTRIC

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

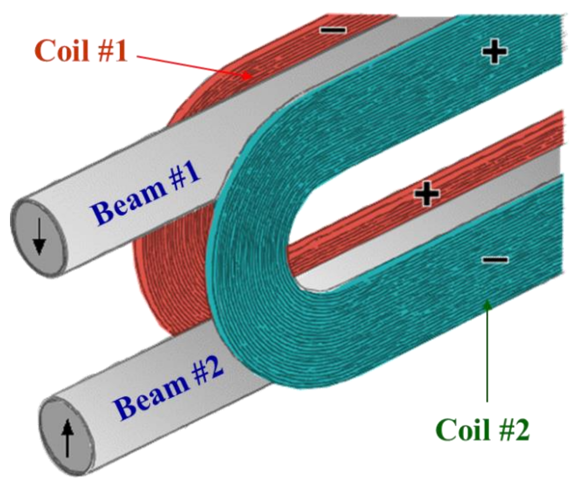




A reduction of the residual strain causes the improvement of SC critical parameters!

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

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



Advantages of React & Wind Approach

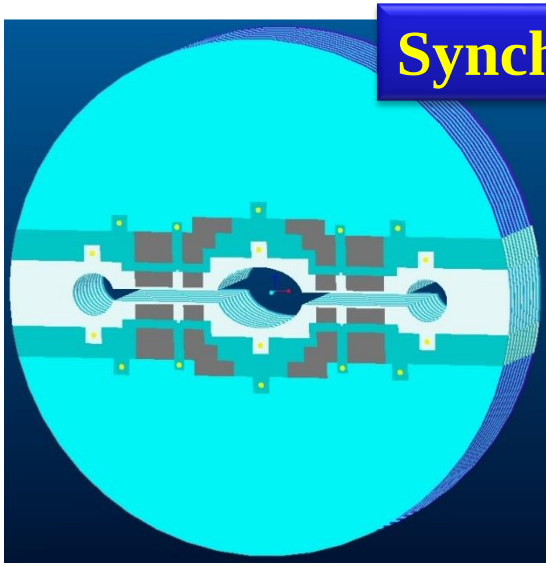
- In the "React & Wind" approach, the coil and associated structures are not subjected to the high temperature reaction. This allows one to use a variety of insulation and other materials in coil modules.
  - » In "Wind & React", one is limited in choosing insulating material, etc. since the entire coil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

Open Midplane Dipole

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

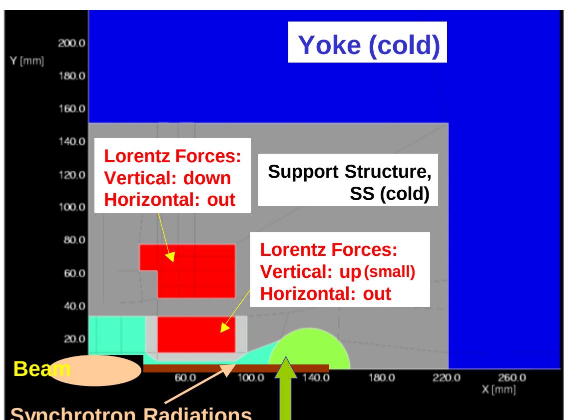
A True Open Midplane Design Design (no structure at the midplane)

Synchrotron radiation could be a major issue in FCC



- 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.



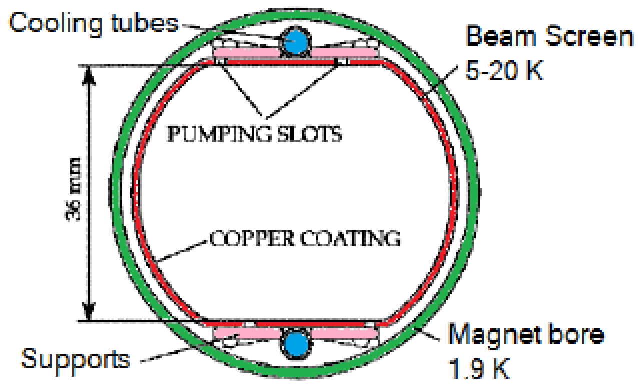
Synchrotron radiations deposit energy in a warm absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

Open Midplane Dipole for FCC

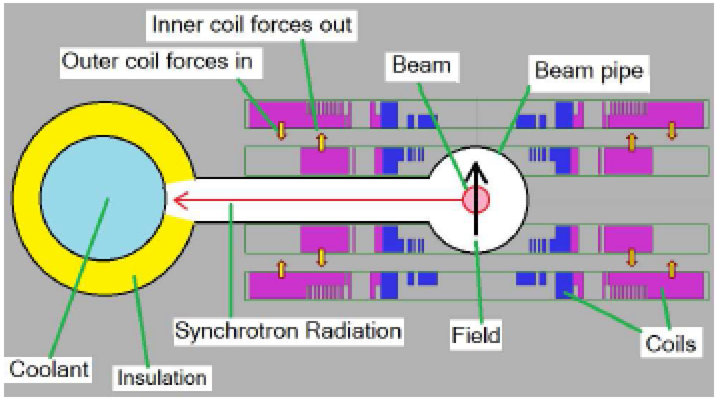
SYNCHROTRON RADIATION

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



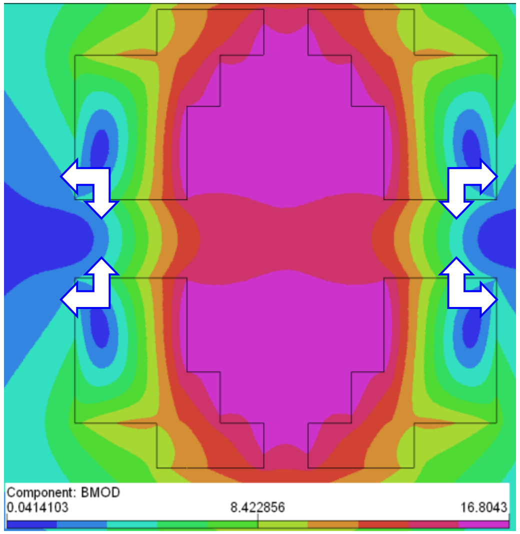
CERN Beam Screen



With Open-Plane Magnet

Courtesy: Bob Palmer, BNL

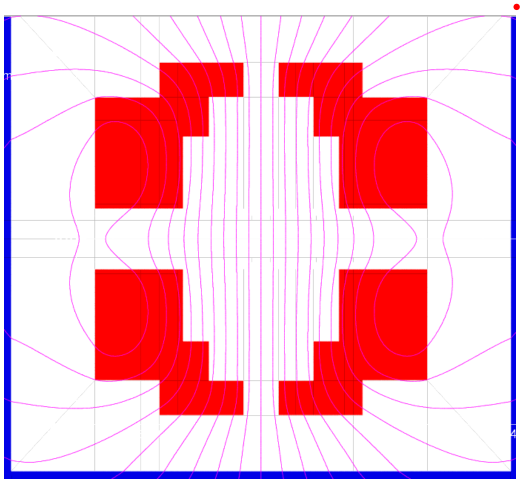
Challenges associated with the "Ideal" or "True" Open Midplane Dipole Design



#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.

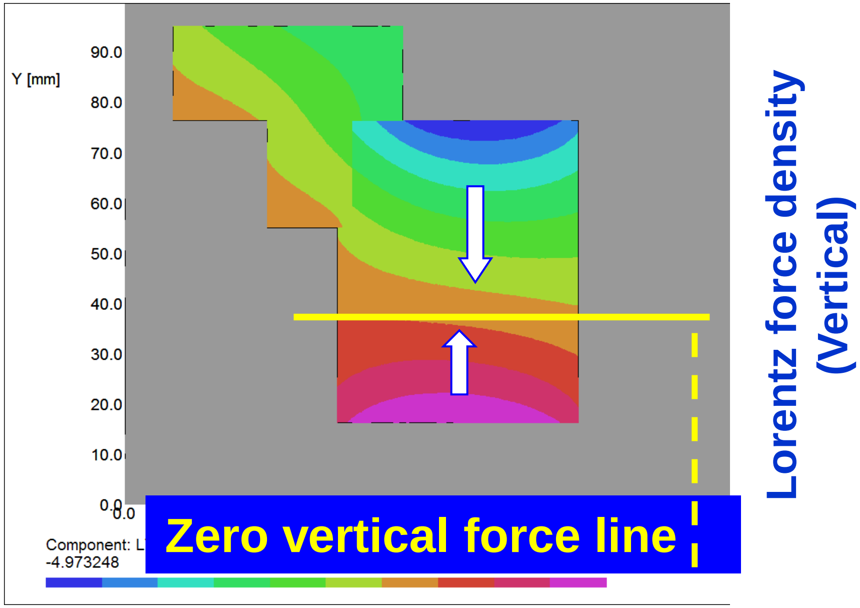


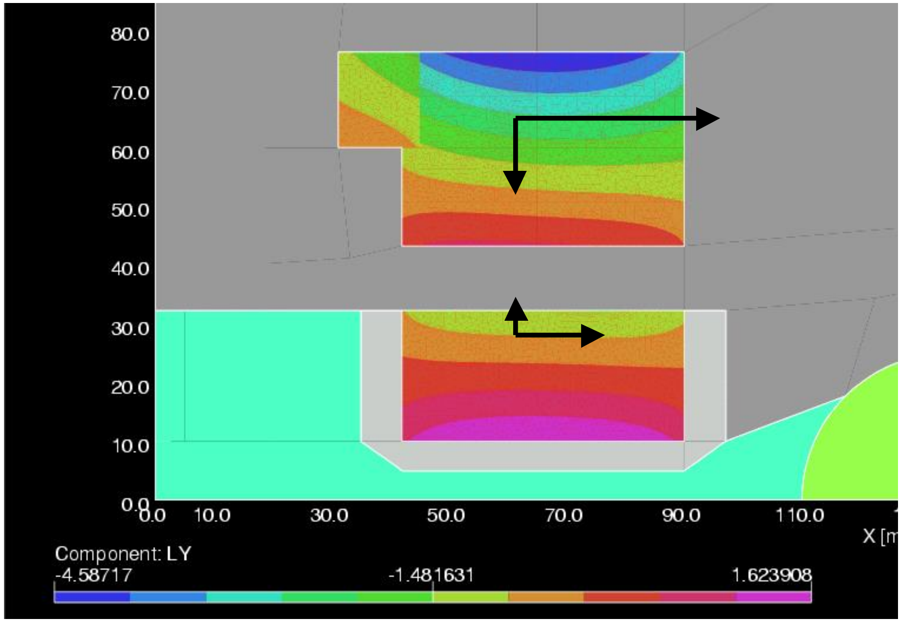
Design solutions were developed to overcome above challenges with funding from LARP for IR dipole and Muon collider for main dipole.

This work may be relevant to FCC Main and/or some IR Dipoles

Challenge #1: Lorentz Forces between coils

A new and major consideration in design optimization

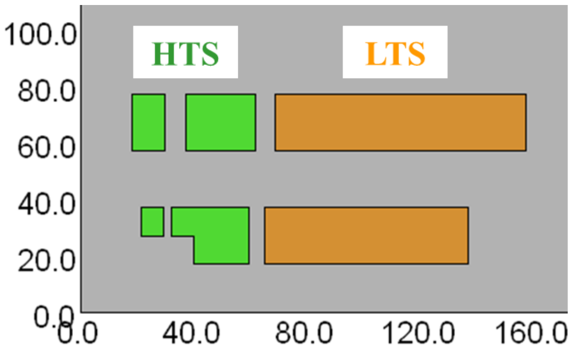


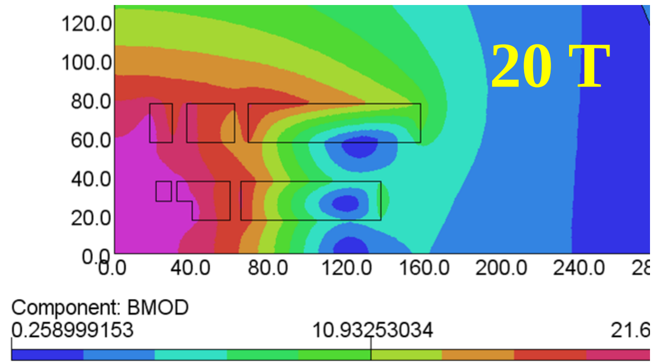


Since there is no downward force on the lower block (there is slight upward force), we do not need structure below. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

A Proof of Principle Demonstration of Open Midplane Dipole (Phase I SBIR Proposal)

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





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

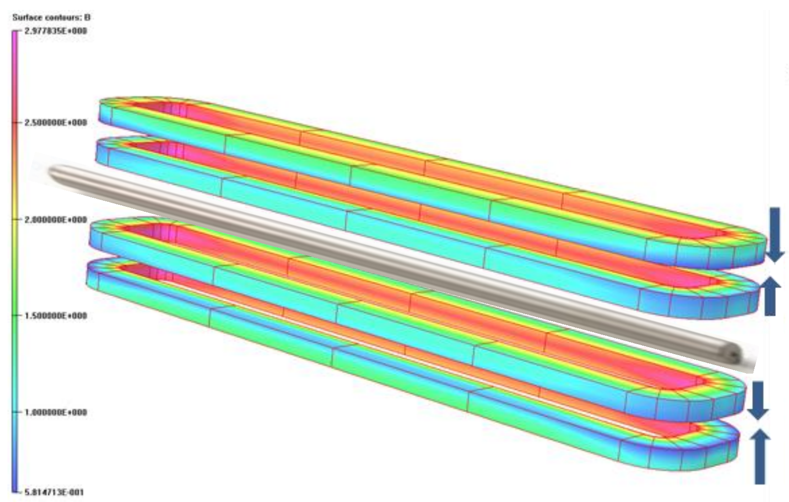
Proof of Principle Demonstration with HTS Coils at 77 K (proposed in Phase I itself)

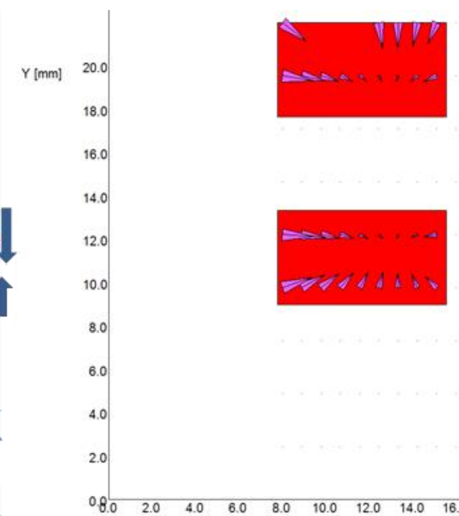
(HTS demo magnets can be cheap to build and test – custom made for graduate research)

Energy to Power Solutions

Novel High Field Hybrid Open Mid-Plane Dipole Coil

- **Phase I E2P/BNL SBIR Application**

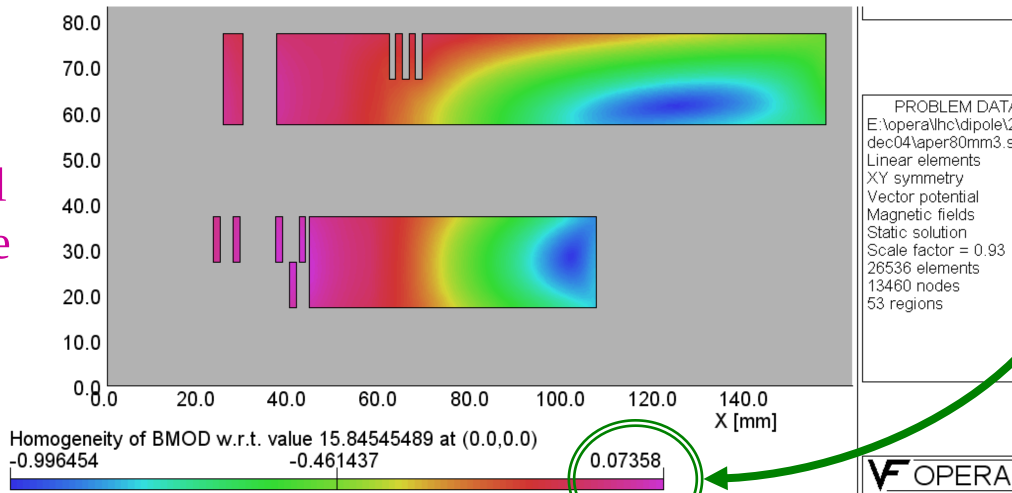




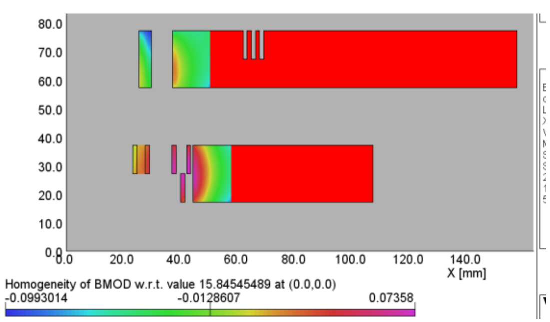
Challenge #2: Peak Field

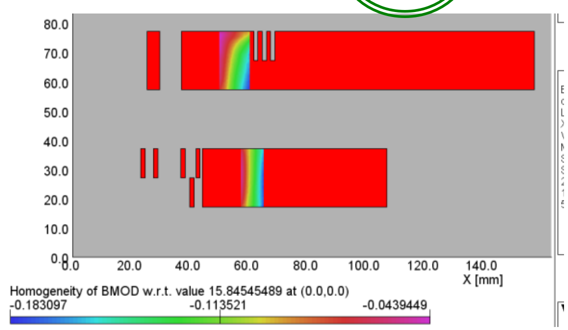
Several designs have been optimized with a small peak enhancement: ~7% over B_o

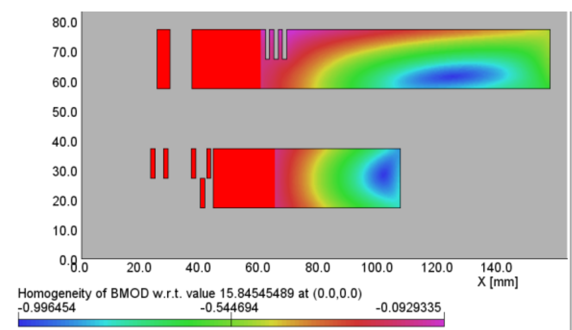
Relative field enhancement in coil (peak field) over the central field



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

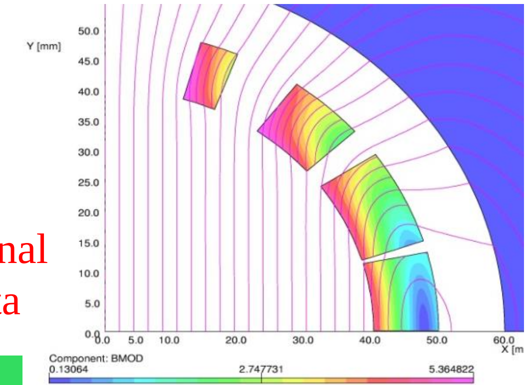
Quench Field: ~15.8 T with J_c = 3000 A/mm^2, Cu/Non-cu = 1.0

Challenge #3: Field Quality

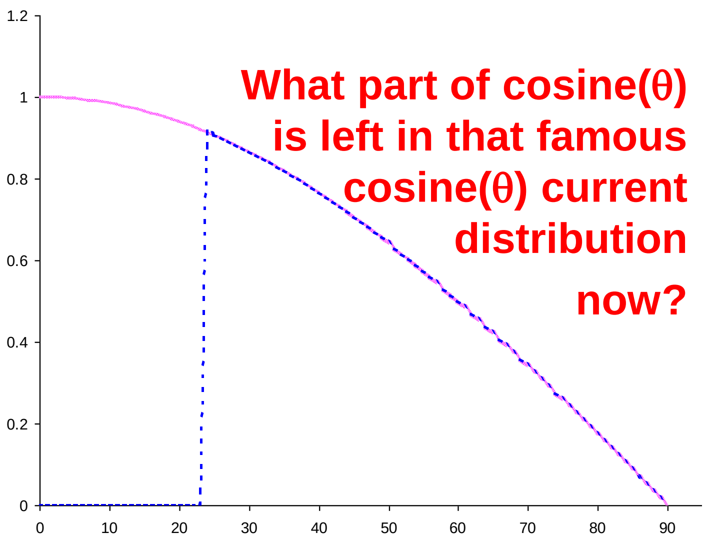
Coil-to-coil gap in this design = 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

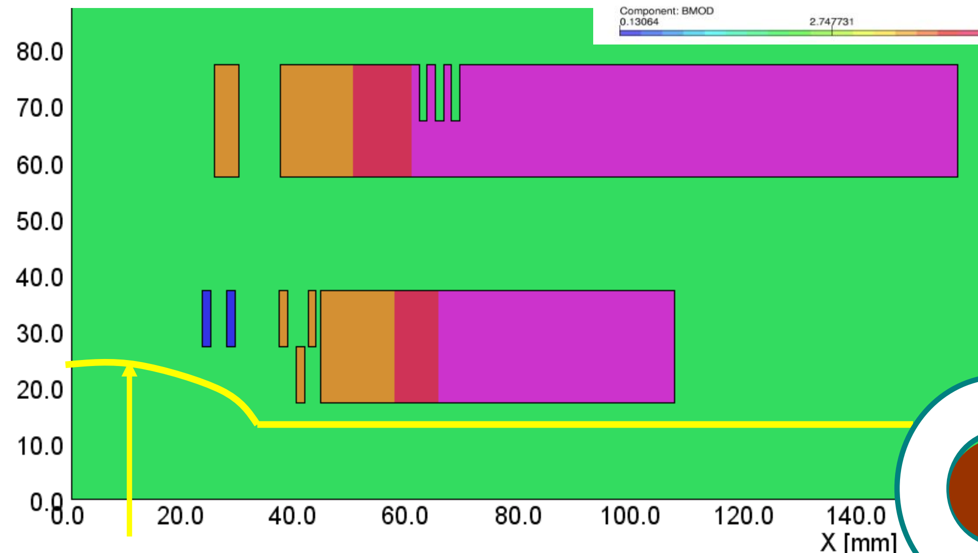
⇒ Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)

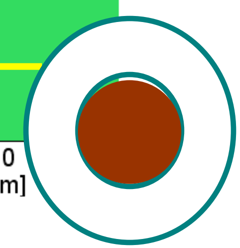


Conventional cosine theta



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



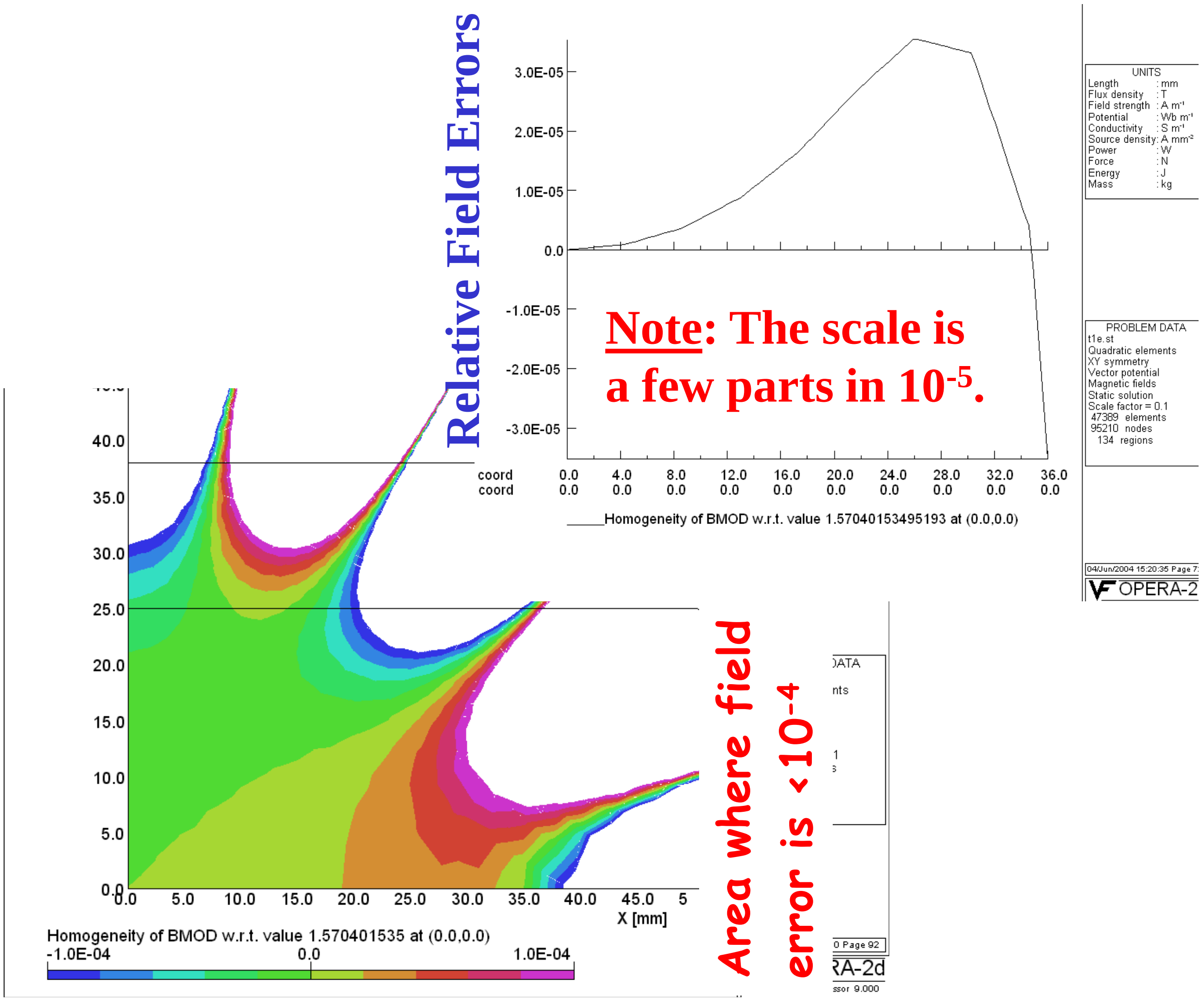


This makes obtaining high field and high field quality a challenging task !

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



Geometric Field Harmonics:

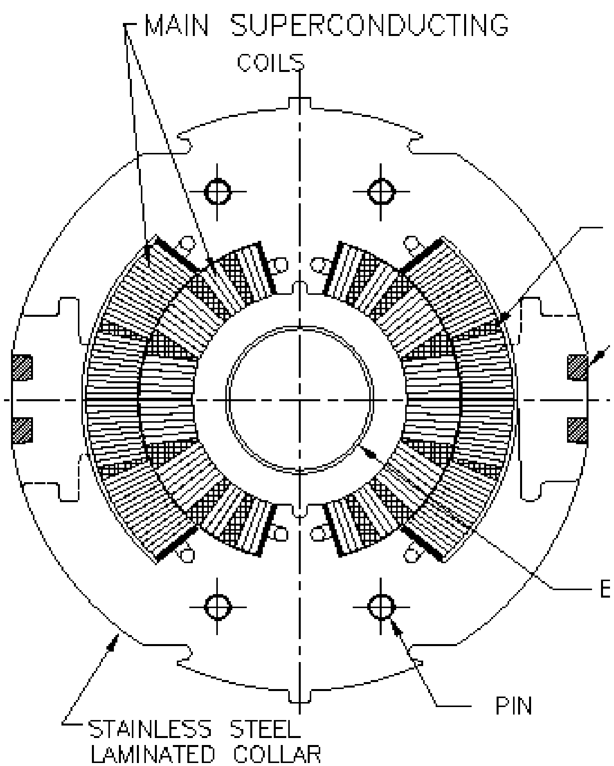
	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
16	0.00	0.00
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

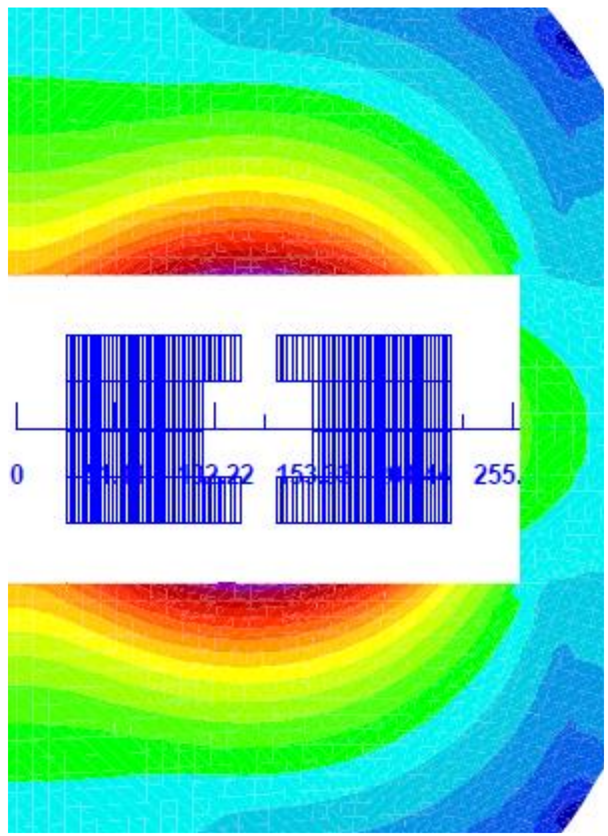
Summary and Opinion

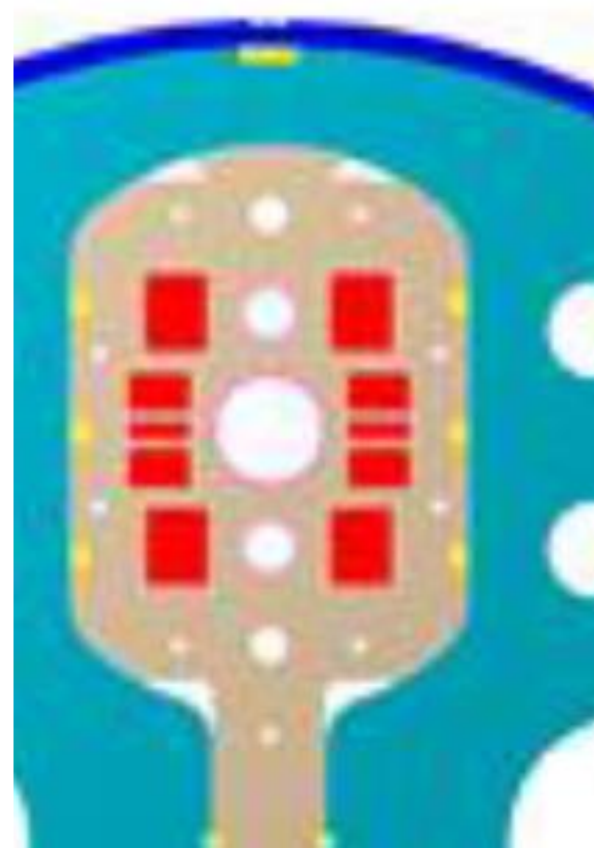
- **Technology for FCC dipole would be different from LHC dipole. It is not necessary that the cosine theta geometry that was suitable for 8.3 T LHC dipole will also be the best option for FCC 16 T dipole.**
- **One should carry out real R&D (build magnets, just not paper studies) to determine the best design objectively early on. Dipole is a big ticket and challenging item and, therefore, in my humble opinion, it deserves that.**
- **Common coil design is suitable for dealing with large forces. Simpler geometry and half number of coils should reduce cost.**
- **Common coil design also offers option for both "Wind & React" and "React & Wind" technologies. Also if magnet aperture changes, it can accommodate that easily without starting all over again.**
- **Open Midplane Design offers an attractive solution for dealing with the synchrotron radiations that will be large in FCC.**

Extra Slides

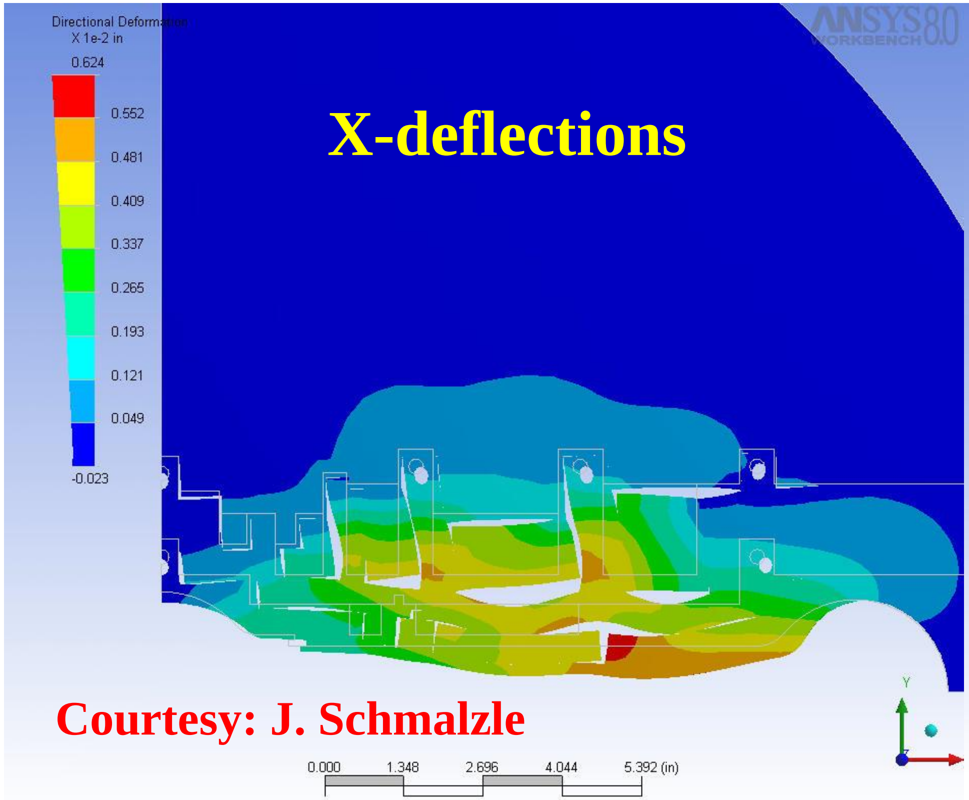
Conductor Requirements in Various Designs

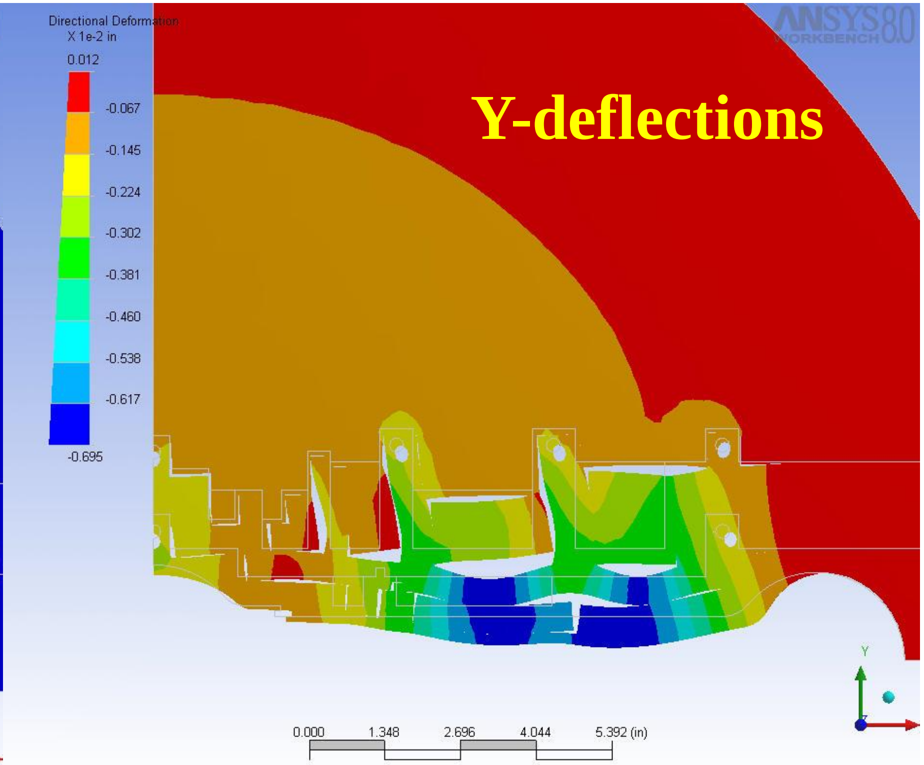






Mechanical Analysis of Open Midplane Dipole Design





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.