U.S. MAGNET DEVELOPMENT PROGRAM

20 T Hybrid Design: Common Coil

Leaping to a New Design Space: Facing the Kodak Moment

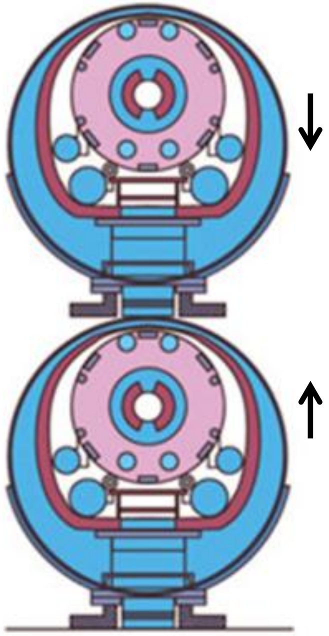
Ramesh Gupta

USMDP Annual Collaboration Meeting 2022

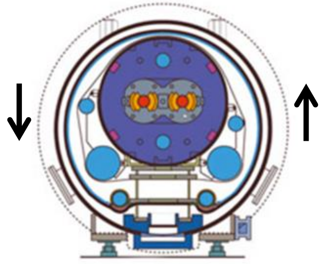
Content

- Explanation of why common coil design uses less conductor in the MDP dipole - 20 T plus margin? The difference is larger for the expensive HTS.
- Why common coil becomes more attractive for very high field collider dipoles
  - Lorentz forces, more cable options, more technology options, costs
- Comparing the cost of R&D dipole
  - Compare two apertures in common coil to single aperture in other designs
- R&D vision based on the common coil geometry
  - Rapid-turn-around and low-cost, change or study one parameter at a time, systematic and innovative R&D (we have a Proof-of-Principle 10 T dipole)
- Summary

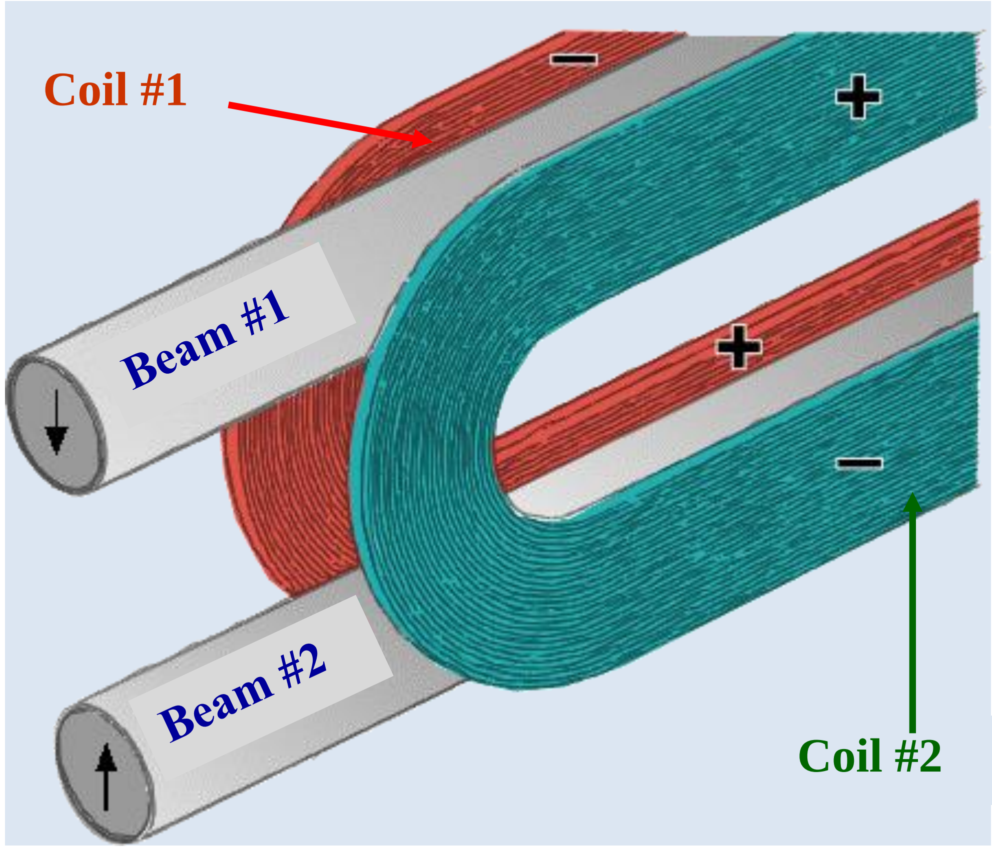
Common Coil Design for Collider Magnets



SSC



LHC

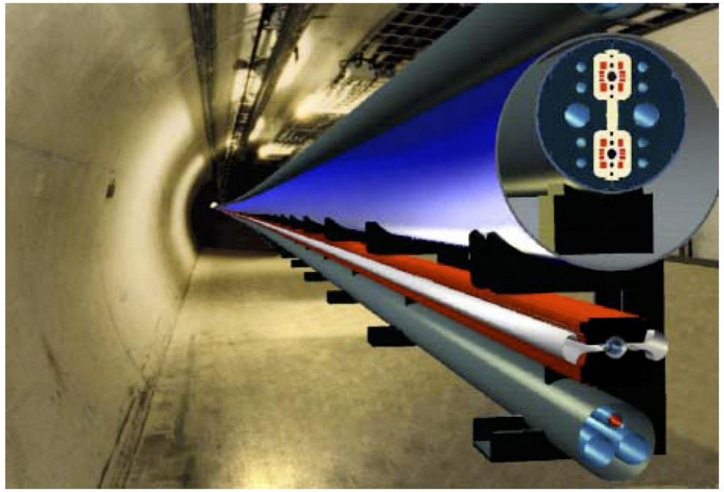


Main Coils of the *Common Coil Design*

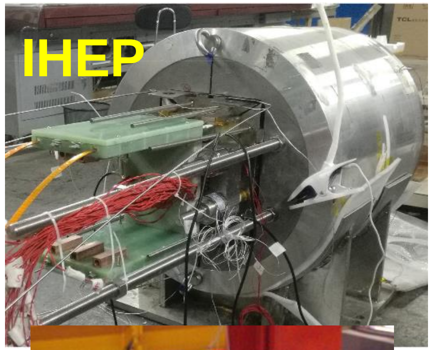
Very Large Hadron Collider
SLAC-R-591
Fermilab-TM-2149
June 4, 2001

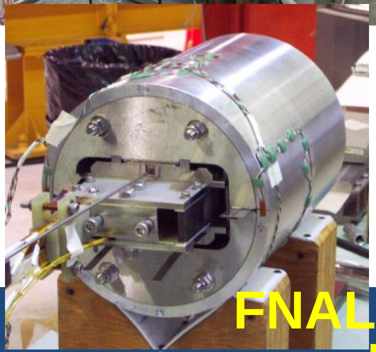
Design Study for a Staged Very Large Hadron Collider

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



Work supported in part by the Department of Energy contract DE-AC03-76SF00515.





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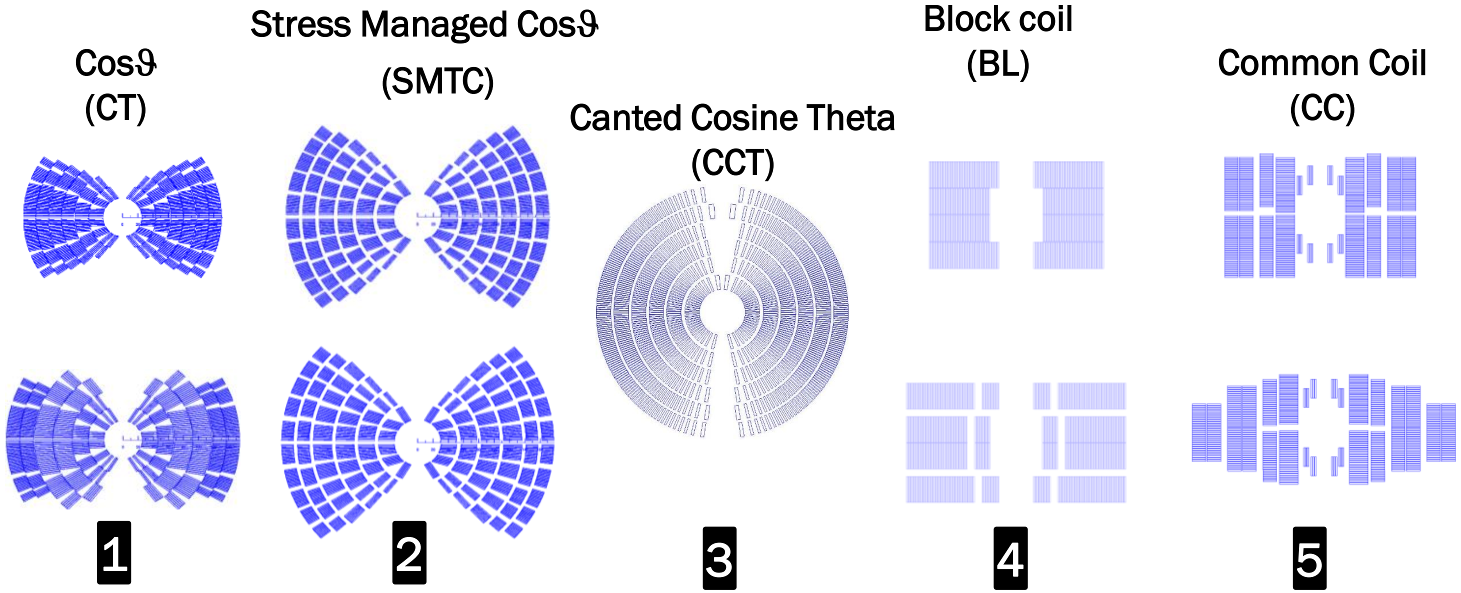
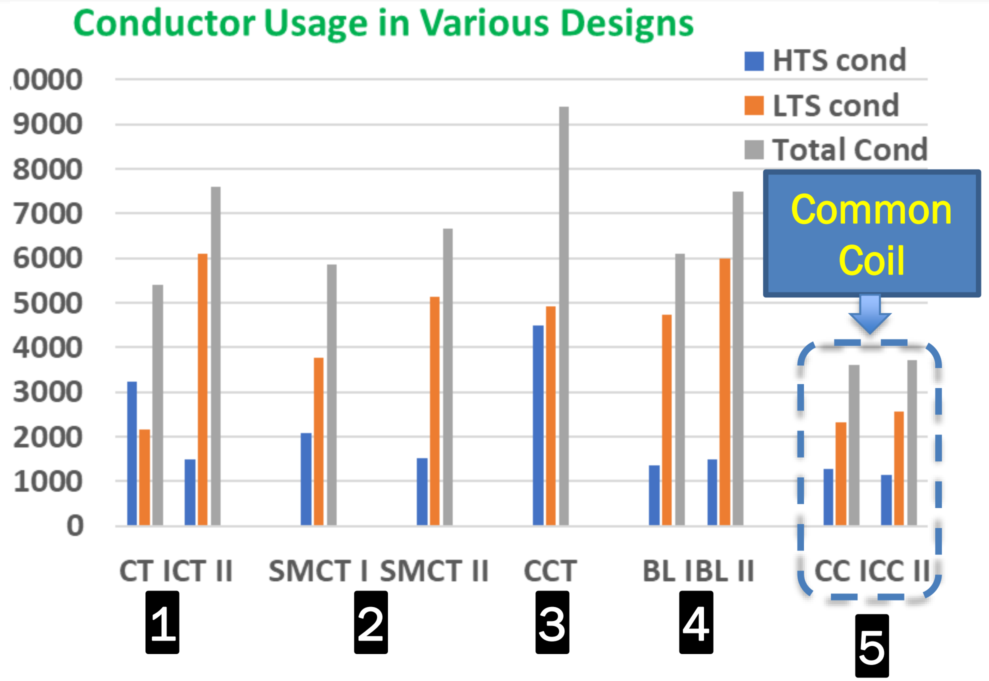
Initial Observation from the Comparative Study of Various Designs





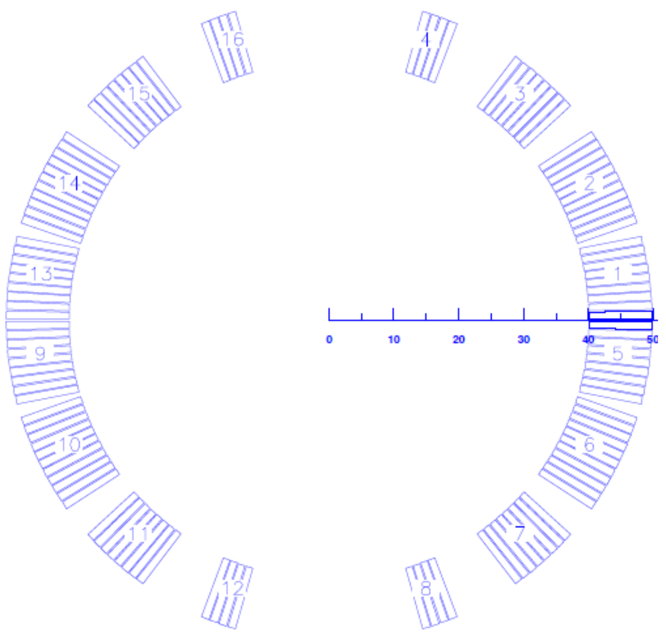
- Comparative studies of 20 T designs (as presented at MT) revealed that the common coil design uses significantly less conductor than the other designs. Small differences in relative margin doesn't explain that.
- This finding is opposite to that expected from the conventional wisdom. Why? Back to the drawing board…
- Explanation comes from the basic design principles. As the design field gets higher, relative ratio between the bore area and the coil area changes significantly. That changes the optimization and the outcome.
- The difference is likely to grow for field quality magnets and particularly on the use of the expensive HTS.

Coil Geometries for Low to Medium Field Dipoles (coil width much less than the magnet bore)

Accelerator magnets typically have circular bore. Therefore, a shell geometry is a natural choice. At low fields, the required width (and area) of conductor needed is much less than bore. One can design magnets with a single layer coil (RHIC). Block coil geometry will require many coils (layers) and may also use more conductor.

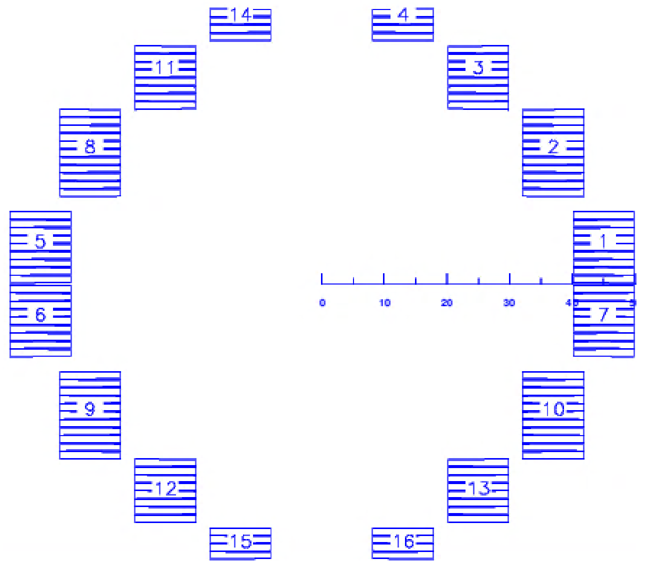
Design guidelines from the first principle:

Cosine theta design

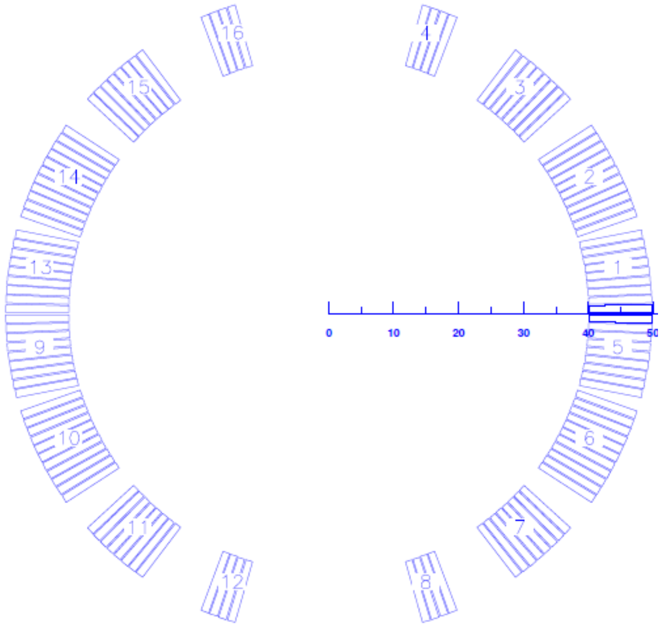


- In a cos (θ) design, coil must extend to 60° (or more with wedges but limited to 90°) for b_3=0
- B is proportional to the width * (current density)
- Conductor area needed to create the dipole field increases linearly with the radius of each layer
- In low field block coil designs, extending coil vertically (with no limit) for field quality or to reduce number of layers is not effective
- At low fields, block coil designs appear less efficient and less elegant. They have not been used in any major conductor dominated design

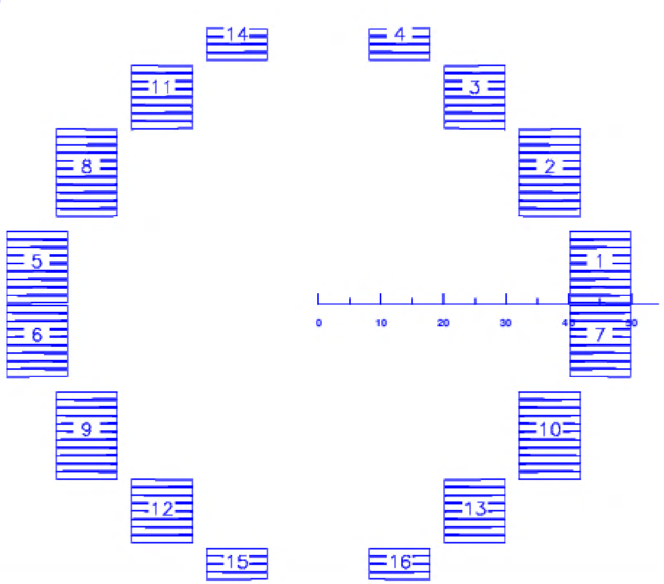
Block Coil Design



In high field magnets, the ratio between the "Bore Area" and "Coil Area" becomes much higher and things change

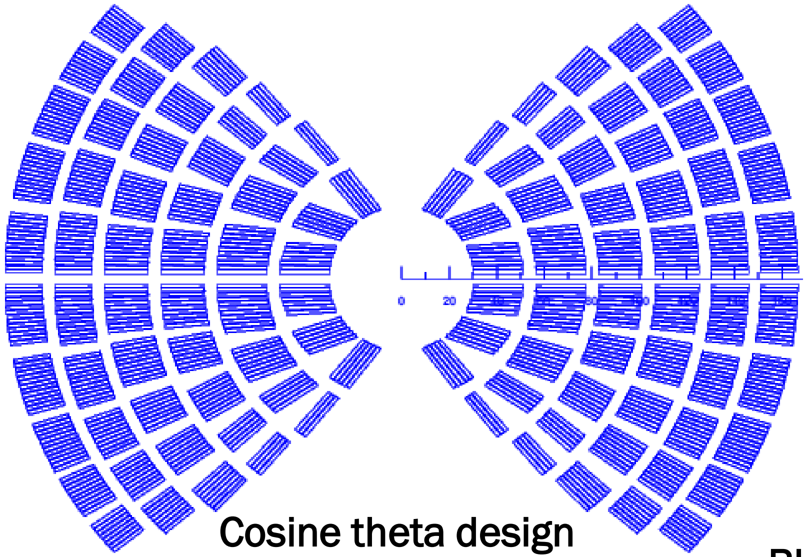


Cosine theta design



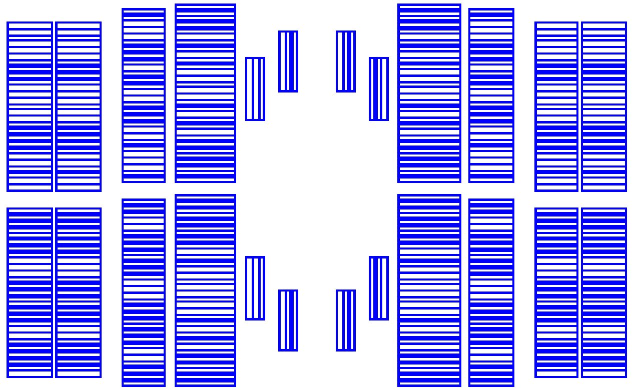
Block coil design

Low Field



Cosine theta design

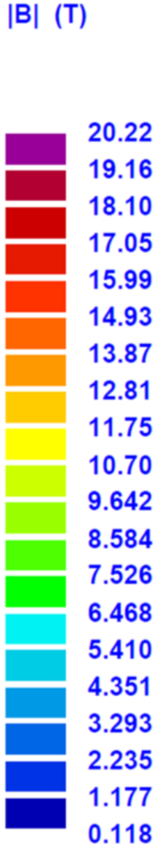
High Field



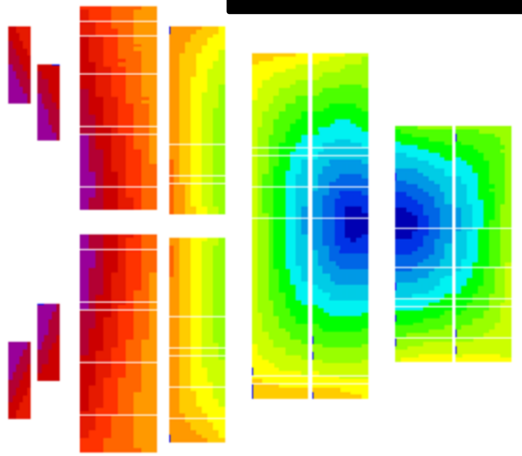
Block coil design (common coil)

Another Observation: Coil Thickness

The coil width (number of layers) is primarily determined by the design field both (a) in cosine theta and (b) in canted cosine theta designs. However, a large flexibility in *coil width* to create the same field was found in the common coil design. Interestingly the *coil width* didn't impact the conductor requirement much.



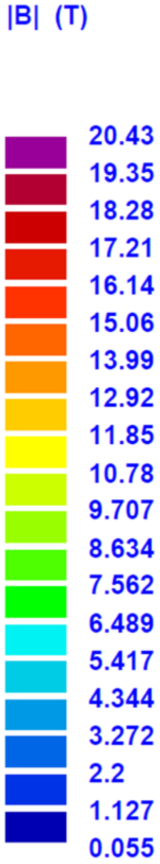
6-layer design



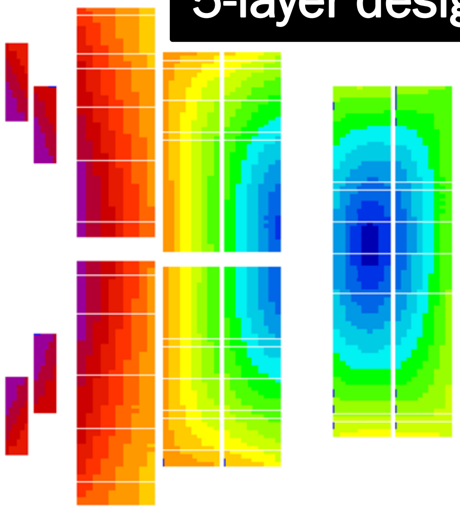
HTS: 1 layer + pole blocks
- 74 turns in ½ bore

LTS: 5 layers
- 198 turns in ½ bore

Total turns = 272



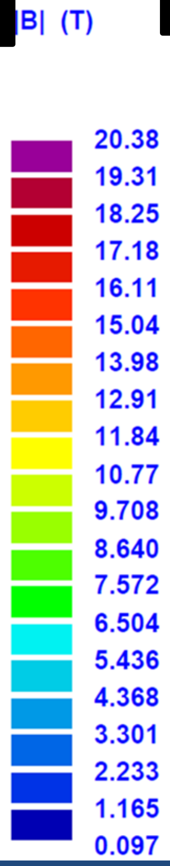
5-layer design



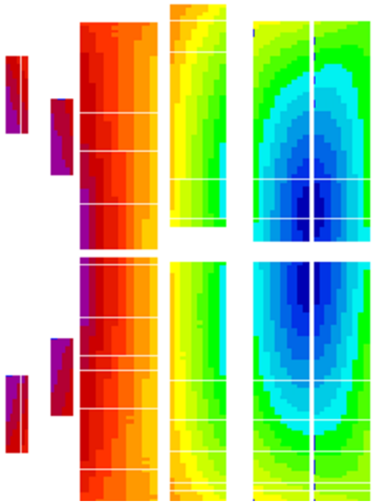
HTS: 1 layer + pole blocks
- 80 turns in ½ bore

LTS: 4 layers
- 188 turns in ½ bore

Total turns = 268



4-layer design



Lowest cost design: 4-layer

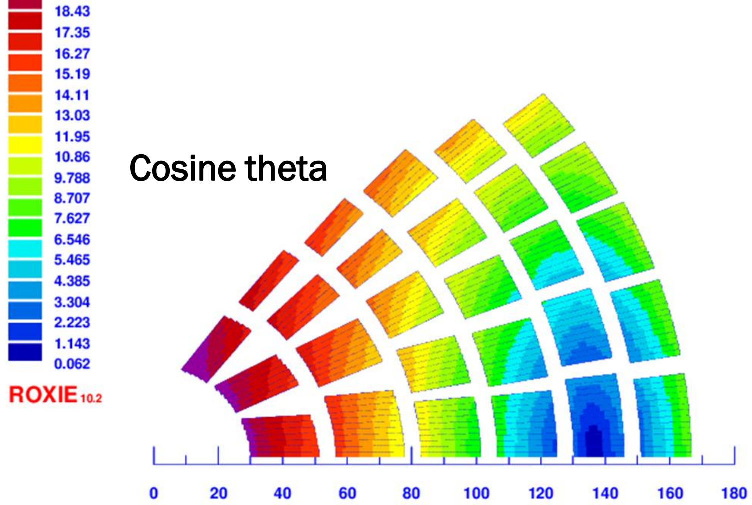
HTS: 1 layer + pole blocks
- 82 turns in ½ bore

LTS: 5 layers
- 180 turns in ½ bore

Total turns = 262

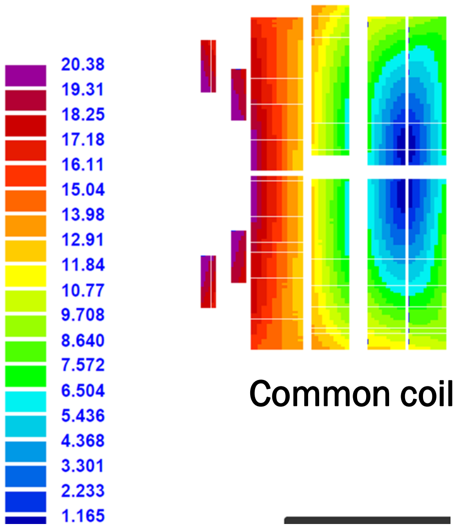
Optimization of 20 T Design – max area & max field (coil area much larger than the bore area)

Need six layers (of which 2 to 4 layers must be of HTS)

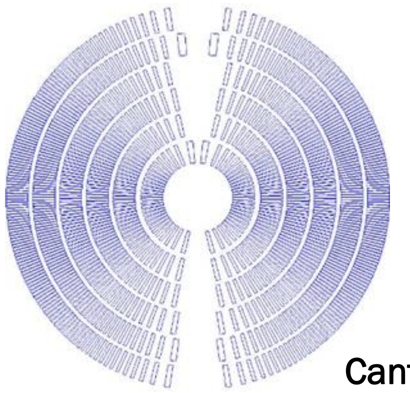


Cosine theta

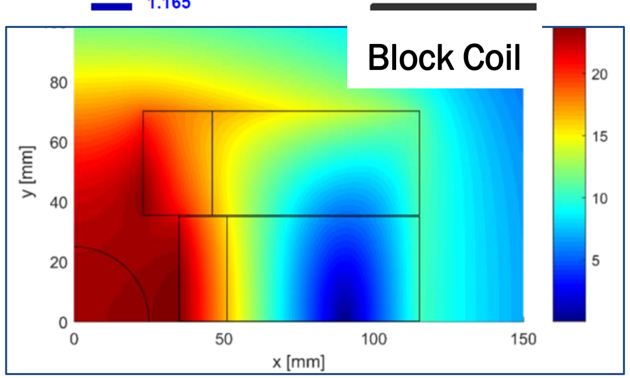
4-layer design (HTS: only 1 layer)



Common coil



Canted cosine theta



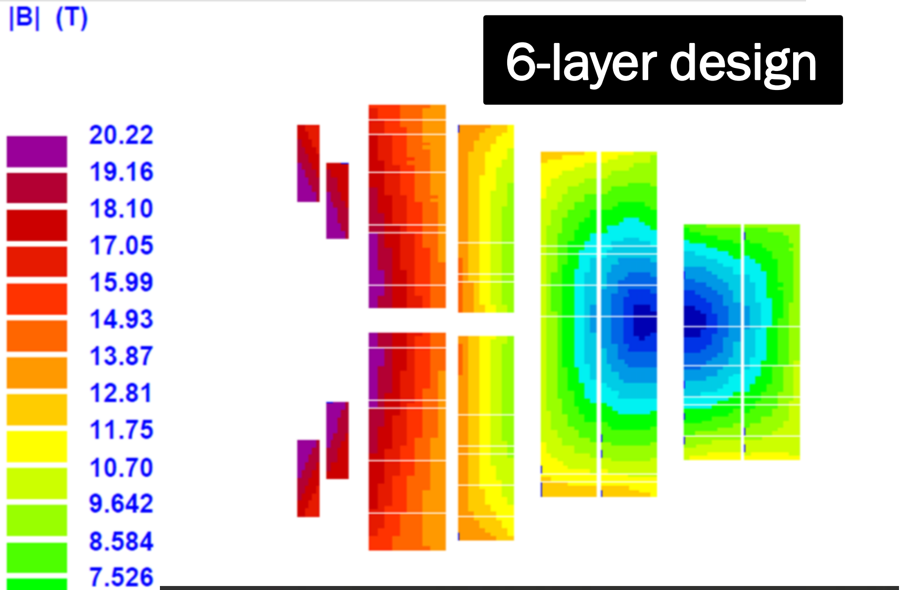
Height change must be discreate

- In cos θ and canted cosine theta, certain coil thickness or # of layers, are needed to create field.
- The same thickness (#of layers) must continue to the pole (60 to 80 degrees), the fill in between is determined by the cosine theta optimization.
- The field remains high at pole for many layers, means may need HTS, depending on the angle.
- Outer layers of current cosine theta designs, need to be extended to larger angle for field quality, which will use more conductor without creating much field.
- Furthermore, since the field will be higher there, the need for HTS and more layers of HTS will grow.

- Situation is very different in the common coil design.
- Horizontal and vertical sizes are decoupled. This provides flexibility and saving on the conductor.
- Moreover, the separation between the very high field and medium field region is good between the layers.
- This means that the HTS is needed only in one layer!

Field Quality in Common Coil Geometries

(all designs presented at MT27 had 10^{-4} harmonics)

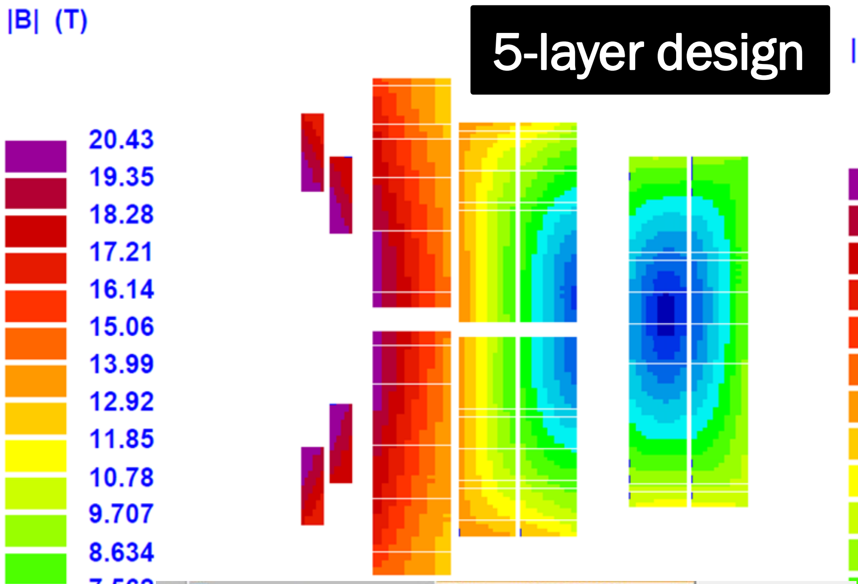


Running ROXIE on file mdp_oct-2021-Bi2212-i0.data...

```
MAIN FIELD (T) .......................................   19.9887
MAGNET STRENGTH (T/(m^(n-1)) .........................     19.98

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      -0.00000  b 3:      -0.00543
b 4:     -0.00000  b 5:      -0.02774  b 6:      -0.00000
b 7:     -0.13070  b 8:      -0.00000  b 9:      -1.40287
b10:     -0.00000  b11:      -0.41513  b12:       0.00000
b13:      0.01694  b14:       0.00000  b15:      -0.00172
b16:     -0.00000  b17:      -0.01059  b18:      -0.00000
b19:     -0.00040  b20:       0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:       0.00838  a 3:       0.00000
a 4:     -0.01362  a 5:       0.00000  a 6:       0.03506
a 7:      0.00000  a 8:      -0.75858  a 9:       0.00000
a10:     -0.26750  a11:       0.00000  a12:       0.01863
a13:      0.00000  a14:      -0.00453  a15:      -0.00000
a16:     -0.01161  a17:       0.00000  a18:       0.00013
a19:      0.00000  a20:       0.00099  a
```

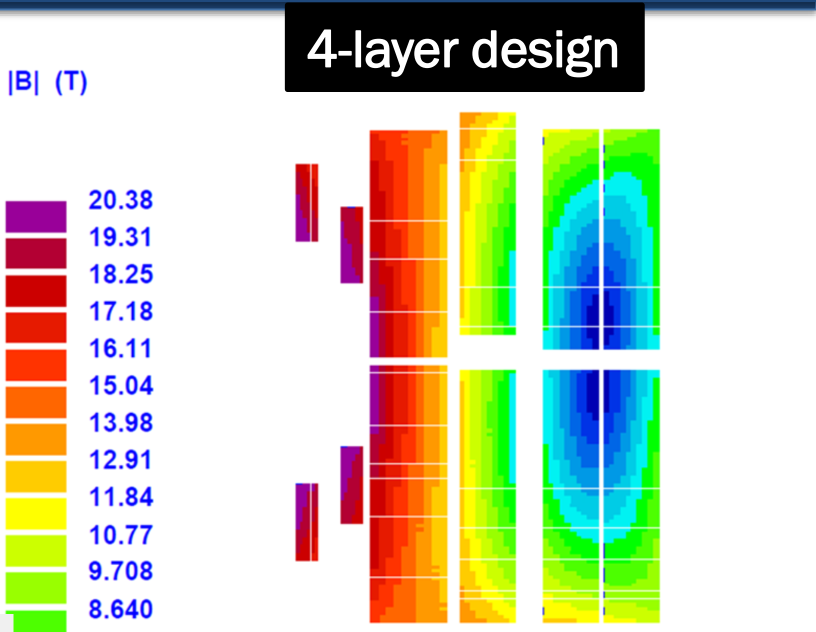


mdp_oct-2021-Bi2212-i0.output | mdp_oct-2021-Bi2212-f40.output

```
MAIN FIELD (T) ......................................   20.171
MAGNET STRENGTH (T/(m^(n-1)) ........................     20.1

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:       0.00000  b 3:       1.74349
b 4:     -0.00000  b 5:      -0.14682  b 6:      -0.00000
b 7:     -0.06433  b 8:       0.00000  b 9:      -1.35518
b10:      0.00000  b11:      -0.33971  b12:      -0.00000
b13:      0.01717  b14:      -0.00000  b15:      -0.00691
b16:     -0.00000  b17:      -0.00836  b18:      -0.00000
b19:     -0.00005  b20:      -0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:       0.51270  a 3:      -0.00000
a 4:     -0.05237  a 5:      -0.00000  a 6:       0.09507
a 7:      0.00000  a 8:       0.84674  a 9:      -0.00000
a10:      0.25613  a11:      -0.00000  a12:      -0.00656
a13:      0.00000  a14:       0.01272  a15:       0.00000
a16:      0.01090  a17:       0.00000  a18:       0.00083
a19:     -0.00000  a20:       0.00046  a
```



mdp_oct-2021-Bi2212-d0.output | mdp_oct-2021-Bi2212-e50.output

```
MAGNET STRENGTH (T/(m^(n-1)) ........   20.0236

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:       0.00000  b 3:       0.03617
b 4:     -0.00000  b 5:       0.08401  b 6:       0.00000
b 7:      0.39419  b 8:      -0.00000  b 9:       0.78556
b10:      0.00000  b11:      -0.00864  b12:      -0.00000
b13:     -0.08354  b14:      -0.00000  b15:       0.01549
b16:      0.00000  b17:       0.00697  b18:      -0.00000
b19:      0.00128  b20:      -0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:       0.01594  a 3:       0.00000
a 4:      0.09502  a 5:       0.00000  a 6:       0.05581
a 7:      0.00000  a 8:      -0.50366  a 9:      -0.00000
a10:      0.49972  a11:       0.00000  a12:       0.15736
a13:     -0.00000  a14:      -0.04431  a15:       0.00000
a16:     -0.00486  a17:      -0.00000  a18:       0.00185
a19:     -0.00000  a20:       0.00141  a
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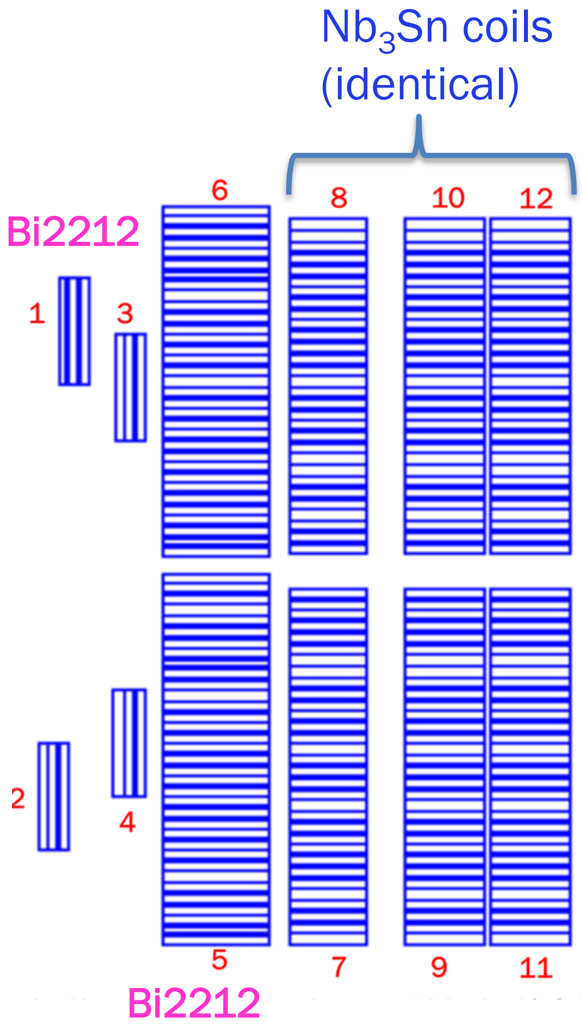
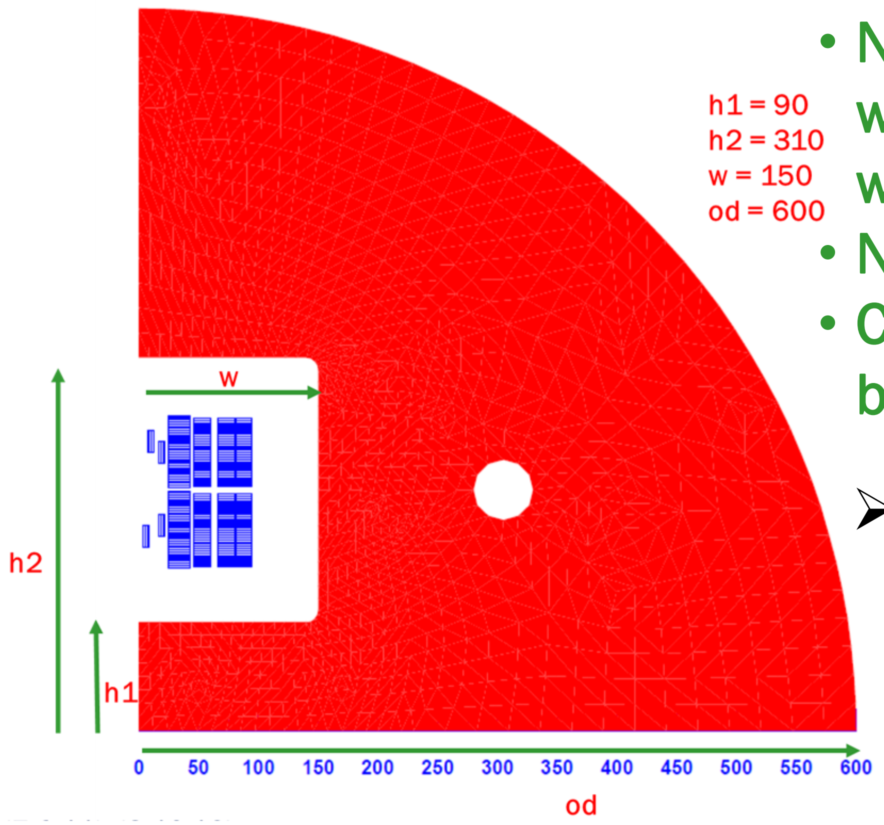
Benefits of the Common Coil Design

All Nb_3Sn Coils Can be Made Identical

Such prospects can't be imagined in the CT/SMCT or CCT designs





- While HTS coils/layers will need separate tooling, all Nb_3Sn coils will need only one set for winding, reaction and impregnation
- Nb_3Sn coils for CT/SMCT or CCT designs will need tooling for at least four layers (all with more complex geometries)
- Need less practice & less spare coils
- Can sort/switch coils between layers, e.g., based on the performance

➢ Question: Will the above savings in cost and time, overcome the cost of extra conductor for the 2nd aperture, at least in the R&D magnets where the relative cost of design and tooling are large?

Summary of Design with Identical Nb_3Sn Coils (still good field quality and matched margins)

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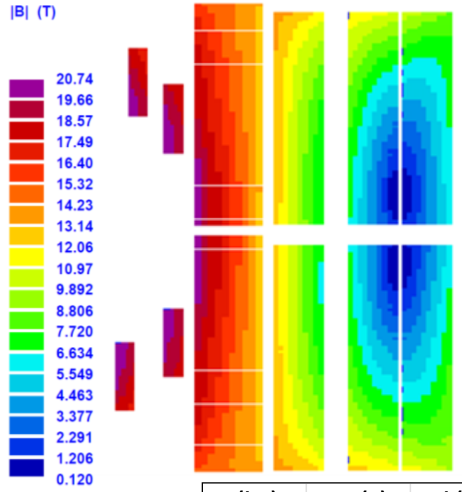
Geometric harmonics < 0.5 10^{-4}

```
MAIN HARMONIC .....................................          1
REFERENCE RADIUS (mm) ...............................    15.0000
X-POSITION OF THE HARMONIC COIL (mm) ...............     0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ...............   200.0000
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................   0.3228E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .....................................   20.000066
MAGNET STRENGTH (T/(m^(n-1)) .......................

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     0.00000  b 3:     0.00537
b 4:     -0.00000  b 5:     0.02576  b 6:     0.00000
b 7:     -0.07742  b 8:    -0.00000  b 9:    -0.41532
b10:      0.00000  b11:    -0.26062  b12:    -0.00000
b13:     -0.00646  b14:    -0.00000  b15:    -0.00448
b16:      0.00000  b17:    -0.00436  b18:     0.00000
b19:     -0.00092  b20:    -0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:    -0.01890  a 3:    -0.00000
a 4:      0.00591  a 5:    -0.00000  a 6:     0.11424
a 7:      0.00000  a 8:     0.02483  a 9:    -0.00000
a10:      0.14186  a11:     0.00000  a12:    -0.00881
a13:      0.00000  a14:     0.00515  a15:    -0.00000
a16:      0.00259  a17:     0.00000  a18:     0.00066
a19:     -0.00000  a20:     0.00012  a
```

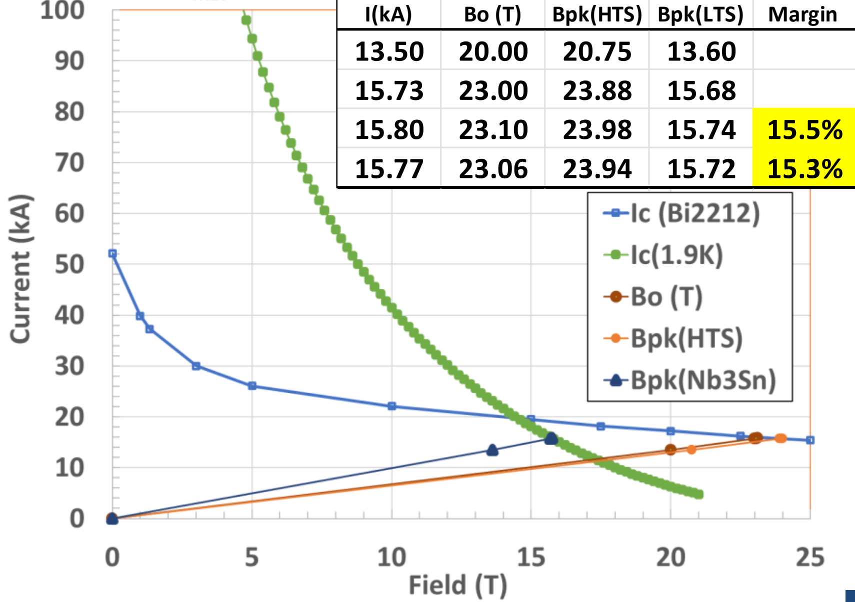


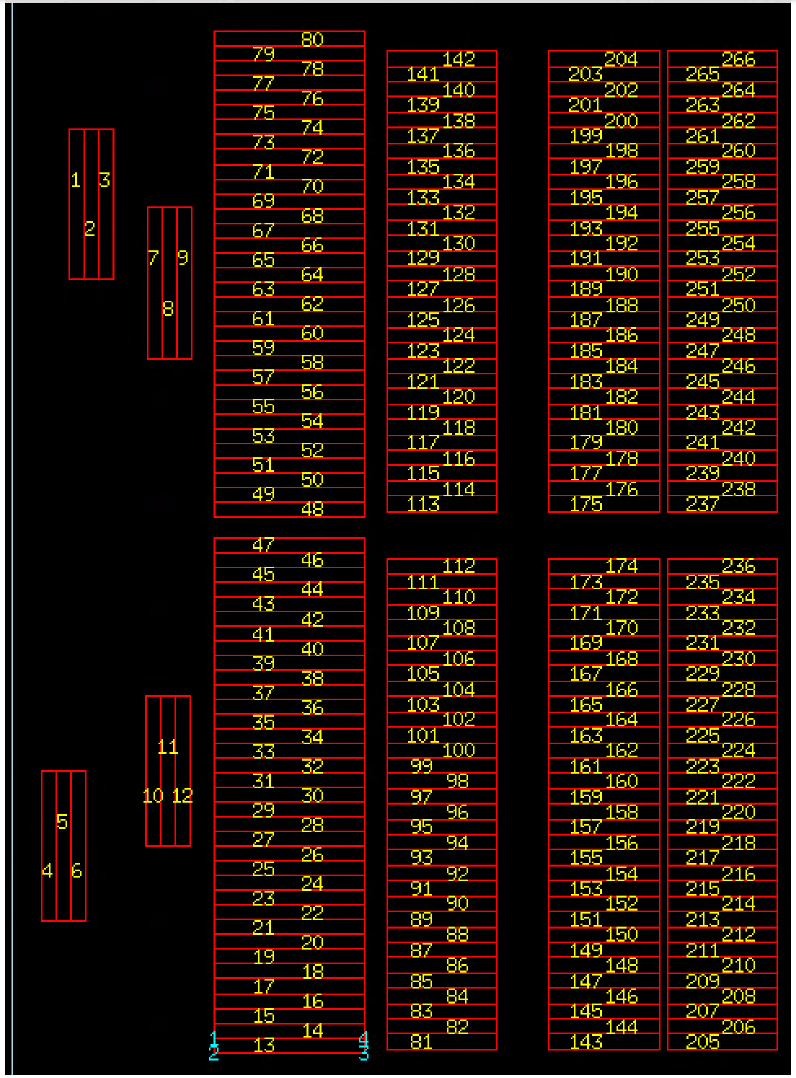
No. of Turns (½ bore)

- HTS: 80
- LTS: 186

Total: 266

I(kA)	Bo (T)	Bpk(HTS)	Bpk(LTS)	Margin
13.50	20.00	20.75	13.60	
15.73	23.00	23.88	15.68	
15.80	23.10	23.98	15.74	15.5%
15.77	23.06	23.94	15.72	15.3%





Dealing with the large Lorentz Forces in the Common Coil Design

- Discussion in next few slides show the benefits of the common coil geometry in dealing with the large Lorentz forces at high fields
- Initial studies (just started) show that a solution can be found for keeping stresses both in Bi2212 coils and in Nb_3Sn coils below the desired limit

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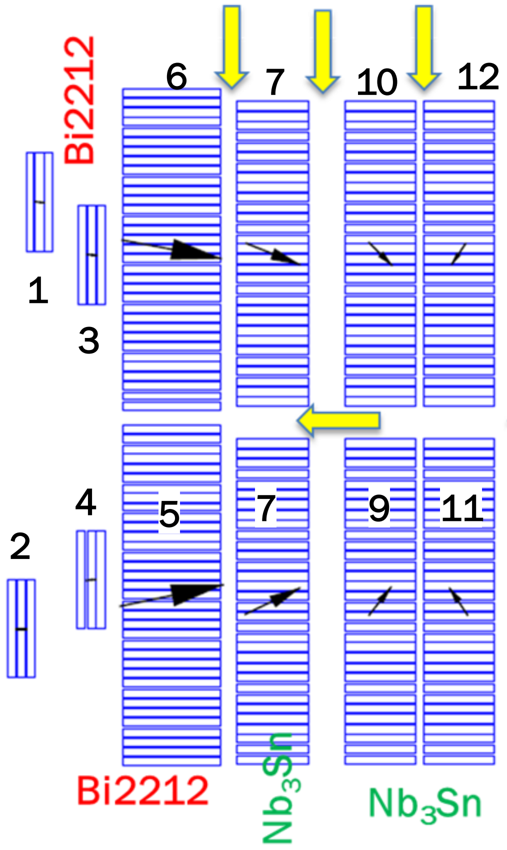
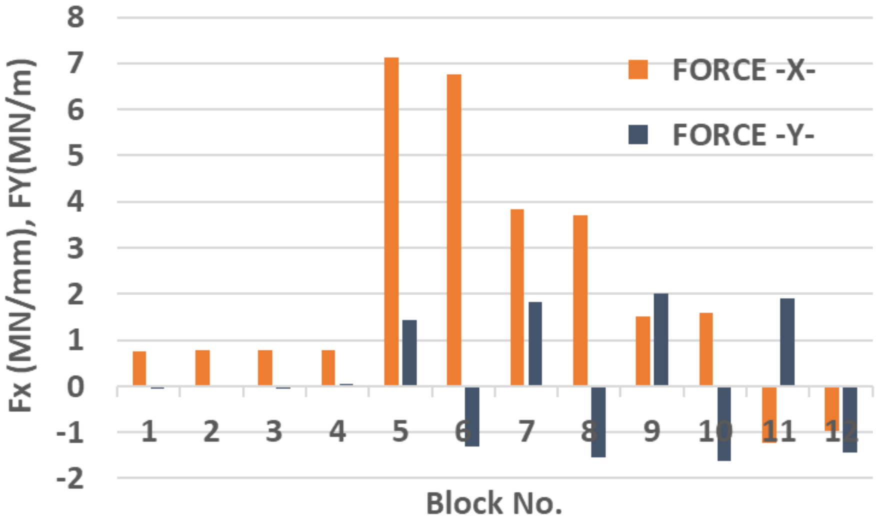
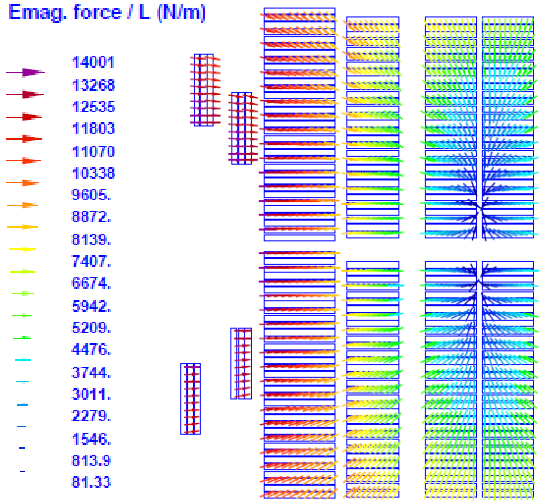
Lorentz Forces in the Common Coil

(design advantageous in dealing with large forces)

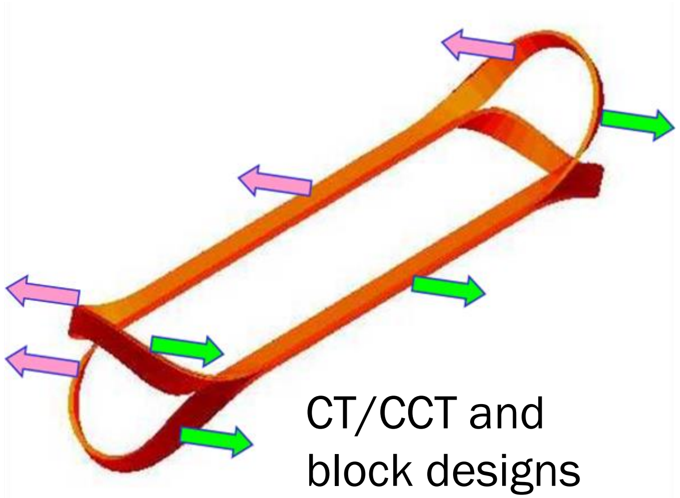
Concept of Stress-managed structure



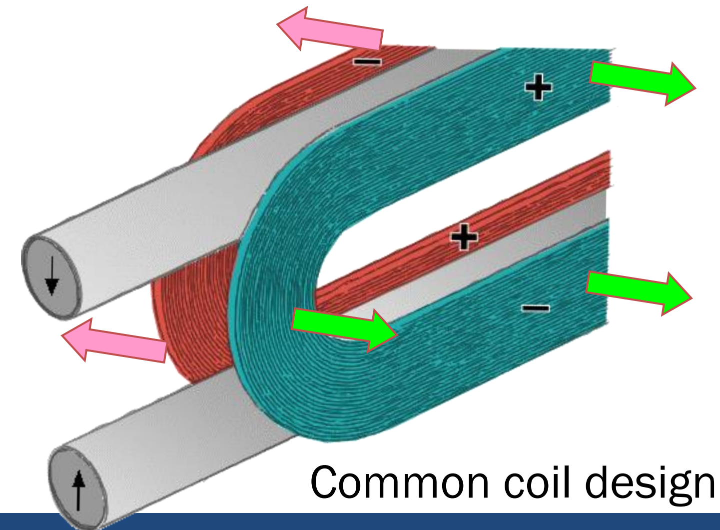




- Horizontal forces much larger than vertical (maximum vertical is 1/3 of horizontal)
- Large horizontal deflection can be tolerated since coils move as a unit - without causing much strain in the end or transition regions
- BNL common coil had 200 μm horizontal deflections and low vertical pre-stress
- Small forces on pole (mostly horizontal)



CT/CCT and block designs



Common coil design

Initial Mechanical Analysis of the 20 T Hybrid Common Coil Design (1)

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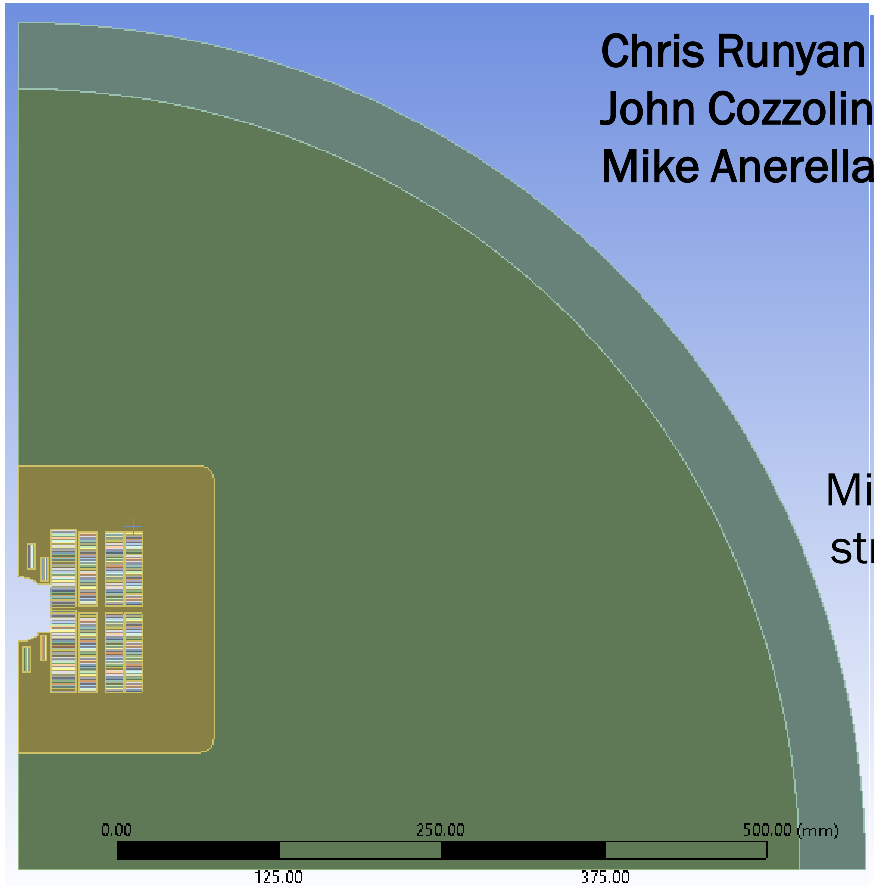
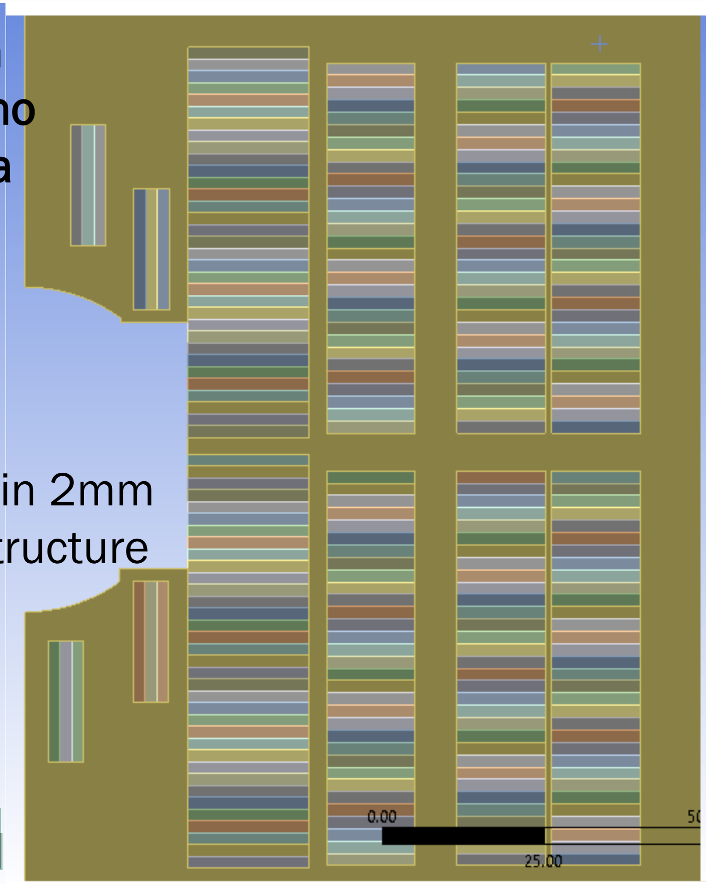
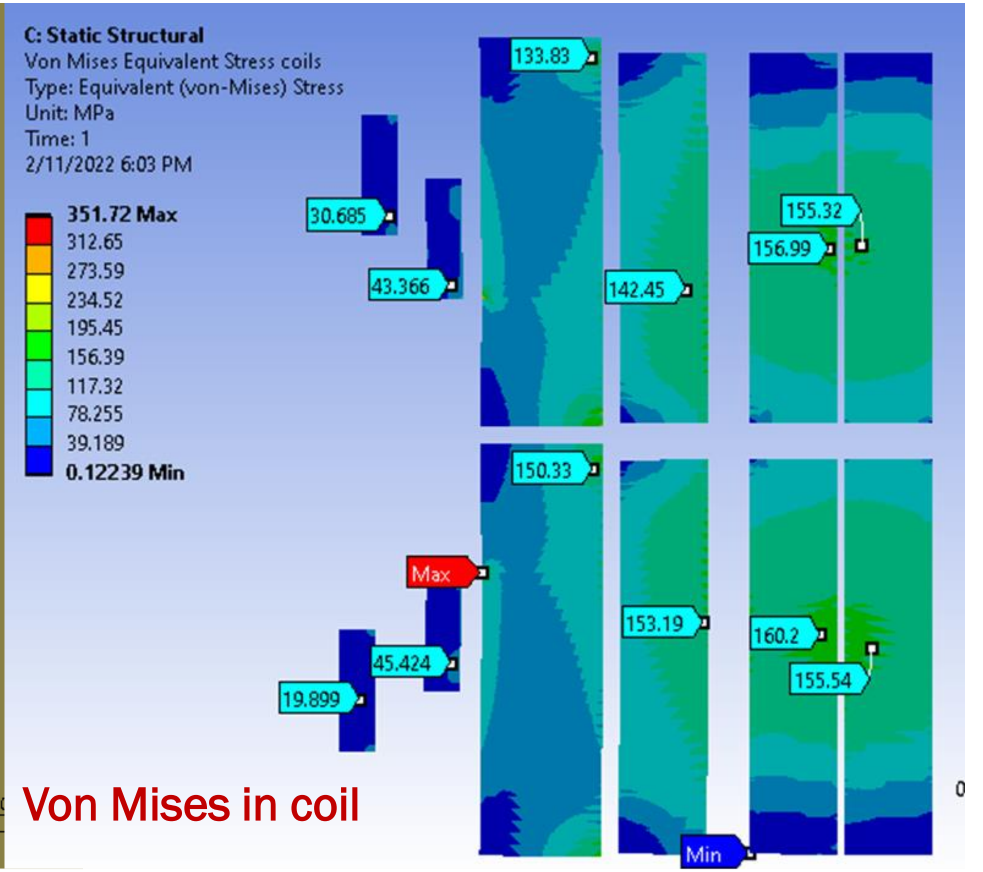
Chris Runyan
John Cozzolino
Mike Anerella



Min 2mm structure





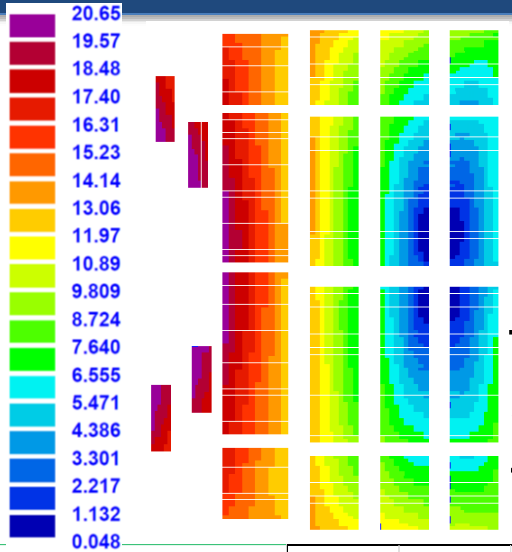
Von Mises in coil

Stress in Nb3Sn coils are already below the maximum specified (180 MPa). The maximum value in Bi2212 coils needs to be reduced a bit (below 120 MPa). Peak value in Bi2212 coils seems to be about 150 MPa.

Magnetic, mechanical & assembly designs will be iterated together (i.e., with feedback from one to other).

Impact of More Space for Structure

(to be iterated with mechanical analysis)



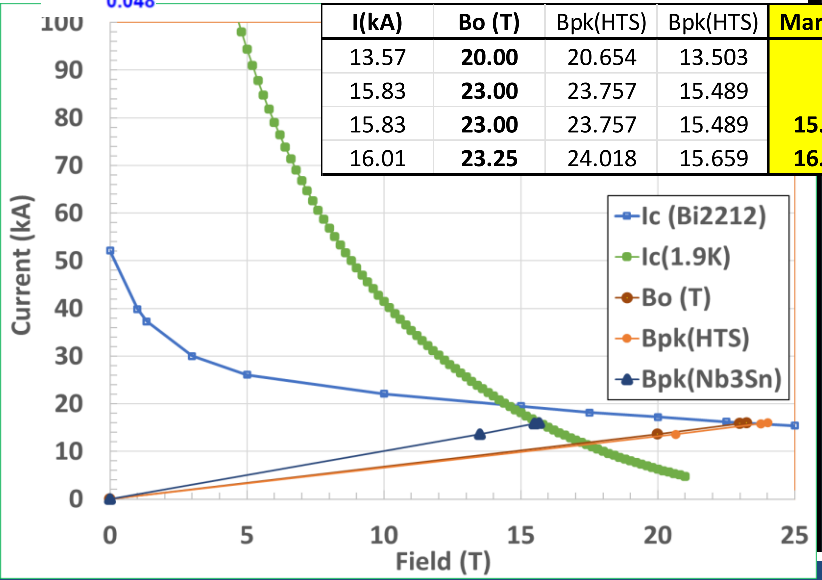
No. of Turns (½ bore)

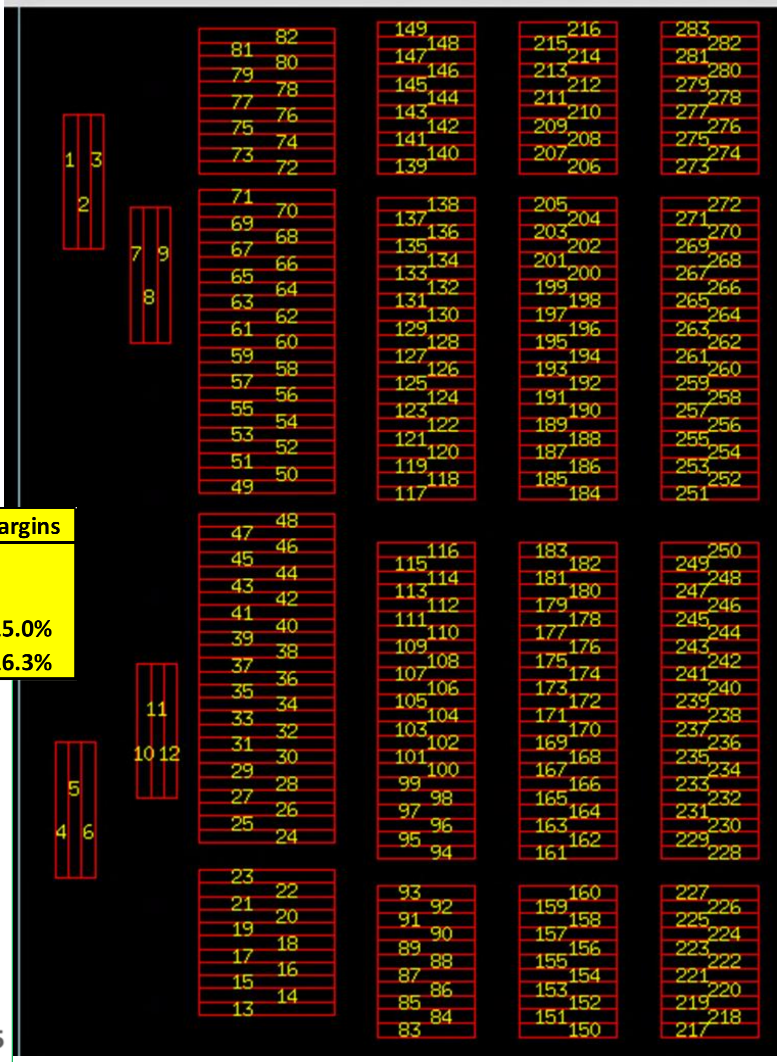
- HTS: 82
- LTS: 201

Total: 283

(increase from 80+186=266)

I(kA)	Bo (T)	Bpk(HTS)	Bpk(HTS)	Margins
13.57	**20.00**	20.654	13.503	
15.83	**23.00**	23.757	15.489	
15.83	**23.00**	23.757	15.489	**15.0%**
16.01	**23.25**	24.018	15.659	**16.3%**





Modest 6% increase in conductor for providing ~3-6 mm vertical and 6 mm horizontal space (space for structure is like that used in SMCT).

We are unlikely to need so much.

Geometric harmonics < 0.4 10^{-4}

```
MAIN HARMONIC ....................................           1
REFERENCE RADIUS (mm) ............................     15.0000
X-POSITION OF THE HARMONIC COIL (mm) .............      0.0000
Y-POSITION OF THE HARMONIC COIL (mm) .............    200.0000
MEASUREMENT TYPE ...................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br .................  0.3463E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

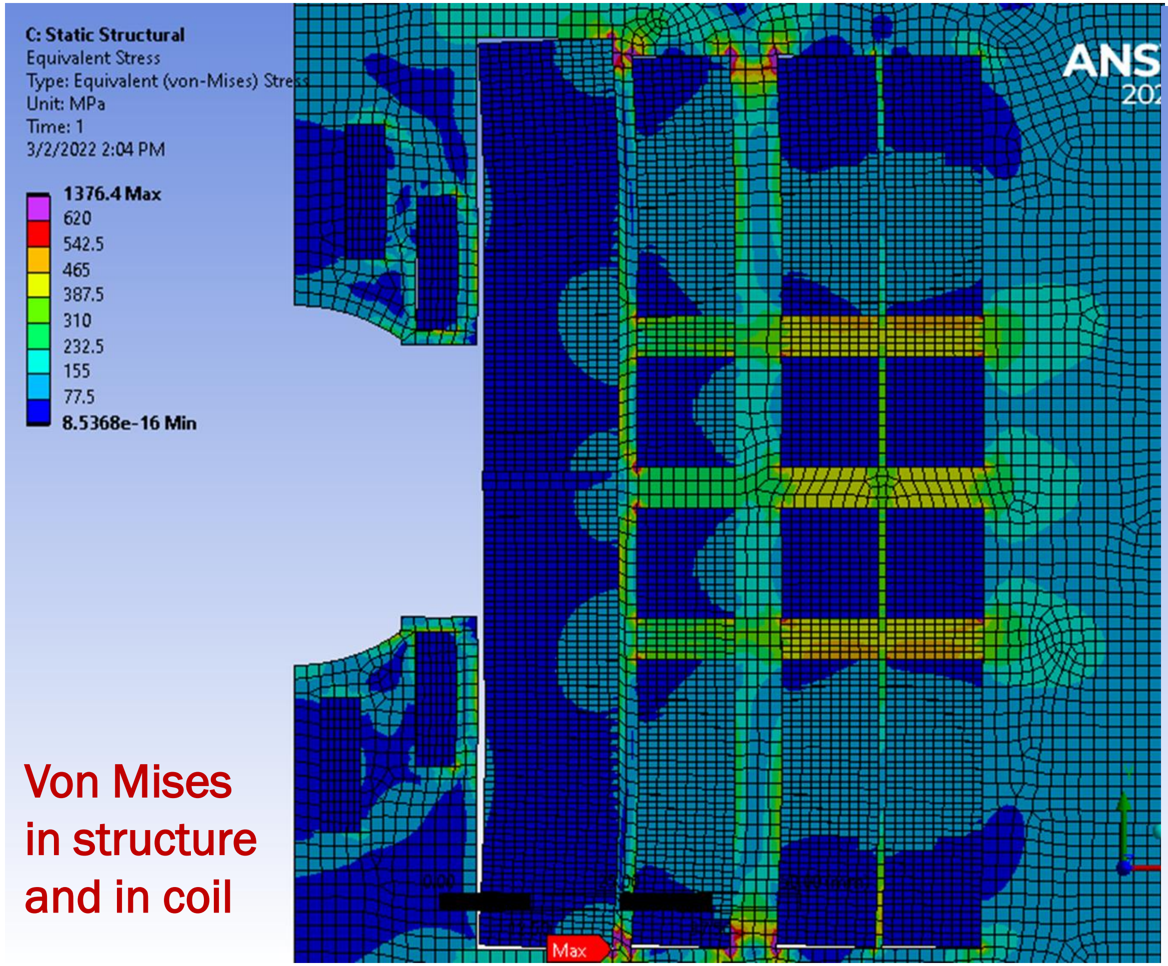
MAIN FIELD (T) ...................................   20.000772
MAGNET STRENGTH (T/(m^(n-1)) .....................     20.0008

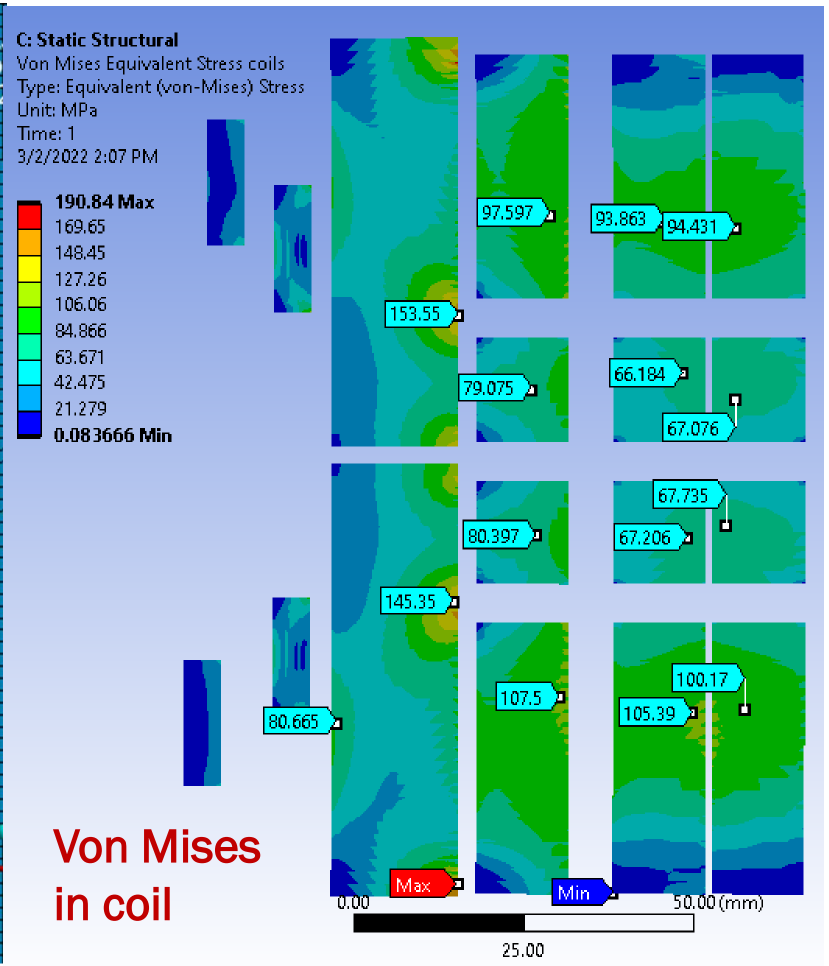
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:      0.00750
b 4:     -0.00000  b 5:      0.03035  b 6:      0.00000
b 7:     -0.03184  b 8:     -0.00000  b 9:     -0.57950
b10:      0.00000  b11:     -0.18084  b12:     -0.00000
b13:     -0.00462  b14:     -0.00000  b15:     -0.00500
b16:      0.00000  b17:     -0.00297  b18:     -0.00000
b19:     -0.00044  b20:      0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:     -0.00000  a 2:      0.00071  a 3:      0.00000
a 4:     -0.03296  a 5:     -0.00000  a 6:     -0.00676
a 7:      0.00000  a 8:      0.35166  a 9:     -0.00000
a10:      0.22734  a11:      0.00000  a12:      0.01060
a13:     -0.00000  a14:      0.00915  a15:      0.00000
a16:      0.00620  a17:     -0.00000  a18:      0.00130
a19:      0.00000  a20:      0.00031  a
```

Initial Mechanical Analysis of the 20 T Hybrid Common Coil Design (2)

Study of adding vertical support structure:





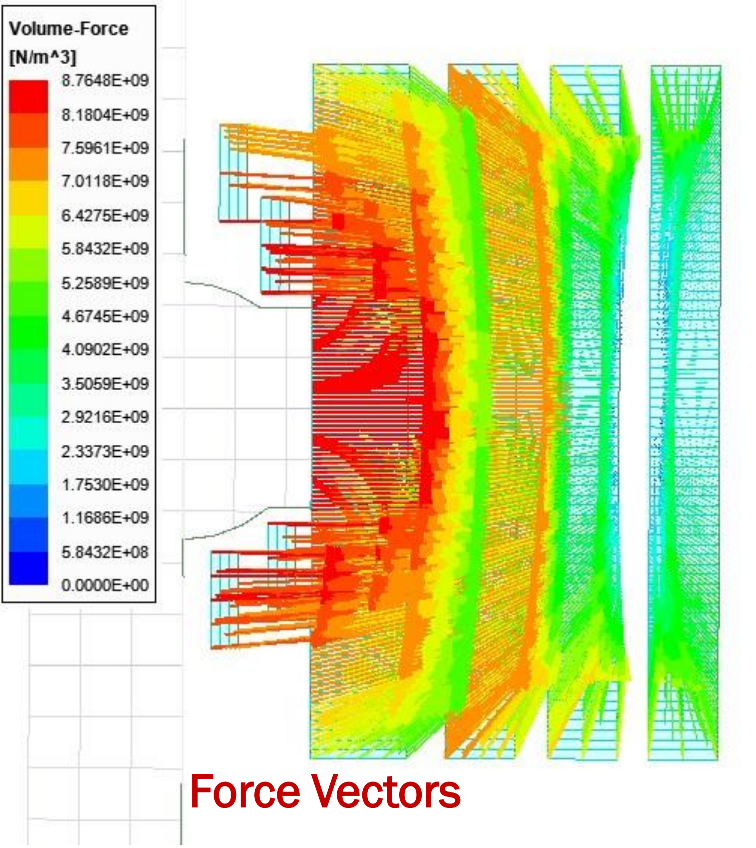
Maximum peak stresses at 20 T are: 105 MPa (well below 180 MPa) in Nb_3Sn.

However, the peak stress on Bi2212 coil is 154 MPa (barring singularities), over 120 MPa desired .

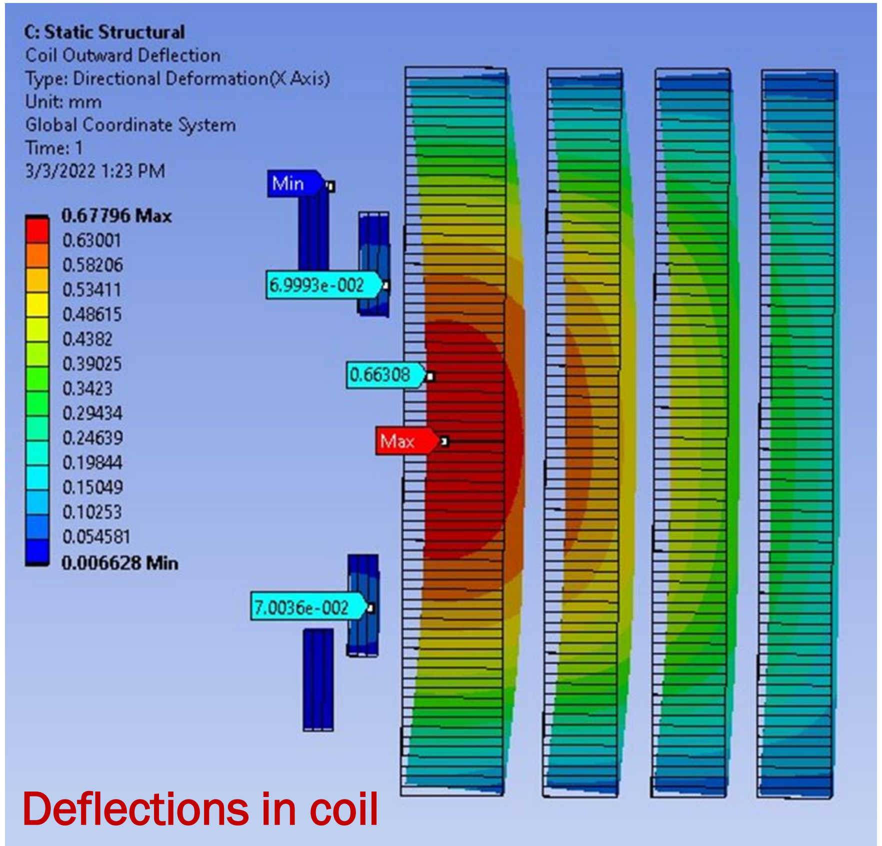
Maximum stress in Bi2212 coil can be reduced by increasing the SS plate thickness (next slide)

Initial Mechanical Analysis of the 20 T Hybrid Common Coil Design (3)

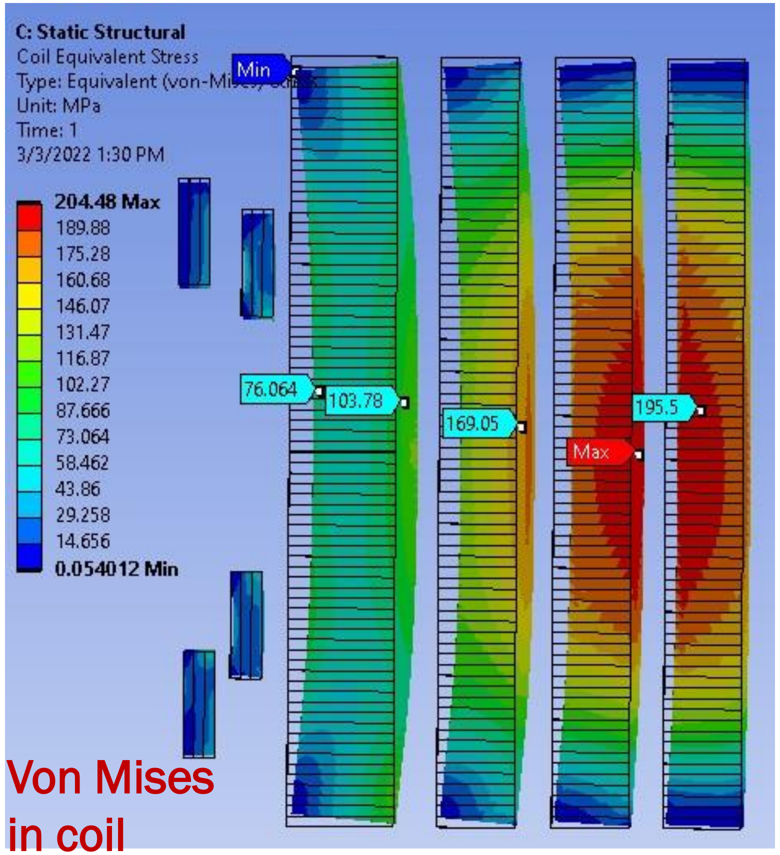
Study of adding horizontal structure: Stress in Bi2212 coils reduced to 104 MPa (<120 MPa)



Force Vectors



Deflections in coil



Von Mises in coil

ANSYS analysis prove working concepts of structures to keep stresses within limit.

Next step: Iterate the magnetic and mechanical design to produce good field quality with acceptable stresses.

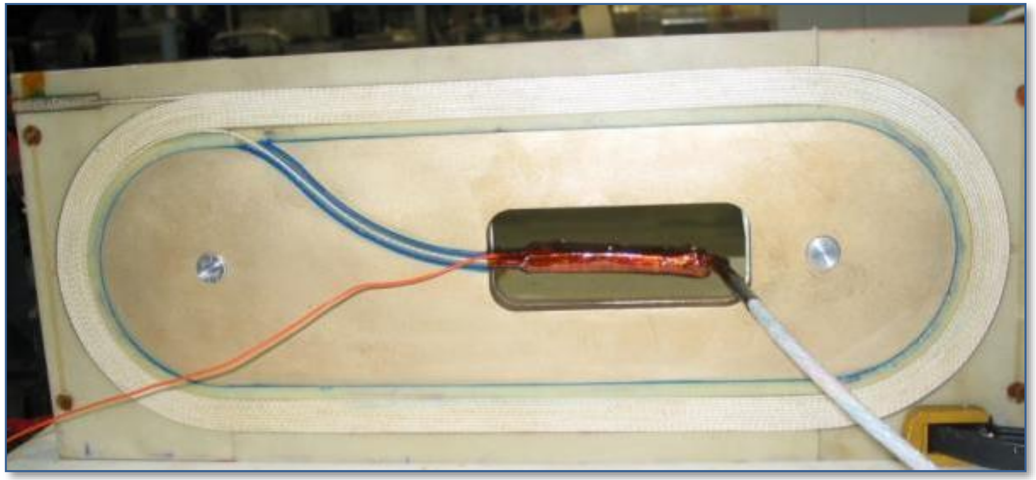
Benefit of Common Coil: Interfaces

- Interfaces are going to be a major issues in very high field magnets where we must deal with large Lorentz forces
- Both Canted Cosine Theta (CCT) and Stress Managed Cosine Theta (SMTC) are going to have many interfaces
- Gaps must be left for expanding cable in reaction and they should be filled with the epoxy. Since epoxy is not a strong material. It shouldn't be too thick to minimize cracking (can that be avoided in complex structures where it will be difficult to fill in the gaps)

➢ **By contrast, the common coil structure, as it appears to be developing now, should have fewer and simpler interfaces!**

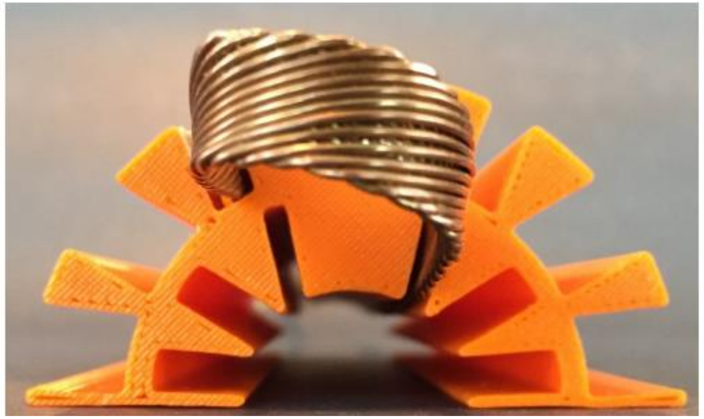
Benefit of CC: Less Conductor Degradation and More Conductor/Cable Options

Common Coil: Conductor friendly design with large bend radii (order of magnitude more than others)



React & Wind Bi2212 Rutherford cable coil built and tested

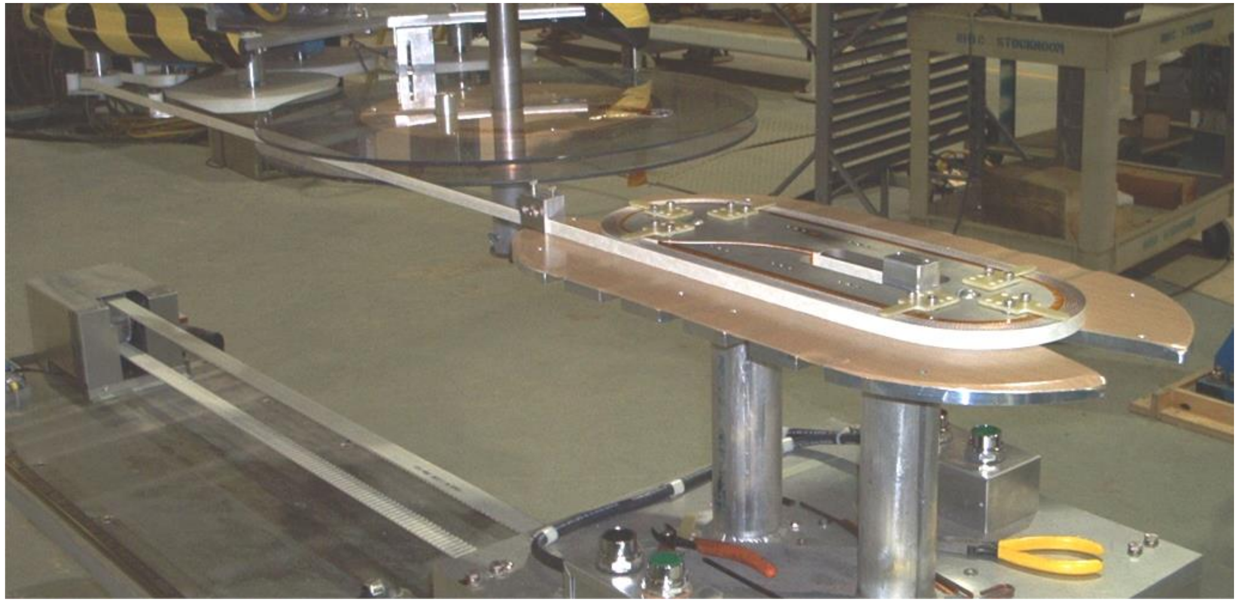
Cables must be bent in much smaller radii in CT/SMCT/CCT as compared to that in CC

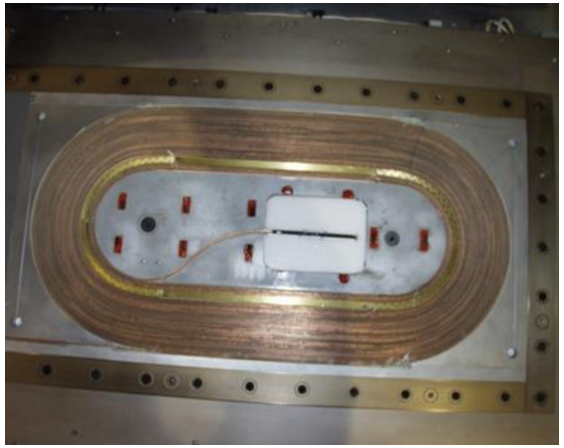


- Conductor degradation (both in Nb_3Sn and in HTS) is a major issue in high field magnets
- Larger degradation expected in coil ends with relatively complex geometries with small bend radii
- Smaller degradation is expected in the common coil designs with simpler ends and large bending radii.

- Many cables, including those that developed for the fusion (where a lot of investment is being made), can't be used in Cos theta or CCT since many of them can't be bent in small radii. However, they can be used in the common coil because of larger radii.
- Performance, reliability and cost of many cables can be reduced if they don't have to be bent so tightly

Common Coil: Allowing More Technology Options





- Common coil design offers the opportunity for “React & Wind” technology, in addition to the “Wind & React”.
- “R&W” technology is attractive for large scale production in industry
- BNL common coil dipole was wound using the “R&W” technology and reached short sample with strain (David - magnet can’t perform better than the conductor)

- Many insulation and coil material options become available as coil doesn’t have to go through the high temperature reaction

What is the most critical thing that must be proven for the common coil design?

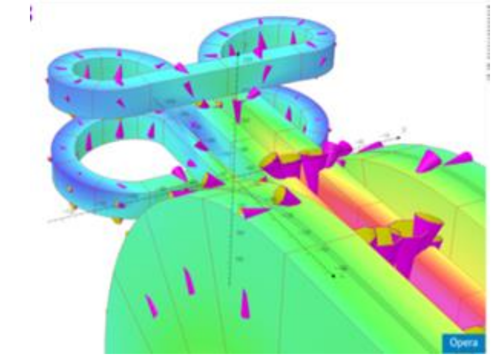
- Although several common coil designs have been designed with a variety of conductor (NbTi, Nb_3Sn, Bi2212, Bi2223, ReBCO), all have been made with the main coil only
- The most efficient design to obtain good field is the one with the pole coils
- We need to demonstrate a proof-of-principle design for pole coils that clear the bore tube. Many geometry considered but none demonstrated.

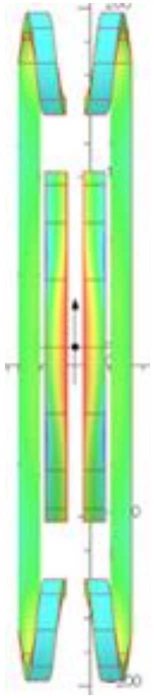
➢ Pole coils can be built, integrated and tested with the main coils in the BNL common coil dipole DCC017. Attempt to do that demo took off three times with SBIR Phase I (see next slide). However, none could be carried out as no Phase II was funded despite the productive work in Phase I.

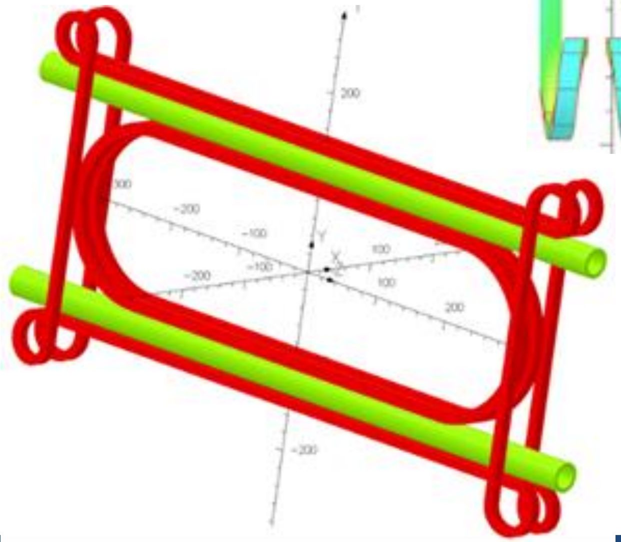
➢ Proof-of-principle demo of the pole coils should be a high priority for MDP. It can be done in a short period and at a low cost for coil made by any lab.

A Few Possible Layouts of Pole Coils Clearing the Bore (other geometries discussed elsewhere)

Overpass/underpass (cloverleaf) design

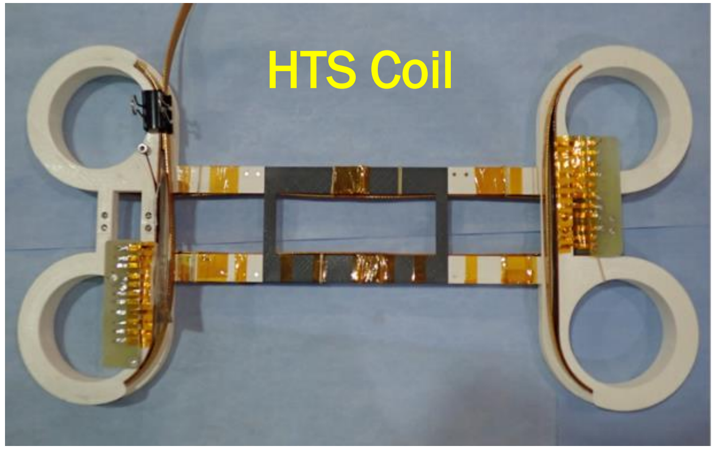


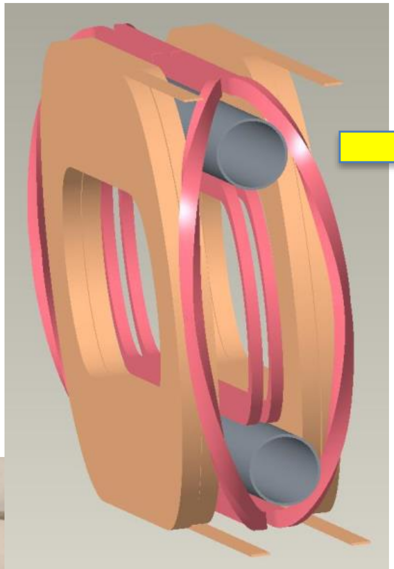




Practice pole coil windings and preliminary designs performed under “three” SBIR Phase I. They can be built and tested at 10^+ T field as a part of common coil dipole DCC017 under MDP.

CERN is also working on this design





CERN (Glyn Kirby) has shown strong interest in collaborating

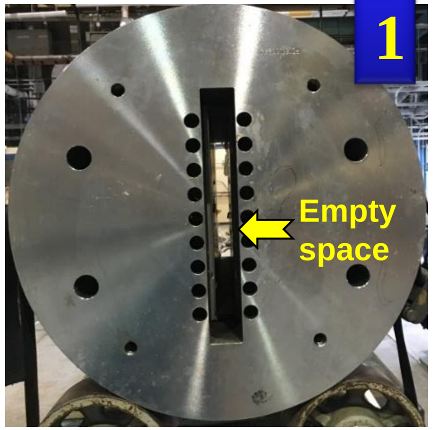
A Vision for the Next High Field Dipole (modular and facilitate low-cost, rapid R&D)

BNL common coil design experience has been very productive for low, cost rapid-turn around R&D for a variety of purpose.

Identical design may not work for high fields, but a similar approach may.

For example, fully open space may be replaced by removable insert, or allow disassembly.

Five steps for testing new design

1


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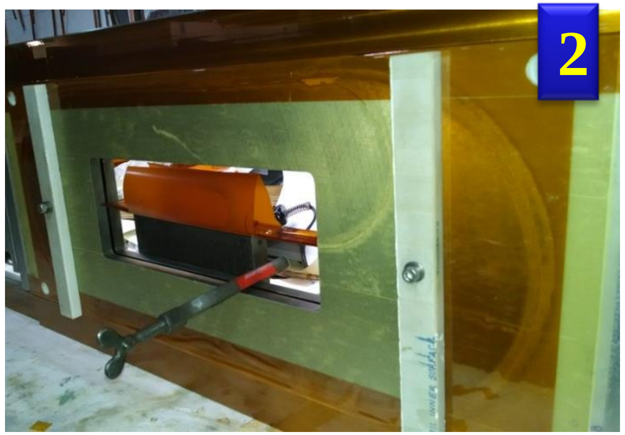

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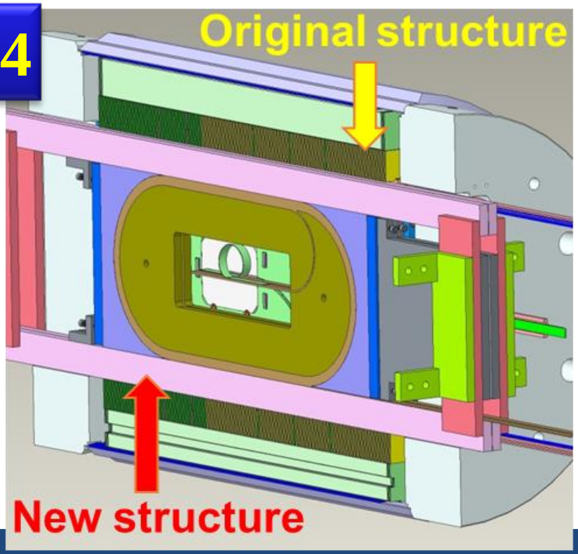
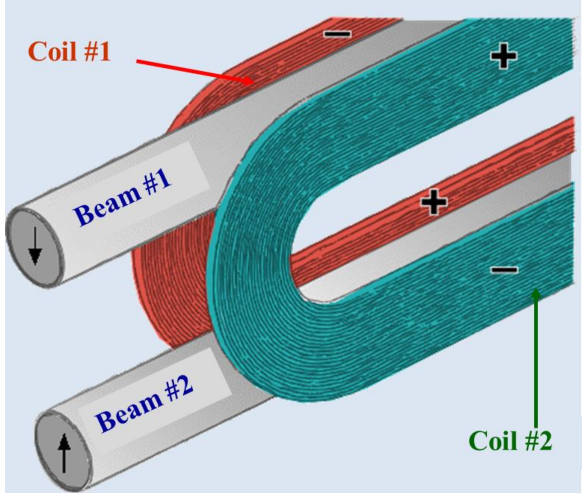
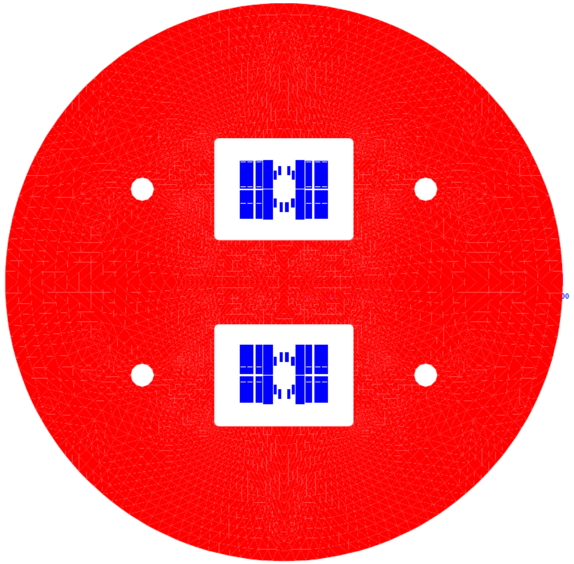


5


1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing

Recap: Benefits of the Common Coil Design

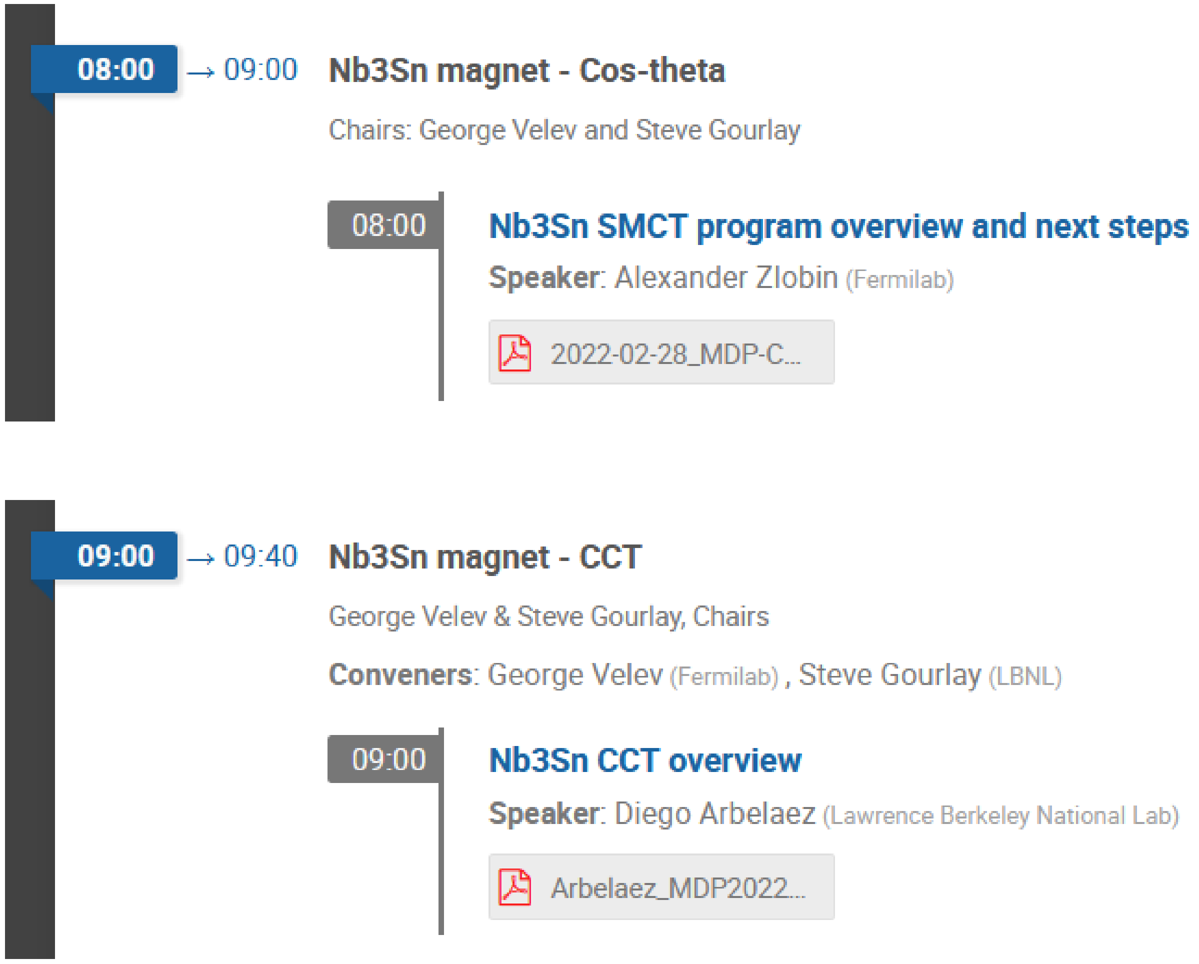




- **Simple 2-d** coil geometry for collider dipoles
- **Conductor friendly design** with large bend radii (determined by the spacing between two apertures). Less sensitive to conductor degradation.
- **20 T dipole uses significantly less conductor** than used in other designs
- **Efficient segmentation** between LTS and HTS coils for HTS/LTS hybrid dipoles
- **Mechanically handles well the large Lorentz forces** associated with the high fields, creating lower internal strain on conductor despite large deflections
- **Fewer coils** (half) as the same coils are common between the two apertures
- **Simple magnet geometry** and **simple tooling,** expect lower costs
- **Identical design** can be used for all Nb_3Sn coils
- **Allows** both React & Wind and Wind & React options
- **Allows more technology options** for insulation, etc.
- **Allows rapid-turn-around, low-cost** R&D for systematic and innovative studies
- … …

Suggestion for the Next Annual Meeting

- We are in an era where the next hadron collider may be decades away.
- Conductor, technologies and designs are evolving, and they may change the equation.
- For long term R&D projects like this, we must re-evaluate our direction every five years so.
- Potential benefits of the common coil geometry are becoming apparent.
- Include common coil design at the top-level discussion, while overviewing the options.
- Compare all designs methodically for their potential advantages and challenges.
- Be ready to adjust directions, specific goals, and milestones, if necessary.



You are invited to join the white paper

U.S. MAGNET DEVELOPMENT PROGRAM

Snowmass 2021 Letter of Interest

Common Coil Dipole for High Field Magnet Design and R&D

Proponents: Ramesh Gupta, Kathleen Amm, Michael Anerella, Anis Ben Yahia, John Cozzolino, Piyush Joshi, Jess Schmalzle (BNL), Ronald Scanlan, Robert Weggel, Erich Willen (PBL), Qingjin Xu (IHEP), Fernando Toral (CIMET), GianLuca Sabbi, Steve Gourlay (LBNL), Danko van der Laan and Jeremy Weiss (ACT)

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Common Coil Dipole for High Field Magnet Design and R&D

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The principle thrust of magnet R&D for the next generation high energy hadron collider is developing and demonstrating magnet designs for building higher field magnets in large volume in industry at a lower cost. All accelerators to date have been built on the strength of the cosine theta magnet designs using NbTi and, more recently, Nb_3Sn Low Temperature Superconductors (LTS). These magnet designs are being extended to reach higher fields. Based on a significant body of experience, the cost of carrying out large-scale production based on this design as well as the challenges in obtaining higher fields both in terms of budget and turn-around-time can be estimated. With the next collider several decades away, a case can be made that this time should be used in demonstrating alternate designs that have potential to produce higher field magnets in industry at a lower cost while meeting the field quality requirements of high energy colliders. There is also a need to include a strong R&D component in the program which facilitates testing and demonstration of new conductors and new technologies in a relatively shorter time frame and at a cost much smaller than building a magnet.

The common coil design [1] is a conductor-friendly block coil design with simple ends that have a large bend radius. The bend radius is determined by the separation between the two apertures of the collider rather than the aperture itself. The common coil design easily accommodates high field, brittle conductors or those cables that require large bend radii. The large bend radii in the common coil geometry allows both "Wind & React" and "React & Wind" technologies. The common coil design is a technically superior solution for high field magnets because the coils are primarily stacked vertically and move as a unit against the large horizontal Lorentz forces. This largely eliminates the internal strain on the conductor at or near the end region of the superconducting coils when the two sides of the coil move apart under Lorentz forces – a very different situation as compared to that in the conventional block coil or cosine theta dipole designs. As compared to the conventional block coil designs, the common coil block coil design eliminates almost all of the hard-way bends (or ends requiring long length). The only remaining hard-way bends are in the small pole coils and some designs practically eliminate the hard-way bends in those as well.

The common coil design facilitates a modular geometry which is particularly attractive for hybrid (HTS/LTS) magnet designs which require combining coils made with different types of conductors. In addition, the common coil design also offers easier vertical segmentation that is ideally suitable for hybrid coil dipole designs. Such magnets use coil modules made with made different conductors (Nb_3Sn, NbTi and HTS). In addition, the design provides natural and easier stress management. These features are applicable for both R&D magnets and for large-scale production magnets.

In addition to allowing versatility in conductors and technologies, the common coil design is also one of the most likely candidates to provide lower cost large scale production of high field 2-in-1 collider dipoles with good technical performance. Lower cost in large volume industrial manufacturing is expected because the common coil design would allow less expensive and more reliable production techniques due to 1) its simpler racetrack coil geometry; 2) half the number of coils required (as the same coils are shared between two apertures), and 3) the geometry requires a smaller volume of structural material.

The common coil dipole design was used in an earlier proposal for the Very Large Hadron Collider (VLHC) in the US [2]. The common coil design has also been used [3] in the present proposal of the Super proton-proton Collider (SppC) in China and is one of the designs under consideration for the proposed Future Circular Collider by CIMET [4].

Several institutes including LBNL [5], BNL [6], FNAL [7], IHEP [3] and CERN collaborators at CIEMAT [4] have carried out significant design studies on common coil magnets. Magnets based on the common coil dipole design have been successfully built at LBNL, BNL, FNAL, IHEP and other institutions with a variety of superconductors such as NbTi, Nb_3Sn, Bi-2212, ReBCO and Iron Based Superconductors (IBS). The very first test magnet based on this design at LBNL (RT1) reached short sample with almost no quenches [8]. Similar results were obtained at many other institutions including at BNL [9]. Further tests also showed that the change in pre-stress causes no degradation in performance. A common coil Nb_3Sn dipole (RD3) built using the "Wind & React" technology reached 14.7 T at LBNL [5]. At BNL a "React & Wind" Nb_3Sn dipole DCC017 [6] was built with essentially no vertical and horizontal pre-stress and it reached over 10 T, its computed short sample limit. FNAL [7] and IHEP [10] have also built and tested magnets based on this design. Despite many successes and even though FNAL built and tested an accelerator type field quality common coil dipole, demonstration of a fully optimized, high quality, high field common coil design with reasonable aperture and good technical performance remains to be done.

Hybrid magnets based on the common coil design have also been built and tested. Some examples of hybrid common coil dipole include a 3.7 T dipole at BNL with Bi-2212 and Nb_3Sn Rutherford cables [11] at BNL, a 10.7 T dipole at 4.2 K with Nb_3Sn and NbTi cables at IHEP [10], a 8.7 T dipole at BNL with ReBCO tape in a perpendicular direction to the primary field and Nb_3Sn cable in collaboration with Particle Beam Lasers, Inc. [12], and a 12.3 T dipole at BNL with ReBCO tape in primary field parallel direction and Nb_3Sn cable [13]. Higher field hybrid common coil dipoles under construction include 13-14 T with CORC® cable and Nb_3Sn cable under a collaboration between the Advanced Conductor Technologies, LLC and BNL [14], and HTS (ReBCO or IBS) at IHEP [15]. A common feature of all these dipoles is easy and better optimized segmentation between coils made with a different conductor.

The common coil design also offers an alternate path for building high field magnets with systematic and/or innovative R&D in a rapid-turn-around and lower-cost flexible R&D program for a variety of superconductors and technologies in a modular fashion [16]. Common coil dipoles, such as DCC017 built at BNL [6] with a large opening, allows new racetrack coil modules to be inserted and tested as an integral part of the high field magnet without requiring any disassembly and re-assembly of the magnet [12]. This, however, requires a larger amount of conductor for 2-in-1 magnet unless the insert coil can tolerate a tighter bend radius and is tested in one aperture only [13]. The design allows the same racetrack coil modules (or adding or replacing only some) to make either a higher field, smaller aperture dipole or a larger aperture, lower field dipole - as was done, for example at LBNL between RD3b and RD3c common coil dipole [5].

The common coil geometry provides an alternate design to the conventional cosine theta dipoles. It allows a wider range of conductor and magnet technologies. It also facilitates a low-cost, rapid-turn-around design and R&D program. Therefore, it should be a part of a long-term R&D program of developing high field magnets for high energy hadron colliders.

20 T Hybrid Design: Common Coil

Leaping to a New Design Space: Facing the Kodak Moment

Kodak knew about the digital photography.
But chose to stay with the print…

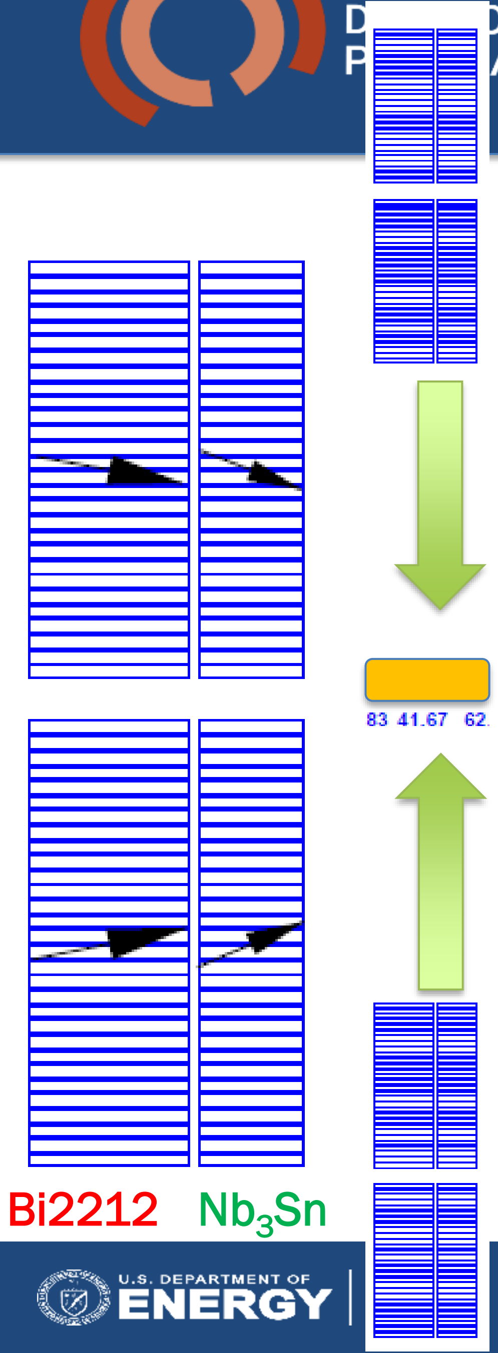
Summary

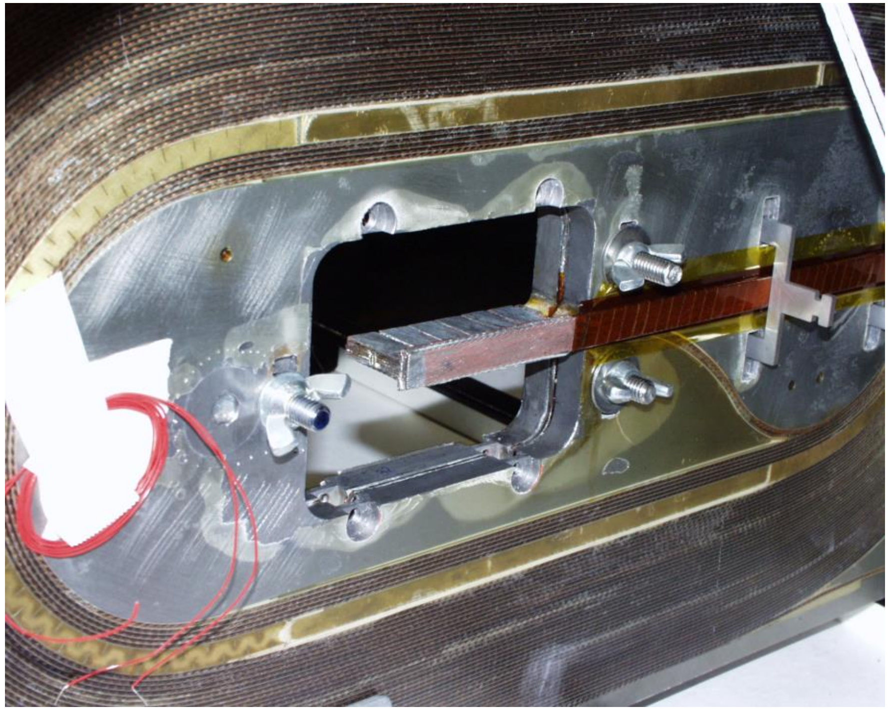
- MDP comparative study revealed that for very high field dipoles (20 T), common coil design uses significantly less conductor than that used in other designs. The analysis presented here explains why?
- Common coil offers several advantages, some outlined in this presentation.
- A focused effort should now be made across the labs to develop this design in more detail (including 3-d design, quench protection, assembly, R&D plan, etc.).
- This is a different design and provides new opportunity. A good opportunity for new scientists and engineers (who come with less to NO pre-conceived notions and biases) for doing pioneering work.
- Suggest that we to do a full comparative study of all options in the next annual meeting and see if an update in direction is warranted.

Extra Slides

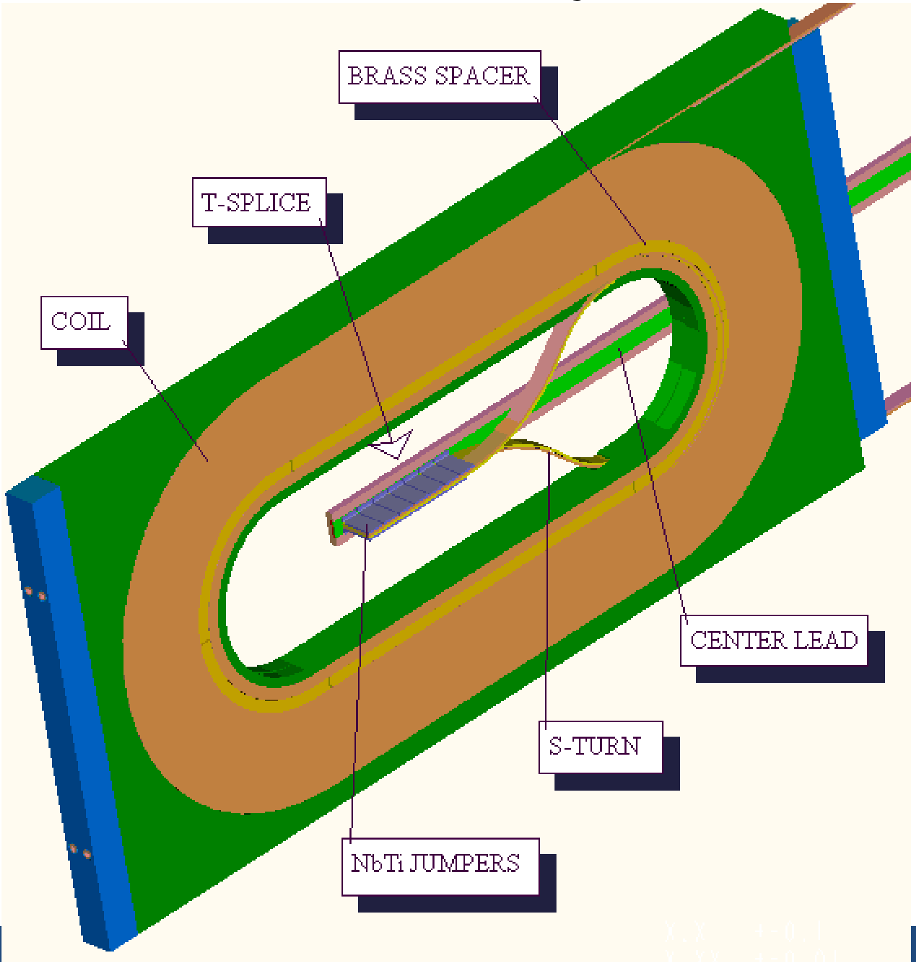
Splices in Common Coil Design (between two single layer coil)

In common coil design, splice (even between two types of coils), can be easily made in the middle of the coil where the field is very low



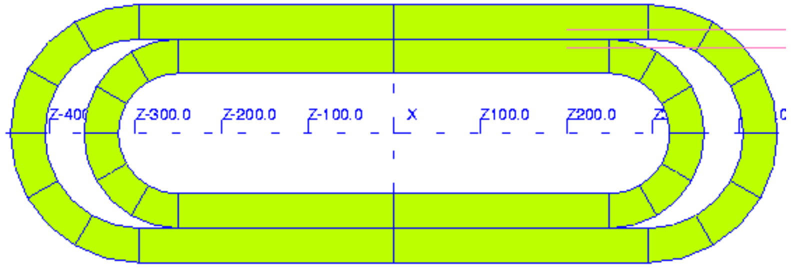


Perpendicular Nb-Ti splice in the low field region of BNL common coil dipole DCC017

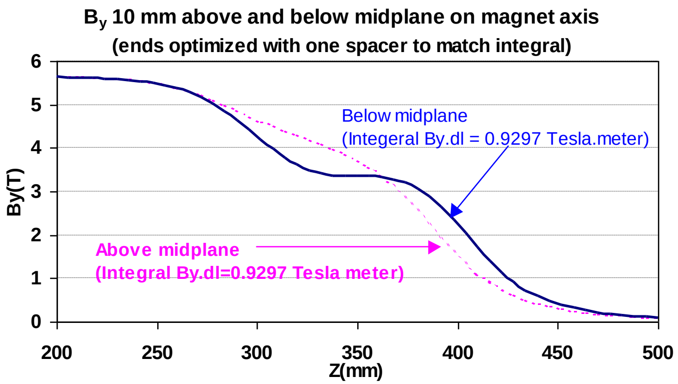


Demonstration of Good Field Quality in Ends

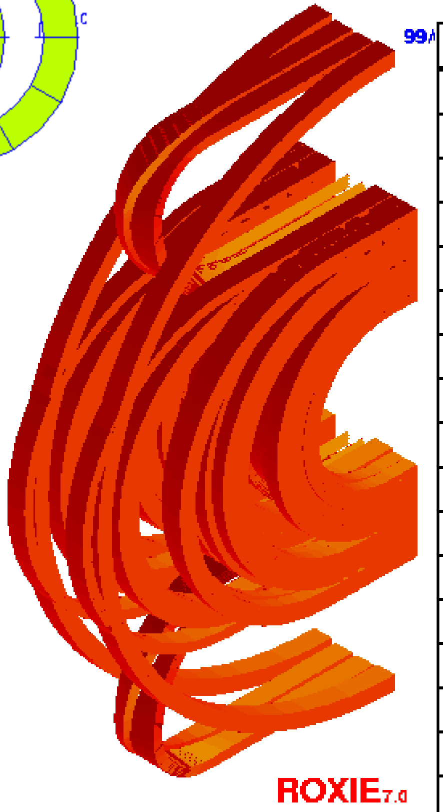
Up-down asymmetry will give large skew harmonics, if done nothing.



However, it can be easily compensated with the end spacers. Integral By.dl 10 mm above & 10 mm below midplane.



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

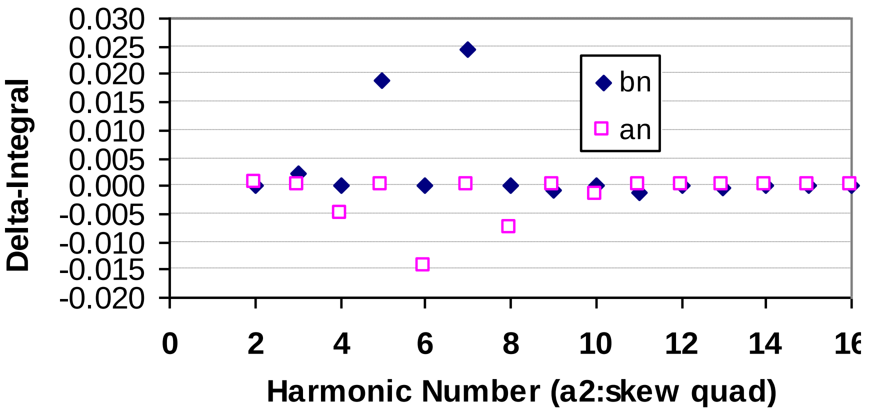


End harmonics in Unit-m
(Very small)

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 ($<10^{-6}$)

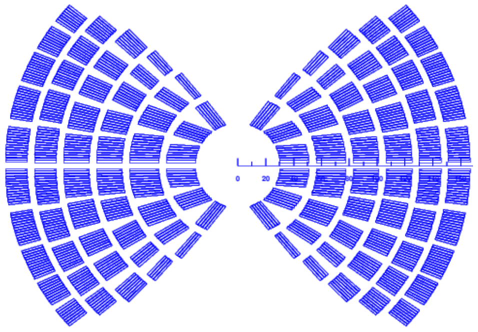
n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000

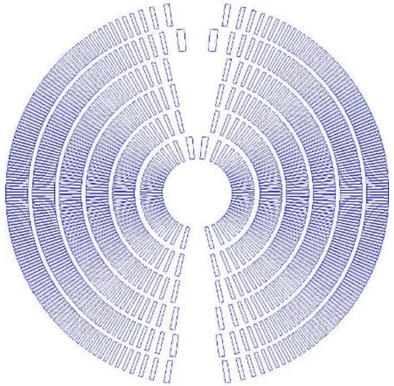


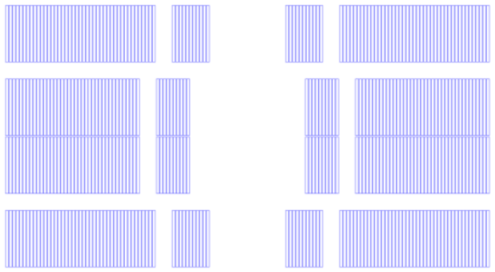
U.S. MAGNET DEVELOPMENT PROGRAM

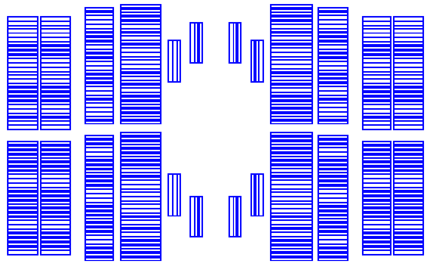
Coil Geometries for Very High Field Dipoles (coil width much greater than the magnet bore)

Situation changes for high field designs when the coil width (area) becomes much larger than the bore (aperture). One must evaluate again the impact on geometry and other constraints.









Variables and constraints to optimize the cosine theta and the canted cosine theta designs:

- Total coil width (radial width – free to grow)
- Pole Angle (limited to 90° max., 60° min. for b_3=0)
- Field quality: use wedges (may be used for structure)
- Radial space between layers for structure element

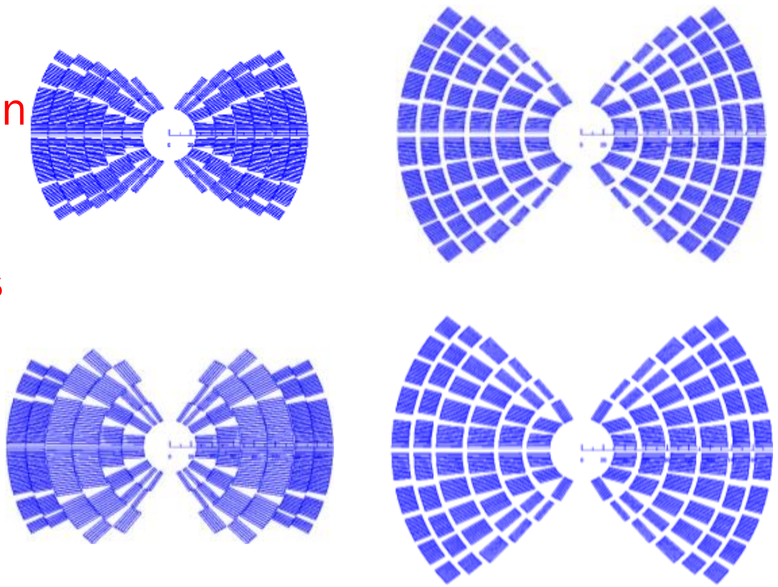
Variables and constraints to optimize the block coil and the common coil designs:

- Total coil width (horizontal width – free to grow)
- Coil Height (vertical height – free to grow) – major difference from the cos ϑ or canted cosine theta
- Field quality: use spacer (structure) & pole coils
- Horizontal space for structure elements

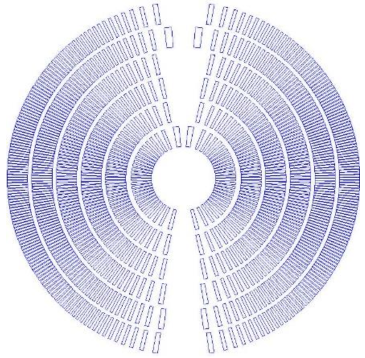
Some Observations and Possible Explanation

- Comparative studies of 20 T designs revealed that in the common coil design, one can get away with fewer layers and it uses less conductor.
- This is opposite to what was the conventional wisdom. Small differences in margin can't explain that.
- Any basic change in going from lower to higher fields?

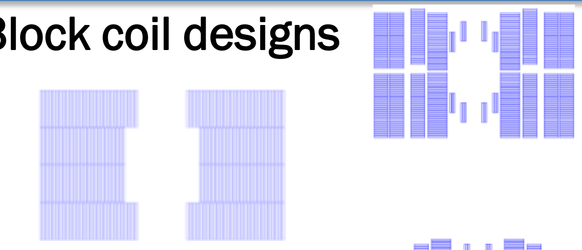
Cosϑ without and "with stress management"



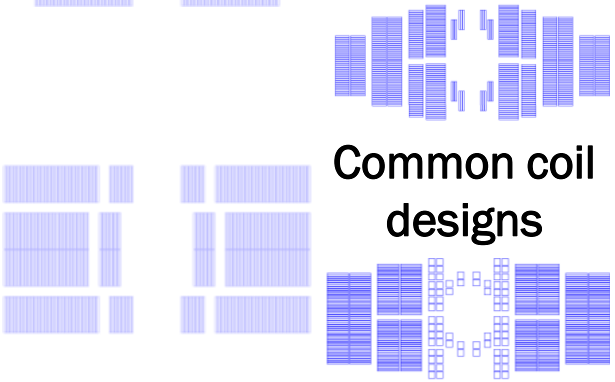
Canted Cosine Theta



Block coil designs



Common coil designs



Parameter	UNIT	CT I	CT II	SMCT I	SMCT II	CCT	BL I	BL II	CC I	CC II	CC III
Ins. cable I width/thick.	mm	10.7/1.5	12.0 / 1.7	12.3 / 1.5	12.3 / 1.5	18.7/1.9	17.1/2.1	17.1/2.1	18.7 / 1.8	18.7 / 1.8	7.5/7.5
Ins. cable II width/thick.	mm	9.4/1.5	14.2 / 2.1	10.7 / 1.5	13.9 / 1.5	-	17.1/2.1	17.1/2.1	13.6 / 1.9	13.6 / 1.9	21.6 / 1.9
Ins. cable III width/thick.	mm	9.3/1.5	7.9 / 1.5	9.1 / 1.5	9.1 / 1.5	-	-	-	-	-	-
Current_op	kA	10.7	13.0	11.4	11.8	12.8	12.6	12.2	14	13.9	17.8
B_bore_op	T	20.0	20.0	20.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0
B_bore_op HTS/LTS	T	20.5 / 12.7	20.3 / 16.1	20.6 / 13.6	20.6 / 16.0	20.2 / 13.2	20.6 / 15.1	20.9 / 15.2	20.4 / 13.8	20.2 / 13.7	21.0 / 17.0
B_bore_ss	T	24.4	23.5	24.4	23.2	23.4	23.6	23.6	22.9	23	21.7
B_bore_ss HTS/LTS	T	24.9/15.4	23.8 / 17.7	24.9 / 16.4	23.8 / 18.4	23.6 / 12.9	24.3 / 17.7	24.7 / 18.0	23.3 / 15.7	23.3 / 15.7	24.7 / 18.2
Load-line margin	%	18 / 25	21 / 15	22 / 18	20 / 15	14 / 14	21/17	22 / 17	13 / 13	13 / 13	15 / 7
Area quad. ins. cable HTS	mm^2	3241	1494	2091	1527	4490	1360	1500	1290	1154	1012
Area quad. ins. cable LTS	mm^2	2150	6106	3780	5148	4915	4740	6000	2326	2558	4191 <=Typo?
Coil width*	mm^2	105	129	144	149	135	80	112	70	104	106
Coil inner radius*	mm	25	25	30	30	30	35	35	25	25	25

Work Ahead

- Mechanical analysis of the 20 T HTS/LTS hybrid design (work just started).
- Provide feedback to magnetic design for the space needed for the structure between layers and within layer. Iterate magnetic and mechanical designs.
- Develop concepts for assembling the magnet.
- Perform 3-d magnetic and mechanical analysis for a 20 T design.
- Perform refined mechanical analysis for practical 3-d structures.
- Perform quench protection analysis.
- Several common coil dipoles with main coils have been built and tested; however, none with the pole coils necessary for the field quality. Build pole coils and demonstrate them in a proof-of-principle magnet (e.g. in DCC017).
- Perform cost estimates of R&D dipoles and for large scale series production.