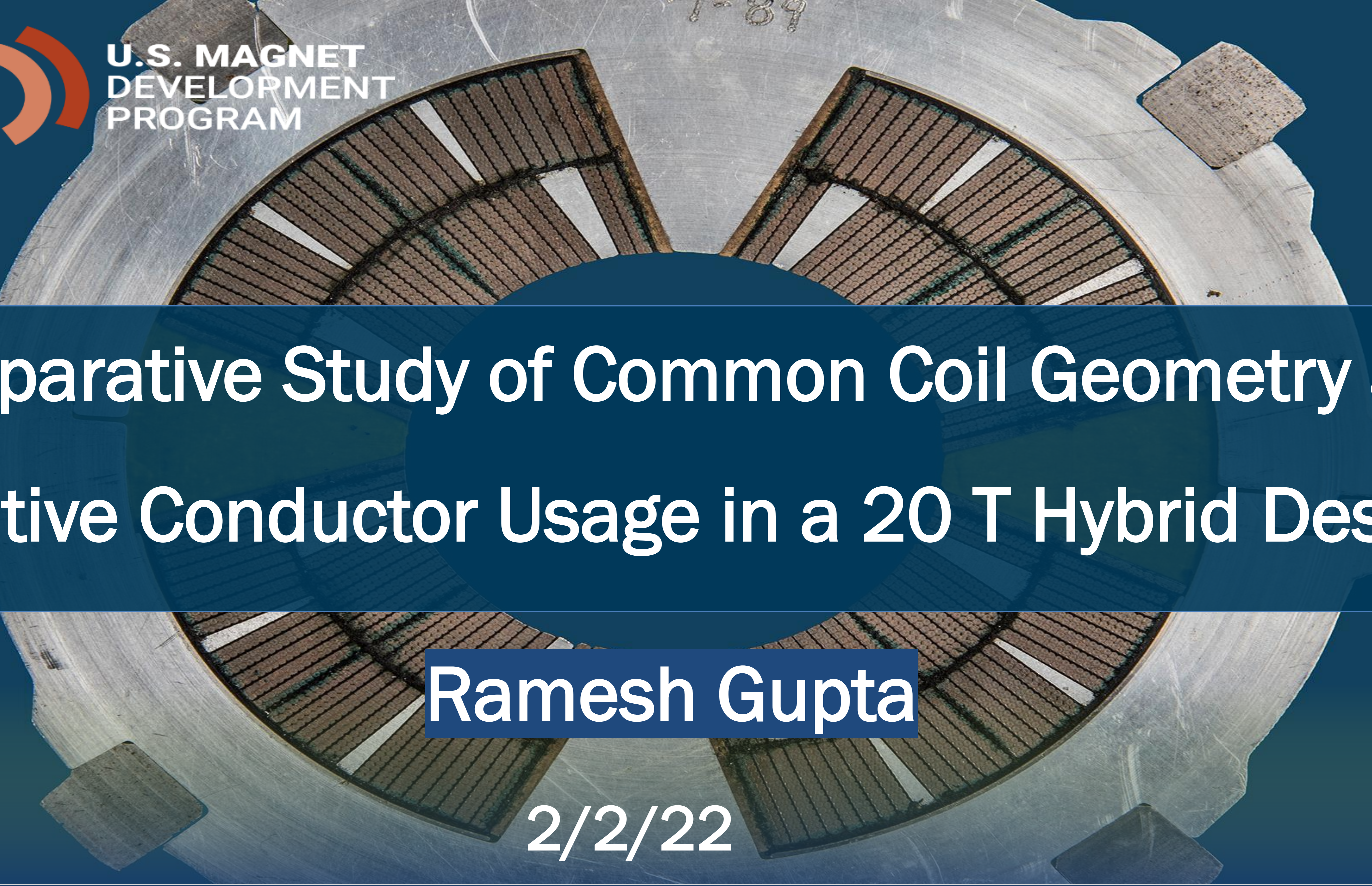


U.S. MAGNET DEVELOPMENT PROGRAM

Comparative Study of Common Coil Geometry and Relative Conductor Usage in a 20 T Hybrid Design

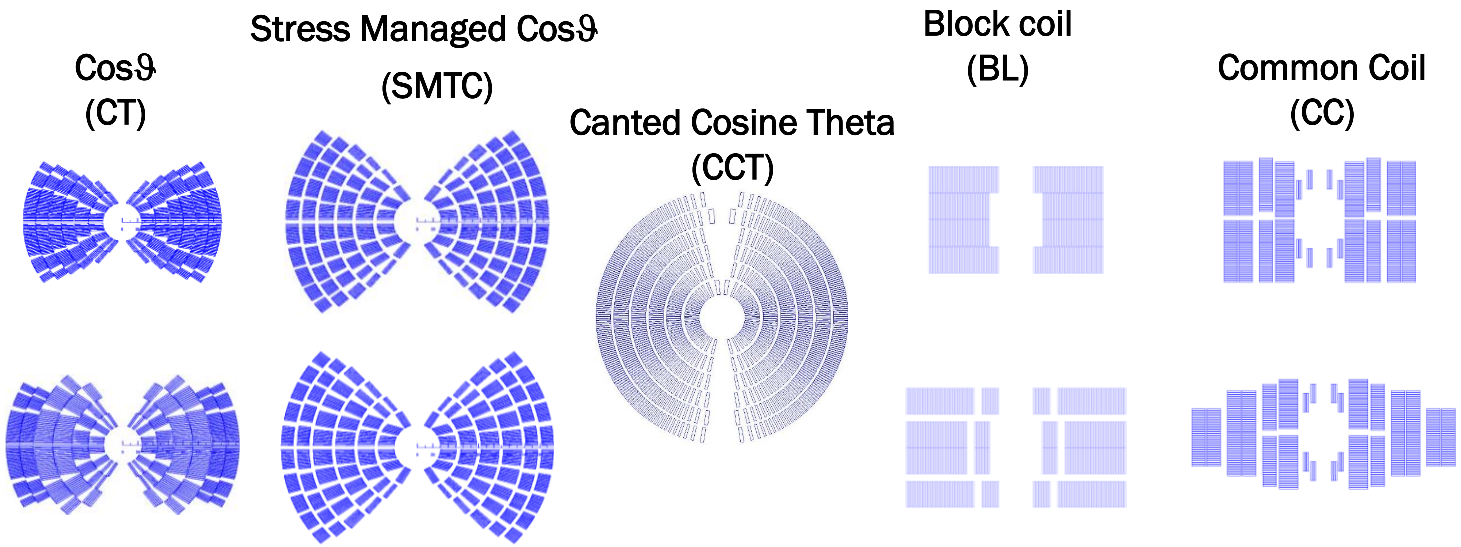
Ramesh Gupta

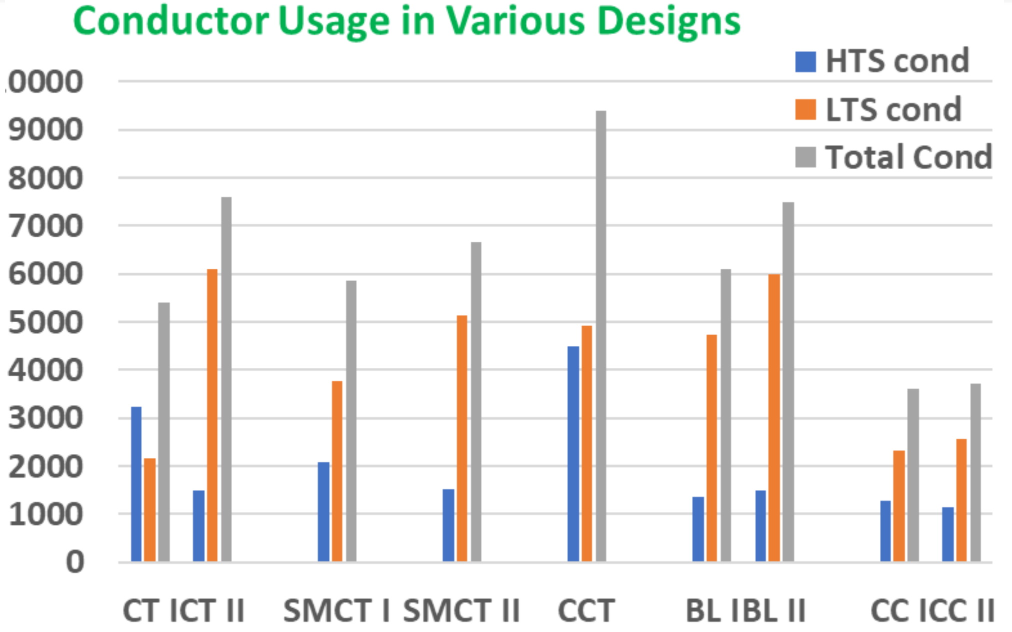
2/2/22

Content

- Initial results of the comparative study of the 20 T designs
  - The conductor usage are significantly lower in the common coil as compared to that in other designs (cosine theta and canted cosine theta).
  - This is opposite to what many expected. Difference is even more for the expensive HTS.
  - Is it real? If so, why?
  - Other interesting findings:
    - flexibility in the common coil design, including in the number of layers
    - overall cost of R&D dipole (for common coil one must have two bores)
- Work ahead and Summary

Initial Observation from the Comparative Study of Various Designs



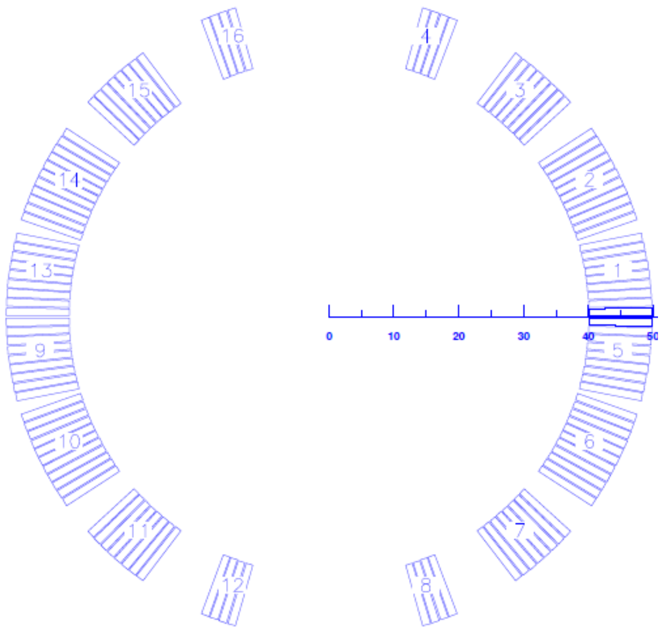


- Comparative studies of 20 T designs (as presented at MT) revealed that the common coil design uses significantly less conductor than the other designs. Small differences in relative margin doesn't explain that.
- This finding is opposite to that expected from the conventional wisdom. Why? Back to the design 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.

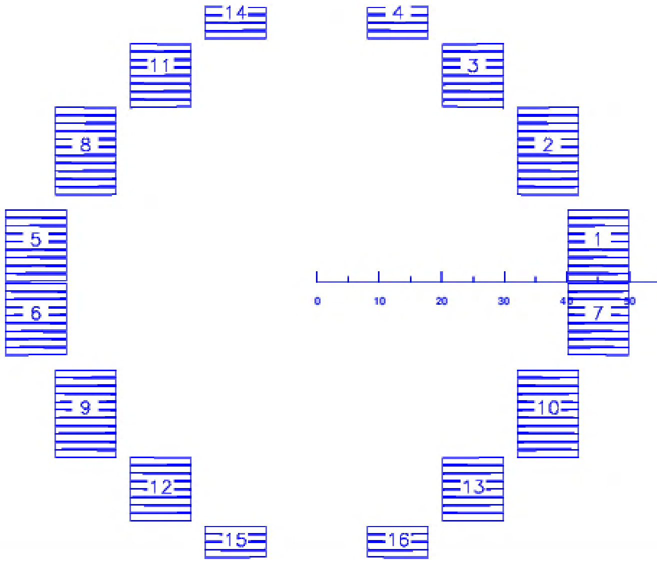
Cosine theta design



The basic rules of the cos theta dipole design:

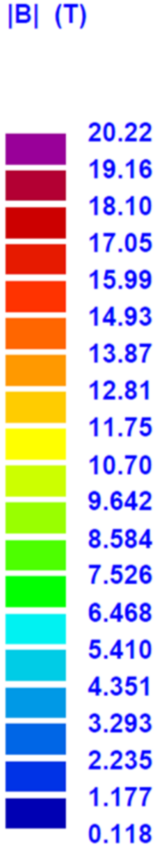
- B is proportional to the width * (current density)
- Conductor area needed to create the dipole field increases linearly with the radius of each layer (worse for fixing higher order multipoles)
- Coil must extend to 60º (or more with wedges) for b_3=0. Maximum is 90º.
- These principles define the geometry and the conductor area, with little flexibility left.
- At low fields, block coil designs appear less efficient and less elegant. They have not been used in any major conductor dominated design

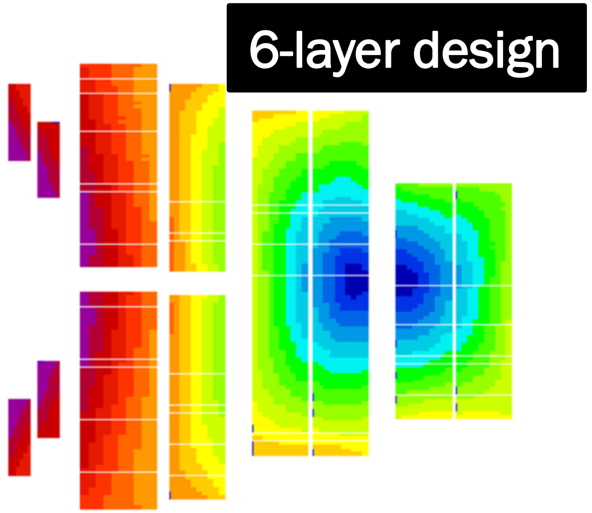
Block Coil Design



Another Observation: Coil Thickness

The coil width (number of layers) is primarily determined by the design field in the cosine theta and in the canted cosine theta designs. A large flexibility in coil width to create same field has been observed in the common coil design. And interestingly the coil width didn't impact the conductor requirement that much.

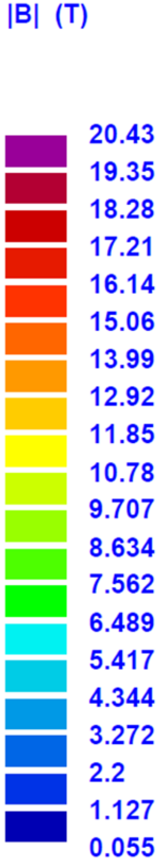


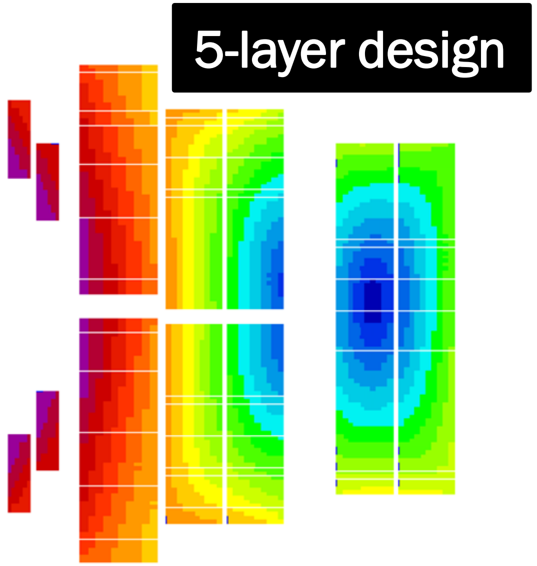


HTS: 1 layer + pole blocks
- ❖ 74 turns in ½ bore

LTS: 5 layers
- ❖ 198 turns in ½ bore

Total turns = 272

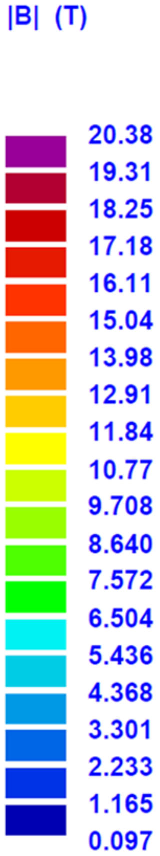


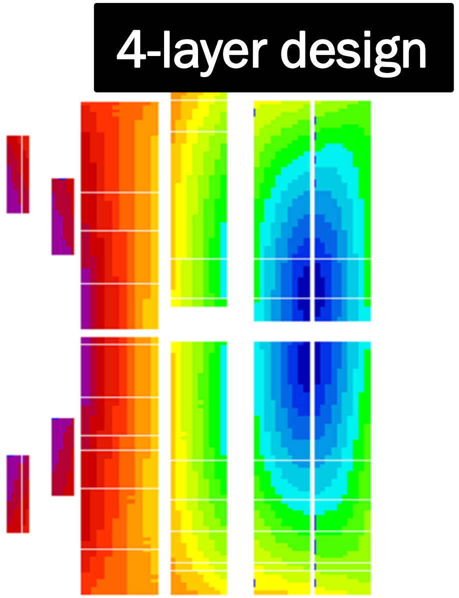


HTS: 1 layer + pole blocks
- ❖ 80 turns in ½ bore

LTS: 4 layers
- ❖ 188 turns in ½ bore

Total turns = 268





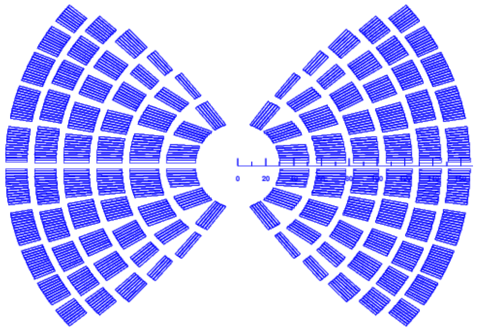
HTS: 1 layer + pole blocks
- ❖ 82 turns in ½ bore

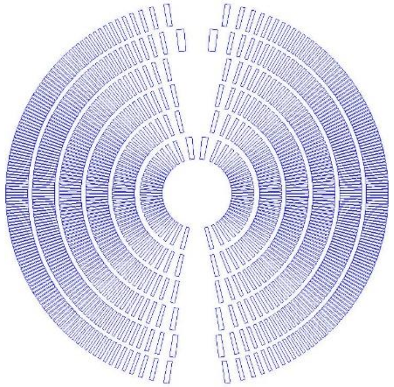
LTS: 5 layers
- ❖ 180 turns in ½ bore

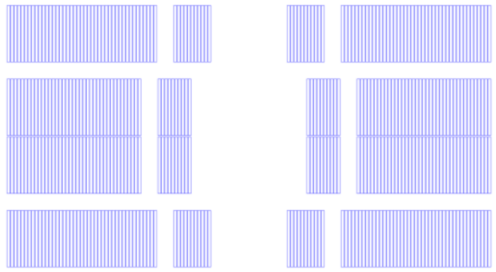
Total turns = 262

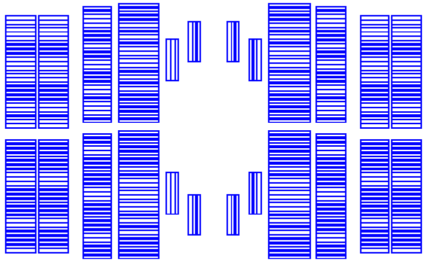
Coil Geometries for Very High Field Dipoles
(coil width much greater than the magnet bore)

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:

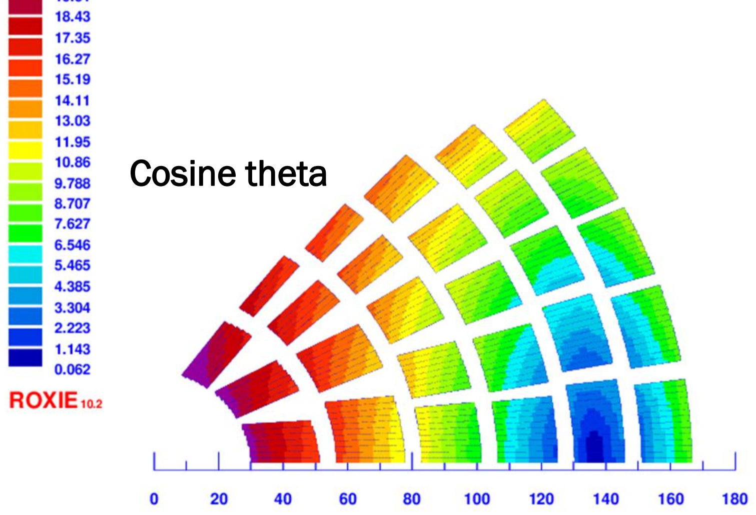
- Total coil width (radial width – free to grow)
- Pole Angle (limited to 90º max., 60º min. for b_3=0)
- Field quality: use wedges (may be used for structure)
- Radial space between layers for structure element

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

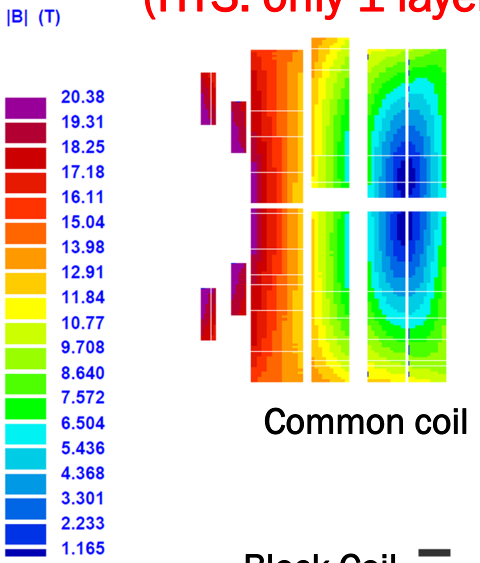
- Total coil width (horizontal width – free to grow)
- Coil Height (vertical height – free to grow) – major difference from the cos ϑ or canted cosine theta
- Field quality: use spacer (structure) & pole coils
- Horizontal space for structure elements

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

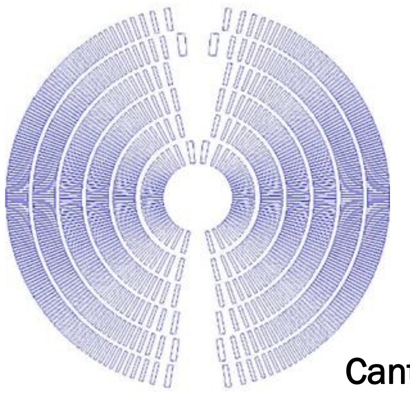
Need six layers (of which 2 to 4 layers must be of HTS)



4-layer design (HTS: only 1 layer)

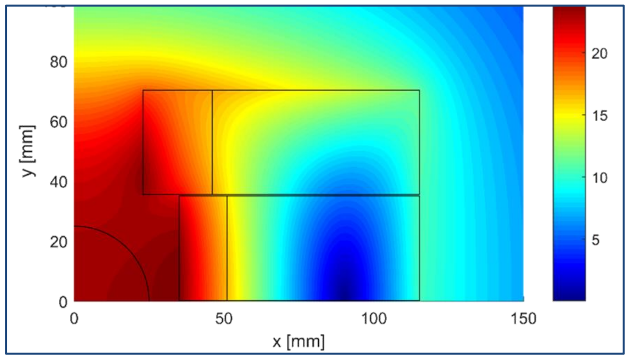


Common coil



Canted cosine theta

Block Coil

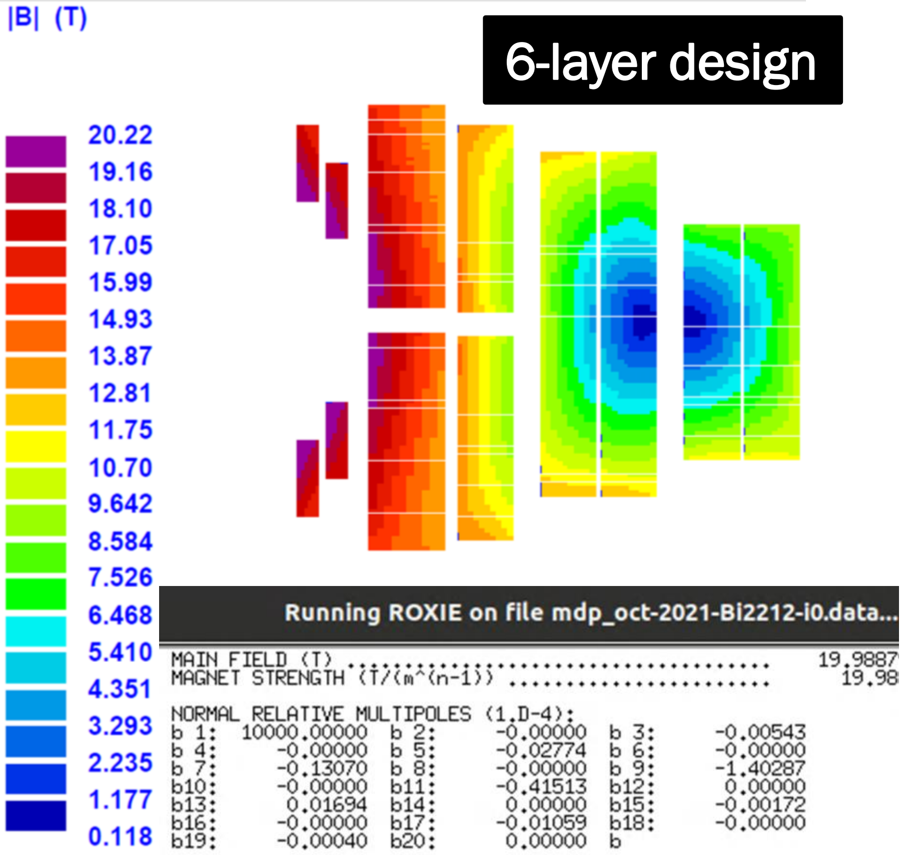


- In cosine theta and canted cosine theta, certain coil thickness or # of layers, is needed to create field.
- The same thickness (#of layers) must continue to the pole (60 to 80 degrees), the fill in between is determined by the cosine theta optimization.
- The field remains high at pole for many layers, 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 fully 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!

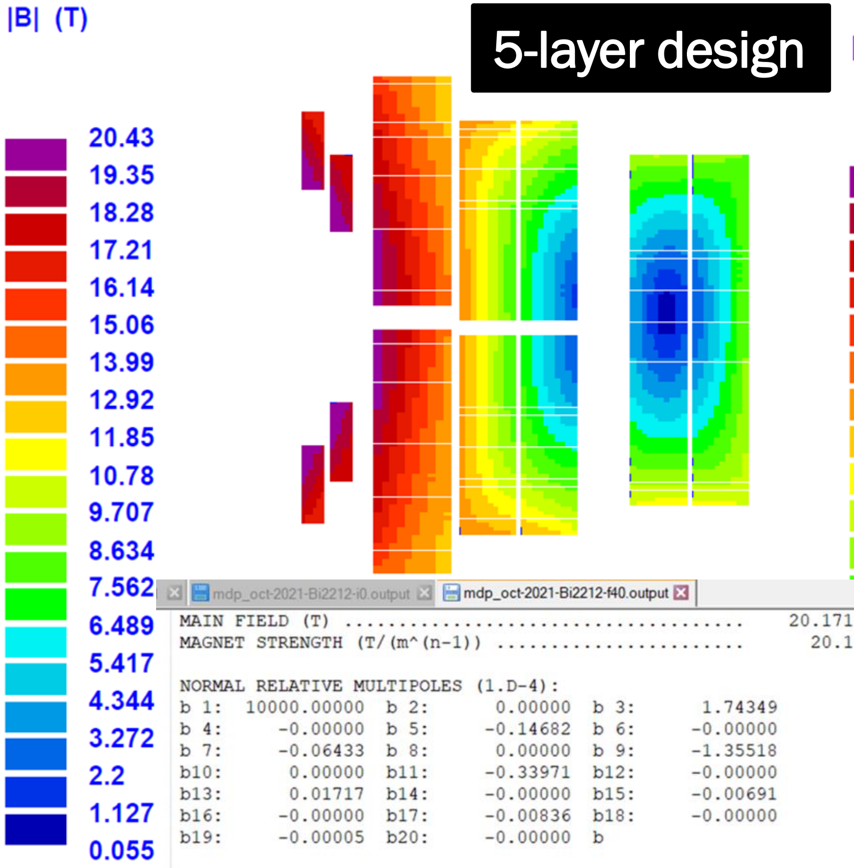
Field Quality in Common Coil Geometries

(all MT designs had 10^{-4} harmonics)



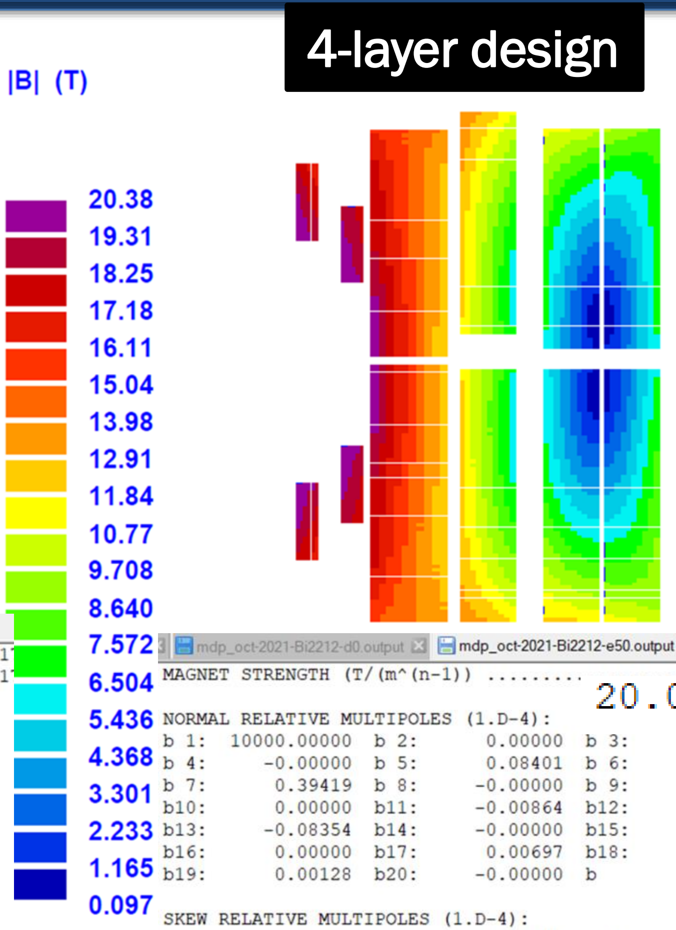
Running ROXIE on file mdp_oct-2021-Bi2212-i0.data...

```
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

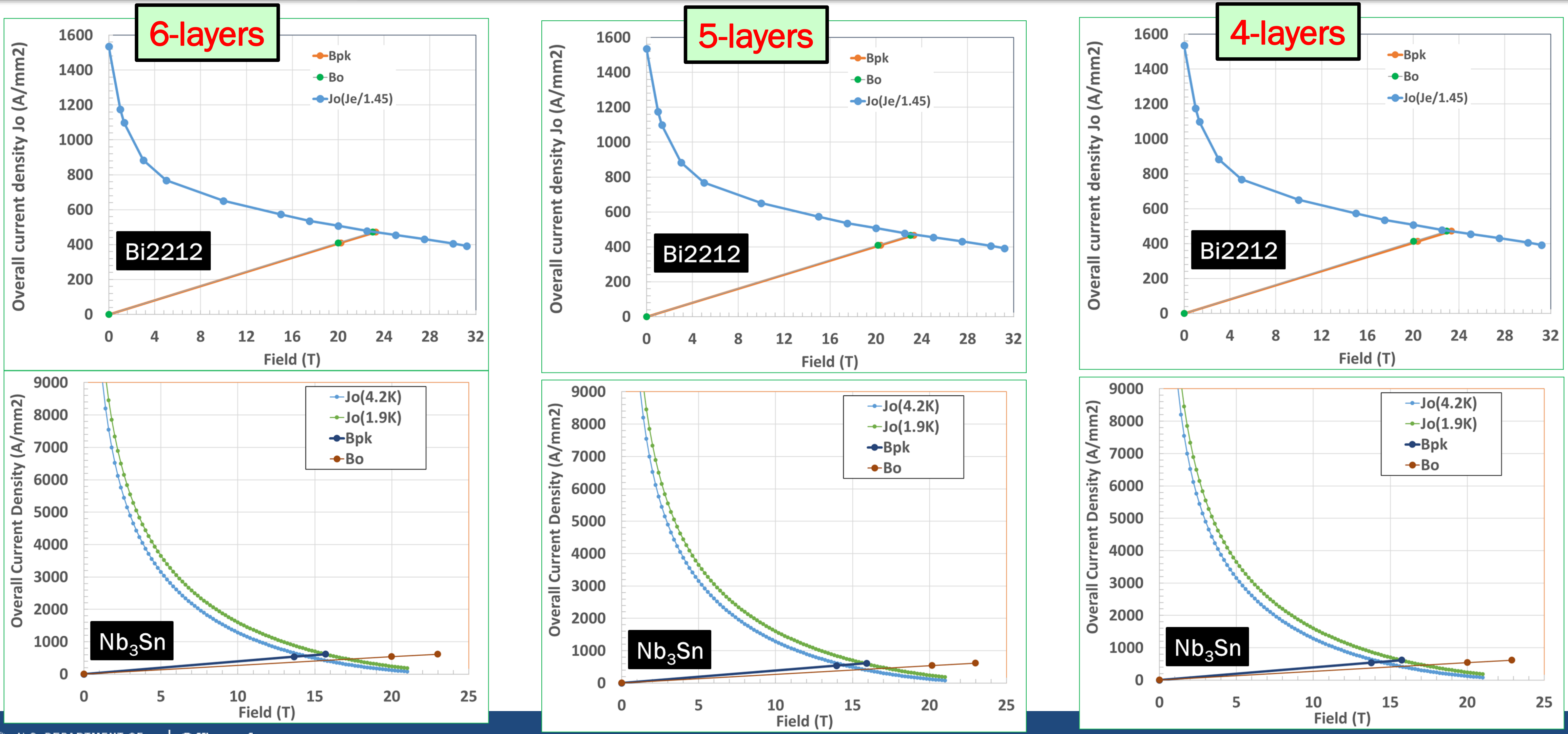
```
MAIN FIELD (T) ....................................   20.171
MAGNET STRENGTH (T/(m^(n-1)) ......................   20.1

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
```



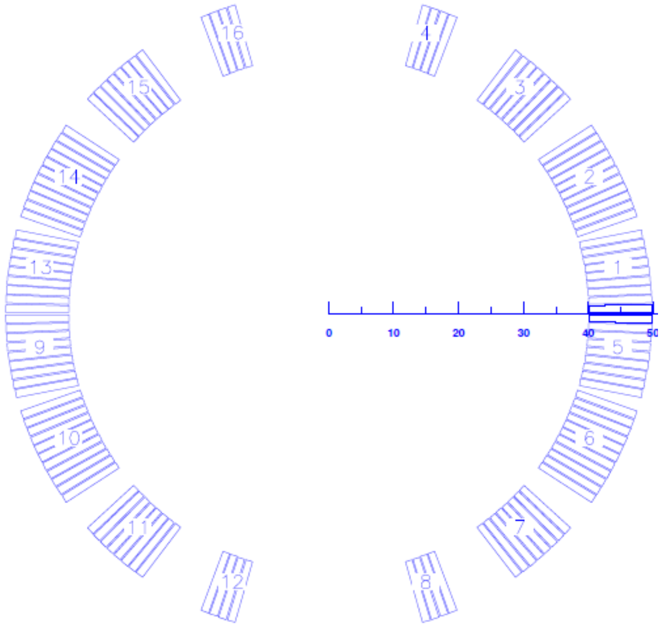
mdp_oct-2021-Bi2212-d0.output | mdp_oct-2021-Bi2212-e50.output

```
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
```

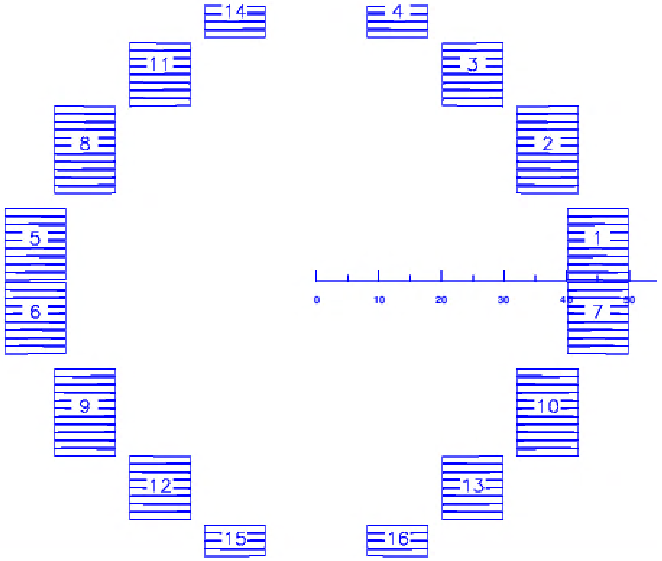
Operating Margins in Common Coil Geometries
(all MT designs had ~23 T Short Sample - 15% over 20 T)



RECAP 1: Relative Difference in the "Bore Area" and "Coil Area" between Low-field and High-field Dipoles

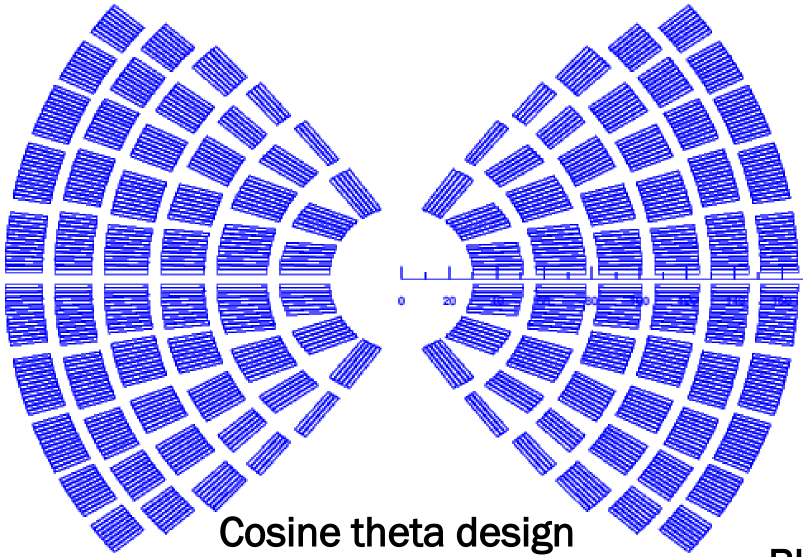


Cosine theta design



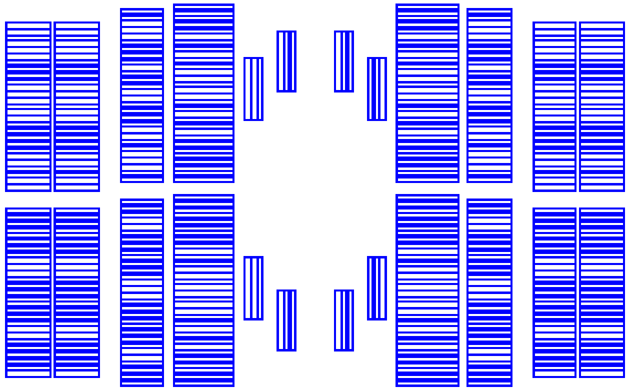
Block coil design

Low Field



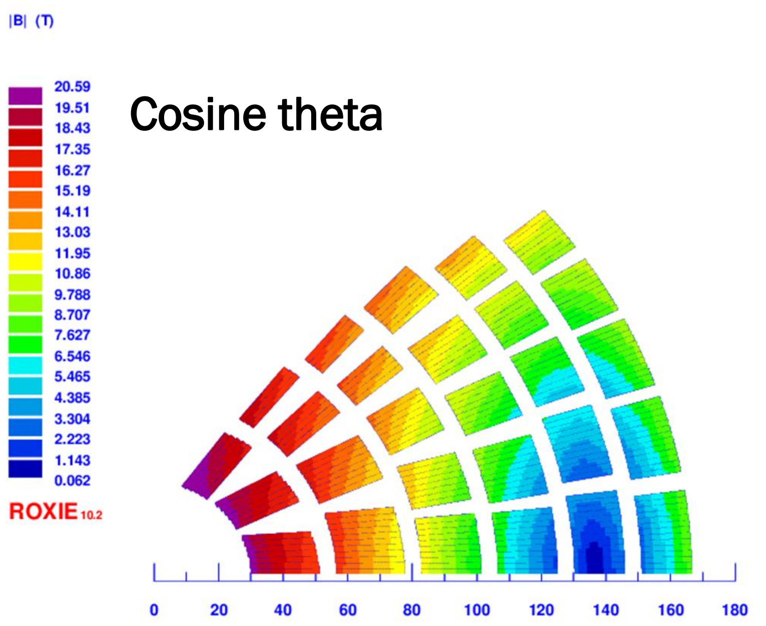
Cosine theta design

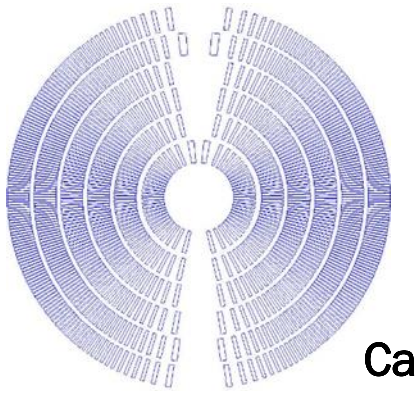
High Field



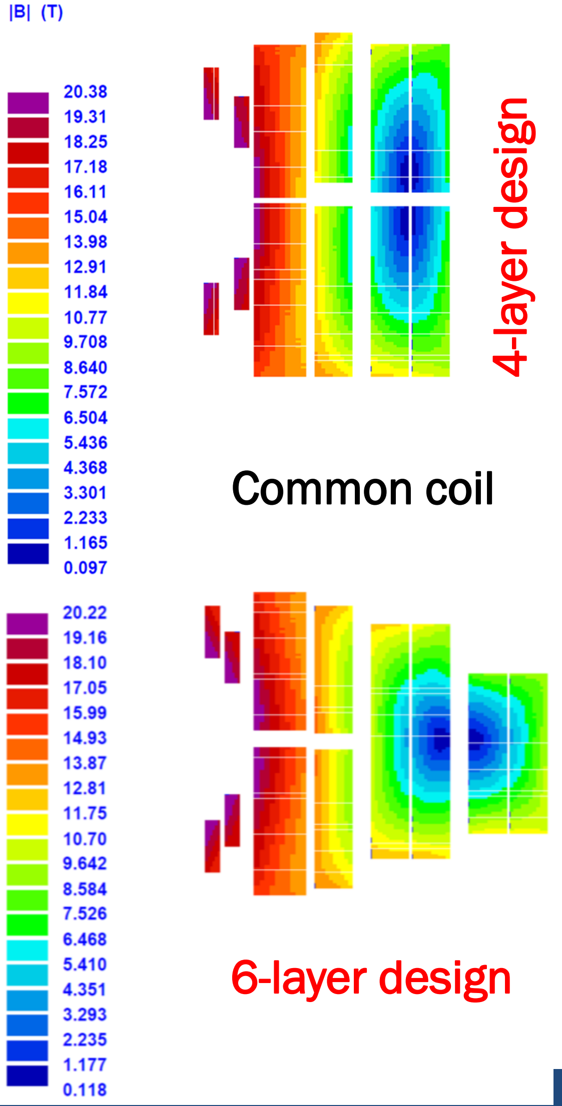
Block coil design (common coil)

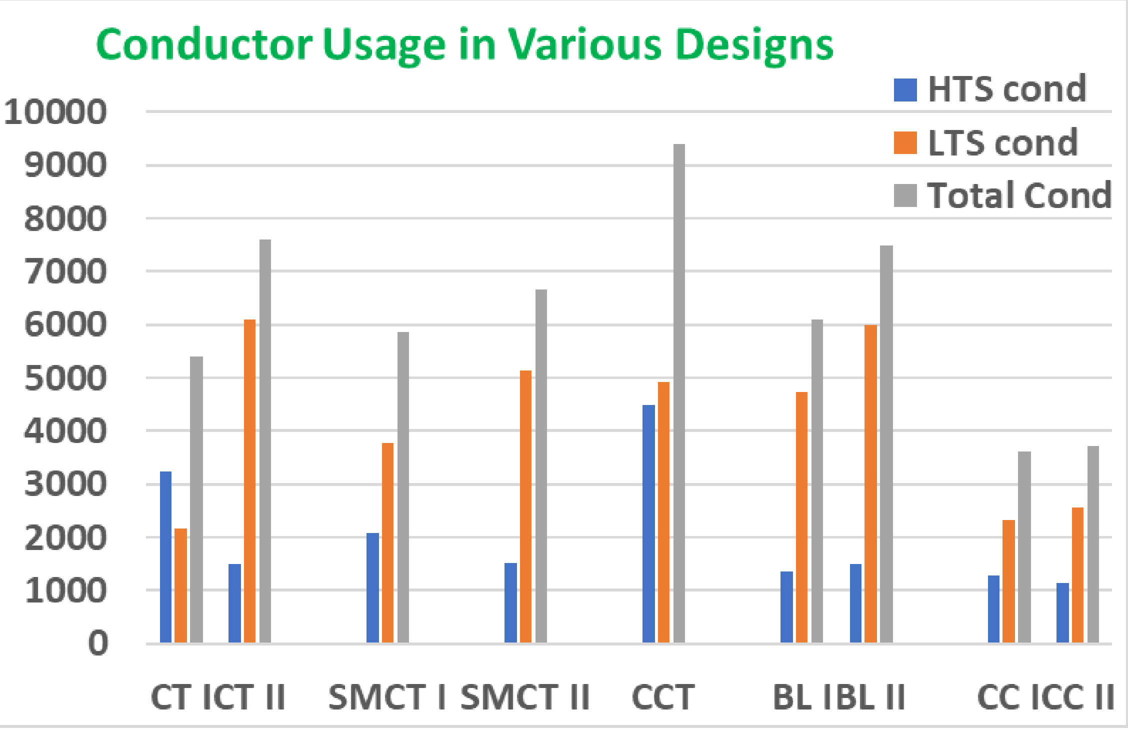
RECAP 2: Initial optimization of 20 T geometries reveals that the common coil designs uses “*significantly*” less conductor (not more) than the other designs

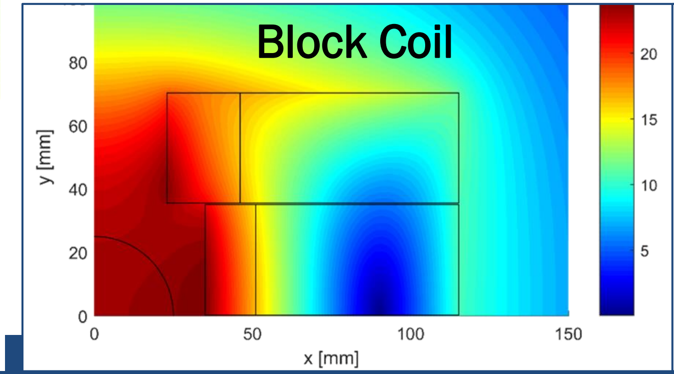


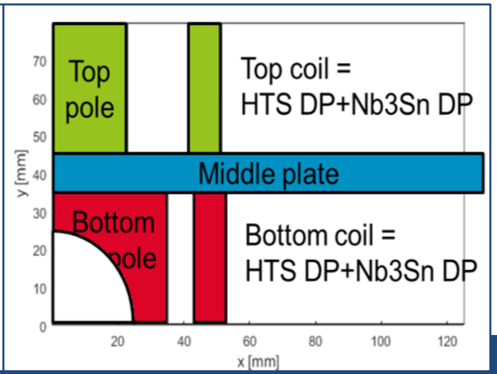


Canted cosine theta









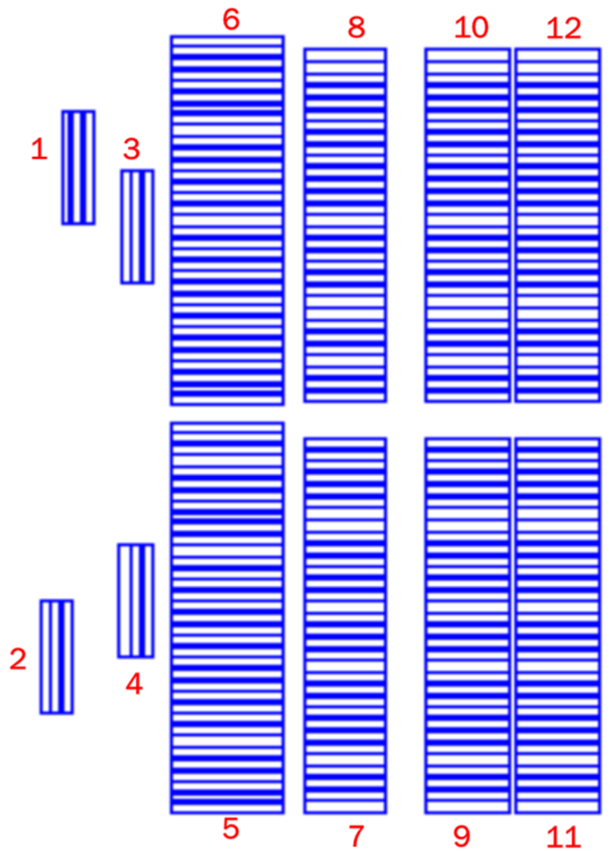
Specific to the Common Coil Design

- Updates
- Challenges, Opportunities, Work Ahead

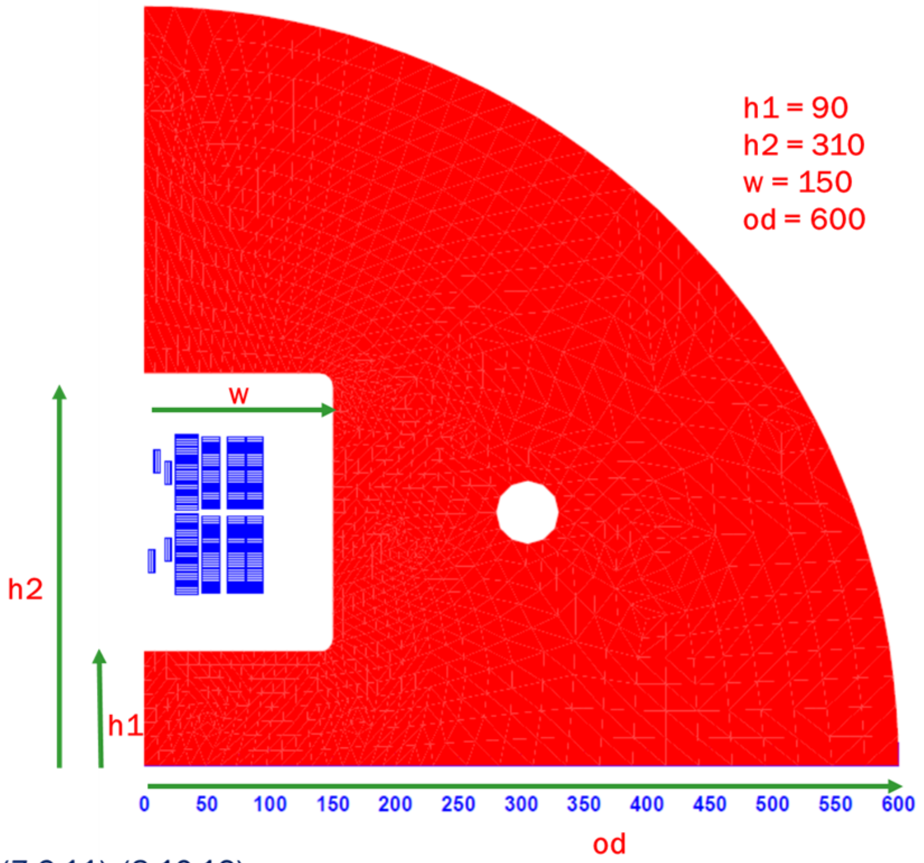
Modular Common Coil Design (1/22)

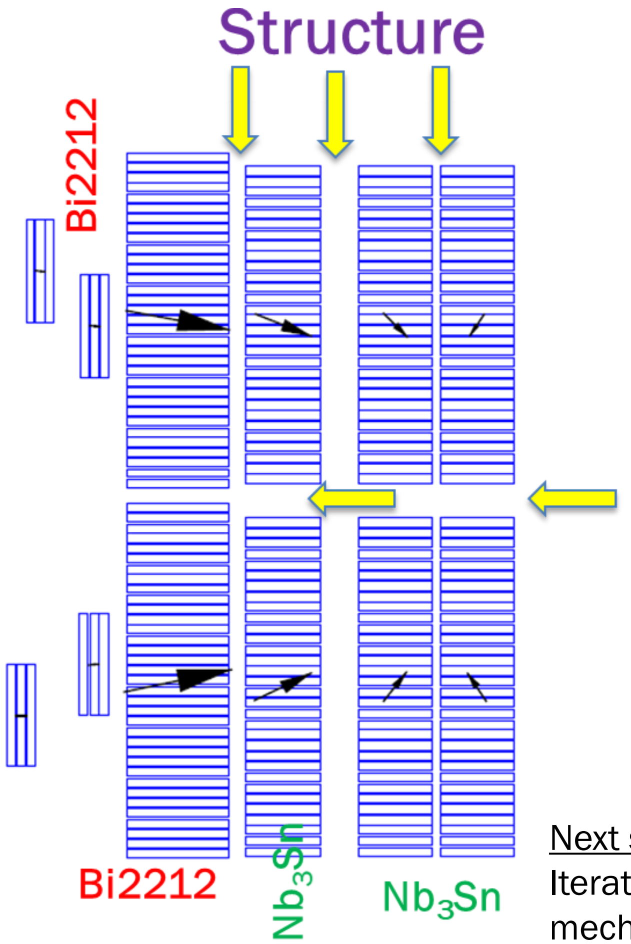
(matched margins, all Nb_3Sn identical, one HTS + pole)

- Three Nb_3Sn layers made identical - less tooling, less spares, sort/switch between layers – reduces cost of R&D magnet
- Good field quality; margins between HTS & LTS matched within a few tenth of a percent; considerations for the structure



Identical in size (and in total current) blocks (1,2,3,4); (7,9,11); (8,10,12)





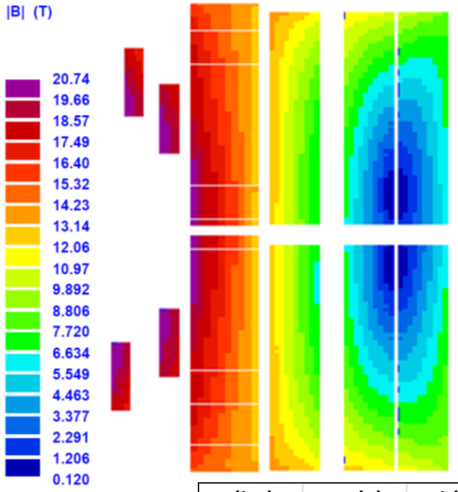
Next step:
Iterate magnetic & mechanical design

Summary of the Modular Design (1/22)

(good field quality, matched margins, HTS & 3 identical Nb_3Sn)

Geometric harmonics < 0.5 10^{-4} (not 5.0 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)) .......................   20.0001

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
```

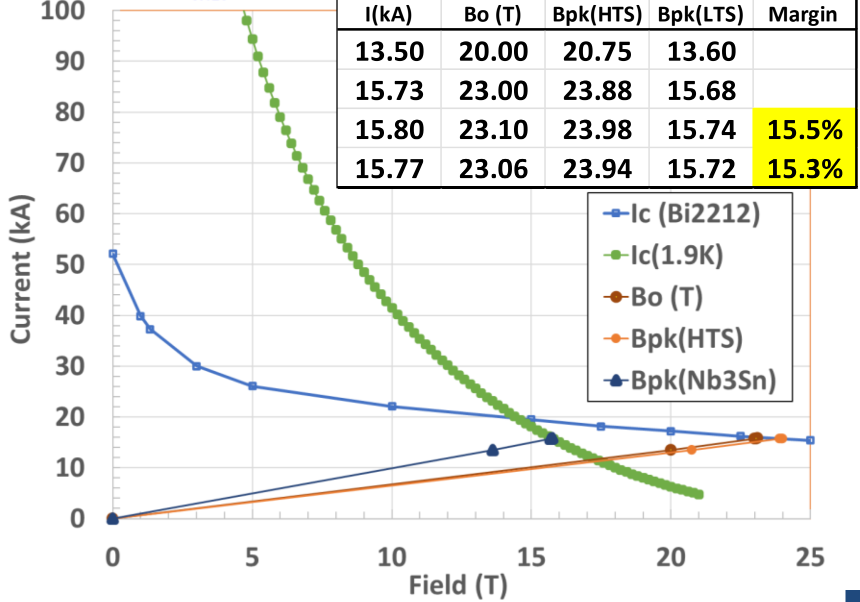


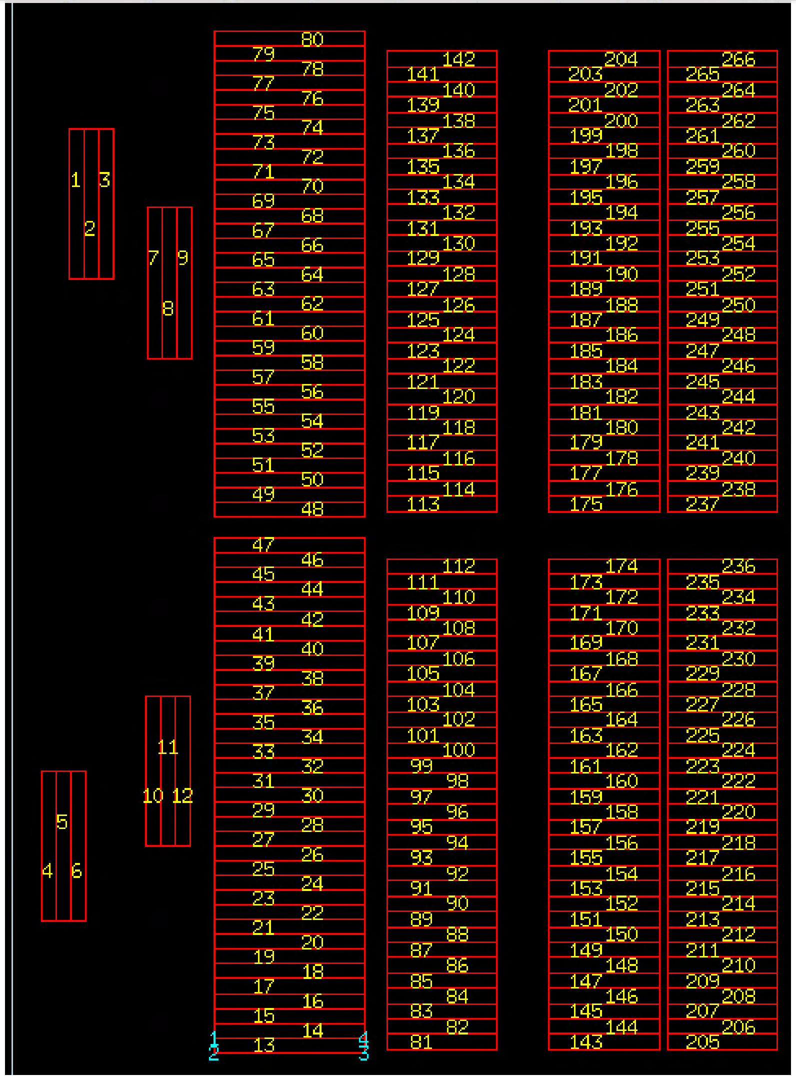
No. of Turns (½ bore)

- HTS: 80
- LTS: 182

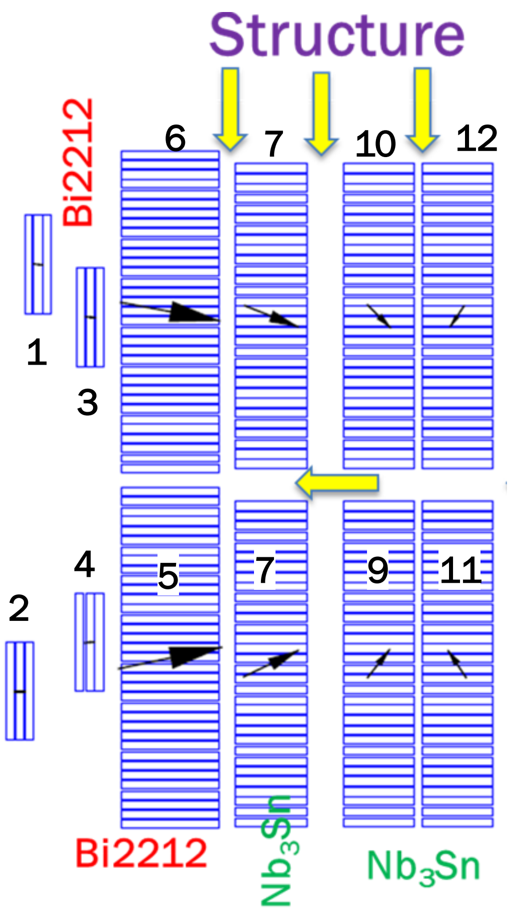
Total: 262

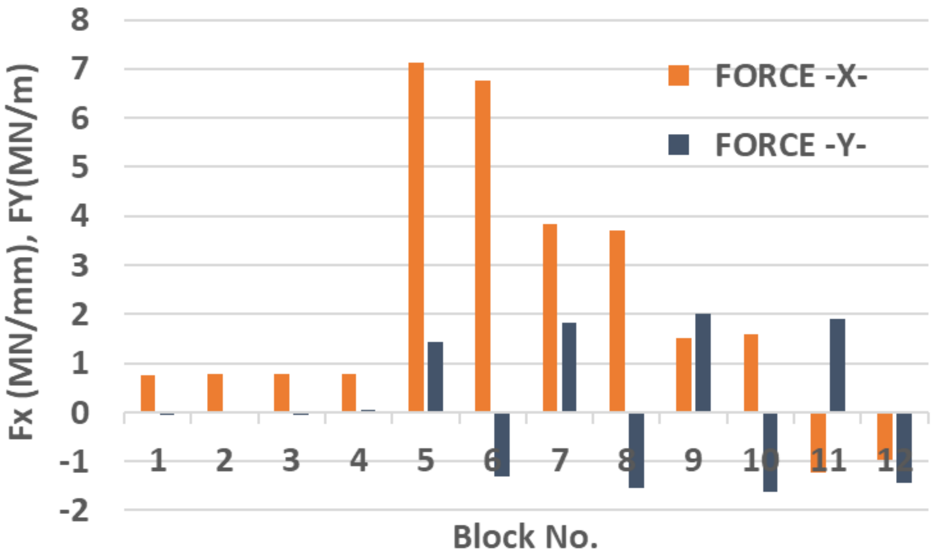
I(kA)	Bo (T)	Bpk(HTS)	Bpk(LTS)	Margin
13.50	20.00	20.75	13.60	
15.73	23.00	23.88	15.68	
15.80	23.10	23.98	15.74	15.5%
15.77	23.06	23.94	15.72	15.3%





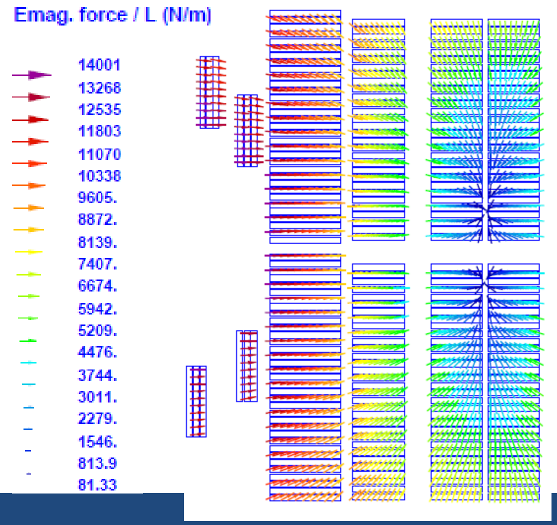
Lorentz Forces in the Common Coil

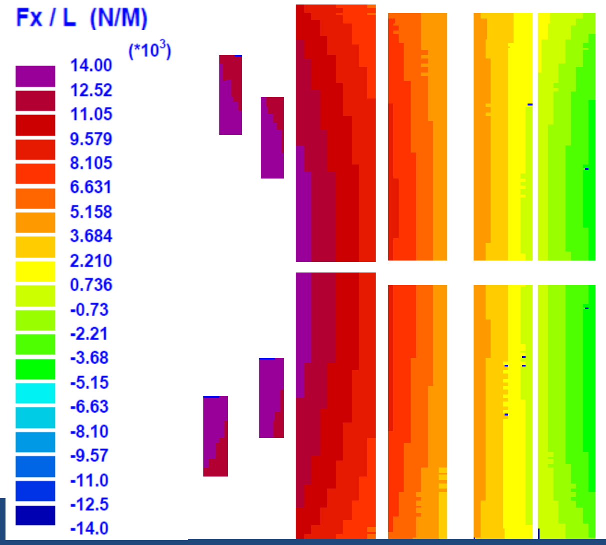


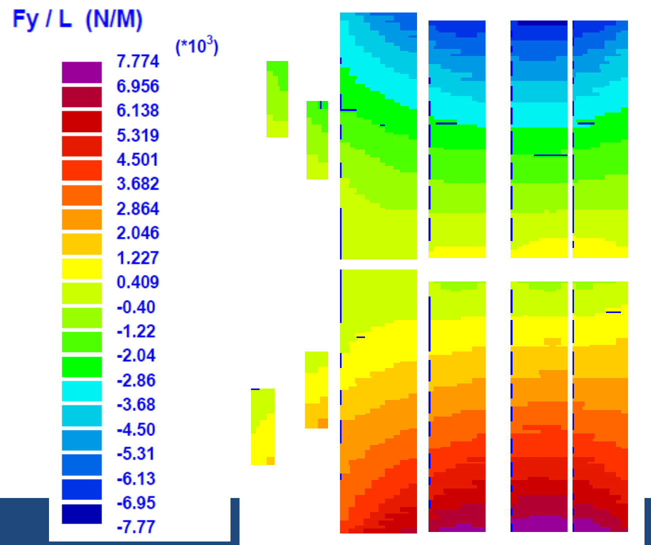


Common coil geometry is advantageous in dealing with the large Lorentz forces

- Primary horizontal (maximum vertical force on any block is 1/3 of horizontal)
- Horizontal forces do not put much strain on conductor in common coil (more later)
- Small forces on pole (mostly horizontal)
- Space for structure to be iterated







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Design with More Space for Structure

(to be iterated with mechanical analysis, may need less)

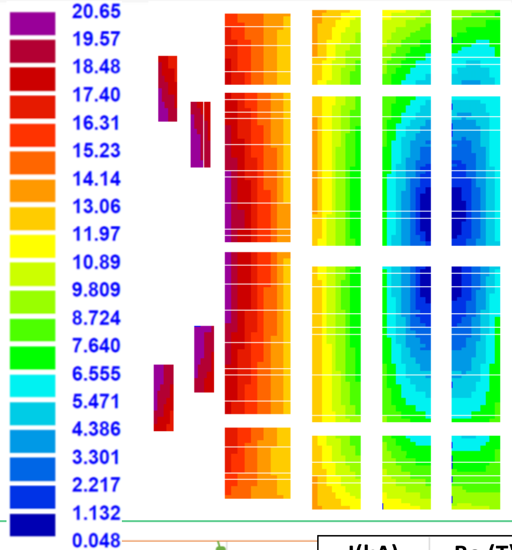
Only 8% increase in conductor for providing ~3-6 mm vertical and 6 mm horizontal space

```
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
```



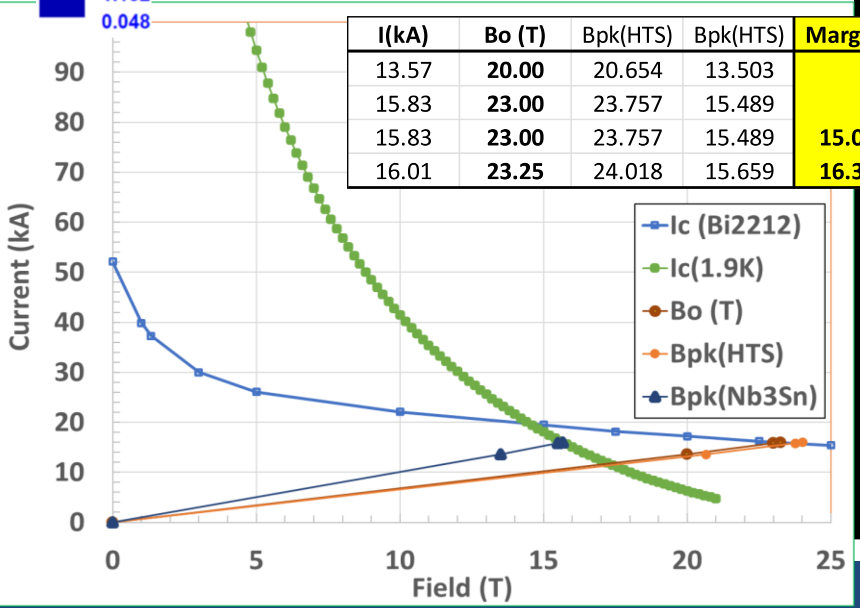
No. of Turns (½ bore)

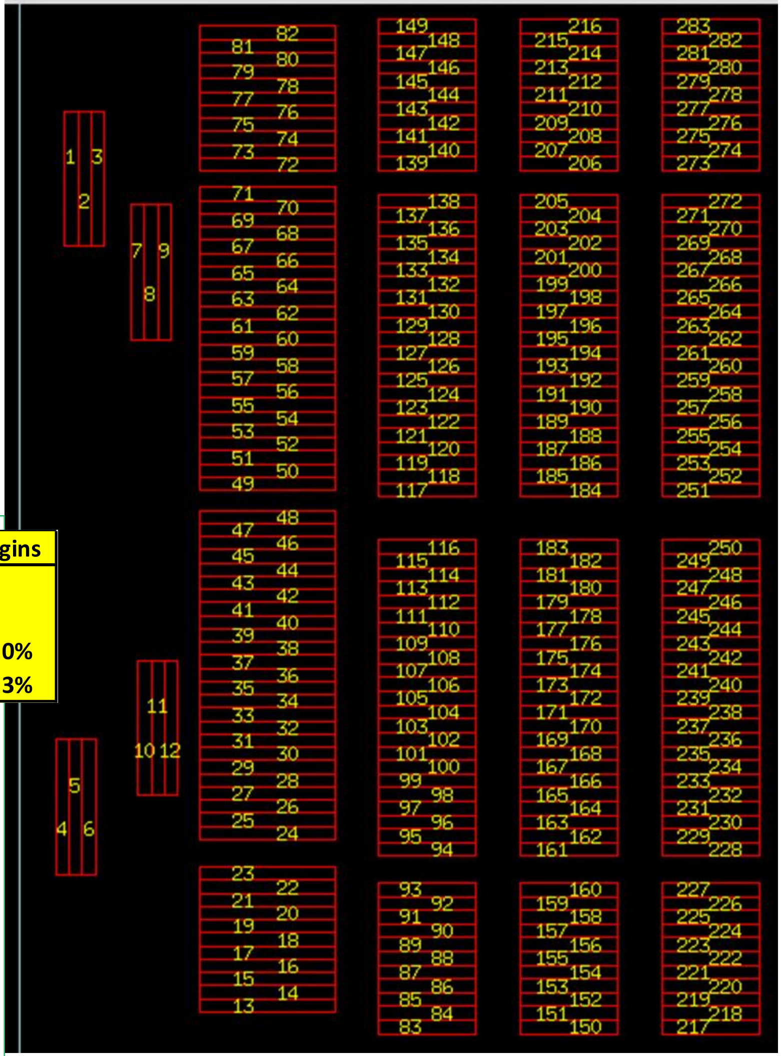
- HTS: 82
- LTS: 201

Total: 283

(increase from 80+182=262)

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%**





Work Ahead (priority mechanical design and analysis)

- **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.**
- **Several common coil dipoles with main coils have been built and tested. However, none have been built with the pole coils necessary for the field quality. Build pole coils and demonstrate them in a proof-of-principle magnet.**
- **Perform cost estimates of R&D dipoles and for large scale series production.**

Key Benefits of the Common Coil Design for HTS/LTS High Field Hybrid Dipoles

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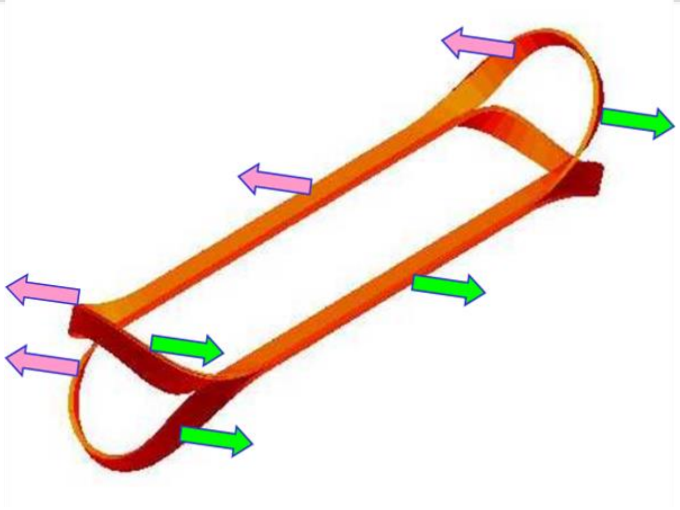
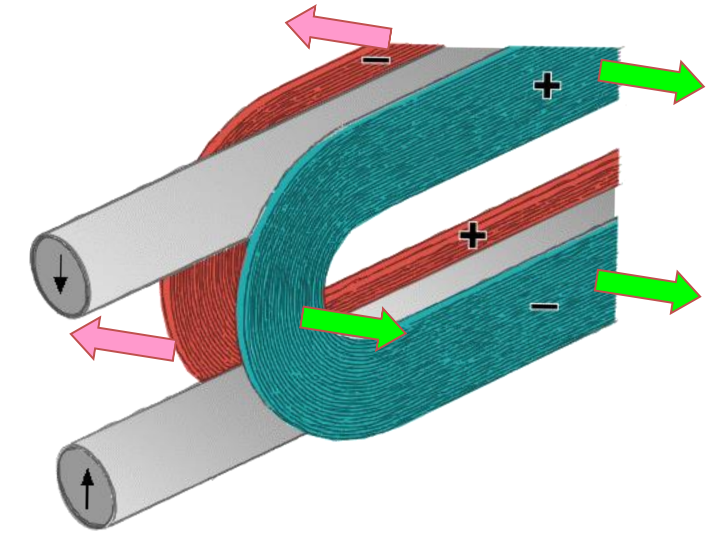
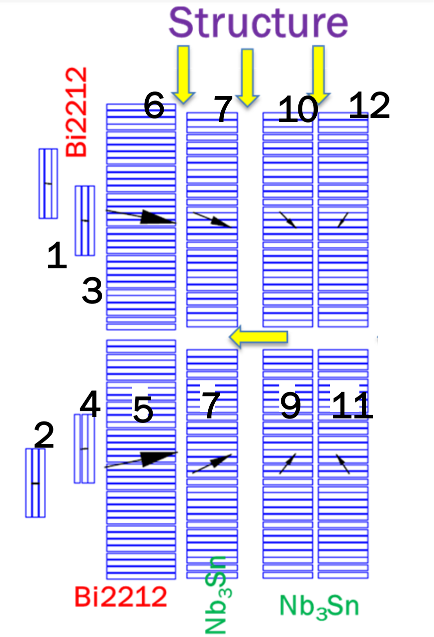
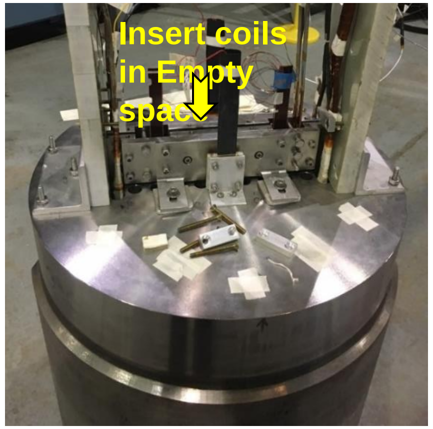


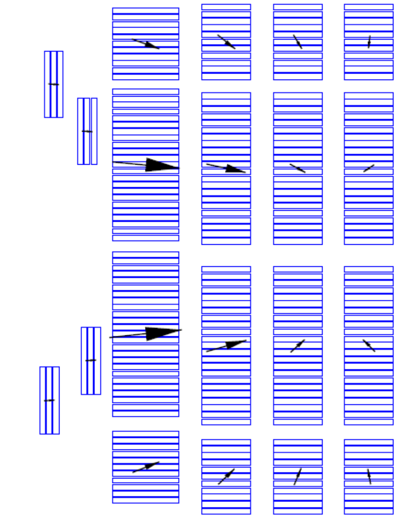


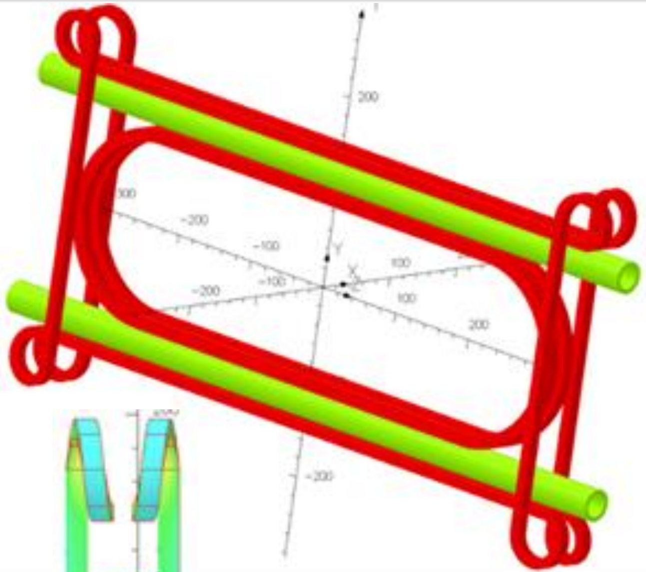
- ❑ Coil layers move as a module without causing strain at ends (BNL common coil had 200 μm). This should also save on the structure needed
- ❑ Flexible space for stress managed structure
- ❑ Natural segmentation between HTS and LTS for efficient optimization of conductor usage
- ❑ Simple coil geometry with large bend radii allow more technologies (W&D, R&W), more cables, more materials, etc.
- ❑ Modular design for low-cost, fast-turn-around R&D (PoP: 12.3 T MDP HTS/LTS hybrid dipole)



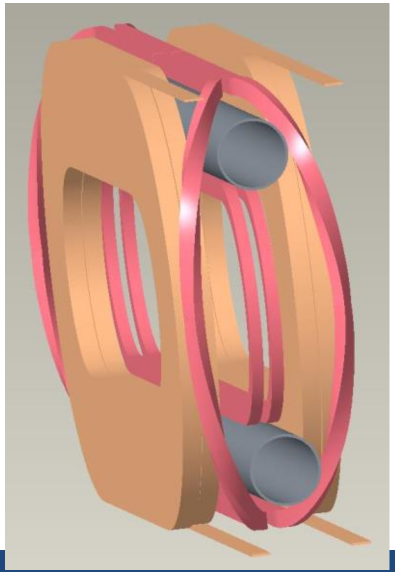


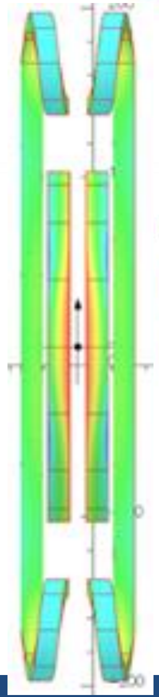
A Few Possible Layouts of Pole Coils Clearing the Bore (other geometries shown elsewhere)

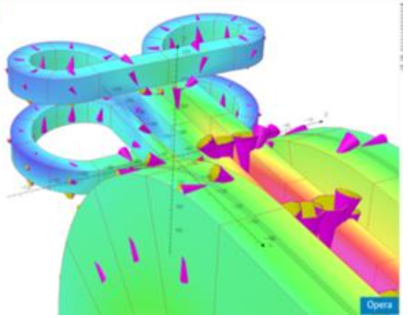


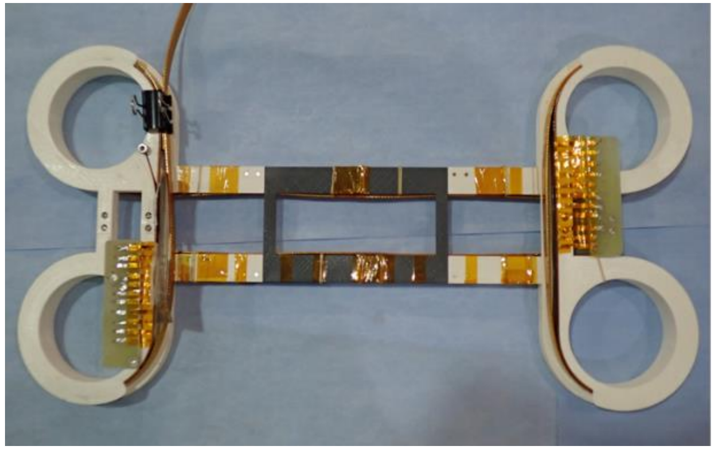


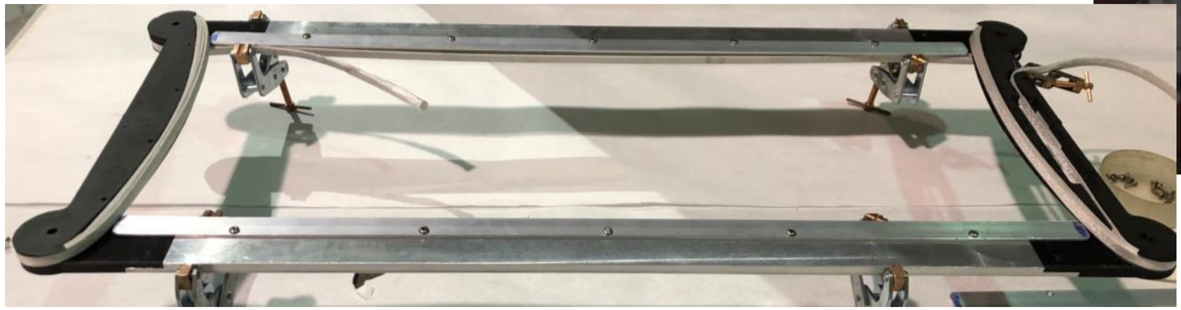
Practice pole coil windings and preliminary designs (performed under three SBIR Phase I; no Phase II).
They can be built and tested under MDP.





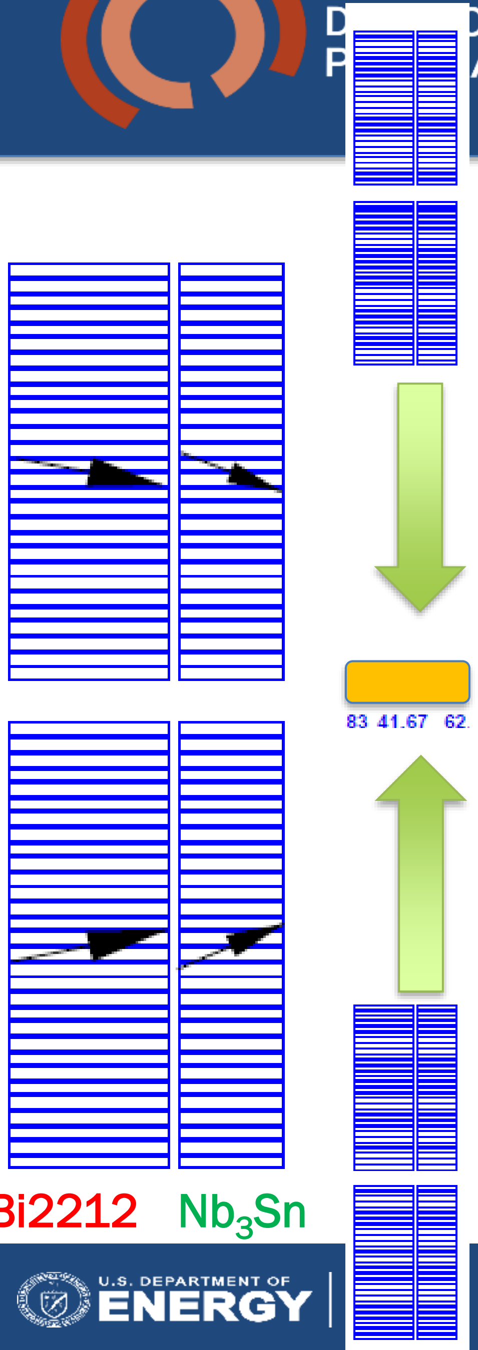




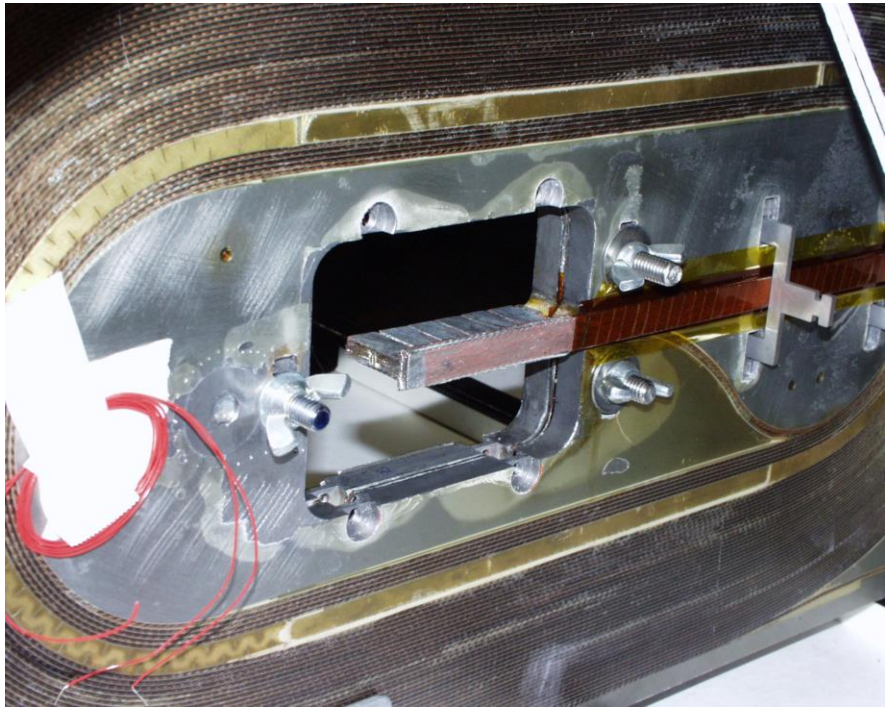


Splices in Common Coil Design (between two single layer coil)

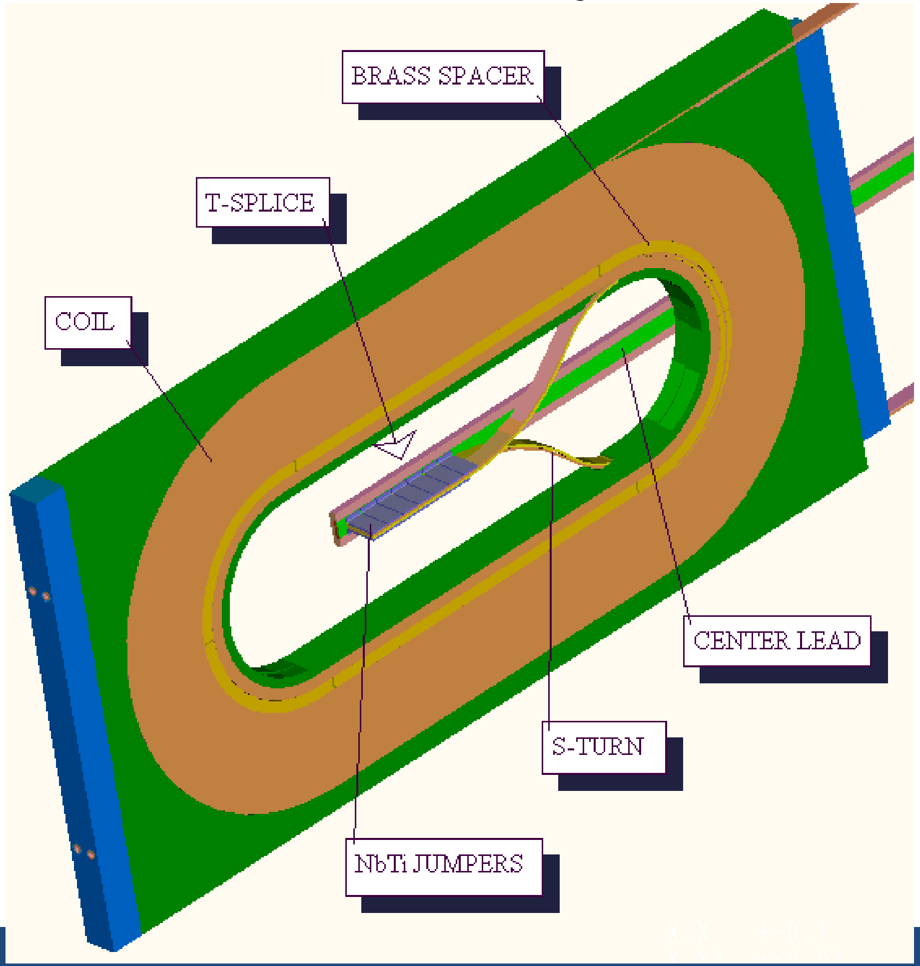
In common coil design, splice (even between two types of coils), can be easily made in the middle of the coil where the field is very low



Bi2212 Nb_3Sn



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



Summary

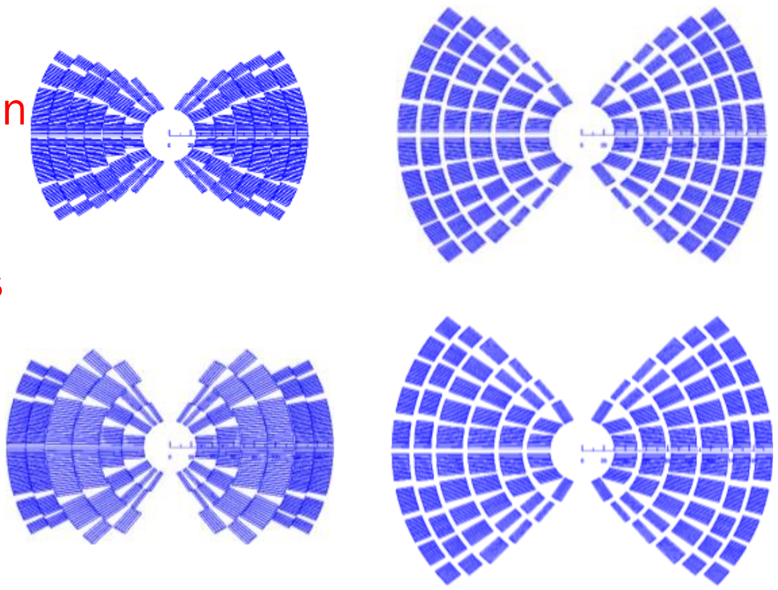
- **MDP comparative study revealed that for very high field dipoles (20 T), common coil design uses significantly less conductor than that used in other designs. The analysis presented here explains why it is so. Is mystery solved?**
- **Common coil allows easy and efficient segmentation between HTS and LTS - only one HTS (Bi2212) layer is needed for creating 20 T with 15% margin.**
- **Designs presented here show that the same design of Nb_3Sn coils can be used for all layers. This provides a significant savings on design, engineering, tooling, number of practice and spare coils, etc. This means that the cost of common coil R&D dipole may be competitive despite the two apertures.**
- **A lot of work is still remaining to fully develop various aspects of the design and technology for all options (including ReBCO). A good opportunity for long term R&D for young scientists and engineers for pioneering work.**

Extra Slides

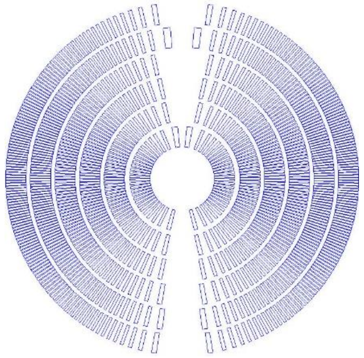
Some Observations and Possible Explanation

- 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 <u>without</u> and "with stress management"

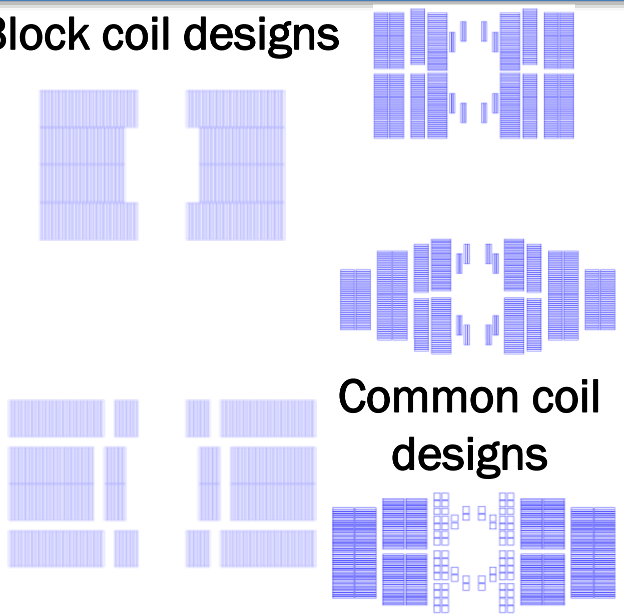


Canted Cosine Theta



Block coil designs

Common coil designs



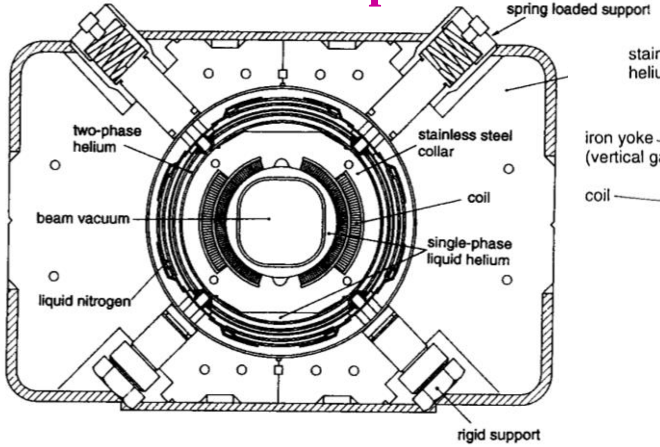
Parameter	UNIT	CT I	CT II	SMCT I	SMCT II	CCT	BL I	BL II	CC I	CC II	CC III
Ins. cable I width/thick.	mm	10.7/1.5	12.0 / 1.7	12.3 / 1.5	12.3 / 1.5	18.7/1.9	17.1/2.1	17.1/2.1	18.7 / 1.8	18.7 / 1.8	7.5/7.5
Ins. cable II width/thick.	mm	9.4/1.5	14.2 / 2.1	10.7 / 1.5	13.9 / 1.5	-	17.1/2.1	17.1/2.1	13.6 / 1.9	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
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

<=Typo?

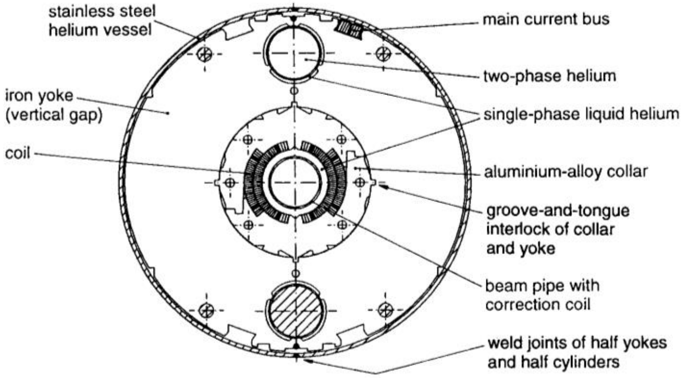
U.S. DEPARTMENT OF ENERGY | Office of Science 11/19/2021 P. Ferracin, "Towards 20 T hybrid accelerator dipole magnets" 20

Magnet Designs for <10 T Dipoles (all use NbTi conductor and cosine θ design)

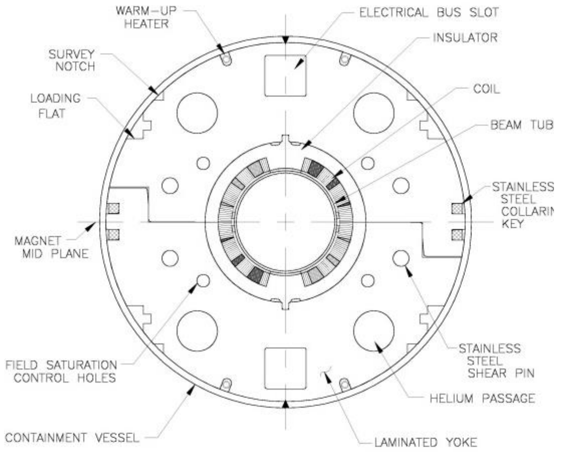
Tevatron Dipole



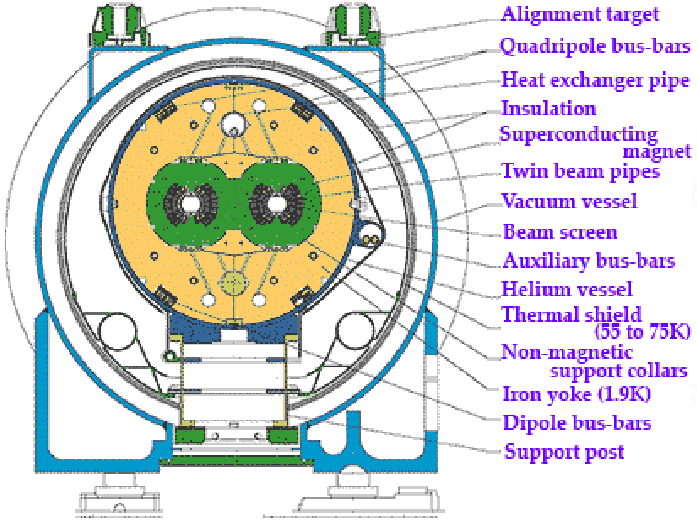
HERA Dipole

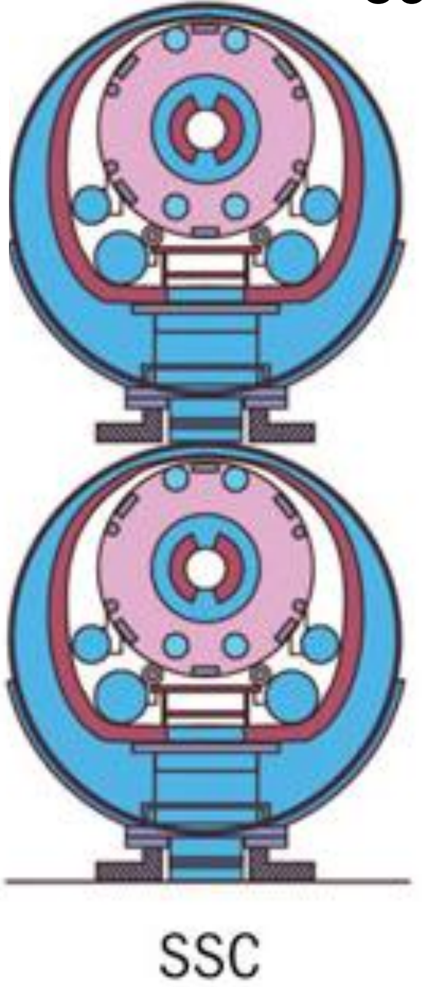


RHIC Dipole

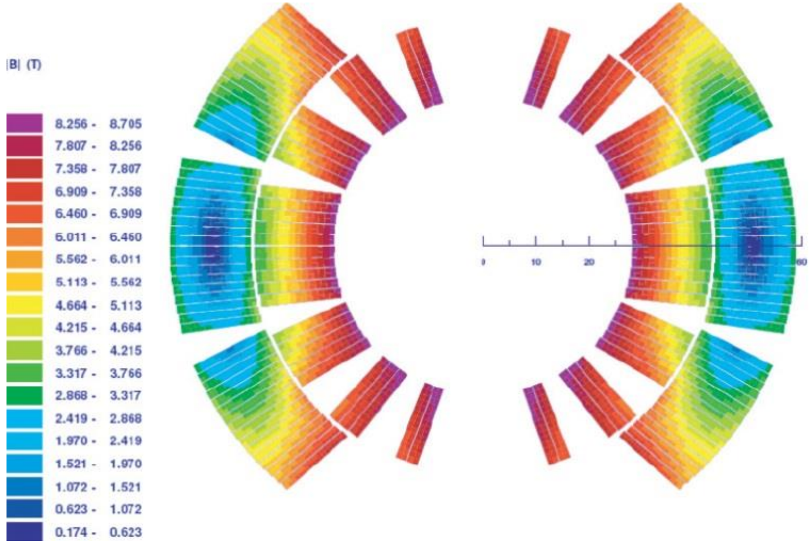


LHC Dipole

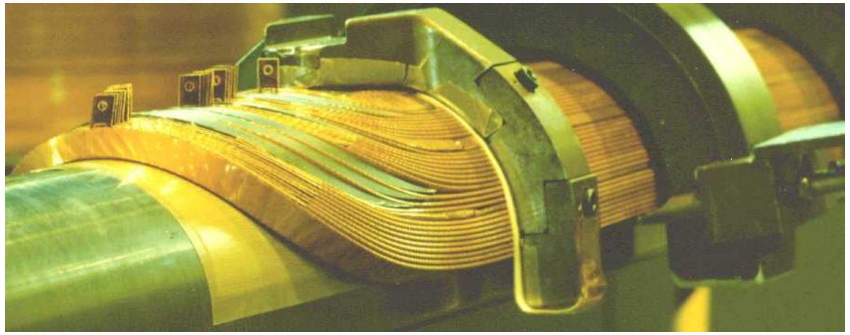




Cosine (θ) like current distribution



complex ends



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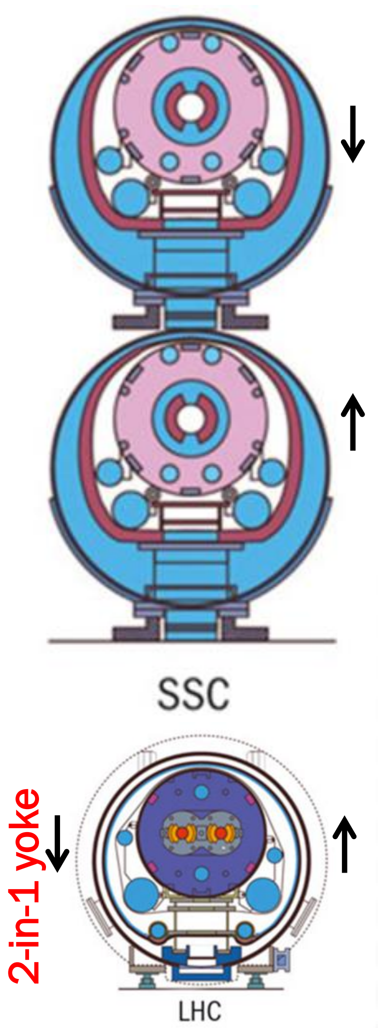
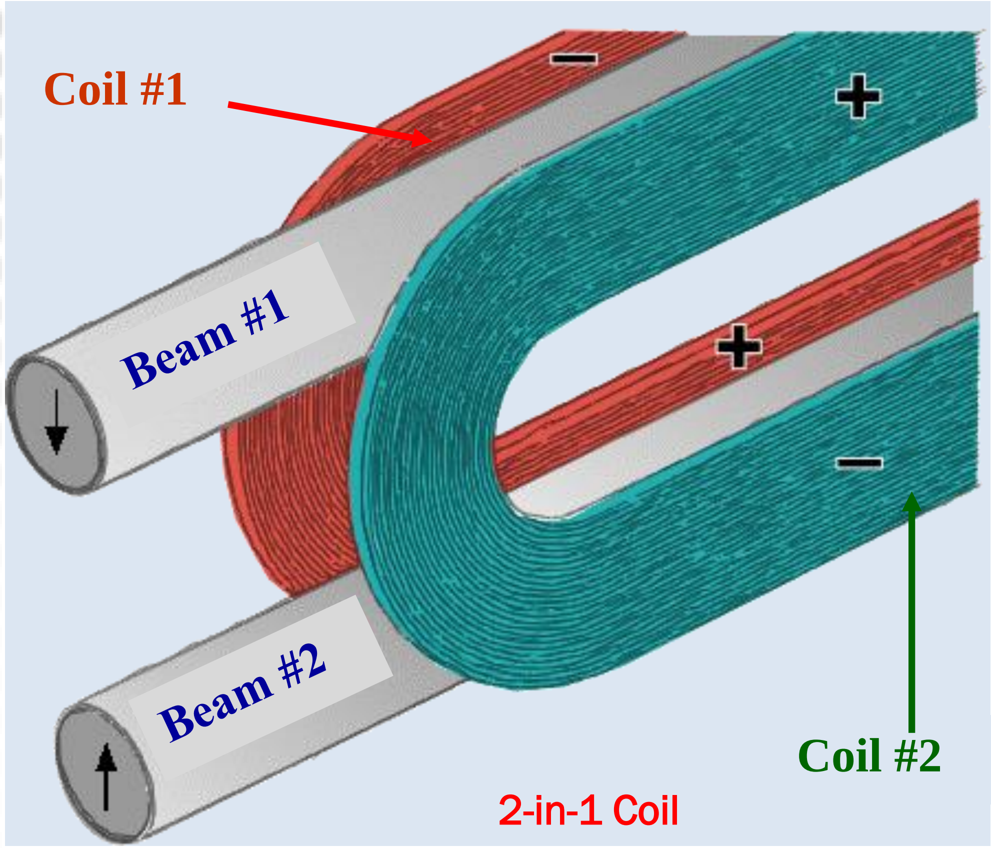
Common Coil Concept for Collider Magnets





Main Coils of the *Common Coil Design*

(more complex pole coils also required for field quality)

- Simple 2-d coil geometry for collider dipoles
- Conductor friendly design with large bend radii (determined by the spacing between two apertures) without complex 3-d ends
- Allows both React & Wind and Wind & React
- Block design with lower internal strain on the conductor under Lorentz forces
- Easier segmentation between LTS and HTS coils for high field magnet (modular design)
- Fewer coils (about half) as the same coils are common between the two apertures
- Simple magnet geometry and simple tooling, expect lower labor and tooling costs
- More options for producing relatively lower cost and more reliable high field magnets