U.S. MAGNET DEVELOPMENT PROGRAM

Common Coil Design and its Application for 20 T Dipole

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- **Brief introduction to the common coil design**
- **Initial design work on 20 T**
- **Work ahead**
- **Summary**

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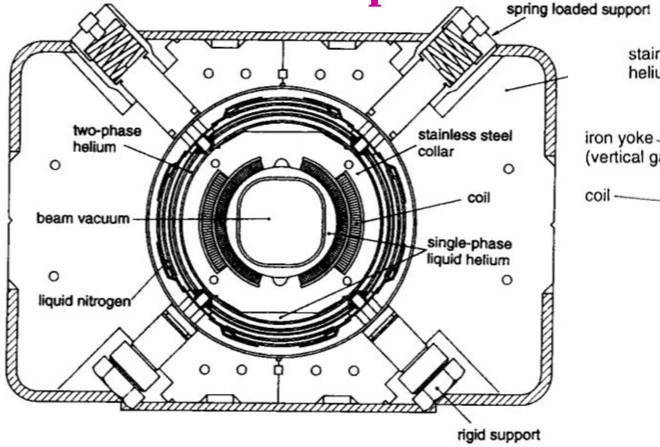
20 T Dipole Challenges and Opportunities

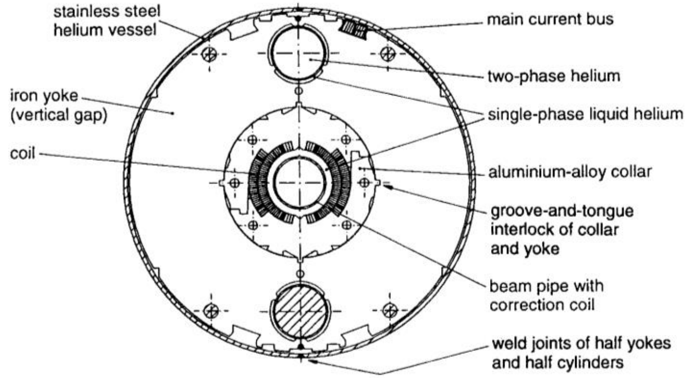
- No dipole magnet anywhere close to 20 T has ever been built.
- Demonstrating a magnet like this is a major challenge as this is more than just an incremental change. Not only that it will involve new conductor (HTS), but also several new technologies (quench protection, etc.) and engineering.
- The forces become so large that designs need to evolve/change significantly.
- Moreover, they must be manufacturable reliably in large quantities at as low cost as possible (different considerations than making a few). Cost is likely to determine if the next collider based on high field dipoles can be built or not.
- However, since the next collider is a few decades away, this is a perfect challenge and opportunity for the next generation scientists and engineers.

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

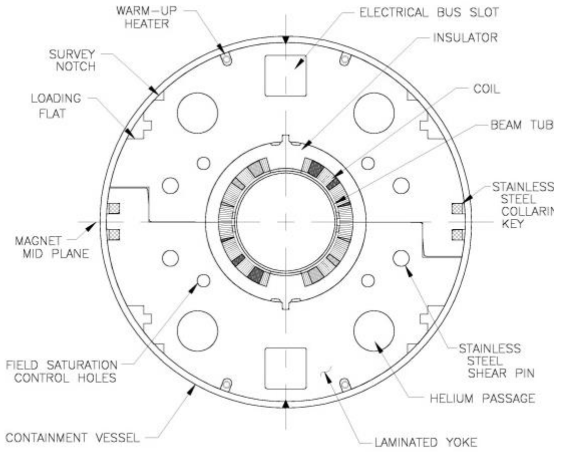
Tevatron Dipole



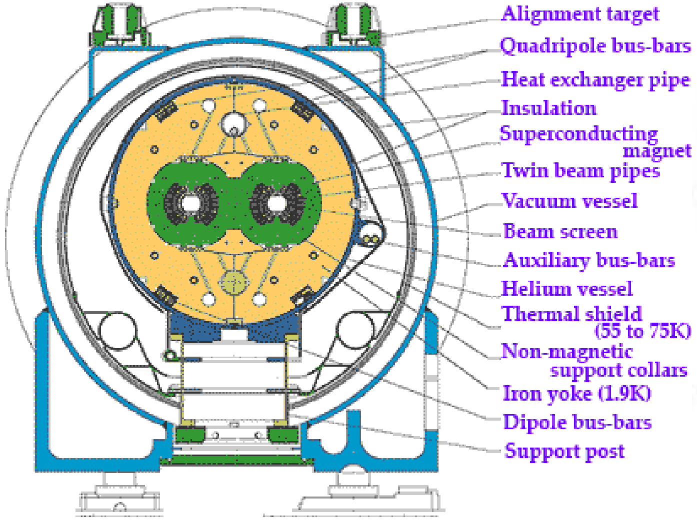
HERA Dipole

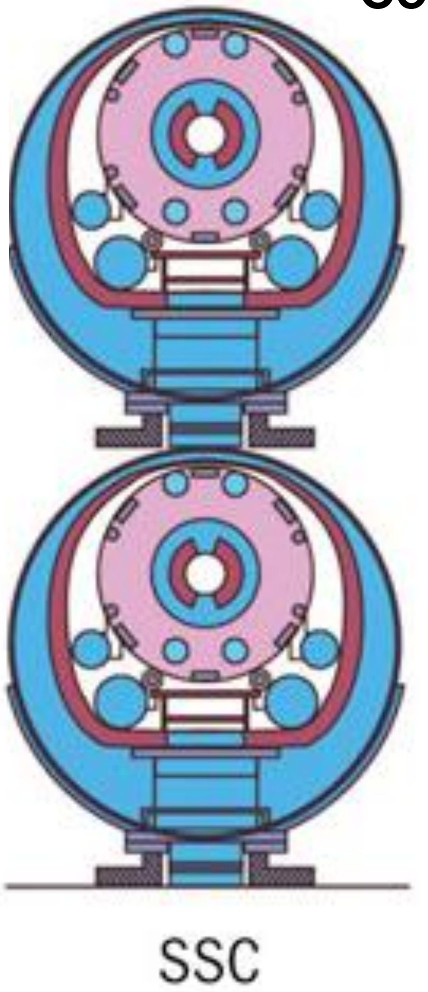


RHIC Dipole

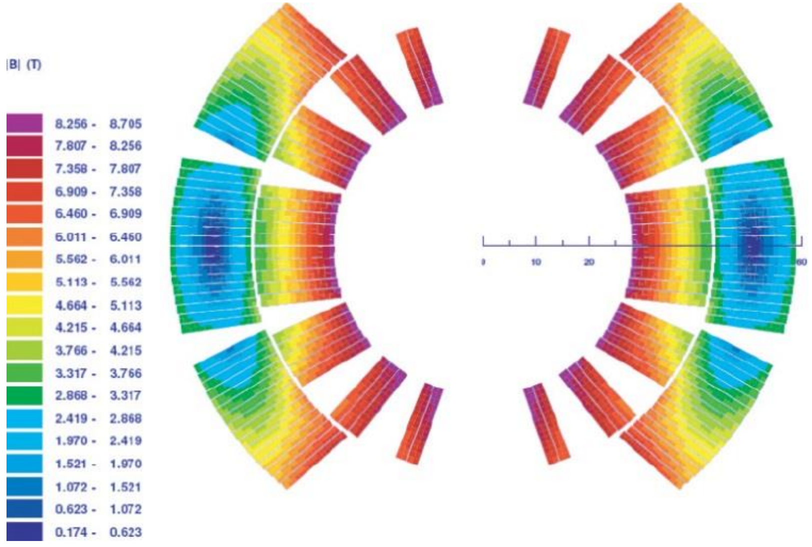


LHC Dipole

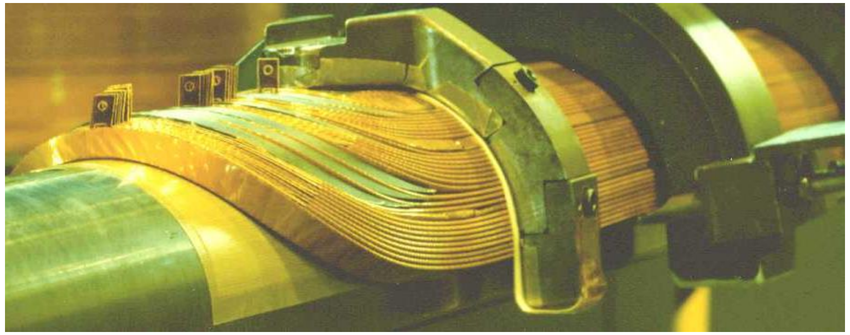




Cosine (θ) like current distribution



complex ends



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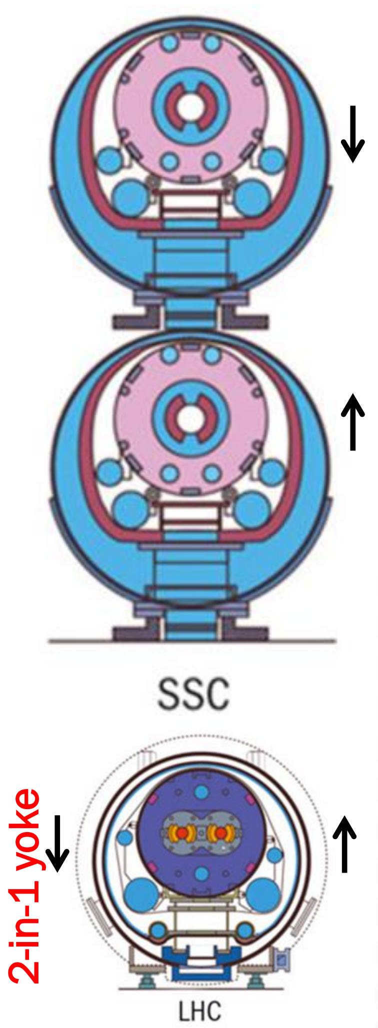
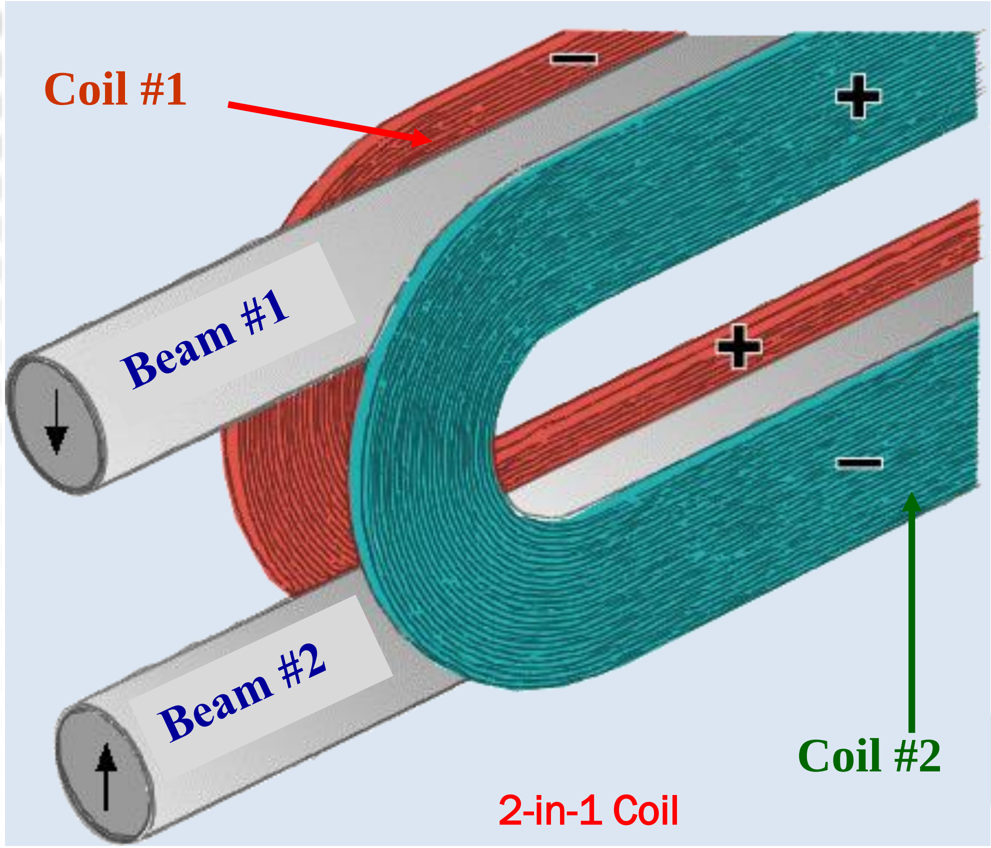
Common Coil Concept for Collider Magnets



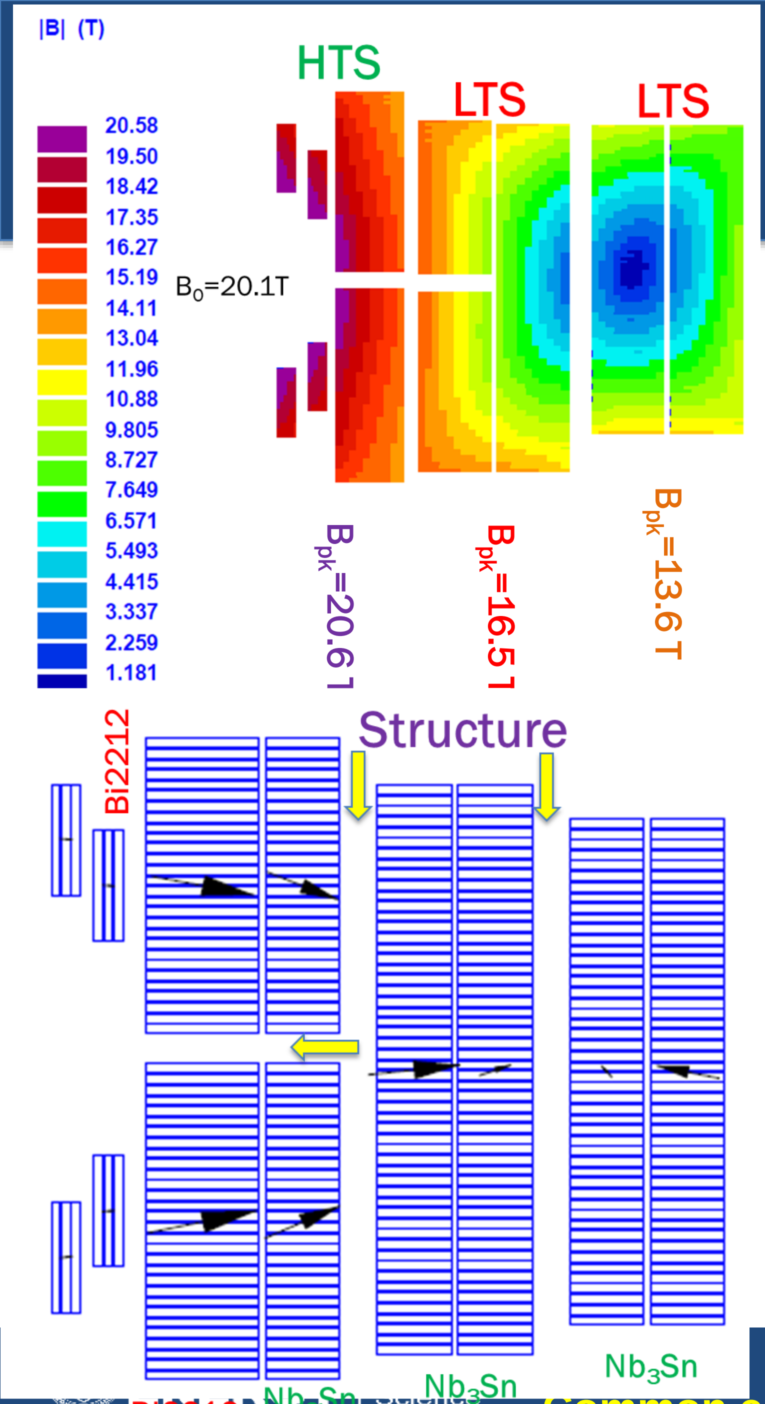


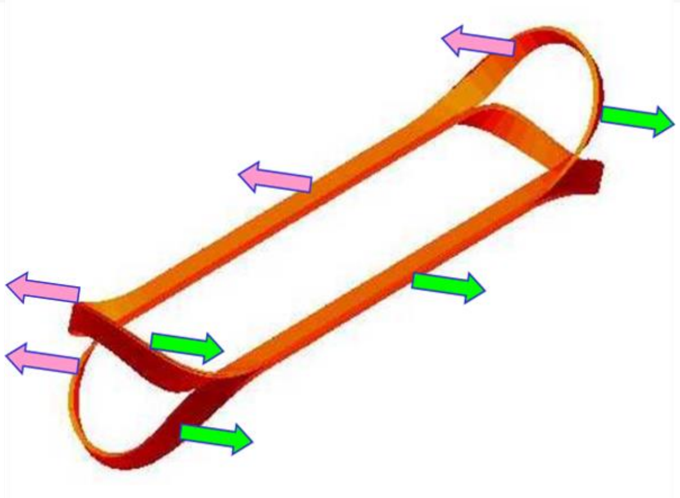
Main Coils of the *Common Coil Design*

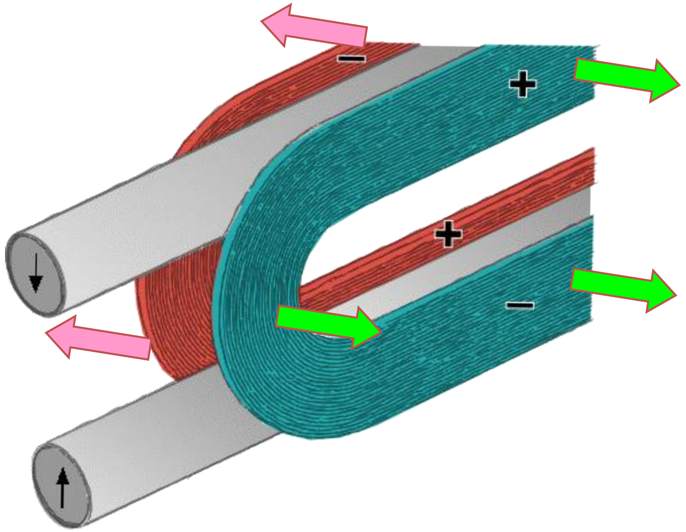
(more complex pole coils also required for field quality)

- 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

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

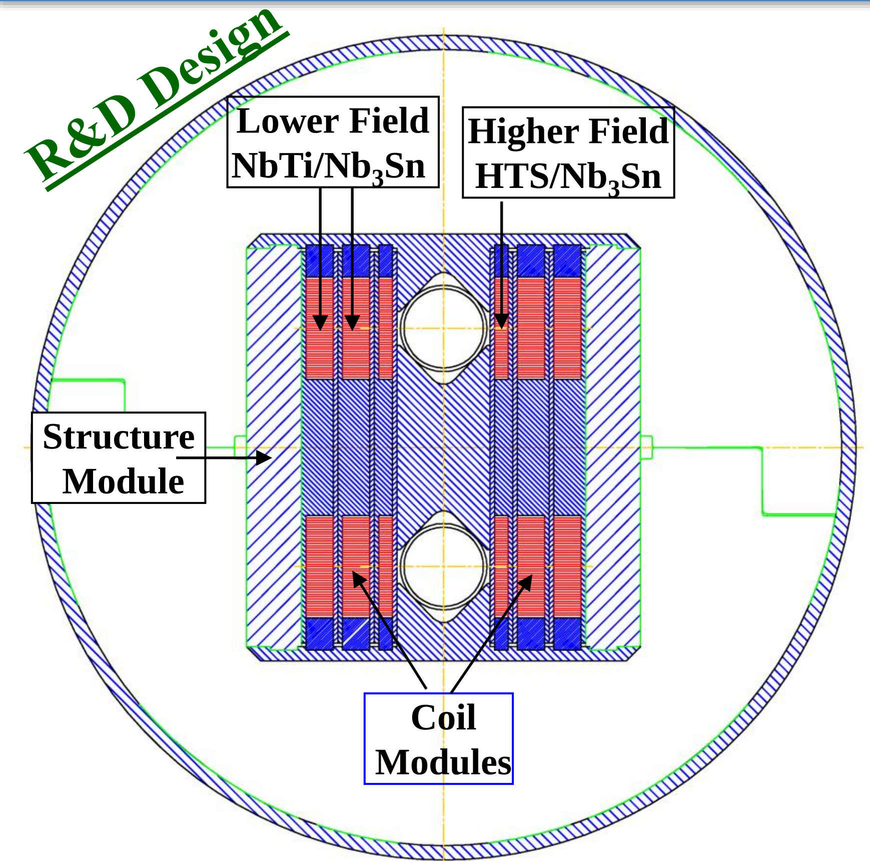






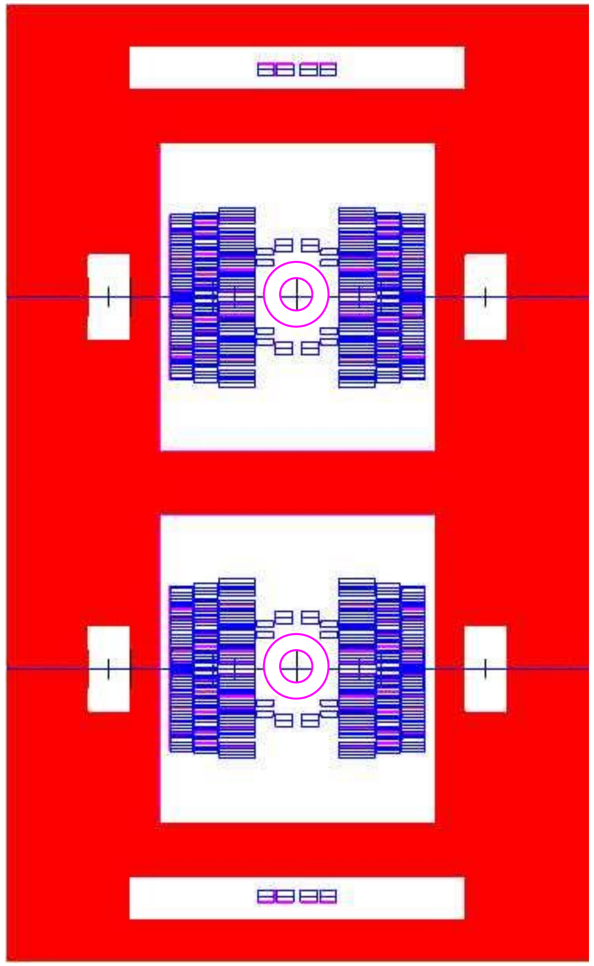
- ❑ Natural segmentation between HTS and LTS (and different cables)
- ❑ Easier tuning between HTS & LTS
- ❑ Coil layers move as a module without causing strain at ends (BNL common coil had 200 μm)
- ❑ Intermediate space for stress management structure. It can be easily adjusted, even at the late stage of the magnet construction

R&D and Field Quality Common Coil Designs

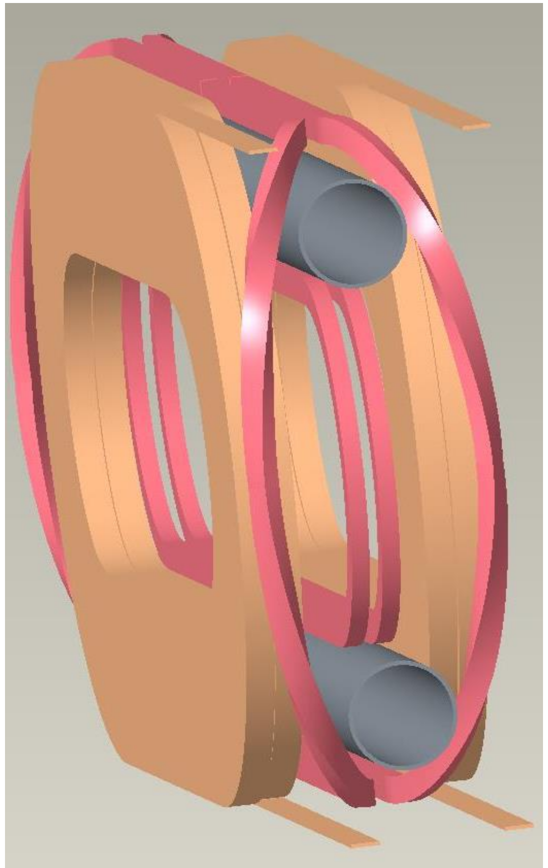


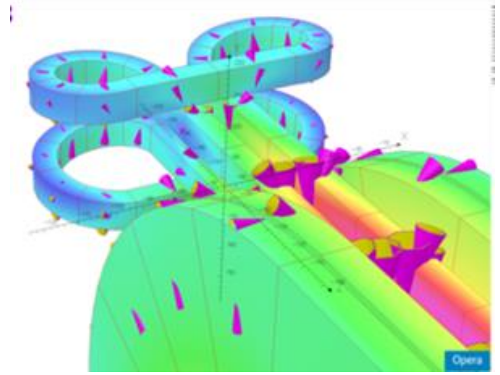
Several R&D designs with the main coils (only) built and tested to demonstrate field performance

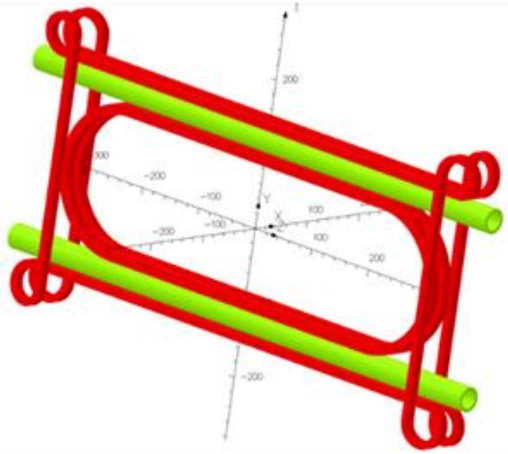
Field quality design also needs pole coils



Some pole coils may not remain as simple as the main coils but the overall benefit of the common coil. Several solutions exist...







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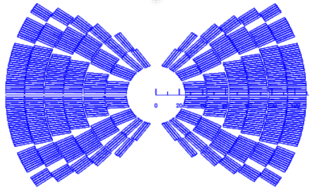
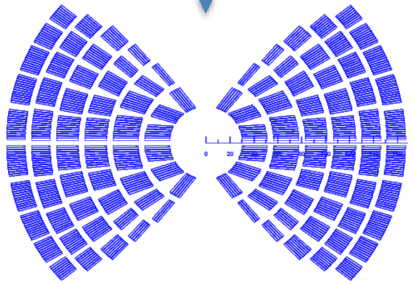
Design Options for 20 T Dipole (MDP)

Cosϑ without and “with stress management”

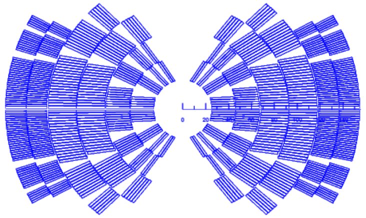
(a)



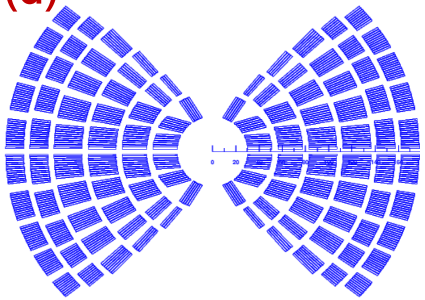
(b)



(c)

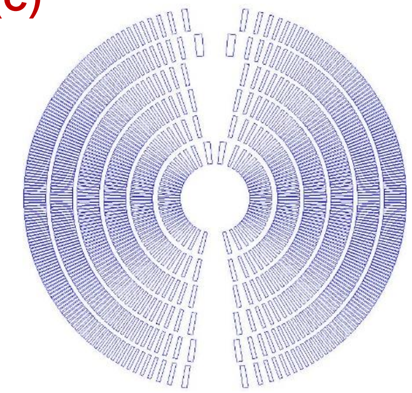


(d)



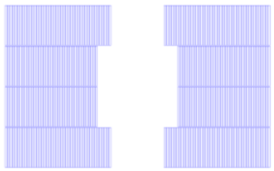
Canted Cosine Theta

(e)

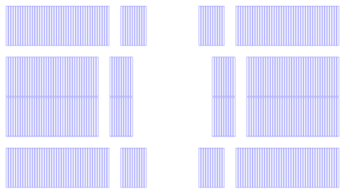


Block coil designs

(f)

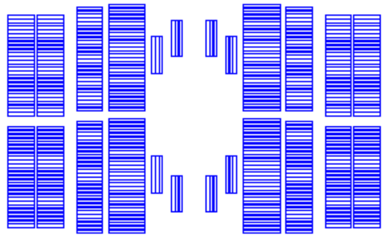


(g)

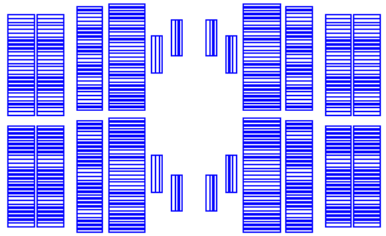


Common coil design

(h)



dual aperture dipole



single aperture dipoles

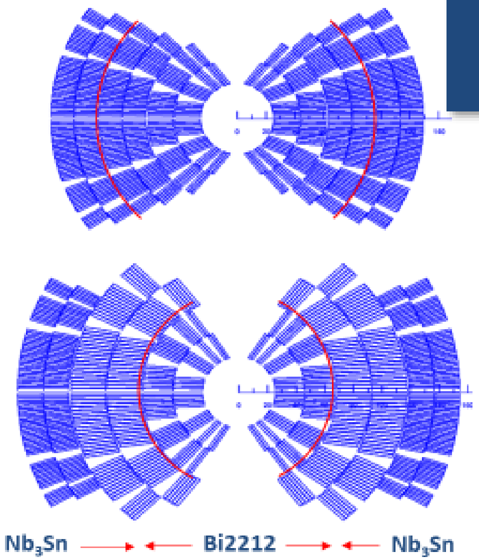
Mechanical Design and Analysis

(one of the most critical component of the high field dipoles)

Structure Considerations in Cosine Theta Dipole

Magnetic analysis
Cosϑ without stress management

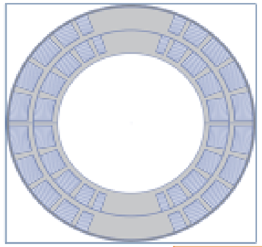
- 6 layers, with cables 13 mm to 21 mm wide
- Two options considered
  - 4 layer HTS, 2 layer LTS: 105 mm coil width
  - 2 layer HTS, 4 layer LTS: 129 mm coil width
    - Much wider outsert coils (sort of "anti-grading") but significant reduction of HTS coil size
- Field quality requirements met
- Accumulated σ_ϑ → 150-160 MPa
- Accumulated σ_r → approaching 200 MPa

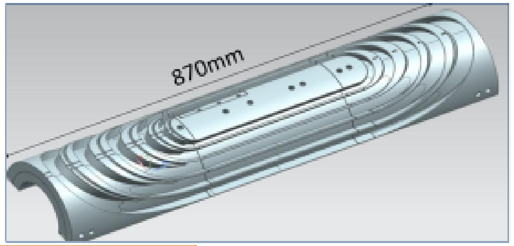


~5 mm radial intermediate radial structure (stress management) is used to keep accumulated stress within stress/strain limit (conductor and other structure must stay

Cosϑ (CT) with Stress Management: SMCT

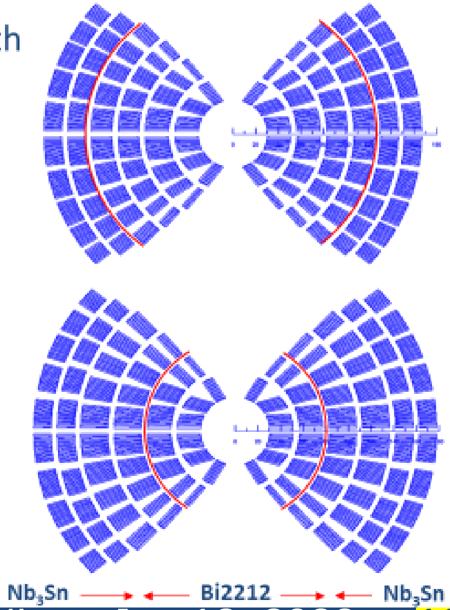
- 6 layers with cables ranging from 15 mm to 21 mm width
- Also in this case, two options considered
  - 4 layer HTS, 2 layer LTS: 144 mm coil width
  - 2 layer HTS, 4 layer LTS: 149 mm coil width
- Field quality requirements met
- Accumulated σ_r intercepted with 5 mm spars
- Accumulated σ_ϑ intercepted in each block by ribs





I. Novitski, TUE-PO1-110-05

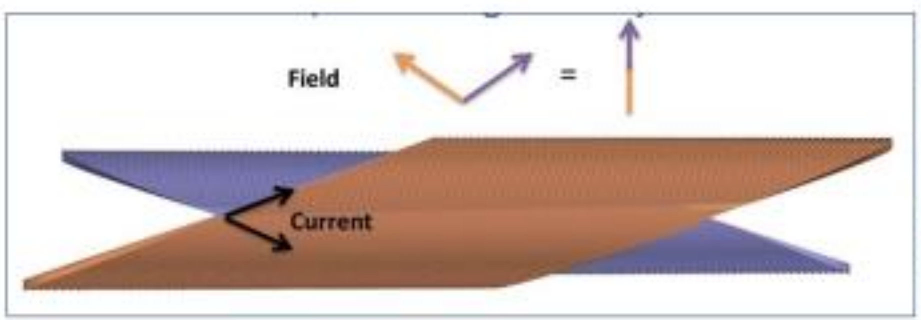
V. Marinozzi, WED-PO2-111-05

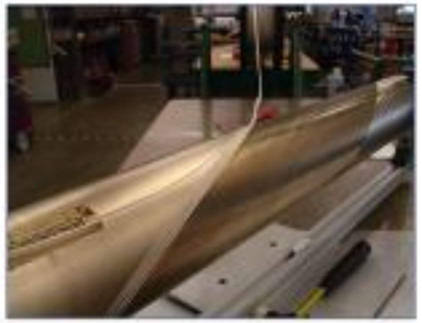


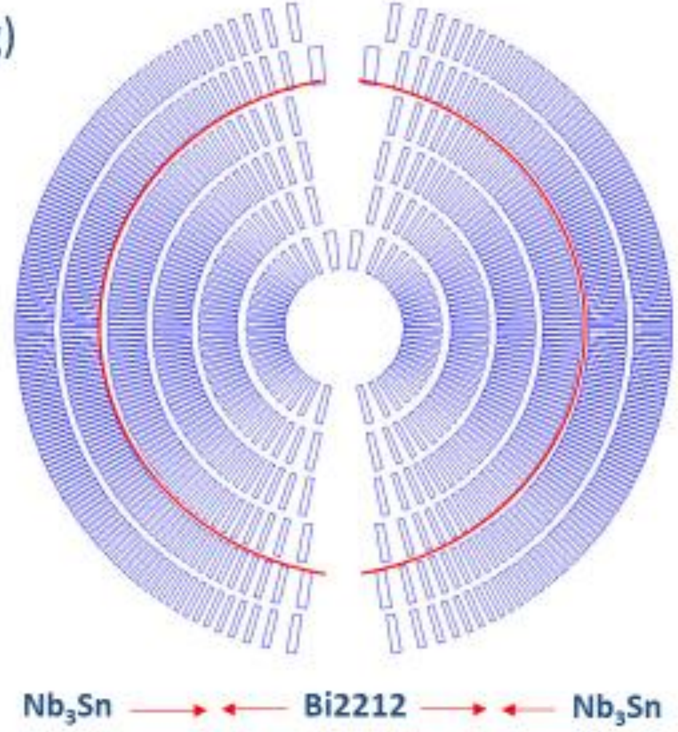
Structure Consideration in Canted Cosine Theta

Magnetic analysis
Canted Cosϑ (CCT)

- 6 layers with 18 mm wide cable (MQXF)
- Possibility of different cable/material on each layer (full grading)
  - in CT, usually double layer coils
- 4 layer HTS, 2 layer LTS: 135 mm coil width
- Field quality requirements met
- Accumulated σ_r intercepted by 5 mm spars
- Accumulated σ_ϑ intercepted in each turns by ribs







L. Brouwer, TUE-PO1-110-04 | D. Arbelaez, WED-OR2-703-08 | J. L. Fernandez Rudeiroz, WED-PO2-723-02

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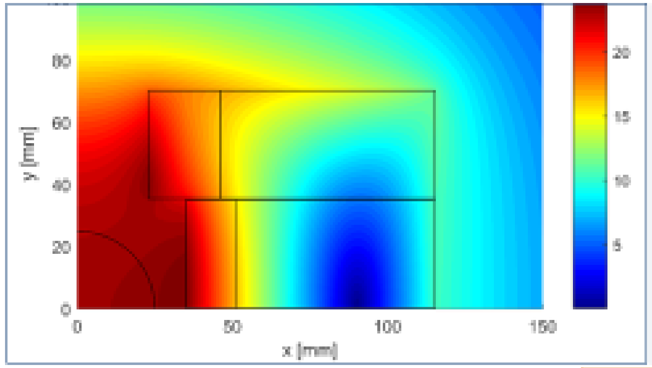
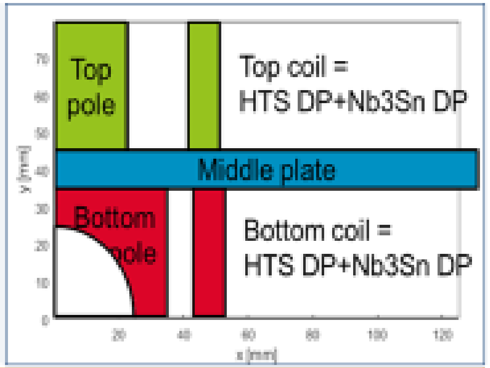
Structure Consideration in Block Coil Dipole

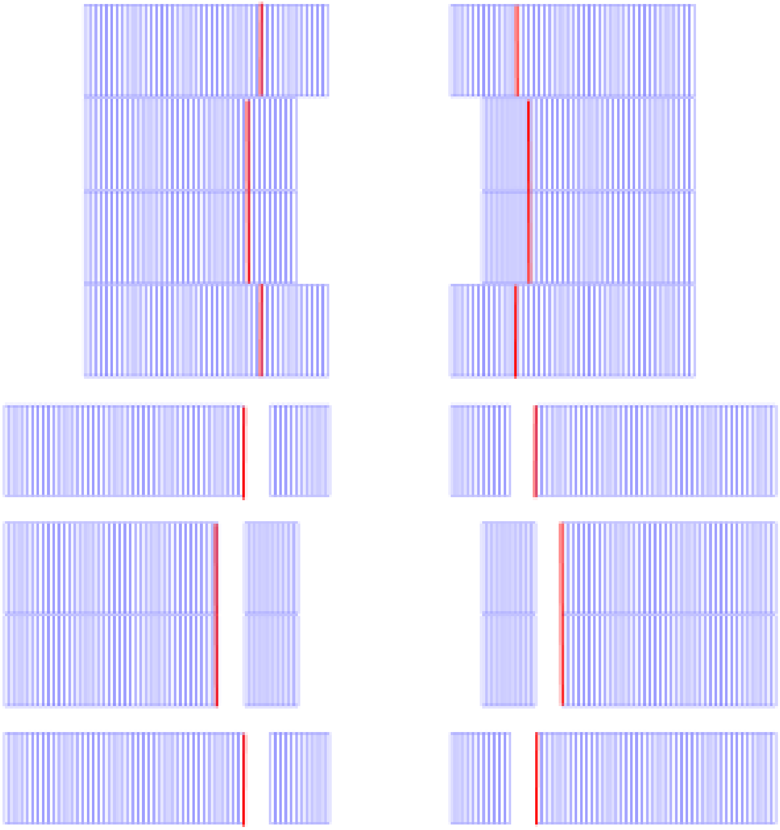
Magnetic analysis
Block-type

- Two double-layer coils with 17 mm wide cable
- Very efficient LTS-HTS boundary: flux lines parallel to cables
  - 81 mm coil width, but σ_x = 275 MPa
- Alternative: vertical and horizontal stress management
  - 111 mm coil width, but σ_x <= 160 MPa
    - Horizontal plate for σ_y ("easy"), vertical ribs for σ_x ("not so easy")
- Field quality requirements not met yet





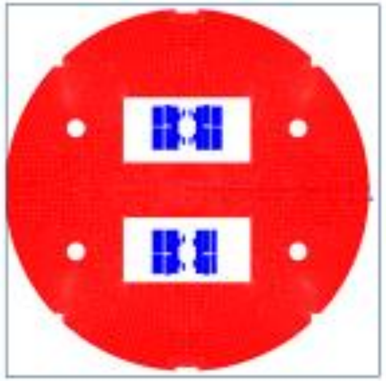
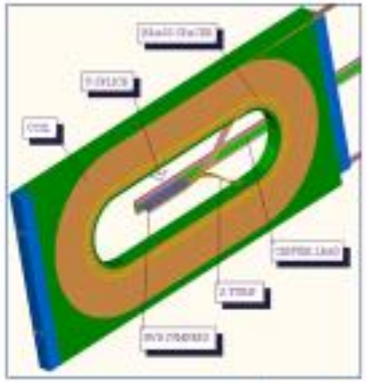
E. Rochepault, WED-PO2-111-01



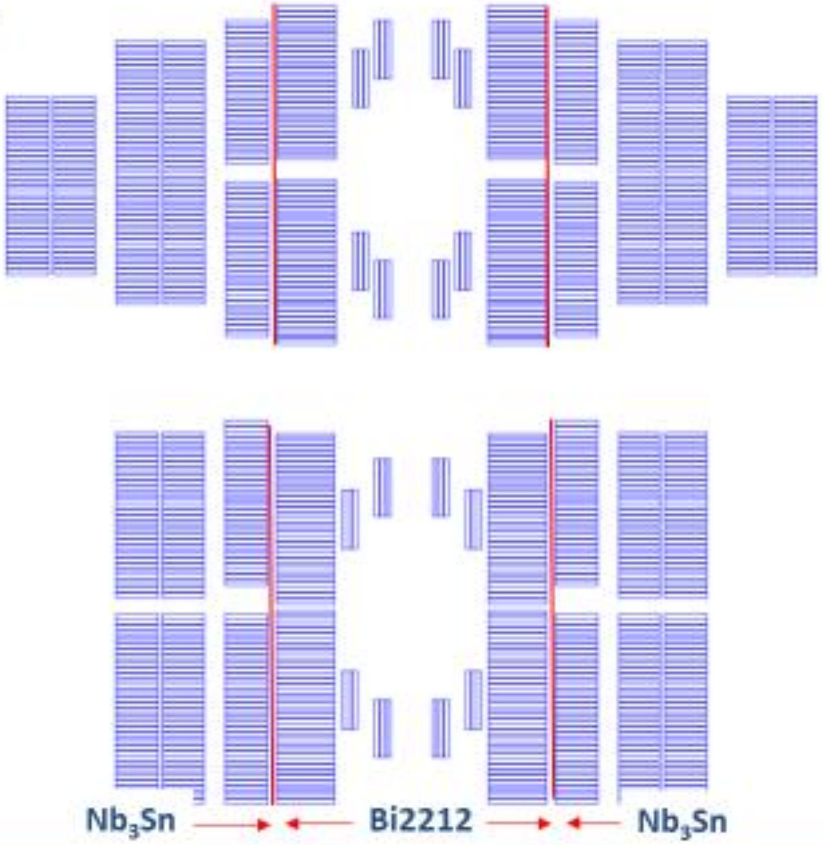
Structure Consideration in Common Coil Dipole

Magnetic analysis
Common-coil (with Bi2212)

- Single or double-layer with cables from 13 mm to 18 mm width
- Very efficient LTS-HTS boundary: flux lines parallel to cables
- Two options:
  - 6 layers: 104 mm coil width; 4 layers: 70 mm coil width
- Field quality requirements met
- Vertical plates plate for σ_x ("easy")
- Horizontal ribs for σ_y (to be included as needed)


By R. Gupta (BNL)



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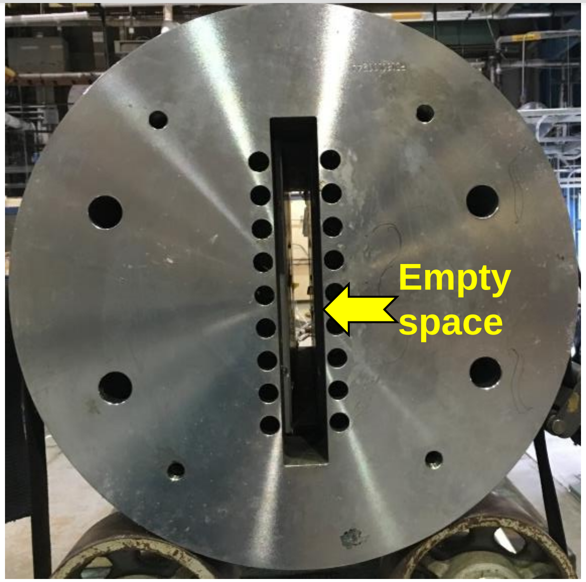
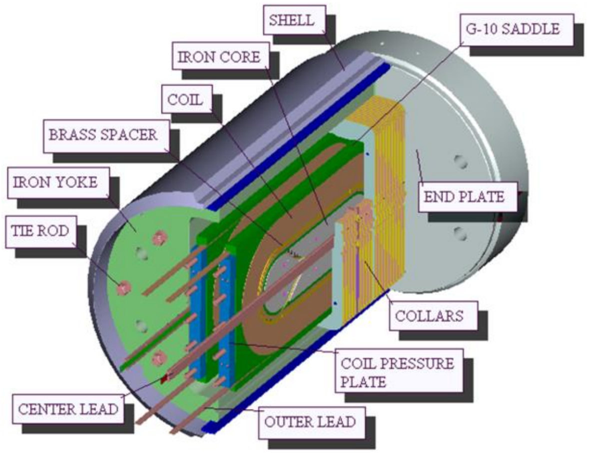
5 mm gap for structure between double pancakes. Mechanical analysis to be performed.

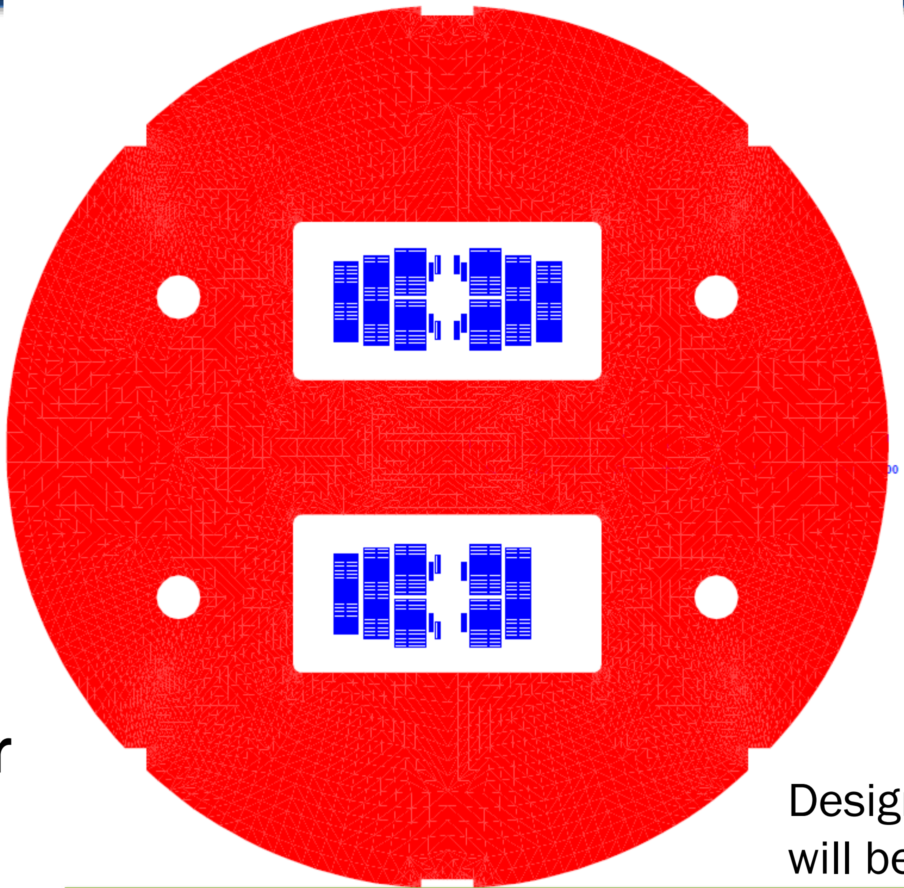
Background on the structure for High Field Common Coil Design

Differences in Support Structure between R&D Dipole (DCC017) and High Field (20 T) Common Coil Dipole





- In DCC017, we wanted a clear space between the upper and lower aperture
- This means a long (vertical) collared structure which creates large deflection or bending (l^3)
- To minimize this in 20 T dipole, we want to have separate structure for upper and lower aperture, which also have a large separation
- We also need structure to support the pole coils.



Design in ends will be different

Common coil design allows large motion of individual coil layer if the internal bending or strain remain low

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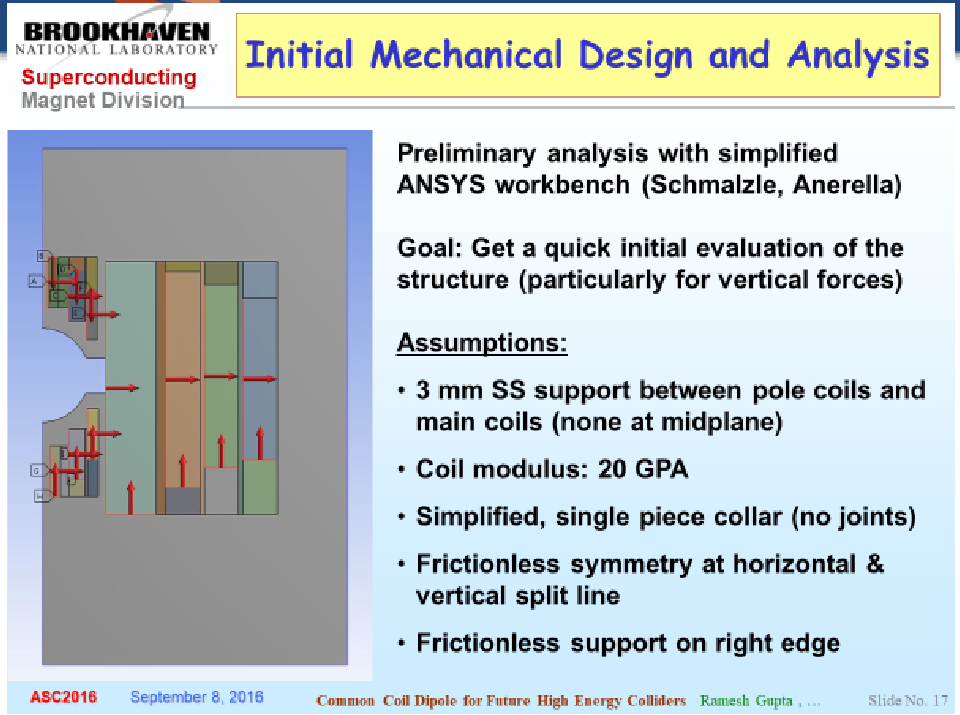
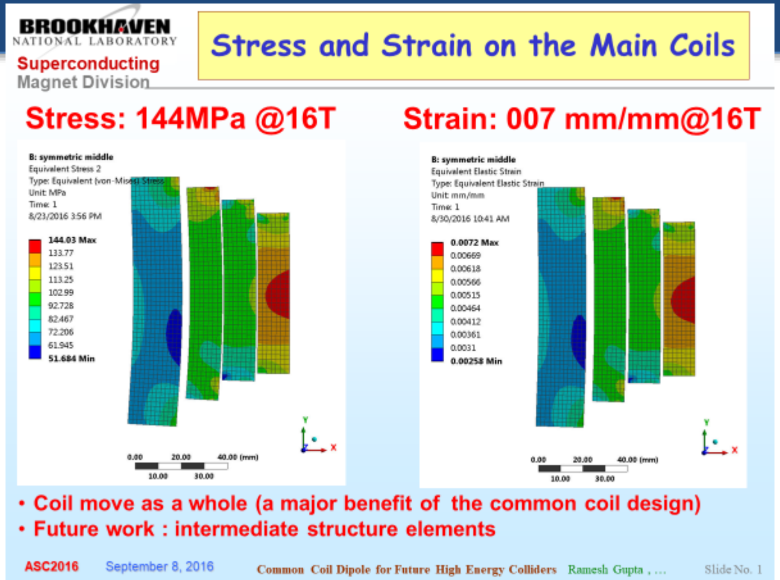
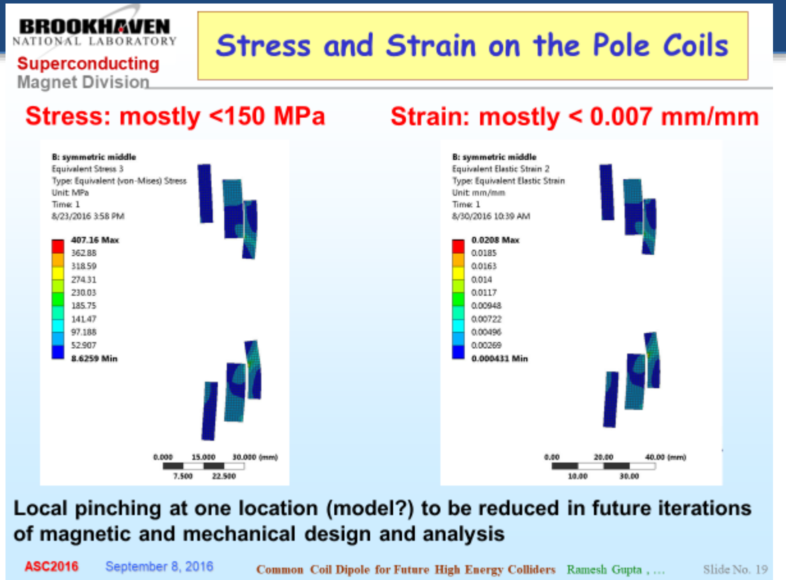
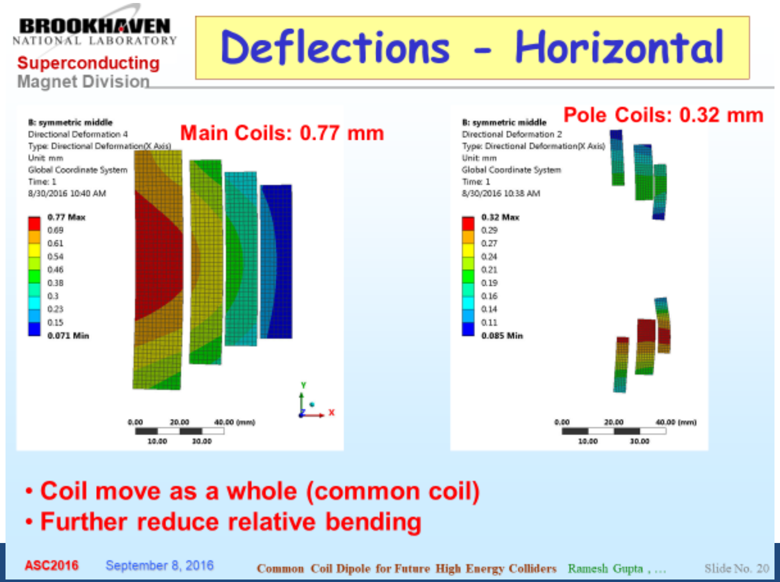
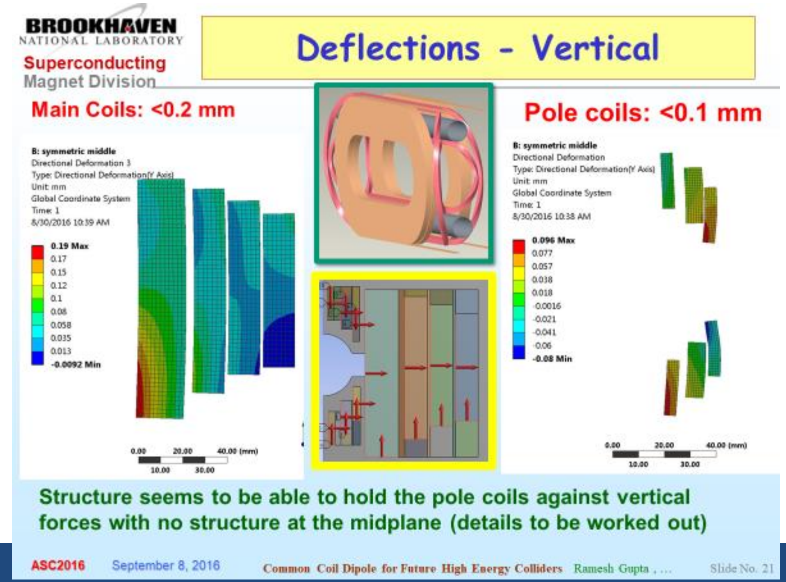
Earlier Preliminary Work on 16 T Design





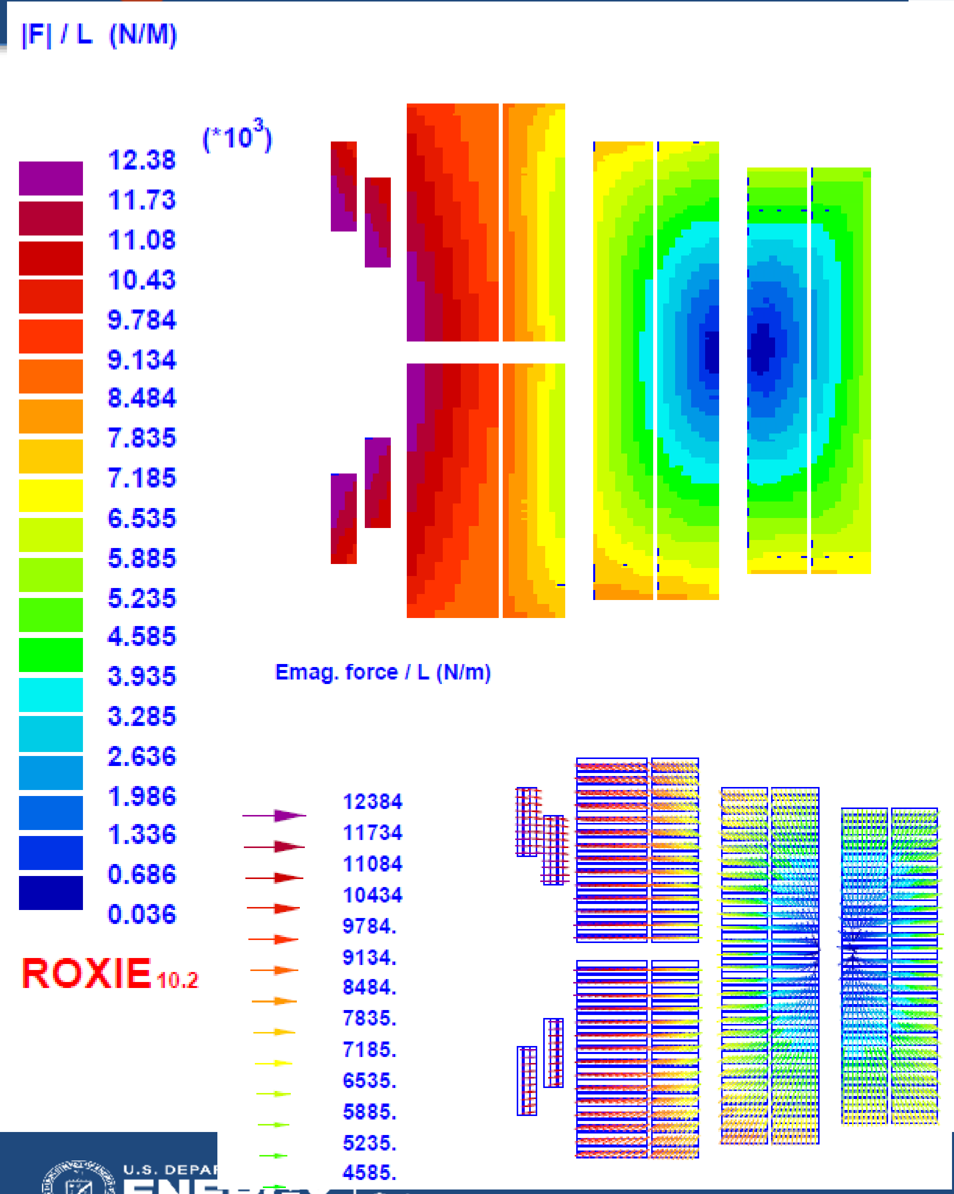


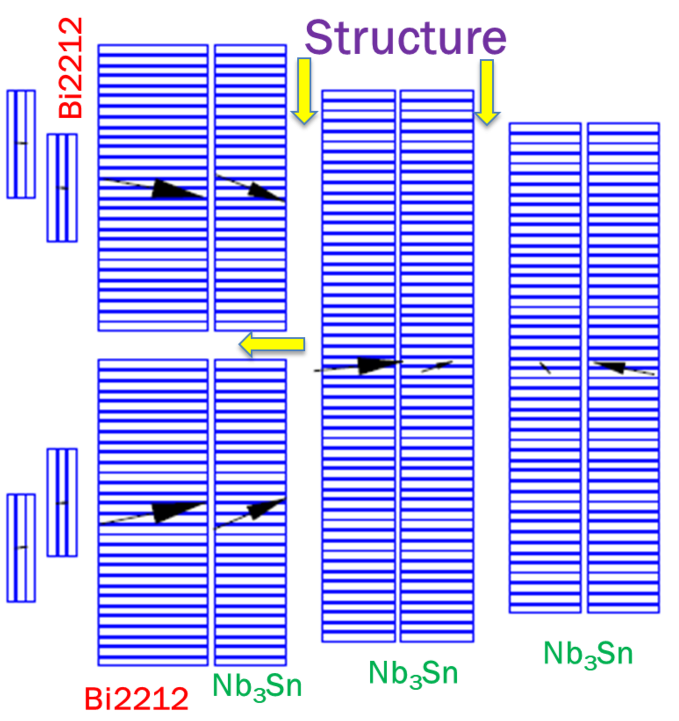


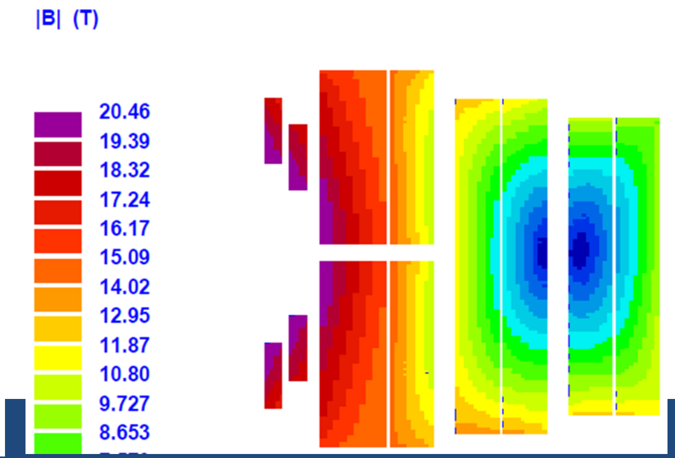


- We need to make model with more realistic assumptions for various options for 20 T dipole
- This will be an iterative work which gives feedback to magnetic design

Lorentz Forces @20 T and Structure Concepts







Note: Major component of the Lorentz force is horizontal

- Space for structure between the coil layers can be adjusted
- Spacer within the layers can be made structural elements and they can be appropriately added to transfer Lorentz forces from one layer to another while minimizing stress/strain on the conductor
- Structure for the pole block (deal with small vertical force)
- Minimize strain on conductor

Magnetic Design and Analysis

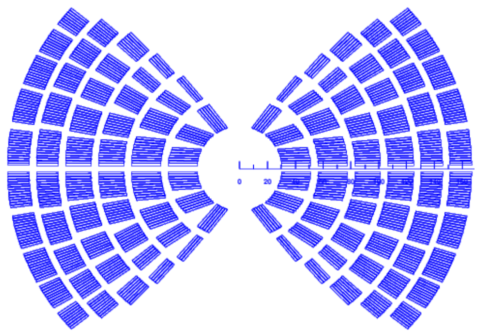
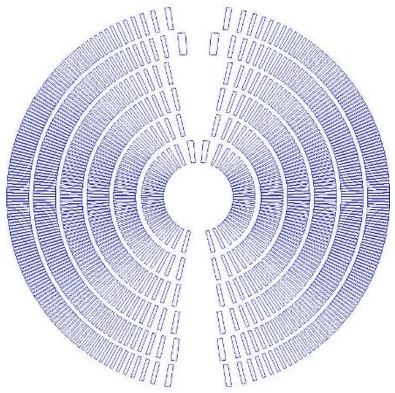
(must use HTS for 20 T)

- Designs should have > 15% margin (both in HTS and LTS)
- Design should have <5 units of harmonics at 2/3 of coil radius for now (typical requirements in accelerators ~1 unit)

Optimization of the field quality

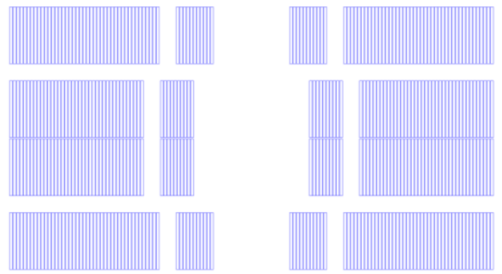
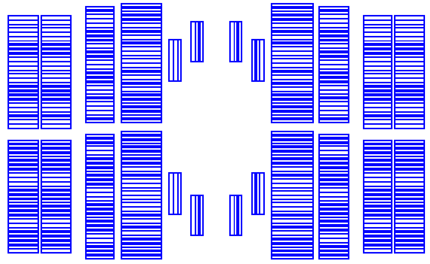
Typical requirements in accelerator magnet is that the field harmonics remain within a few parts in 10^4 (relaxed in the preliminary design study to 5 parts in 10^4)

Variable to optimize the cosine theta and the canted cosine theta designs

- Total coil width (radial extent – free to grow)
- Pole Angle (maximum 90°, minimum 60° for b_3=0)
- Wedges (critical for one or two-layer magnets)

Variable 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)
- Spacers (can be used to aid structure also)

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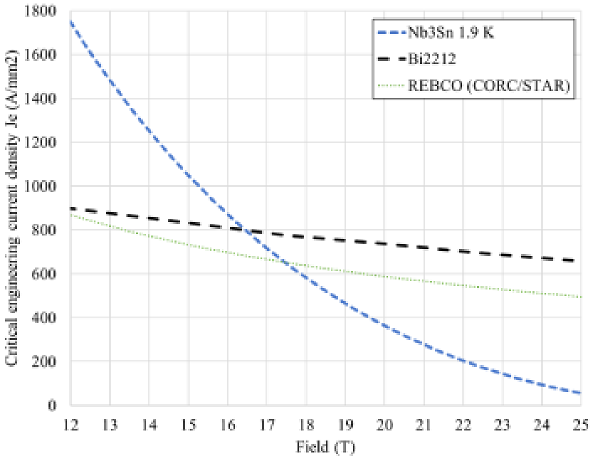
Field Margin Calculations

Maximum achievable field is determined by the current carrying capacity at the peak field on the conductor (different from the bore field)

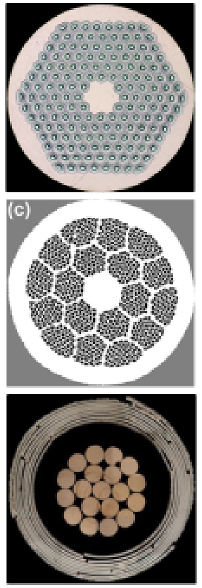
Superconducting materials: J_e and J_o

- Assumptions for magnetic analysis
  - J_e = Strand current / strand area
    - J_{e_LTS} = 875 A/mm² (1.9 K, 16 T, 5% degrad.)
      - 3000 A/mm² J_c (4.2 K, 12 T, virgin)
    - J_{e_HTS} = 740 A/mm² (20 T)
      - Bi2212 value
  - J_o = Cable current / Cable$_{insulated}$ area
    - $J_o = J_e \cdot 0.67$ (typical Rutherford cable)
      - Assumed also for HTS (Bi2212)
- Nb_3Sn and HTS cross at 16.5 T
- CORC wire still lower in both J_e (600 A/mm², 20 T) and J_o / J_e (0.54)



Superconducting materials
Wires and cables

- Nb_3Sn
  - 0.7 – 1.1 mm strands
    - Typical properties of 127 or 169 (***Bruker-OST***) RRP stacks
  - Rutherford cables: 8-26 mm wide, 1.3-2.0 mm thick
- Bi2212
  - Isotropic, round, multifilamentary
    - ***Bruker-OST*** architecture 19 × 36, 37 × 18 or 55 × 18 for 0.8 mm diameter wires
  - On paper, possible same strand and Rutherford cable dimensions as Nb_3Sn
- REBCO
  - CORC (***ATC LLC***) and STAR (***AMPeers***) wires: tapes around Cu former
  - Wire diameter from 1.3 to 3.6 mm
  - Multi-wire cable for accelerator magnets not available yet (R&D in progress)



Conductor Used

HTS - Bi2212

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

NUMBER OF BLOCK	1
NUMBER OF CONDUCTORS	3
POSITIONING ANGLE (DEG)	214.4000
INCLINATION ANGLE (DEG)	-90.0000
CURRENT IN EACH CONDUCTOR OF THE BLOCK (A)	-13900.0000
INNER RADIUS OF THE BLOCK (MM)......................	18.2000
CABLE HEIGHT (MM).(INSULATED)	18.6500
CABLE INNER WIDTH (MM).(INSULATED)	1.8200
CABLE OUTER WIDTH (MM).(INSULATED)	1.8200
CABLE HEIGHT (MM).(BARE)	18.3500
CABLE INNER WIDTH (MM).(BARE)	1.5200
CABLE OUTER WIDTH (MM).(BARE)	1.5200
RADIAL INSULATION THICKNESS (MM)....................	0.1500
AZIMUTHAL INSULATION THICKNESS (MM).................	0.1500
NUMBER OF STRANDS	40
DIAMETER OF STRANDS (MM)...........................	0.8000
CU/SC RATIO	3.0000
RESIDUAL RESISTIVITY RATIO.........................	100.0000
TEMPERATURE AT WHICH JC AND DJC ARE GIVEN (K)	1.9000
LINEAR APPROXIMATION JC(20.0 T) (A/MM**2)...........	2944.000
LINEAR APPROXIMATION DJC/DB (A/MM**2 T)............	64.000
CABLING ANGLE (DEG)	1.389
NUMBER OF DISCRETISATION POINTS AZIMUTHAL	2
NUMBER OF DISCRETISATION POINTS RADIAL	10
CONDUCTOR NAME	BI2212R

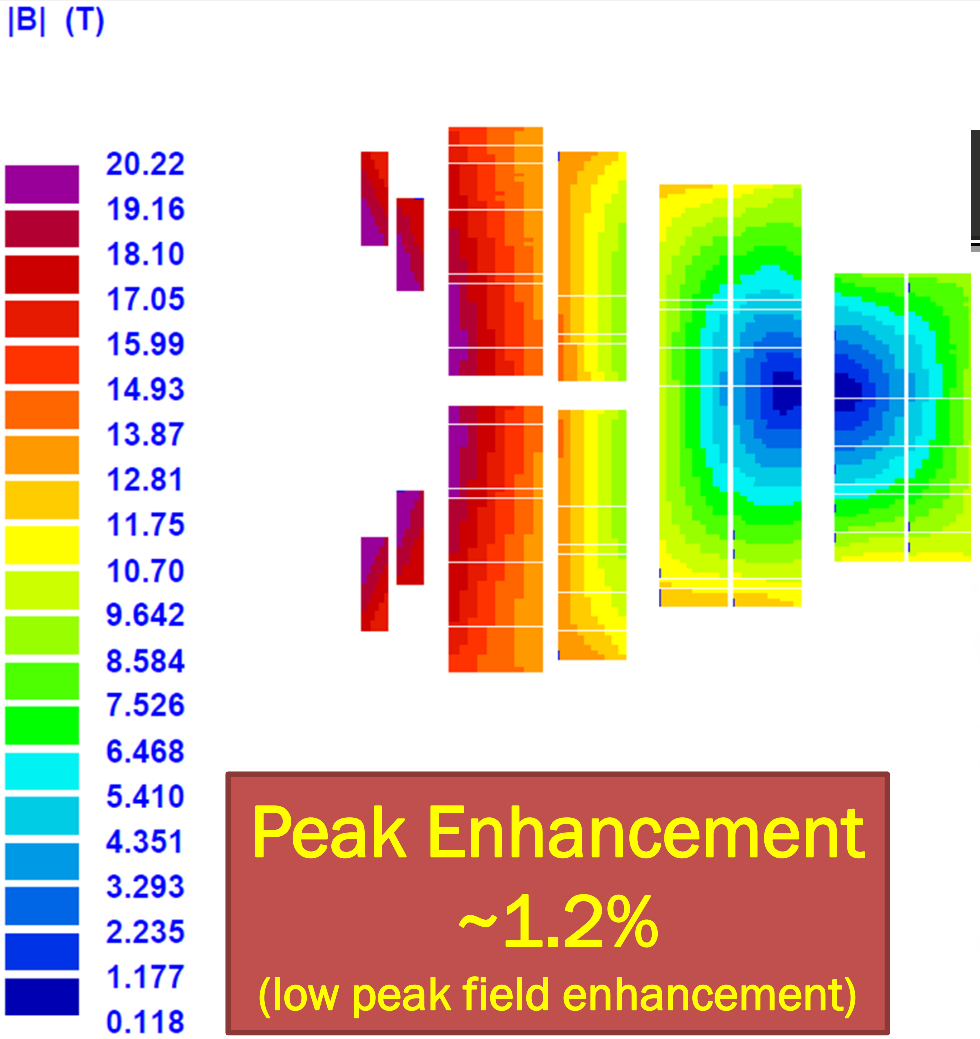
LTS - Nb_3Sn

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

NUMBER OF BLOCK	5
NUMBER OF CONDUCTORS	25
POSITIONING ANGLE (DEG)	105.1100
INCLINATION ANGLE (DEG)	0.0000
CURRENT IN EACH CONDUCTOR OF THE BLOCK (A)	-13900.0000
INNER RADIUS OF THE BLOCK (MM)......................	45.4000
CABLE HEIGHT (MM).(INSULATED)	13.6000
CABLE INNER WIDTH (MM).(INSULATED)	1.9000
CABLE OUTER WIDTH (MM).(INSULATED)	1.9000
CABLE HEIGHT (MM).(BARE)	13.3000
CABLE INNER WIDTH (MM).(BARE)	1.6000
CABLE OUTER WIDTH (MM).(BARE)	1.6000
RADIAL INSULATION THICKNESS (MM)....................	0.1500
AZIMUTHAL INSULATION THICKNESS (MM).................	0.1500
NUMBER OF STRANDS	37
DIAMETER OF STRANDS (MM)...........................	0.8000
CU/SC RATIO	1.0000
RESIDUAL RESISTIVITY RATIO.........................	100.0000
TEMPERATURE AT WHICH JC AND DJC ARE GIVEN (K)	1.9000
LINEAR APPROXIMATION JC(16.0 T) (A/MM**2)...........	1928.000
LINEAR APPROXIMATION DJC/DB (A/MM**2 T)............	371.000
CABLING ANGLE (DEG)	1.439
NUMBER OF DISCRETISATION POINTS AZIMUTHAL	2
NUMBER OF DISCRETISATION POINTS RADIAL	10
CONDUCTOR NAME	MDPH2

October 2021 Design #1 (6 layers in main coil)

U.S. MAGNET DEVELOPMENT PROGRAM



Peak Enhancement ~1.2%

(low peak field enhancement)

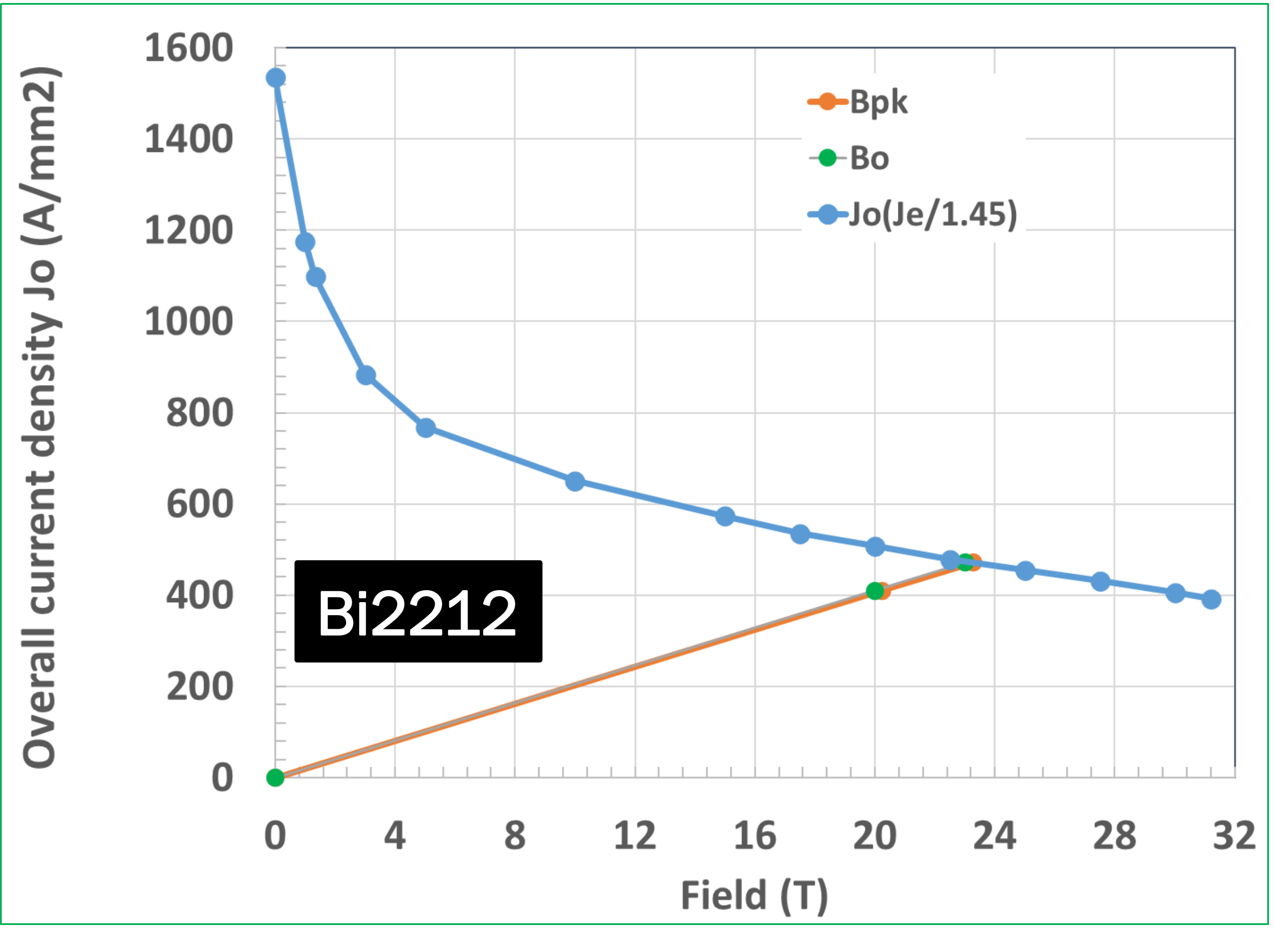
Good field quality: harmonics about a unit or less

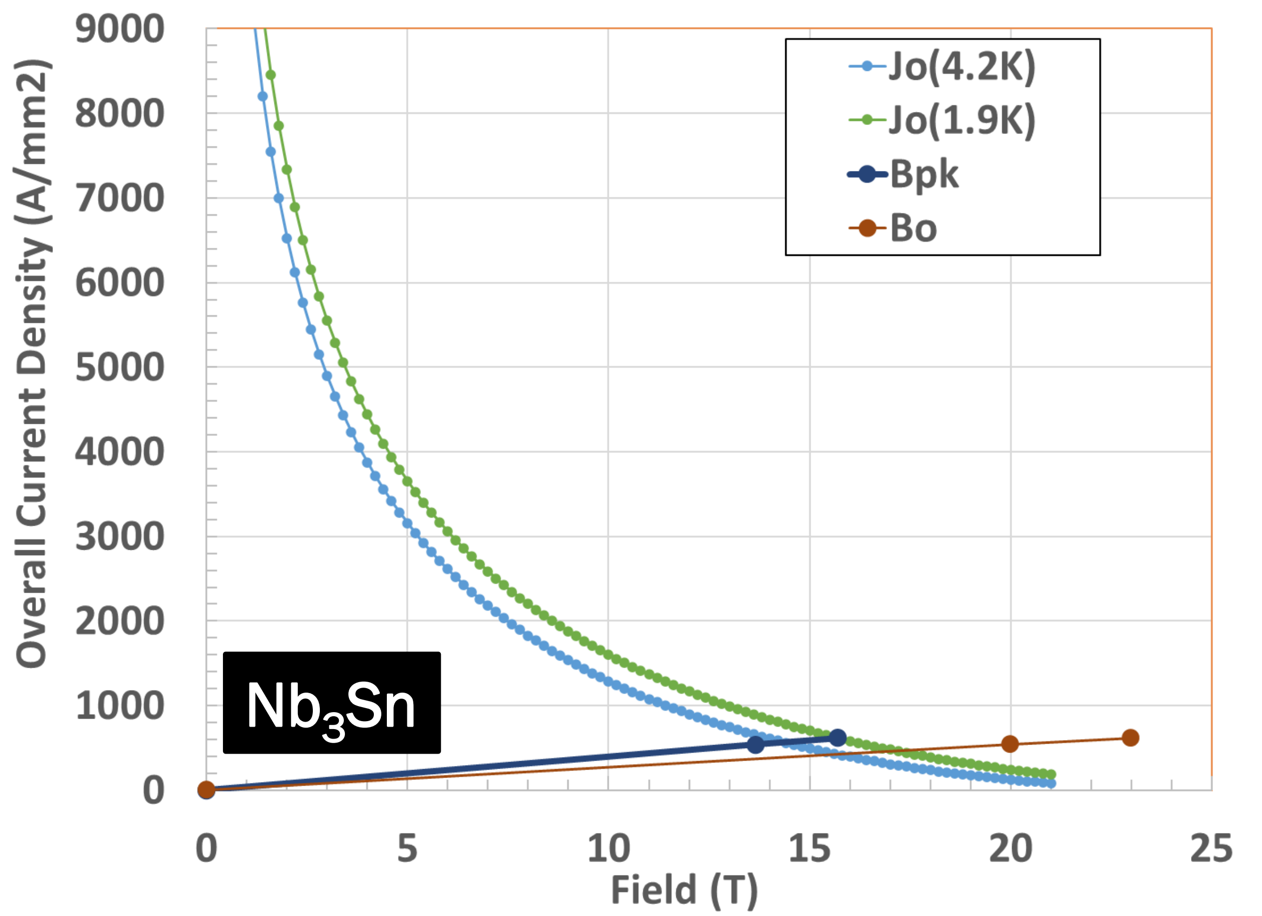
Running ROXIE on file mdp_oct-2021-Bi2212-i0.data...

```
MAIN FIELD (T) ..........................................     19.988791
MAGNET STRENGTH (T/(m^(n-1)) ...........................       19.9888

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
```

Computation of Field Margins

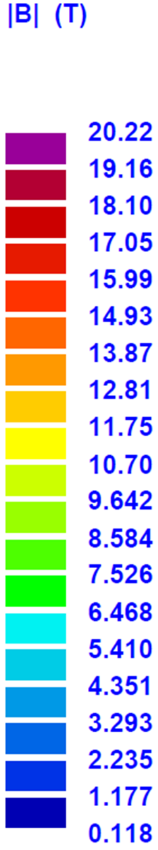
Designs are matched margins – 15% over 20 T – in both Bi2212 and Nb_3Sn coils for the reference J_o

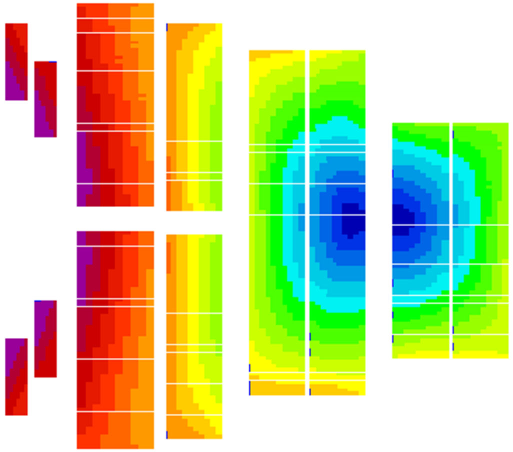




Flexibility in Common Coil Design (Vertical Vs. Horizontal)

6-layer design



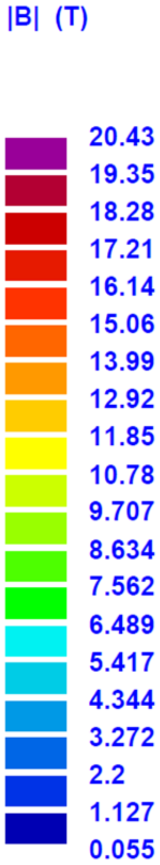


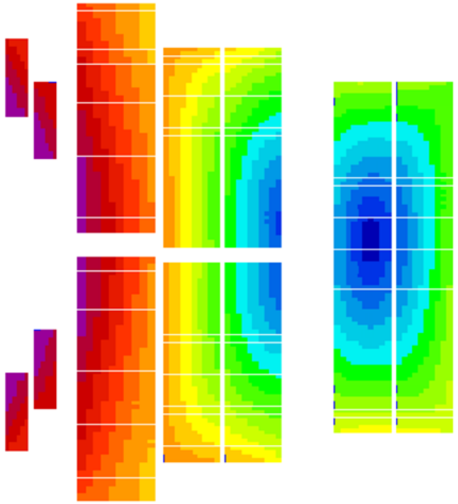
HTS: 1 layer + pole blocks
- ❖ 74 turns in ½ bore

LTS: 5 layers
- ❖ 198 turns in ½ bore

Total turns = 272

5-layer design



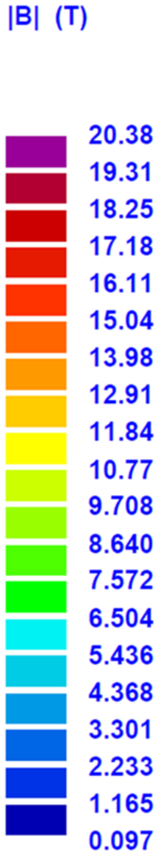


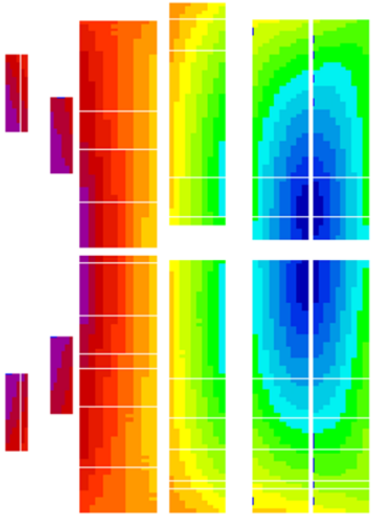
HTS: 1 layer + pole blocks
- ❖ 80 turns in ½ bore

LTS: 4 layers
- ❖ 188 turns in ½ bore

Total turns = 268

4-layer design





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

LTS: 5 layers
- ❖ 180 turns in ½ bore

Total turns = 262

Less layers use slightly more HTS, however, may still provide significant savings in construction costs

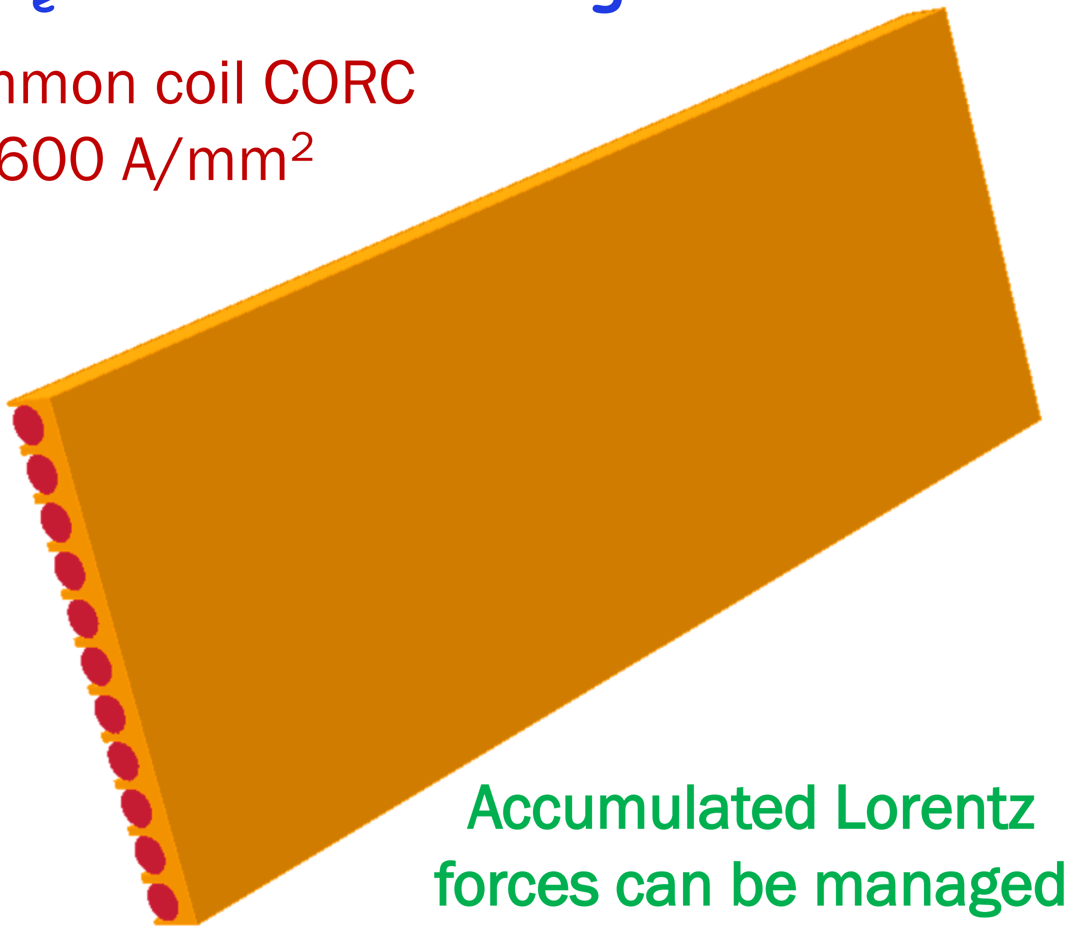
All three design use less conductor as comparable cosine theta or canted cosine theta (particularly HTS)

CORC based Common Coil

➢ **Common coil design allows higher J_e CORC due to large bend radii**

❖ STTR with ACT anticipated a future common coil CORC with an engineering current density of 600 A/mm^2

❑ 800 A/mm^2 possible (STAR –Selva)
❑ Designs based on 600 A/mm^2 only



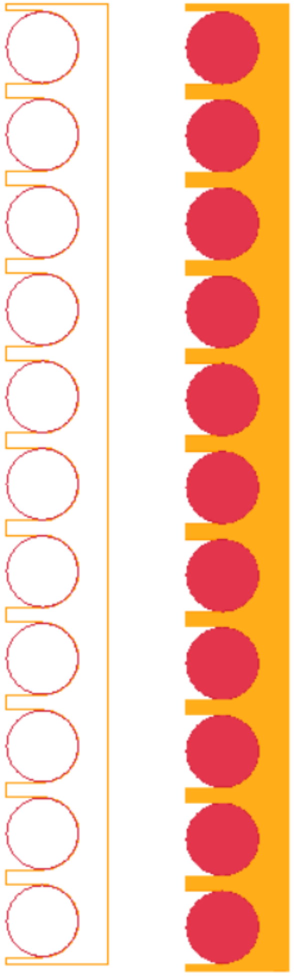
Overall Current density with structure:

- Area for 6 mm wire: pi*6*6/4 = 28.3 mm^2
- Area for 6.5mm X 8mm rectangle = 52 mm^2

J_o for Je = 600 A/mm2:

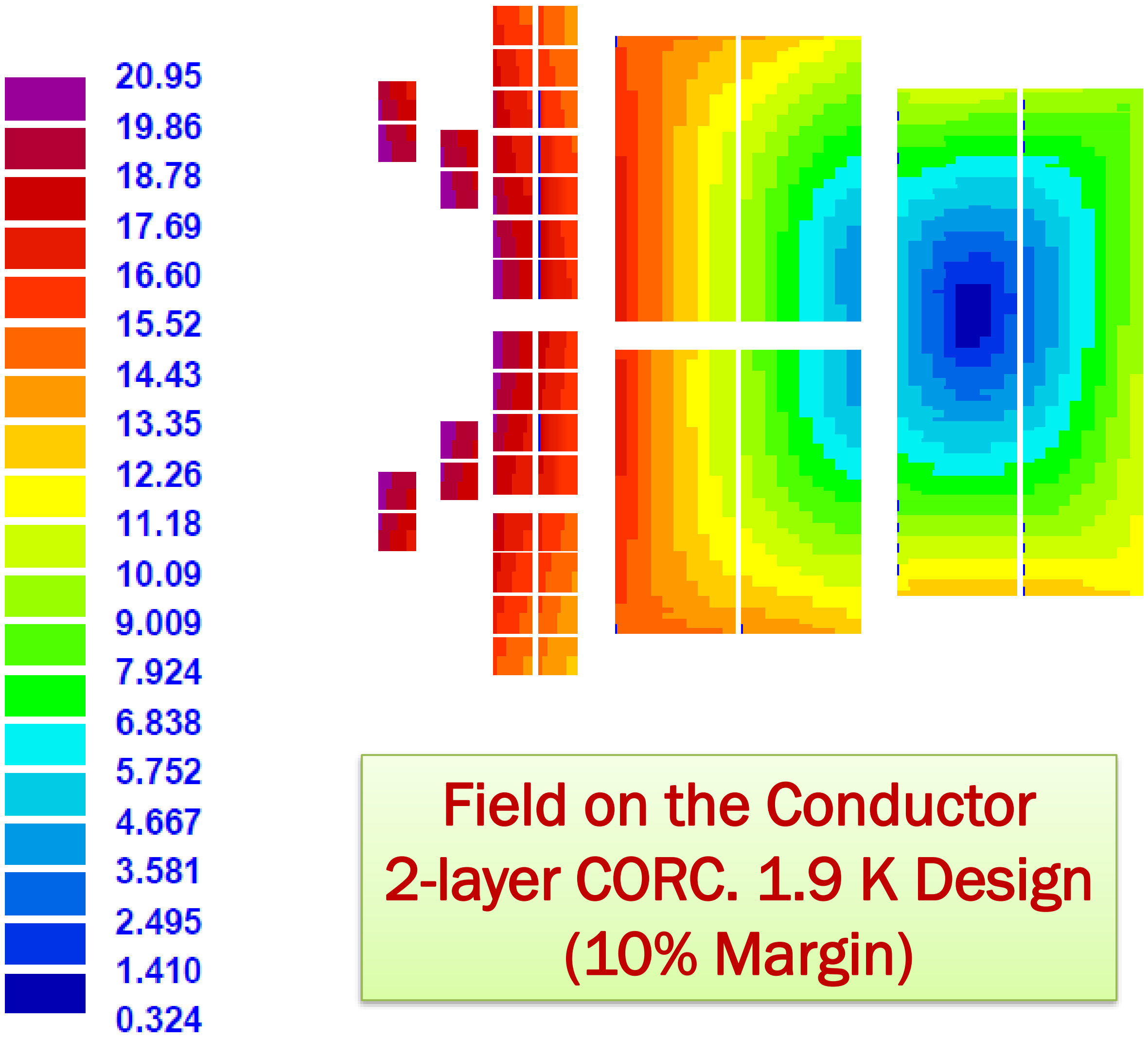
❑ J_o =600*28.3 /52 = 326 A/mm^2

➢ Similar to Bi2212; but with a structure

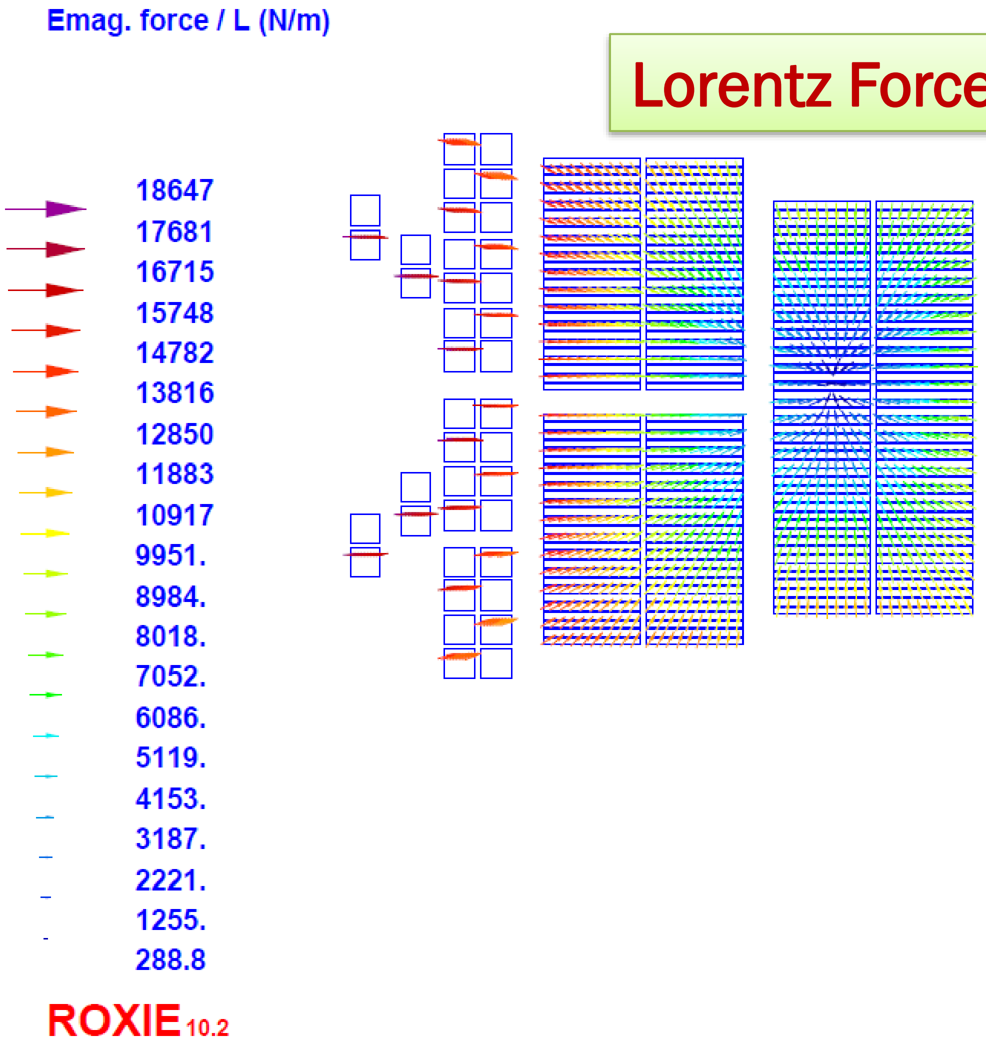


Accumulated Lorentz forces can be managed in a structure

50 mm, 20 T Common Coil CORC/Nb_3Sn Hybrid Design (design yet to be optimized for 15% margin)



Field on the Conductor
2-layer CORC. 1.9 K Design
(10% Margin)



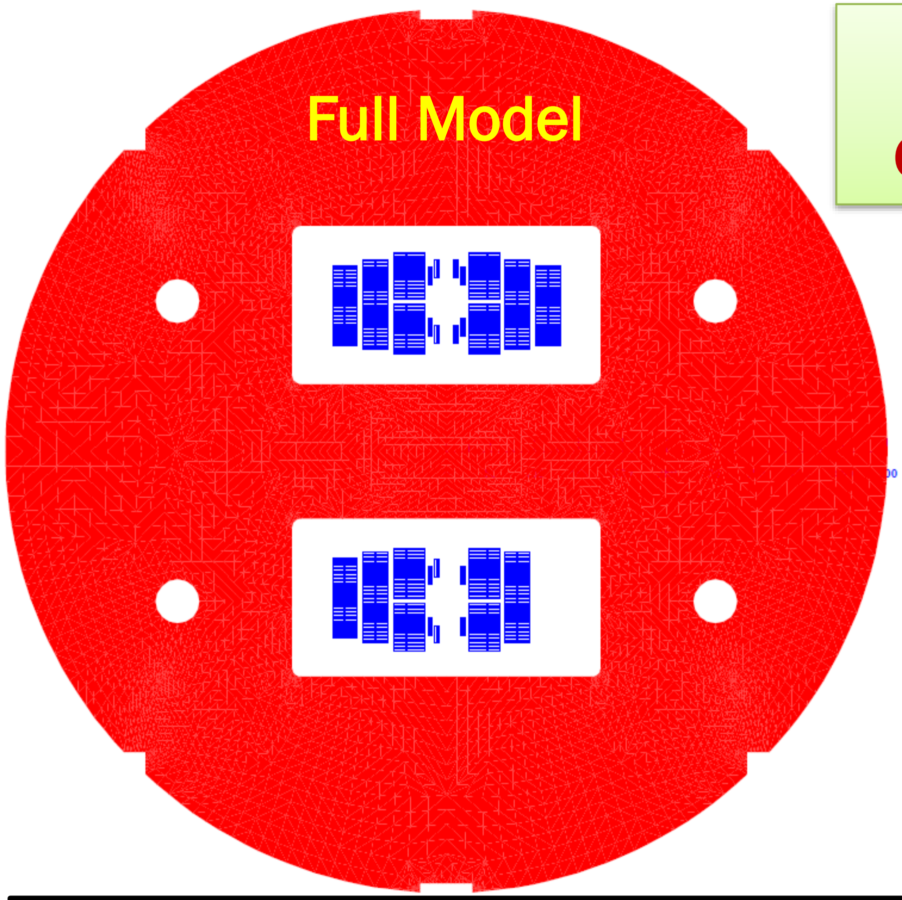
Lorentz Forces

Work Ahead in Near Future

Optimization of Overall Design

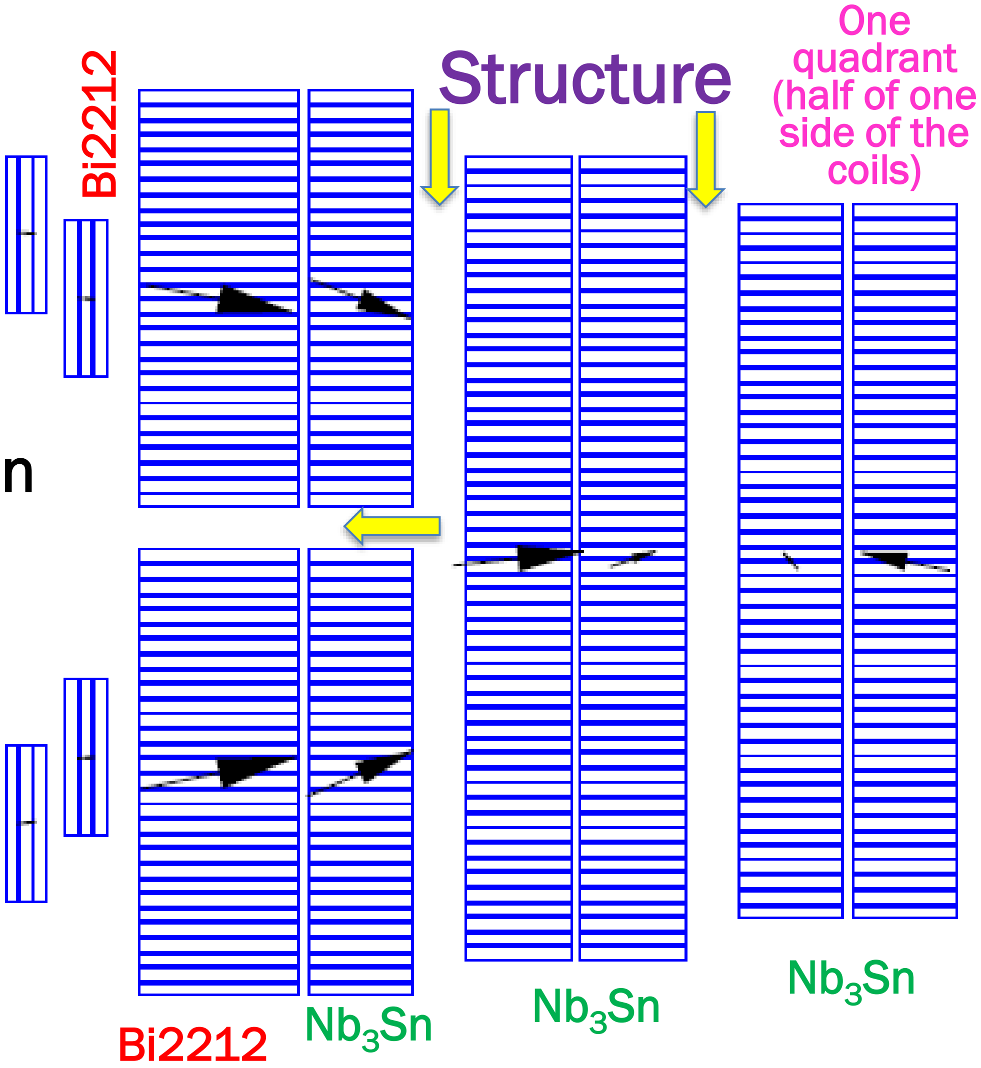
(magnetic and mechanical together and concepts of how we will assemble it)

50 mm, 20 T Bi2212/Nb_3Sn Common Coil



Proof-of-principle designs examined

- 1 Layer of Bi2212 (+pole coils)
- 3 to 5 Layers of Nb_3Sn
- ~15% margin
- 20 T at ~14 kA
- Space for structure



Next generation designs will be integrated magnetic & mechanical design. Magnetic designs will have feedback from the mechanical analysis to provide sufficient space for the structure.

U.S. MAGNET DEVELOPMENT PROGRAM

Specific Work Ahead

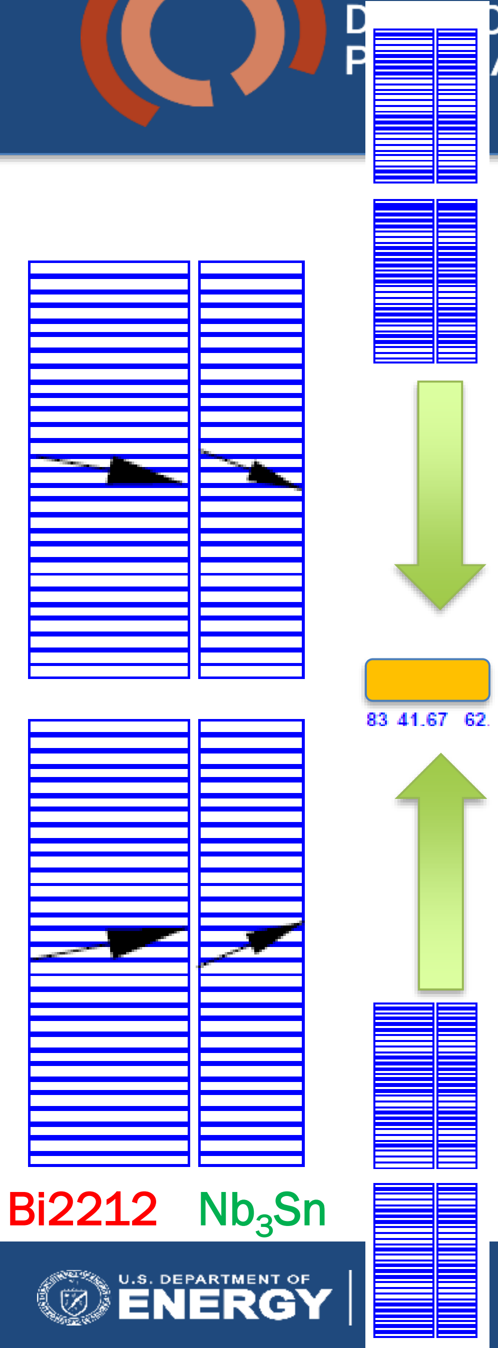
- Perform a quick mechanical analysis of the 20 T design (just as performed for the 16 T dipole (include collars, yoke and SS shell)
- Provide feedback to magnetic design for the space needed for structure between layers and within layer
- Develop concepts for assembling the magnet
- Perform refined mechanical analysis with interacted structure
- Perform 3-d magnetic and mechanical analysis

Summary

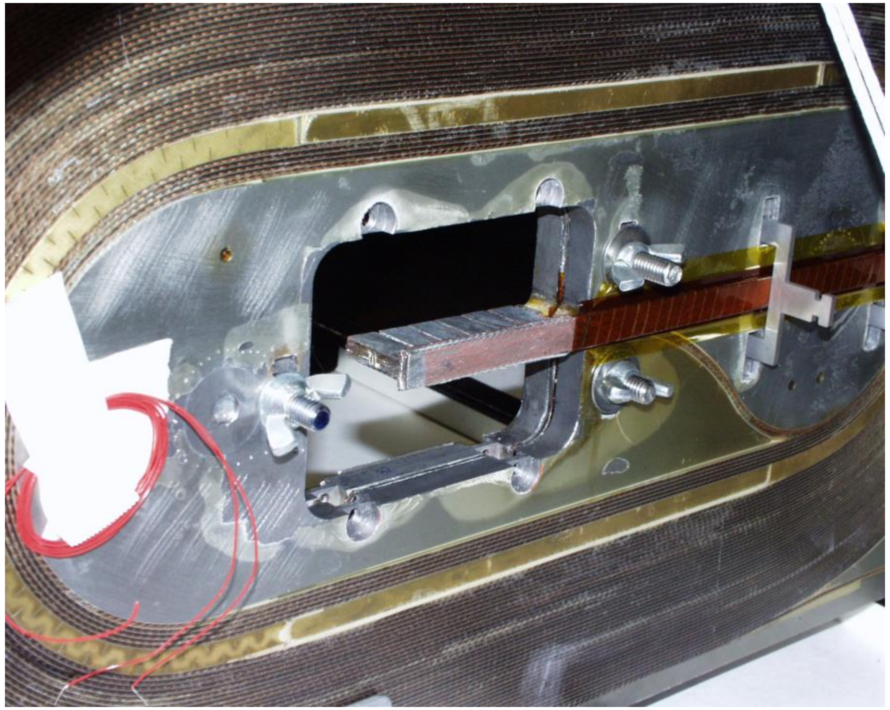
- Common coil design is appearing to look more and more attractive for high field (20 T) HTS/LTS hybrid dipoles
- For such high fields, common coil design uses less conductor, particularly HTS (opposite to what people think)
- Common coil allows easy and efficient segmentation between HTS and LTS
- Common coil allows larger deflections without putting high strain on coils
- It allows more technological options than the other designs (R&W, insulation)
- Simple geometry should facilitate more reliable and lower cost manufacturing
- A lot of work remaining to fully develop the design. A good opportunity for long term R&D where your work will be pioneering and will make a difference
- WELCOME ABROAD…

Extra Slides

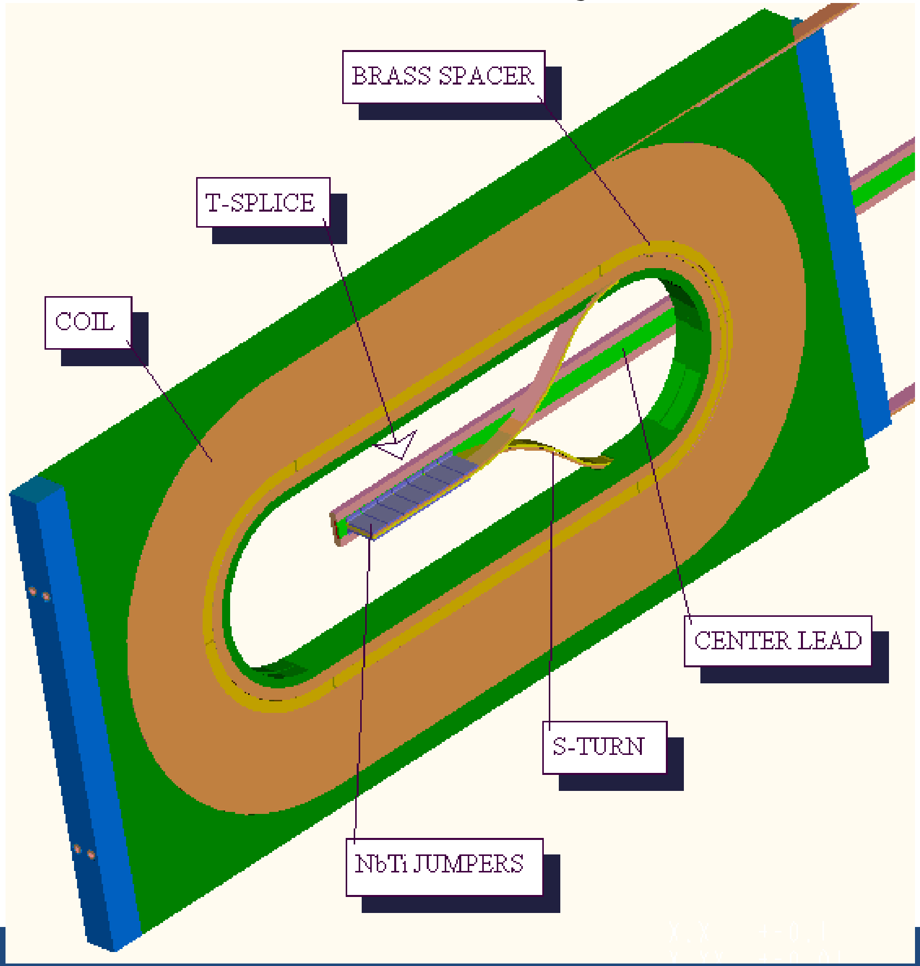
Splices in Common Coil Design (between two single layer coil)



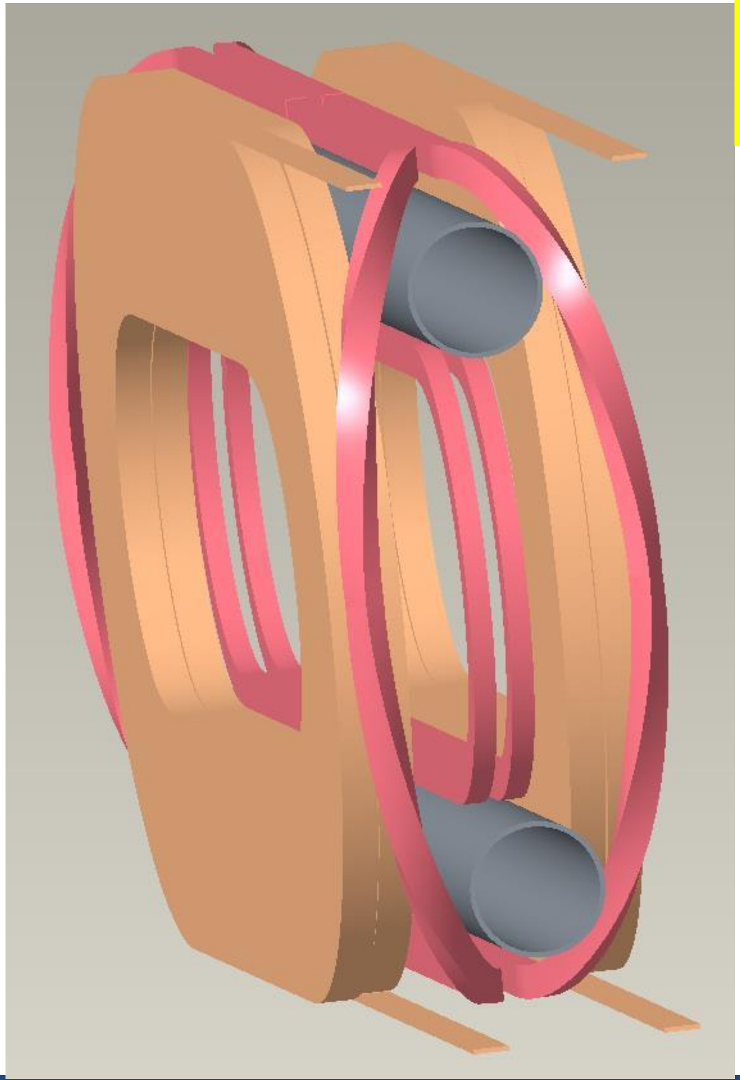
In common coil design, splice (even between two types of coils), can be easily made in the middle of the coil where the field is very low



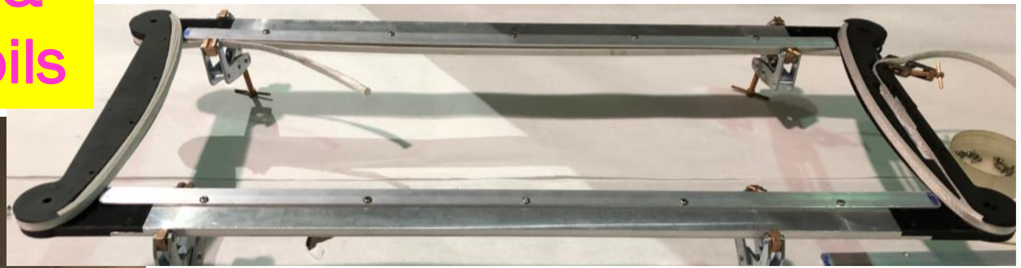
Perpendicular Nb-Ti splice in the low field region of BNL common coil dipole DCC017

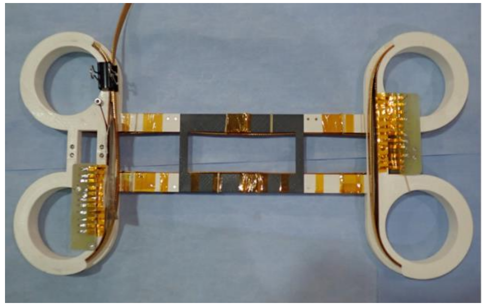


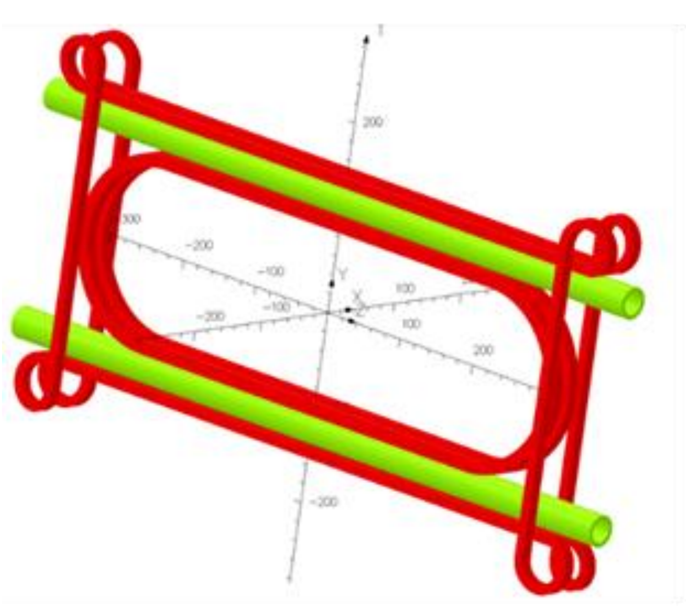
A Few Possible Layout of Away Pole Coils Clearing Bore (others shown elsewhere)

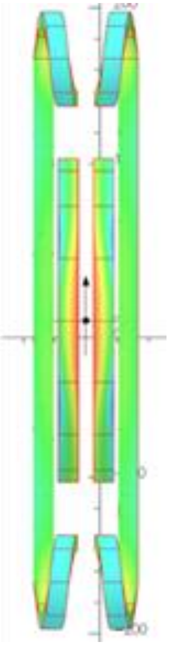


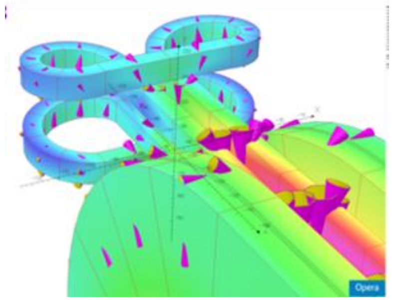
Practice & Tested Coils











CORC coil can be bent first away and then up/down