U.S. MAGNET DEVELOPMENT PROGRAM

20T Common Coil Design Status
Ramesh Gupta, BNL

MDP General Meeting
August 3rd, 2022

Overview

- ❑ **Onward from what was presented at the annual meeting**

  Question: Do the advantages of common coil design still hold after a more detailed analysis? Review them one by one for 20 T hybrid

- ❑ **Progress made since the annual meeting**

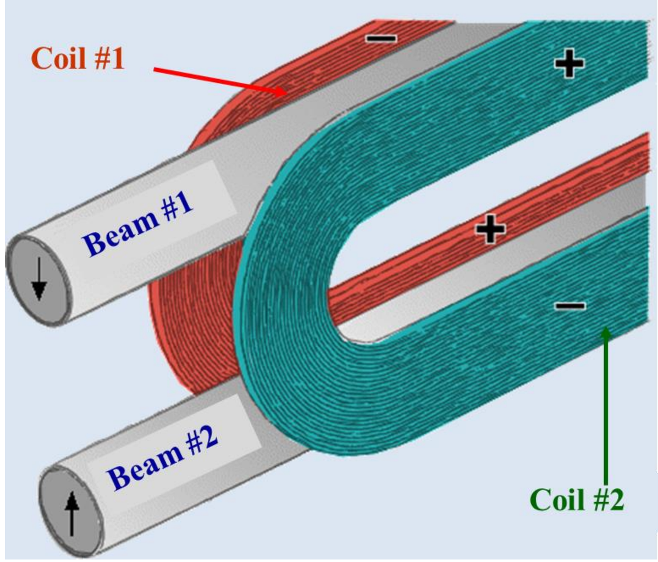
  Question: Are the design requirements met when the same (not similar) design is used for the magnetic and mechanical analysis?

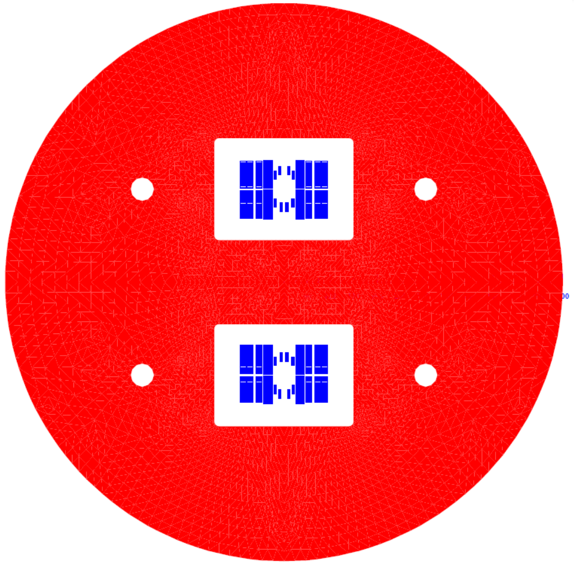
- ❑ **Future plans (including a proof-of-principle demo magnet)**

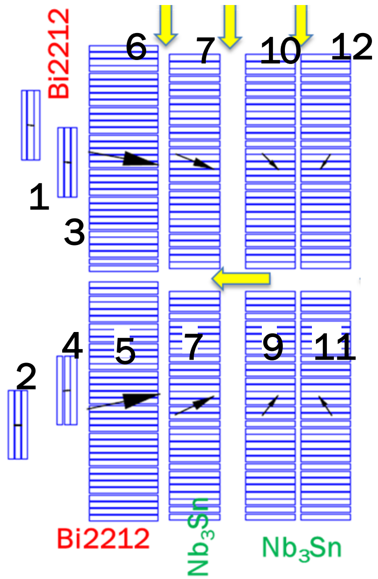
  Question: Apart from developing the design of 20 T dipole, can an accelerator type common coil dipole be demonstrated within MDP?

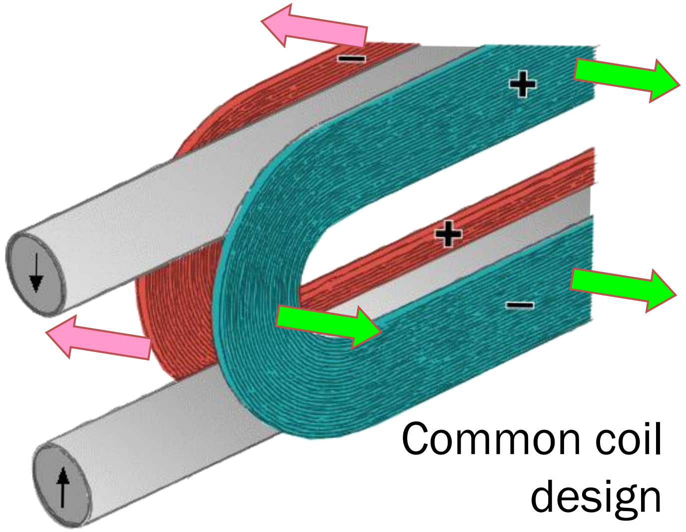
- ❑ **Summary**

Common Coil Geometry for High Field HTS/LTS Hybrid Collider Dipole



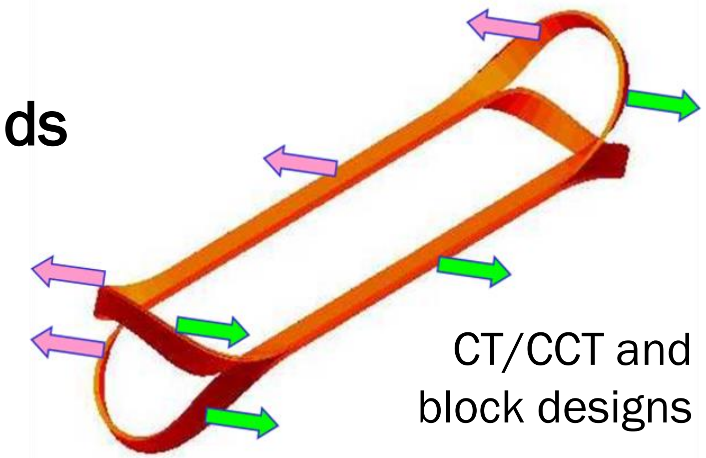






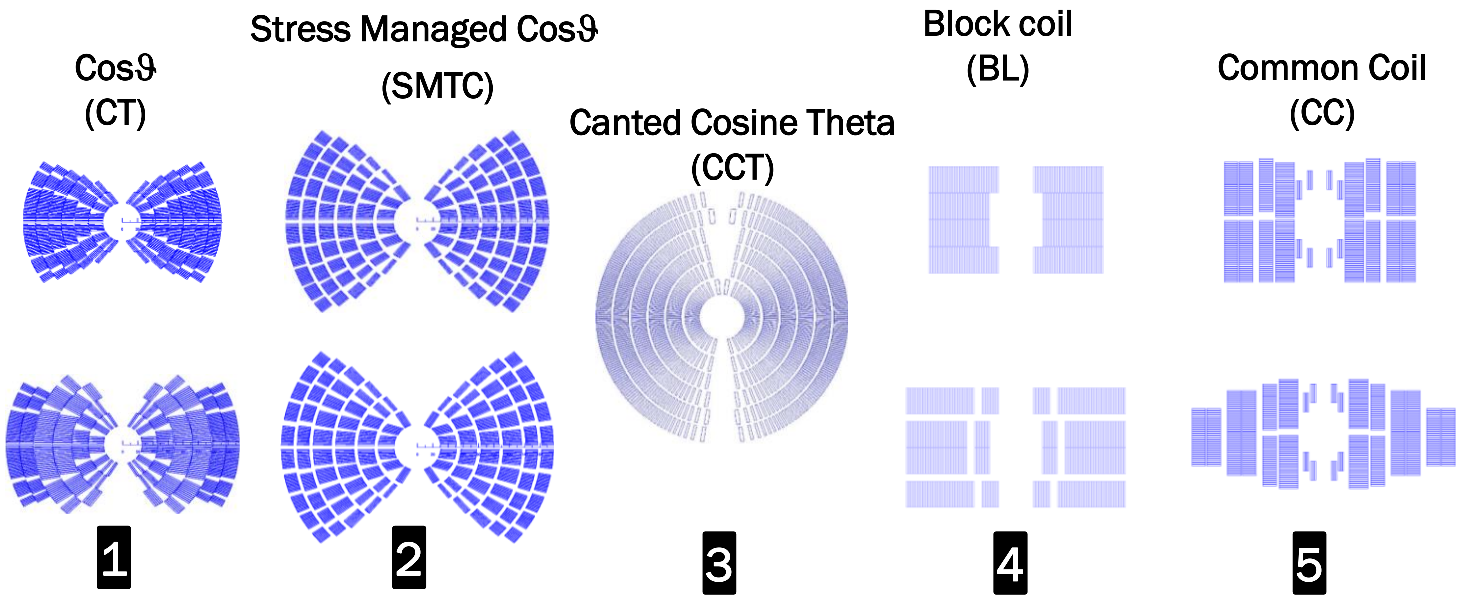
Common coil design

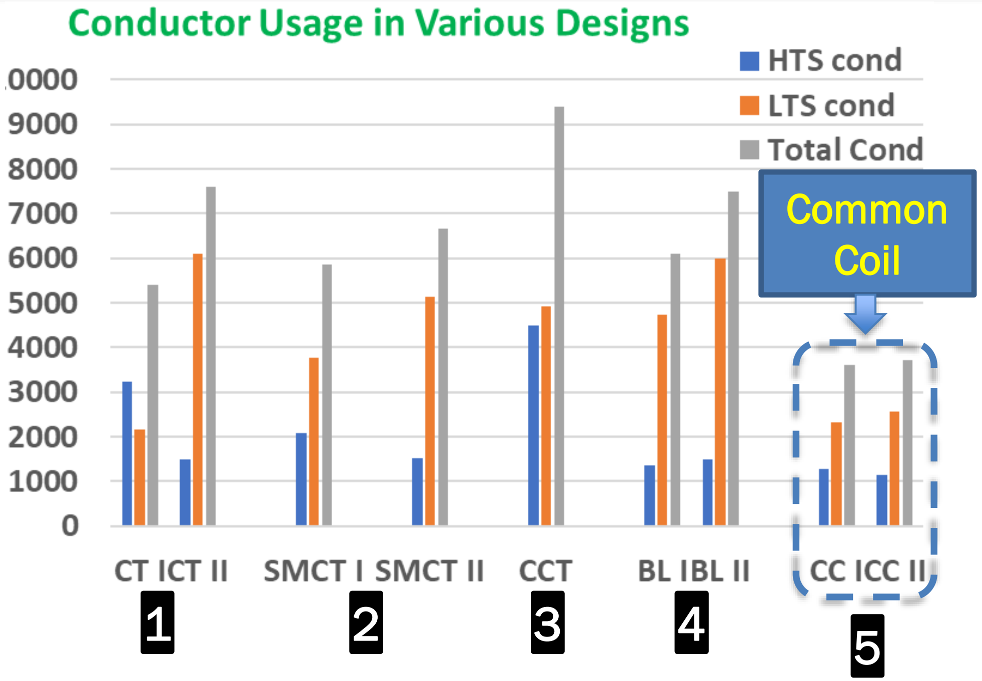
- Inherent benefits/limitation of the geometry
- Significantly lower conductor usage over other designs at high fields
- Easier and efficient segmentation between HTS and LTS coils
- All LTS coils identical – significant savings, particularly in R&D
- Good field quality and required 15% operating margin over 20 T
- Unique geometry for managing large Lorentz forces at high fields



CT/CCT and block designs

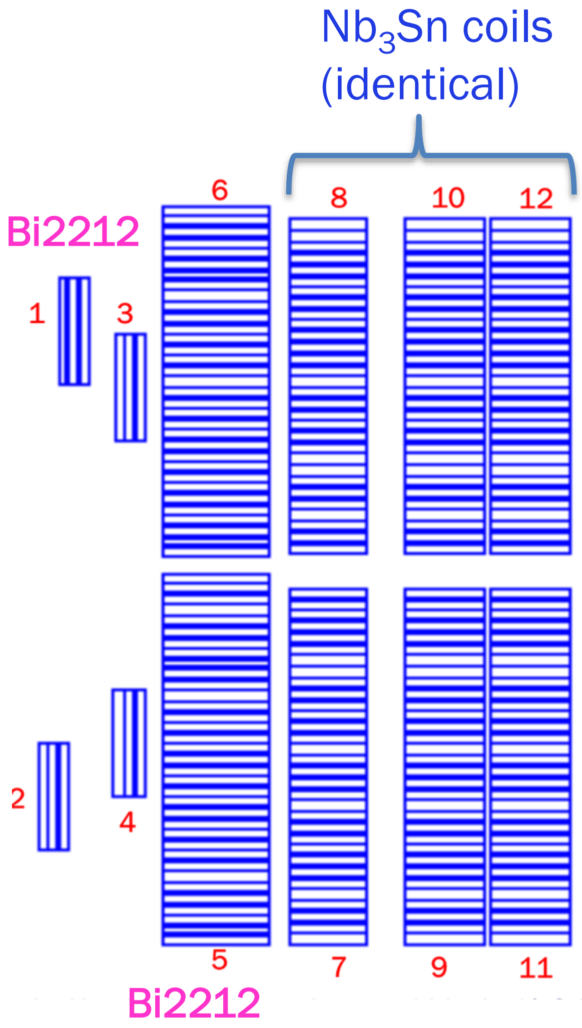
Common Coil Design Uses Less Conductor for Very High Field Dipole



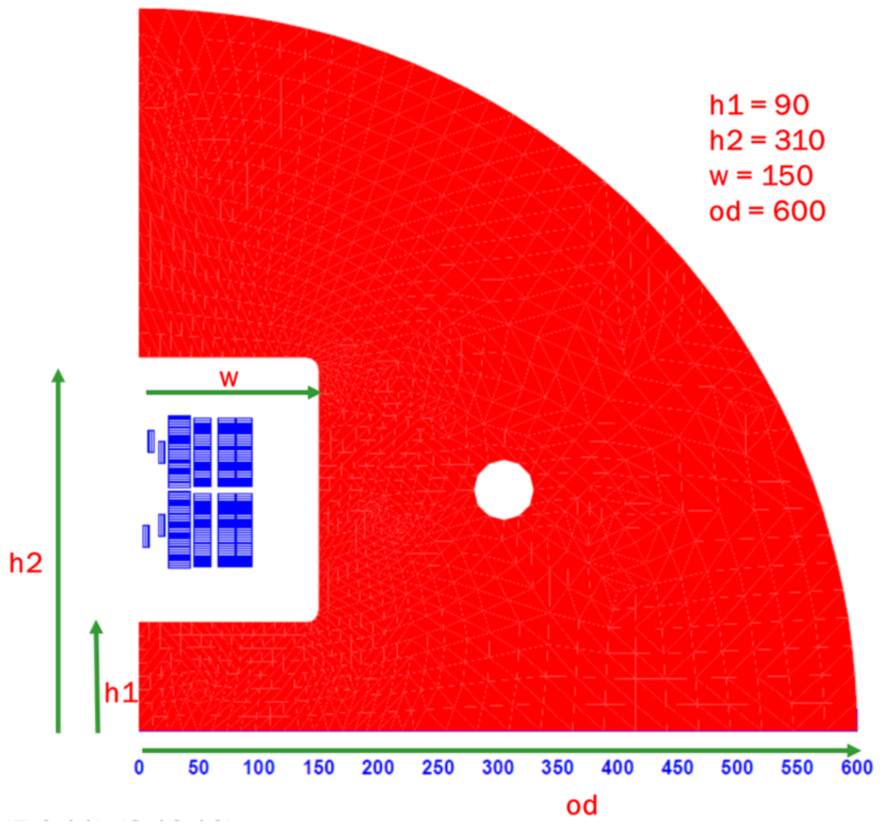


- Comparative studies of 20 T designs (as presented at MT) revealed that the common coil design uses significantly less conductor (including less HTS) than the other designs. This was a surprise initially; now understood and validated.
- Question: Is that still valid after a more detailed analysis? YES

Efficient Segmentation between HTS and LTS Coils; + Identical Nb_3Sn Coils



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



- Efficient segmentation between HTS and LTS coils; only HTS coil for the main coil (plus small pole coils)
- All Nb_3Sn coils can be made identical. Meaning only one set for winding, reaction and impregnation tooling with a simple racetrack coil geometry.
- Need less practice & spare coils; can sort/switch coils between layers. These two offer significant savings.
- Question: Is that still valid after a more detailed analysis? YES

Design Meets the Field Quality and Operating Margin Requirements

- Question: Is that still valid after a more detailed analysis? YES

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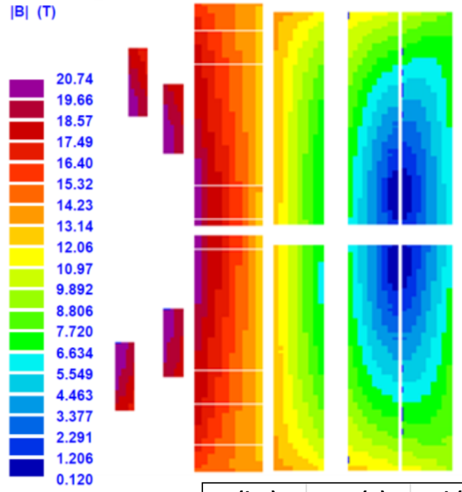
MAIN HARMONIC .....................................           1
REFERENCE RADIUS (mm) .............................     15.0000
X-POSITION OF THE HARMONIC COIL (mm) ..............      0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..............    200.0000
MEASUREMENT TYPE ......................... ALL 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
```

Geometric harmonics < 0.5 10^{-4}

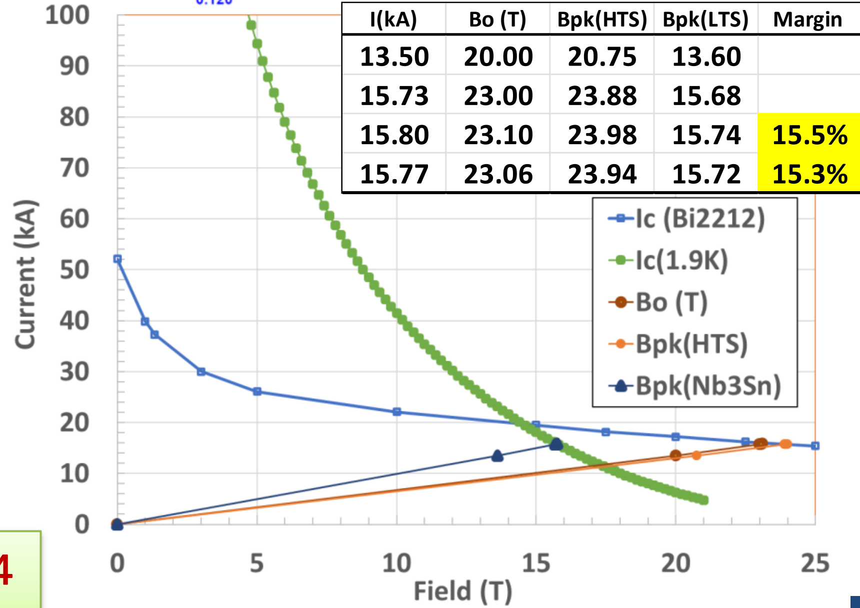


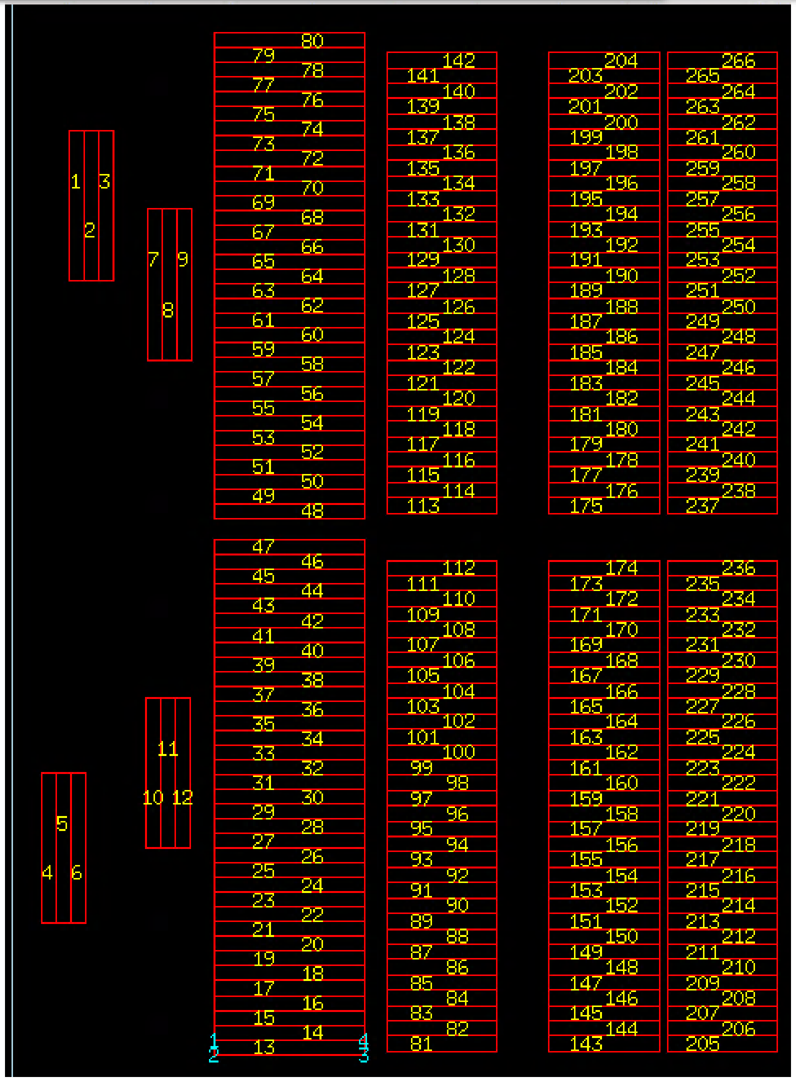
No. of Turns (½ bore)

- HTS: 80
- LTS: 186

Total: 266

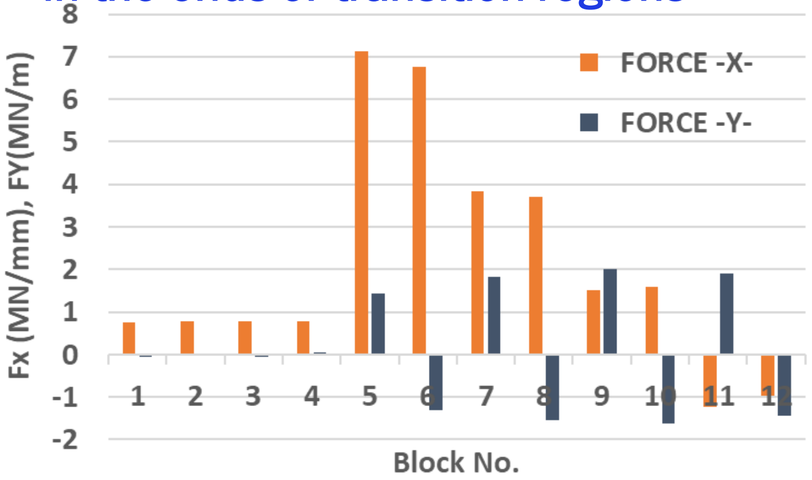
I(kA)	Bo (T)	Bpk(HTS)	Bpk(LTS)	Margin
13.50	20.00	20.75	13.60	
15.73	23.00	23.88	15.68	
15.80	23.10	23.98	15.74	15.5%
15.77	23.06	23.94	15.72	15.3%

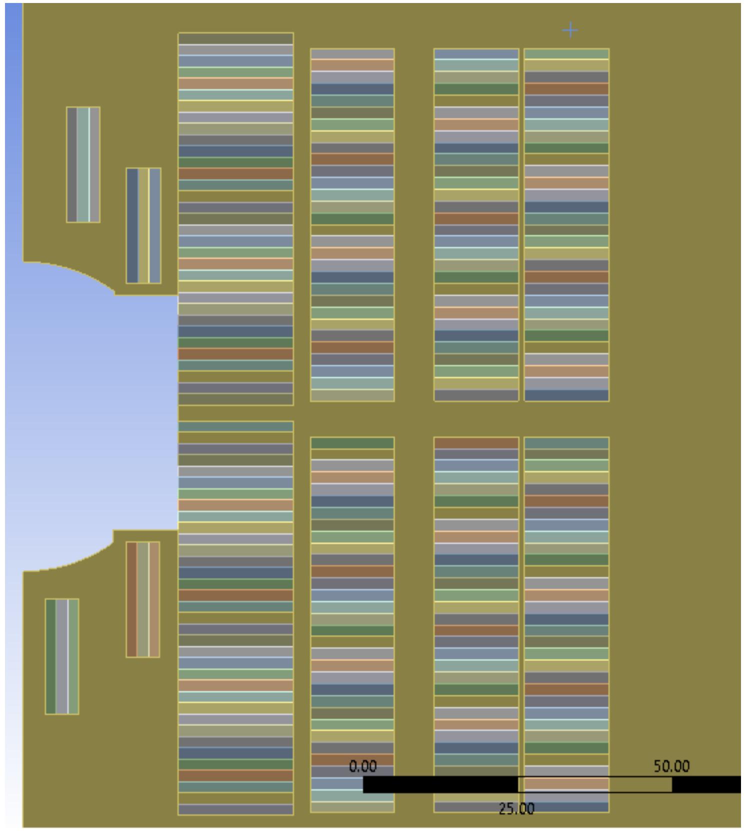


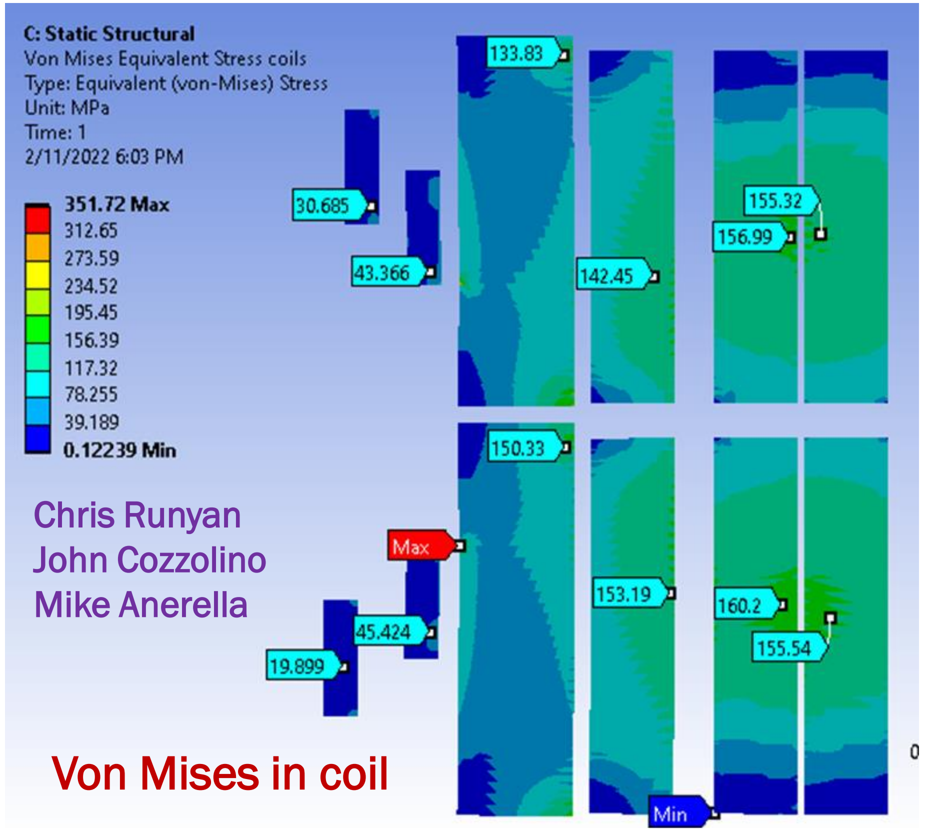


Initial Mechanical Analysis of the 20 T Hybrid Common Coil Design

- Horizontal forces much larger than vertical (vertical is 1/3 of horizontal)
- Large horizontal deflection can be tolerated since coils move as a unit - without causing much internal strain in the ends or transition regions



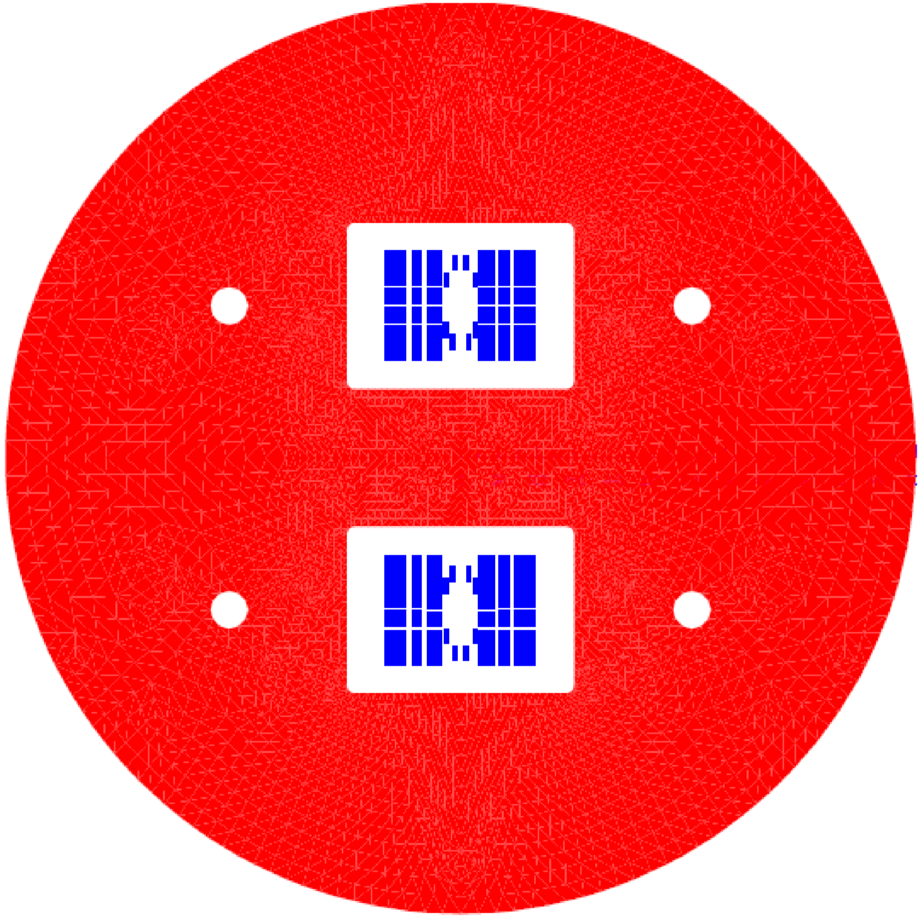


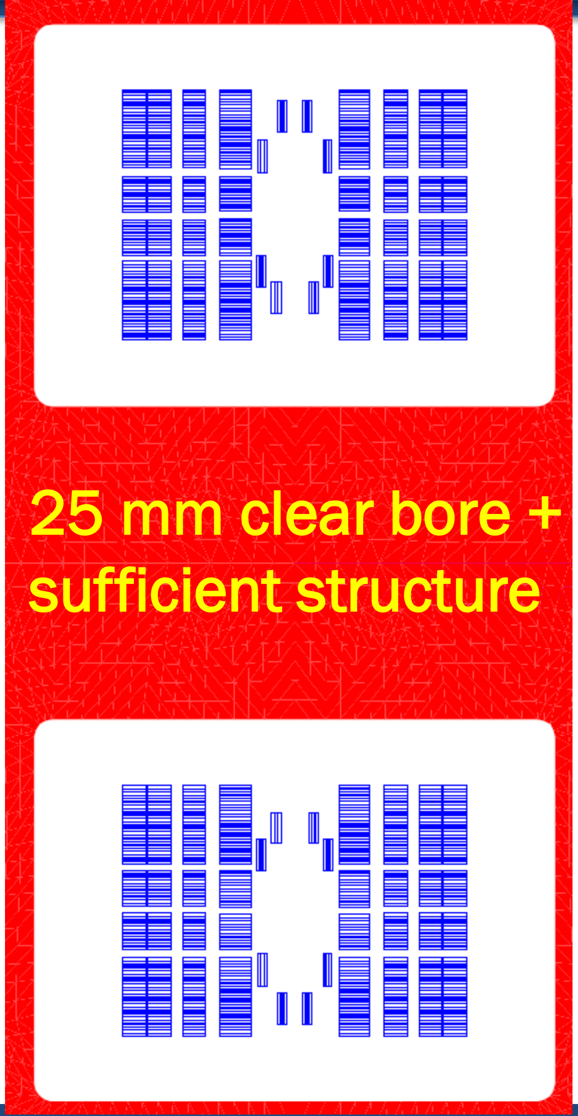


Different models showed that the stresses in coils can be kept below the maximum specified. However, it was not demonstrated in the same geometry and not exactly the geometry that was used in the magnetic design.

- Now we are using the same geometry for all analysis to find a self-consistent solution. Good progress.

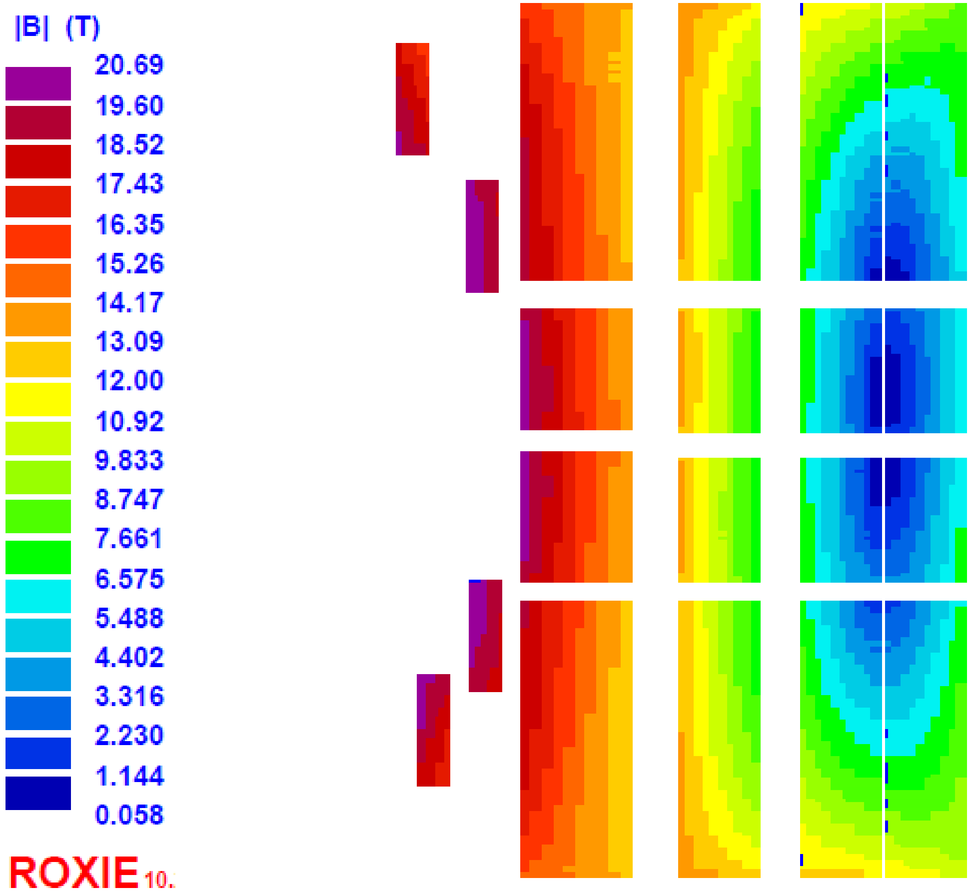
New 20 T HTS/LTS Hybrid Design (May 2022) (spacers in magnetic design takes input from mechanical)





25 mm clear bore + sufficient structure

Low Peak Field Enhancement (<3.5%) means more margin



Magnetic Design (May 2022) with 15% Margin

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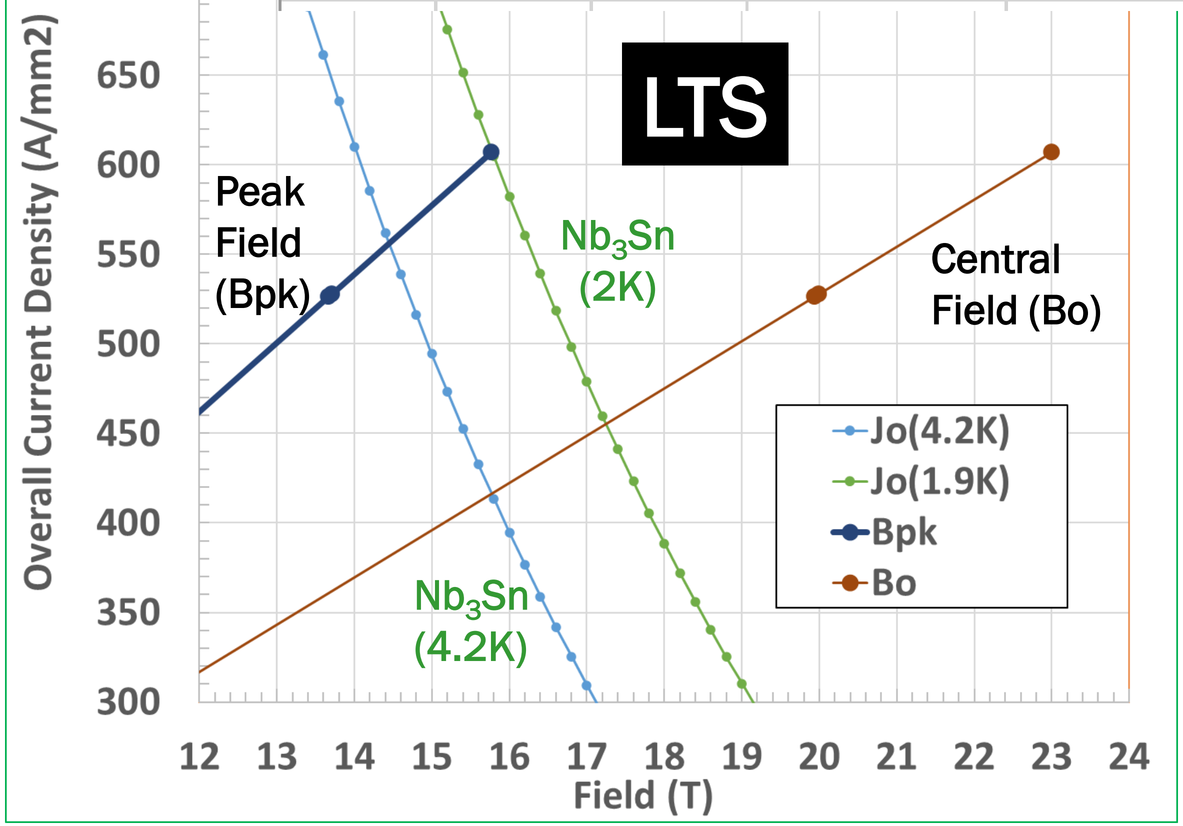
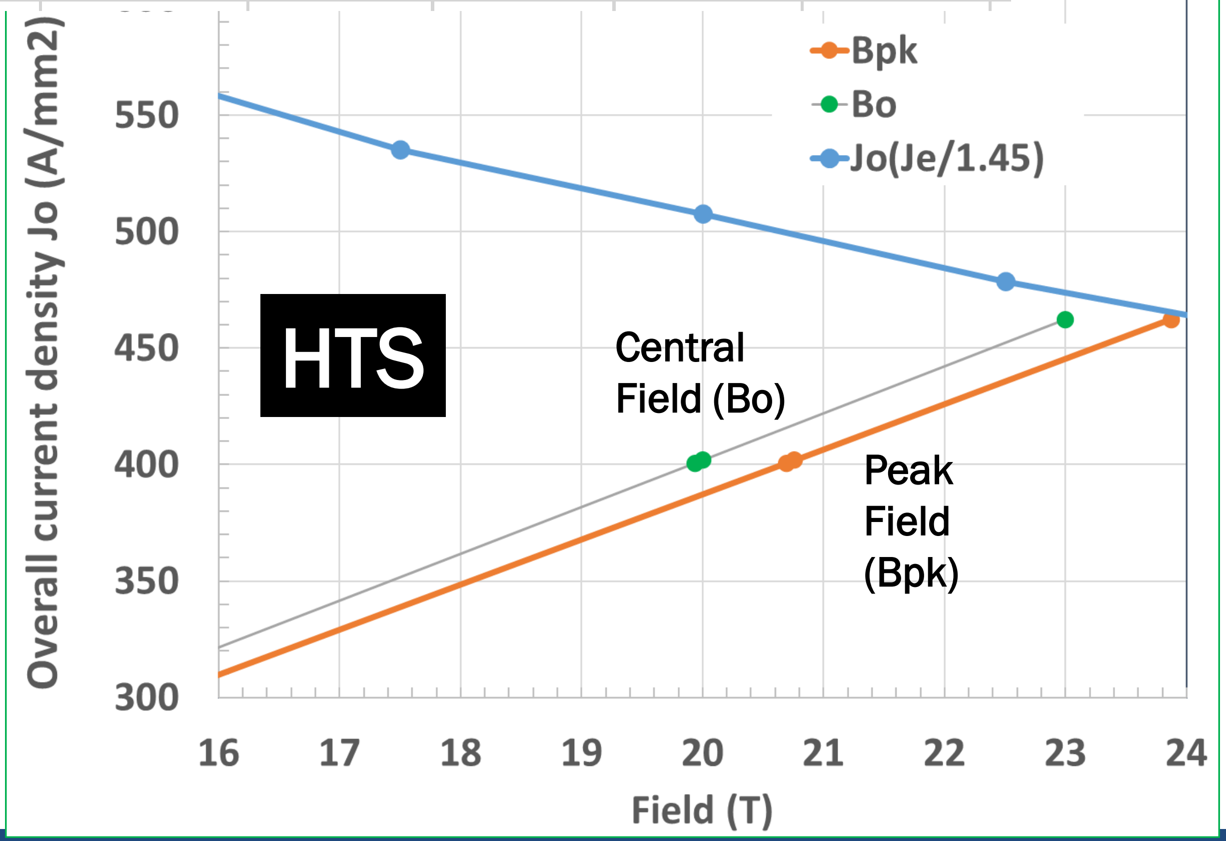
	I(HTS), A	I(Nb3Sn)	Je(HTS), A/mm^2	Jo(HTS), A/mm^2	Je(Nb3Sn)	Jo(Nb3Sn)	Bo (T)	Bpk(HTS), T	Bpk(Nb3Sn)
	0	0	0	0	0	0	0	0	0
	13600	13600	487.60	400.672	639.10	526.316	19.938	20.695	13.670
1.0031	13642.2	13642.2	489.107	401.914	641.079	527.947	20.000	20.759	13.712
1.15355	15688.3	15688.3	562.465	462.195	737.231	607.132	23.000	23.873	15.769





Magnetic Design (May 2022) Good Field Quality

MODEL	mdp_may2022-v2
BI2212R	Bi2212
Bare w	1.52
Bare h	18.35
Insulation	0.15
Ins w	1.82
Ins h	18.65
Ins Area	33.943
Current	13600
Je (A/mm^2)	487.60
Jo (A/mm^2)	400.67
Bpeak (T)	20.6951
MDPH2	Nb_3Sn
Bare w	1.6
Bare h	13.3
Insulation	0.15
Ins w	1.9
Ins h	13.6
Ins Area	25.840
Current	13600
Je (A/mm^2)	639.10
Jo (A/mm^2)	526.32
Bpeak (T)	13.6701
Bo	19.9382

```
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000   b 2:     -0.00000   b 3:      0.05059
b 4:     -0.00000   b 5:      0.09440   b 6:      0.00000
b 7:     -0.78244   b 8:      0.00000   b 9:     -0.92602
b10:      0.00000   b11:     -0.18313   b12:     -0.00000
b13:     -0.02800   b14:      0.00000   b15:     -0.01273
b16:      0.00000   b17:     -0.00410   b18:     -0.00000
b19:     -0.00094   b20:      0.00000

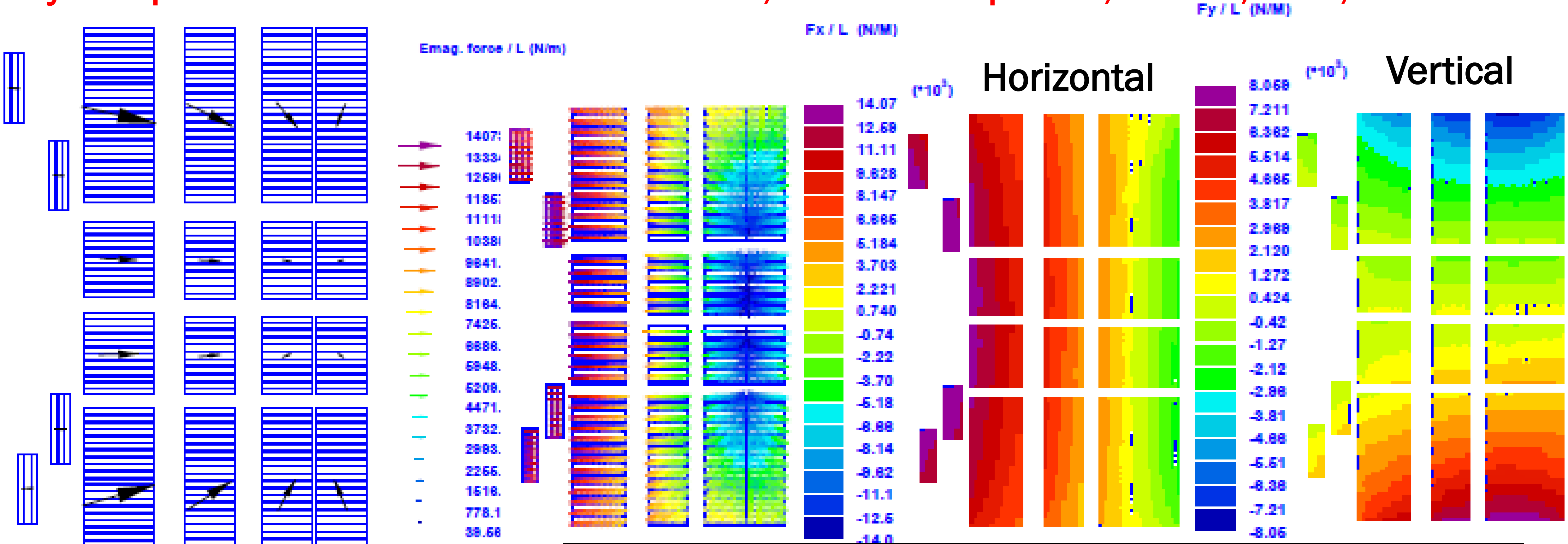
SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000   a 2:     -0.00405   a 3:      0.00000
a 4:     -0.02333   a 5:     -0.00000   a 6:     -0.15914
a 7:      0.00000   a 8:      0.20675   a 9:      0.00000
a10:      0.08678   a11:     -0.00000   a12:      0.00779
a13:      0.00000   a14:      0.00593   a15:     -0.00000
a16:      0.00258   a17:      0.00000   a18:      0.00056
a19:     -0.00000   a20:      0.00019   a
```

All harmonics <1 unit

Strategy Behind the Mechanical Structure (take advantage of the force distribution)

New Design: Forces @20 T (Mostly horizontal, particularly on HTS coils)

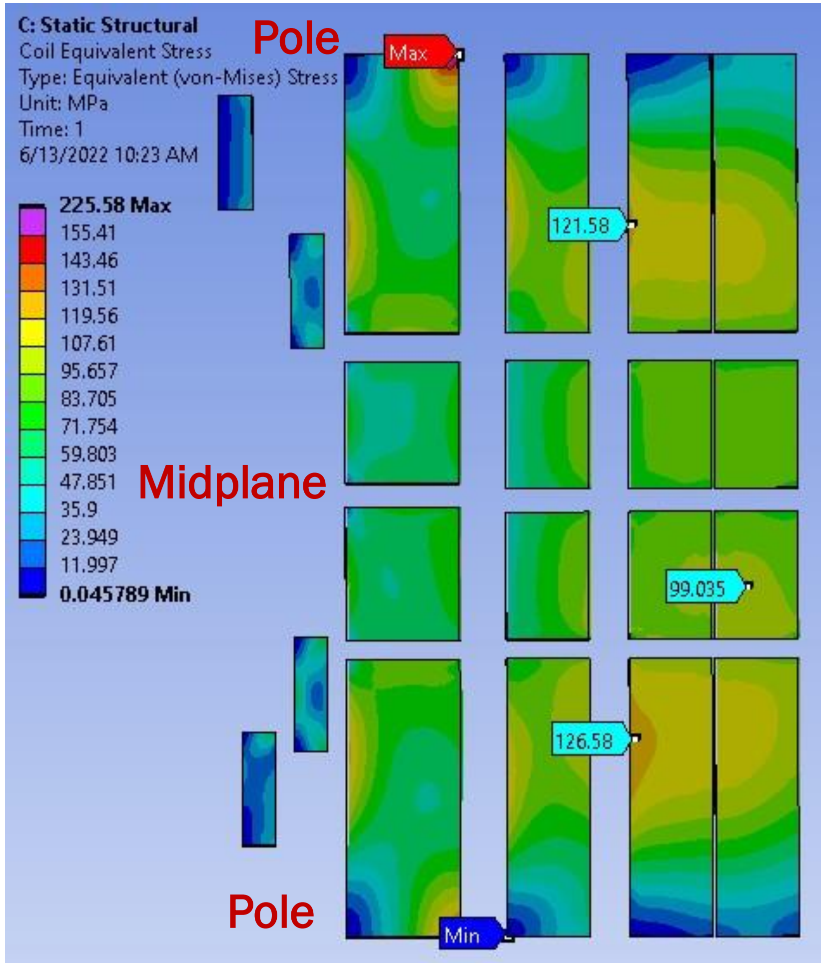
Key Components of Structure: Vertical Plates, Horizontal Spacers, Collars, Yoke, Shell + ???



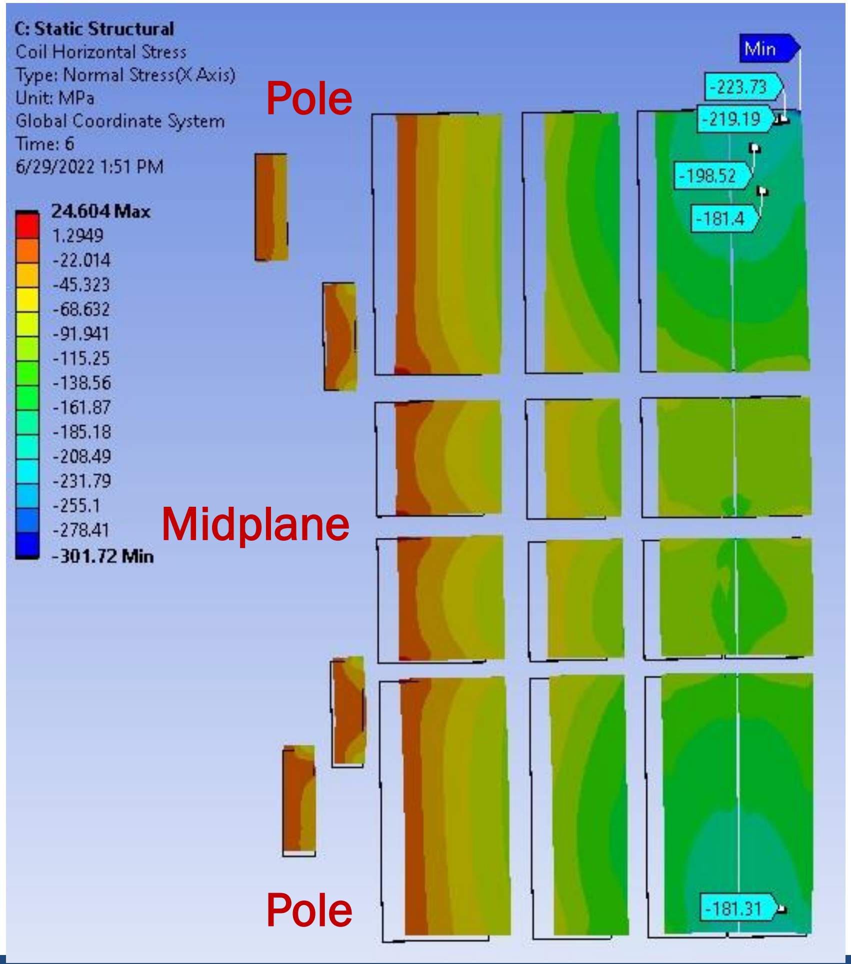
Advantage Common Coil: Forces can be easily managed

Developing Mechanical Structure

Original Case
(vertical spacers bonded to the collar)



SST vertical separators are allowed
to slide relative to the collar



- Stresses and Strain are within acceptable limits at most places See John Cozzolino's presentation
- However, at pole the exceed the limit either in HTS or in LTS, depending on the contact (bonded or sliding)
- Attempt to make things better increased the local peak
- This is because of the bending of the coil layer. The two cases show that it can be balanced out
- Next slide for some possibilities

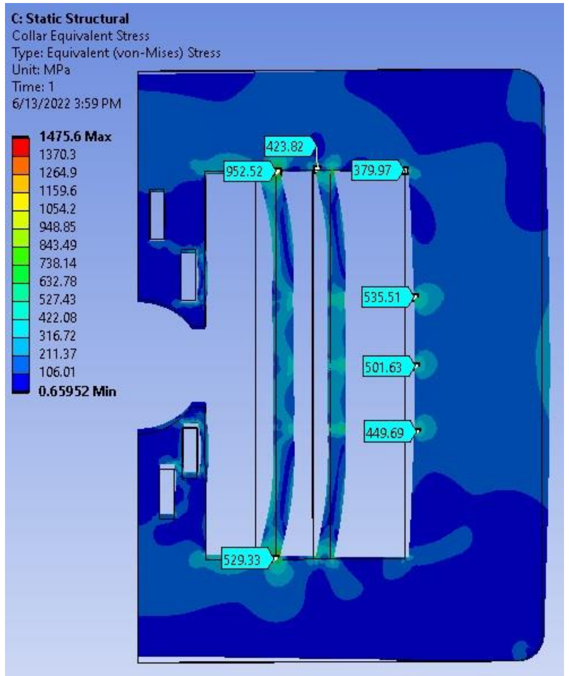
Balancing the stresses
HTS Vs LTS & Midplane Vs Pole

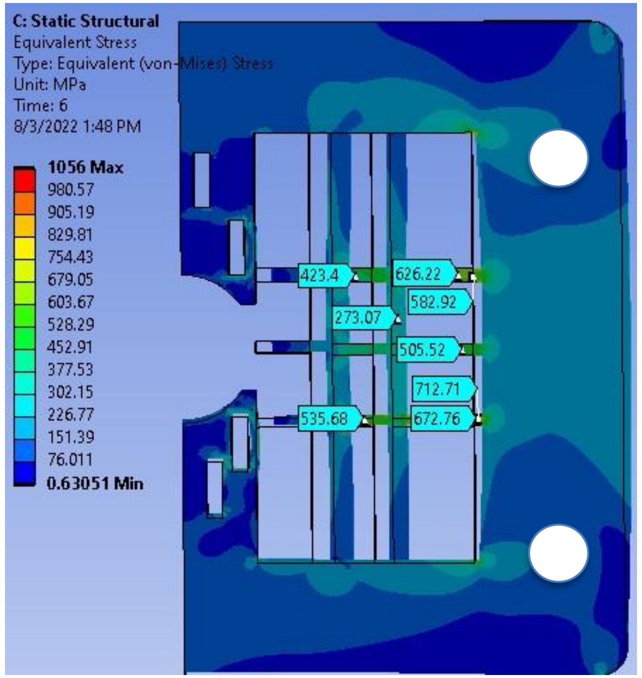
Concept to reduce the bending stress at the top and bottom of the coils:

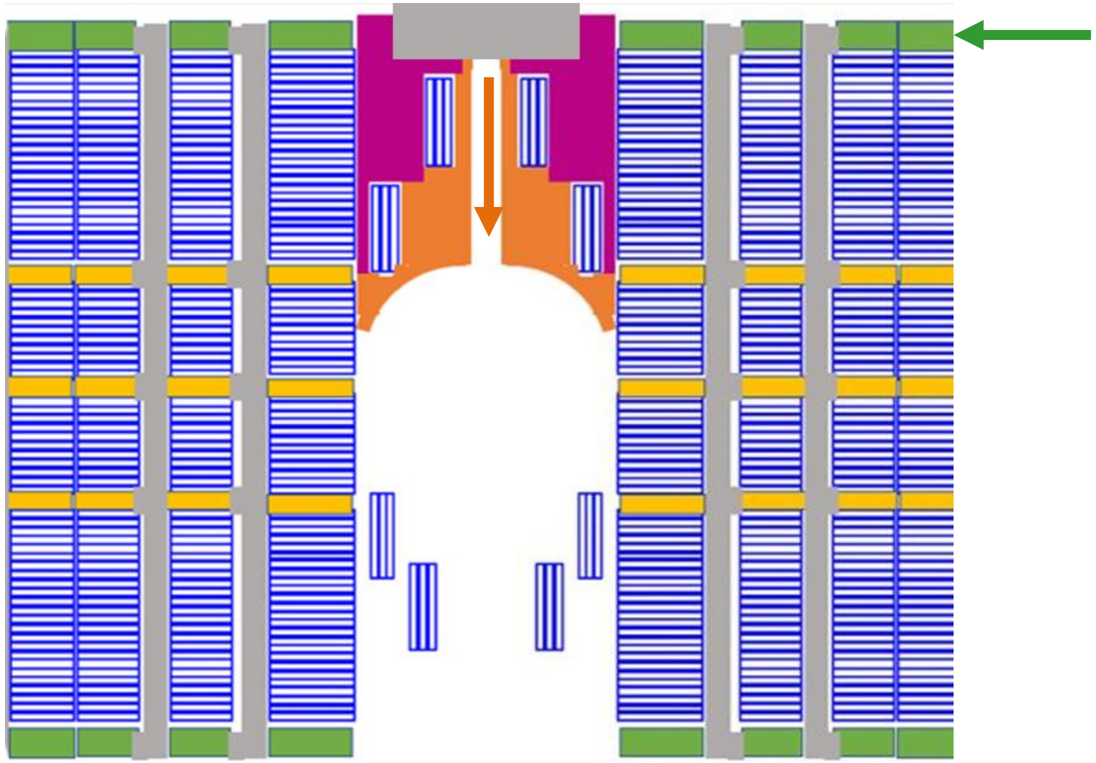
(a) Weaken collars near the pole region to allow more deflection at the top and bottom

(b) Use spring or softer material or gaps to allow some limited deflection to transfer the stress

Holes in the collar to control deflection (to make them uniform), like the holes in the iron to control saturation







Softer material Or Gap Or Spring

Next Step

Tasks after completing the iterations of the mechanical structure:

- **Perform quench protection analysis.**
- **Develop concepts for assembling the magnet.**
- **Perform 3-d magnetic and 3-d 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 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.**
- **As a part of "comparative" task force, compare the complete package with other designs (including unique advantages and disadvantages)**

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

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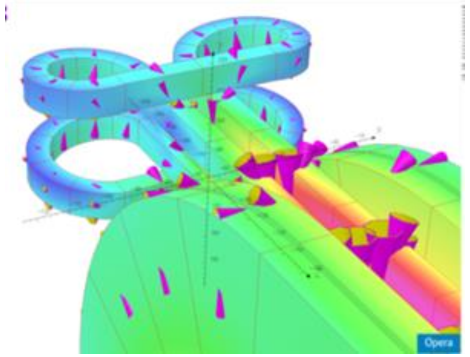
- Although several common coil designs have been designed with a variety of conductor (NbTi, Nb_3Sn, Bi2212, Bi2223, ReBCO), all have been made with the main coil only
- The most efficient design to obtain good field is the one with the pole coils
- We need to demonstrate a proof-of-principle design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

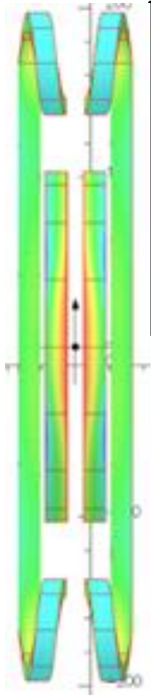
➢ Pole coils can be built, integrated and tested with the main coils in the BNL common coil dipole DCC017. Attempt to do that demo took off three times with SBIR Phase I (see next slide). However, none could be carried out as no Phase II was funded despite the productive work in Phase I.

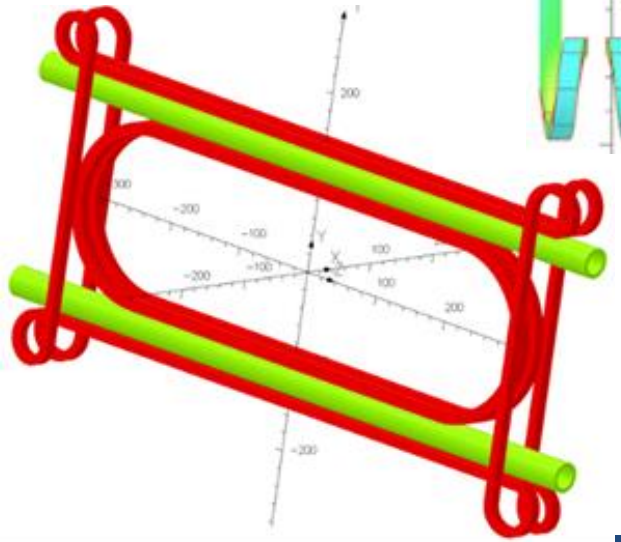
➢ Proof-of-principle demo of the pole coils should be a priority for MDP. It can be done in a short period at a low cost for insert coil made anywhere

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

Overpass/underpass (cloverleaf) design

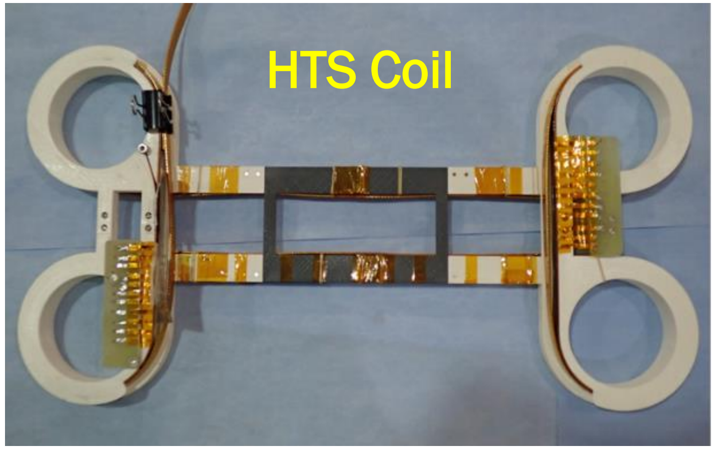


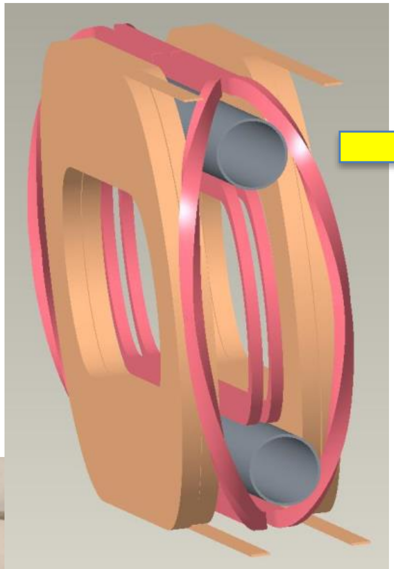




- Practice pole coil windings and preliminary designs performed under “three” Phase I SBIR/STTR.
- A part of MDP can be a Proof-of-Principle demo of an accelerator type common coil dipole at 10+ T

CERN is also working on this design





Insert coils pole coils will be wound & tested with DCC017

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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.