U.S. MAGNET DEVELOPMENT PROGRAM

20 T Bi2212/Nb_3Sn Hybrid Common Coil Design with 15% Margin

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November 2, 2021

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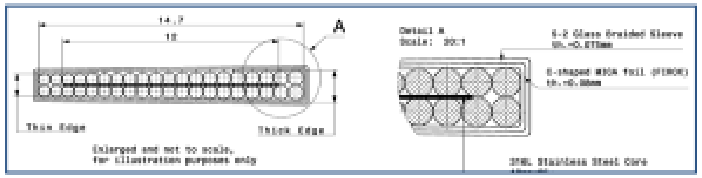
20 T HTS/LTS Hybrid Common Coil Design

- New hybrid designs for Bi2212 in series with Nb_3Sn having 15%
- All design use the Nb_3Sn and Bi2212 Performance as of 9/29/2021
- All designs are optimized for a good field quality
- Configurations for 4 to 6 layers of main coil (+pole coil)
- Space included for an intermediate mechanical structure for stress management (next step - optimize with proper analysis)

Performance Assumptions of Nb_3Sn & Bi2212

Design criteria for a 20 T hybrid magnet
Reference J_o

- **Nb_3Sn:** $J_0 = 900$ A/mm² (12 T, 4.2 K)
  - Assuming $J_e = 1350$ A/mm² (12 T, 4.2 K) and 0.67 ratio
- **Bi2212:** $J_o = 500$ A/mm² (20 T)
  - Assuming $J_e = 740$ A/mm² (20 T) and 0.67 ratio
  - Based on RC5/6 J_e
- **REBCO:** $J_o = 430\text{-}540$ A/mm² (20 T)
  - Assuming $J_e = 800$ A/mm² (20 T) and 0.54-0.67 ratio
    - Depending of cable design: CORC/STAR wire in groove or multi-strand cable with CORC/STAR wires
- So, in conclusions, a $J_e = 740$ A/mm² and a $J_o = 500$ A/mm² at 20 T seems a reasonable assumption for both Bi2212 and REBCO CORC/STAR



Nb_3Sn

T [K]	4.2			Ref Jo(12T,4K), A/mm2	900
t [/]	**0.2625**			Scaling Factor	0.6673
Bc2 [T]	25.87188				
C	182715.3				
Bp	b	Jc	Jc 5% degr.	Je 5% deg., 1.1 Cu/non-Cu	Jo(4.2K)
[T]		A/mm2	A/mm2	A/mm2	A/mm2
12.0	0.46382	2981.158	2832.0998	1348.618959	900.00

Nb_3Sn

Bi2212

			Je/Jo=1.45
B [T]	**I at 100% SSL**	**Je**	J0
20	370	736	508

Bi2212

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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

September 2021 Design with New Jo

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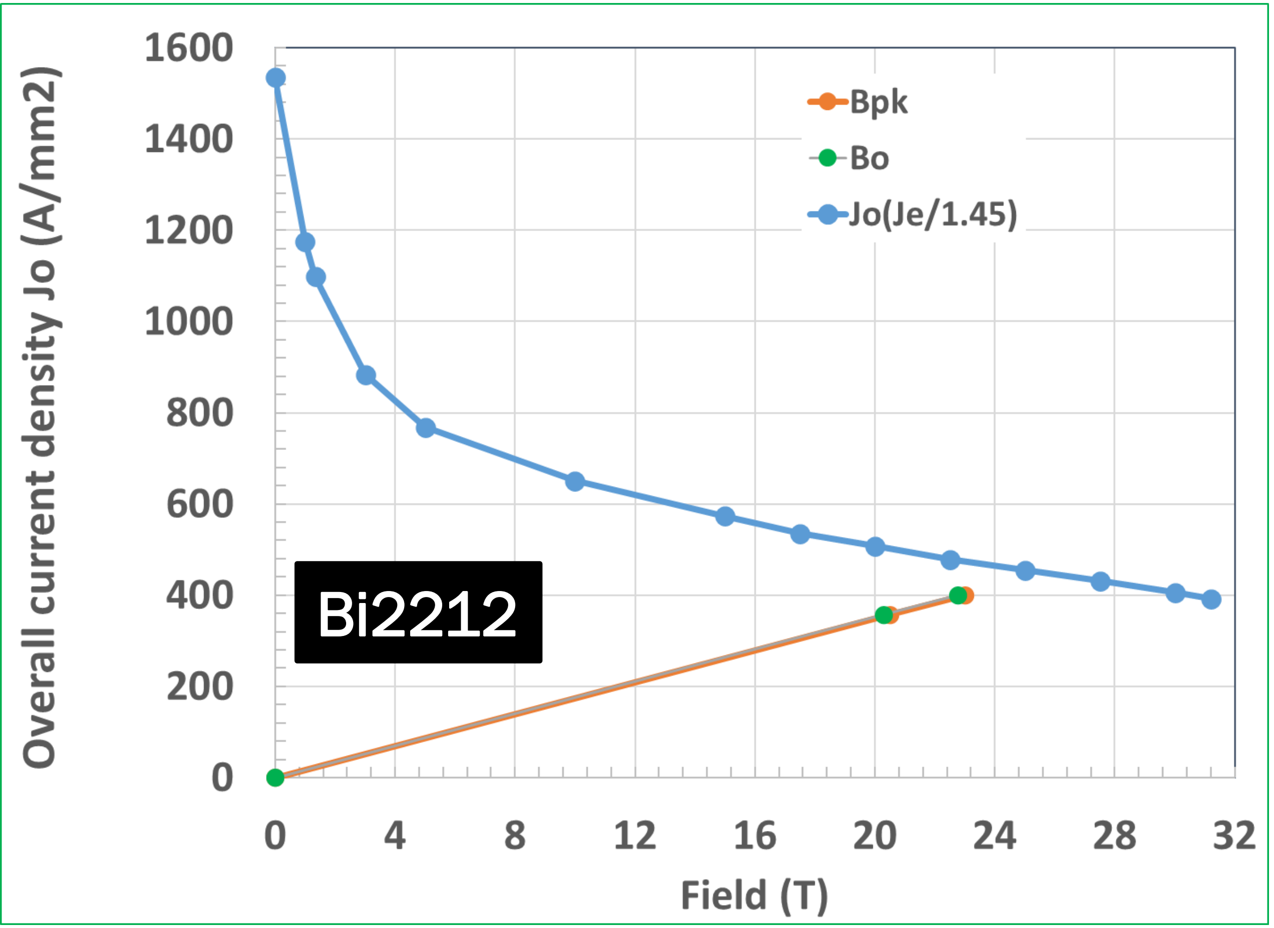
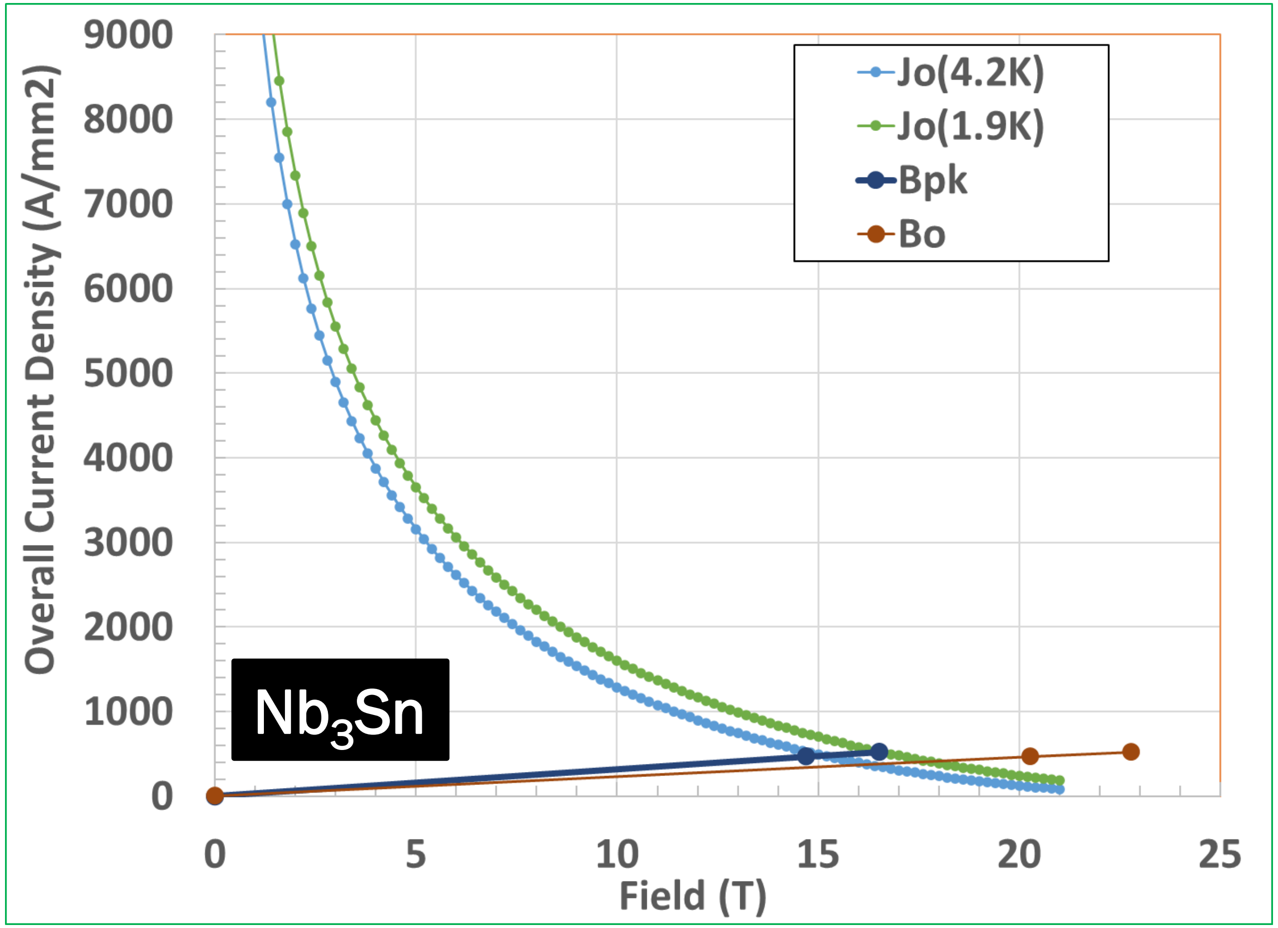
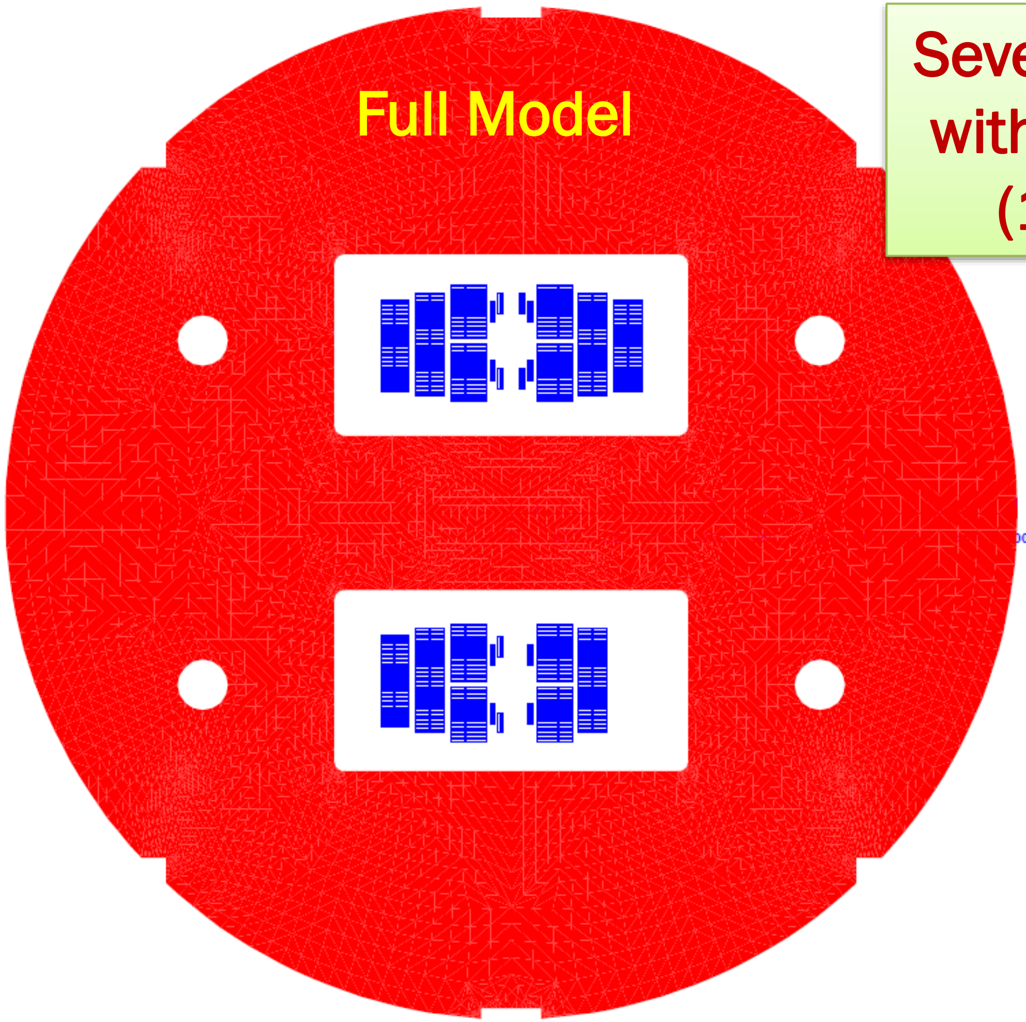
Mismatched Margins (new designs have matched margins – 15% over 20 T)





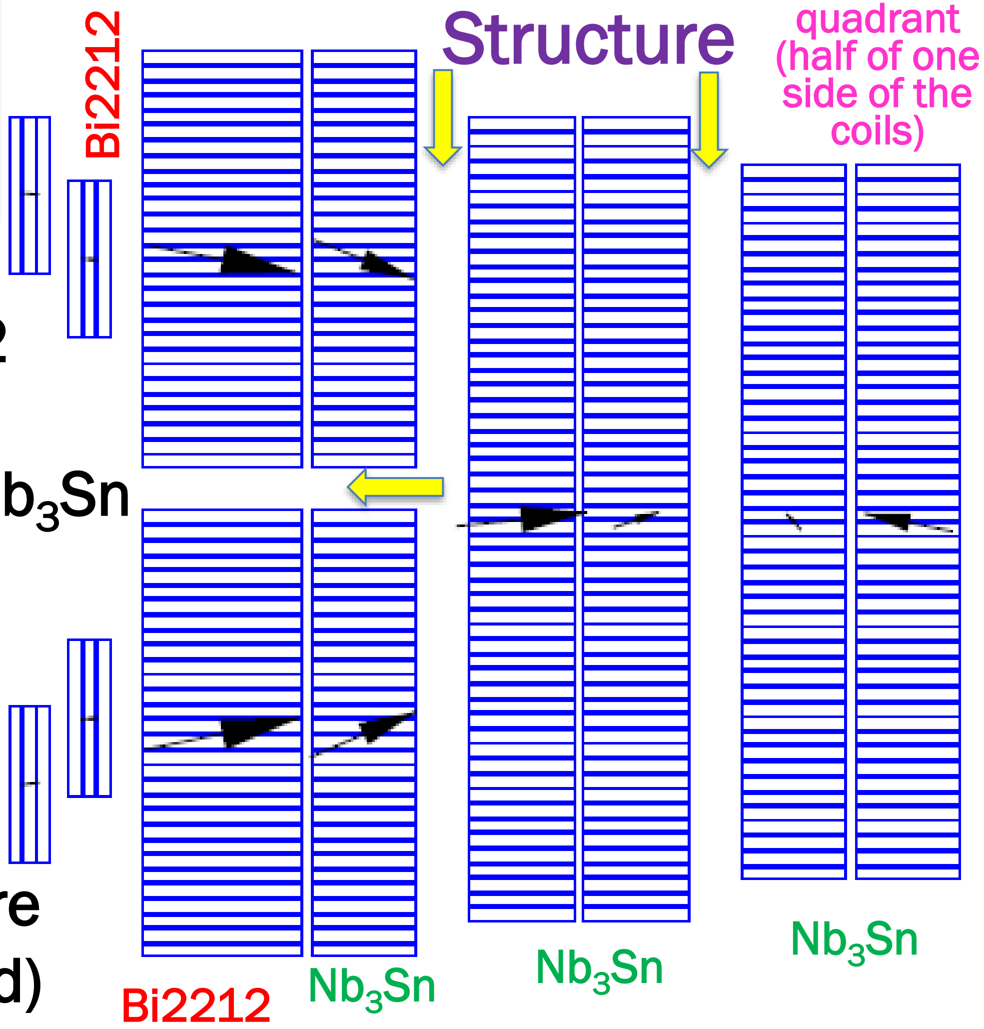
50 mm, 20 T Bi2212/Nb_3Sn Common Coil



Several configurations with matched margin (15%) examined

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

- Space for structure (size to be iterated)



Configurations Examined for Nb_3Sn/Bi2212 Hybrids

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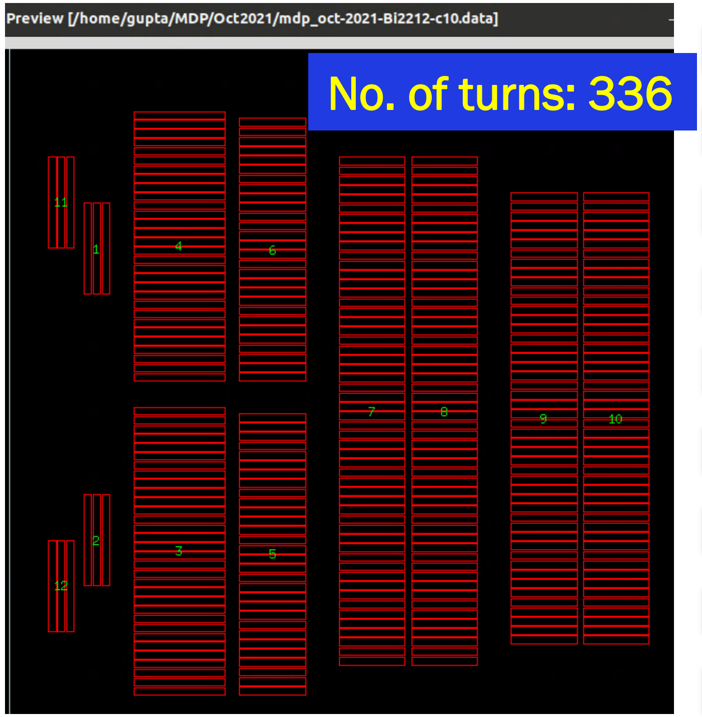
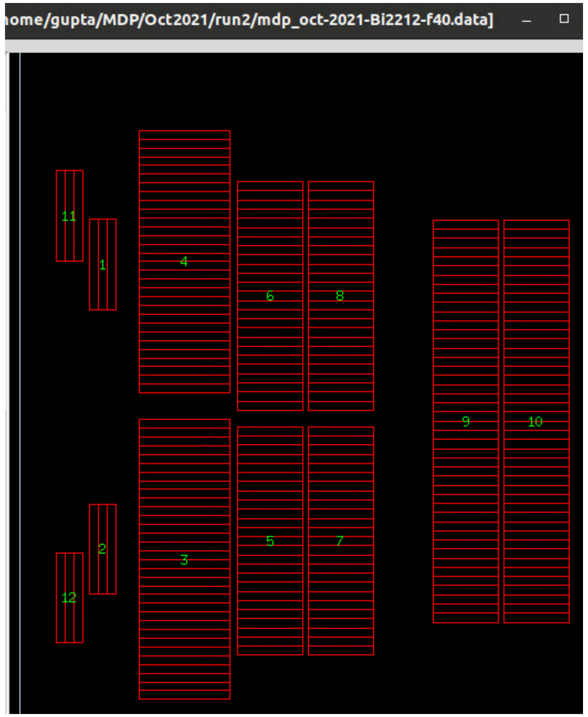
New configurations (October 2021) with matched margins
(Number of turns gets reduced, in some cases number of layers as well)

Configuration of September 2021
(mismatched margins with new J_0)

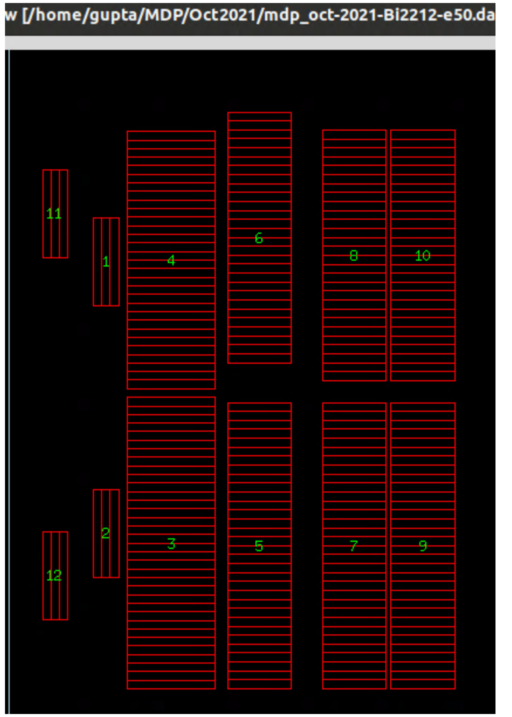


One layer of Bi2212
+Five layers of Nb_3Sn

One layer of Bi2212
+Five layers of Nb_3Sn



One layer of Bi2212
+Four layers of Nb_3Sn



One layer of Bi2212
+Three layers of Nb_3Sn

- All configurations have 1 layer of Bi2212 main coils and 6 turns of Bi2212 in pole coils

Configurations Examined for Nb_3Sn/Bi2212 Hybrids

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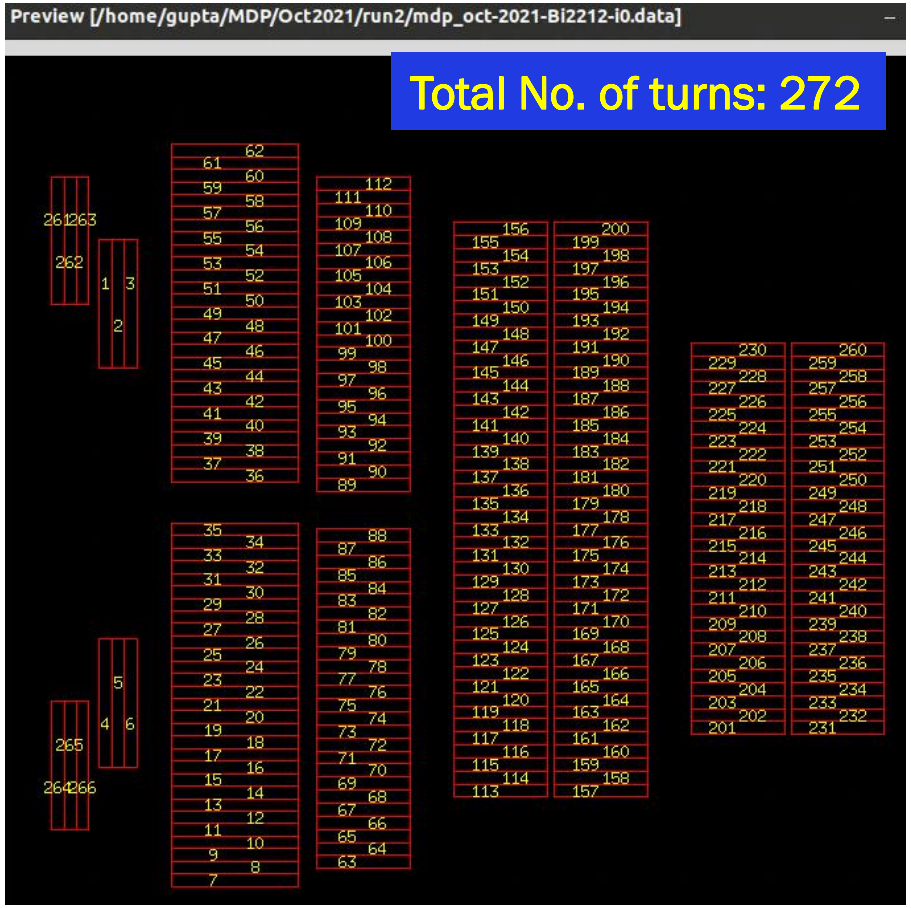
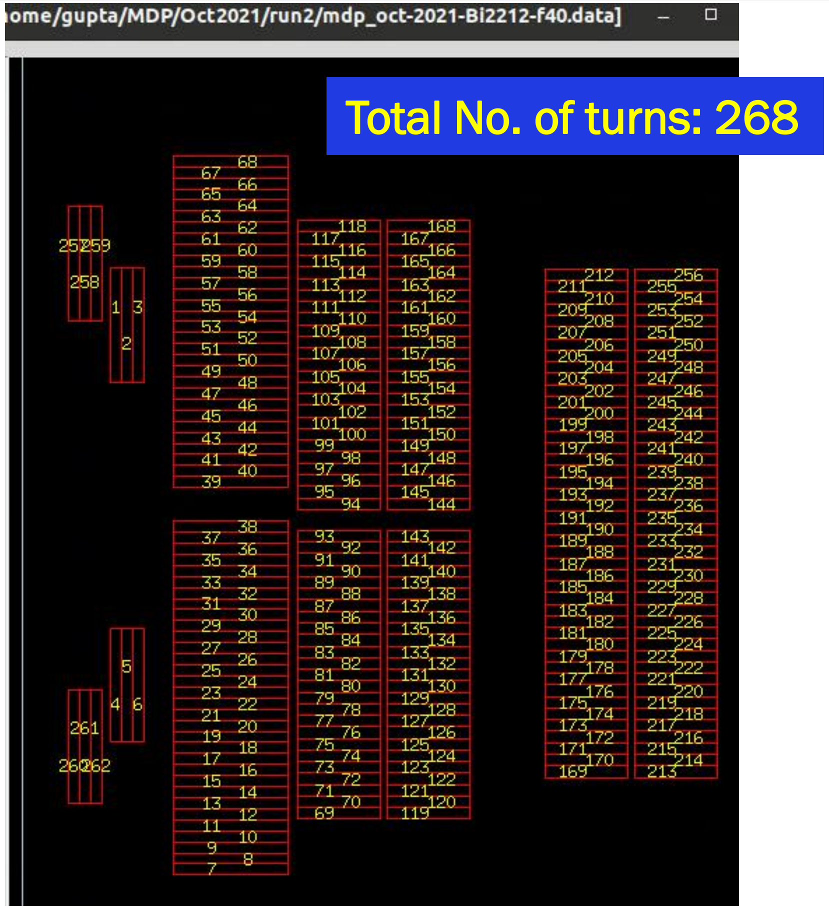
New configurations (October 2021) with matched margins

(Total number of turns gets reduced from 336, see also number of layers too)



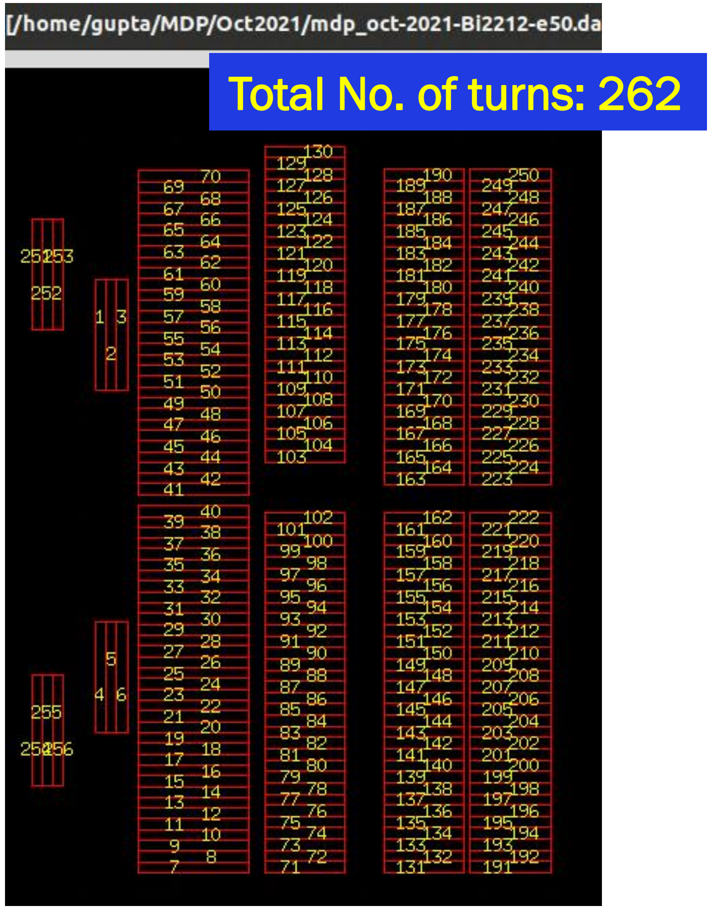
No. of turns of Bi2212 per aperture = 74

No. of turns of Nb_3Sn in 5 layers = 198



# of turns of Bi2212 per aperture = 80

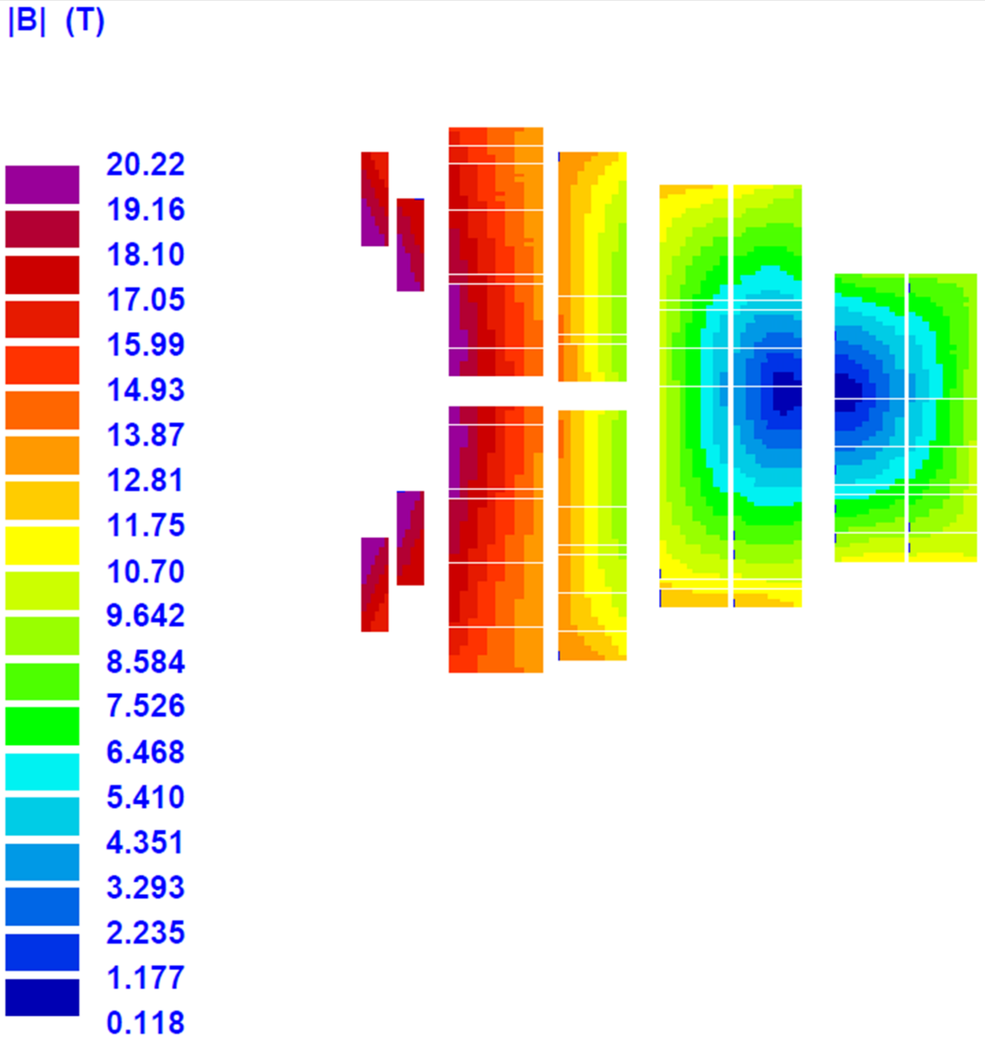
# of turns of Nb_3Sn in 4 layers = 188



# of turns of Bi2212 per aperture = 82

# of turns of Nb_3Sn in 3 layers = 180

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



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	

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

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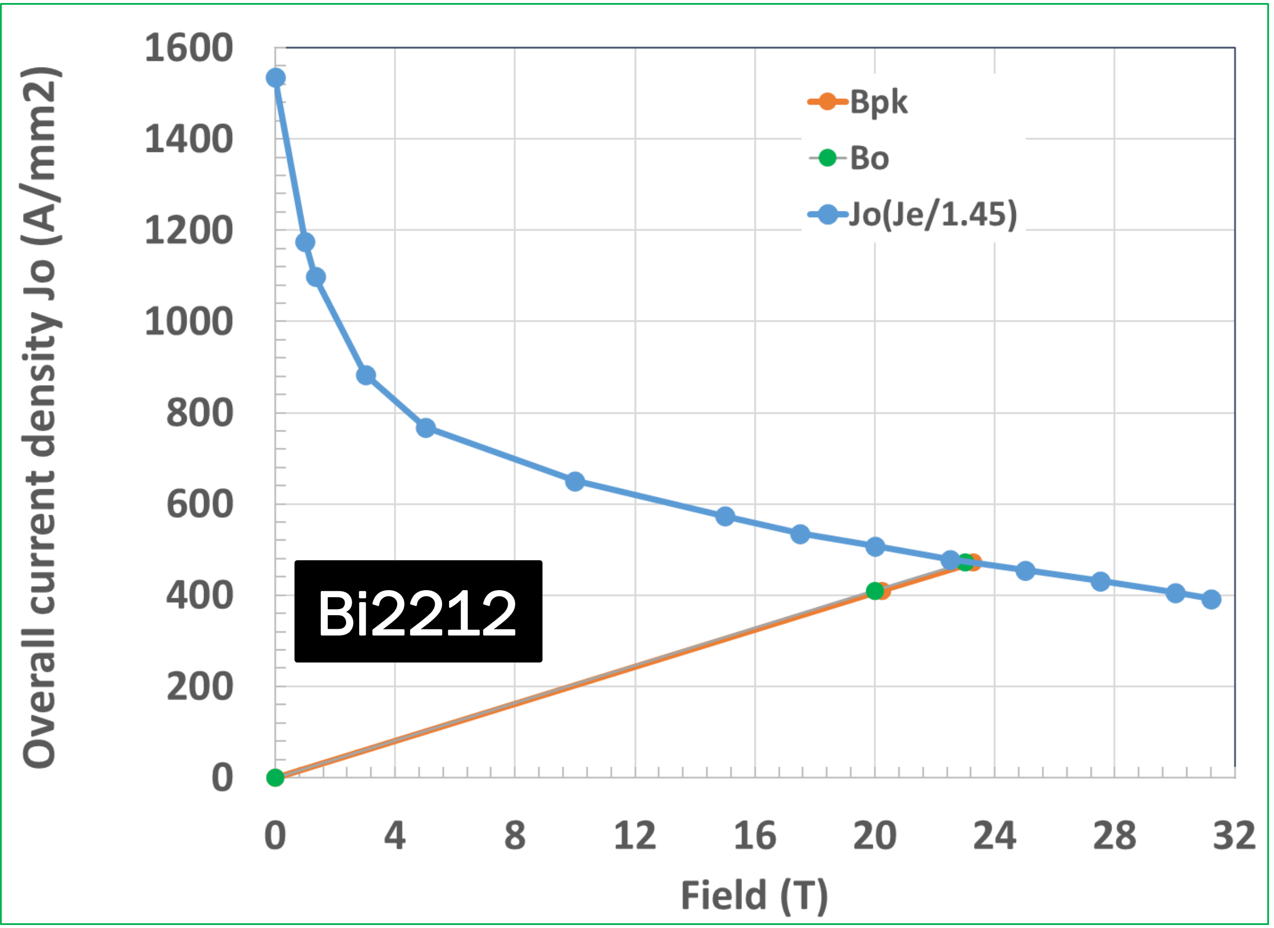
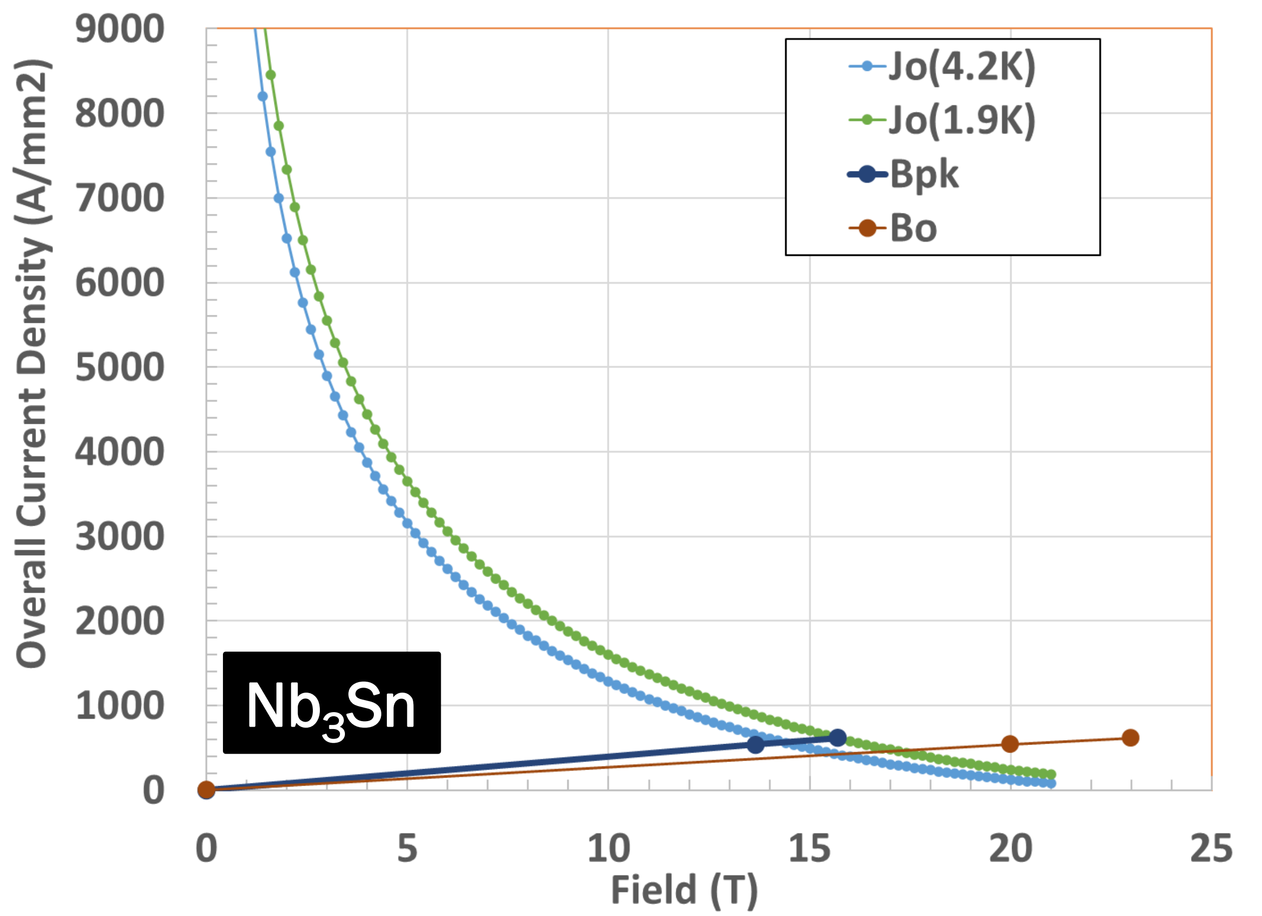
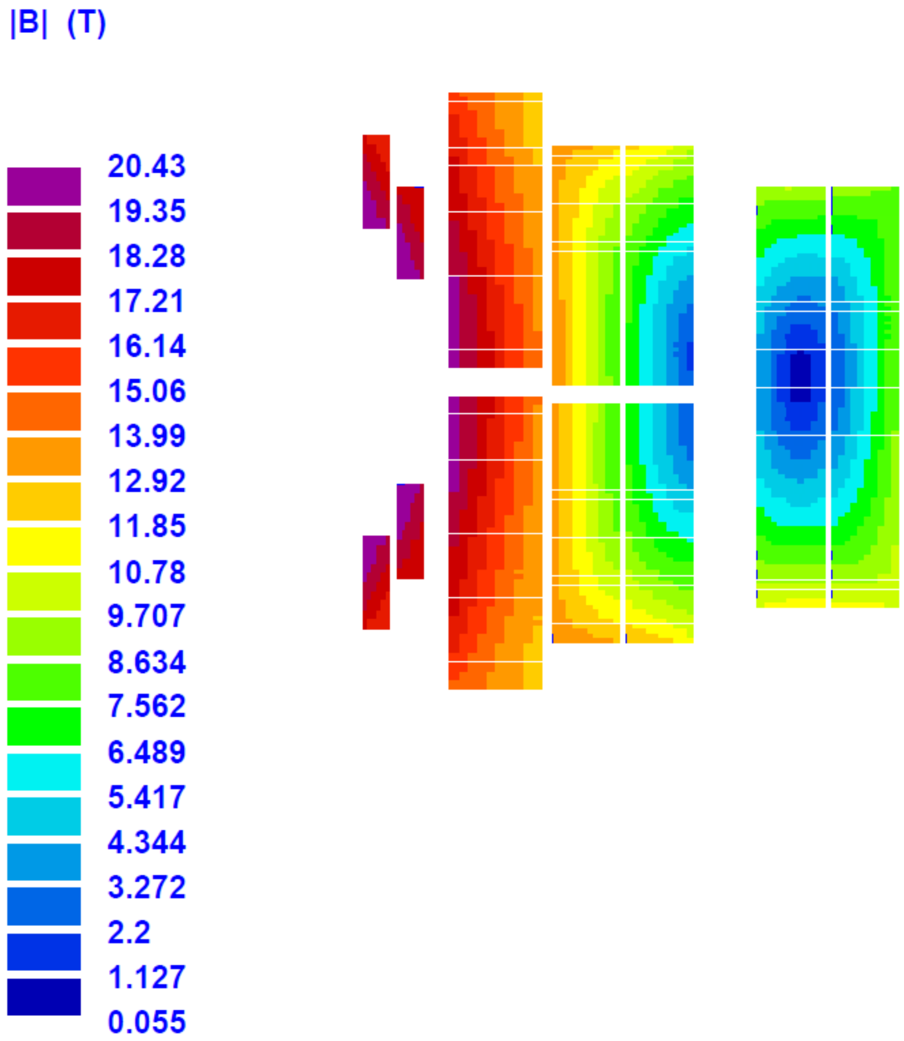
New designs have matched margins – 15% over 20 T – in both Bi2212 and Nb_3Sn coils for the reference J_o





October 2021 Design #2 (5 layers in main coil)



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

```
MAIN FIELD (T) .....................................   20.171752
MAGNET STRENGTH (T/(m^(n-1)) .......................     20.1718

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
```

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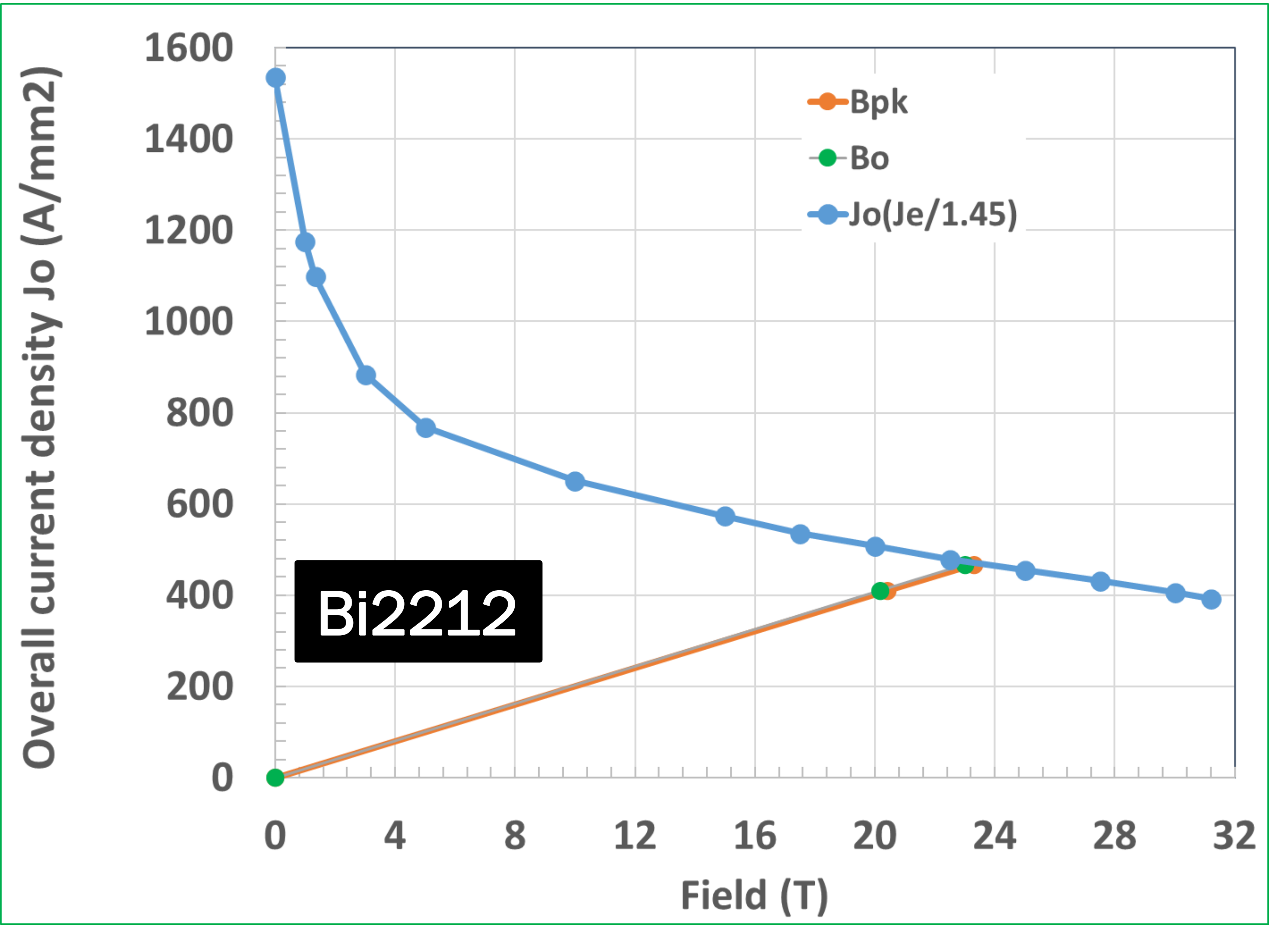
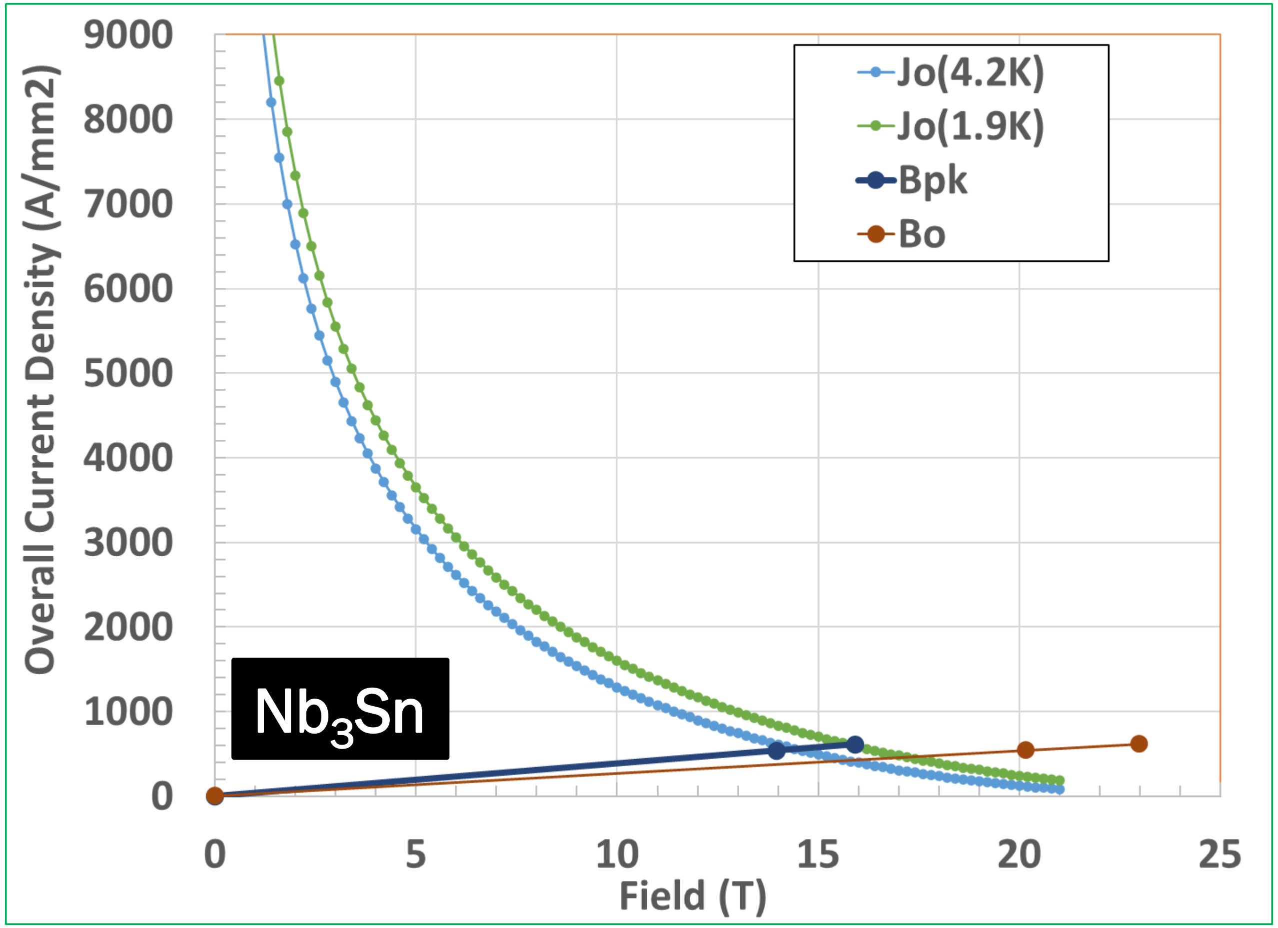
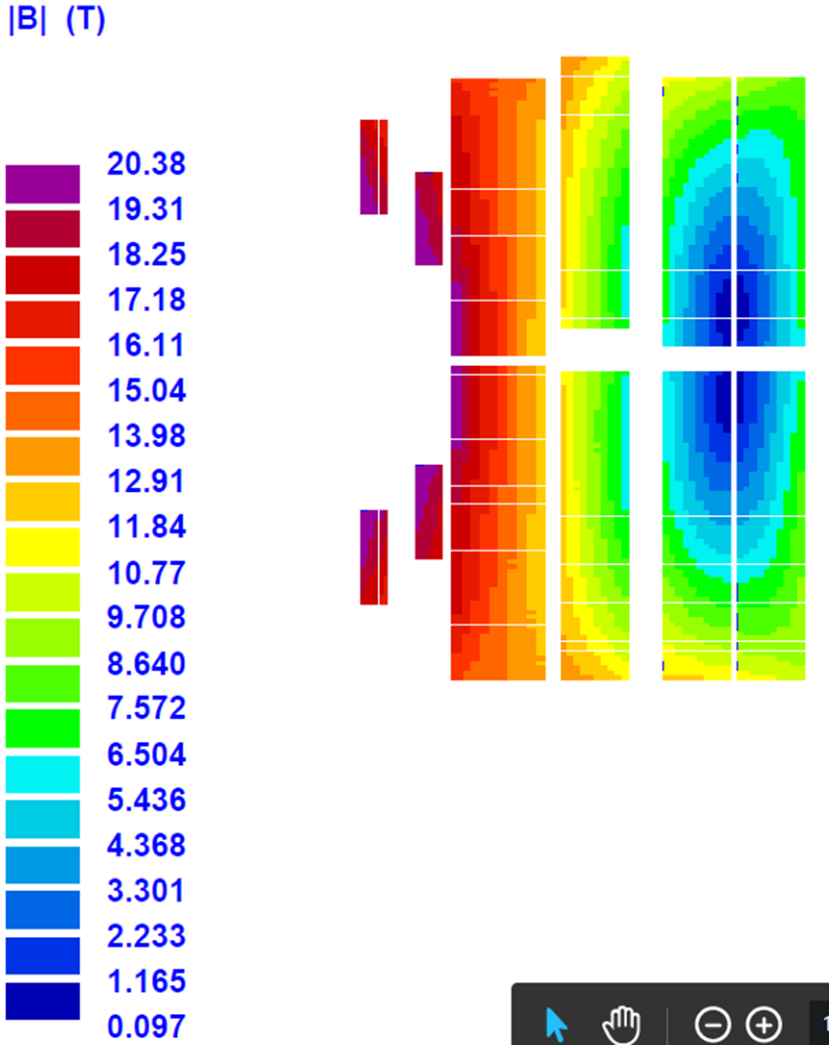
October 2021 Design #1 (margins for 5 layers in main coil)

New designs have matched margins – 15% over 20 T – in both Bi2212 and Nb_3Sn coils for the reference J_o





October 2021 Design #3 (4 layers in main coil)



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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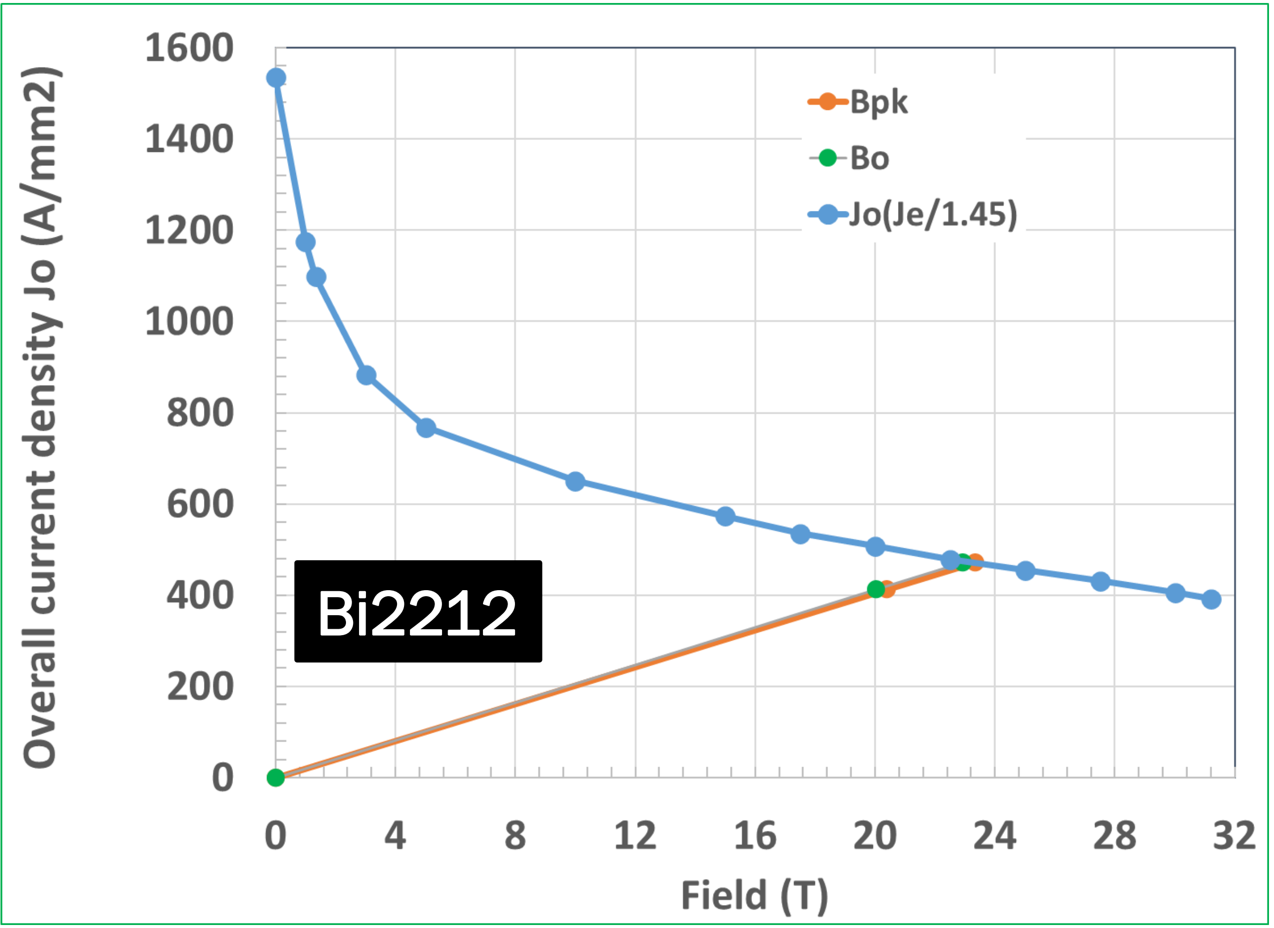
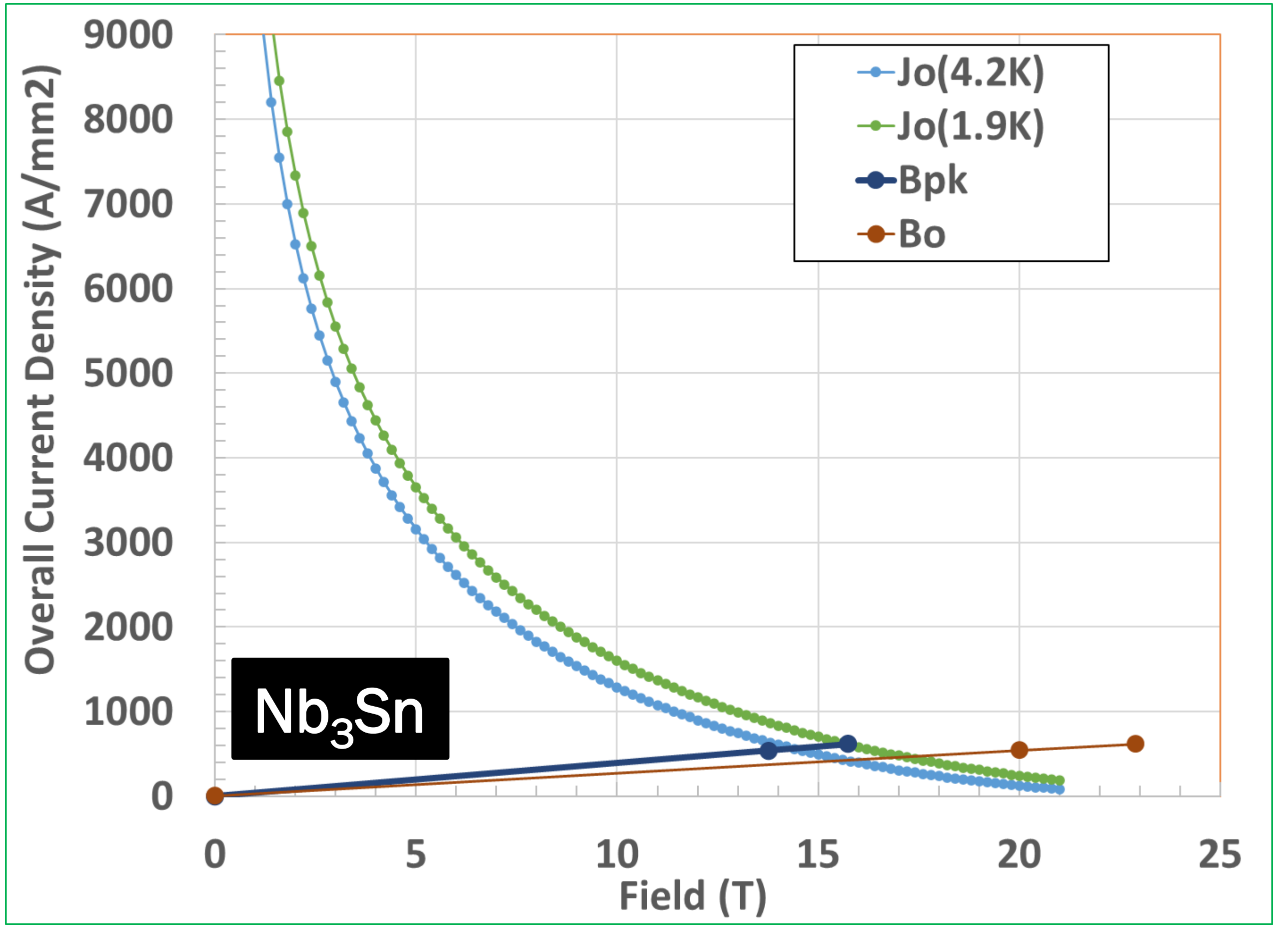
October 2021 Design #3 (margins for 4 layers in main coil)

New designs have matched margins – 15% over 20 T – in both Bi2212 and Nb_3Sn coils for the reference J_o





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Summary

- Three hybrid configurations optimized for Bi2212 in series with Nb_3Sn having 15% margin for the reference J_0 ($J_{overall}$)
- They are ranging from 4 to 6 layers in main coil (+pole coil)
- All designs are optimized for a good field quality as well
- Common coil design is well suited for the very high field hybrid dipoles and seems to be more efficient than other designs. They also seem to need lower number of layers and less conductor
- Space included for an intermediate mechanical structure for stress management (next step - optimize with proper analysis)

Old slides from the last presentation in September 2021

50 mm, 20 T Common Coil Bi2212/Nb_3Sn Hybrid Design (Design Presented last time - September 2021)

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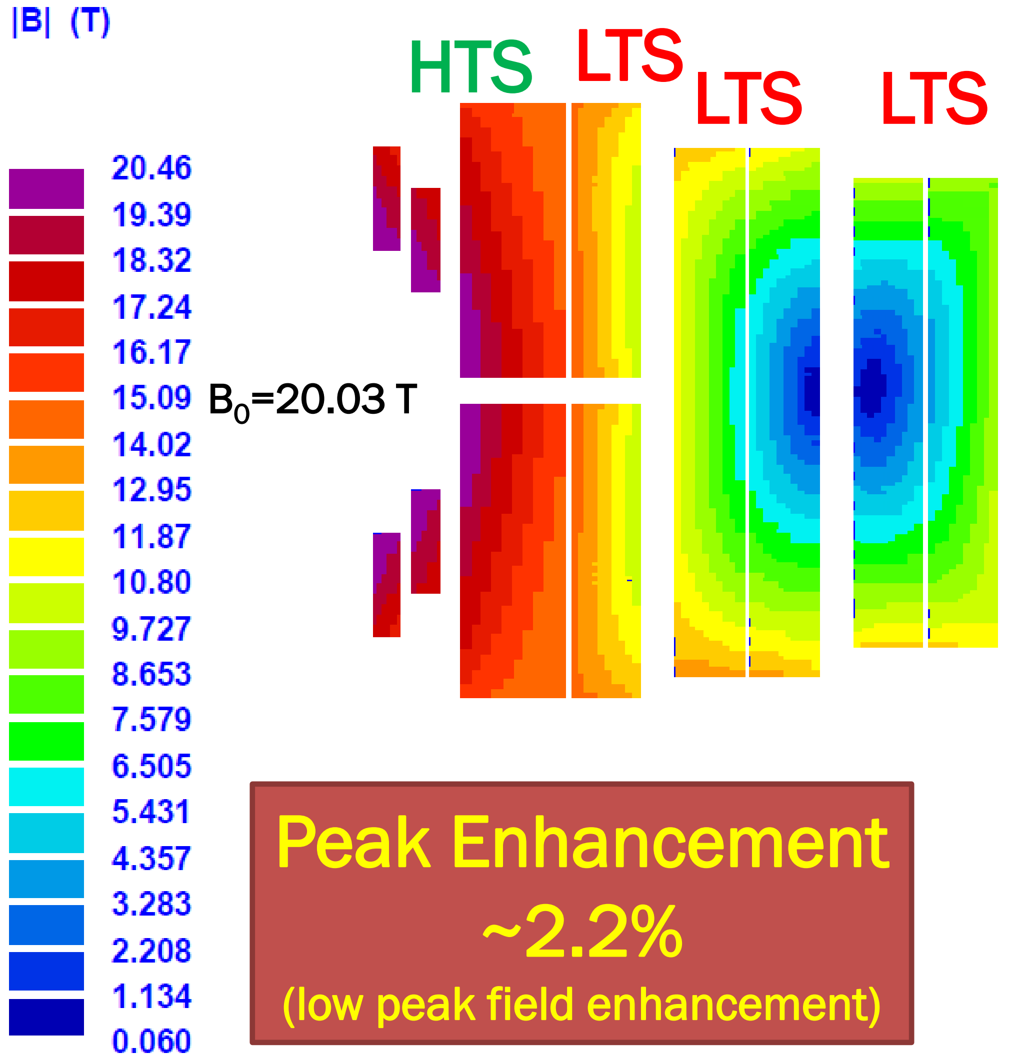
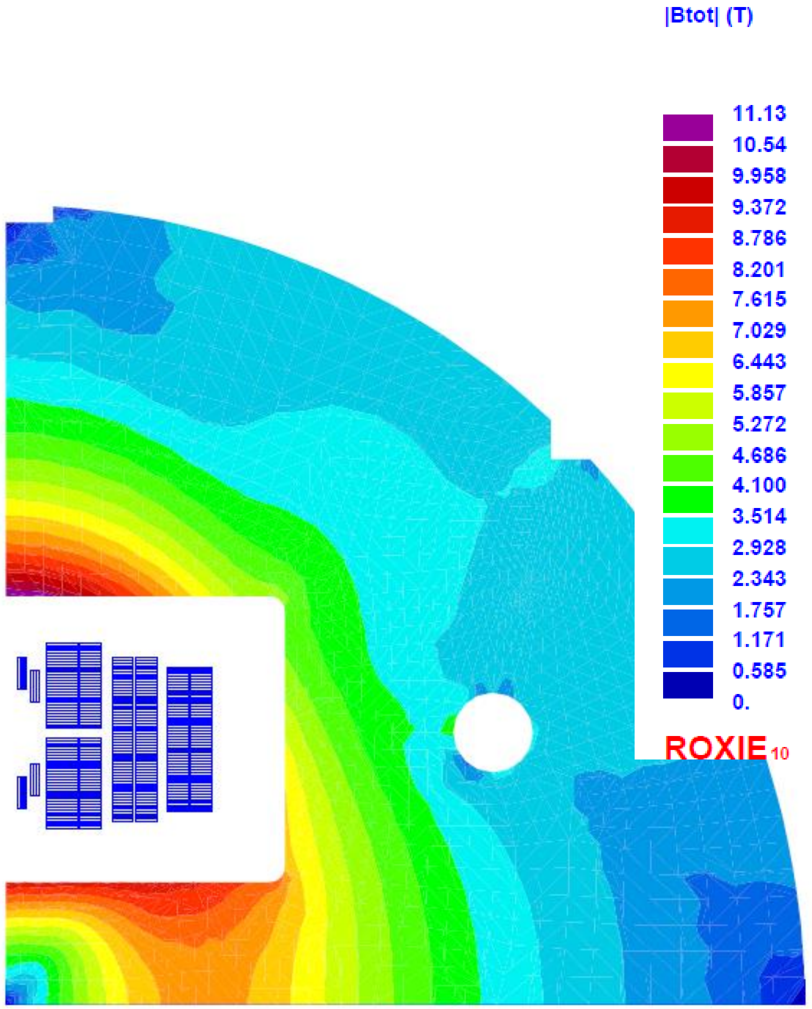


Peak Enhancement
~2.2%
(low peak field enhancement)

MDPCCCORC	Bi2212
Ins w	1.9
Ins h	20.3
Ins Area	38.570
Current	12100
Jo (A/mm^2)	313.72
Bpeak (T)	20.458
MDPH2	Nb_3Sn
Ins w	1.9
Ins h	13.6
Ins Area	25.840
Current	12100
Jo (A/mm^2)	468.27
Bpeak (T)	15.055



Field Quality in 20 T Common Coil Bi2212/Nb_3Sn Hybrid Design (last September 2021 design)

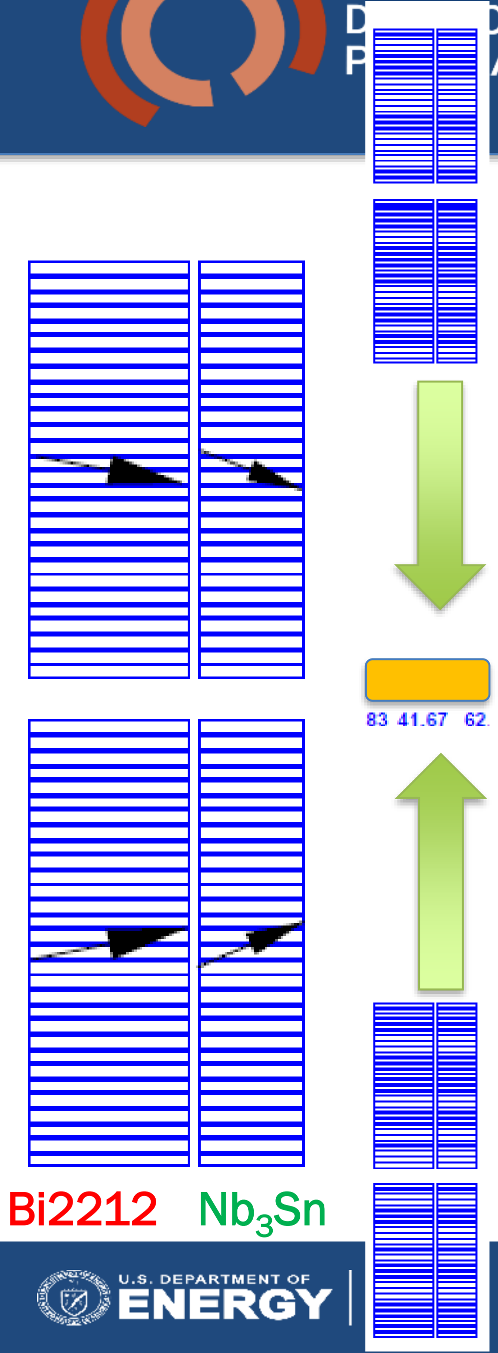
```
REFERENCE RADIUS (mm) .............................    15.0000
X-POSITION OF THE HARMONIC COIL (mm) ...............     0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ...............   169.0000
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ...................   0.2696E-03
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .....................................   20.025677
```

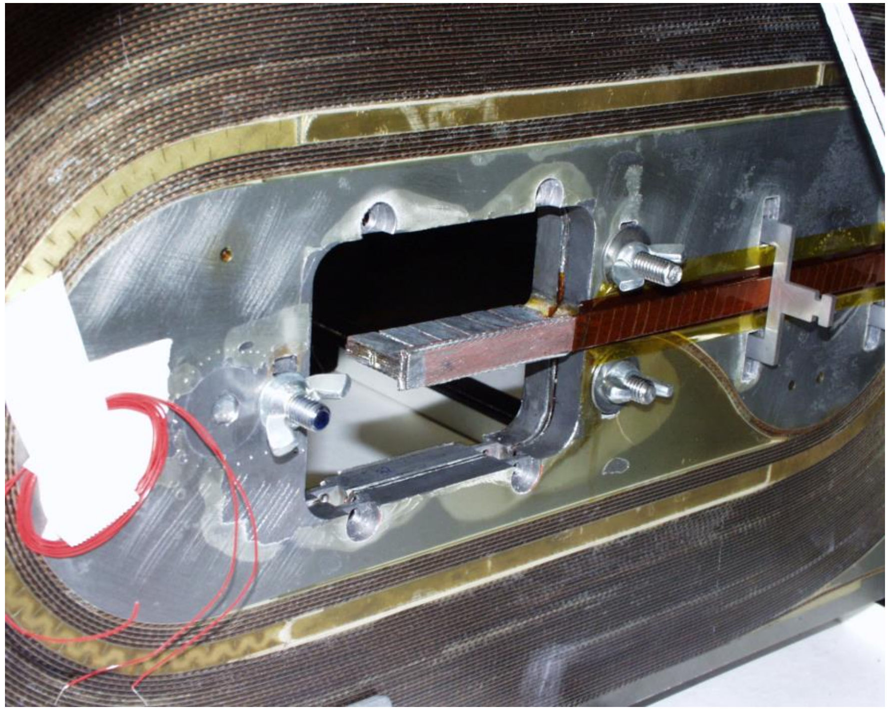
All harmonics <10^{-4} (normal and skew)

```
NORMAL RELATIVE MULTIPOLES (1.D-4):                SKEW RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     0.00000  b 3:     0.00275   a 1:     0.00000  a 2:    -0.00613  a 3:    -0.00000
b 4:      0.00000  b 5:     0.00067  b 6:    -0.00000   a 4:     0.00048  a 5:     0.00000  a 6:     0.00101
b 7:      0.00388  b 8:     0.00000  b 9:    -0.78484   a 7:    -0.00000  a 8:     0.28080  a 9:     0.00000
b10:      0.00000  b11:    -0.33370  b12:    -0.00000   a10:     0.14694  a11:     0.00000  a12:     0.00855
b13:     -0.01708  b14:     0.00000  b15:     0.00605   a13:     0.00000  a14:    -0.00321  a15:    -0.00000
b16:      0.00000  b17:    -0.00669  b18:     0.00000   a16:     0.00545  a17:    -0.00000  a18:     0.00152
```

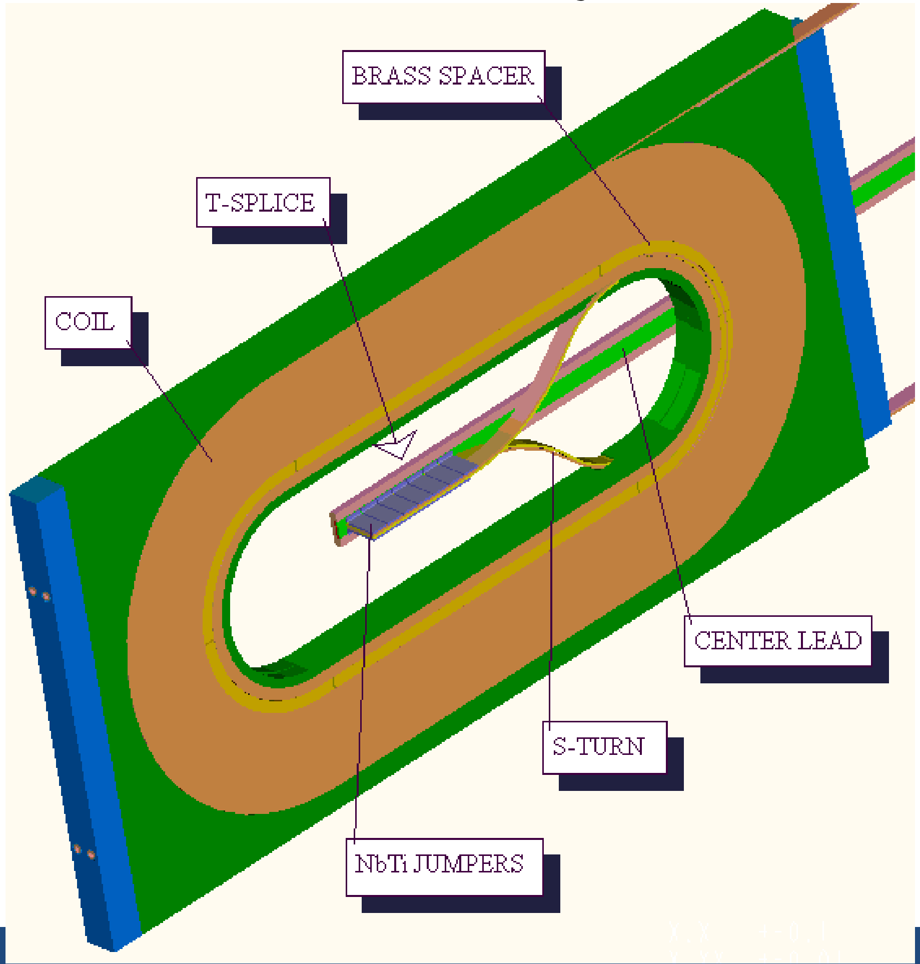
Splices in Common Coil Design (between two single layer coil)



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



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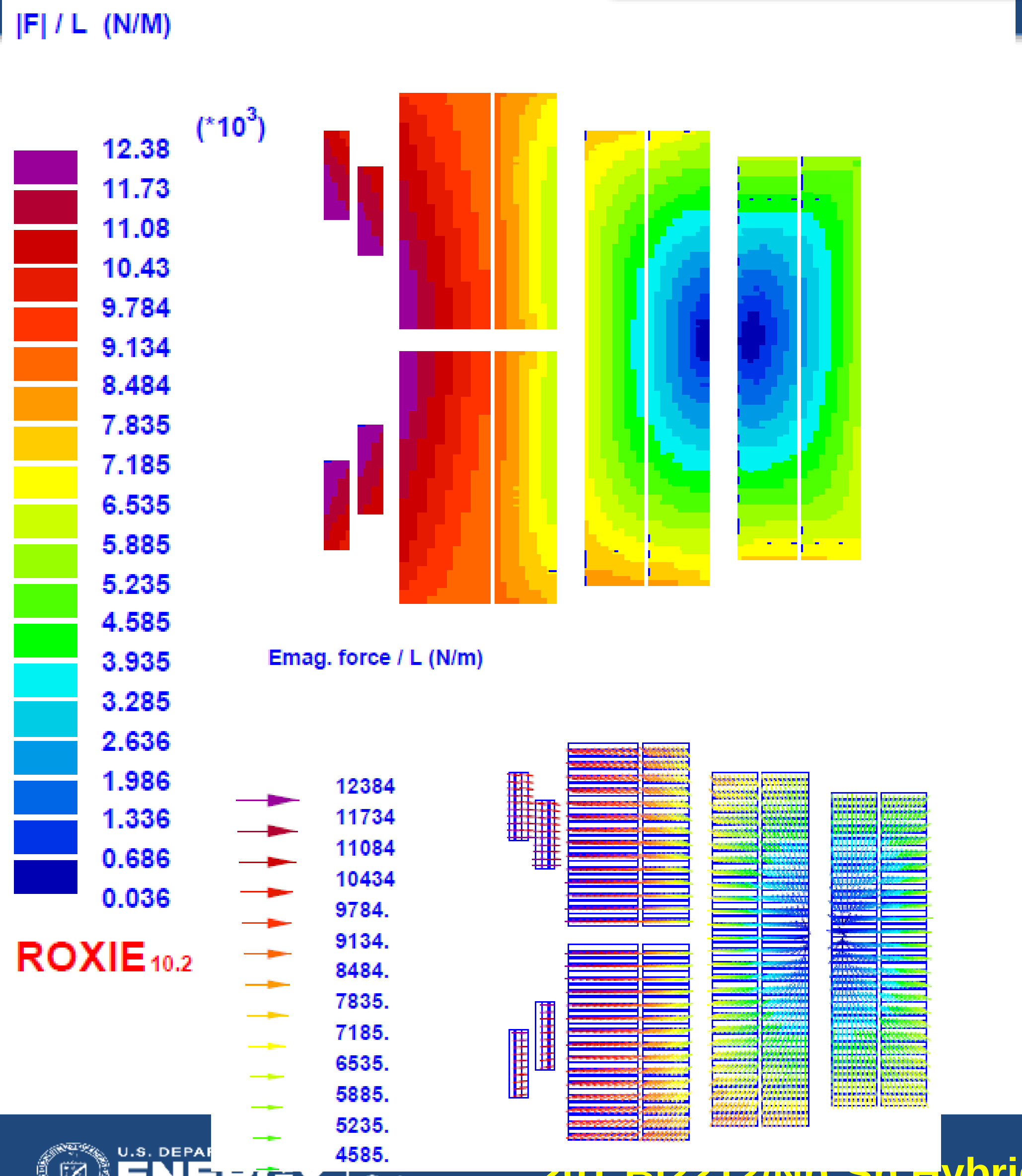
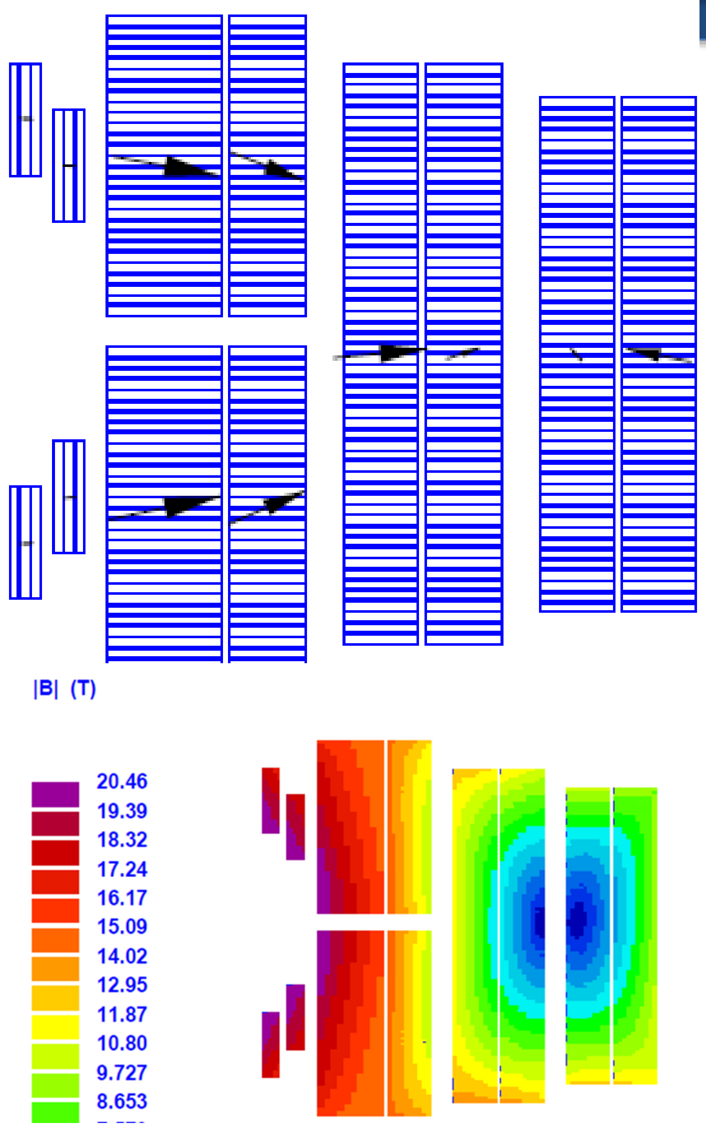
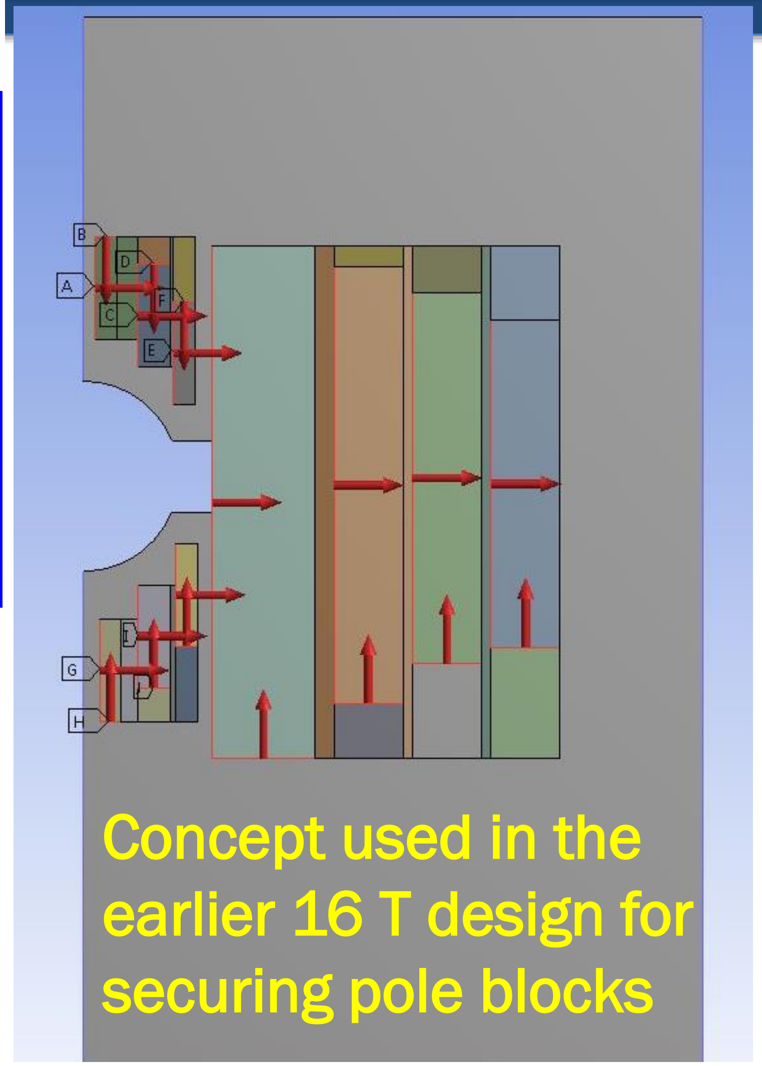
Lorentz Forces @20 T in Bi2212/Nb$_3$Sn Hybrid

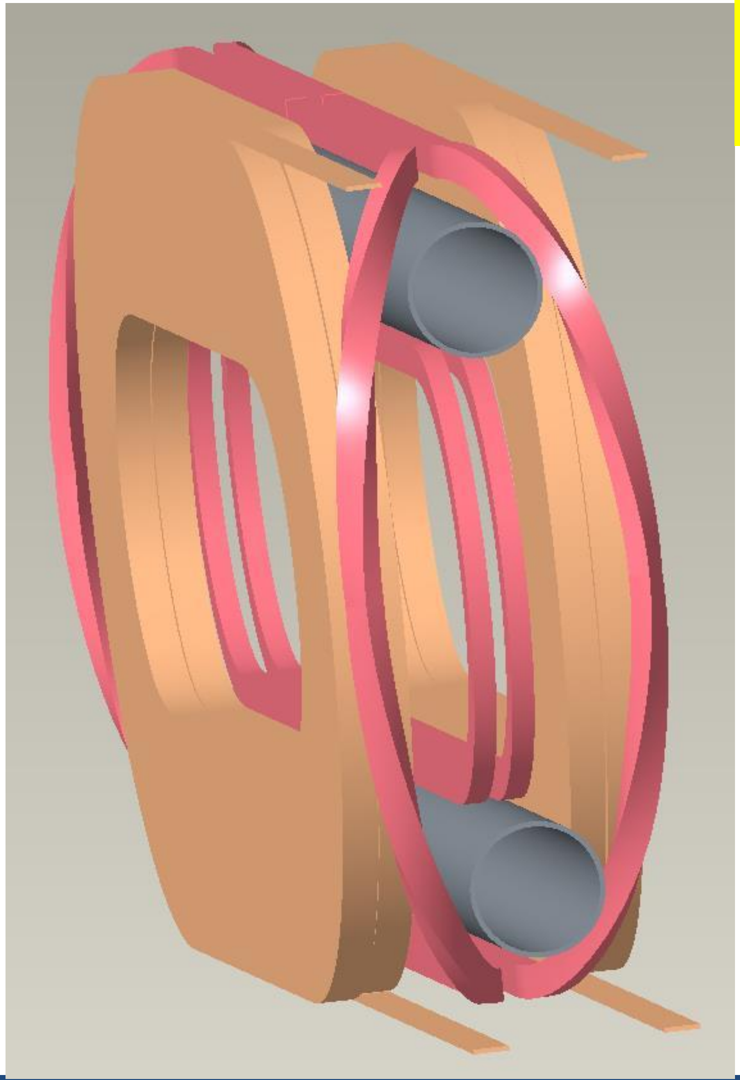




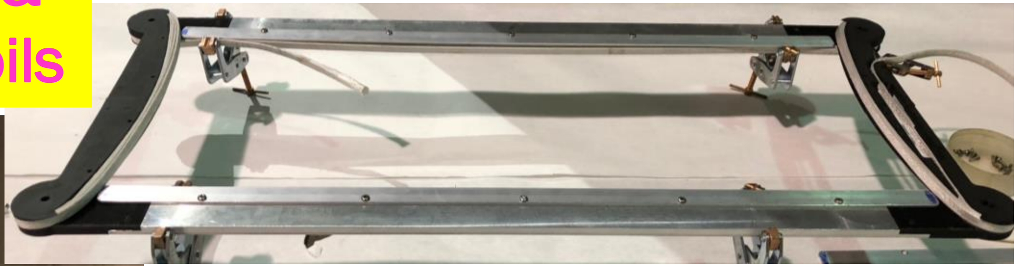


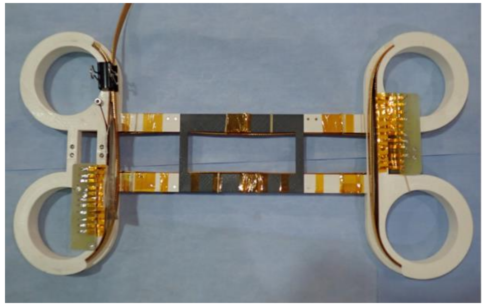
Concept used in the earlier 16 T design for securing pole blocks

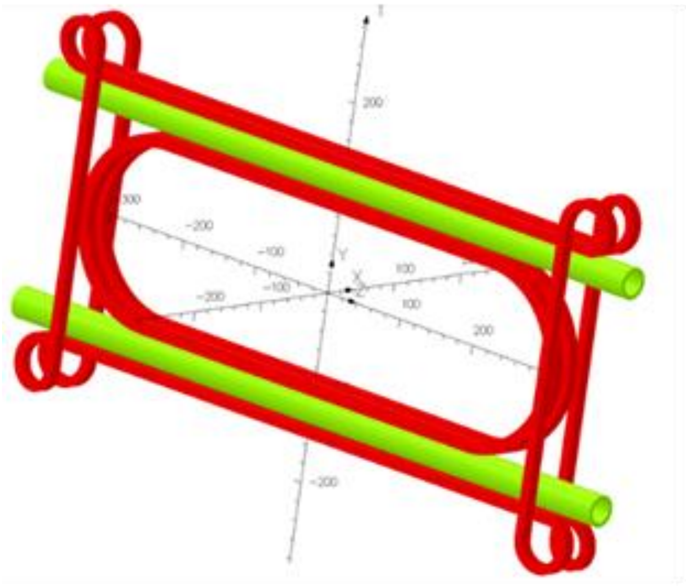
A Few Possible Layout of Away Pole Coils Clearing Bore (others shown elsewhere)

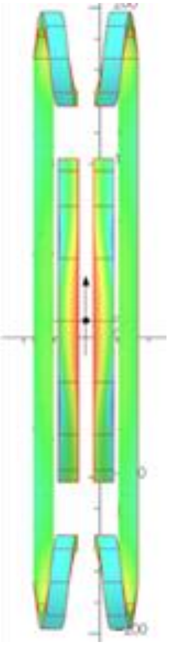


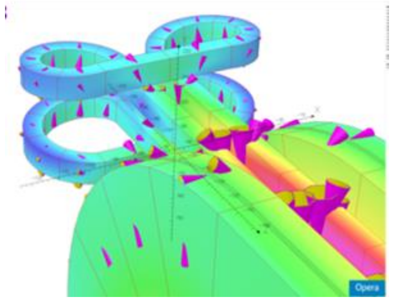
Practice & Tested Coils



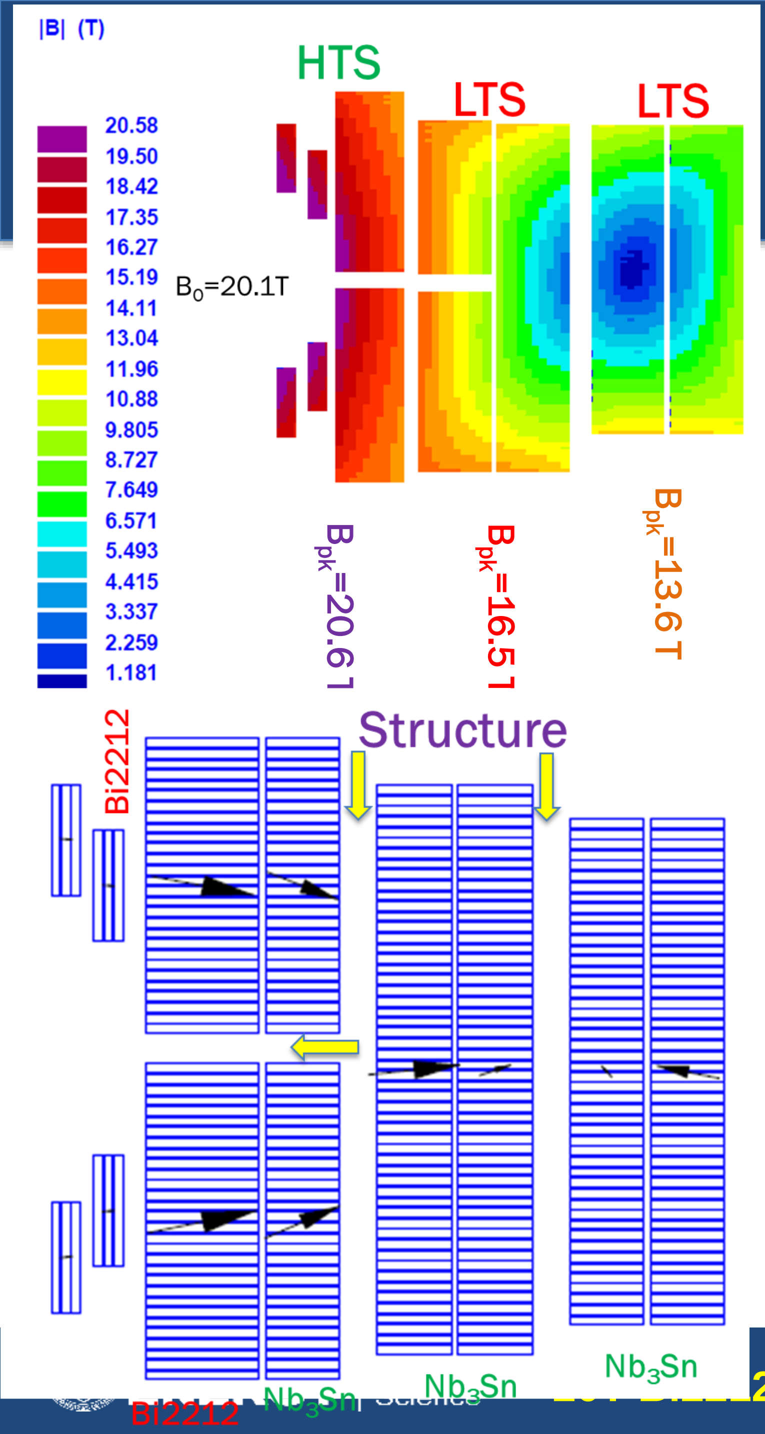




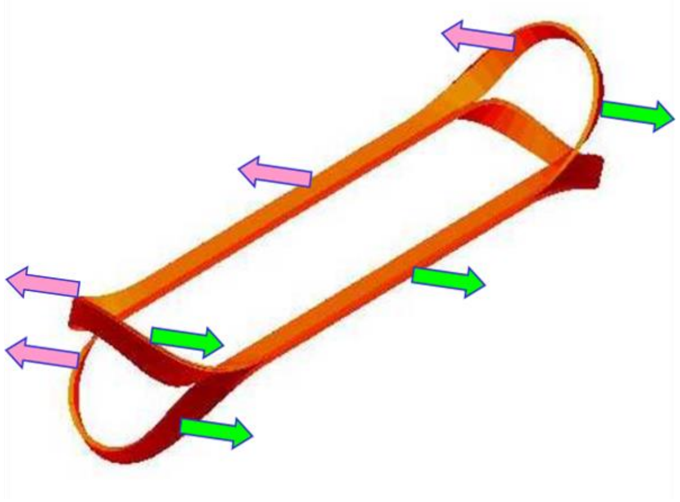


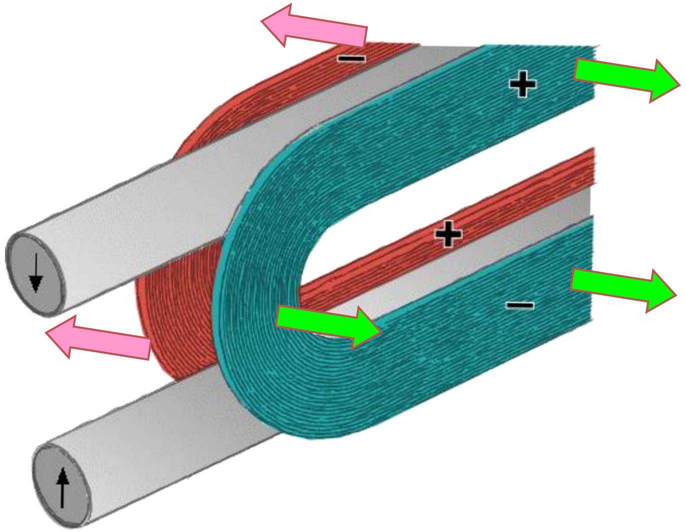


CORC coil can be bent first away and then up/down



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