U.S. MAGNET DEVELOPMENT PROGRAM

20 T HTS/LTS Hybrid Common Coil Design

Ramesh Gupta

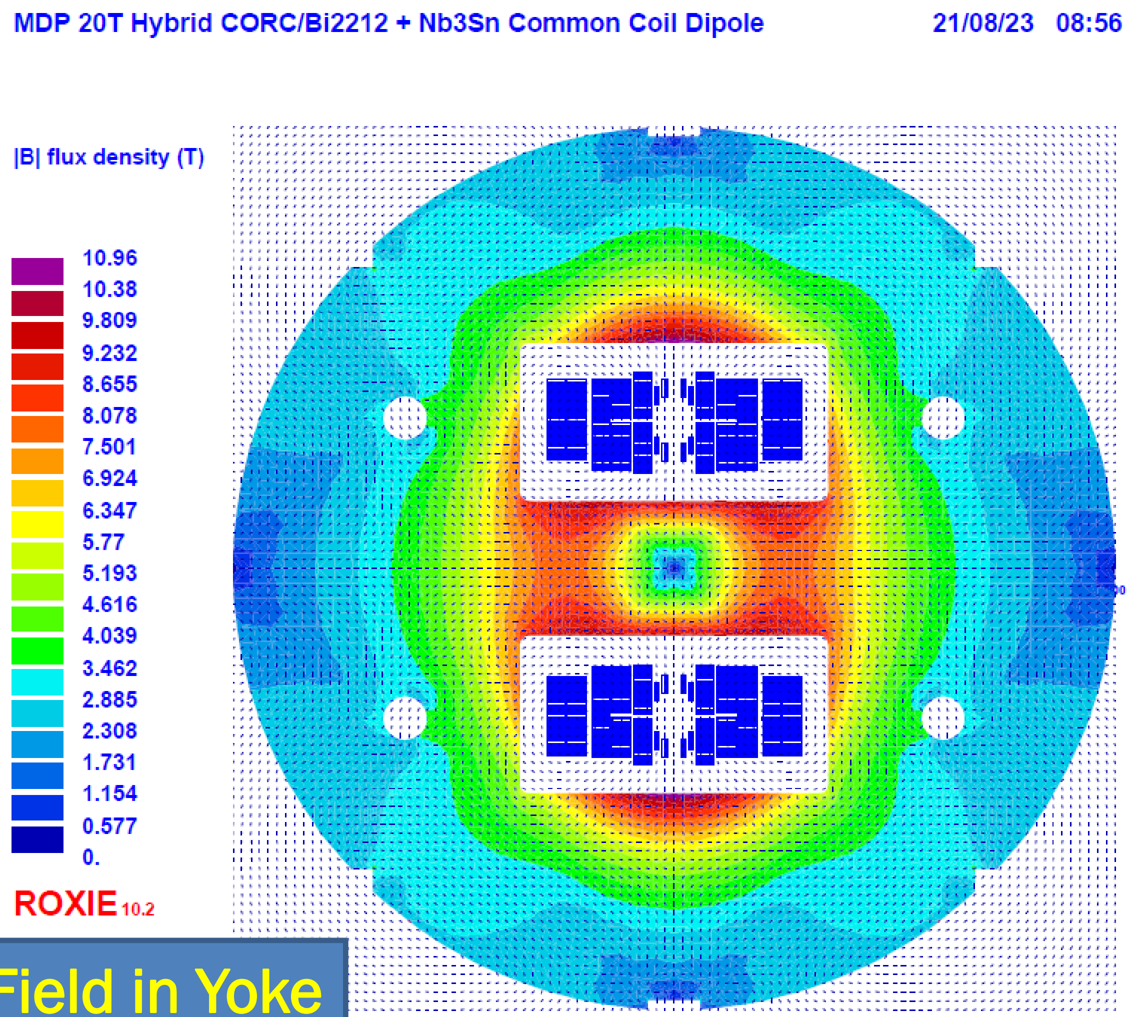
September 7, 2021

Content

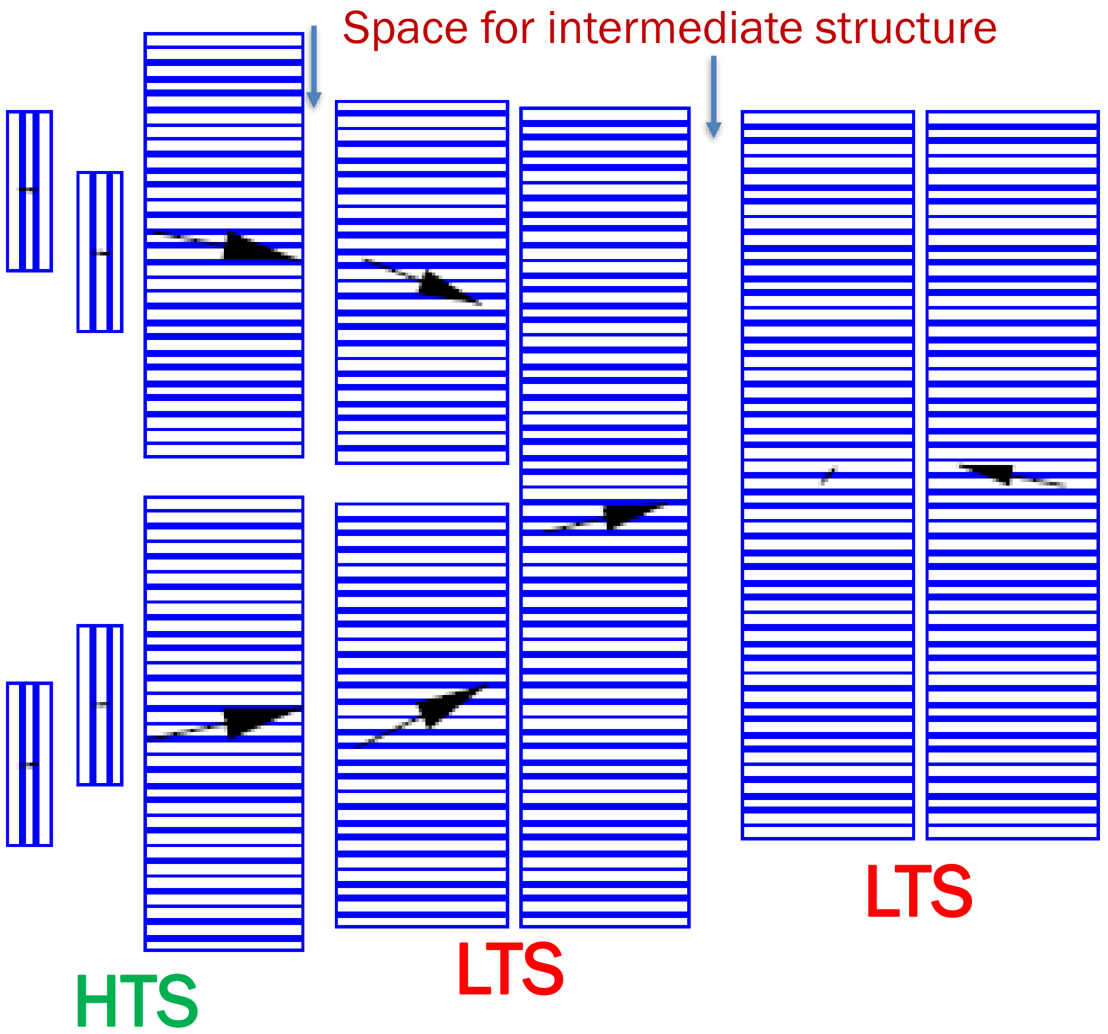
A reasonably evolved HTS/LTS Hybrid Common Coil Design

- **Optimized for a good field quality**
- **Provides desired margin for both CORC and Bi2212 cable**
- **Same initial magnetic design is used for both CORC and Bi2212**
- **New design for including space for structure in CORC option**
    - **To be verified by the actual mechanical analysis**
    - **Common coil design allows higher J_e or J_o CORC**

50 mm, 20 T Common Coil Hybrid Design



Field in Yoke



Field Quality in 20 T Common Coil Hybrid Design

U.S. MAGNET DEVELOPMENT PROGRAM

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HARMONIC ANALYSIS NUMBER ..........................          1
MAIN HARMONIC .....................................          1
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 ..................  0.2915E-03
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ....................................  20.097535
MAGNET STRENGTH (T/(m^(n-1)) ......................    20.0975
```

All harmonics $<10^{-4}$

* Mostly 10^{-5} *

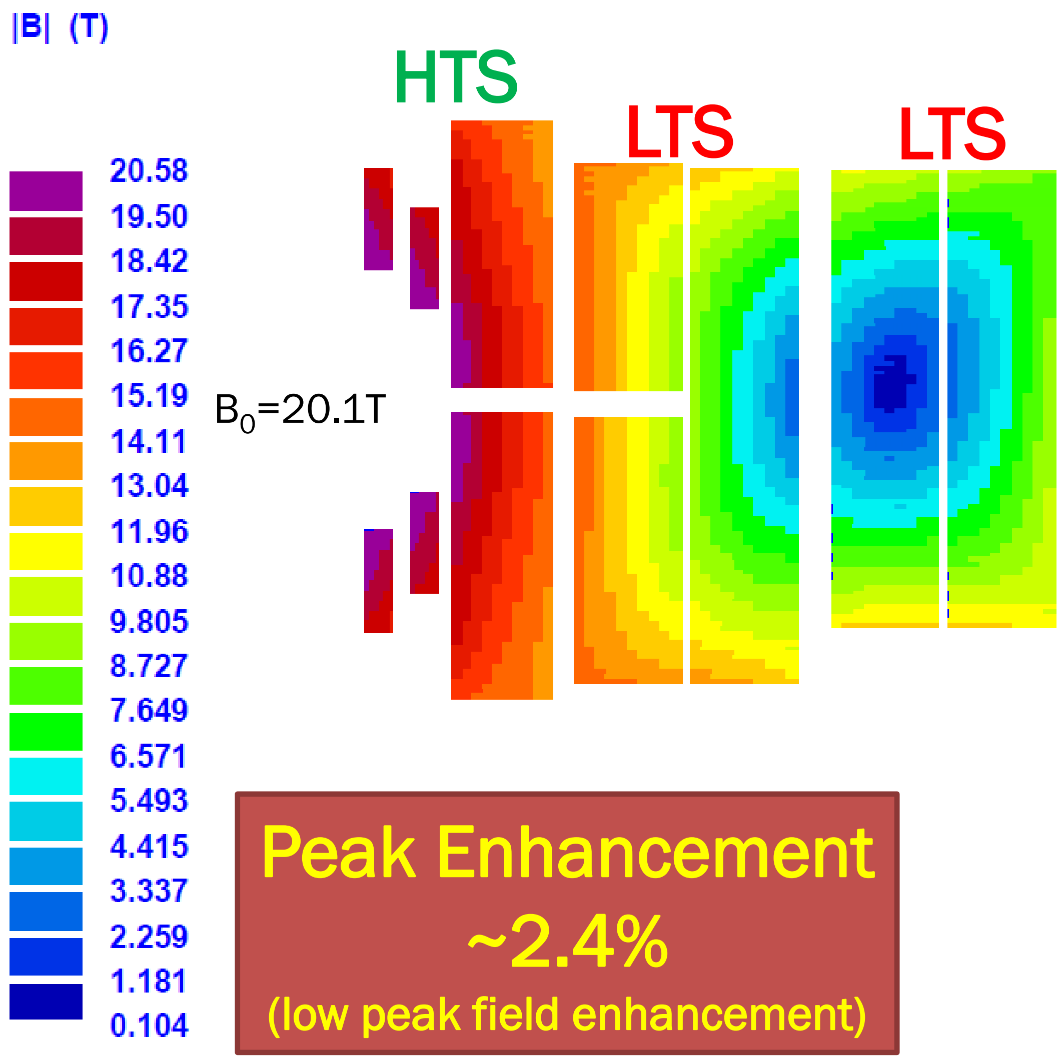
NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	0.00000	b 3:	0.00886
b 4:	0.00000	b 5:	0.00866	b 6:	-0.00000
b 7:	-0.12569	b 8:	0.00000	b 9:	-0.14757
b10:	0.00000	b11:	-0.25870	b12:	-0.00000
b13:	-0.09200	b14:	0.00000	b15:	0.01722
b16:	0.00000	b17:	0.00085	b18:	-0.00000

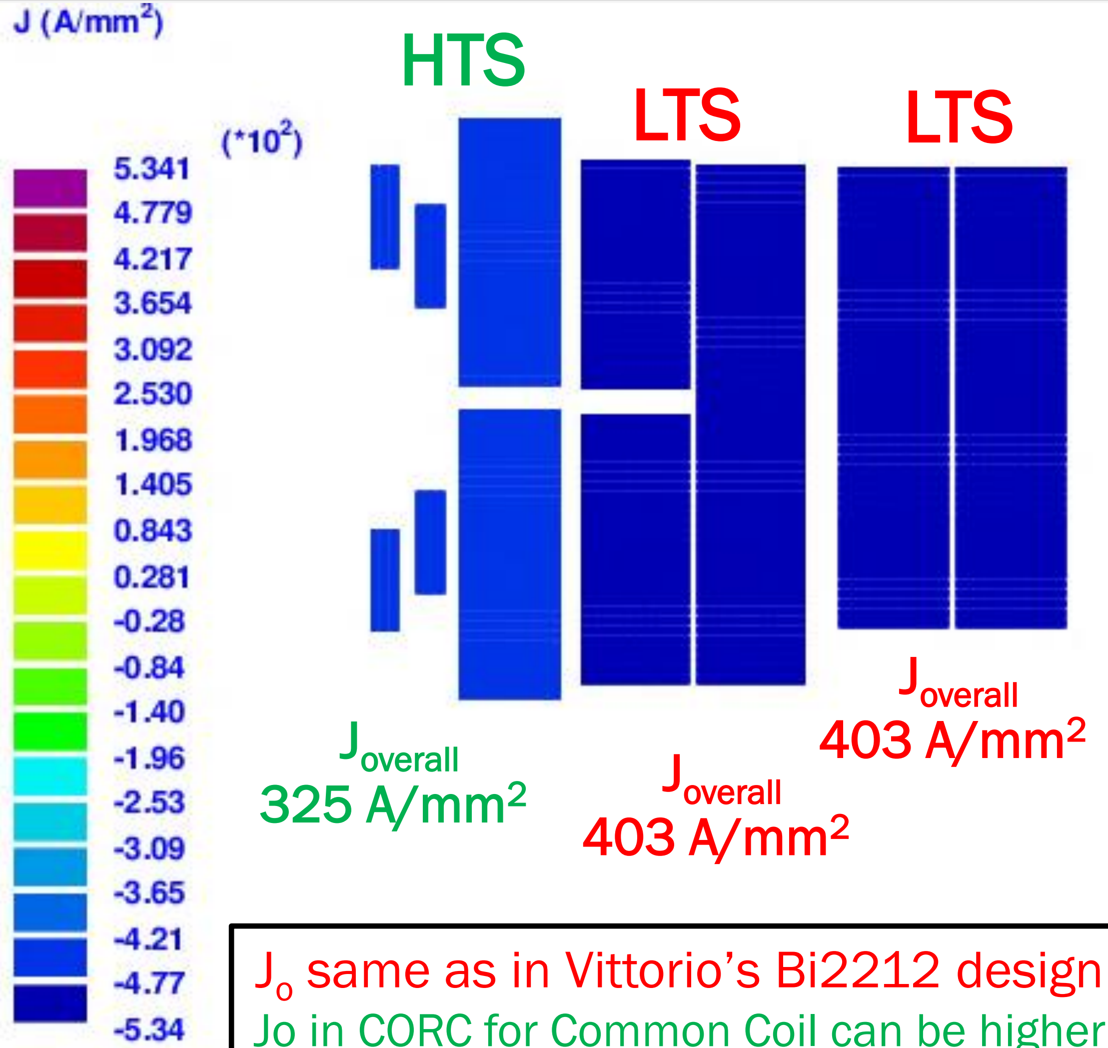
SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	0.00000	a 2:	0.01125	a 3:	0.00000
a 4:	0.02070	a 5:	-0.00000	a 6:	0.09133
a 7:	0.00000	a 8:	-0.18568	a 9:	-0.00000
a10:	-0.32507	a11:	-0.00000	a12:	-0.10123
a13:	0.00000	a14:	0.02355	a15:	-0.00000
a16:	-0.00354	a17:	-0.00000	a18:	-0.00405

50 mm, 20 T Common Coil Hybrid Design



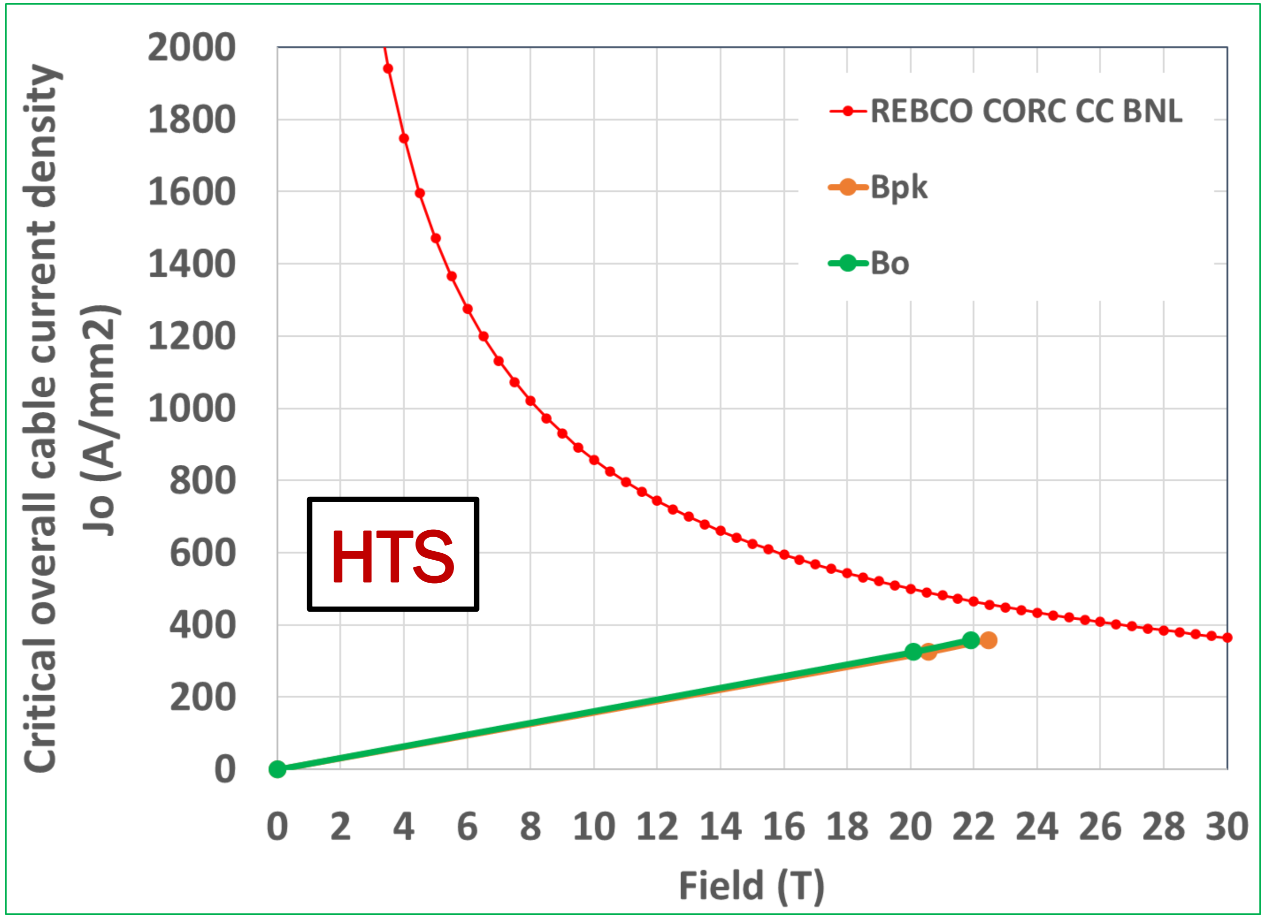
Peak Enhancement
~2.4%
(low peak field enhancement)

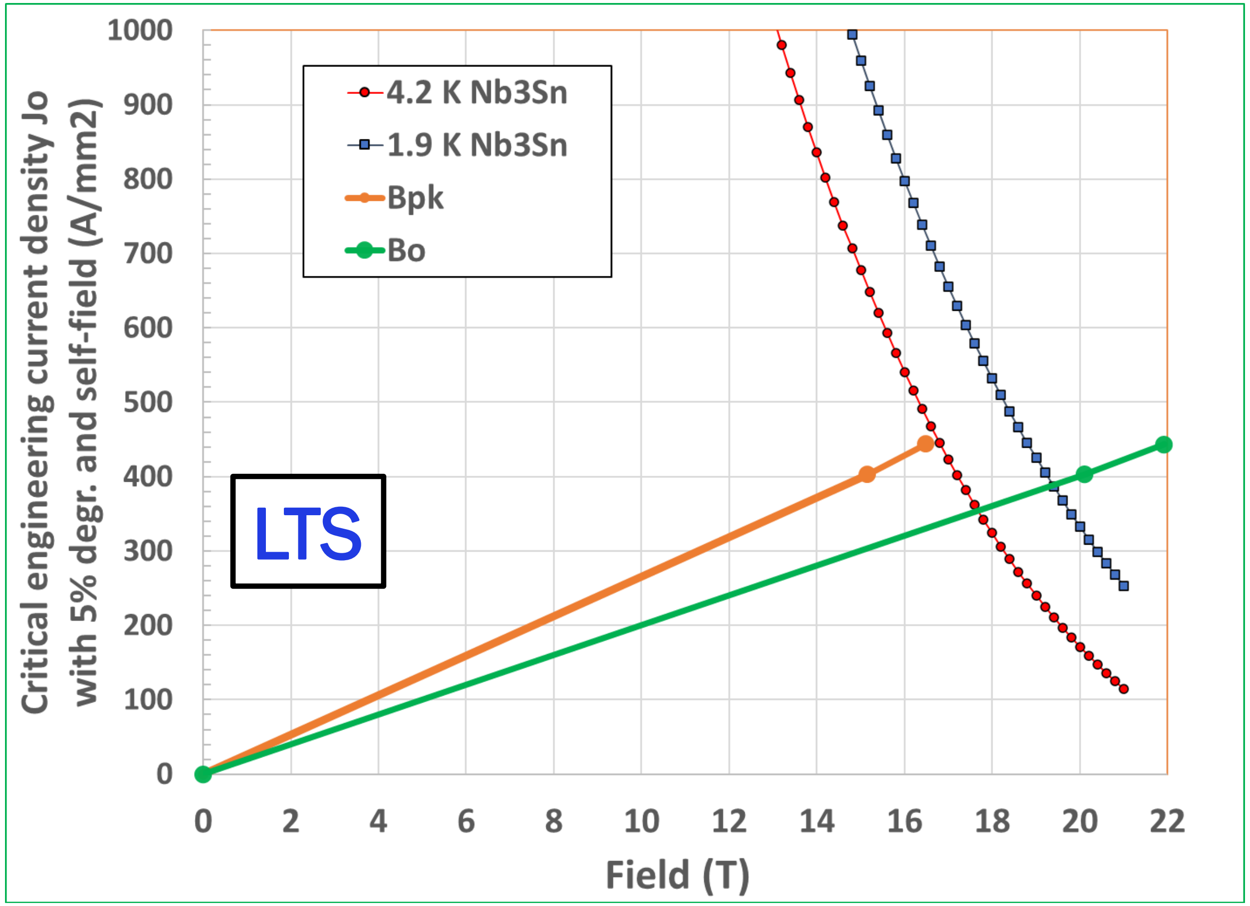


J_o same as in Vittorio's Bi2212 design
Jo in CORC for Common Coil can be higher

Margins in 20 T Hybrid Common Coil Design

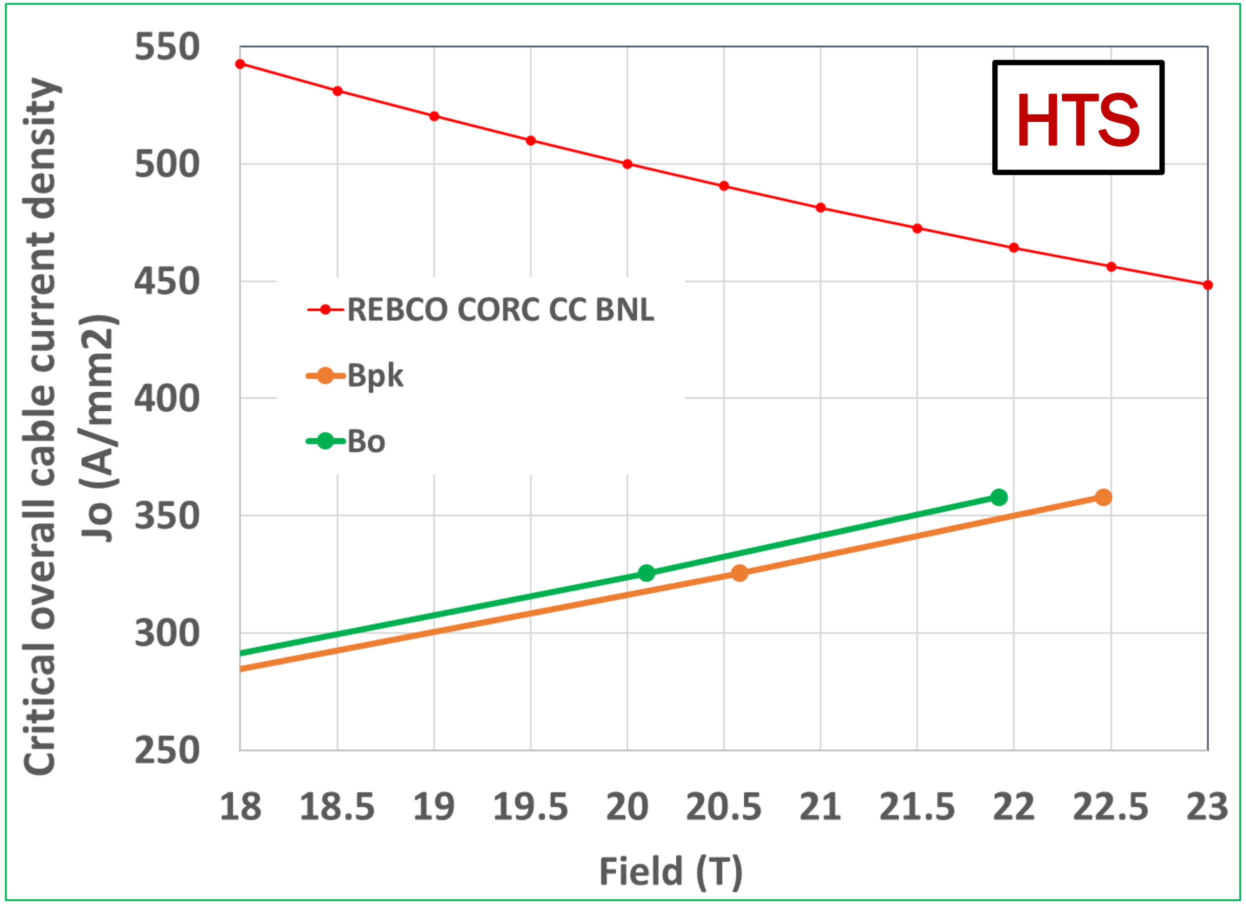
➢ Enough margin at 4.2 K as well (plots for Jo)

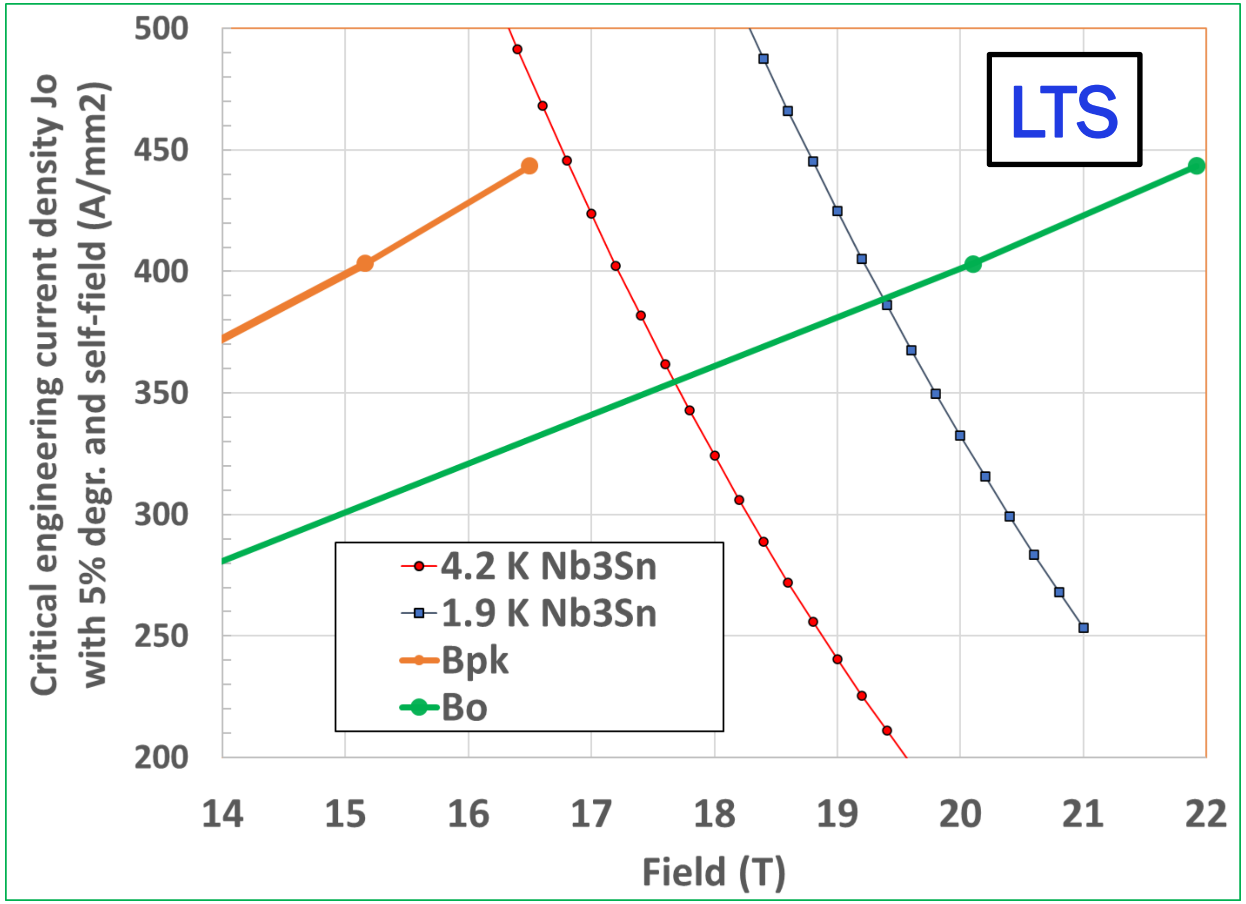




Margins in 20 T Hybrid Common Coil Design

- Enough margin at 4.2 K as well (plots for Jo)





Conductor Used (1)

HTS (Bi2212 or CORC)

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)	-12500.0000
INNER RADIUS OF THE BLOCK (MM).....................	18.1636
CABLE HEIGHT (MM).(INSULATED)	20.2594
CABLE INNER WIDTH (MM).(INSULATED)	1.8962
CABLE OUTER WIDTH (MM).(INSULATED)	1.8962
CABLE HEIGHT (MM).(BARE)	19.9600
CABLE INNER WIDTH (MM).(BARE)	1.5968
CABLE OUTER WIDTH (MM).(BARE)	1.5968
RADIAL INSULATION THICKNESS (MM)...................	0.1497
AZIMUTHAL INSULATION THICKNESS (MM)................	0.1497
NUMBER OF STRANDS	50
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)	1.373
NUMBER OF DISCRETISATION POINTS AZIMUTHAL	2
NUMBER OF DISCRETISATION POINTS RADIAL	10
CONDUCTOR NAME	MDPB2212

Nb_3Sn

NUMBER OF BLOCK	5
NUMBER OF CONDUCTORS	28
POSITIONING ANGLE (DEG)	110.0000
INCLINATION ANGLE (DEG)	0.0000
CURRENT IN EACH CONDUCTOR OF THE BLOCK (A)	-16500.0000
INNER RADIUS OF THE BLOCK (MM).....................	48.9020
CABLE HEIGHT (MM).(INSULATED)	21.5867
CABLE INNER WIDTH (MM).(INSULATED)	1.8962
CABLE OUTER WIDTH (MM).(INSULATED)	1.8962
CABLE HEIGHT (MM).(BARE)	21.2873
CABLE INNER WIDTH (MM).(BARE)	1.5968
CABLE OUTER WIDTH (MM).(BARE)	1.5968
RADIAL INSULATION THICKNESS (MM)...................	0.1497
AZIMUTHAL INSULATION THICKNESS (MM)................	0.1497
NUMBER OF STRANDS	55
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)	1.361
NUMBER OF DISCRETISATION POINTS AZIMUTHAL	2
NUMBER OF DISCRETISATION POINTS RADIAL	10
CONDUCTOR NAME	MDPH1

Conductor Used (2)

Edit Cable Data [/home/gupta/MDP/aug2021/roxie_mdp-aug-2021-cc.cadata]

File Display

Cable Definition

No	Name	Cable Geom.	Strand	Filament	Insul	Trans	Quench Mat.	T_o	Comment
41	MDPW1	MDPW1	MDPWJC	NB3SN	MDPW1	NONE	NONE	1.9	MDP
42	MDPW2	MDPW2	MDPWJC	NB3SN	MDPW1	NONE	NONE	1.9	MDP
43	MDPH1	MDPW1	MDPHJC	ECC2	MDPW1	NONE	NONE	1.9	MDP
44	MDPH2	MDPW2	MDPHJC	ECC2	MDPW1	NONE	NONE	1.9	MDP
45	MDPB2212	MDPB2212	MDPW2212	NB3SN	MDPW1	NONE	NONE	1.9	MDP
46	MDPCCCORC	MDPCCCORC	MDPCCCORC	NB3SN	MDPW1	NONE	NONE	1.9	MDP Common Coil CORC

Edit Cable Data [/home/gupta/MDP/aug2021/roxie_mdp-aug-2021-cc.cadata]

File Display

Transient

Quench Material Properties

Cable Geometry

No	Name	height	width_i	width_o	ns	transp.	degrd	Comment
42	MDPW1	21.33	1.6	1.6	55	100	0	MDP NB3SN
43	MDPW2	13.3	1.6	1.6	37	100	0	IMDP NB3SN
44	MDPB2212	20	1.6	1.6	50	100	0	MDP Bi2212
45	MDPCCCORC	20	1.6	1.6	50	100	0	MDP Common Coil CORC

File Display

Filament

Strand

No	Name	diam.	cu/sc	RRR	Tref	Bref	Jc@BrTr	dJc/dB
20	MDPWJC	0.8	1	100	1.9	16	1928	371
21	MDPHJC	0.8	1	100	1.9	16	1928	371
22	MDP2JC	1.1	1	100	1.9	16	1928	371
23	MDPW2212	0.8	3	100	1.9	20	2944	64
23	MDPCCCORC	0.8	3	100	1.9	20	2944	64

Edit Cable Data [/home/gupta/MDP/aug2021/roxie_mdp-aug-2021-cc.cadata]

File Display

Filament

No	Name	fildiao	fildiai	Jc-Fit	Comment
4	NBTIO	6	0	FIT1	NBTI OUTER CABLES
5	NB3SN	22	12	FIT1	NB2SN TWENTE
6	NBTIS	5	0	FIT1	NBTI SIEMAT(ALSTOM)
7	NBTIG	6	0	GSIFIT	NBTI GSI001
8	SIS3NBTI	3.5	0	SISFIT	NBTI SIS300
9	NB3AL	50	0	NBALK1	Nb3Al tes
10	NB3SNI	10	0	FIT1	ITER RF
11	EUNB3SN	30	0	EUFIT1	EUROCIRCOIL NB3SN
12	ECC2	50	0	ECCB2	NB3SN FCC 2300 A/mm^2

Edit Cable Data [/home/gupta/MDP/aug2021/roxie_mdp-aug-2021-cc.cadata]

le Display Help

Insulation

Jc-Fit

No	Name	Type	Jcref	Tc0	alpha	beta	gamma	C0	Bc20	N/a	N/a	N/a	N/a	Comment
1	FIT1	1	3E+09	9.2	0.57	0.9	2.32	27.04	14.5	0	0	0	0	MB FILAMENT TYPE
2	TES1	1	3E+09	9.2	0.57	0.9	2.32	27.04	14.5	0	0	0	0	FILAMENT TEST TYPE alph
3	GSIFIT	1	3E+09	9.2	0.7	1.57	1	25	14.5	0	0	0	0	APPROXIMATE THE WILSON
4	SISFIT	1	3E+09	9.33517	0.68	0.8477	2.23234	25	14.5	0	0	0	0	Glyn MQYT5 FIT at 4.5K
5	NBALK1	5	1.4E+10	36.2	17.8	0	0	0	0	0	0	0	0	Jc fit of Nb3Al K1 at 4
6	EUFIT1	5	4.75E+10	28.9	18	0	0	0	0	0	0	0	0	EUROCOIL NB3SN FIT1
7	ECCB2	11	2.67845E+11	29.38	16	0.96	1.52	0.5	2	0	0	0	0	1350 A/MM^2 AT 16 T 4.2

Insulation

No	Name	Radial	Azimut	Comment
24	MDPW1	0.15	0.15	MDP insulation
25	EUINS	0.15	0.15	EUROCIRCOIL INS

CORC in Common Coil

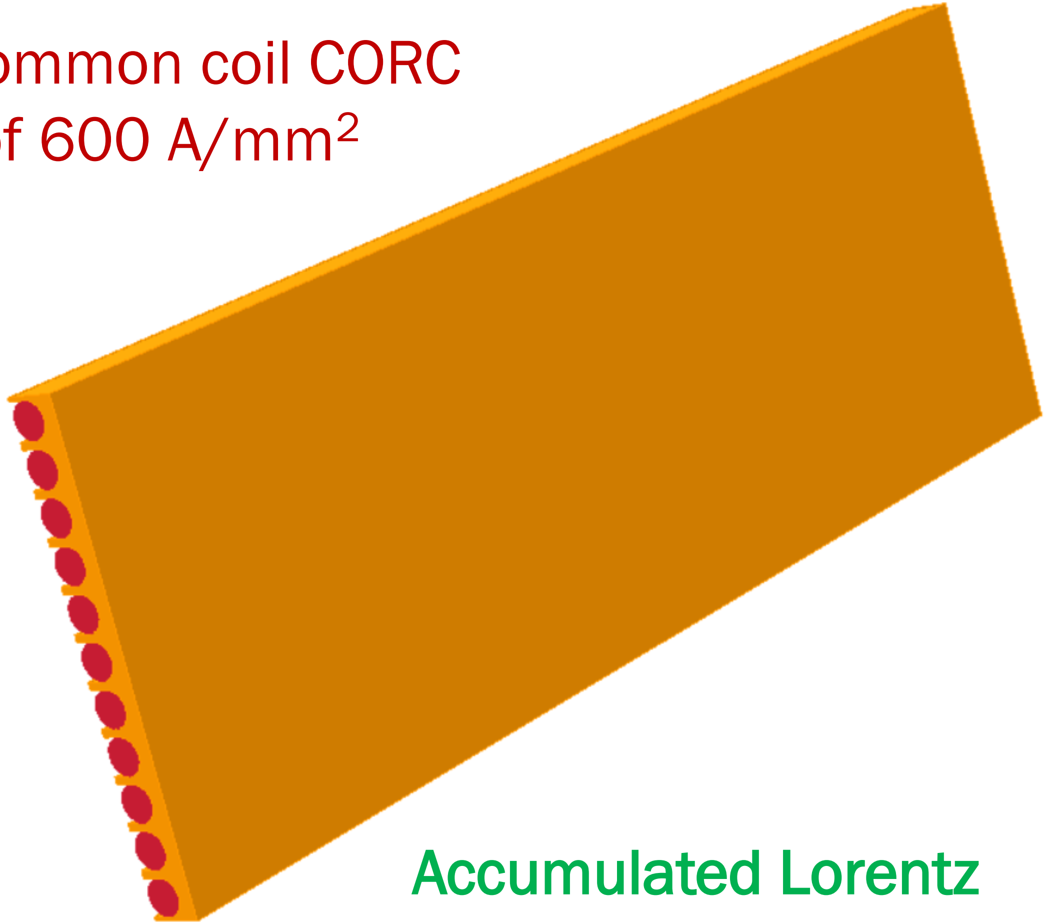
- STTR with ACT anticipated a future common coil CORC with an engineering current density of 600 A/mm^2
- Checked with Danko – still possible

Overall Current density with structure:

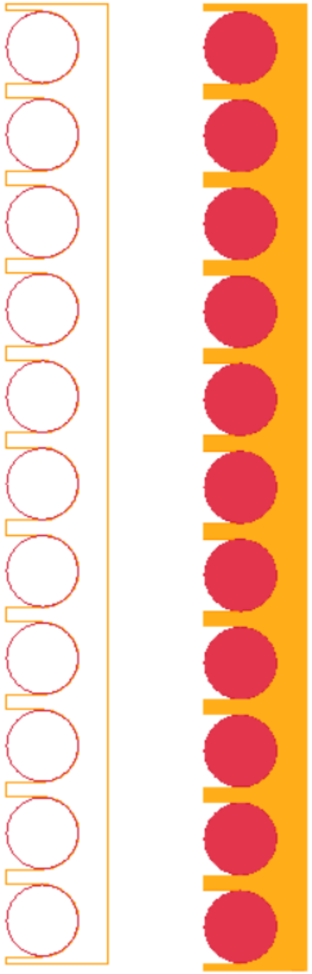
- Area for 6 mm wire: pi*6*6/4 = 28.3 mm^2
- Area for 6.5mm X 8mm rectangle = 52 mm^2

J_o for Je = 600 A/mm2:

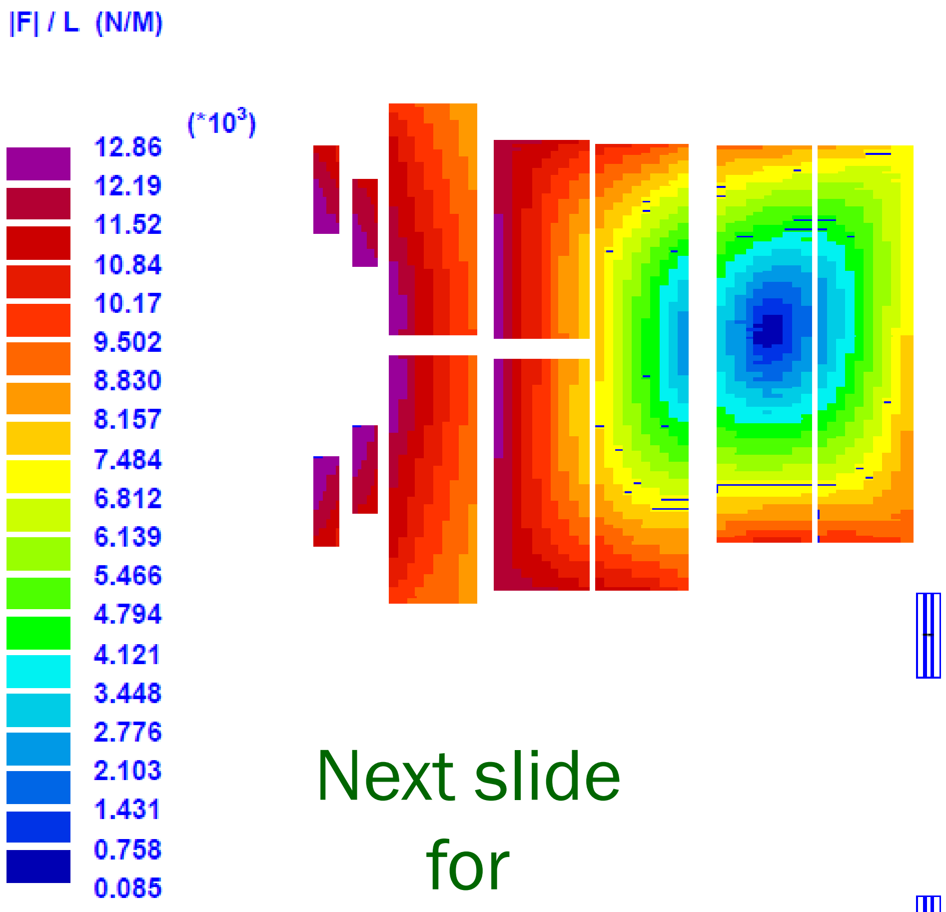
- J_o =600*28.3 /52 = 326 A/mm^2
- Similar to Bi2212; but with a structure



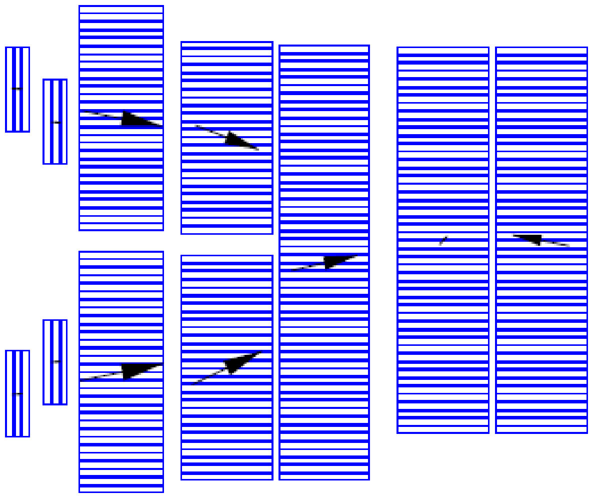
Accumulated Lorentz forces can be managed in a structure

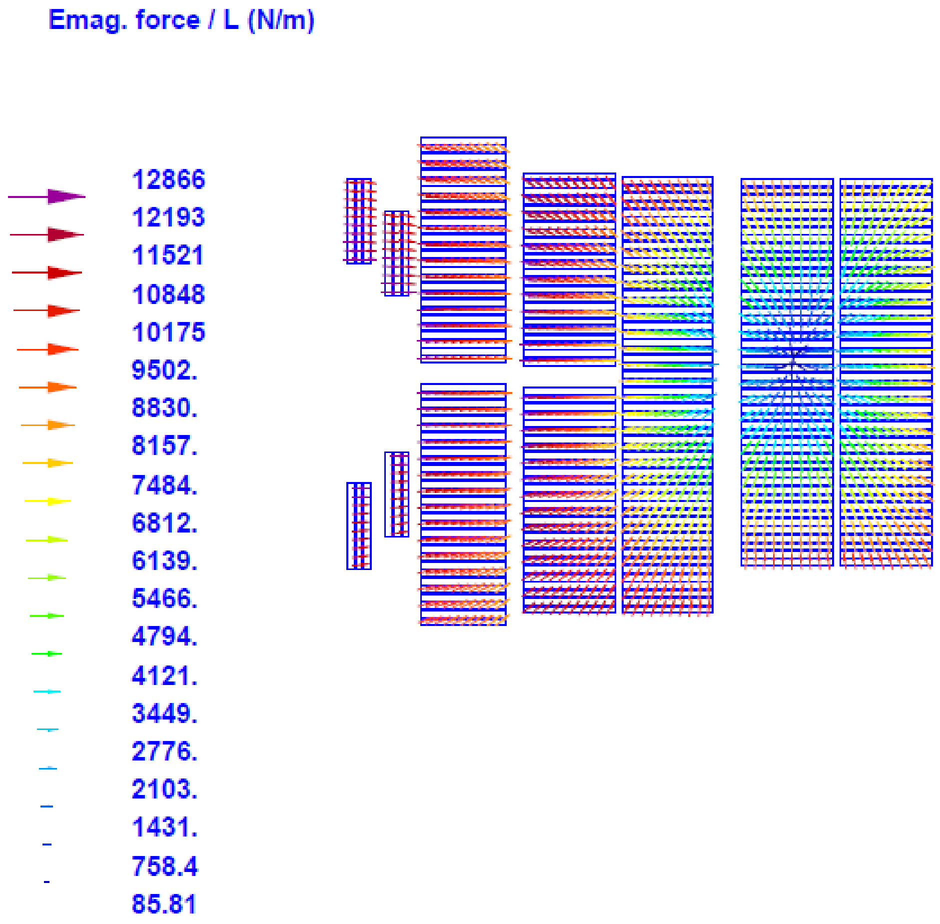


Lorentz Forces at the Design Field (1)



Next slide
for
F_x and F_y





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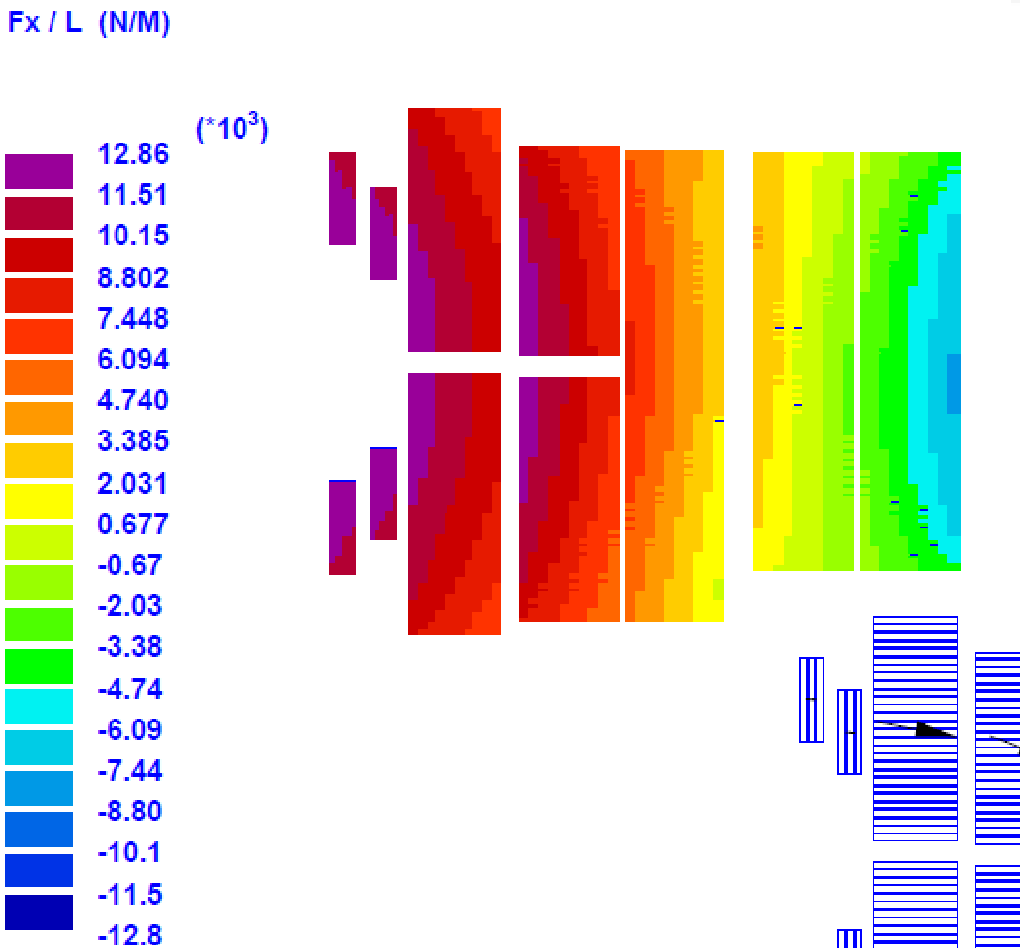
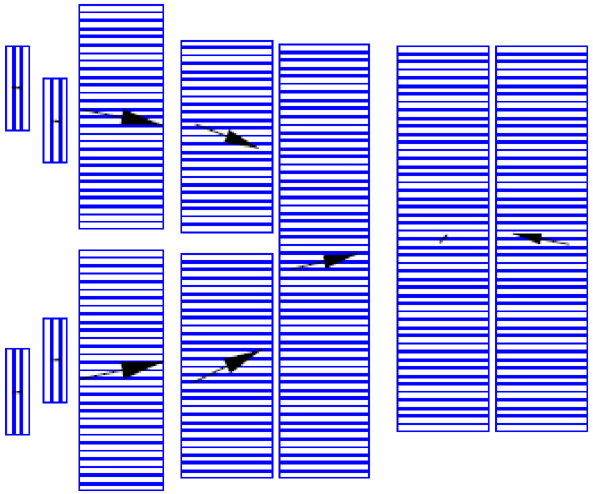
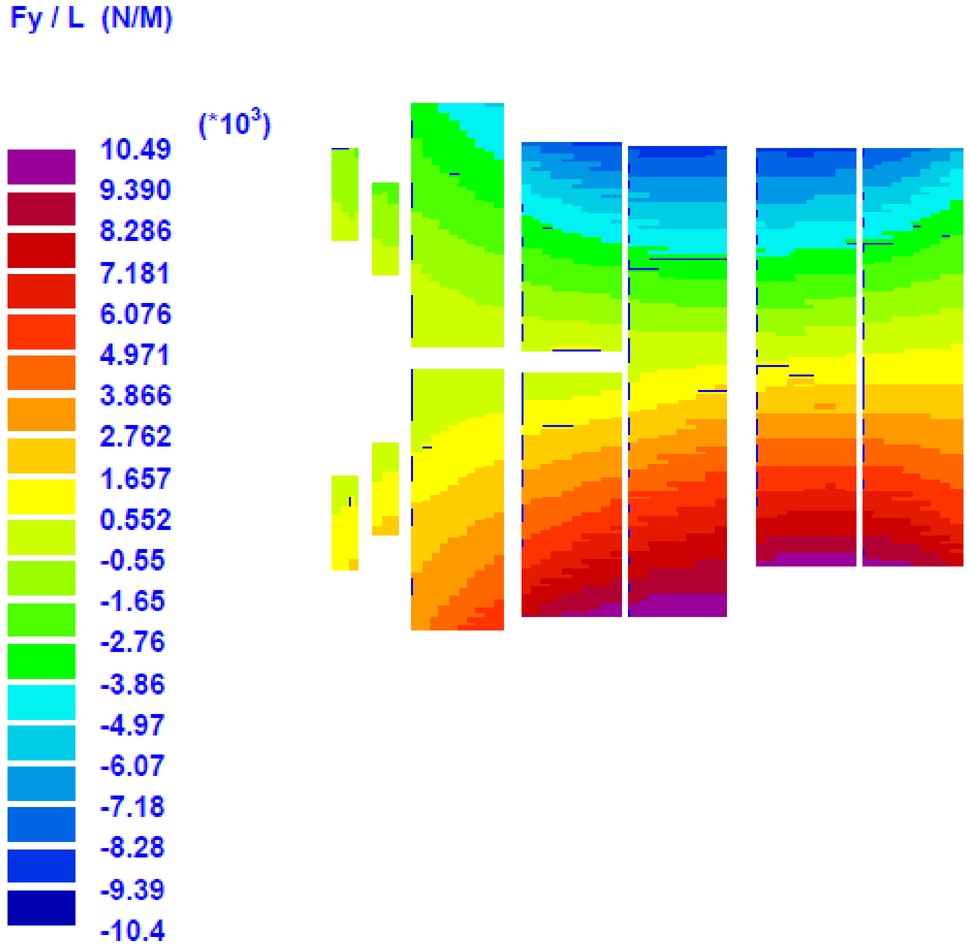
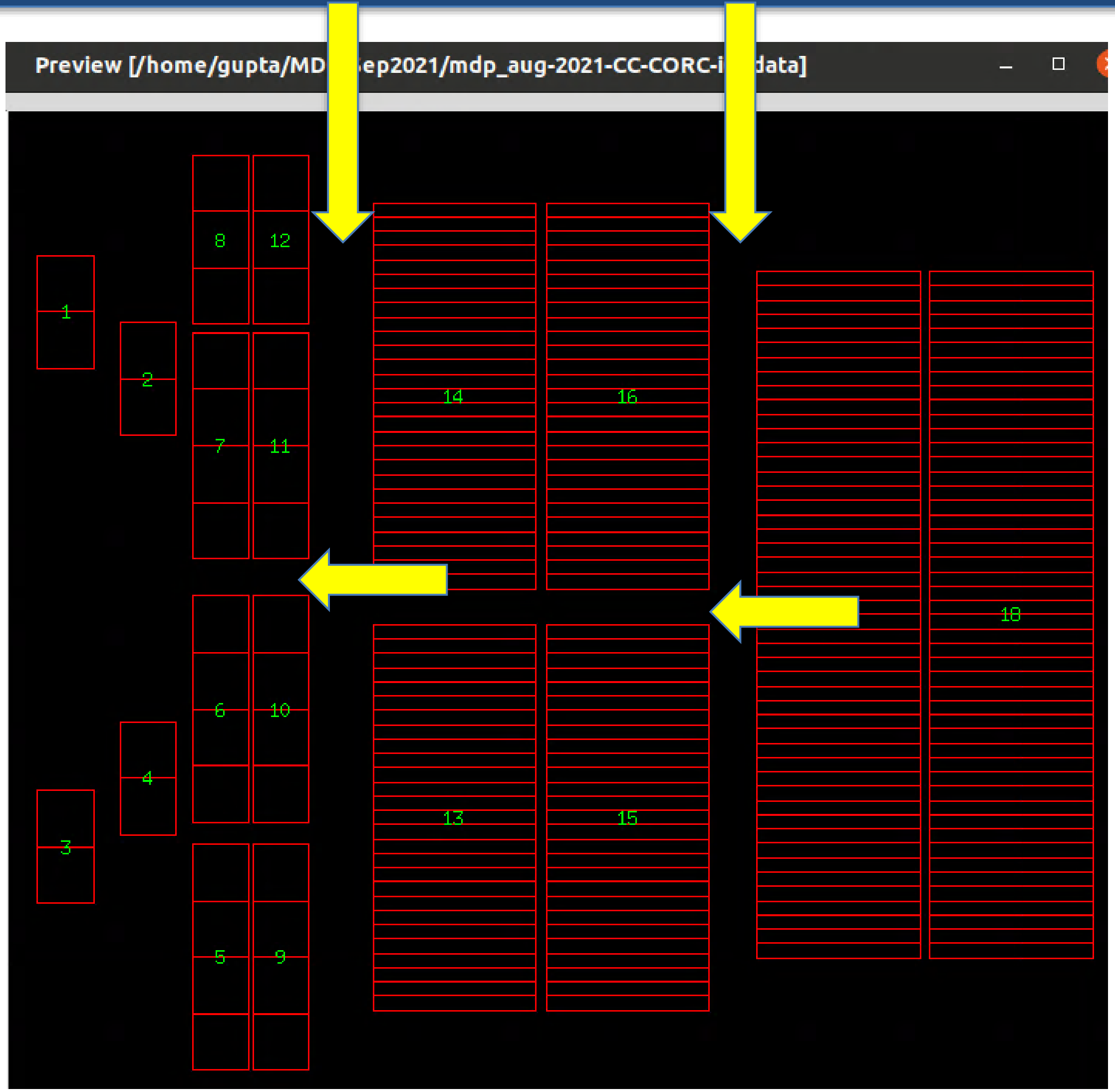


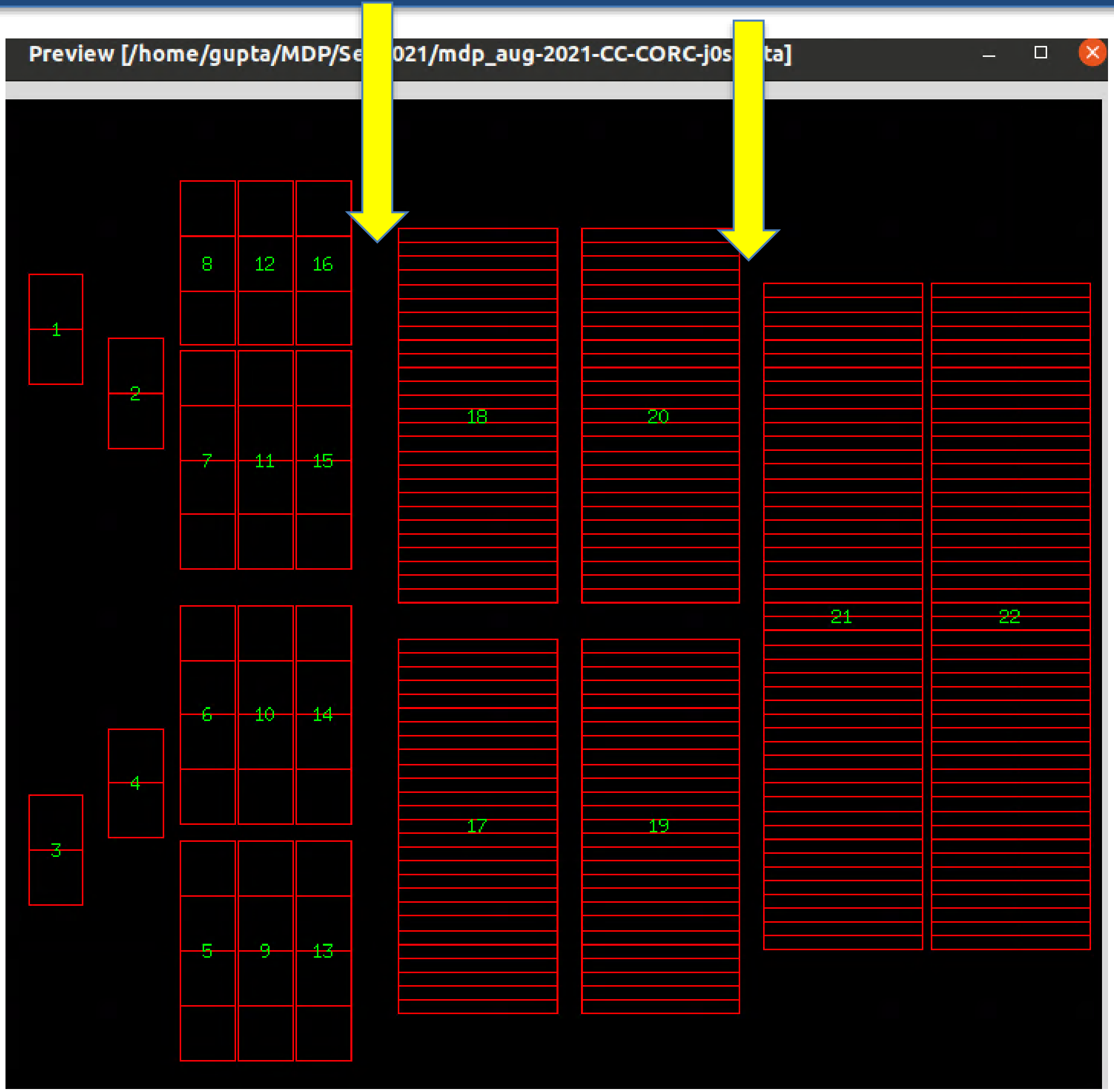




Design with Space for Structure (example CORC Coils)

Designs Allowing Space for Stress Management

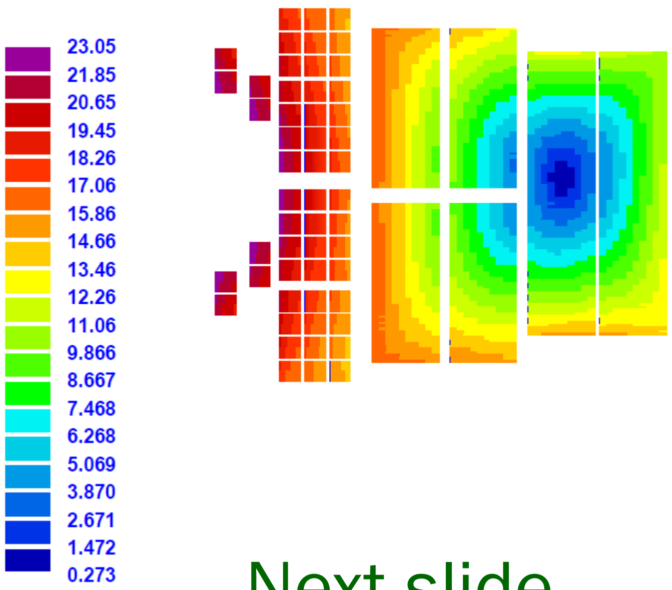




Lorentz Forces at the Quench Field (1)

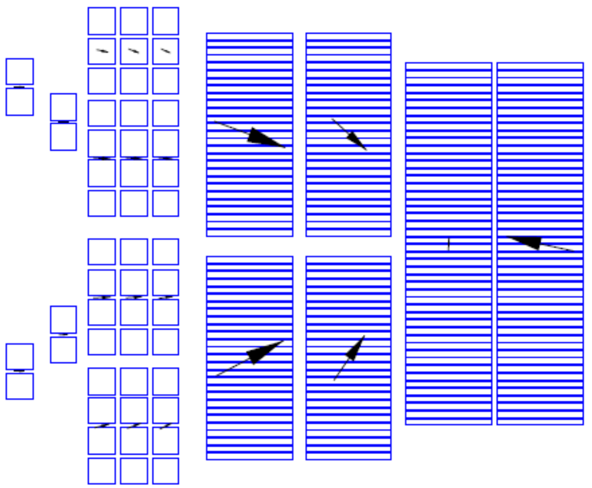
MDP 22T Hybrid CORC/Bi2212 + Nb3Sn Common Coil Dipole

|B| (T)

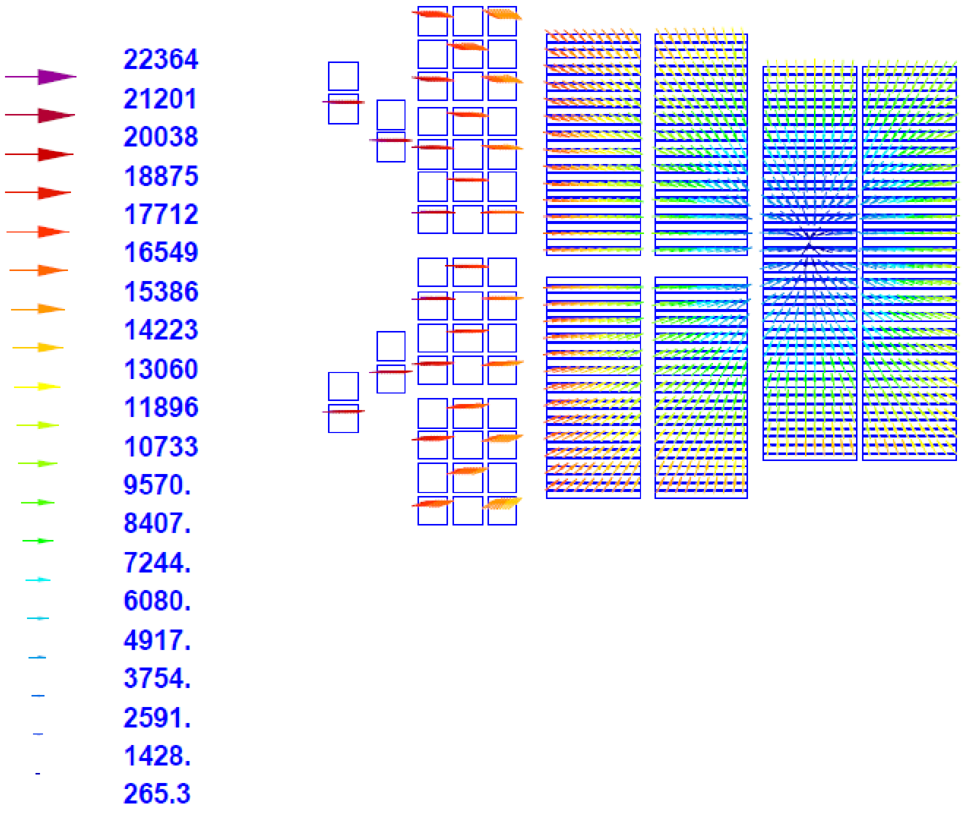


Lorentz forces at 22 T

Next slide for F_x and F_y



Emag. force / L (N/m)



ROXIE 10.2

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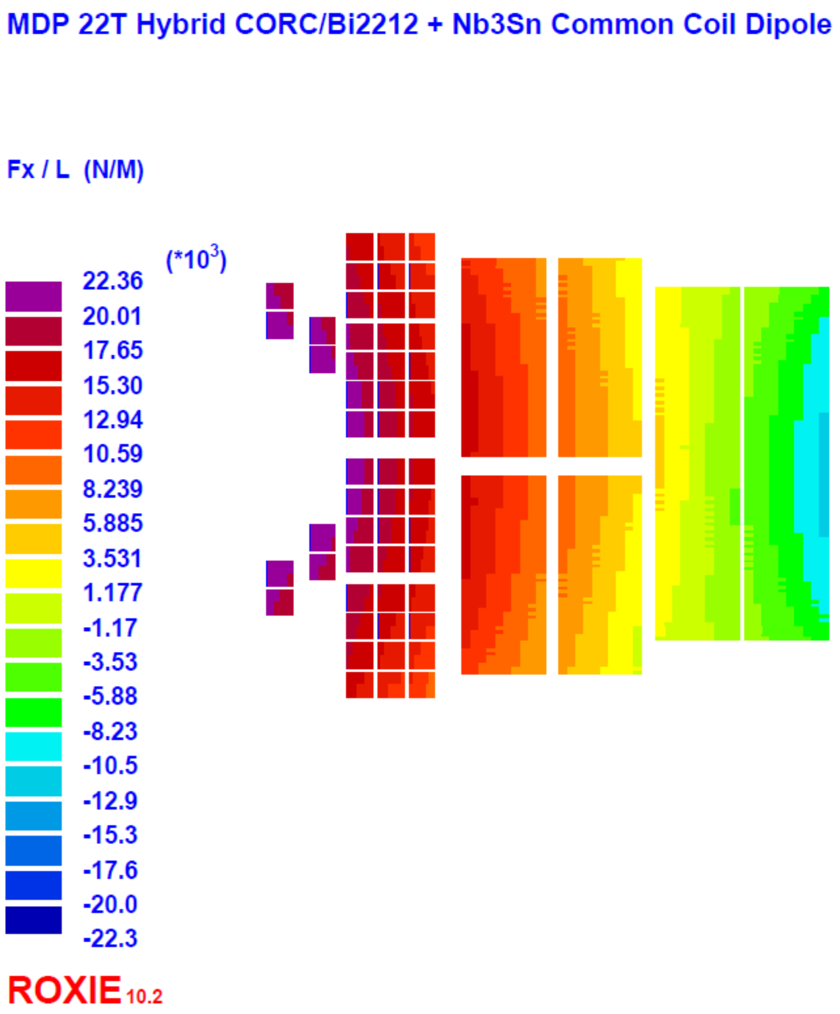
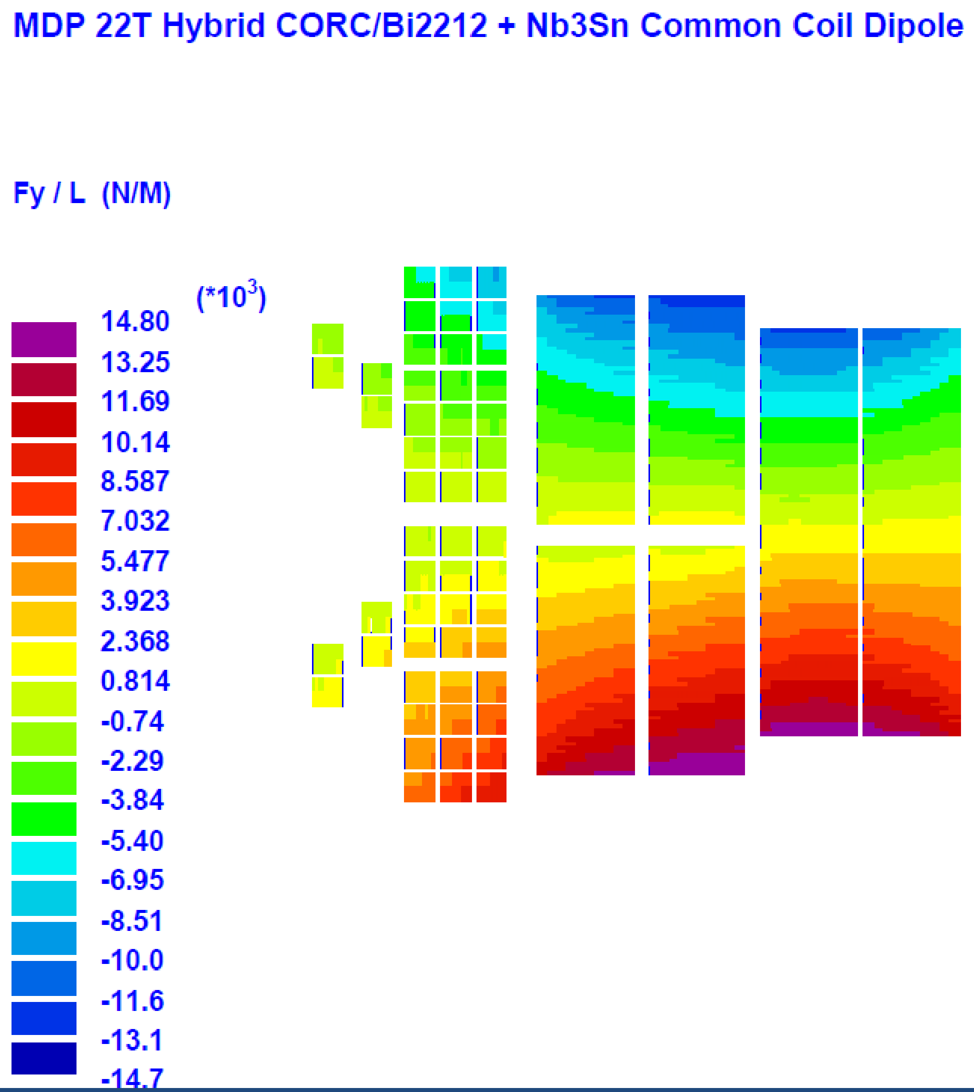
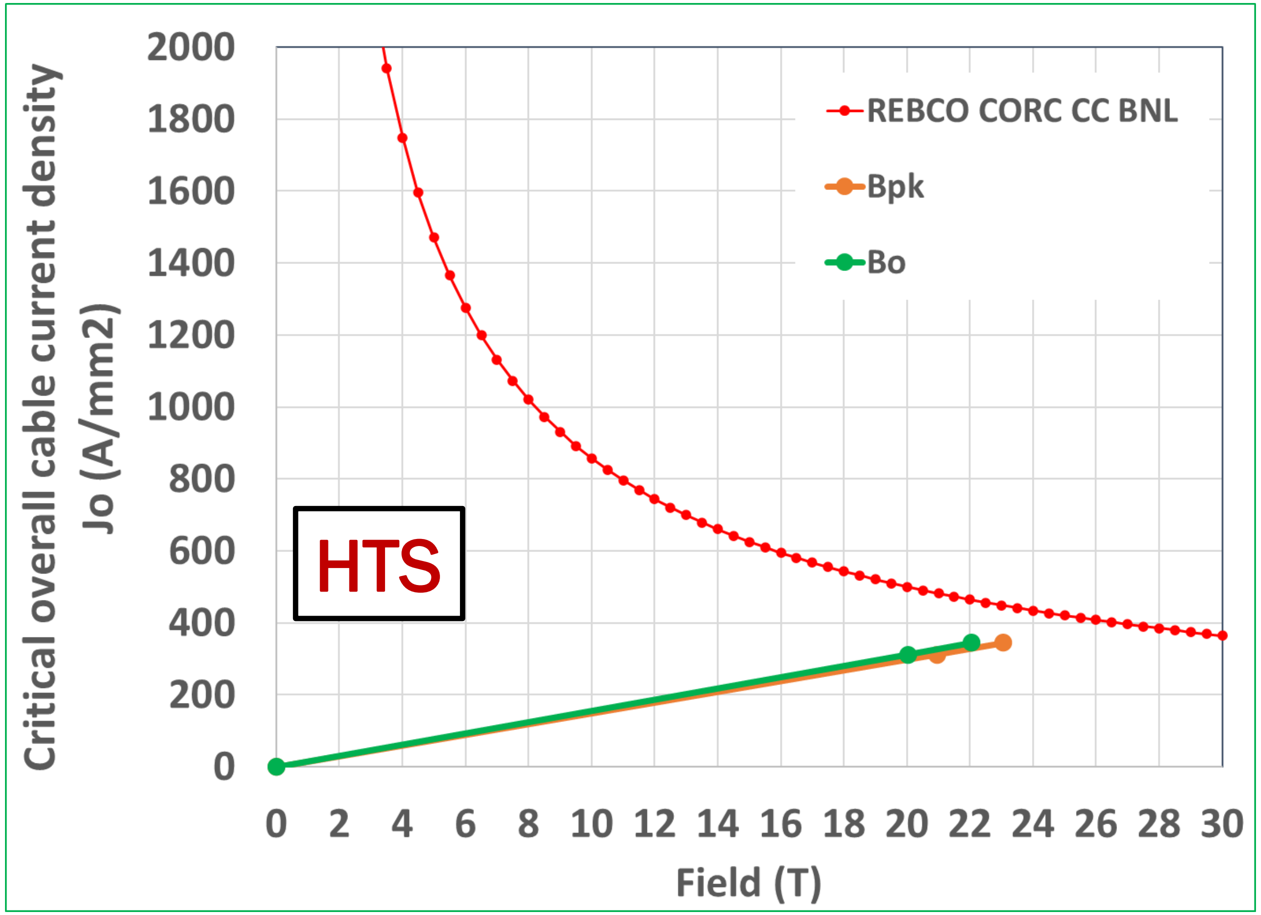
Lorentz Forces at the Quench Field (2)

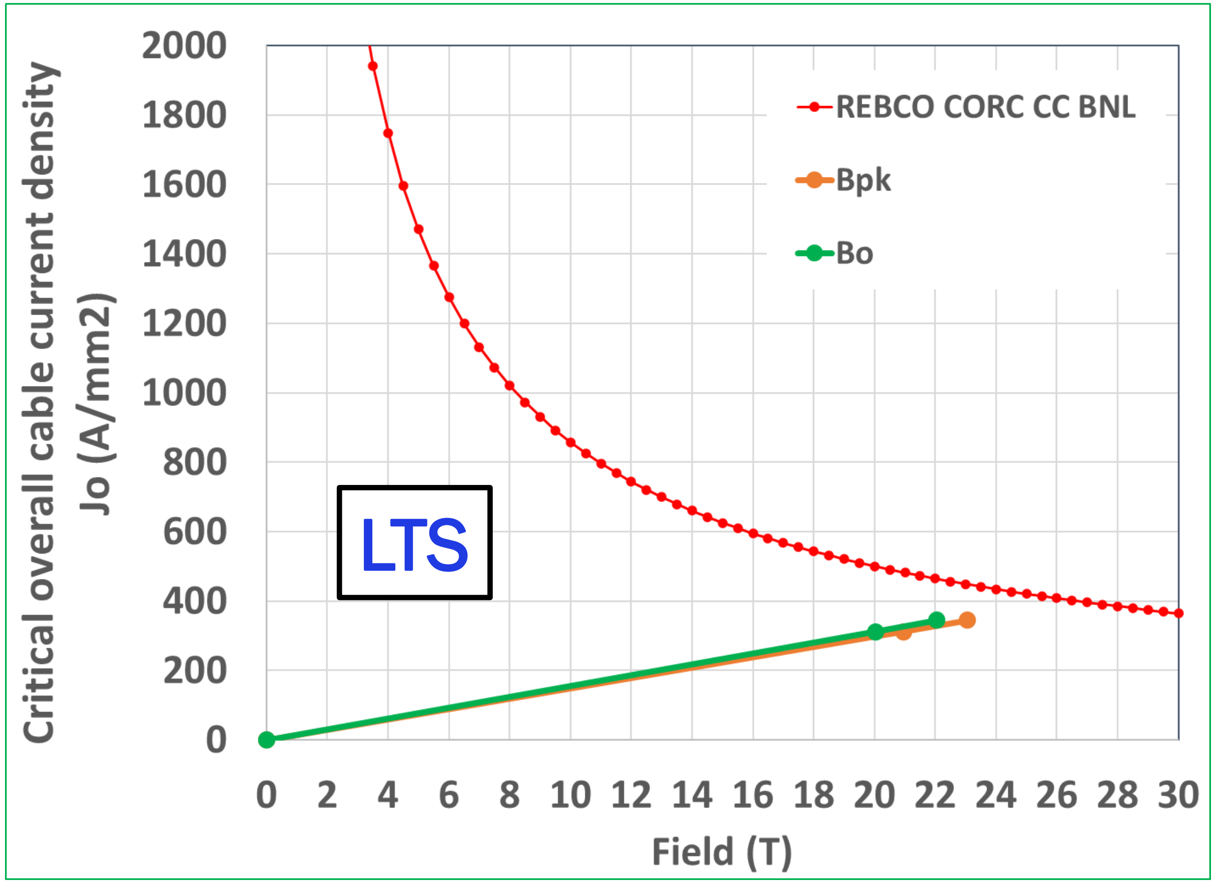




Margins in 20 T Hybrid CORC Common Coil

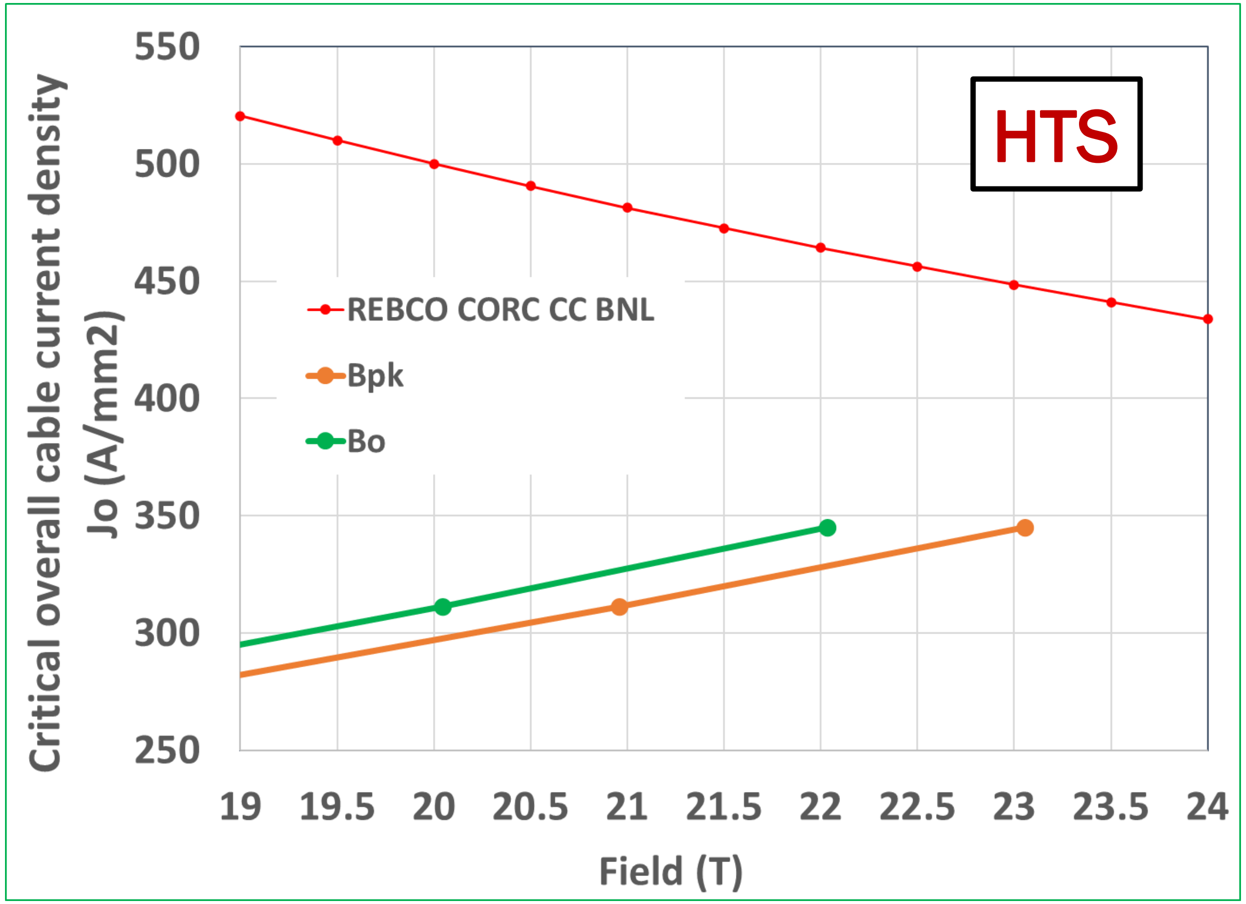
- 8% margin at 4.2 K, 18% at 1.8 K (plots for Jo), limited b y LTS

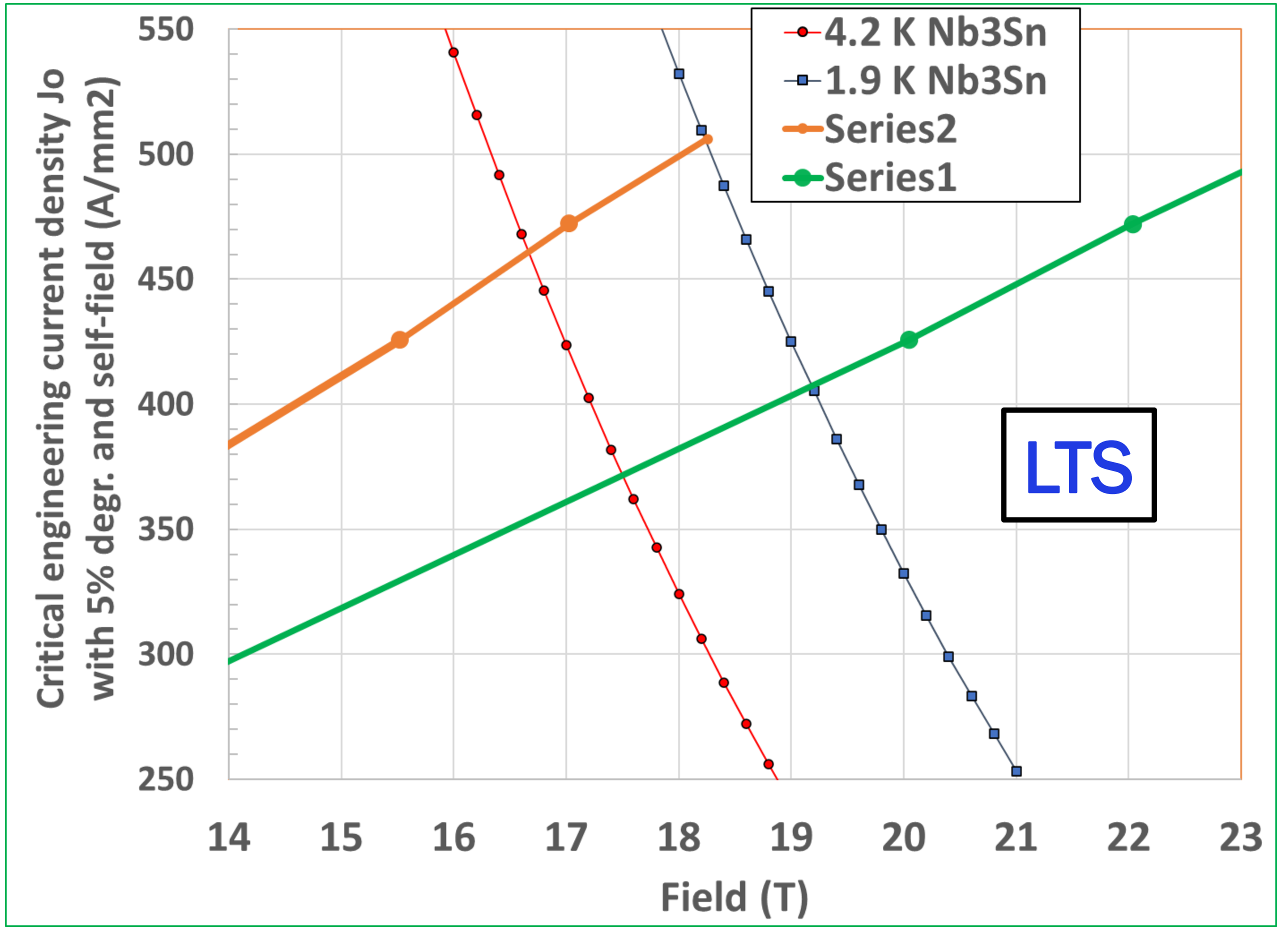




Margins in 20 T Hybrid CORC Common Coil (2)

- 8% margin at 4.2 K, 18% at 1.8 K (plots for Jo), limited b y LTS





New Design for CORC/Nb_3Sn Common Coil

MAIN FIELD (T) 20.046534

MODEL	mdp_aug-2021-CC-CORC-j0s	
MDPCCCORC	Bi2212	CORC STTR
Ins w		7.5
Ins h		7.5
Ins Area		56.250
Current		17500
Jo (A/mm^2)		311.1
Bpeak (T)		20.96
MDPH1	Nb3Sn	
Ins w	1.9	
Ins h	21.63	
Ins Area	41.097	
Current	17500	
Jo (A/mm^2)	425.8	
Bpeak (T)	15.52	
B0(T)	20.046	

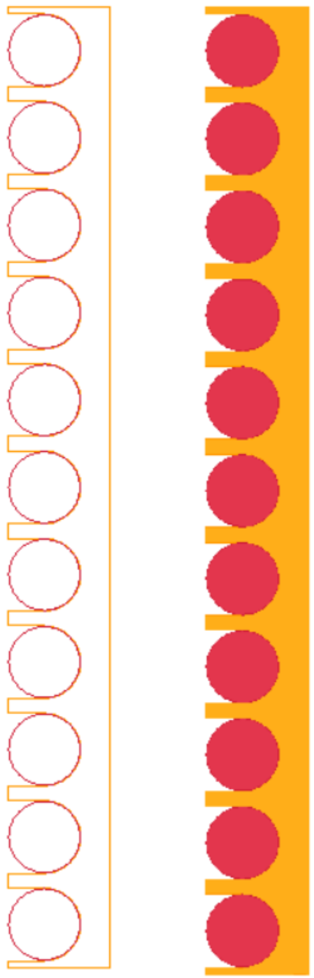
mdp_aug-2021-CC-CORC-j0s.output

NUMBER OF BLOCK	1
NUMBER OF CONDUCTORS	2
POSITIONING ANGLE (DEG)	223.4000
INCLINATION ANGLE (DEG)	0.0000
CURRENT IN EACH CONDUCTOR OF THE BLOCK (A)	-17500.0000
INNER RADIUS OF THE BLOCK (MM)......................	4.8000
CABLE HEIGHT (MM).(INSULATED)	7.5000
CABLE INNER WIDTH (MM).(INSULATED)	7.5000
CABLE OUTER WIDTH (MM).(INSULATED)	7.5000
CABLE HEIGHT (MM).(BARE)	6.5000
CABLE INNER WIDTH (MM).(BARE)	6.5000
CABLE OUTER WIDTH (MM).(BARE)	6.5000
RADIAL INSULATION THICKNESS (MM)....................	0.5000
AZIMUTHAL INSULATION THICKNESS (MM).................	0.5000
NUMBER OF STRANDS	5
DIAMETER OF STRANDS (MM)............................	6.5000
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)	0.994
NUMBER OF DISCRETISATION POINTS AZIMUTHAL	2
NUMBER OF DISCRETISATION POINTS RADIAL	10
CONDUCTOR NAME	MDPCORC1

Xroxie [/home/gupta/MDP/Sep2021/mdp_aug-2021-CC-CORC-j0s.data]

mdp_aug-2021-CC-CORC-j0s.output

NUMBER OF BLOCK	17
NUMBER OF CONDUCTORS	27
POSITIONING ANGLE (DEG)	110.0000
INCLINATION ANGLE (DEG)	0.0000
CURRENT IN EACH CONDUCTOR OF THE BLOCK (A)	-17500.0000
INNER RADIUS OF THE BLOCK (MM)......................	55.0000
CABLE HEIGHT (MM).(INSULATED)	21.6300
CABLE INNER WIDTH (MM).(INSULATED)	1.9000
CABLE OUTER WIDTH (MM).(INSULATED)	1.9000
CABLE HEIGHT (MM).(BARE)	21.3300
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	55
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)	1.361
NUMBER OF DISCRETISATION POINTS AZIMUTHAL	2
NUMBER OF DISCRETISATION POINTS RADIAL	10
CONDUCTOR NAME	MDPH1



Field Quality in 20 T CORC Common Coil Hybrid

```
HARMONIC ANALYSIS NUMBER .............................             1
MAIN HARMONIC ........................................             1
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 ....................    0.2729E-03
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .......................................     20.046534
MAGNET STRENGTH (T/(m^(n-1)) .........................       20.0465
```

All harmonics $<10^{-4}$

* Mostly 10^{-5} *

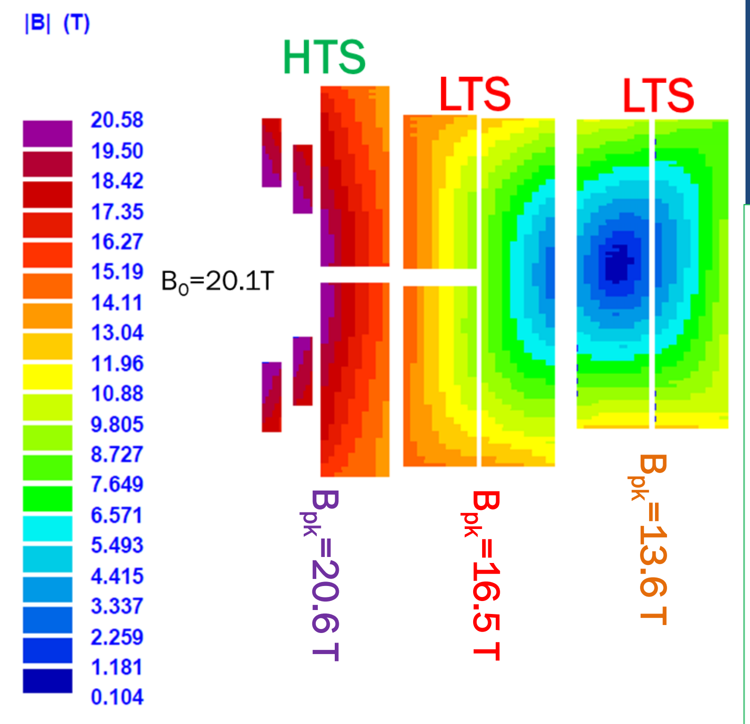
NORMAL RELATIVE MULTIPOLES (1.D-4):

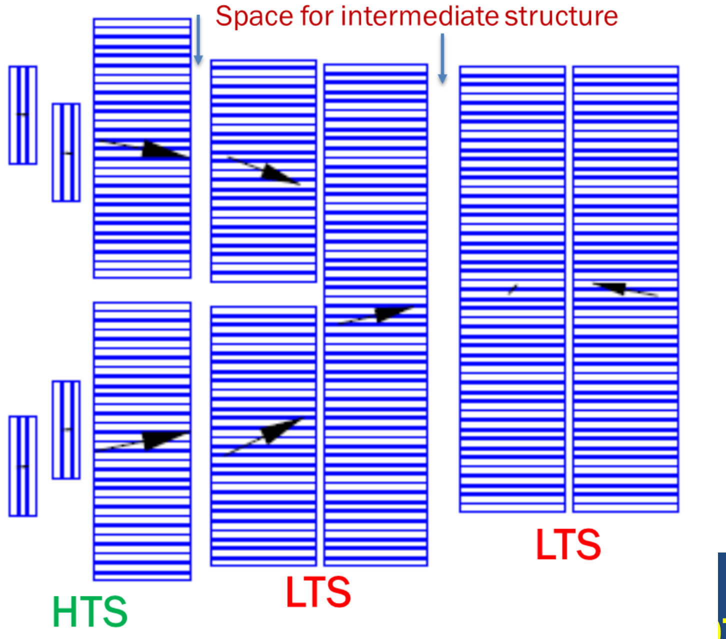
b 1:	10000.00000	b 2:	0.00000	b 3:	-0.00014
b 4:	0.00000	b 5:	-0.00361	b 6:	-0.00000
b 7:	-0.05091	b 8:	0.00000	b 9:	-0.45866
b10:	0.00000	b11:	-0.43506	b12:	-0.00000
b13:	-0.00984	b14:	-0.00000	b15:	0.00047
b16:	0.00000	b17:	-0.00743	b18:	-0.00000
b19:	-0.00114	b20:	-0.00000	b	

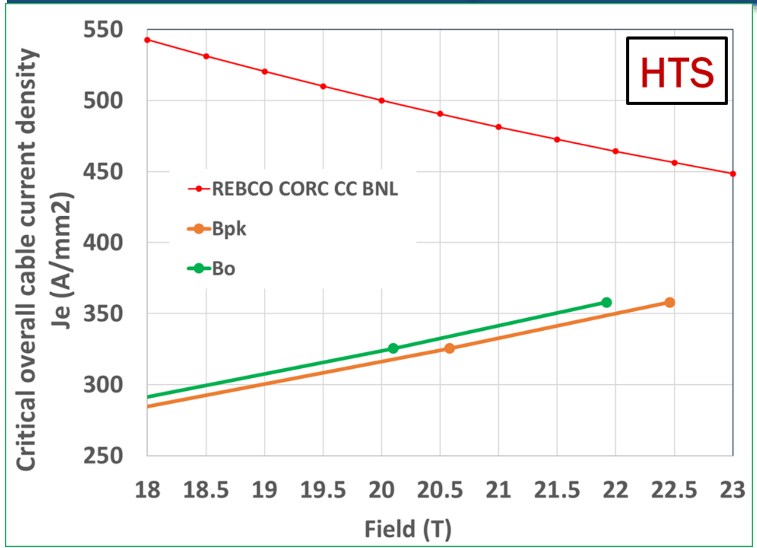
SKEW RELATIVE MULTIPOLES (1.D-4):

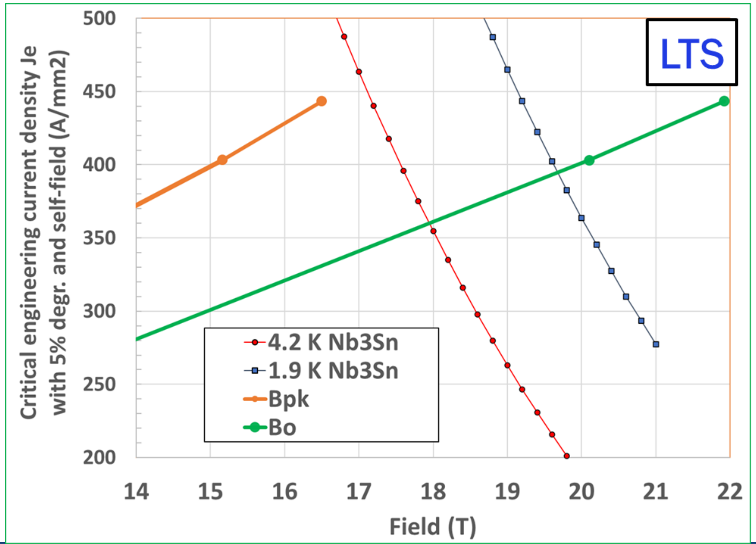
a 1:	-0.00000	a 2:	0.01028	a 3:	0.00000
a 4:	0.00234	a 5:	0.00000	a 6:	0.02195
a 7:	0.00000	a 8:	0.26544	a 9:	-0.00000
a10:	0.22283	a11:	0.00000	a12:	0.01183
a13:	-0.00000	a14:	0.00324	a15:	-0.00000
a16:	0.00720	a17:	0.00000	a18:	0.00183
a19:	0.00000	a20:	0.00055	a	

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





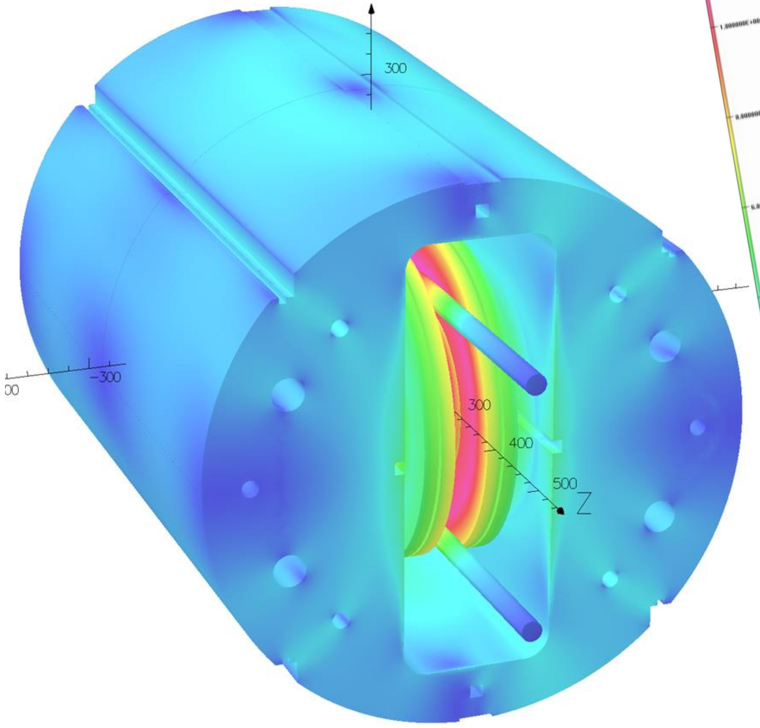


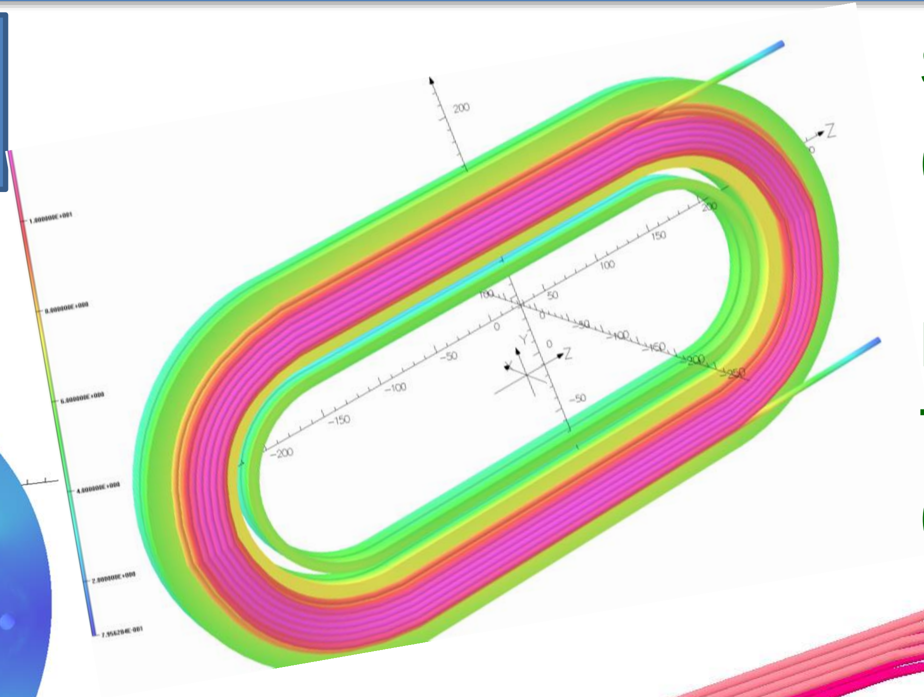


- Natural segmentation between HTS and LTS (and different cables)
- Easier tuning between HTS & LTS
- Coil layers move as a module without causing strain at ends (BNL common coil had 200 μm)
- Intermediate space for stress management structure. It can be easily adjusted, even at the late stage of the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

CORC Coil Programs with the Common Coil Dipole

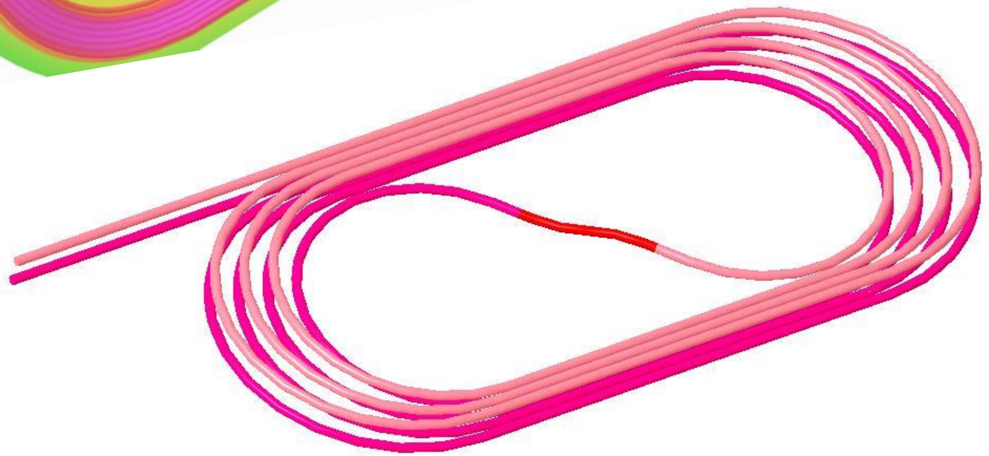
STTR Coils two sets:
Each with 6 and 8 turns





STTR: High field Demo
(13-14 T with 10 T from LTS)

MDP: Quench studies and technology demo
(10.7 T with 10 T from LTS)

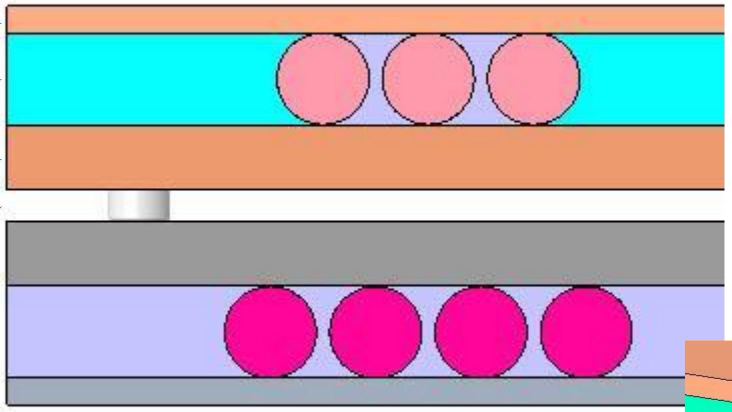


MDP Coil
4+4 turns
with an S-turn

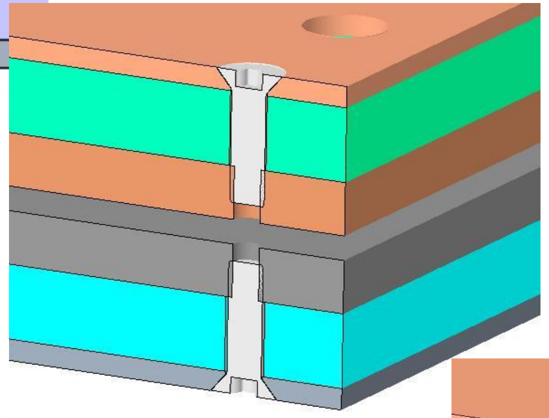
CORC® coils will run in series with the Nb_3Sn coils

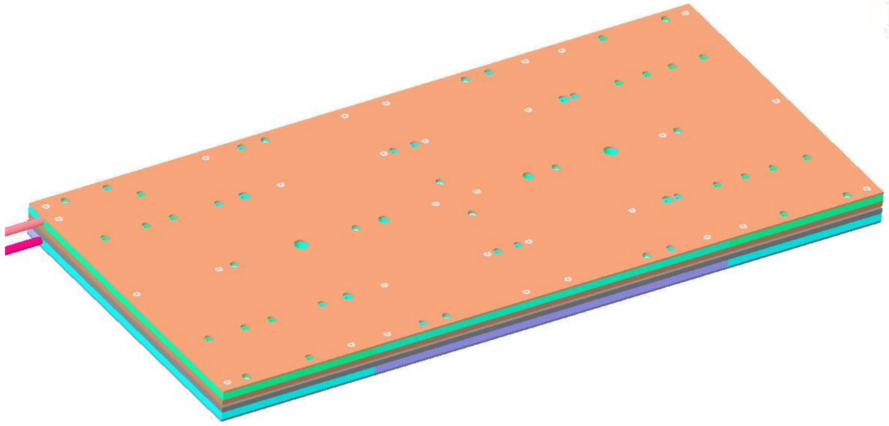
CORC Coil Package (MDP)

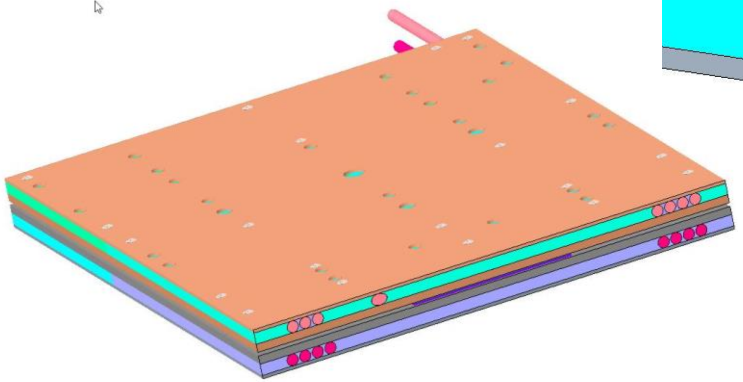
- Overall thickness – 30.3 mm
- Outer plates – 2 mm
- Coil spacers – 7 mm
- Inner plates – 5 mm
- Gap between layers – 2.3 mm

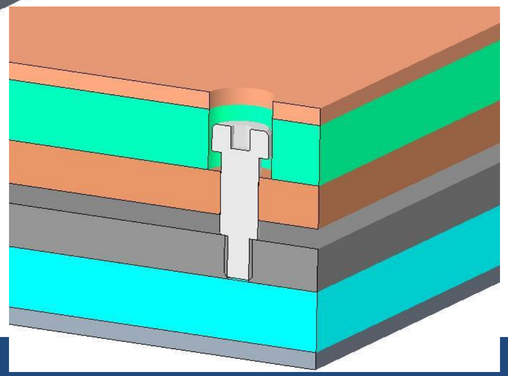


- Each layer held together with flat head screws
- Assembly held with shoulder screws to allow separation of layers.

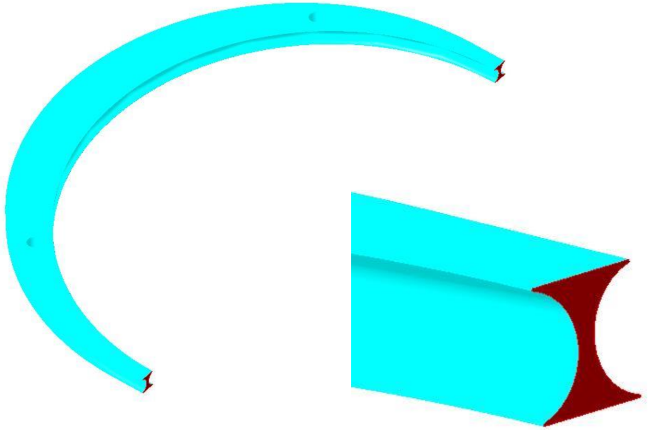


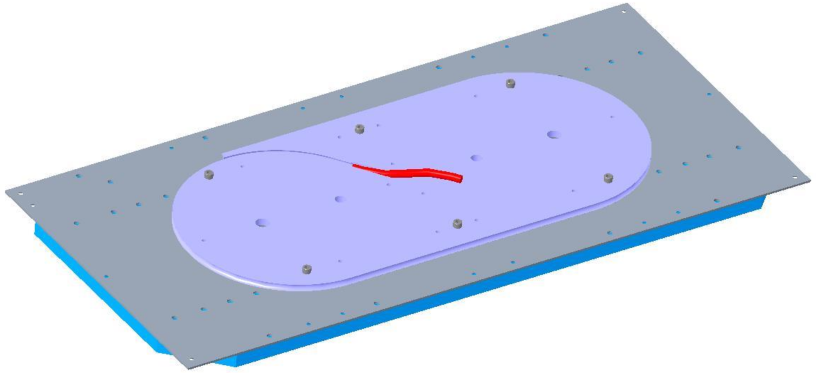


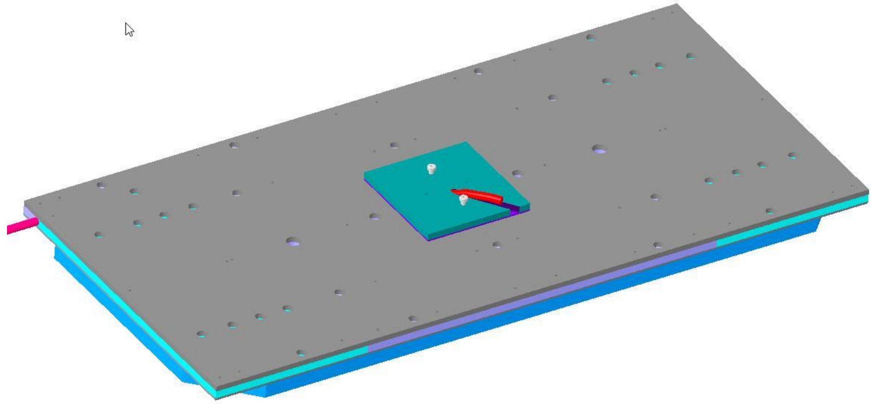


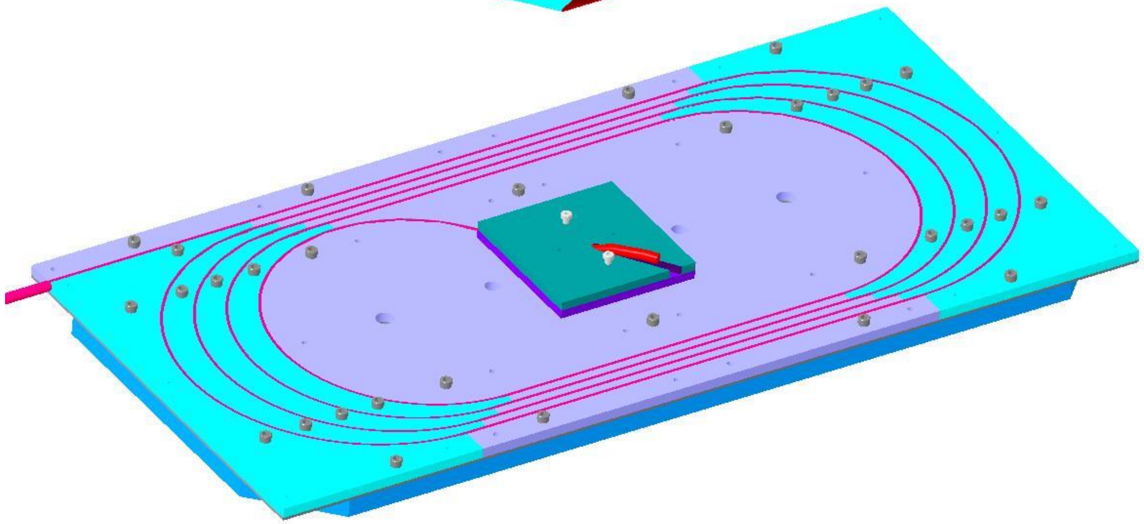


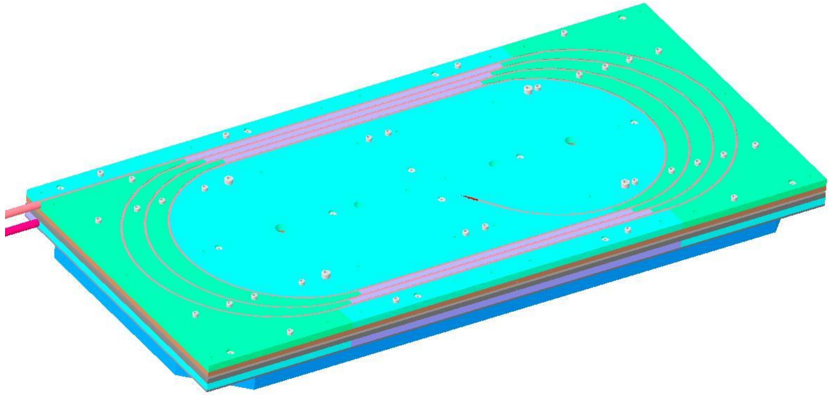
Coil & Structure Parts, as Designed



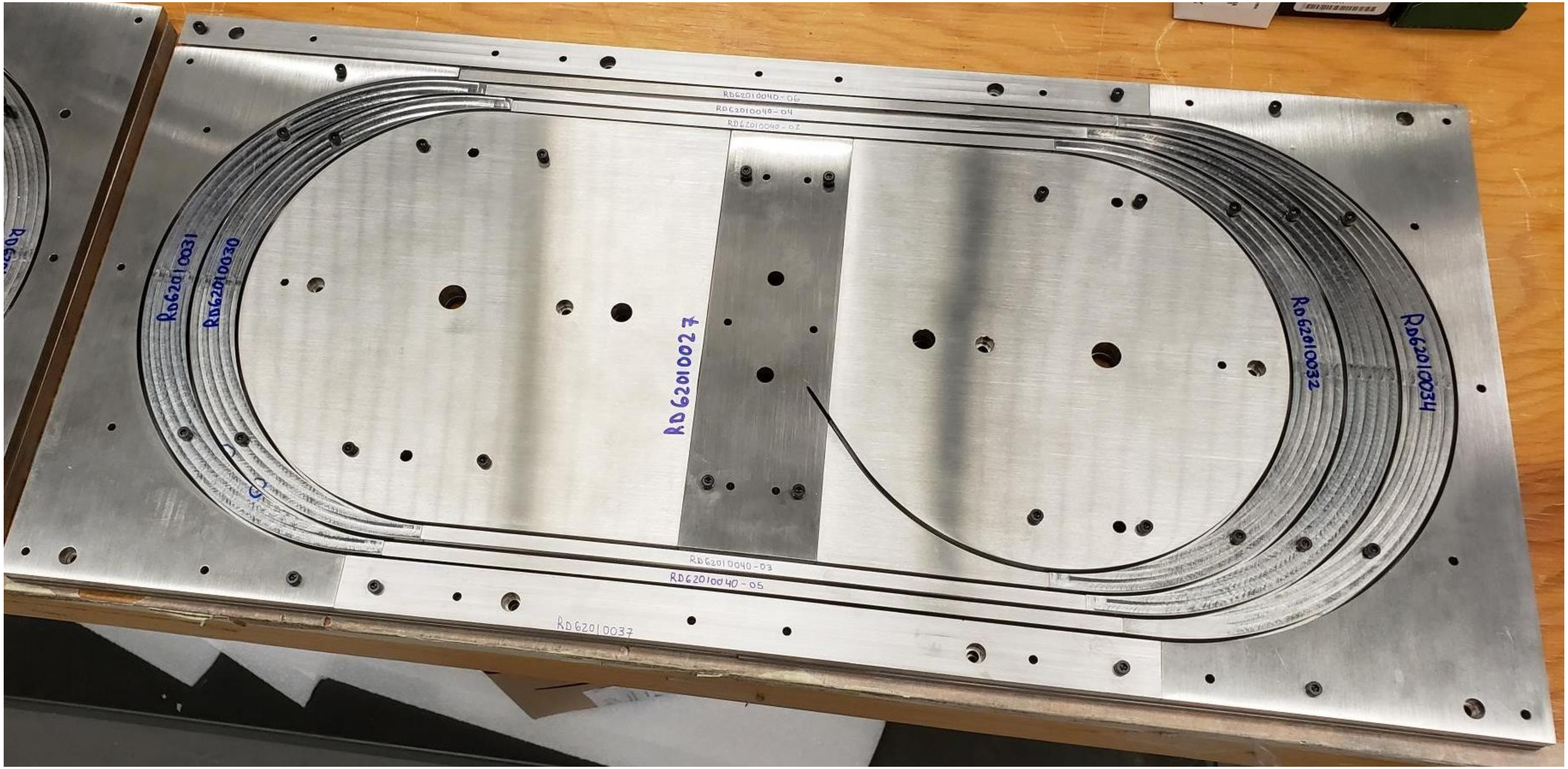








Parts, as Made or Delivered (all parts in hand now)



Parts for one-side of the coil

Summary and Discussion

Observations on the HTS/LTS hybrid common coil design presented today:

- The design provides the desired margin for both HTS and Nb_3Sn, even at 4 K
- Same magnetic design is used for both CORC and Bi2212
  - ➢ Common coil design allows higher J_e or higher J_o for CORC
- The design is reasonably well optimized for a good field quality
- We, however, should be able to optimize the conductor usage as LTS coils still have room. As such the common coil design is well suited for hybrid designs.
- Space for the managed structure is included and more/less can be adjusted, as needed
  - ➢ Next Step – mechanical analysis and structure design
  - ➢ Expect that the magnetic and mechanical design to be iterated together
- Stress management should be relatively easier and effective in the common coil design
- All files (ROXIE, EXCEL, etc.) are available for sharing