U.S. MAGNET DEVELOPMENT PROGRAM

Optimization of Common Coil Geometry and Relative Conductor Usage for a 20 T Design

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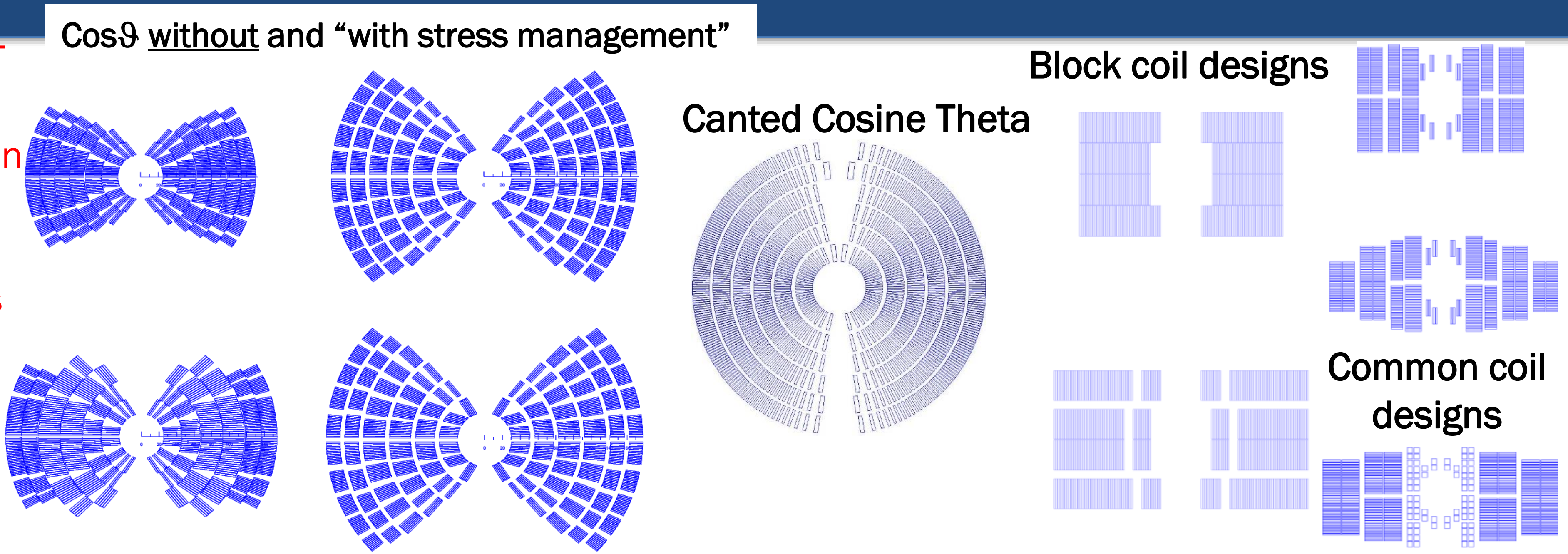
January 25, 2022

Content

- Comparative study – conductor usage in different designs
  - Why the conductor usage appears to be lower in the common coil design as compared to the other designs based on the initial design work on 20 T
- Updated design satisfying the 15% margin requirements and flexibilities
- Work ahead – mostly mechanical design and analysis
- Summary

Some Observations and Possible Explanation

- Comparative studies of 20 T designs revealed that in the common coil design, one can get away with fewer layers and it uses less conductor.
- This is opposite to what was the conventional wisdom. Small differences in margin can't explain that.
- Any basic change in going from lower to higher fields?



Parameter	UNIT	CT I	CT II	SMCT I	SMCT II	CCT	BL I	BL II	CC I	CC II	CC III
Ins. cable I width/thick.	mm	10.7/1.5	12.0 / 1.7	12.3 / 1.5	12.3 / 1.5	18.7/1.9	17.1/2.1	17.1/2.1	18.7 / 1.8	18.7 / 1.8	7.5/7.5
Ins. cable II width/thick.	mm	9.4/1.5	14.2 / 2.1	10.7 / 1.5	13.9 / 1.5	-	17.1/2.1	17.1/2.1	13.6 / 1.9	13.6 / 1.9	21.6 / 1.9
Ins. cable III width/thick.	mm	9.3/1.5	7.9 / 1.5	9.1 / 1.5	9.1 / 1.5	-	-	-	-	-	-
Current_op	kA	10.7	13.0	11.4	11.8	12.8	12.6	12.2	14	13.9	17.8
B_bore_op	T	20.0	20.0	20.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0
B_bore_op HTS/LTS	T	20.5 / 12.7	20.3 / 16.1	20.6 / 13.6	20.6 / 16.0	20.2 / 13.2	20.6 / 15.1	20.9 / 15.2	20.4 / 13.8	20.2 / 13.7	21.0 / 17.0
B_bore_ss	T	24.4	23.5	24.4	23.2	23.4	23.6	23.6	22.9	23	21.7
B_bore_ss HTS/LTS	T	24.9/15.4	23.8 / 17.7	24.9 / 16.4	23.8 / 18.4	23.6 / 12.9	24.3 / 17.7	24.7 / 18.0	23.3 / 15.7	23.3 / 15.7	24.7 / 18.2
Load-line margin	%	18 / 25	21 / 15	22 / 18	20 / 15	14 / 14	21/17	22 / 17	13 / 13	13 / 13	15 / 7
Area quad. ins. cable HTS	mm^2	3241	1494	2091	1527	4490	1360	1500	1290	1154	1012
Area quad. ins. cable LTS	mm^2	2150	6106	3780	5148	4915	4740	6000	2326	2558	4191
Coil width*	mm^2	105	129	144	149	135	80	112	70	104	106
Coil inner radius*	mm	25	25	30	30	30	35	35	25	25	25

<=Typo?

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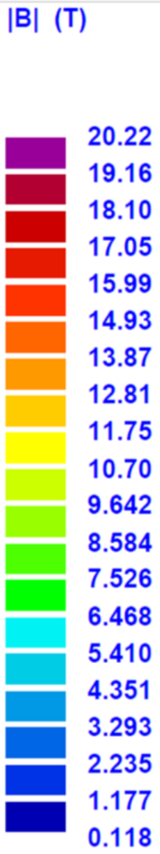
11/19/2021

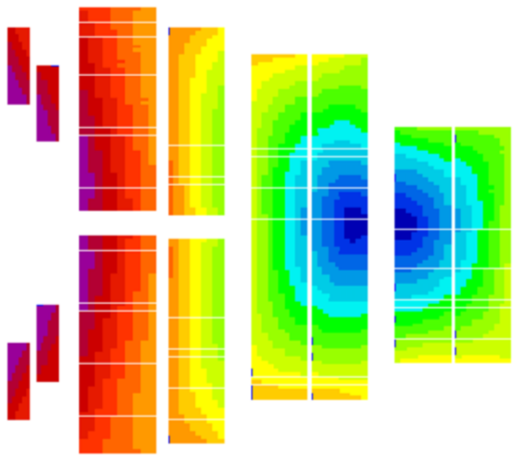
P. Ferracin, "Towards 20 T hybrid accelerator dipole magnets"

20

Observation: Multiple solutions

6-layer design



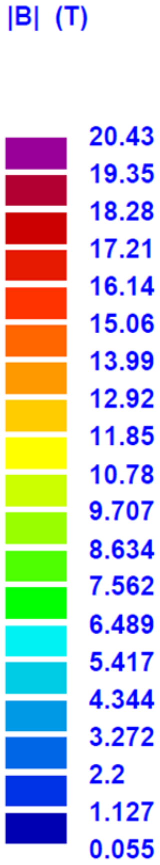


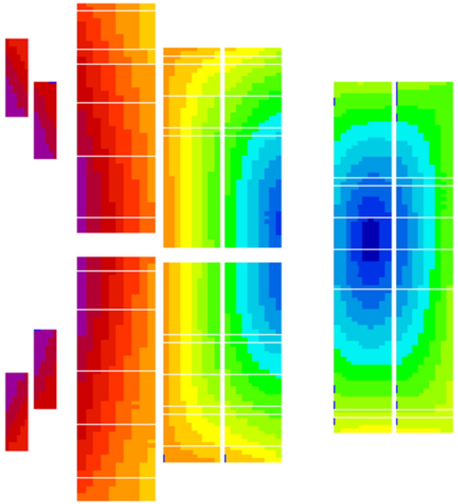
HTS: 1 layer + pole blocks
- ❖ 74 turns in ½ bore

LTS: 5 layers
- ❖ 198 turns in ½ bore

Total turns = 272

5-layer design



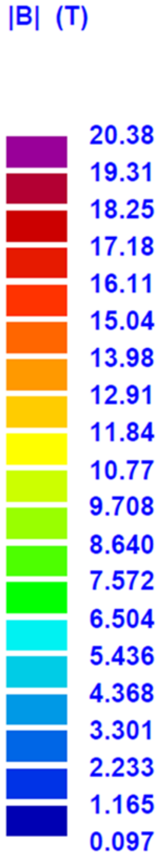


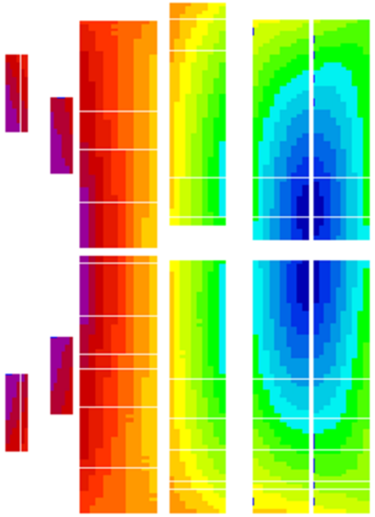
HTS: 1 layer + pole blocks
- ❖ 80 turns in ½ bore

LTS: 4 layers
- ❖ 188 turns in ½ bore

Total turns = 268

4-layer design





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

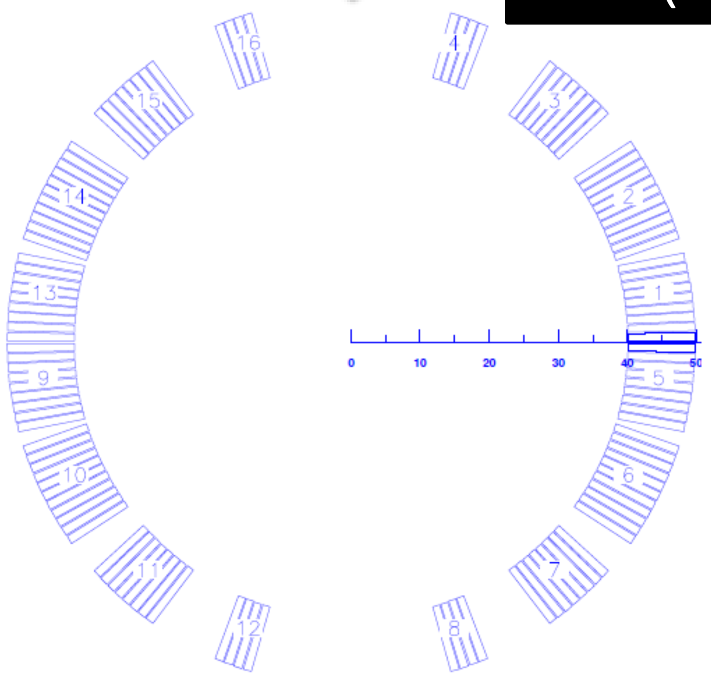
LTS: 5 layers
- ❖ 180 turns in ½ bore

Total turns = 262

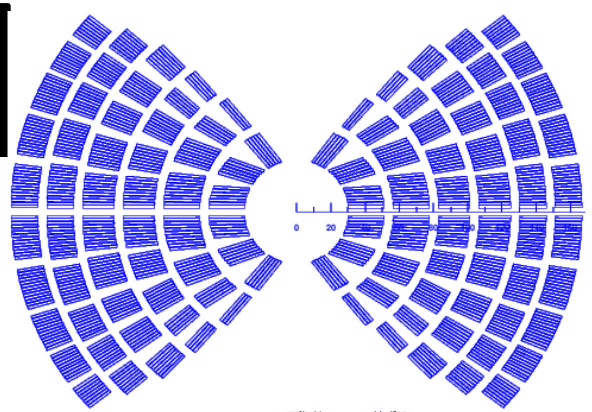
Only relatively small changes in the overall conductor uses despite a significant change between “height” Vs. “width”, while maintaining a good (10^{-4}) field quality

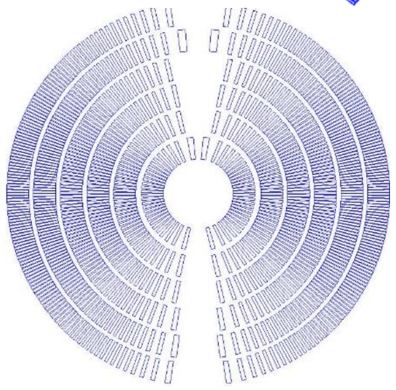
Evolution of Cosine Theta Geometry with Fields (requirement on conductor from the 1st principle)

Accelerator magnets typically have circular bore. Therefore, a shell geometry is a natural choice. At low fields, the required width (and area) of conductor needed is much less than bore. One can design magnets with a single layer coil (RHIC). Block coil geometry will require many coils (layers) and may also use more conductor.



However, the situation changes when the required conductor width (and area) becomes larger than that of the bore (MDP)





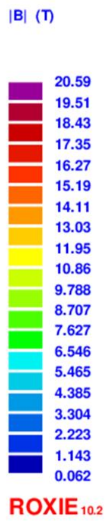
__The basic rules of the cos theta dipole design:__

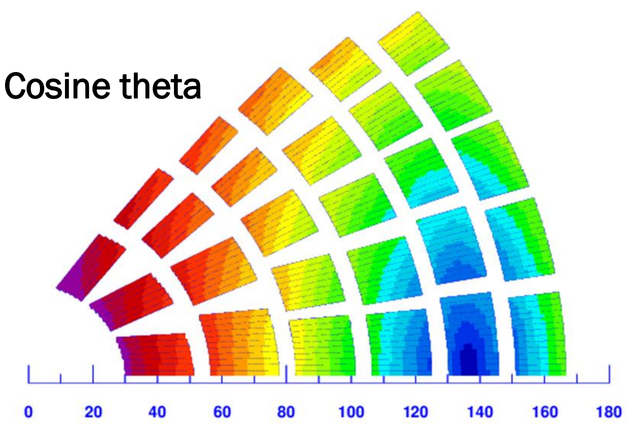
- B is proportional to the width * (current density)
- Conductor area needed to create the dipole field increases linearly with the radius of each layer (worse for fixing higher order multipoles)
- Coil must extend to 60° or more for b_3=0 (weighted average for multi-layer). These principles define the geometry and conductor area, with little freedom left

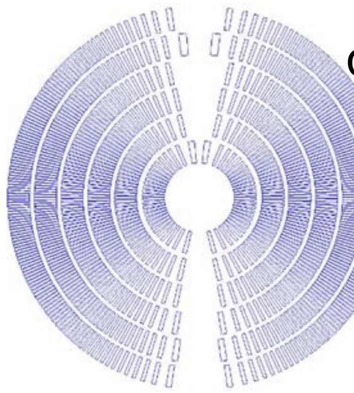
➢ Canted cosine theta design also faces similar geometrical issues on the required conductor

More Complications in Minimizing Expensive HTS in 20 T +15% margin HTS/LTS hybrid design

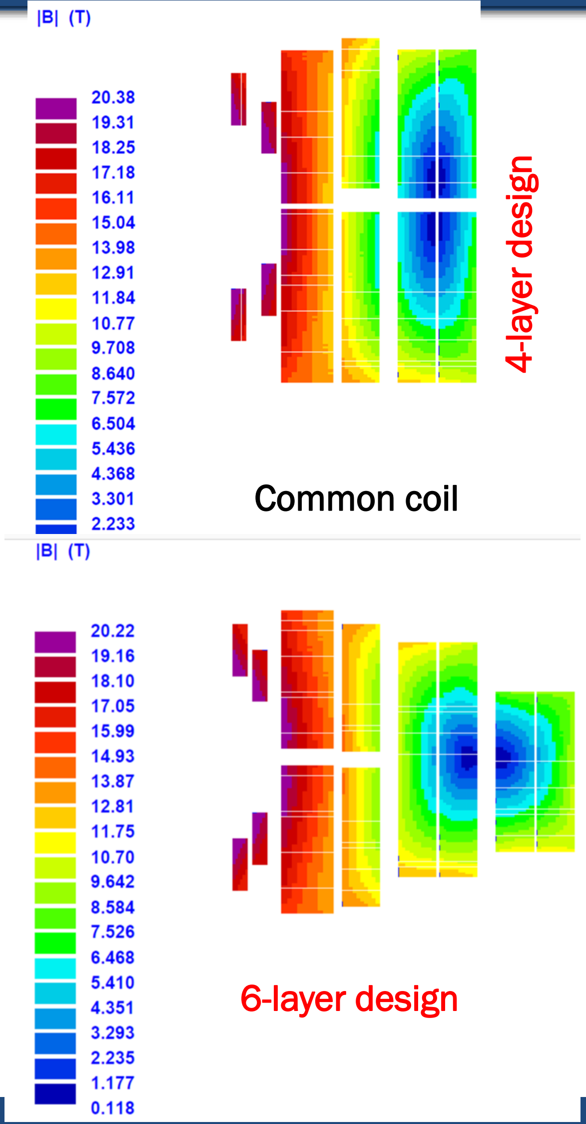
Need 2 to 4 layers of HTS. Blocks at higher pole angle need HTS (needed for field quality)



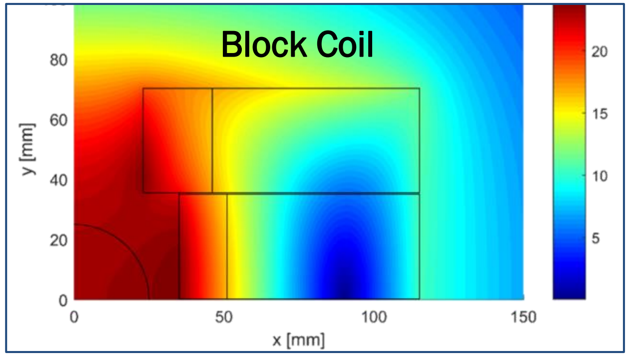


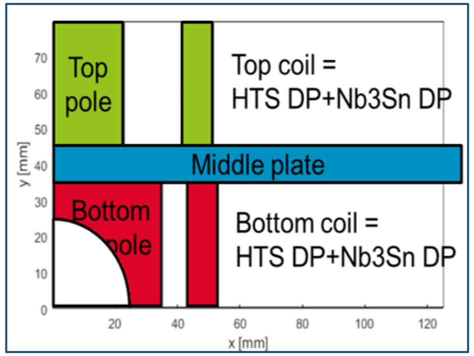


Similar issues in canted cosine theta (peak field issues may be worse for outer layer)



- Common coil design naturally provides excellent field boundary for separating HTS and LTS layers
- Only one layer of HTS required, irrespective of the number Nb_3Sn layers in the MDP 20 T design
- Coils can be extended vertically up for good field quality without increasing the number of layers
- Only design to produce <10^{-4} harmonics
- Flexible for optimizing between the width (number of layers) and height. The two are locked in cosine theta and canted cosine theta

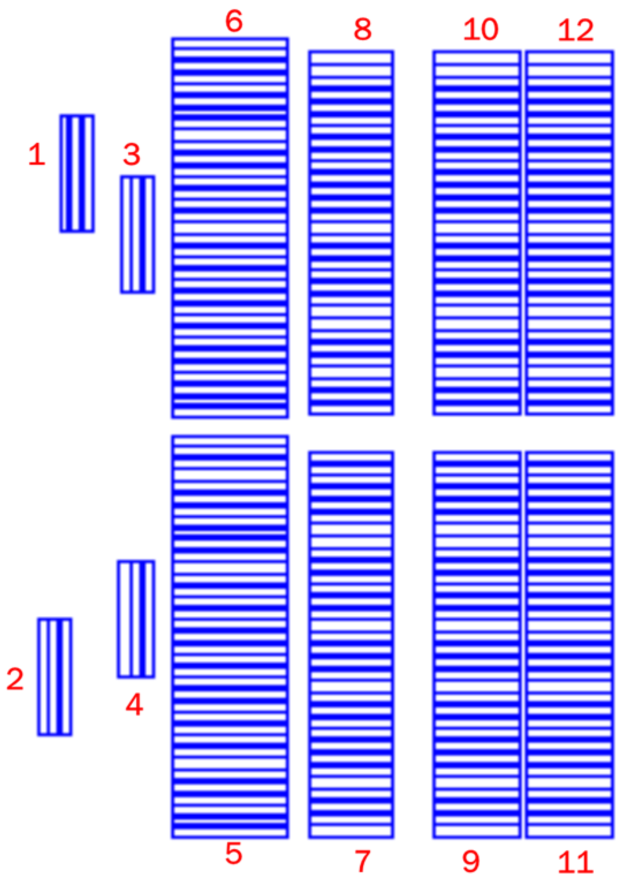




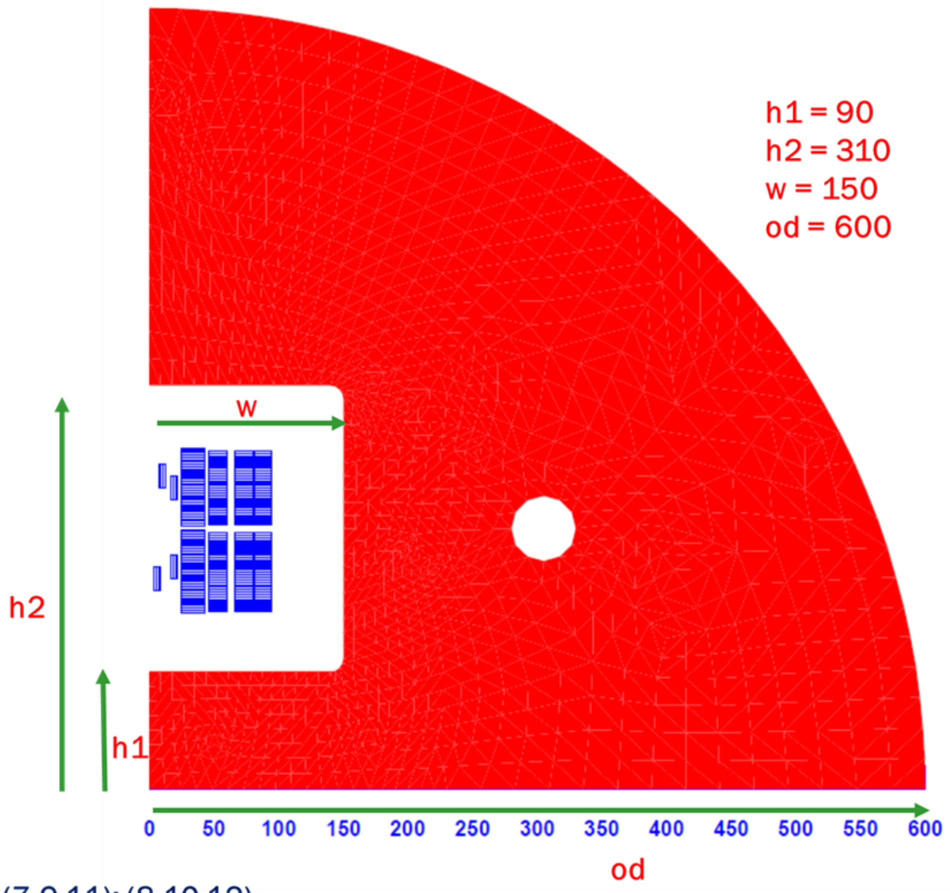
Both upper and lower layers need partly HTS (internal splice). Realistic design may need several layers

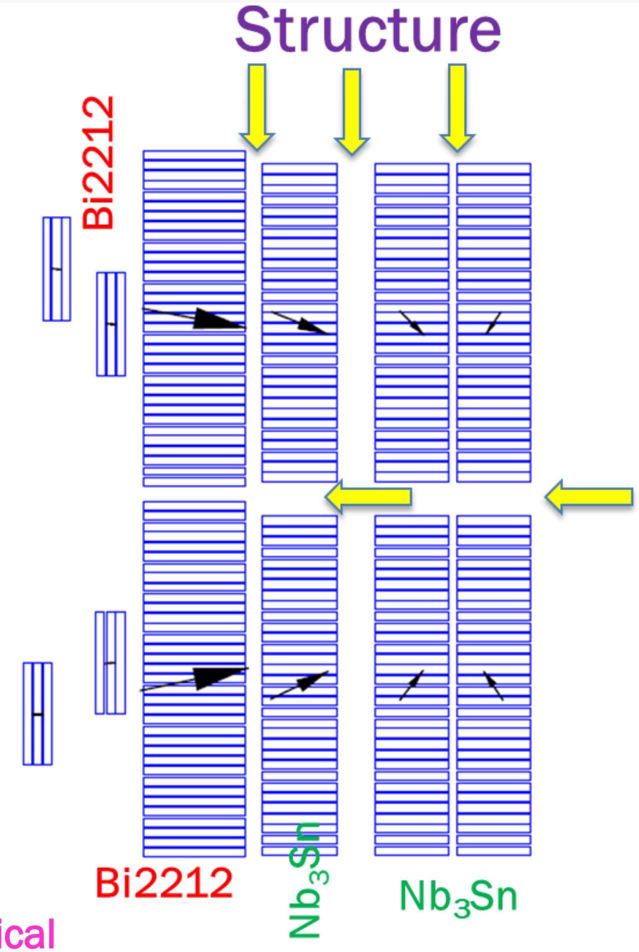
Specific Design Chosen for Jan 2022

(matched margins, fewer layers - some identical)



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

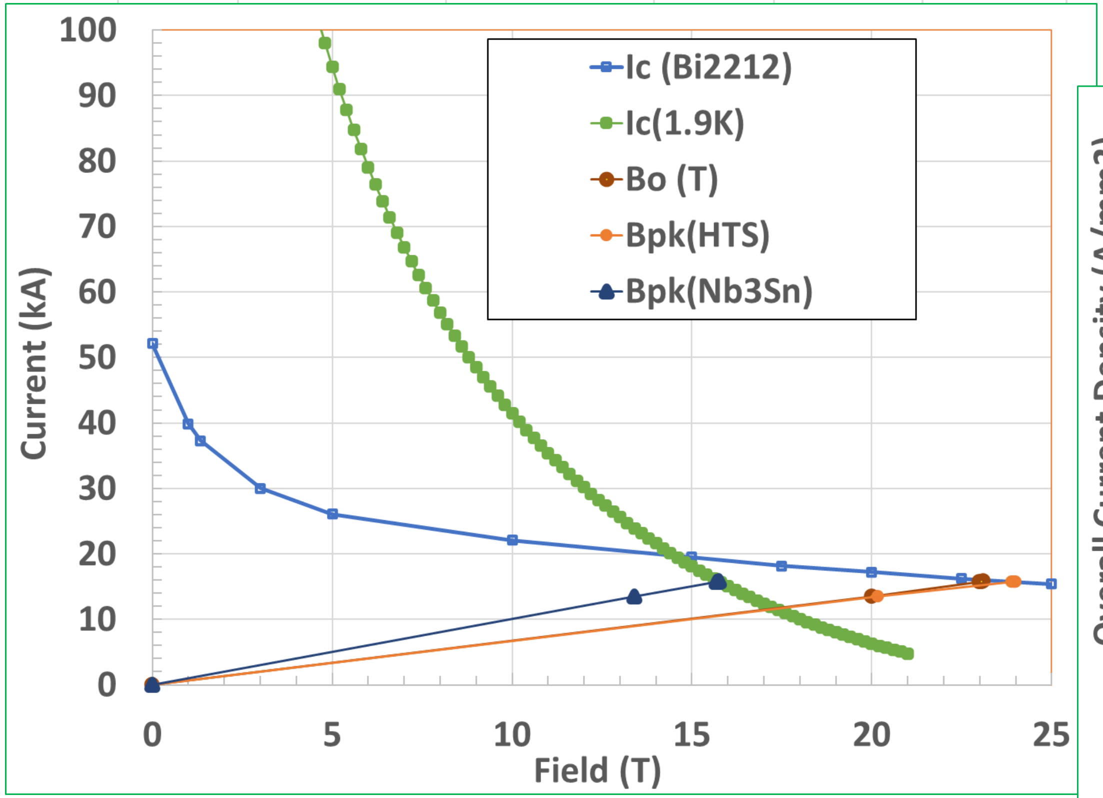


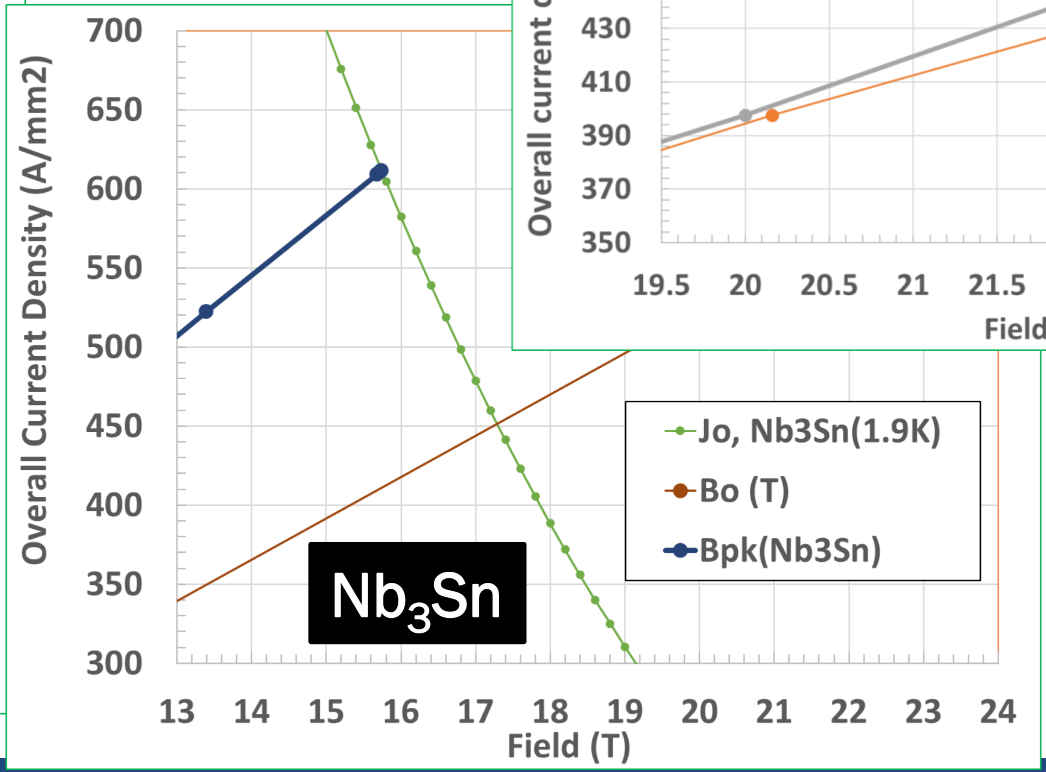


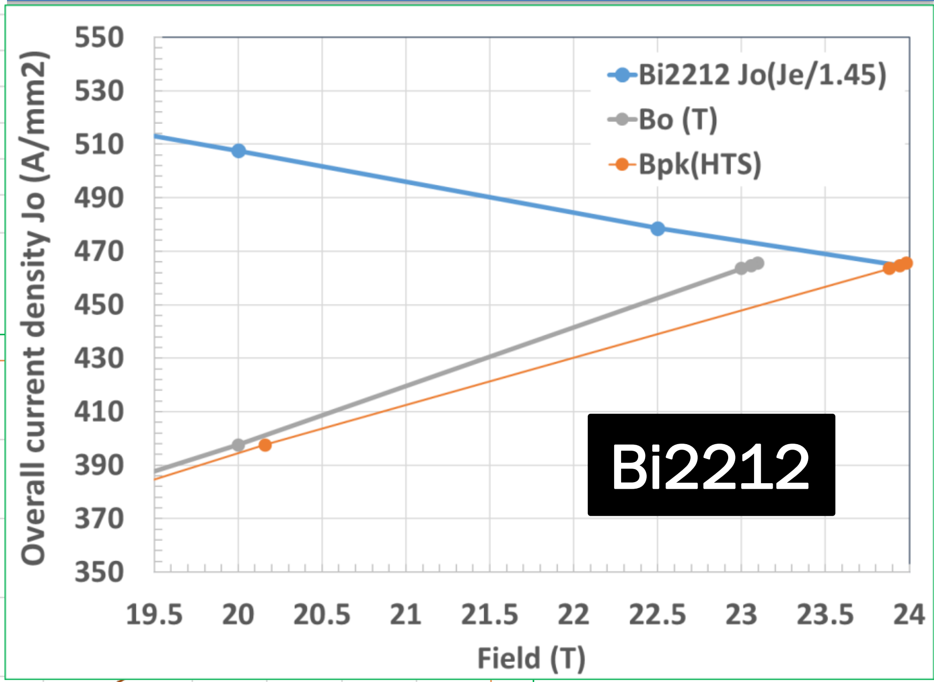
- All three Nb_3Sn coils (layers) are made identical
- Less tooling and spares required, important for reducing costs of R&D magnets
- HTS & LTS matched with a few tenth of a percent

Computation of Field Margins

I(kA)	I(Nb3Sn)	Je(HTS), A/mm^2	Jo(HTS), A/mm^2	Je(Nb3Sn)	Jo(Nb3Sn)	**Bo (T)**	Bpk(HTS)	Bpk(Nb3Sn)	**Margins**
0	0	0	0	0	0	**0**	0	0	
13.495	13495	483.83	397.578	634.16	522.252	**20.000**	20.161	13.397	
15.733	15733	564.07	463.512	739.33	608.862	**23.000**	23.883	15.676	
15.7991	15799.1	566.438	465.459	742.438	611.419	**23.097**	23.983	15.742	**15.5%**
15.7723	15772.3	565.479	464.671	741.181	610.384	**23.058**	23.942	15.715	**15.3%**







Field Quality and Fields on the Conductors

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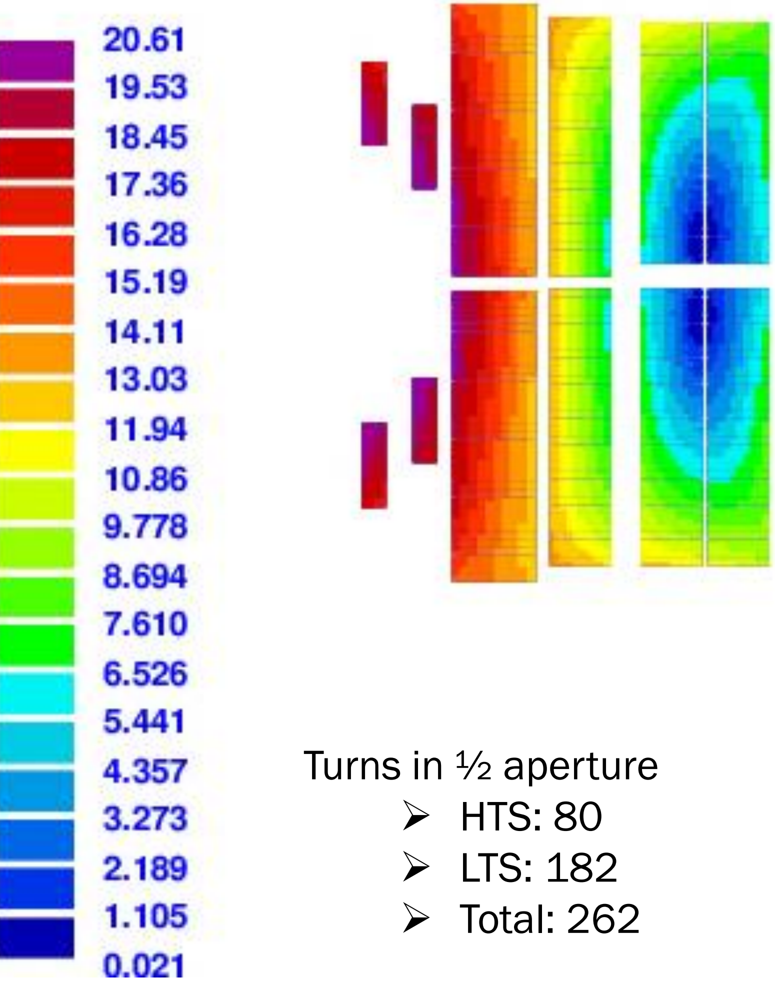
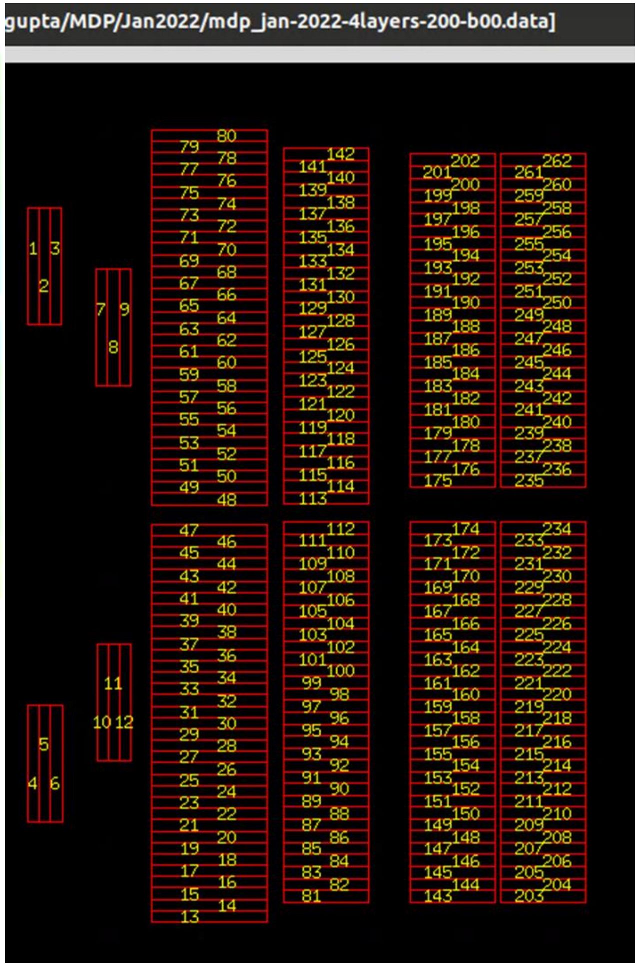


Turns in ½ aperture
- ➢ HTS: 80
- ➢ LTS: 182
- ➢ Total: 262



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

-4layers-200-h15.iron | mdp_jan-2022-4layers-200-h00.output

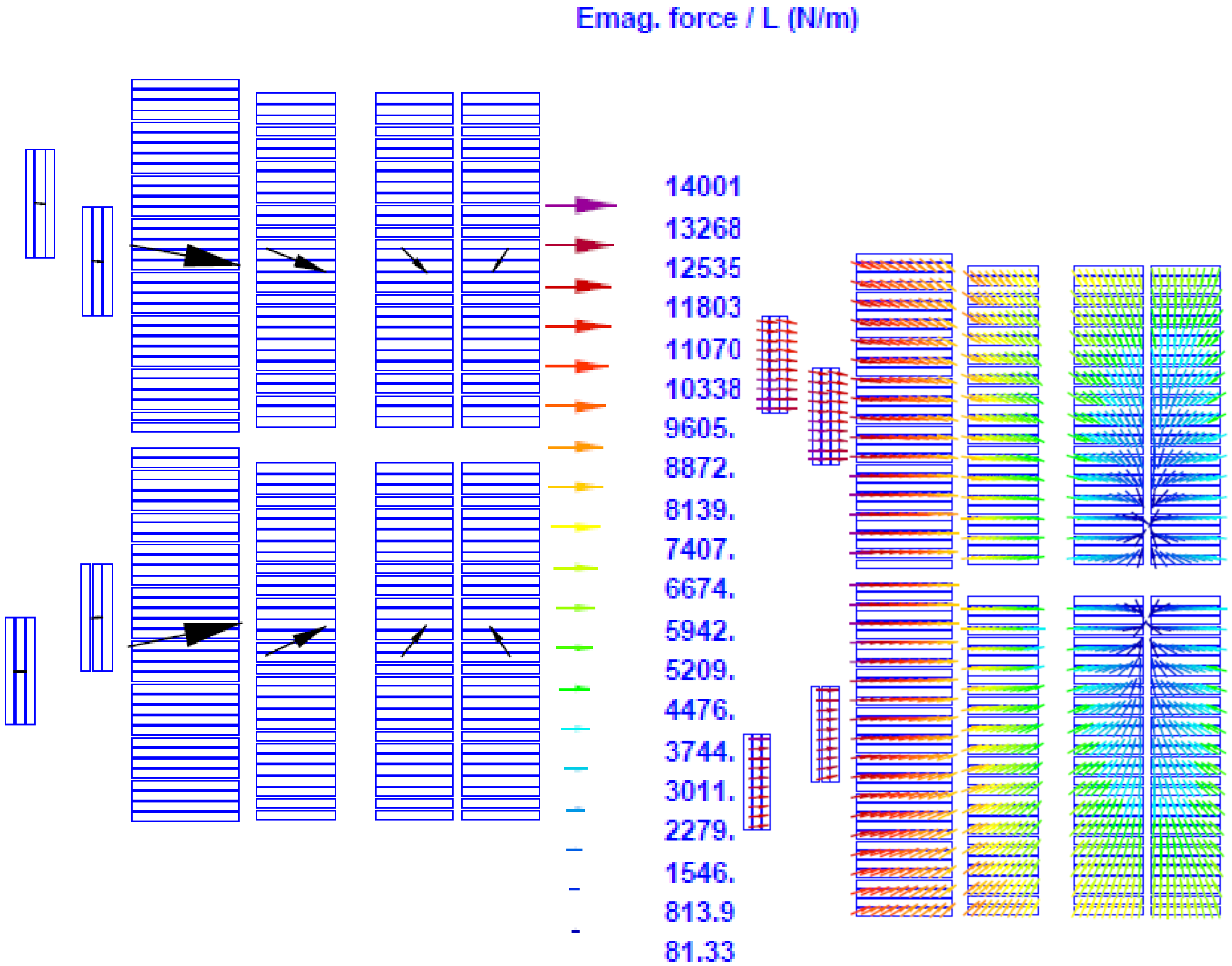
```
MAIN HARMONIC ......................................          1
REFERENCE RADIUS (mm) ..............................    15.0000
X-POSITION OF THE HARMONIC COIL (mm) ..............     0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..............   200.0000
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................  0.3228E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

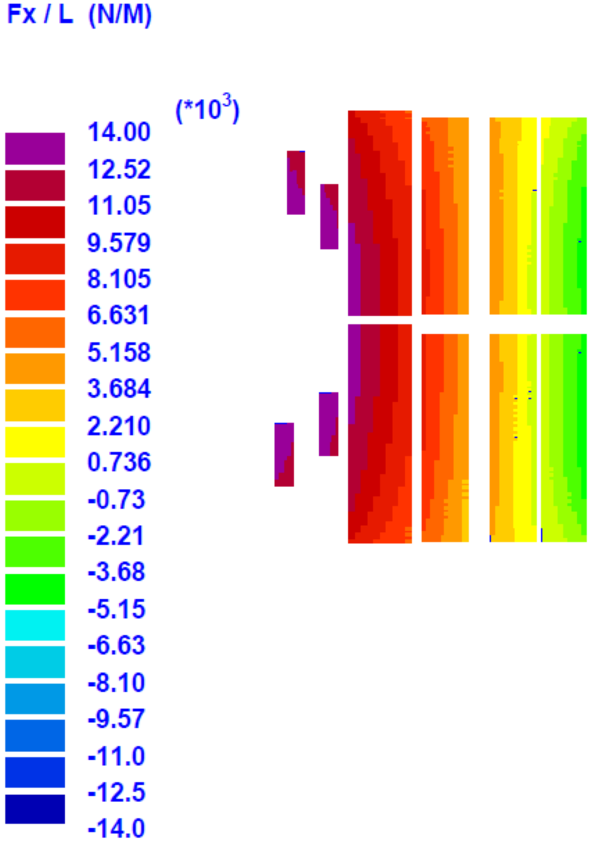
MAIN FIELD (T) ....................................   20.000066
MAGNET STRENGTH (T/(m^(n-1)) ......................     20.0001

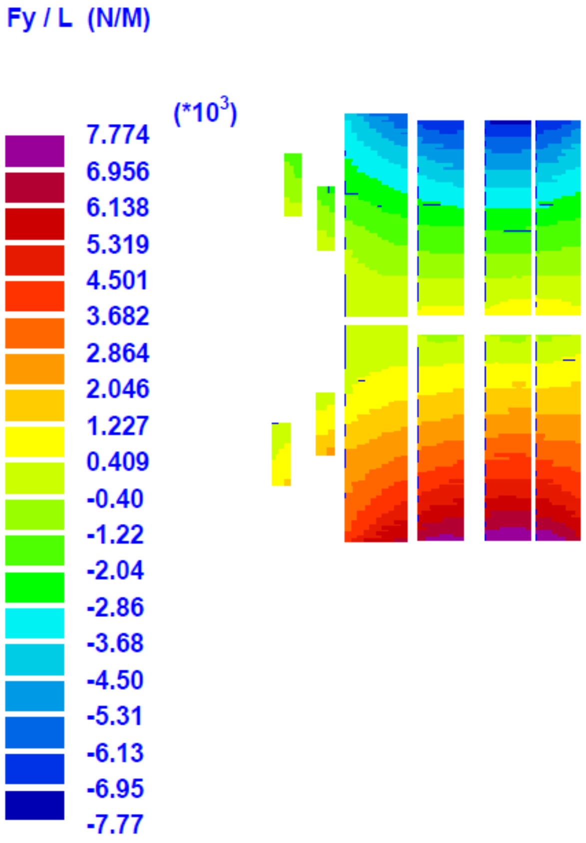
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:      0.00537
b 4:     -0.00000  b 5:      0.02576  b 6:      0.00000
b 7:     -0.07742  b 8:     -0.00000  b 9:     -0.41532
b10:      0.00000  b11:     -0.26062  b12:     -0.00000
b13:     -0.00646  b14:     -0.00000  b15:     -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
```

Distribution of Lorentz Forces

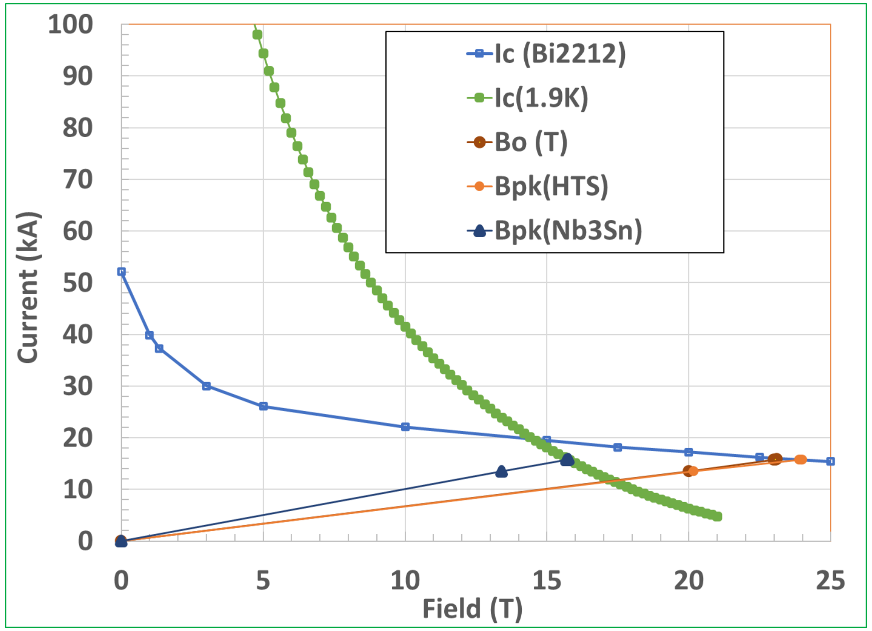


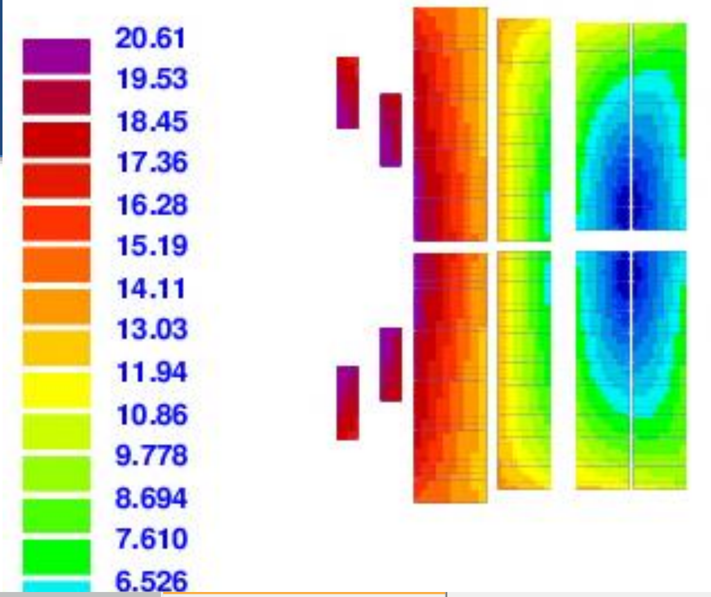




Flexibility in design

- Apart from the number of layers, cases examined for the number of turns in each layer (no limit on vertical)
- Also examined 2 + 2 turns in pole coil
- In most cases, good solution found





-4layers-200-g00.output | mdp_jan-2022-4layers-200-g15.output

```
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) ..............    200.0000
MEASUREMENT TYPE ...................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................  0.2092E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ....................................   23.001015
MAGNET STRENGTH (T/(m^(n-1)) ......................     23.0010

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:    -0.00000  b 3:     0.00500
b 4:      0.00000  b 5:    -0.00063  b 6:    -0.00000
b 7:     -0.11968  b 8:     0.00000  b 9:    -0.05058
b10:     -0.00000  b11:    -0.07182  b12:    -0.00000
b13:     -0.07519  b14:     0.00000  b15:     0.01084
b16:     -0.00000  b17:     0.00456  b18:     0.00000
b19:     -0.00053  b20:    -0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:    -0.01090  a 3:    -0.00000
a 4:     -0.00085  a 5:     0.00000  a 6:     0.00498
a 7:      0.00000  a 8:     0.02967  a 9:     0.00000
a10:      0.31552  a11:    -0.00000  a12:     0.17620
a13:     -0.00000  a14:    -0.03228  a15:     0.00000
a16:      0.00069  a17:    -0.00000  a18:     0.00500
a19:      0.00000  a20:     0.00042  a
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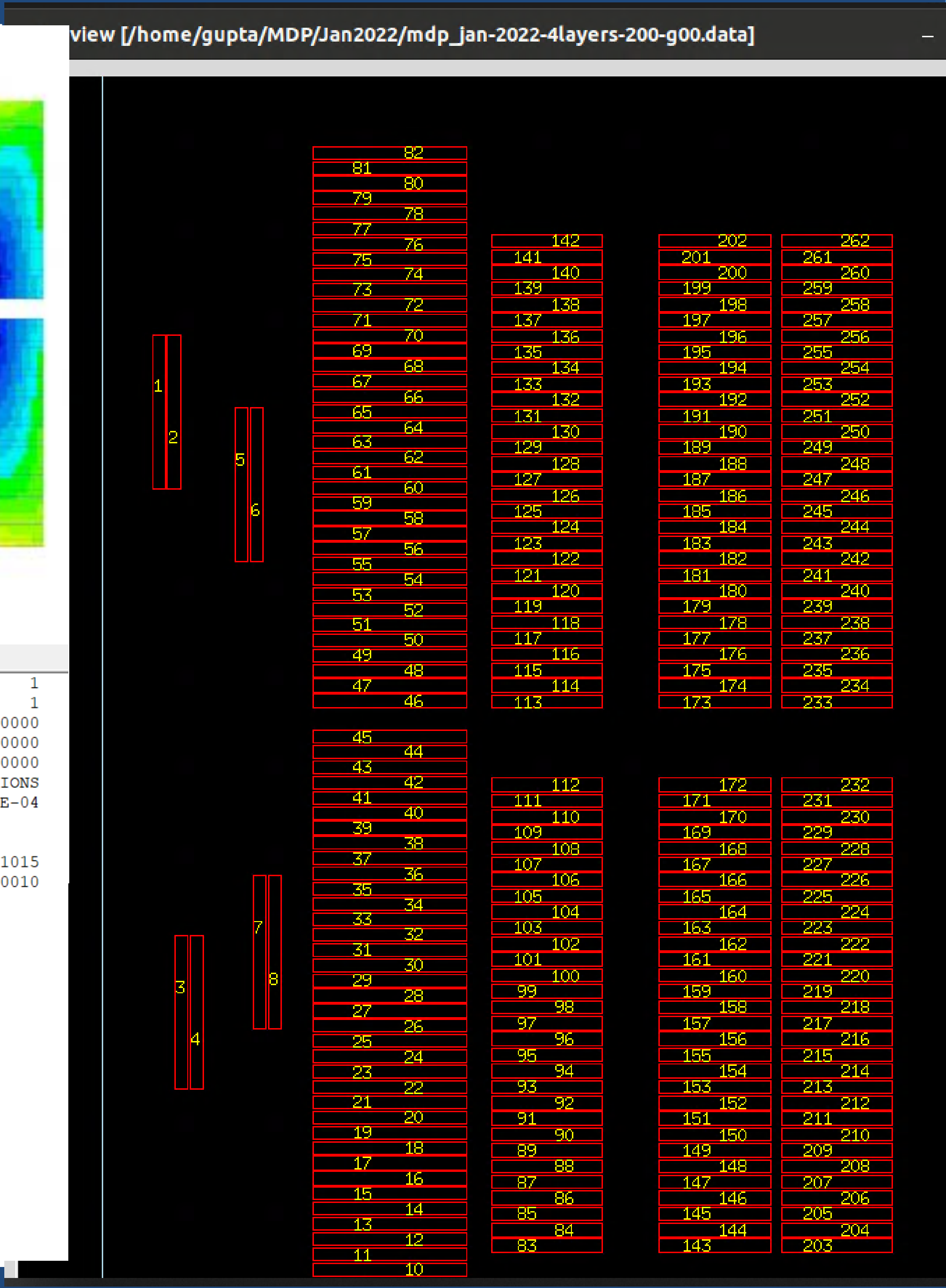
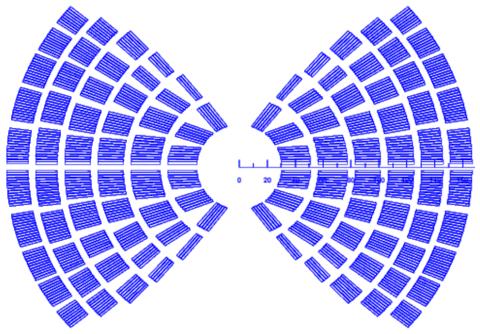
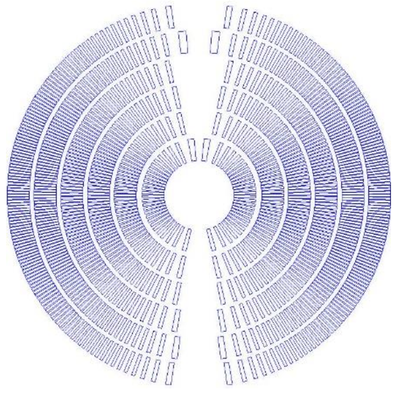


Optimization in Various Geometries

Typical requirements in accelerator magnet is that field harmonics due to coil geometry remain within a few parts in 10^4 (we demonstrated <1 parts in 10^4)

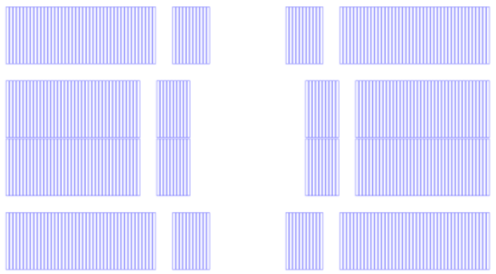
Variable to optimize the cosine theta and the canted cosine theta designs

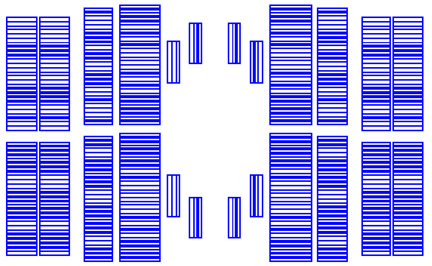




- Total coil width (radial extent – free to grow). However, more width means more layers for given cable
- Pole Angle (limited to 90º max. & 60º min. for b_3=0)
- For field quality wedges (may use for structure)
- Radial space between layers for structure element

Variable to optimize the block coil and the common coil designs





- Total coil width (horizontal width – free to grow). However, more width means more layers.
- Coil Height (vertical height – free to grow) – major difference from the cos ϑ or canted cosine theta
- For field quality spacer (also structure) & pole coils
- Horizontal space for structure elements

Work Ahead (priority mechanical design and analysis)

- 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 for a 20 T design

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Summary

- **For such high fields, common coil design uses less conductor, particularly HTS (opposite to what people think) – is mystery solved?**
- **Common coil allows easy and efficient segmentation between HTS and LTS**
- **Based on DCC017, Common coil allows larger deflections without putting high strain on coils (to be shown with the mechanical analysis for this design also)**
- **Simple geometry should facilitate more reliable and lower cost manufacturing. All Nb_3Sn coils are identical, saving costs in engineering for tooling and spare**
- **Common coil design is appearing to look more and more attractive for high field (20 T) HTS/LTS hybrid dipoles – both R&D dipoles and collider dipoles**
- **A lot of work is remaining to fully develop the design. A good opportunity for long term R&D for young scientists and engineers for pioneering work**