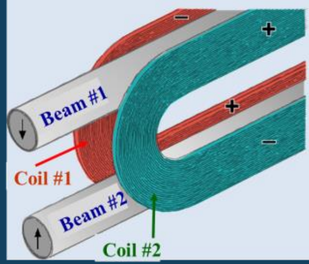


# HTS/LTS Hybrid Common Coil Dipole Design for 20 T Operational Field

**Ramesh Gupta, Michael Anerella, John Cozzolino, Mithlesh Kumar, Chris Runyan, BNL; Paolo Ferracin, LBL; Douglas M. Araujo, PSI; Vittorio Marinozzi, FNAL; Emmanuele Ravaioli, CERN**

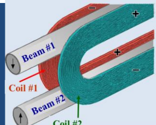
ASC 24 SALT LAKE CITY
SEPTEMBER 1 - 6
SALT PALACE CONVENTION CENTER

September 4, 2024

U.S. MAGNET DEVELOPMENT PROGRAM

# Content

- Common coil design
  - Introduction and high field magnet R&D strategies
- Status of HTS/LTS Hybrid 20 T common coil design
  - Studies under US MDP and by European collaborators
  - A significant work by IHEP (not covered here)
- Magnet designs and R&D for future collider dipoles
  - 20 T @20 K (leveraging fusion cable development)?
- Summary



U.S. MAGNET
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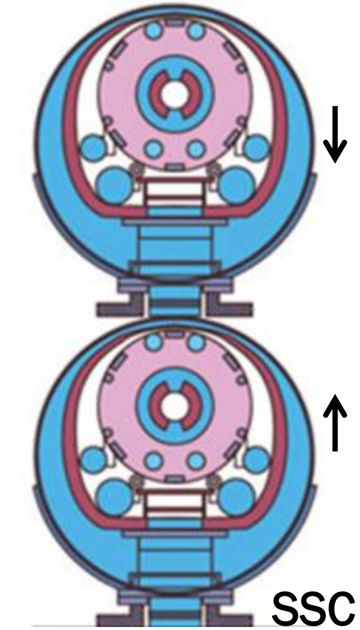
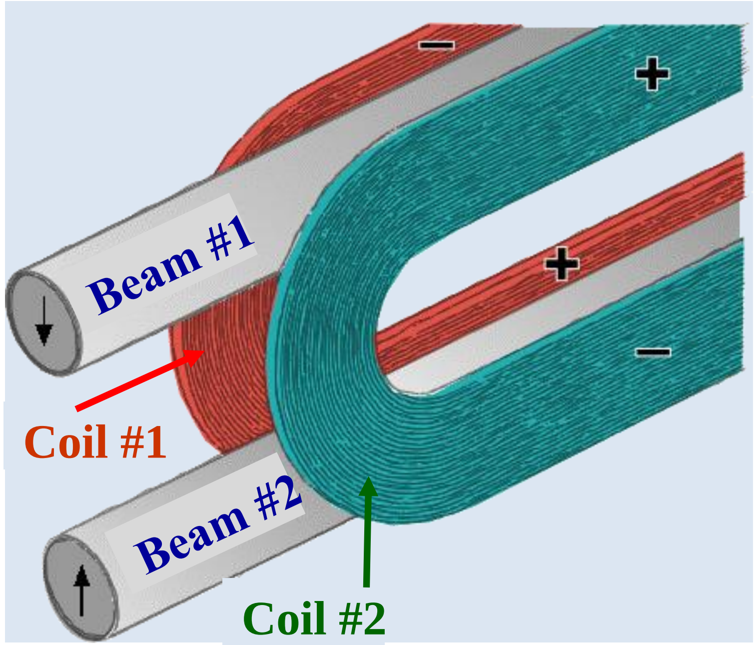
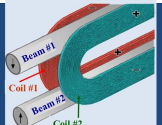
# Common Coil Design for the Collider Dipoles





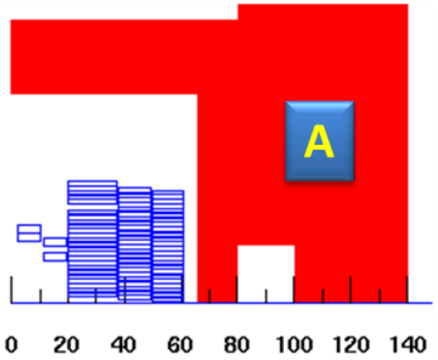
Common Coil Concept

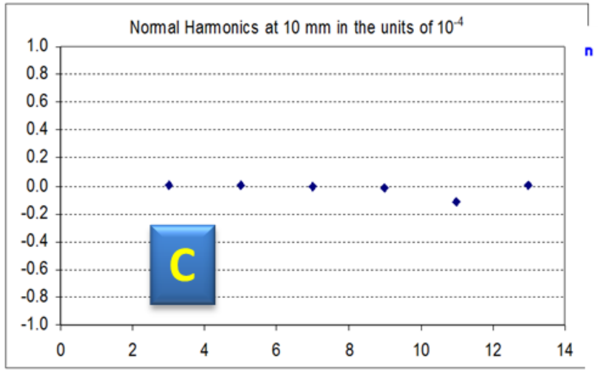
- ➢ **Simpler 2-d geometry for collider dipoles**
- ➢ **Large bend radii, determined by the spacing between the two apertures rather than the aperture itself**
- ➢ **Allows both “React & Wind” and “Wind & React” Technologies for $Nb_3Sn$ & HTS**
- ➢ **Allows a variety of HTS cables, including the new high current fusion cables**
- ➢ **Easier stress management and efficient segmentation between HTS and LTS coils**

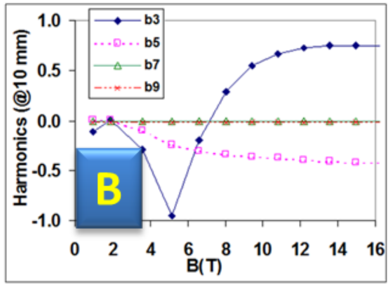


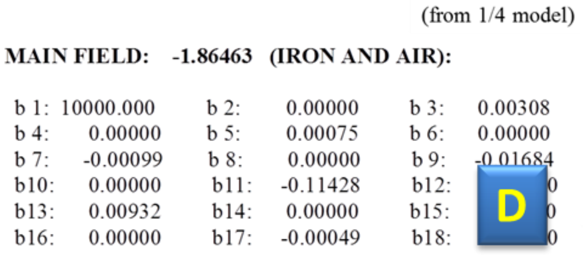
# Good Field Quality (few parts in $10^{-4}$) in Earlier Common Coil Designs

*Optimization for good field quality in a 15 T $Nb_3Sn$ common coil design (coil aperture 40 mm, reference radius 10 mm).*





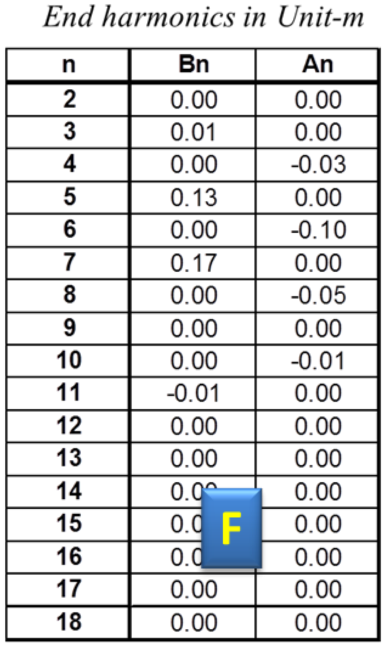




(from 1/4 model)

```
MAIN FIELD:   -1.86463   (IRON AND AIR):

 b 1:  10000.000      b 2:     0.00000      b 3:    0.00308
 b 4:     0.00000     b 5:     0.00075      b 6:    0.00000
 b 7:    -0.00099     b 8:     0.00000      b 9:   -0.01684
 b10:     0.00000     b11:    -0.11428      b12:   [illegible]
 b13:     0.00932     b14:     0.00000      b15:   [illegible]
 b16:     0.00000     b17:    -0.00049      b18:   [illegible]
```

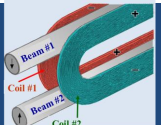


*End harmonics in Unit-m*

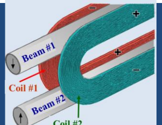
| n | Bn | An |
|---|---|---|
| 2 | 0.00 | 0.00 |
| 3 | 0.01 | 0.00 |
| 4 | 0.00 | -0.03 |
| 5 | 0.13 | 0.00 |
| 6 | 0.00 | -0.10 |
| 7 | 0.17 | 0.00 |
| 8 | 0.00 | -0.05 |
| 9 | 0.00 | 0.00 |
| 10 | 0.00 | -0.01 |
| 11 | -0.01 | 0.00 |
| 12 | 0.00 | 0.00 |
| 13 | 0.00 | 0.00 |
| 14 | [illegible] | 0.00 |
| 15 | [illegible] | 0.00 |
| 16 | [illegible] | 0.00 |
| 17 | 0.00 | 0.00 |
| 18 | 0.00 | 0.00 |

*(a) 1/4 cross section in one aperture*
*(b) saturation induced-harmonics*
*(c) plot of geometric harmonics*
*(d) values of geometric harmonics*
*(e) optimized end geometry*
*(f) Low end harmonics*

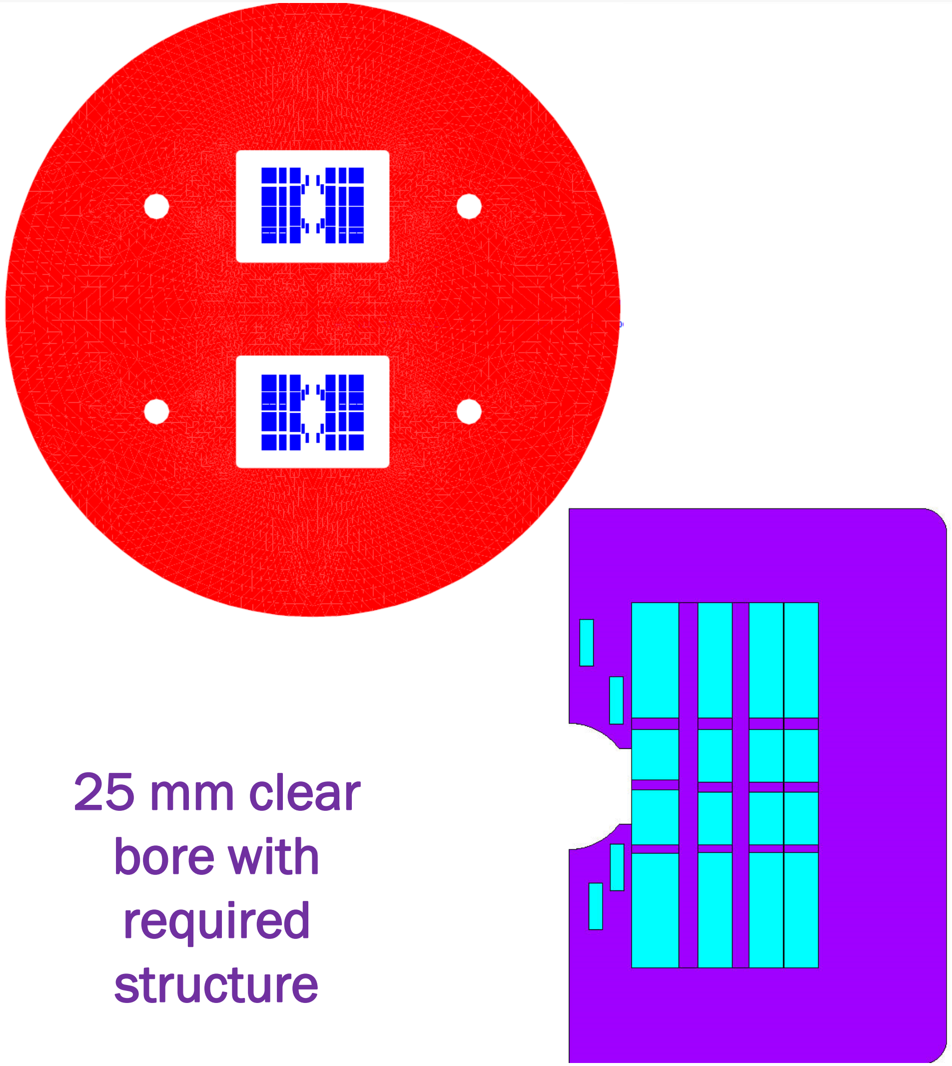
**Many other common coil designs with good field quality have been developed since the above was presented**



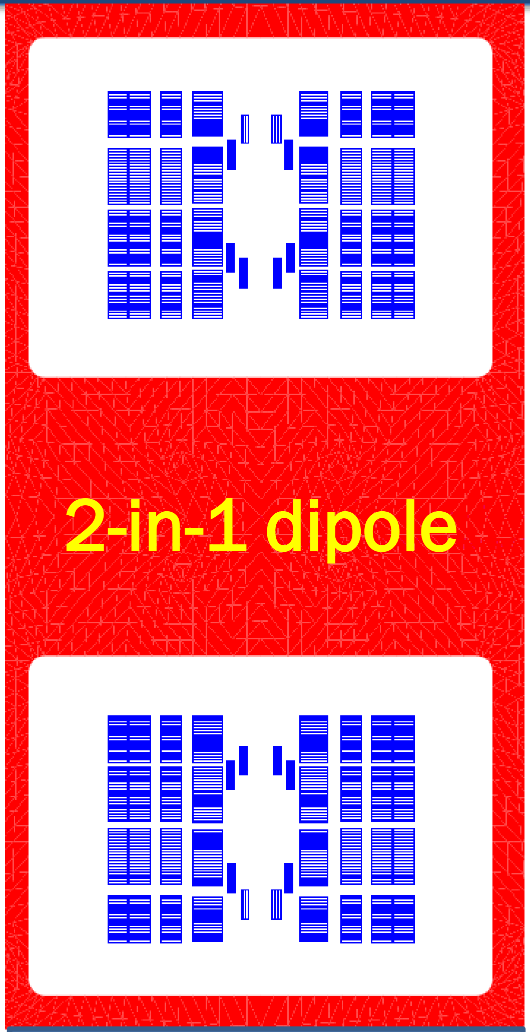
# Magnetic Design of a 20 T HTS/LTS Common Coil Dipole with >15% Margin



# Magnetic Design of the HTS/LTS Hybrid Dipole

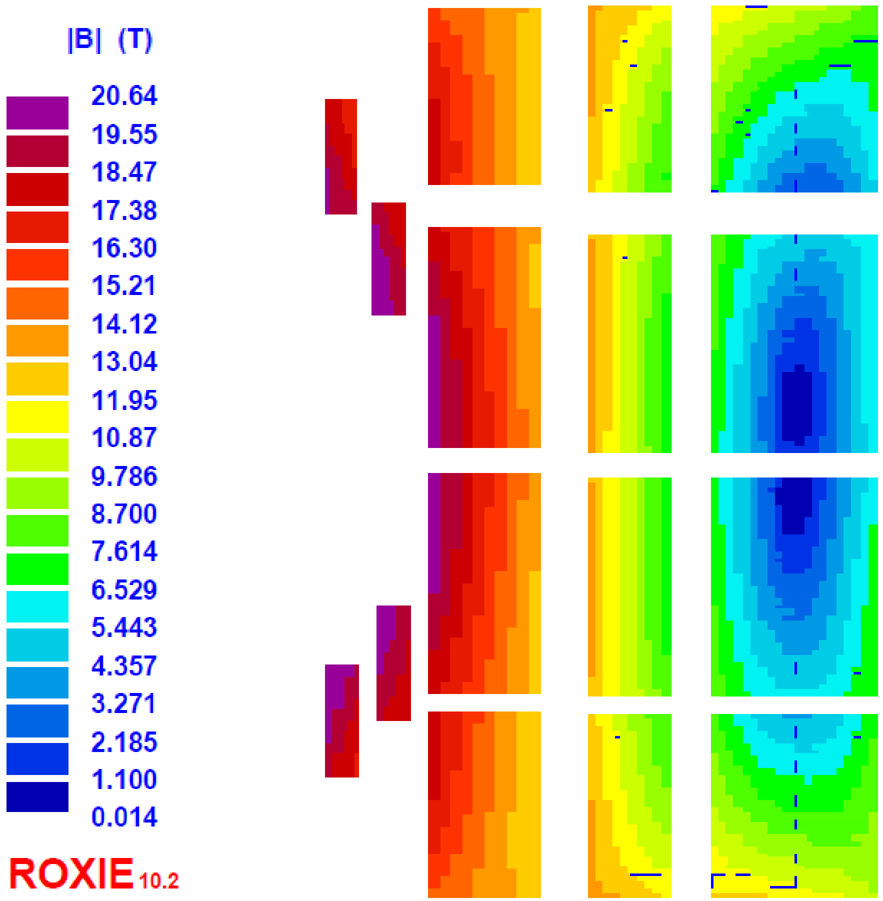


25 mm clear bore with required structure

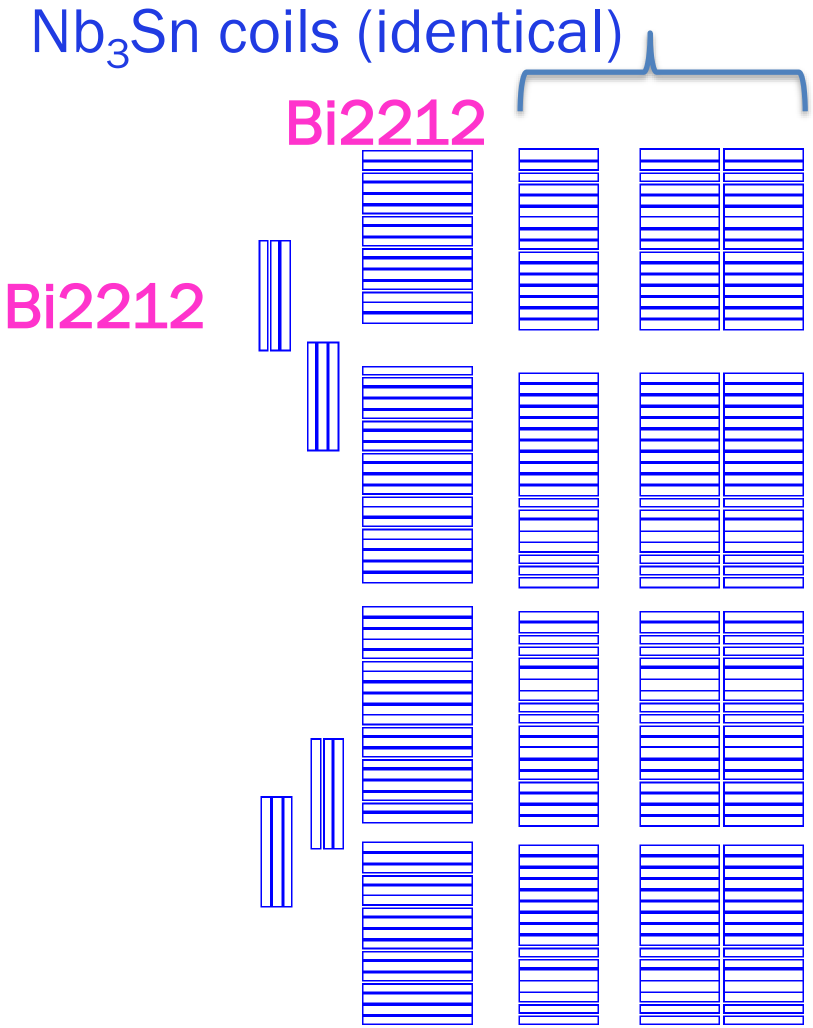


(identical $Nb_3Sn$ coils)

Efficient segmentation between HTS & LTS coils.
HTS coils only for one main coil (plus pole coils).

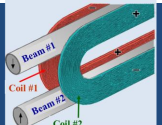


# Identical $Nb_3Sn$ Coils



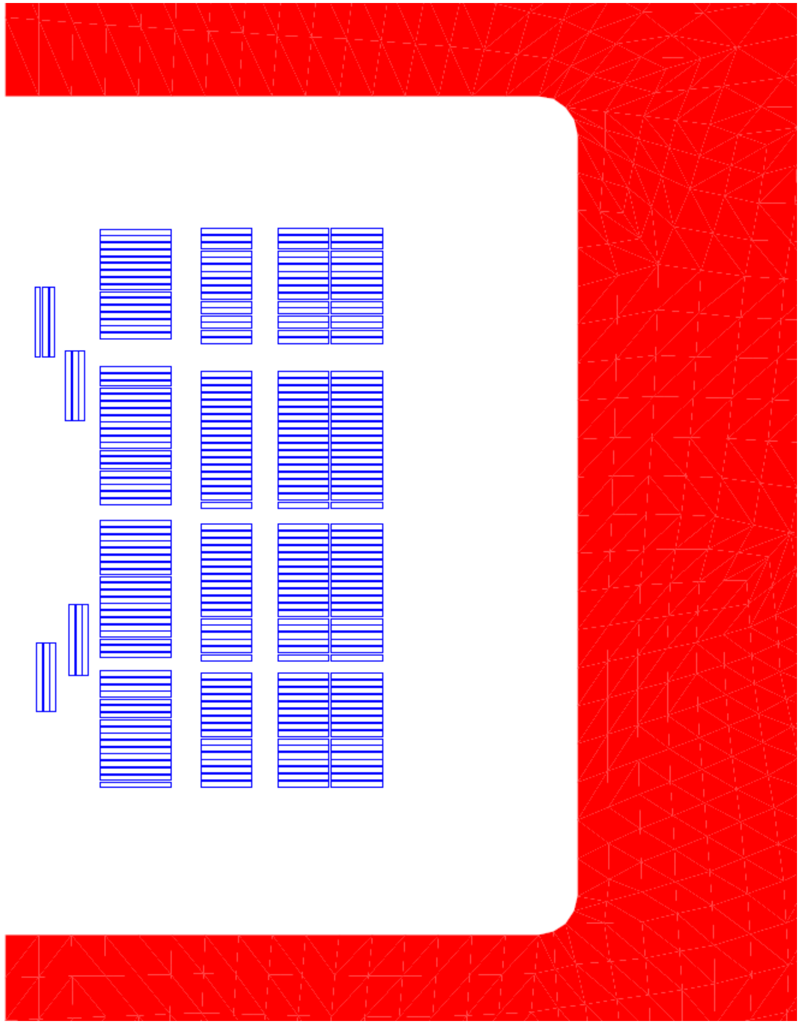
- All $Nb_3Sn$ coils can be made identical. Meaning only one set for winding, impregnation, and other tooling.
- Need less practice and spare coils; can sort/switch coils between layers. These two offer significant savings.

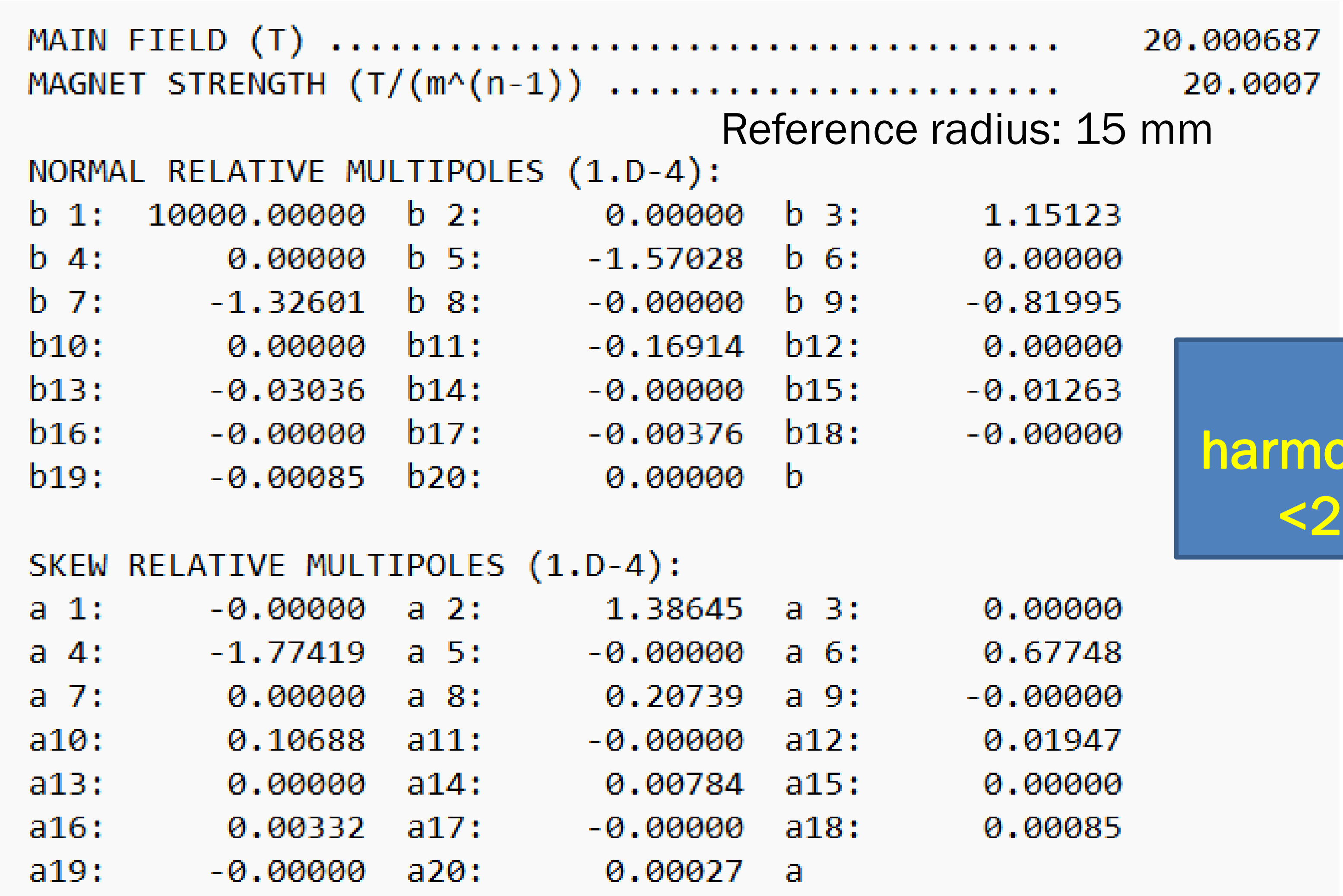
*Such a possibility can't be imagined in the other designs*



# Good Geometric Field Quality

## (MDP design goal: all harmonics <3 unit)





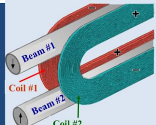
```
MAIN FIELD (T) .......................................   20.000687
MAGNET STRENGTH (T/(m^(n-1)) ........................     20.0007

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:       0.00000  b 3:       1.15123
b 4:       0.00000  b 5:      -1.57028  b 6:       0.00000
b 7:      -1.32601  b 8:      -0.00000  b 9:      -0.81995
b10:       0.00000  b11:      -0.16914  b12:       0.00000
b13:      -0.03036  b14:      -0.00000  b15:      -0.01263
b16:      -0.00000  b17:      -0.00376  b18:      -0.00000
b19:      -0.00085  b20:       0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      -0.00000  a 2:       1.38645  a 3:       0.00000
a 4:      -1.77419  a 5:      -0.00000  a 6:       0.67748
a 7:       0.00000  a 8:       0.20739  a 9:      -0.00000
a10:       0.10688  a11:      -0.00000  a12:       0.01947
a13:       0.00000  a14:       0.00784  a15:       0.00000
a16:       0.00332  a17:      -0.00000  a18:       0.00085
a19:      -0.00000  a20:       0.00027  a
```

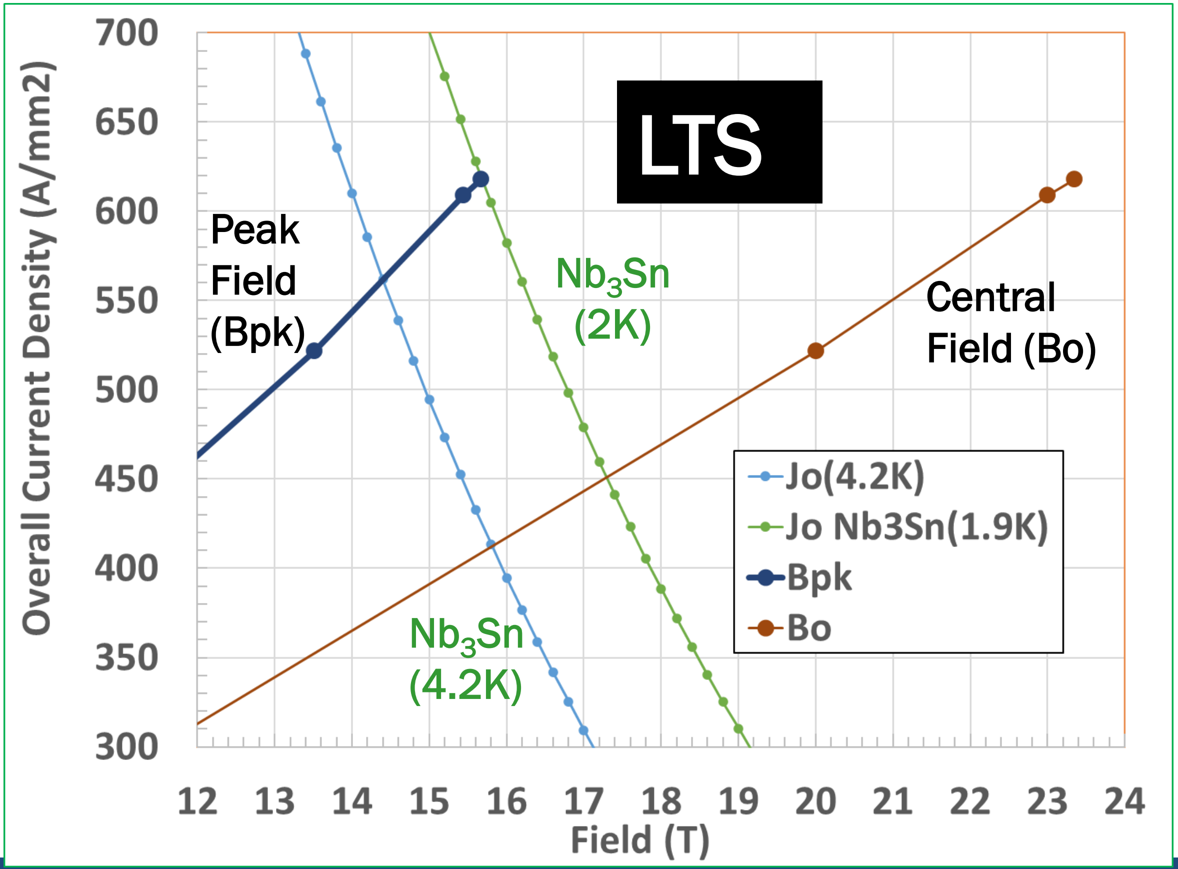
Reference radius: 15 mm

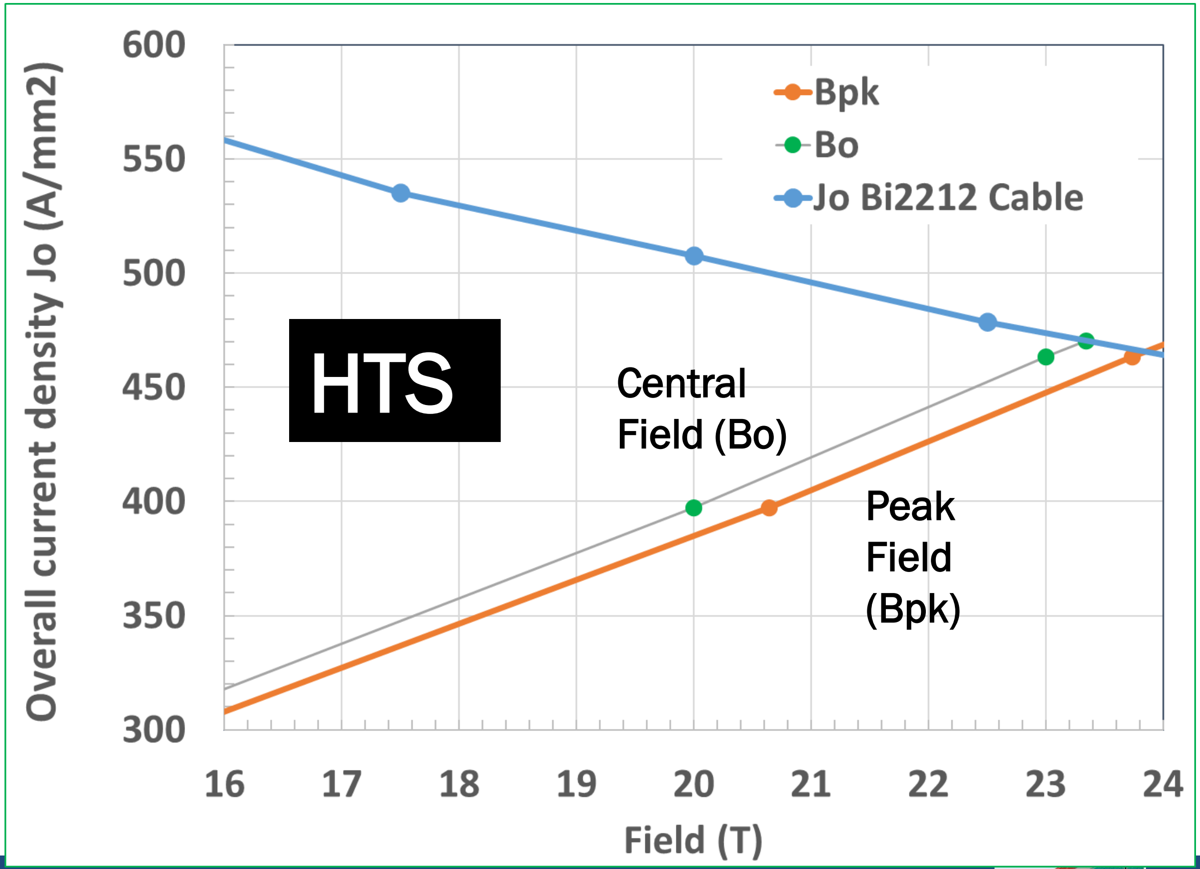
**All harmonics <2 unit**

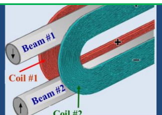


# Matched Margin Between LTS and HTS (>15%)

| 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 |
| 13485 | 13485 | 483.47 | 397.284 | 633.69 | 521.865 | **20.001** | 20.644 | 13.519 |
| 15729 | 15729 | 563.925 | 463.395 | 739.145 | 608.707 | 23.001 | 23.736 | 15.442 |
| 15965 | 15965 | **572.39** | **470.35** | **750.23** | **617.84** | **23.35** | **24.09** | **15.67** |
| 16043.6 | 16043.6 | 575.204 | 472.662 | 753.928 | 620.882 | 23.461 | 24.211 | 15.751 |







# CORC® based 20 T Common Coil Design

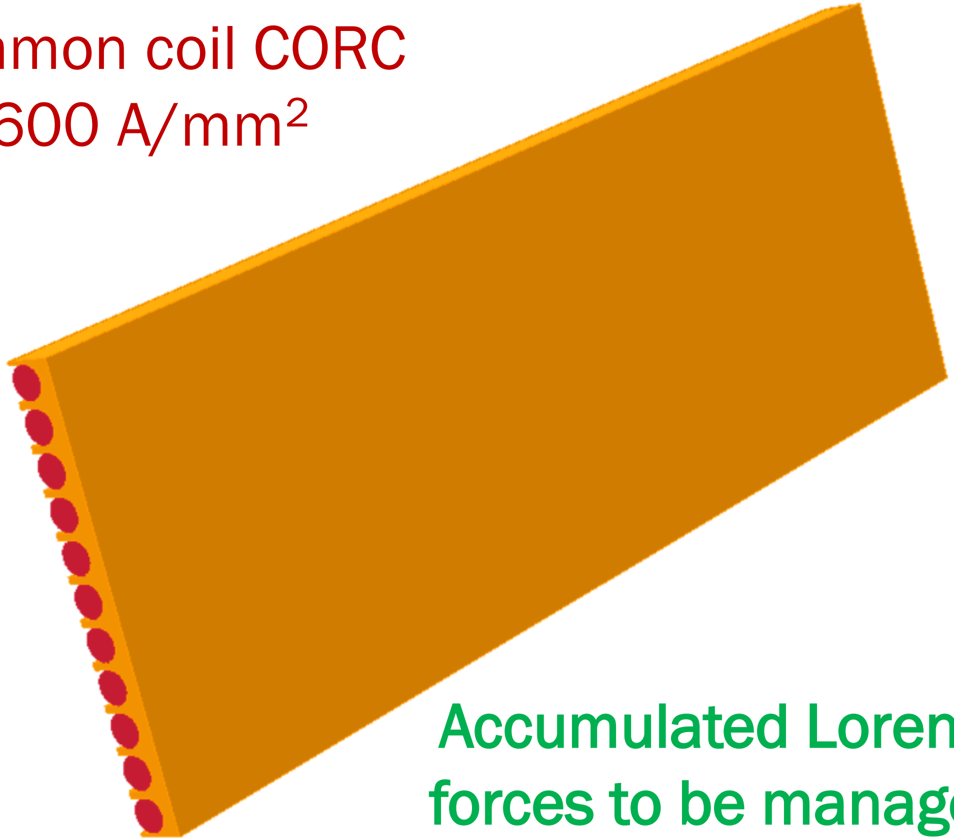
- **Common coil design allows higher Je CORC due to large bend radii**
  - ❖ STTR with ACT anticipates a future common coil CORC with an engineering current density of 600 A/mm$^2$

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

## $J_o$ for Je = 600 A/mm2:

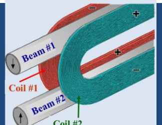
☐ $J_o = 600*28.3/52 = 326$ A/mm$^2$

- Similar to Bi2212; but with a structure

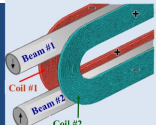


Accumulated Lorentz forces to be managed in a structure

Good field quality and 15% margin also obtained

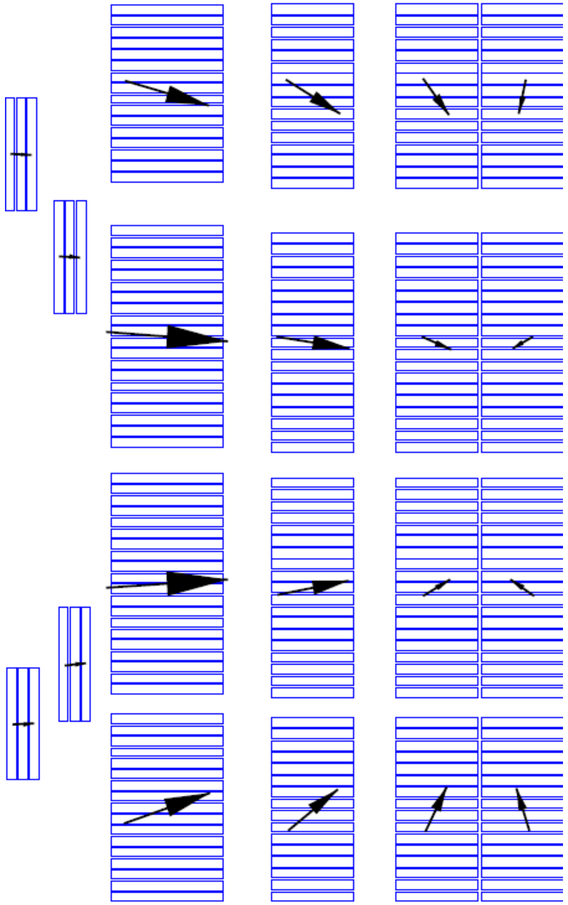


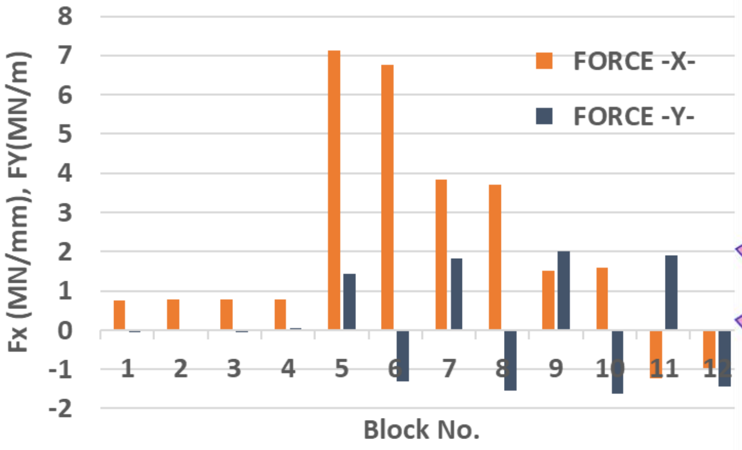
# Initial Mechanical Analysis

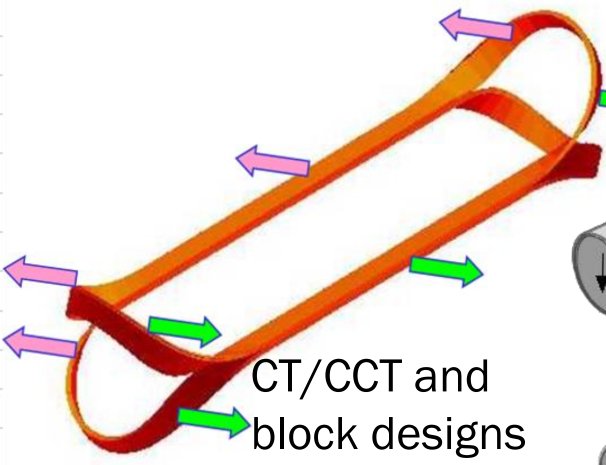


# Lorentz Forces in the Common Coil Geometry

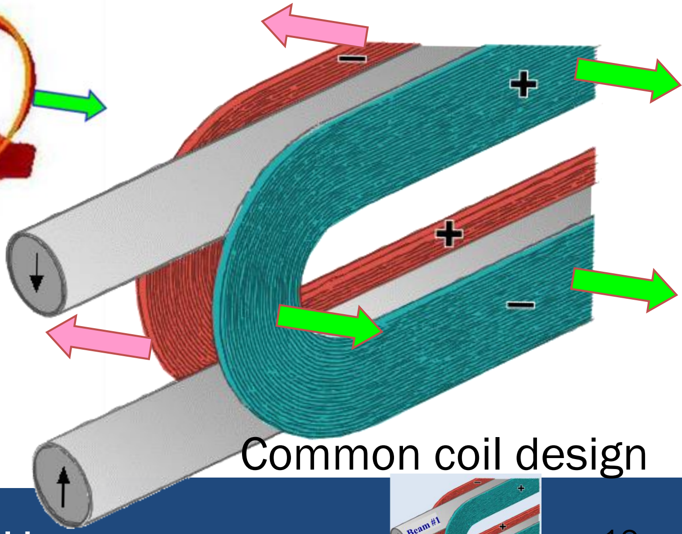
- ➢ Vertical forces much smaller than horizontal (maximum vertical is 1/3 of the maximum horizontal)
- ➢ Small forces on pole block (mostly horizontal)
- ➢ Since coils move as a unit in the common coil design, this motion doesn't create strain in the coil end region. Therefore, a larger horizontal movements can be tolerated.
- ➢ This is very different from the other designs. BNL common coil dipole had 200 µm horizontal deflections and low vertical pre-stress



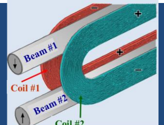




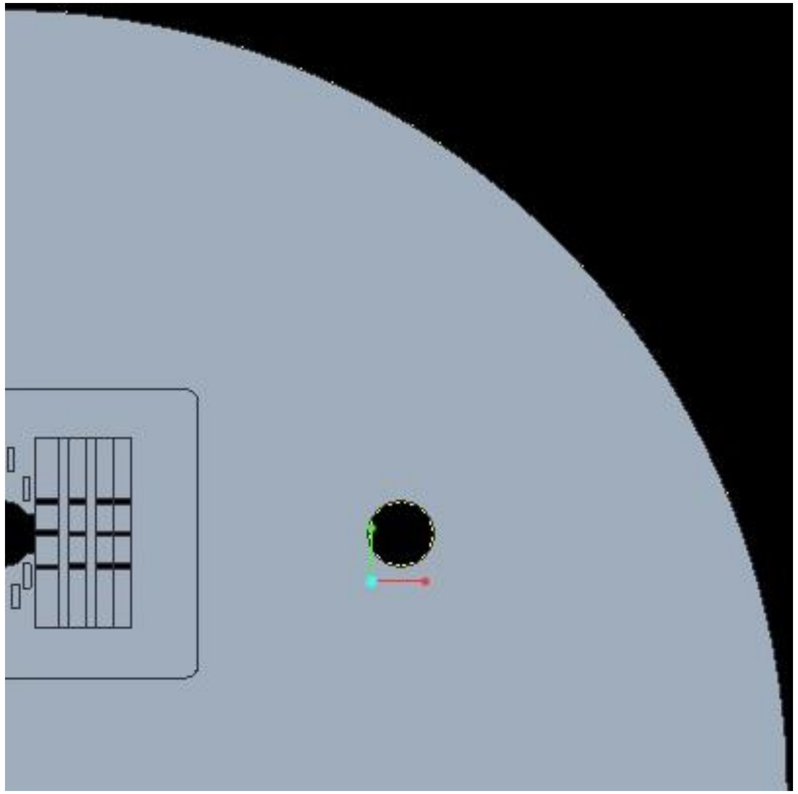
CT/CCT and block designs



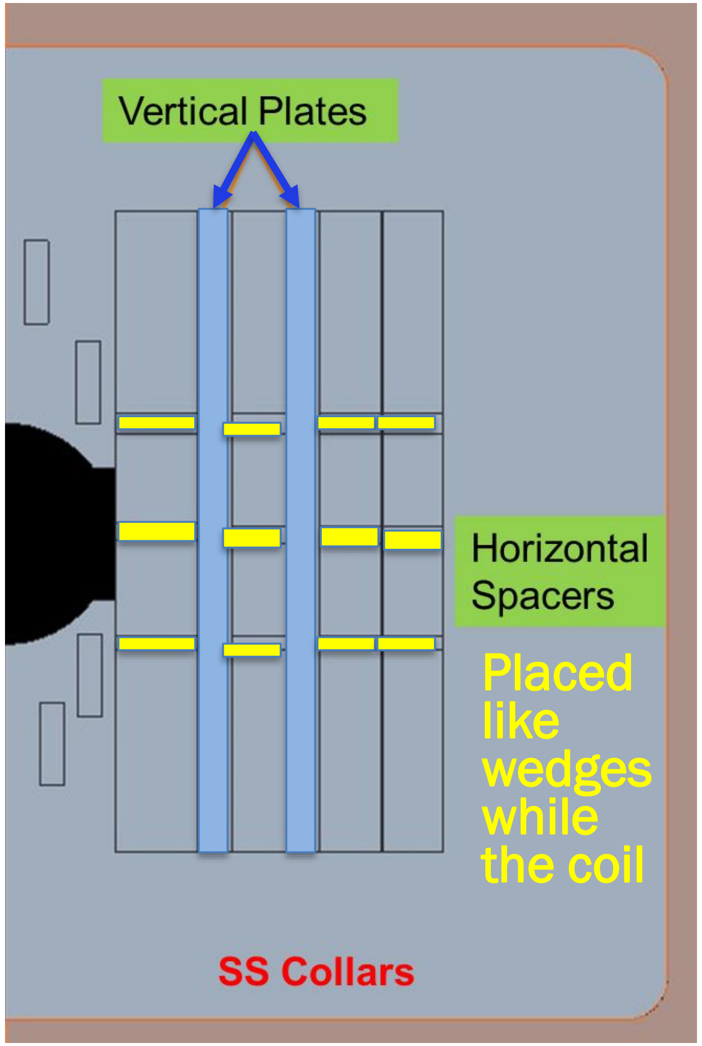
Common coil design



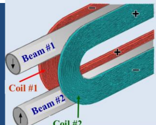
# Main Features of the Mechanical Structure



¼ of the full model



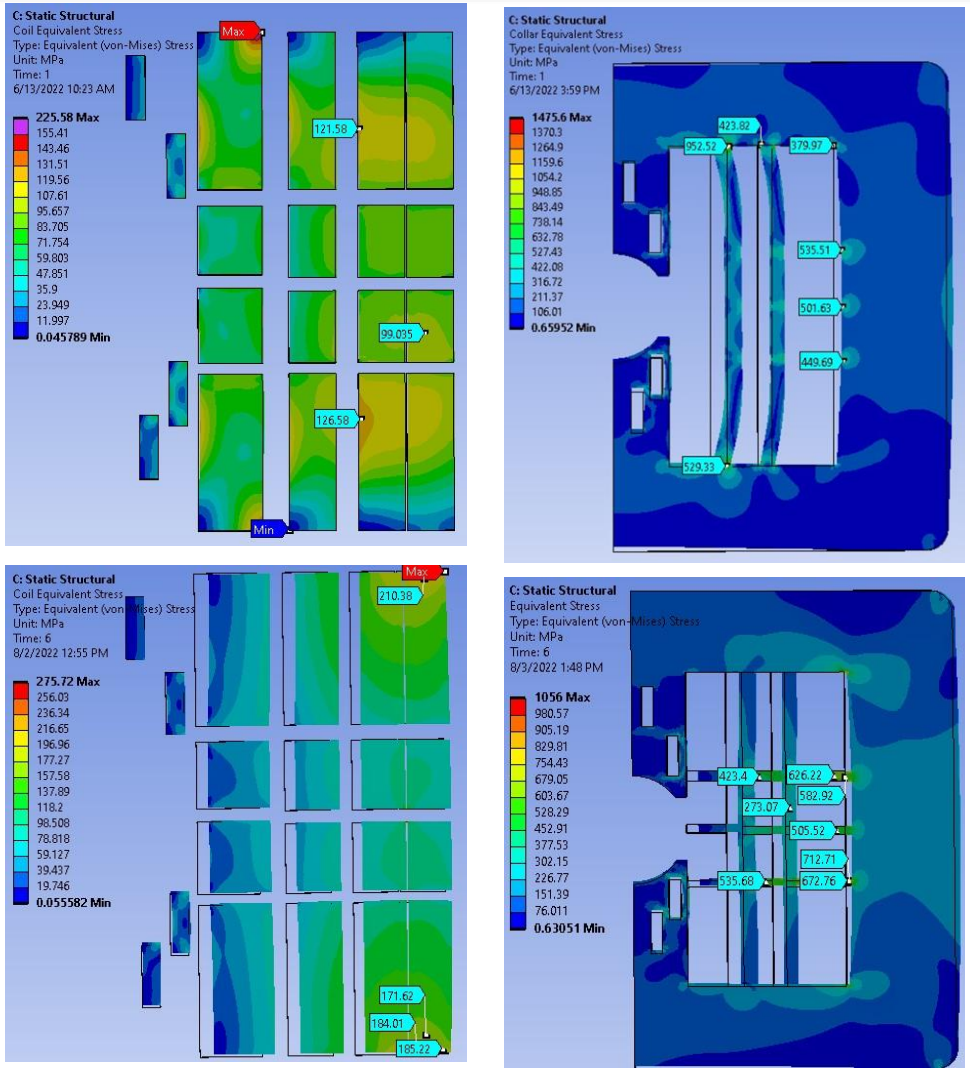
- 25 mm clear bore
- SS collars (+yoke and shell)
- Horizontal spacers and vertical plates for stress management.
- They transfer partial load to collar rather than all to conductor in the next layer.
- Vertical plates to distribute and transfer partial loads.
- Simple structure.



# Mechanical Analysis when Vertical Plates Bonded and NOT Bonded
## (overall results encouraging but the structure not yet optimized)

Vertical plates bonded to the collar at the top and bottom

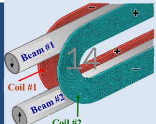
Vertical plates <u>NOT</u> bonded to the collar at the top and bottom



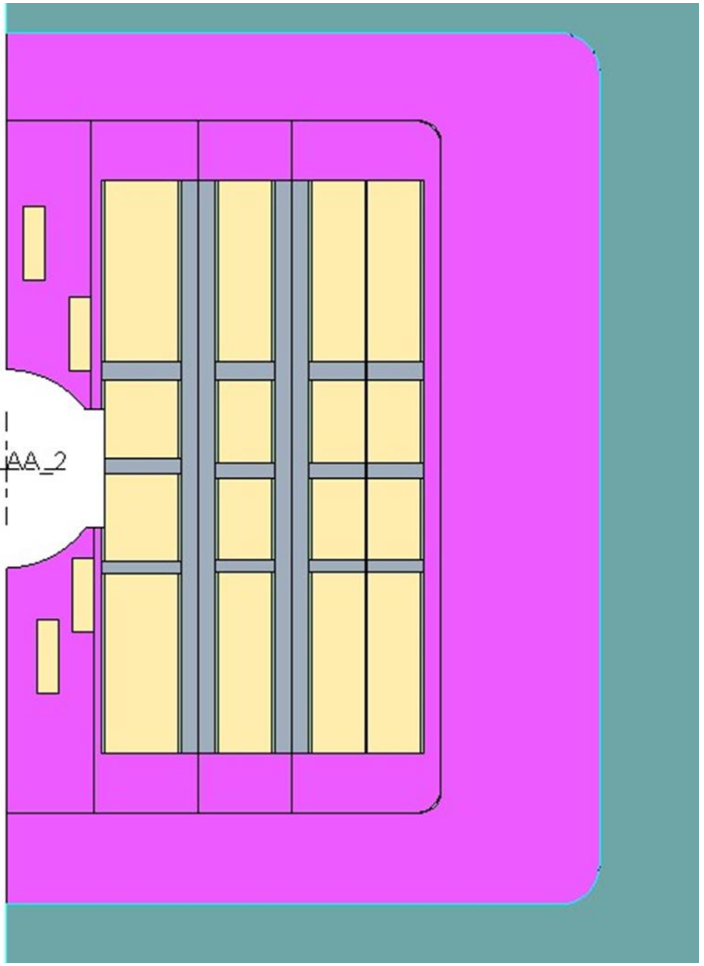
Equivalent Stresses (coils) Equivalent Stresses (collar)

- Horizontal forces create bending at upper and lower corners of the coils generating local stresses
- In bonded plate case, stresses in $Nb_3Sn$ coils are ok (max < 180 MPa) but more in HTS coil locally
- In non-bonded case, HTS coils ok (~100 MPa) but $Nb_3Sn$ >270 MPa

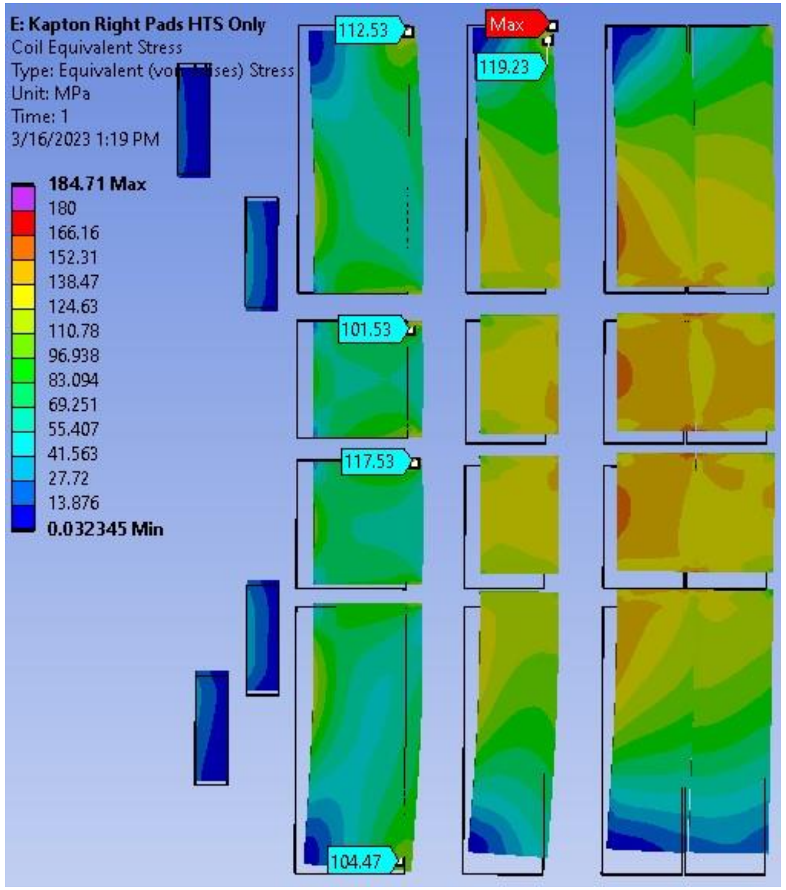
**A relatively simple structure and the pole coils are held well**



# Mechanical Design Approach Under Consideration (vertical spacers with softer material next to coils)



Work under progress,

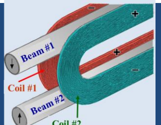


E: Kapton Right Pads HTS Only
Coil Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
3/16/2023 1:19 PM

Courtesy: Anerella, Cozzolino and Runyan

## Softer material (or springs) between coils reduces local bending and local stresses

- Coil Equivalent Stress – Fixed Vertical Separators
- Stainless steel collars are fully bonded together.
- Right pads are Kapton on HTS only. All others are stainless steel
- Horizontal stress supports are stainless steel.
  - ✓ 112MPa max in HTS
  - ✓ ~180MPa max* in LTS



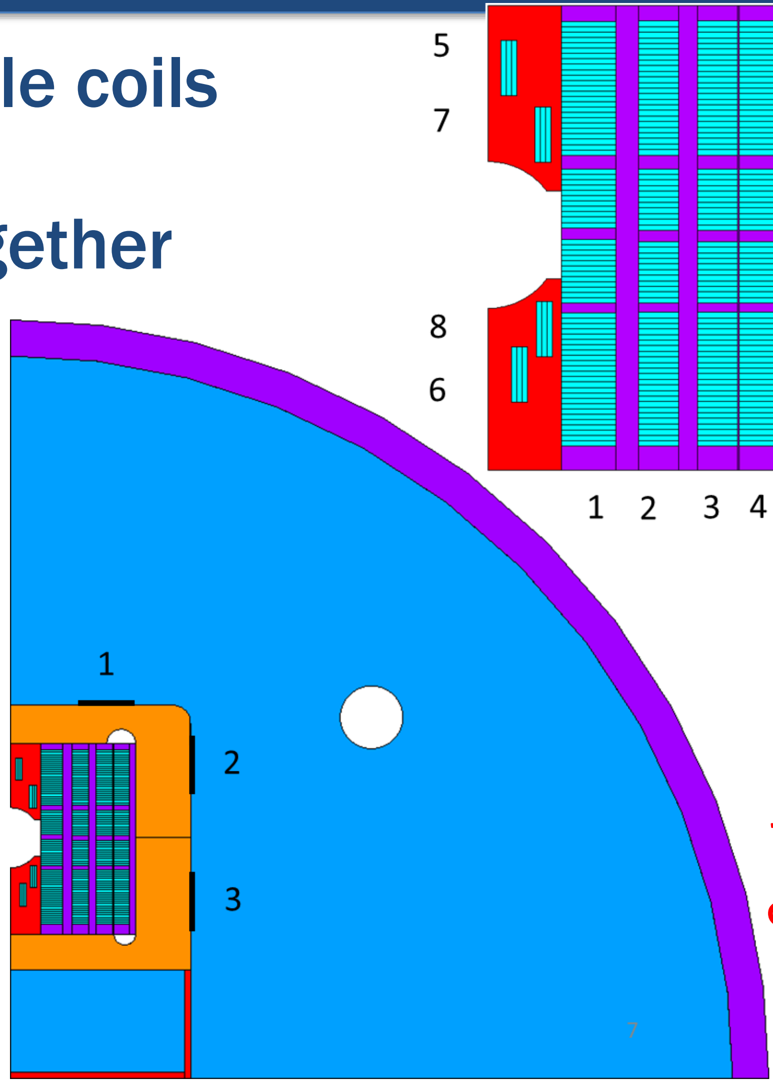
# Another Approach by Douglas M. Araujo, PSI

- Shell, pads/collars, common-coils formers and pole coils forms made of 314 L
- Turns belonging to the same block are bonded together
- Pads/collars pieces are bonded
- Layers can slide and detach from each other and from the surrounding pads/collars
- Pole formers are attached to the pad/collar
- Pre-load is applied with three keys (contacts)

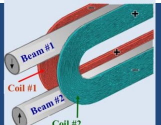
- Keys are 40 mm long
- Many DoFs to be optimized

| key | Interference in mm |
|---|---|
| 1 | 0.1 |
| 2 | 0.8 |
| 3 | 0.8 |

with pads, collars, shell apply some pre-stress

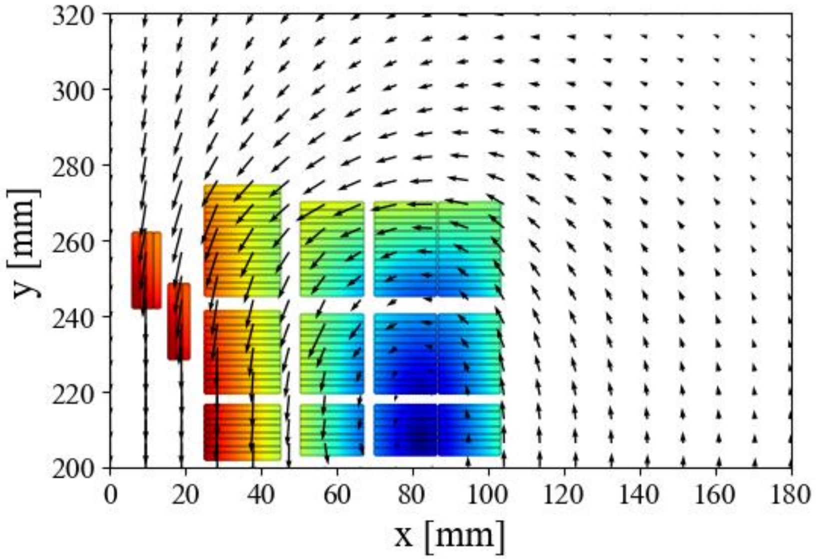


Courtesy: Douglas M. Araujo, PSI

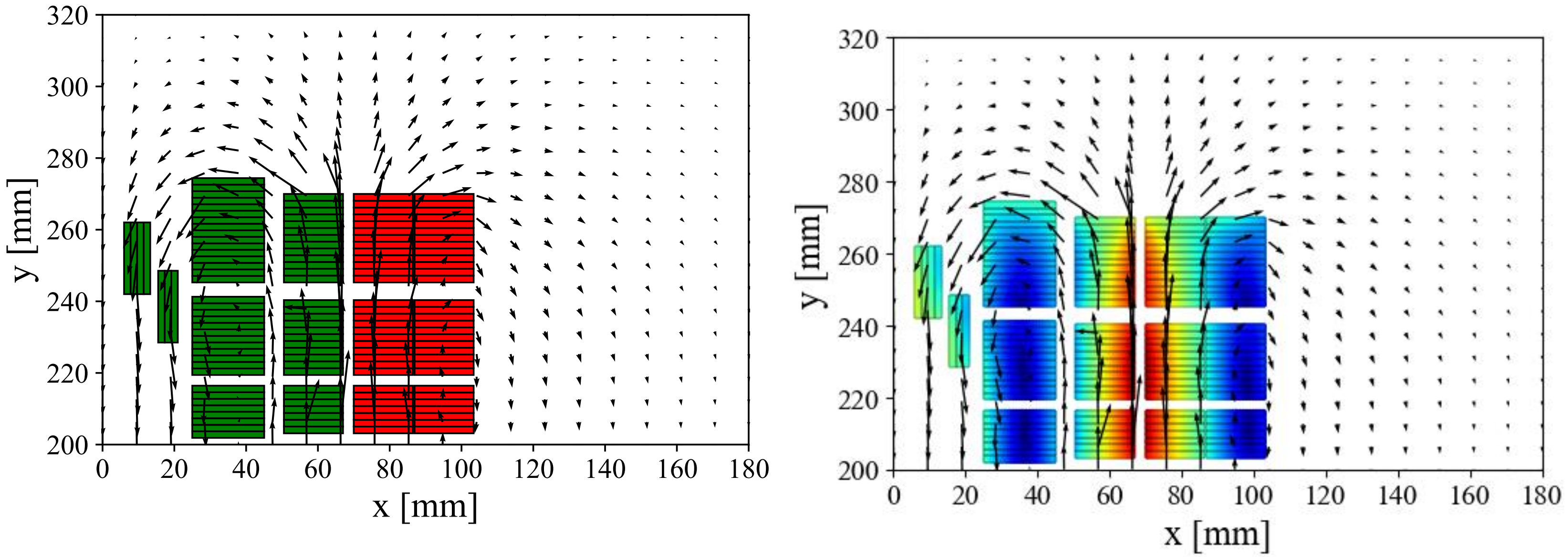


# Quench Protection in 20 T Common Coil Dipole (Emmanuele Ravaioli, CERN)

## SIMPLIFIED CROOS-SECTION OF THE 20 T COMMON COIL DESIGN

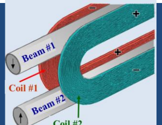


## POLARITY AND MAGNETIC FIELD CHANGES INDUCED BY **CLIQ**

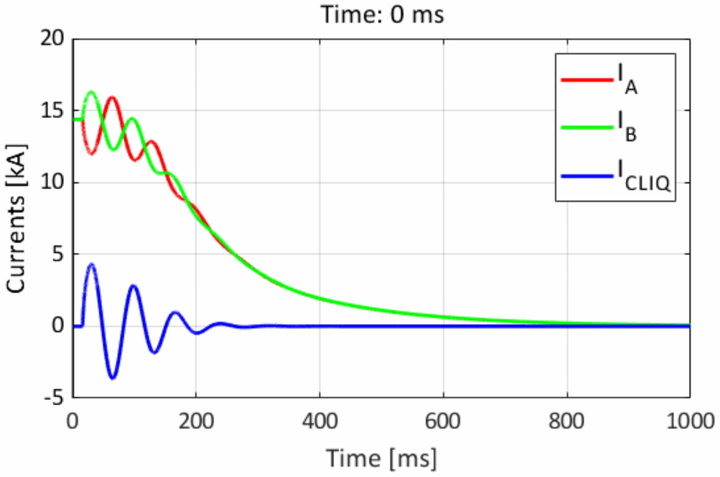


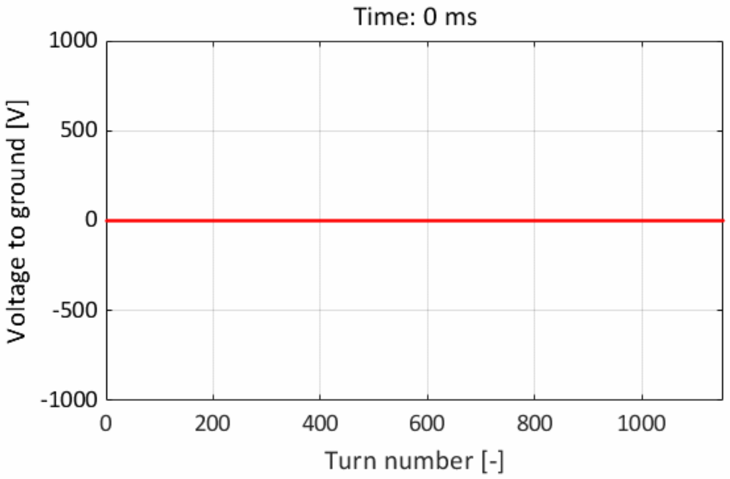
Courtesy:
Emmanuele Ravaioli, CERN

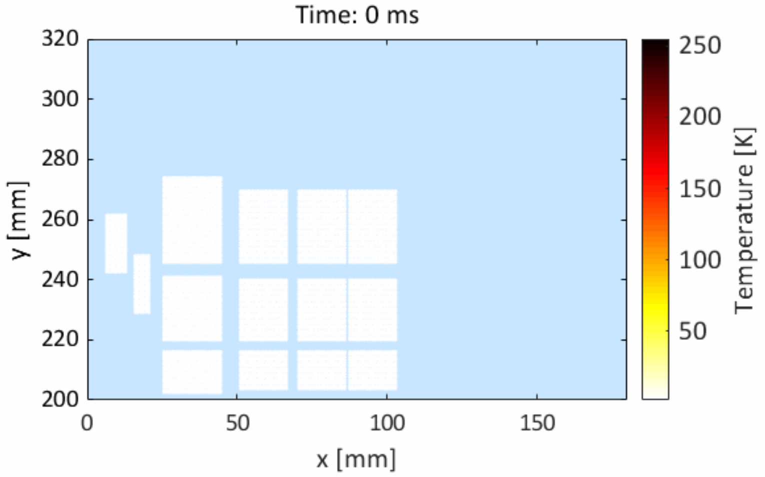
More and other methods and presentations:
4LOr1B-06, 5LOr2B-01, 5LOr2C-05



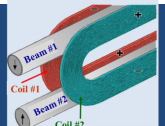
# Quench protection of 1 m long Common-coil dipole







Courtesy:
Emmanuele Ravaioli, CERN

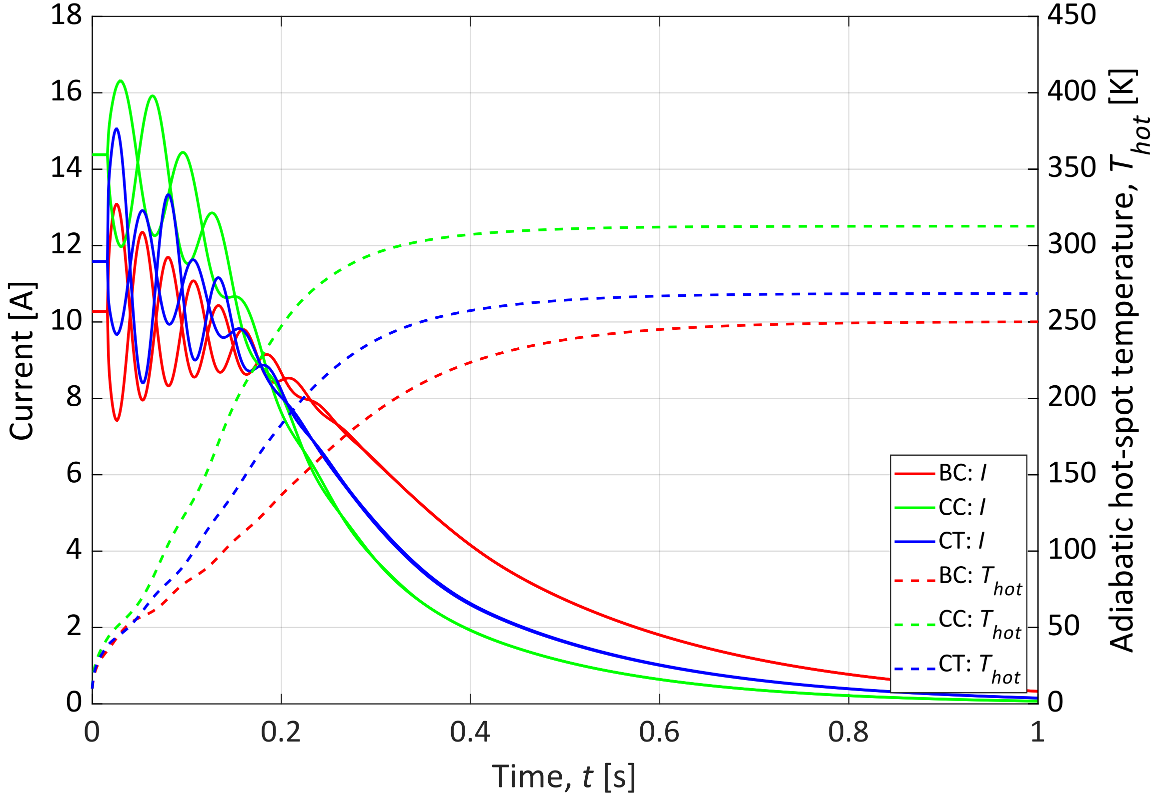


# Quench protection of 1 m and 5 m long magnets

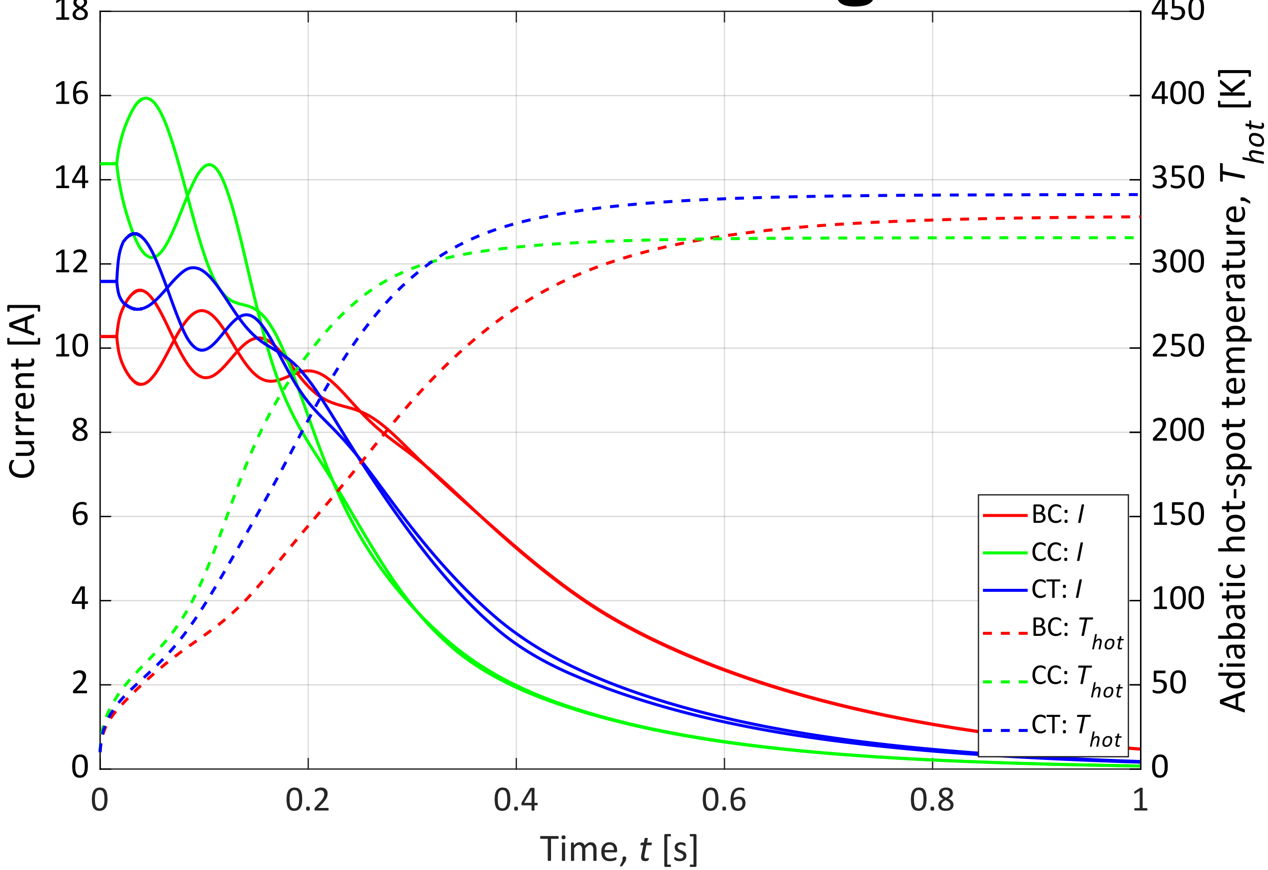
**Courtesy:**
**Emmanuele Ravaioli, CERN**

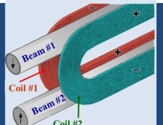
LEDET

## 1-meter long



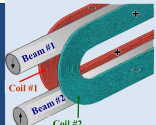
## 5-meter long





# A Possible 20/20 Target:

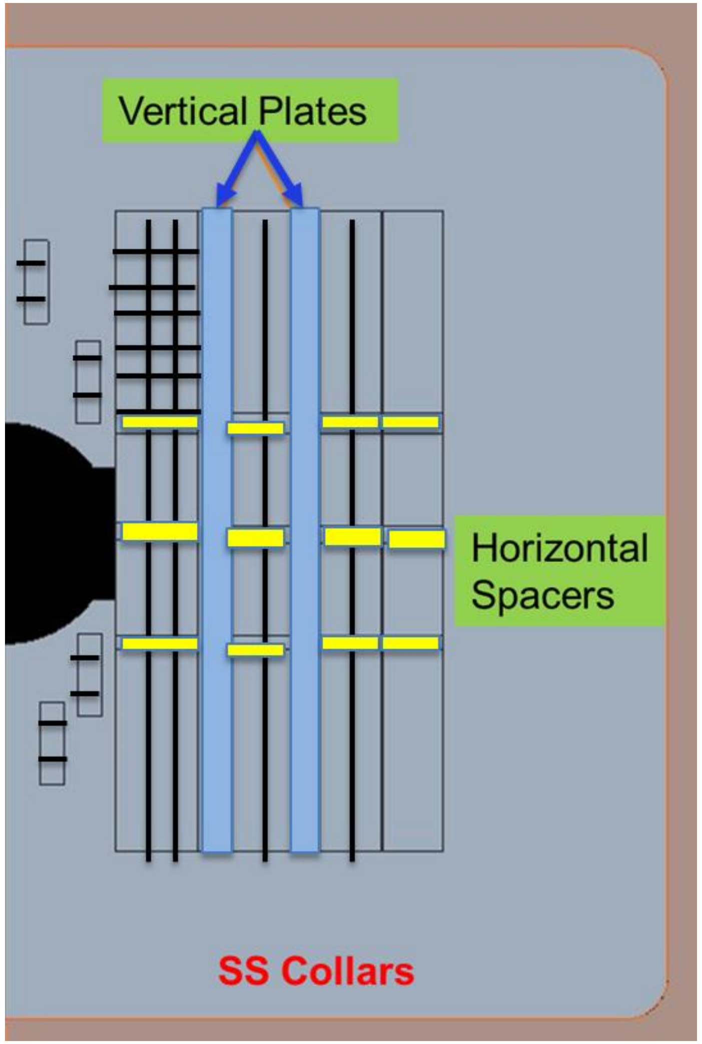
- Operating temperature: 20 K
- Design operating field: 20 T
- Field Margin: 20%
- Time for the first demonstration: 20 years



# Leveraging Fusion R&D

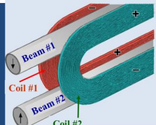
## Design Strategies:

- 20 K operation needs high current HTS cables
- Developing HTS cable will be demanding (expensive and time consuming)
- We benefit enormously if we can leverage HTS cable and magnet technologies being developed for fusion
- Perhaps we may want to use them in a stainless-steel jacket for simpler winding and for structure purpose
- High current fusion cable need larger bend radius
- Common coil design allows large bend radius
- Stress-management will be easier larger deflections and larger local bending (turn-to-turn) are allowed

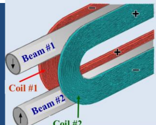


# Summary

- Common coil offers several advantages, some outlined in this presentation.
- Initial comparative study by MDP with European collaborators show that for a 20 T HTS/LTS hybrid dipole, common coil design uses less or similar conductor than that in other designs, while similarly meeting other requirements.
- These are preliminary results with a significant list of tasks are remaining to be completed before this design can be used in a future collider.
- Common coil offers opportunities for leveraging R&D on fusion cable and several magnet technologies for a future 20 T collider dipole operating at 20 K.
- A good opportunity for new scientists and engineers (who come with NO to little pre-conceived notions and biases) for doing pioneering work.



# Extra Slide(s)



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U.S. MAGNET DEVELOPMENT PROGRAM

# A Unique Common Coil Design Dipole at BNL

## (facilitates low-cost, rapid-turn-around variety of R&D)

BNL common coil design experience has been very productive for low, cost rapid-turn around R&D for a variety of purpose.

Identical design may not work everywhere, but a similar approach may.

For example, fully open space may be replaced by removable insert for a field quality coils; or build a structure that can be disassembled easily.

### Five steps for testing new design

1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing