U.S. MAGNET DEVELOPMENT PROGRAM

20 T hybrid dipole R&D at Fermilab

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Outline

- Introduction – justification and goals
- Bi2212/Nb_3Sn CT dipole design concept and parameters
  - *presented at IPAC2023*
- REBCO/Nb_3Sn CT dipole design concept and parameters
  - *will be reported in FERMILAB-TM-2807-TD - in preparation*
- Design comparison
- Summary and next steps

Introduction

- 20 T dipoles are being considered for the next generation of particle accelerators.
- The nominal field of 20 T is above the practical limit of Nb_3Sn accelerator magnets, and it requires using High Temperature Superconductors (HTS).
- High cost of HTS and complicated technology of HTS magnets make attractive a hybrid approach, which uses both materials and technologies.
- Several design options of 20 T dipole with a 50 mm clear aperture are being studied in the framework of US-MDP, including the Cos-theta (CT), Block-type (BL) and Common-Coil (CC) coil configurations.
- Design concepts of a hybrid dipole with 50 mm aperture and 20 T nominal field based on the CT (shell-type) coil with SM and a cold iron yoke have been developed at Fermilab.
- The magnet magnetic design and analysis are presented and compared with the similar magnet designs based on BL and CC coils.

Bi2212 and Nb_3Sn cable and coil parameters

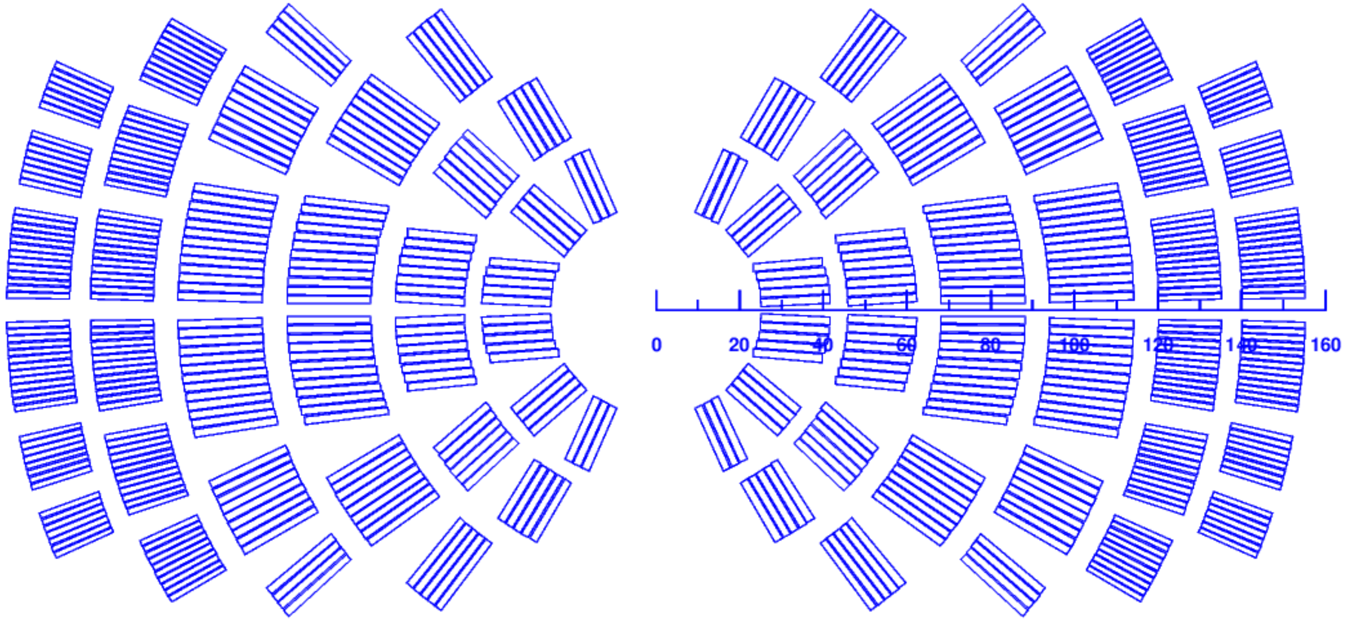
Cable parameters

Parameter	Cable 1	Cable 2	Cable 3
Superconductor	Bi2212	Nb_3Sn	Nb_3Sn
Strand diameter, mm	1.0	1.0	0.7
Cu/nonCu ratio	3.0	1.1	1.1
J_c(15T;1.9K), A/mm^2	3750	2000	2000
Number of strands	32	40	40
Cable width, mm	16.5	20.1	15.0
Cable small edge, mm	1.85	1.70	1.22
Cable large edge, mm	1.95	1.90	1.38
Cable packing factor	0.83	0.90	0.81

Coil parameters

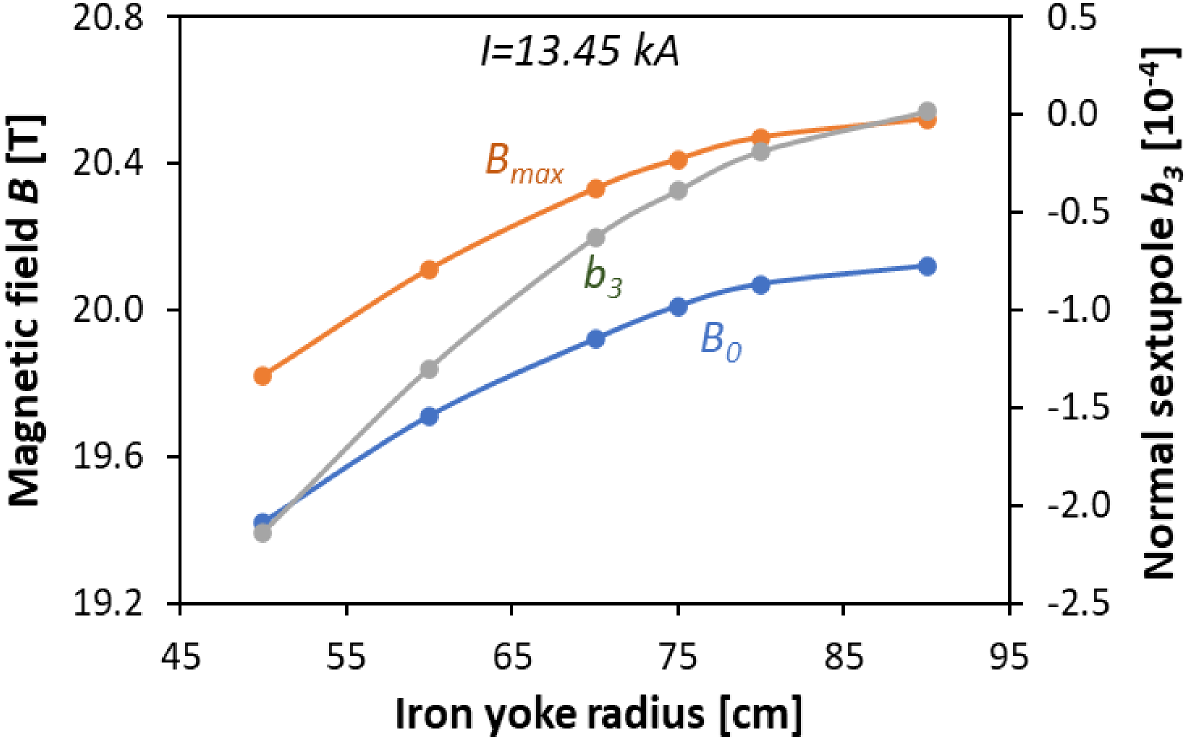
Parameter	Value
Number of layers	6
Number of blocks	6 HTS+12 LTS
Number of turns/coil, L1-2/L3-4/L5-6	31/52/63
Coil inner/outer diameter, mm	50/310
Bi2212 coil area/quadrant, mm^2	972
Nb_3Sn coil area/quadrant, mm^2	3110

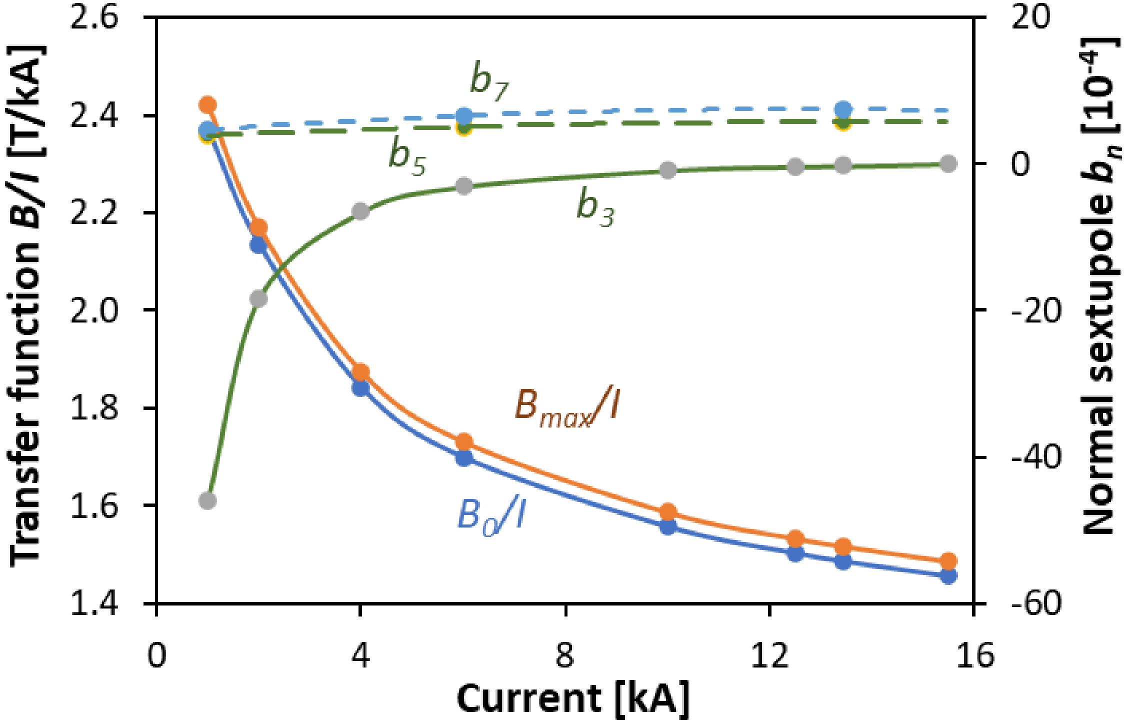
Coil cross-section



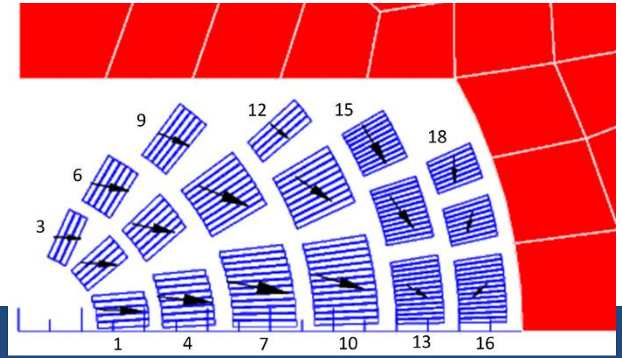
- The coil uses Rutherford cables made of Bi2212 (HTS) and Nb_3Sn (LTS) composite superconducting wires.
- Turns are grouped into blocks separated by radial and azimuthal spacers to optimize the field quality in aperture and provide mechanical stress management in the coil.

Effect of the iron yoke

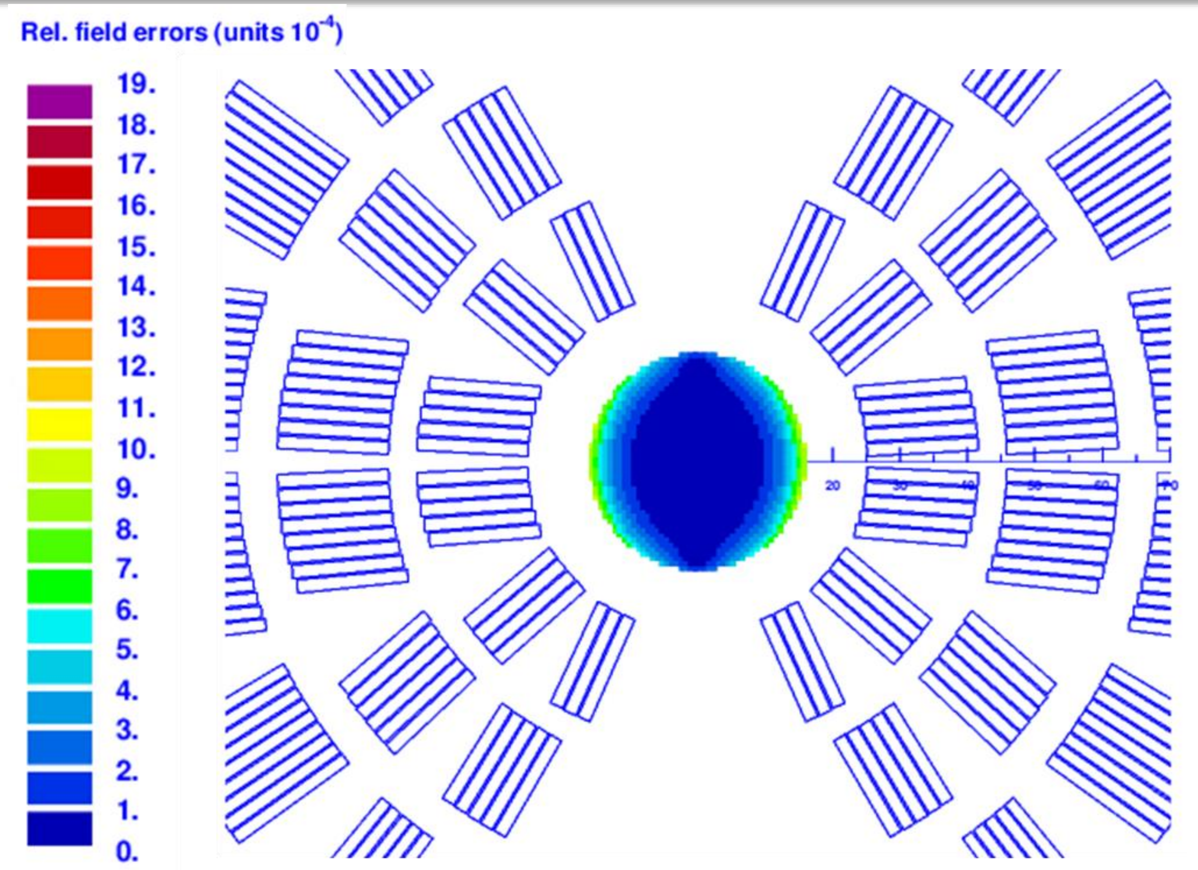




- The effect of yoke OD above 150 cm is small.
- Iron saturation effect is large
- Circular yoke inner surface reduces *TF=B/I* by 3.3%.
- Iron OD of 150 cm and the flat iron inner shape were selected.

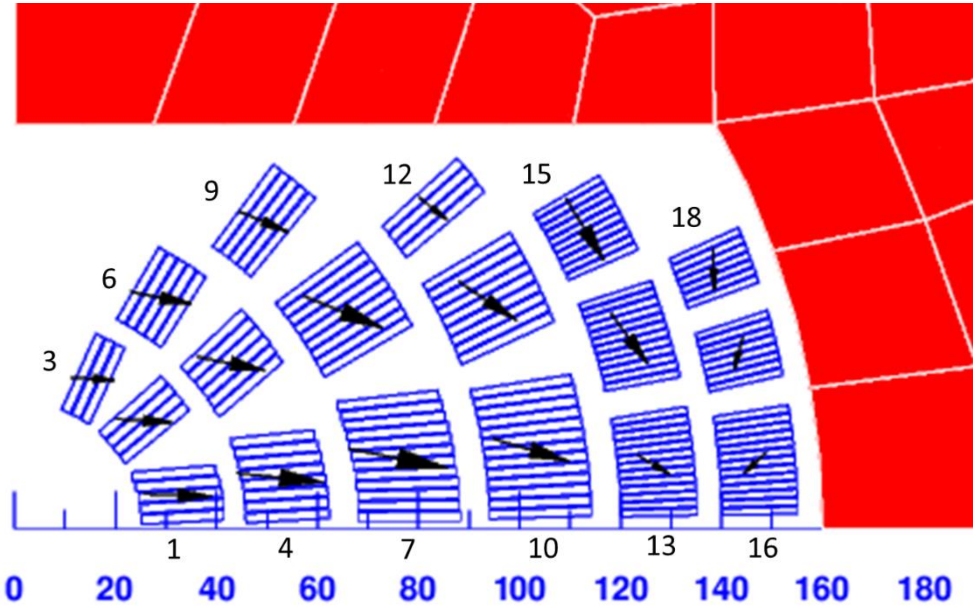


Field harmonics and magnet main parameters



Field harmonics at R_{ref}=17 mm and B=20 T

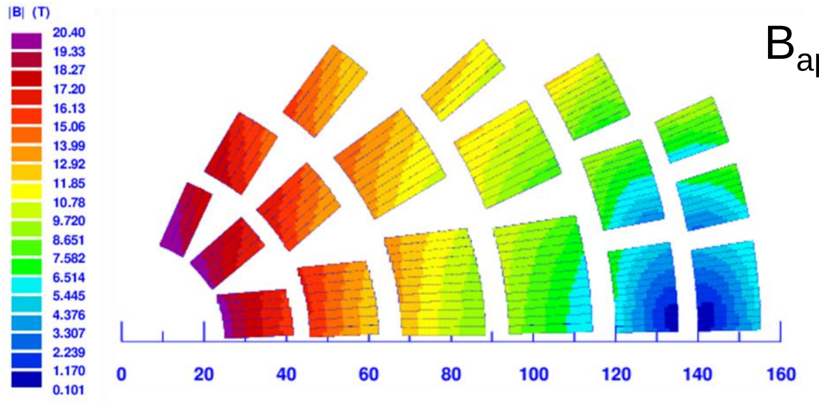
n	3	5	7	9
b_n 10^{-4}	-0.24	5.83	7.54	-0.98



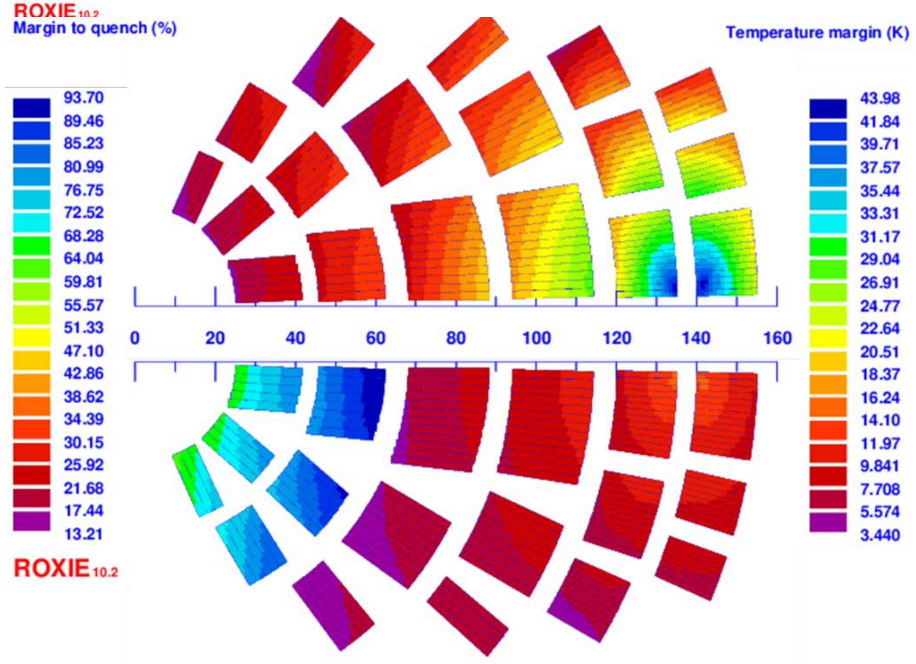
Magnet parameters

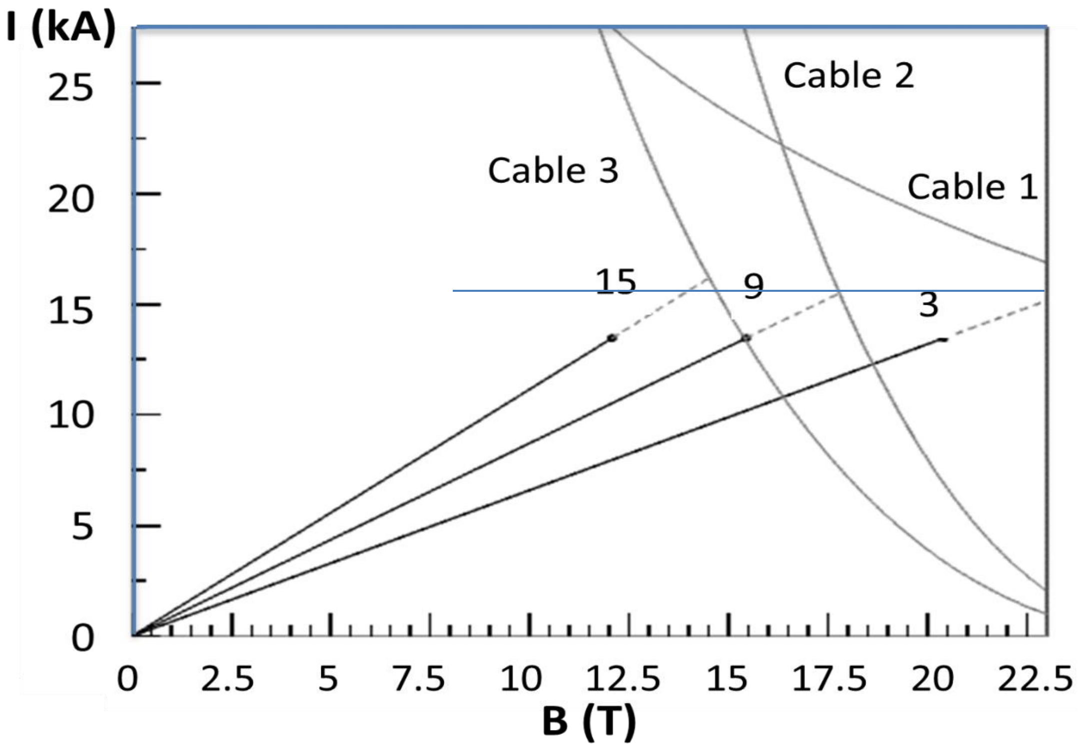
Parameter	Value
Coil nominal current I_{nom}, kA	13.45
Coil nominal field B_{nom}, T	20.0
Coil to aperture field ratio B_{max}/B_o	1.002
Coil inductance @I_{nom}, mH/m	52
Stored energy @I_{nom}, MJ/m	4.7
Lorentz forces F_x/F_y @I_{nom}, MN/m	14.9/-7.4

Magnet margins



B_{ap}=20 T

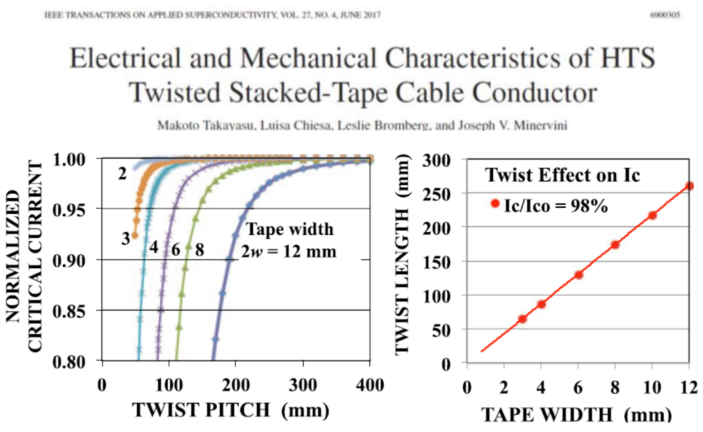


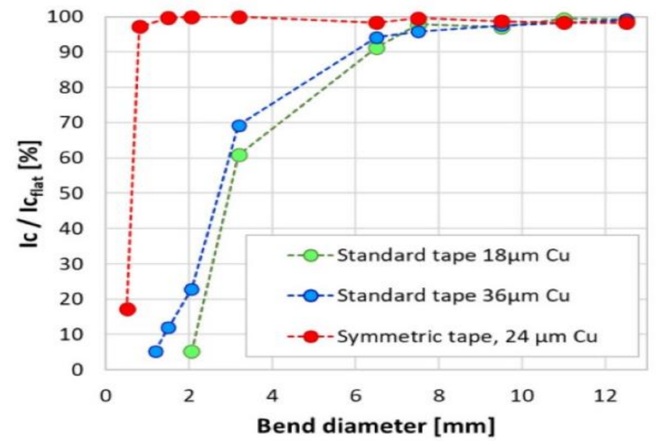


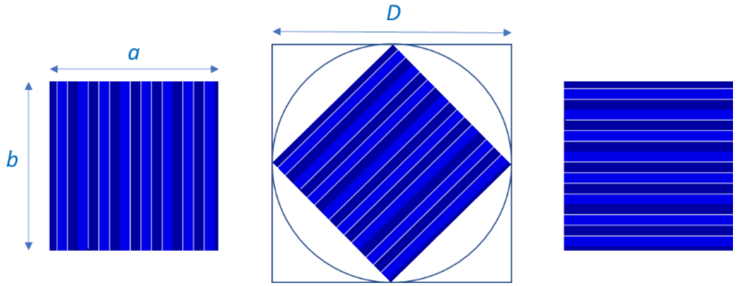
- B_{max} is reached in block 3 for Cable 1, block 9 for Cable 2 and block 15 for Cable 3
- Margin to quench is 16.2% for Bi2212 coil (L1-2), 13.2% for Nb_3Sn Coil 2 (L3-4), and 16.9% for Nb_3Sn Coil 3 (L5-6)
- Magnet margins (T and Ic) are limited by the Nb_3Sn coil

REBCO/Nb_3Sn hybrid dipole

- The HTS part uses Twisted Stacked-Tape (TST) REBCO cable
    - allows small easy-bend radius and twist
- REBCO/Nb_3Sn coil cross-section was obtained by filling the radial space of 2L Bi2212 coil with 4L REBCO coil keeping the 4L graded Nb_3Sn coil.
- The Nb_3Sn cables have the same parameters as in 20 T Bi2212/Nb_3Sn dipole.
- TST cable has a square stack of parallel 5-mm wide tapes.
- Due to stack twisting, the equivalent width *D* of rectangular cable cross-section is √2 larger than the REBCO stack width.







- *For 4 mm wide 0.1 mm thick tape minimal L_t~80 mm*
- *Minimal bending D~8 mm*

Cable and coil parameters

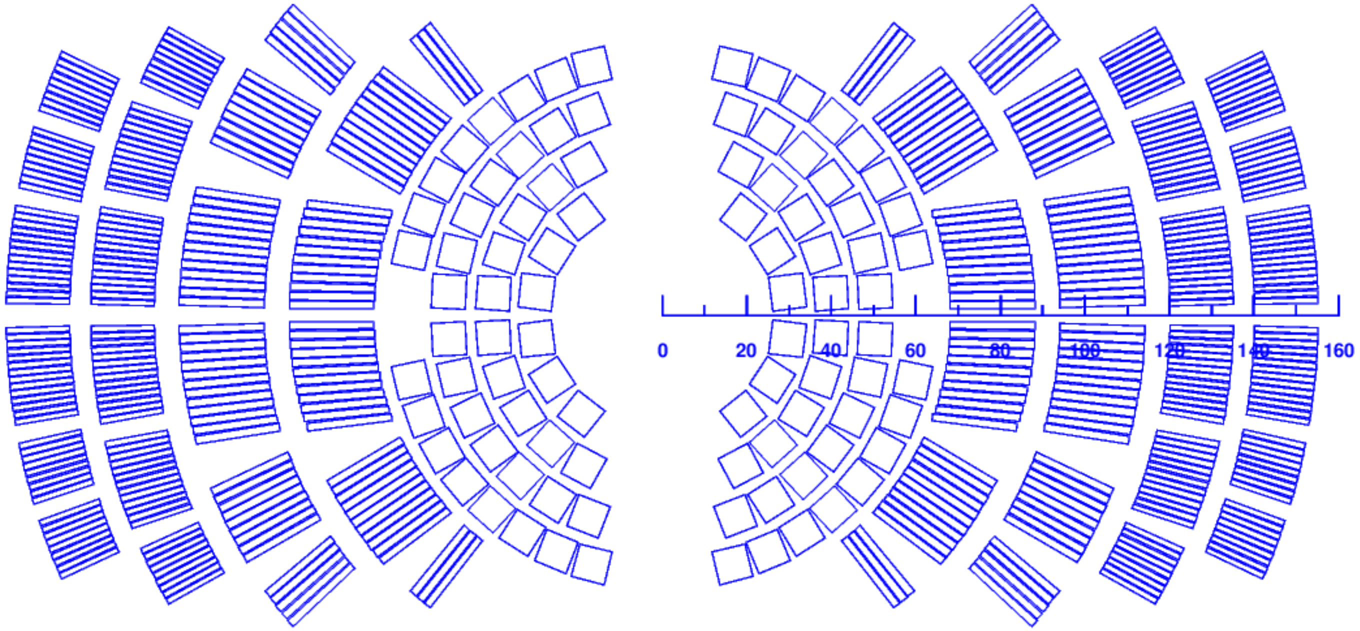
Cable parameters

Parameter	Cable 1	Cable 2	Cable 3
Superconductor	REBCO	Nb_3Sn	Nb_3Sn
Strand size, mm	5×0.1	1.0	0.7
Cu/nonCu ratio	0.67	1.1	1.1
I_c(15T;1.9K), kA	23	29/35	14/17
Number of strands	50	40	40
Cable width, mm	8	20.1	15.0
Cable small edge, mm	8	1.70	1.22
Cable large edge, mm	8	1.90	1.38
Cable packing factor	0.39	0.90	0.81

Coil parameters

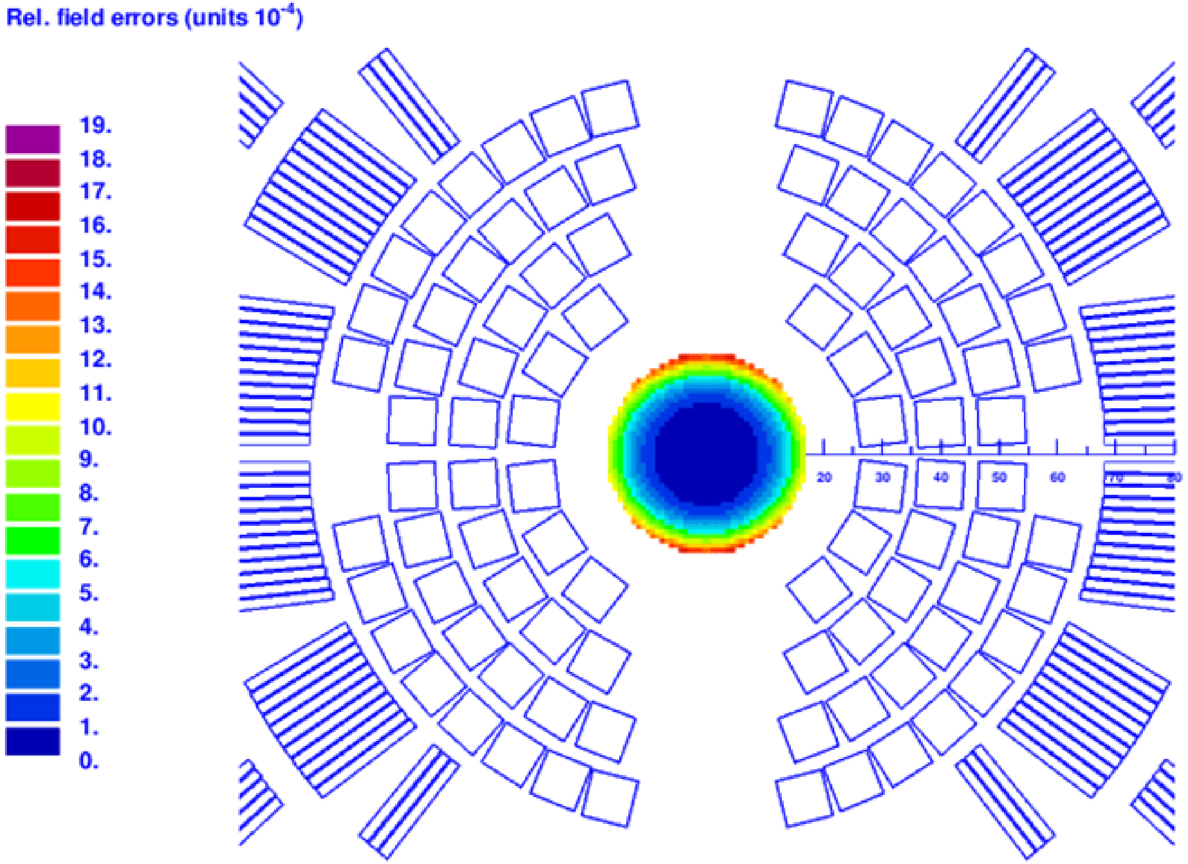
Parameter	Value
Number of layers	8
Number of HTS blocks	23
Number of LTS blocks	12
Number of turns in L1-2/L3-4/L5-6/L7-8	8/15/54/65
Coil inner diameter, mm	50
Coil outer diameter, mm	310
REBCO tape area/quadrant, mm^2	575
Nb_3Sn wire area/quadrant, mm^2	3221

Coil cross-section



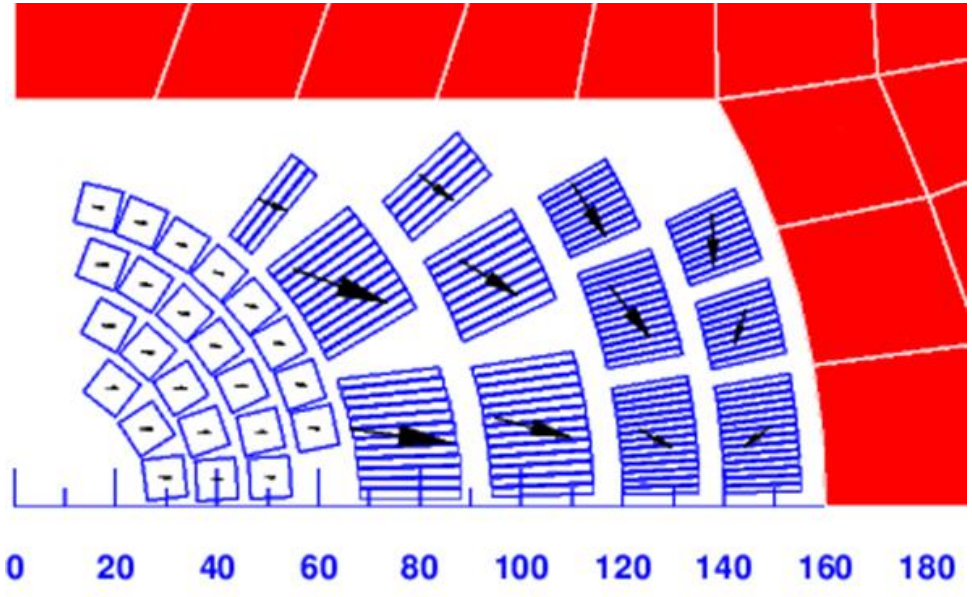
- REBCO layers are made of individual turns.
- Space between the REBCO turns is used for SM.
- *TF* and field quality in aperture were optimized by varying the number and position of REBCO turns and Nb_3Sn block parameters (number of turns, azimuthal angle and tilt).

Field harmonics and magnet main parameters



Field harmonics at R_{ref}=17 mm and B=20 T

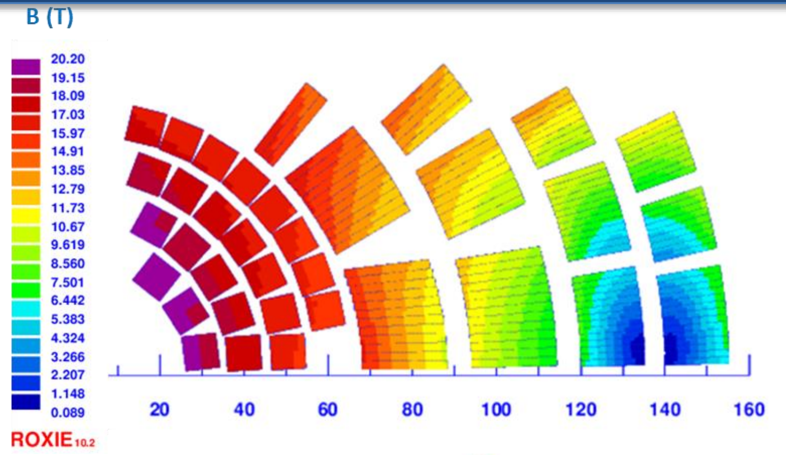
n	3	5	7	9
b_n, 10^{-4}	0.01	-13.12	3.06	-0.34

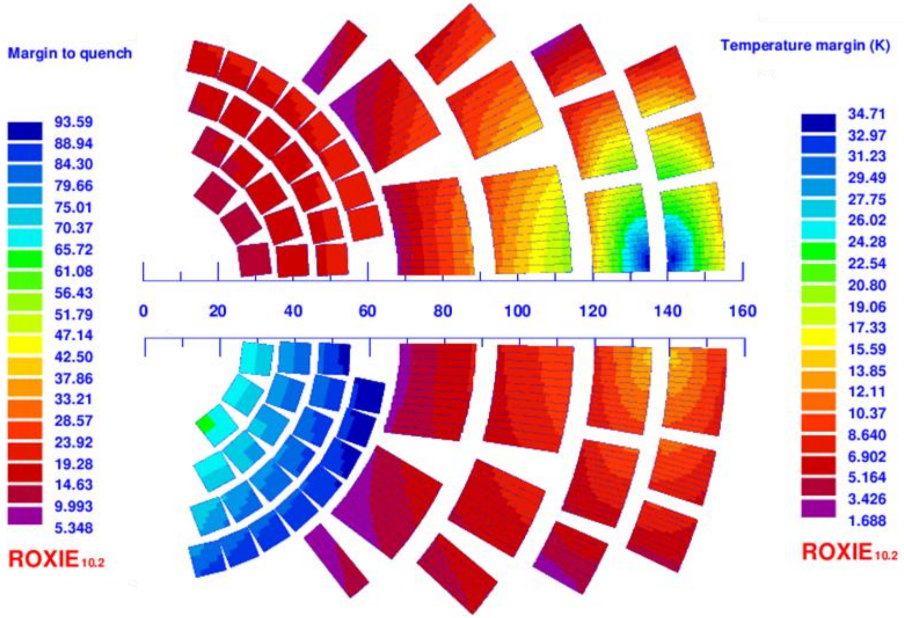


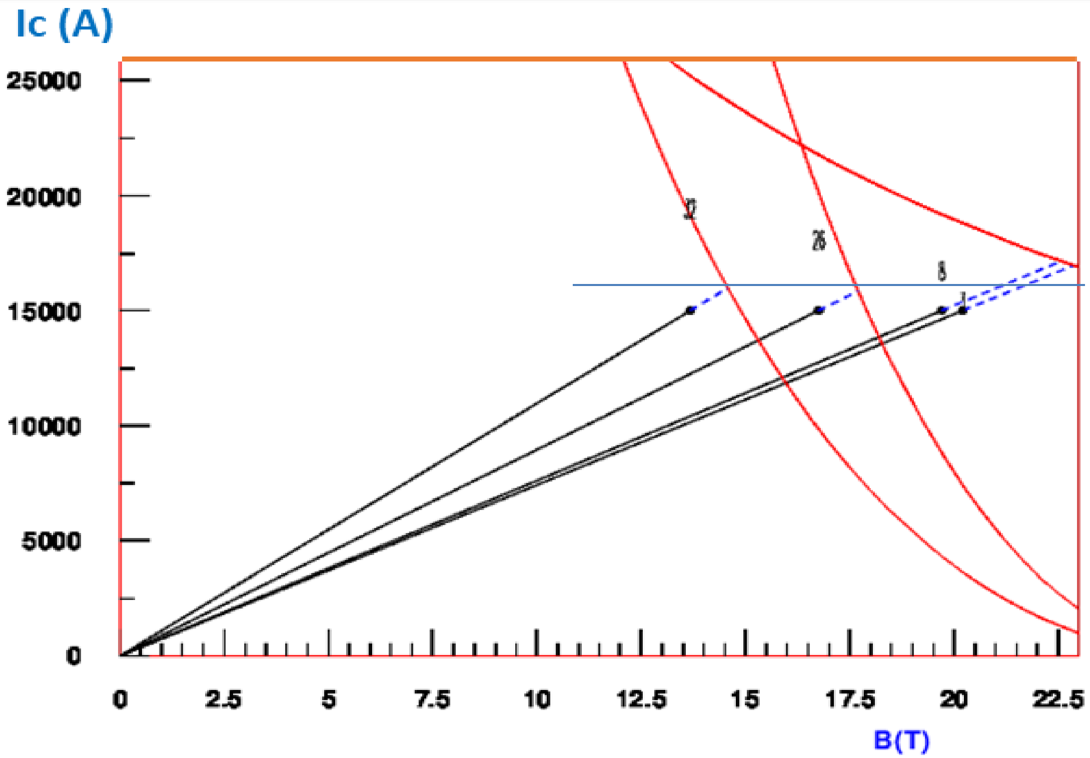
Magnet parameters

Parameter	Value
Coil nominal current I_{nom}, kA	14.92
Coil nominal field B_{nom}, T	20.0
Coil to aperture field ratio B_{max}/B_o	1.005
Coil inductance @I_{nom}, mH/m	54
Stored energy @I_{nom}, MJ/m	6.1
Lorentz forces F_x/F_y @I_{nom}, MN/m	17.9/-9.9

Magnet margins



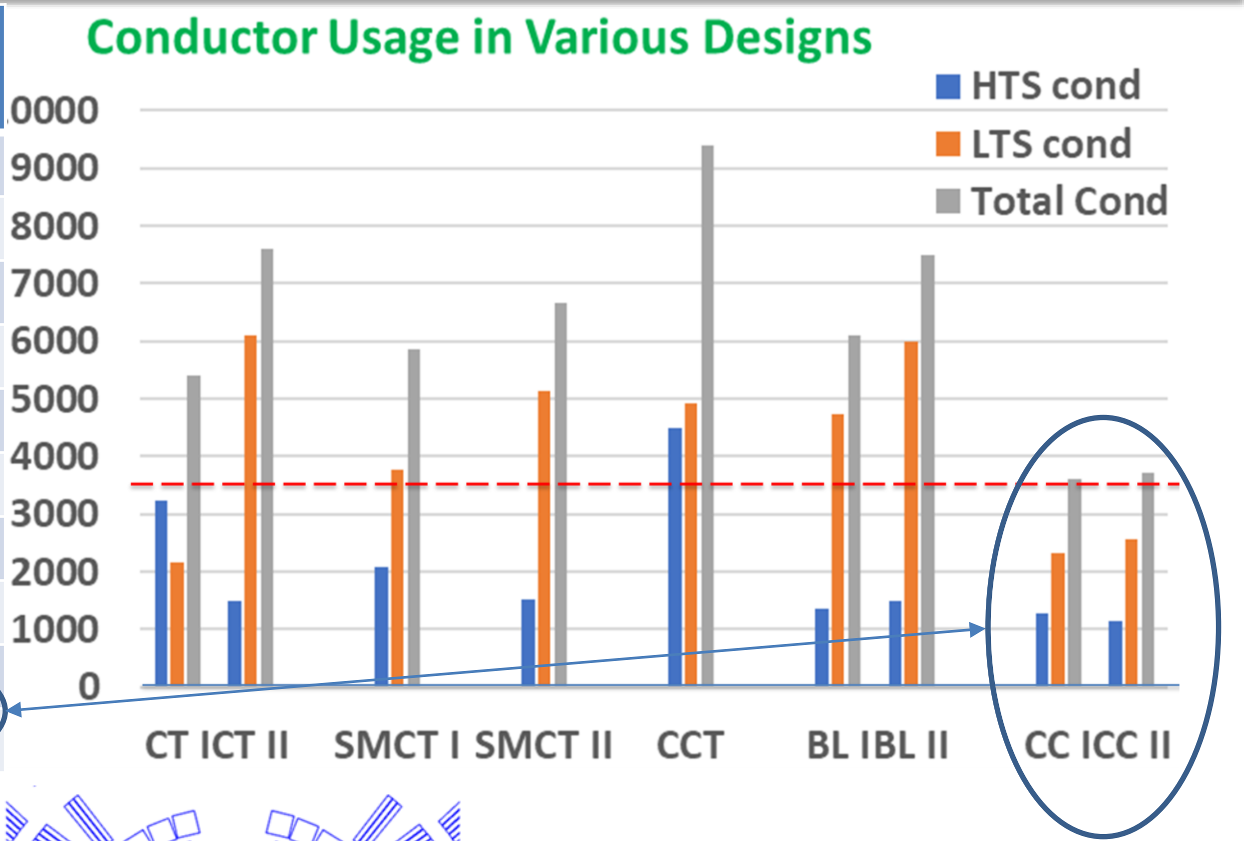


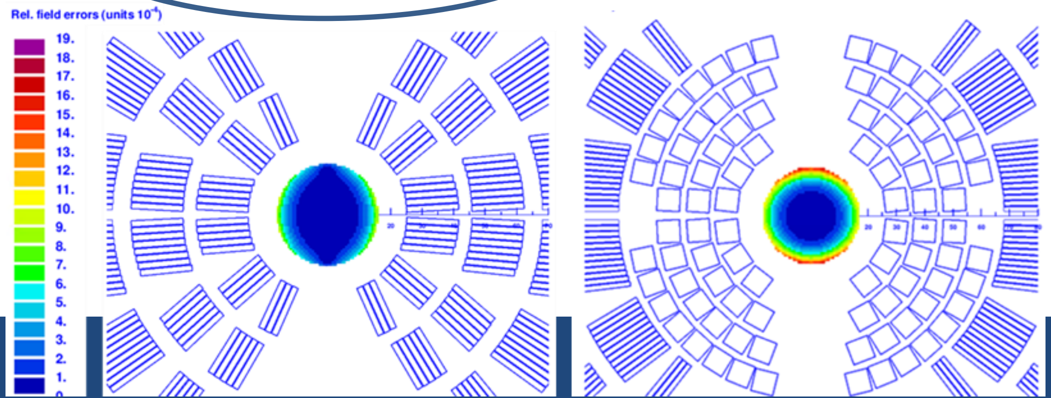


- B_{max} is reached in block 3 for Cable 1, block 24 for Cable 2 and block 30 for Cable 3
- Margins to quench are 11.7% for REBCO Coils 1 and 2 (L1-2 and L3-4), 5.4% for Nb_3Sn Coil 3 (L5-6), and 6.2% for Nb_3Sn Coil 4 (L7-8)
- Magnet margins (T and I) are limited by the Nb_3Sn coil

Magnet parameter comparison

Parameter	REBCO/ Nb_3Sn	Bi2212/ Nb_3Sn
Nominal current I_{nom}, kA	14.92	13.45
Nominal bore field B_{nom}, T	20.0	20.0
Coil nominal field B_{nom}, T	20.10	20.04
Coil to aperture field ratio B_{max}/B_o	1.005	1.002
Magnet margin at 1.9 K, %	5.4	13.2
Coil inductance @I_{nom}, mH/m	54	52
Stored energy @I_{nom}, MJ/m	6.0	4.7
Lorentz force F_x/F_y @I_{nom}, MN/m	17.8/-9.8	14.9/-7.4
Total HTS coil area, mm^2	575	972
Total Nb_3Sn coil area, mm^2	3221	3110





Summary and next steps

- Complementary conceptual designs of a 20 T hybrid dipole based on HTS and Nb_3Sn shell-type coils with realistic SC parameters and 150 mm cold iron yoke have been developed and analyzed.
- Bi2212/Nb_3Sn dipole
  - 13.2% load line margin at 1.9 K
  - S_{Bi2212} and S_{tot} are noticeably smaller with respect to other US-MDP designs
- REBCO/Nb_3Sn dipole
  - 5.4% load line margins at 1.9 K
    - magnet load line margin is lower than the design criteria
    - possibilities of increasing the total margin to the acceptable level needs to be studied
  - S_{REBCO} and S_{tot} smaller then in Bi2212/Nb_3Sn hybrid design
    - increasing the coil cross-section provides possibility to increase the magnet operation margin
- In both designs SM elements are integrated in the coil cross-section to keep the mechanical stresses in brittle HTS and Nb_3Sn superconductors within the acceptable limits.
- Next steps:
  - mechanical and quench protection analysis for both designs
  - magnetic design optimization of REBCO/Nb_3Sn dipole
  - HTS coil technology development – *in progress*