U.S. MAGNET DEVELOPMENT PROGRAM

Development of HTS/LTS Hybrid Dipole Magnets by the US Magnet Development Program

P. Ferracin

Joint MSC seminar and HFM Forum
July 10th, 2024

Acknowledgement (20 T working group)

- Members US MDP 20 T working group
  - LBNL: D. Arbelaez, L. Brouwer, M. D'Addazio, L. Garcia Fajardo, J.L. Rudeiros Fernandez, M. Juchno, S. Prestemon, T. Shen, R. Teyber, G. Vallone, X. Wang
  - FNAL: G. Ambrosio, M. Baldini, E. Barzi, S. Gourlay, V. Kashikhin, V. Marinozzi, I. Novitski, G. Velev, A. Zlobin
  - NHMFL: L. Cooley, D. Larbalestier
  - BNL: K. Amm, M. Anerella, J. Cozzolino, R. Gupta, F. Kurian, B. Yahia

- European Contributors
  - Emmanuele Ravaioli (CERN)
  - Douglas Martins Araujo (PSI)
  - Etienne Rochepault (CEA)

Outline

- Introduction and motivations
  - US Magnet Development Program and the 20 T working group
  - Why hybrid and why 20 T
- 20 T design
  - Design criteria
  - Preliminary considerations based on sector coils
  - Current reference cross-sections
- Overview of hybrid activities
  - Nb_3Sn outserts
  - HTS inserts
- Conclusions

US Magnet development program

- US MDP, a collaboration between 4 US laboratories (BNL, FNAL, LBNL, NHMFL) was established in 2016 as a result of the 2013 P5 report
- The general goal is to perform basic R&D towards next generation high-field accelerator magnets
  - So, R&D not specifically directed towards one of the possible next accelerators, but still relevant to them
- More specifically the strategic priorities are
  - Explore the performance limits of Nb_3Sn accelerator magnets
    - Focus on minimizing the operating margin and training → Cost
  - Probing stress management structures
    - To cope with strain sensitive Nb_3Sn and HTS conductors operating at very high fields
  - Perform R&D on HTS accelerator magnets
    - Characterize materials allowing fields and temperatures beyond Nb_3Sn limits
  - Develop LTS/HTS hybrid magnets
    - Economically viable option for field > 16 T
  - Investigate fundamental aspects of magnet design and technology
    - Towards substantial performance improvements and magnet cost reduction

US Magnet development program

- Road-map updated in 2020
  - and to be updated again in by the end 2024

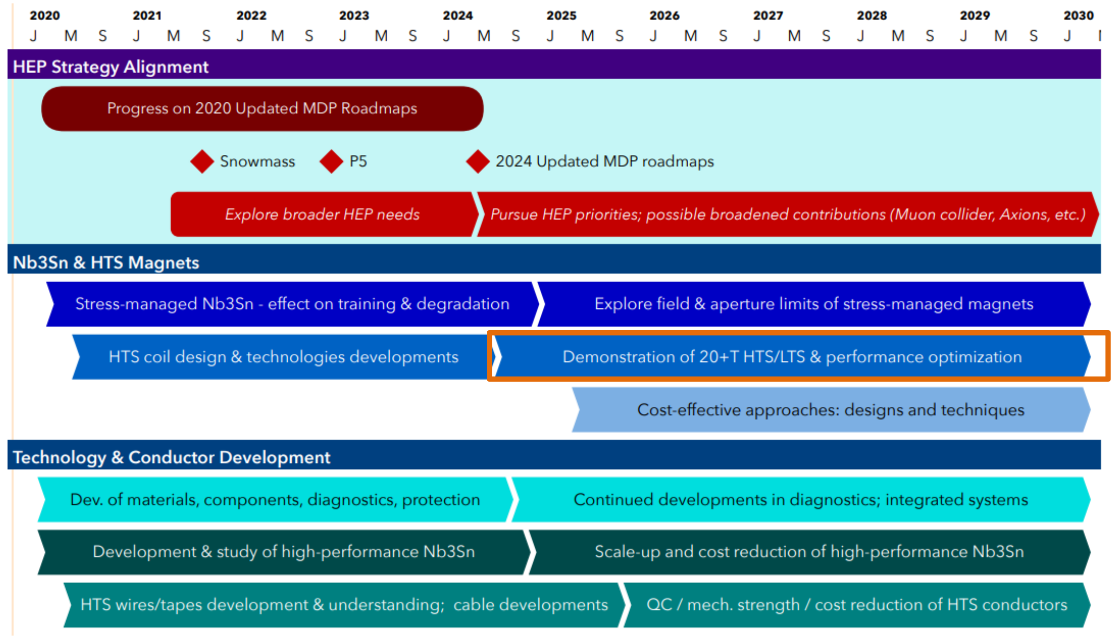

Figure 8. A high-level ten-year roadmap for the US Magnet Development Program, designed to align with the US Physics community planning process.

https://arxiv.org/abs/2011.09539

MDP 20 T working group

- Established in 2020 to
  - Perform a conceptual design of a 20 T hybrid HTS-LTS magnet
    - Comparative analysis of different design options for a 20 T hybrid
      - Cosϑ design and its stress-management options
      - Block-type coil design (*block with flared ends*)
      - Common-coil design (*block with racetrack coils*)
  - Review and follow-up of work on hybrid magnets
    - Collect and organize information to provide inputs for 20 T hybrid design and feed-backs to hybrid program

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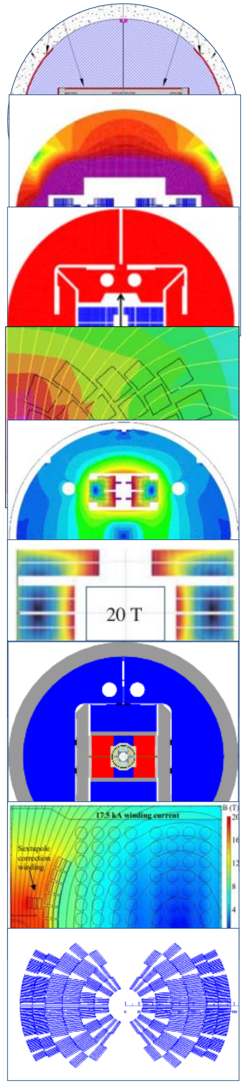
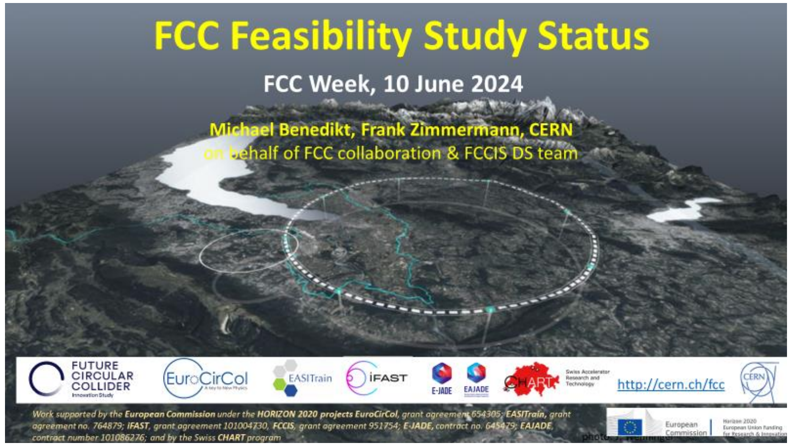
Motivations of a 20 T hybrid design
Previous work

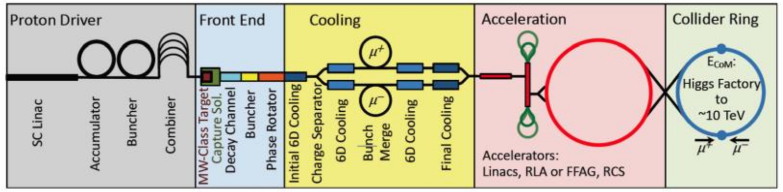


- 2005, P. McIntyre, *et al.*, 24 T hybrid for LHC tripler (TAMU)
- 2011, 2014, E. Todesco, *et al.*, 20 T hybrid for LHC upgrade (CERN)
- 2015, G. Sabbi, *et al.*, 20 T hybrid for SPPC China and FCC (LBNL)
- 2015, R. Gupta, *et al.*, 20 T hybrid for LHC upgrade (BNL)
- 2016, Q. Xu, *et al.*, 20 T hybrid for SPPC China (IHEP)
- 2018, J. van Nugteren, *et al.*, 20+ T HTS for LHC upgrade or FCC (CERN)
- 2020, D. Martins Araujo , *et al.*, towards 20 T FRESCA2+Feather (CERN)
- 2021, J.S. Rogers, *et al.*, 18 T hybrid (TAMU)
- 2022, P. Ferracin, *et al.*, 20 T hybrid demonstrator (US MDP)

Motivations of a 20 T hybrid design

- Relevant to…
  - FCC-hh
    - "high-field superconducting magnets: 14-20 T"
  - Muon colliders
    - Collider ring dipole
      - Large aperture (100-160 mm), 12-16 T
        - » Similar to the outsert of a 20 T hybrid
    - IR quadrupole magnets
      - "…with a peak field of 20 T, also associated with, large apertures, up to 300 mm"





IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 5, AUGUST 2024 4005708

Magnets for a Muon Collider—Needs and Plans

L. Bottura, C. Accettura, N. Amemiya, *Senior Member, IEEE*, B. Auchmann, J.S. Berg, A. Bersani, A. Bertarelli, F. Boattini, B. Bordini, P. Borges de Sousa, M. Breschi, B. Caiffi, X. Chaud, *Senior Member, IEEE*, F. Debray, A. Dudarev, M. Eisterer, S. Fabbri, S. Farinon, P. Ferracin, *Senior Member, IEEE*, H. De Gersem, *Member, IEEE*, A. Kario, A. Kolehmainen, J. Kosse, J. Lorenzo Gomez, R. Losito, S. Mariotto, M. Mentink, T. Mulder, R. Musenich, D. Novelli, T. Ogitsu, M. Palmer, J. Pavan, H. Piekarz, *Senior Member, IEEE*, A. Portone, L. Quettier, E. Rochepault, L. Rossi, *Fellow, IEEE*, T. Salmi, H. Schneider-Muntau, C. Senatore, *Senior Member, IEEE*, M. Statera, H.H.J. Ten Kate, *Senior Member, IEEE*, P. Testoni, G. Vallone, A. Verweij, R. Van Weelderen, M. Wozniak, A. Yamamoto, Y. Yang, Y. Zhai, *Member, IEEE*, and A. Zlobin

Motivations of a 20 T hybrid design

- In summary, from the MPD perspective, the HTS/LTS hybrid is a very effective tool to perform R&D on a broad spectrum magnets similar to those considered for FCC-hh or Muon Colliders

- So far, it is also an economically viable option to explore the very high field
  - 16+ T range

- On a side note (but still important)
  - It is a very interesting and fun problem for magnet designers
  - Excellent case study for students and Postdocs
    - It contains almost everything: different SC materials…different cable geometries…magnetics… mechanics…quench detection and protection…..
  - It forces HTS and LTS teams to work together on integrated designs

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  - Nb_3Sn outserts
  - HTS inserts
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Design criteria

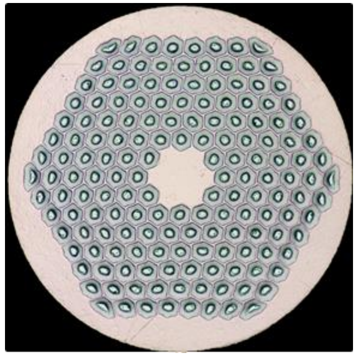
- Coil and magnet parameters
  - Free coil aperture (diameter) 50 mm
  - Operational bore field 20 T
  - load-line fraction @ 1.9K: I_{op}/I_{ss} <= 87 %
  - 2D Geometrical harmonics b_n<3 units for n<10 (at R_{ref}=17 mm)
- Quench protection
  - All coils powered in series
  - Maximum hot spot temperature 350 K
- Mechanics
  - Maximum Nb_3Sn coil stress <180 (<150) MPa at 1.9 (293) K
  - For the HTS <120 MPa

Design criteria: some comments

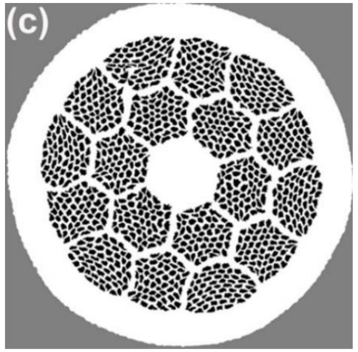
- Size
  - No limits or constraints set (request from the working group)
  - So far the goal has been to minimize coil size, but not significant effort has been devoted to minimize the structure (next step)
- Quench protection
  - We focus for now on a 1 m long magnet, with CLIC/dump.
  - But we start considering also the issue of protecting a long accelerator magnet
- Mechanics
  - Good knowledge of mechanical properties and limits of Nb_3Sn, recent interesting results from Twente on Bi2212 cables → the assumptions seem reasonable
  - Much less knowledge on REBCO CORC/STAR stress limits and properties

Design criteria: Wires and cables

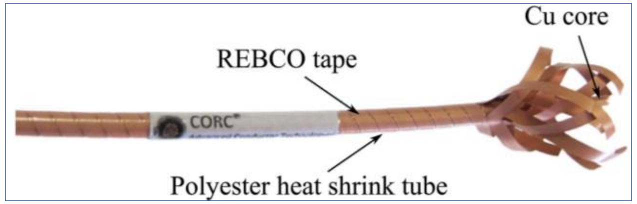
- Nb_3Sn
  - 0.7 – 1.1 mm strands
    - Typical properties of 127 or 169 (***Bruker-OST***) RRP stacks
  - Rutherford cables: 8-26 mm wide, 1.3-2.0 mm thick

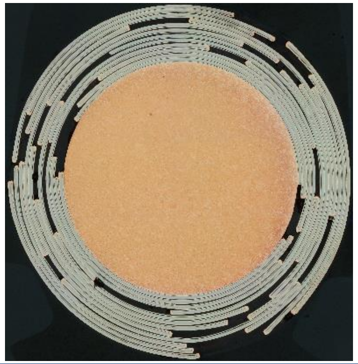


- Bi2212
  - Isotropic, round, multifilamentary
    - ***Bruker-OST*** architecture 19 × 36, 37 × 18 or 55 × 18 for 0.8 mm diameter wires
  - On paper, possible same strand and Rutherford cable dimensions as Nb_3Sn



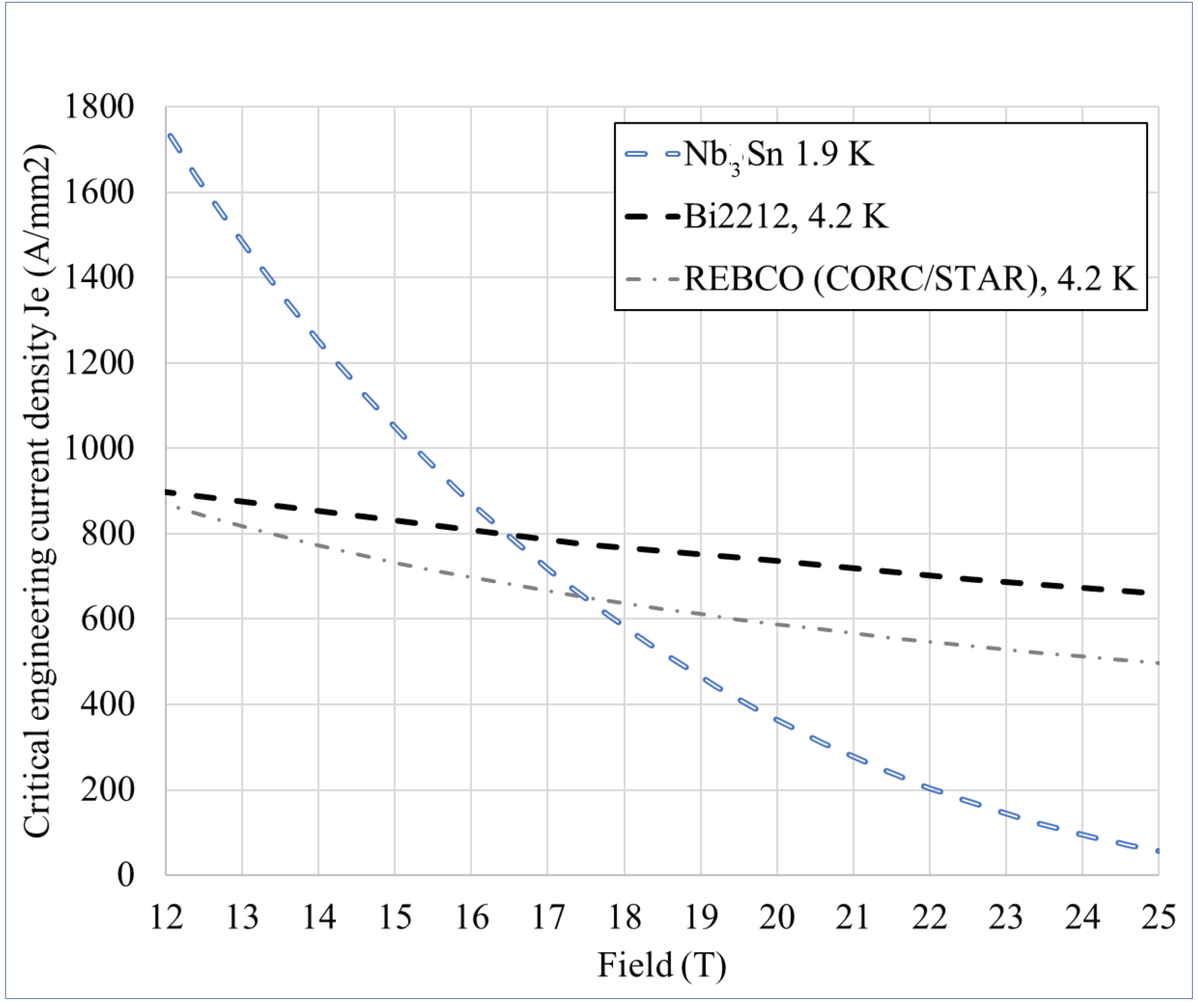
- REBCO
  - CORC (***ATC LLC***) cable and STAR (***AMPeers***) wires:
    - Tapes around Cu former
      - Diameter from 1.3 to 3.6 mm
  - 6-around-1 STAR cable





Superconducting materials: J_e and J_o

- Assumptions for magnetic analysis
  - J_e = Strand current / strand area
    - *J_{e_LTS} = 875 A/mm² (1.9 K, 16 T, 5% degrad.)*
      - *3000 A/mm² J_c (4.2 K, 12 T, virgin)*
    - *J_{e_HTS} = 740 A/mm² (20 T)*
      - Bi2212 value
- Nb_3Sn and HTS cross at 16.5 T
- CORC/STAR wire still lower in J_e *(600 A/mm², 20 T)*



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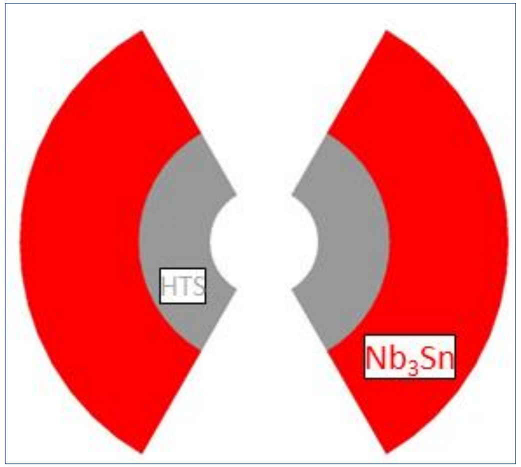
Sector coils

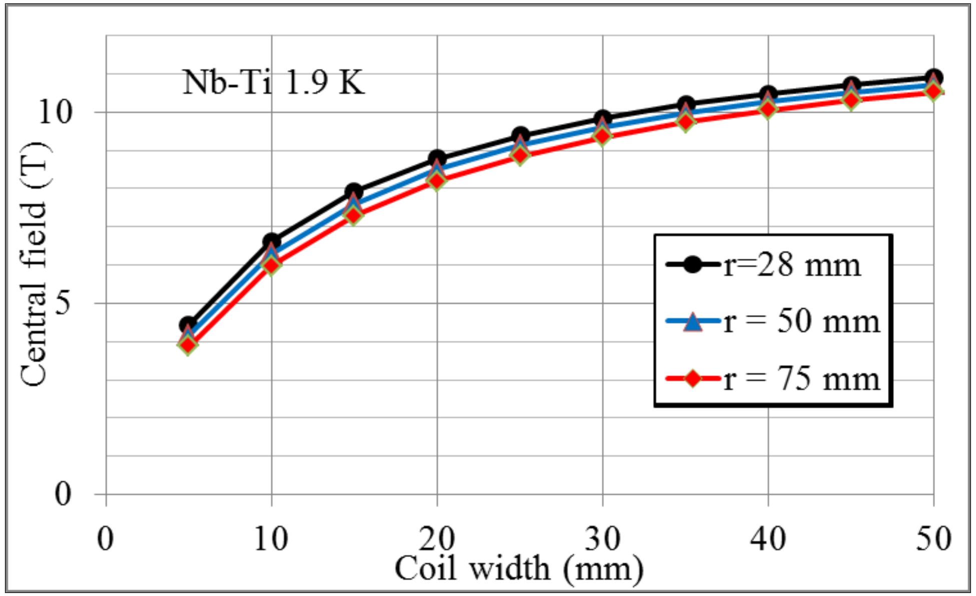
- 60° coil with $J = J_0$ constant current distribution
  - Two different areas: HTS insert and LTS outsert
- Very simplified model, but still very useful for preliminary investigation on
  - Field limits and coil size, stress, and LTS to HTS ratio

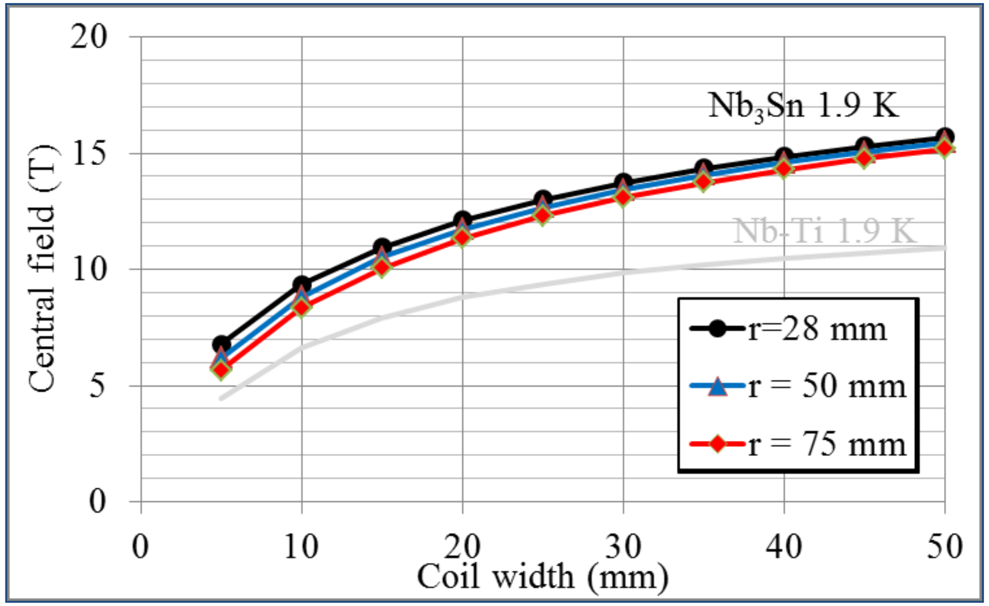


More advanced study: D. Novelli et al., “Performance limits of accelerator dipole and quadrupole for a muon collider,” *IEEE Trans. Appl. Supercond.*, vol. 34, no. 5, Aug. 2024, Art. no. 4002405.

About field limits and coil size

- In general, the larger the coils, the higher the field, but up to a point
- Practical limits: 9-10 T for Nb-Ti, 15-16 T for Nb_3Sn

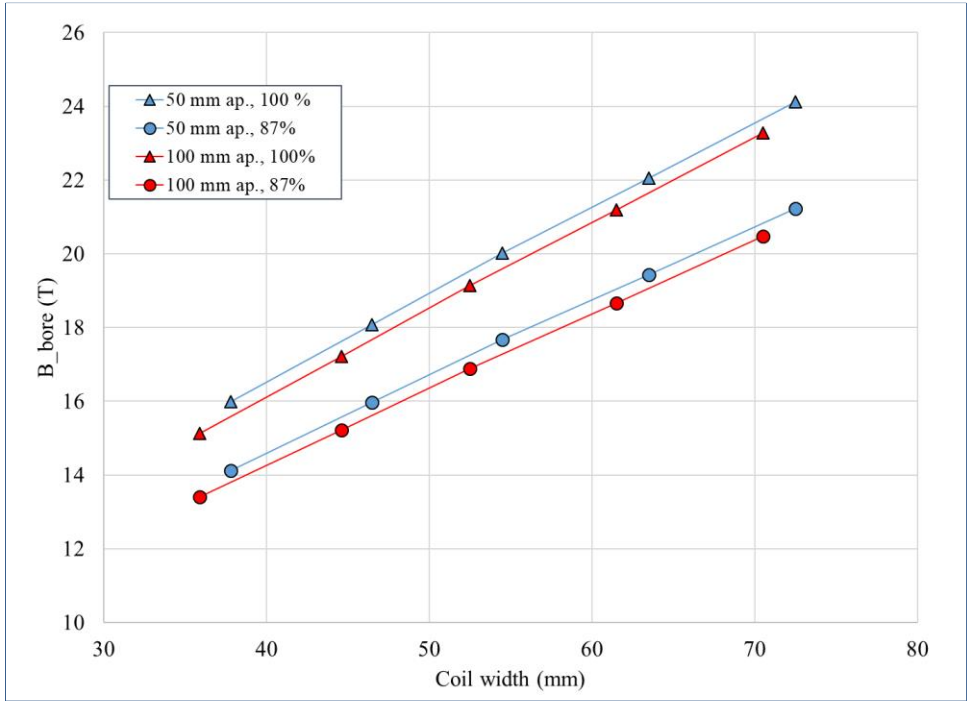




L. Rossi and E. Todesco, "Electromagnetic design of superconducting dipoles based on sector coils", ***Phys. Rev. ST Accel. Beams 9 (2006) 102401***

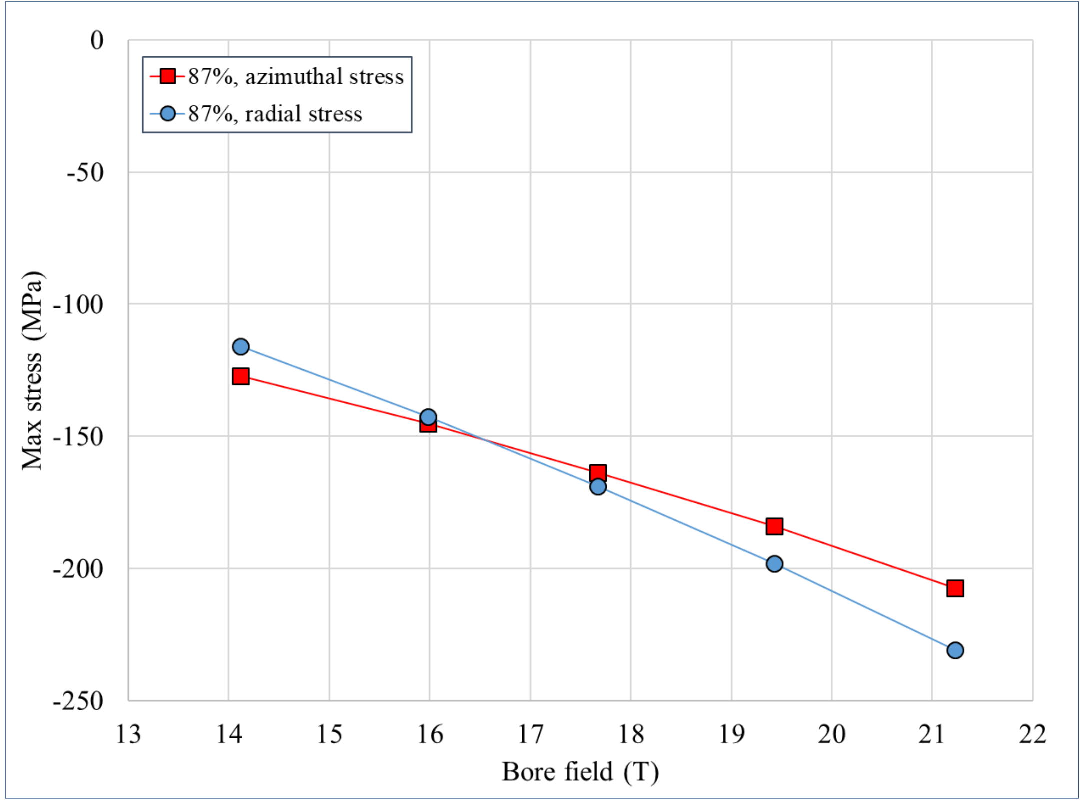
About field limits and coil size

- With HTS material
  - More linear behavior, due to the “flat” HTS critical curve
  - For 20 T bore field, coil 70+ mm wide



About the stress

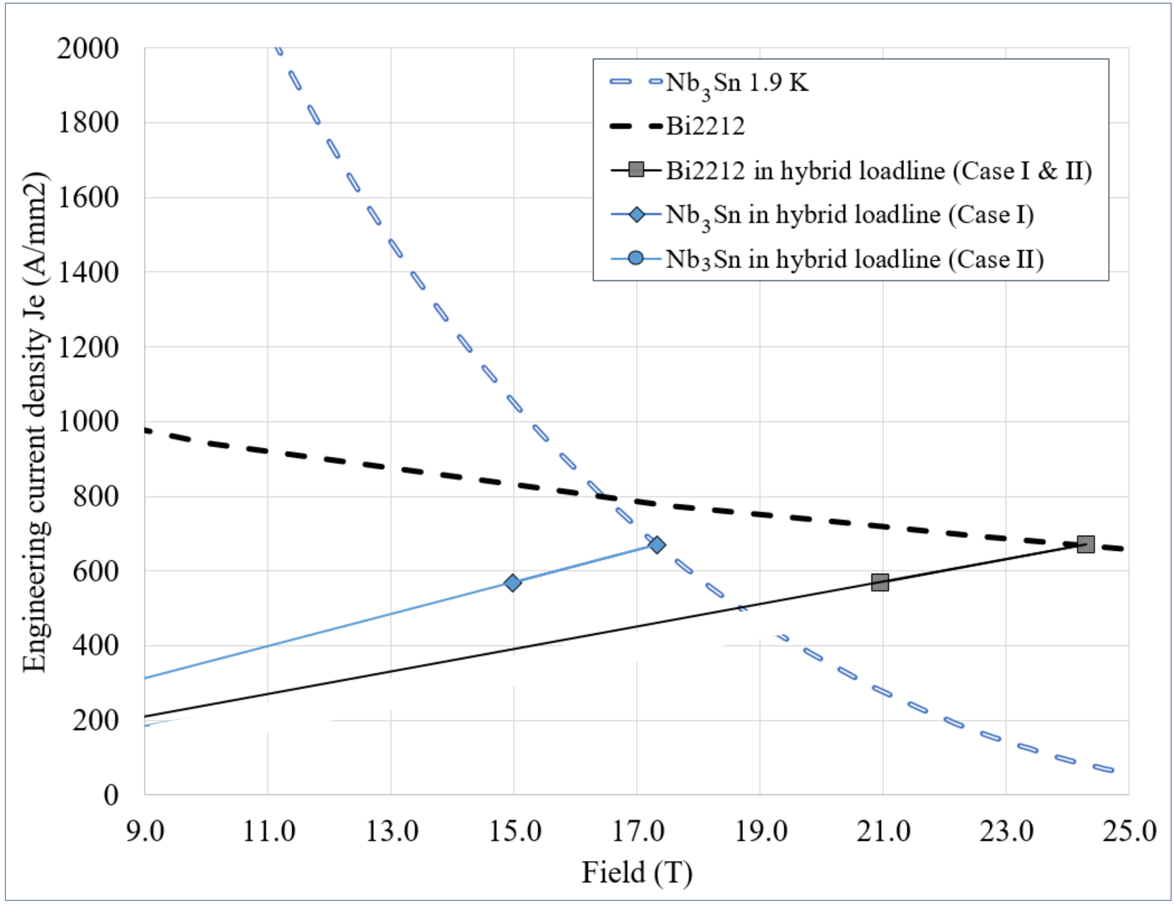
- As expected, high azimuthal stress on the mid-plane
- Less expected: even higher radial stress
- Some sort of stress management required, both on the azimuthal and the radial direction



E. Todesco, et al., Analytical estimates of stress in accelerator dipoles based on sector coils", seminar April 27, 2023.

About the ratio LTS vs HTS

- Two different approaches
  - *Case I*: minimum coil size
  - *Case II*: minimum HTS size, by lowering J_o outsert
    - sort of anti-grading



About the ratio LTS vs HTS

- More specifically, in *case I* we need a ~14 T HTS stand-alone magnet inside a 11-12 T Nb_3Sn stand-alone outsert
- In *case II*, a 11 T HTS stand-alone magnet inside a ~16 T Nb_3Sn stand-alone outsert
- Under the present LTS and HTS cost differences, both options are conceivable, but they lead to very different designs

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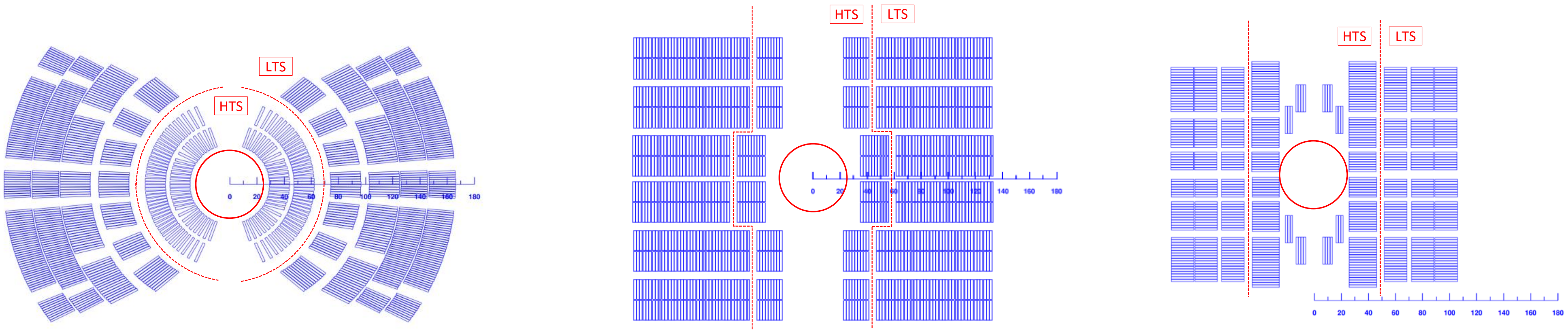
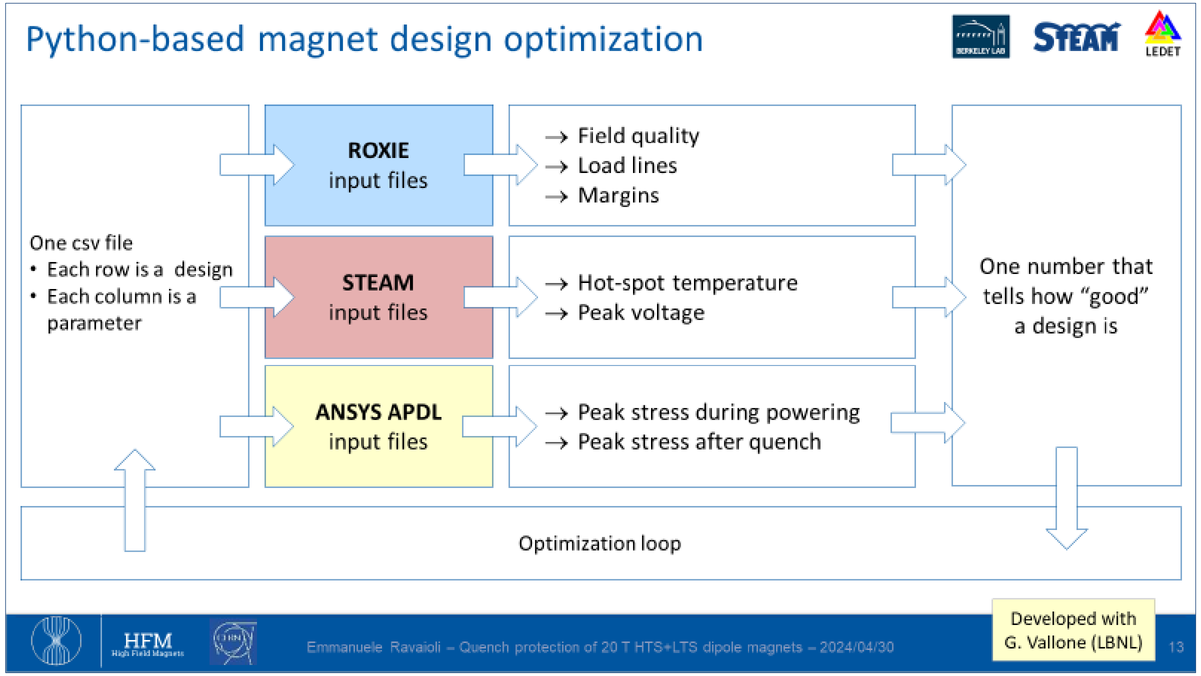
Current reference cross-sections Overview



- Three options considered (CT, BL, CC), for now focusing mainly on an HTS coil made with Bi2212 cable
- Iterative process on going
  1. Magnetic analysis → Margin and field quality
  2. Mechanical analysis → stress in HTS and LTS coils (and the structure)
  3. Quench protection → Non-SC/SC ratio, strand-cable design, CLIC, dump…..
  - …. And back and forth
- More focus on CT and CC, less on BL so far

Current reference cross-sections
Optimization process



Cos-theta magnet variants – Qualitative evaluation

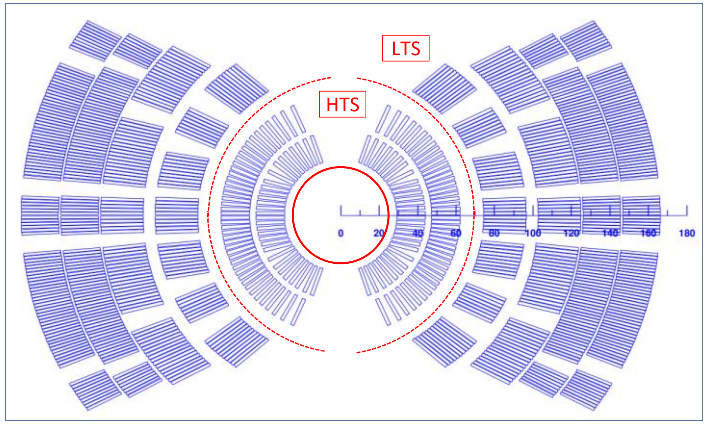
#	Efficiency HTS/LTS	Margin	Field Quality	Mechanics HTS/LTS	Quench Protection (1 m)	Quench Protection (15 m)
26	~/x	√	√	~/~	x	x
28	x/x	√	√	√/~	x	x
28_14	√/~	x	~	√/√	x	x
28_17	~/√	~	√	√/√	~	x
28_20	√/x	~	√		√	x
28_22	~/x	√	~		x	x
28_27	x/√	√	~	~/√	√	x
28_28	~/√	√	~	√/~	√	x
28_53	√/~	~	~	√/x	√	x
28_56	√/~	√	x		√	x
28_58	√/~	~	√	x/x	~	x
28_60	√/~	√	√	x/√	√	x
28_63	x/√	x	~	x/√	~	x
28_65	x/√	x	x	~/√	x	x

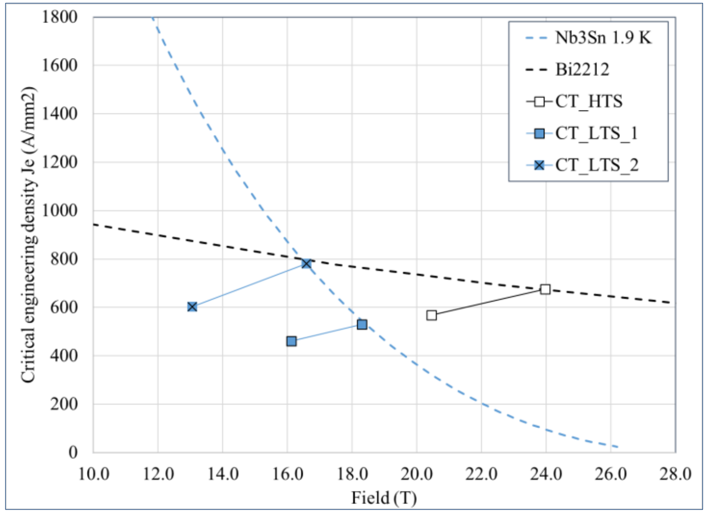
More details on the mechanics in M. D'Addazio's presentation

HFM Emmanuele Ravaioli – Quen... s – 2024/04/30 12

Current reference cross-sections
Cos-theta

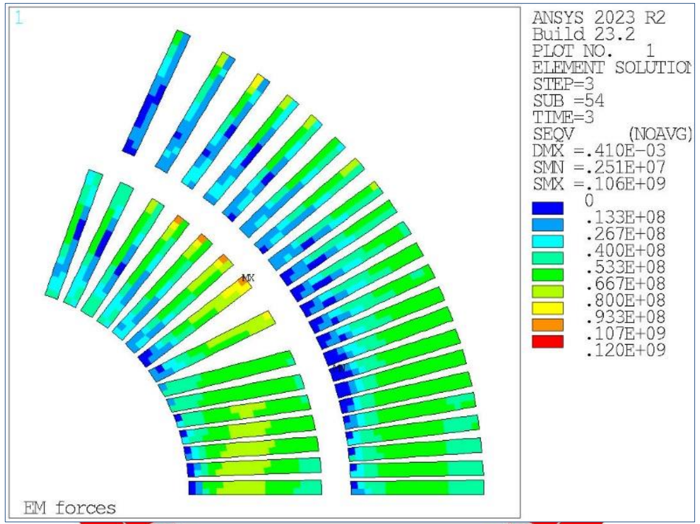
- Coil inner diameter 60 mm
  - Internal support structure
- Design constraint: double-layer coils
- 6 layers, with cables 15 to 22 mm wide
  - 2 layer HTS, 4 layer LTS
- HTS: CCT-like or “single turn” SMCT
- LTS: SMCT design + CT
- Field quality and margin in spec
- j_e= 450-600 A/mm^2, j_o= 300-400 A/mm^2
- OR coil: 165 mm

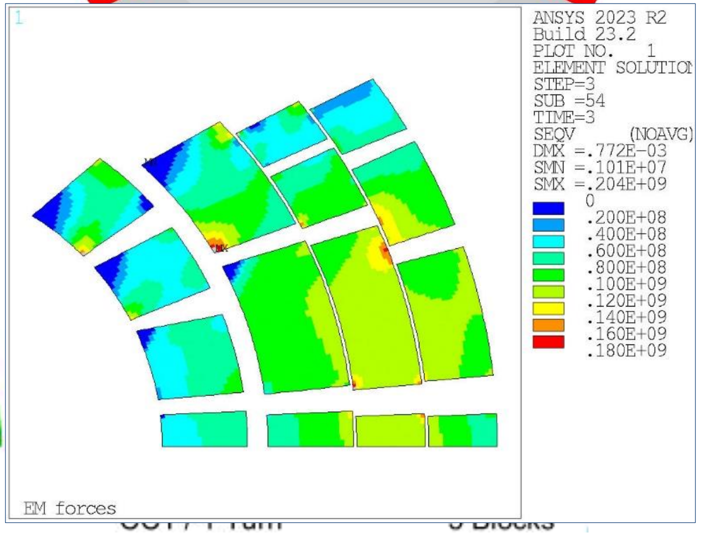


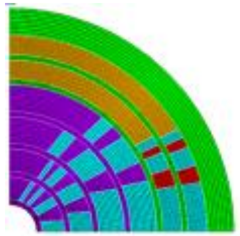


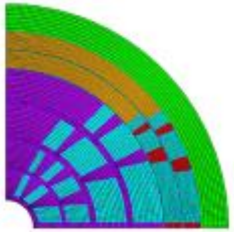
Current reference cross-sections
Cos-theta

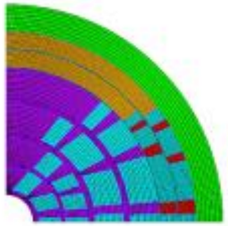
- 4 out of 6 layers with stress management
  - Result of several iterations
- First two layers (HTS) with a CCT-type design
  - Single cable in grove, with ribs and spar
- Second two layers (LTS) with SMCT-type design
  - Single block in grove, with ribs and spar
- Last two layers traditional CT
- Coil stress in spec
  - but very high stress in the mandrel (Inconel or Nitronic?)

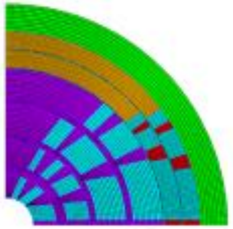


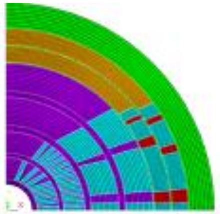


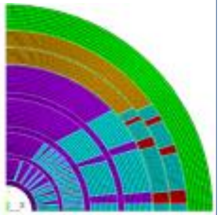

Test 1


Mid Plane Rib


Aligned Wedges

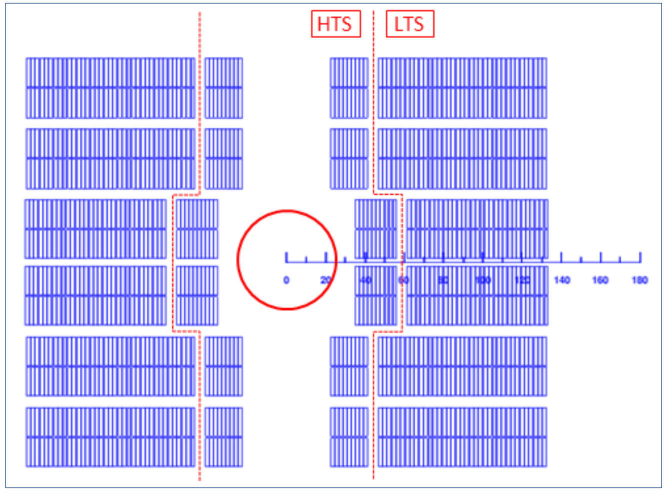

Shared Mandrel

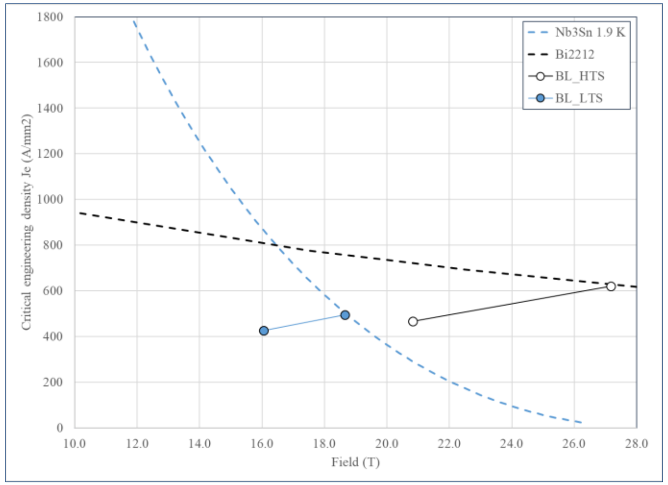

Coil 1
2 Turns


Layer 1
3/2/1 Turns

Current reference cross-sections
Block

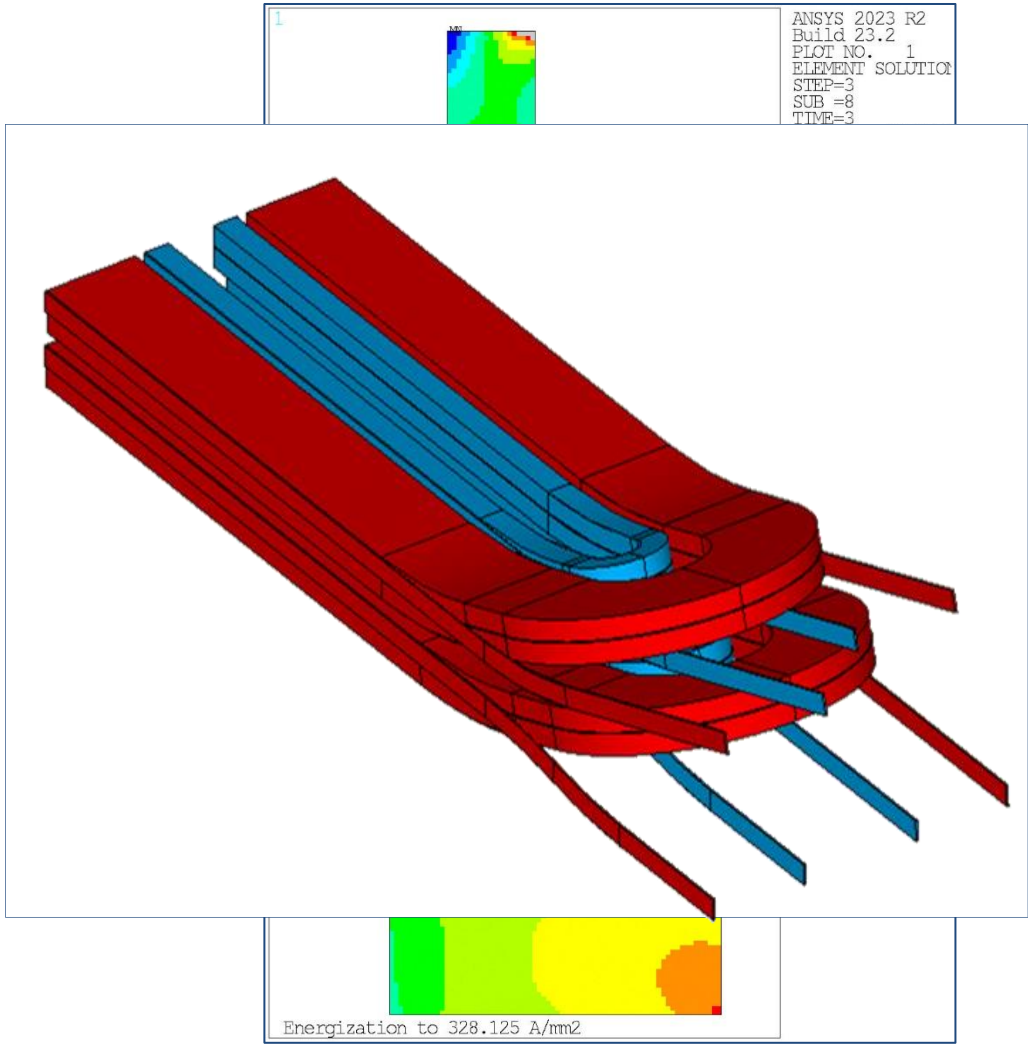
- Coil inner diameter 70 mm
  - Internal support structure
- Design constraint
  - double-layer coils
  - HD2/FRESCA2 style coil
- 3 double-layer coils, with 15 mm wide cable
- Field quality and margin in spec
- j_e= 450 A/mm^2, j_o= 300 A/mm^2
- OR coil: 130 mm
  - Less efficient than CT (50% more HTS, 15% more LTS), but less optimized





Current reference cross-sections
Block

- 10 mm thick winding pole
  - FRESCA2 style
- Coils vertically separated by horizontal plates
  - Vertical stress management
- HTS and LTS separated by vertical ribs
  - Horizontal stress management
- Stress not yet in spec
- Challenges: “insertion” of HTS coil inside LTS coils, grading and splicing

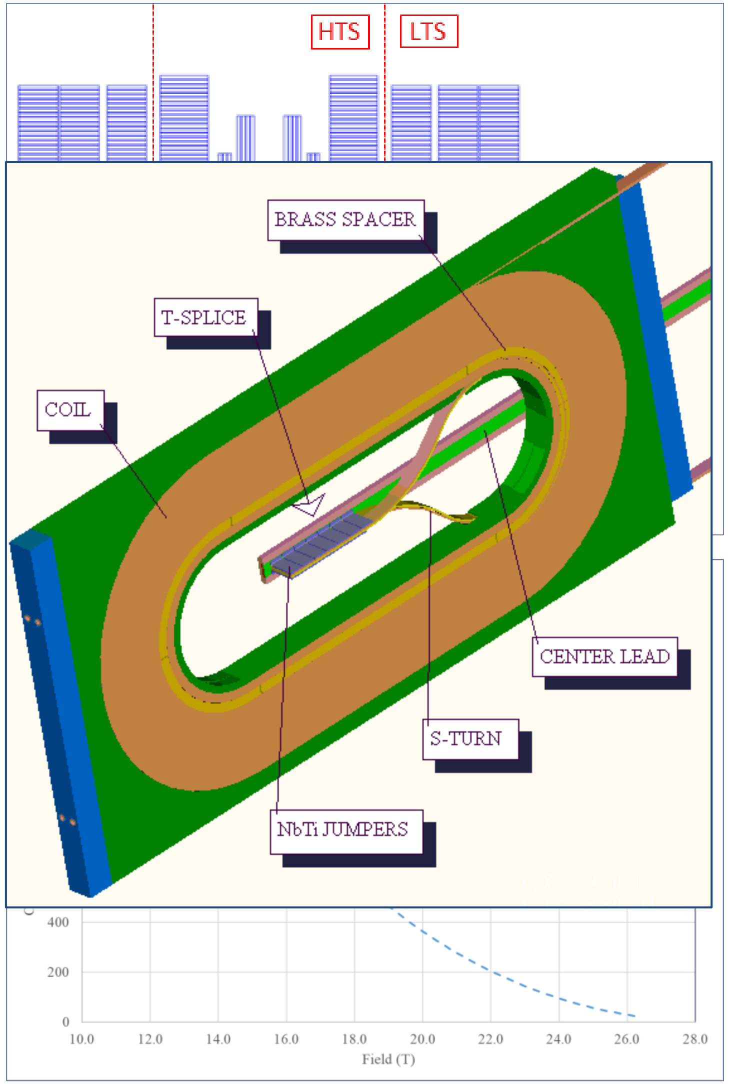


Current reference cross-sections
Common-coil

- Coil inner diameter 50 mm
  - No internal support structure
- Single layer coils allowed : splice in the central pole
  - So, more vertical and horizontal flexibility
- 4 layers, with cables 16 mm to 20 mm wide
  - 1 layer HTS (plus pole coils), 3 layer LTS

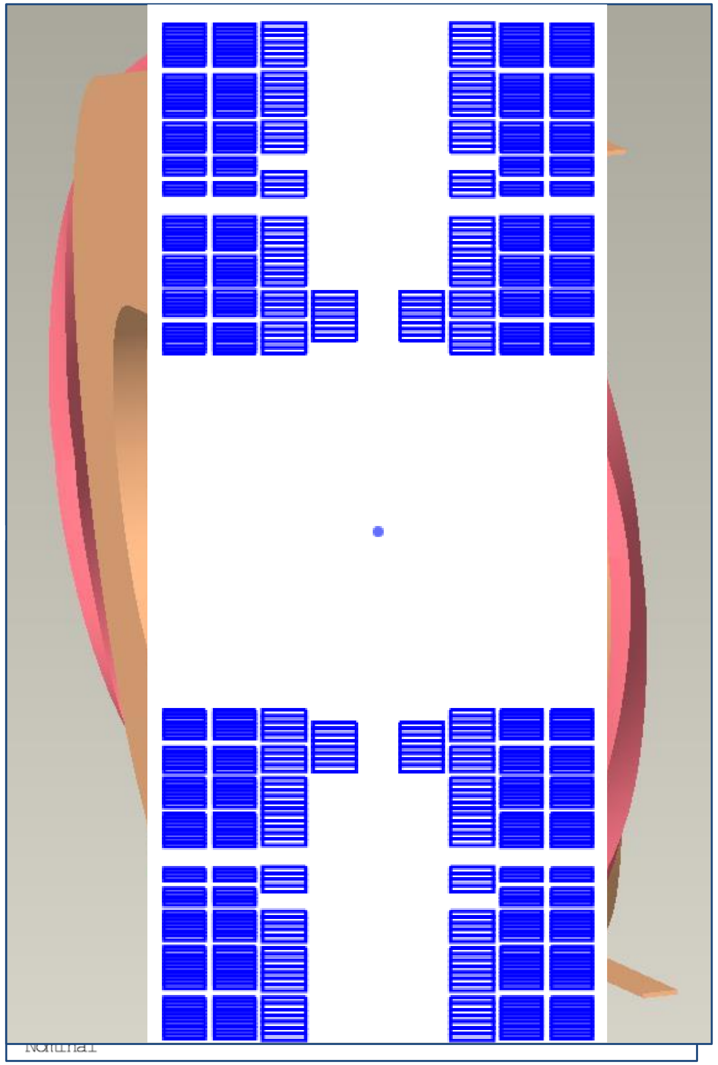
- Field quality and margin in spec
- j_e= 550-650 A/mm^2, j_o= 400-450 A/mm^2

- OR coil: 110 mm
  - ~50% more HTS than CT, but ~50% less LTS
    - Overall smaller coil, but at the expense of larger HTS coil
  - CT vs CC similar to Case II vs Case I



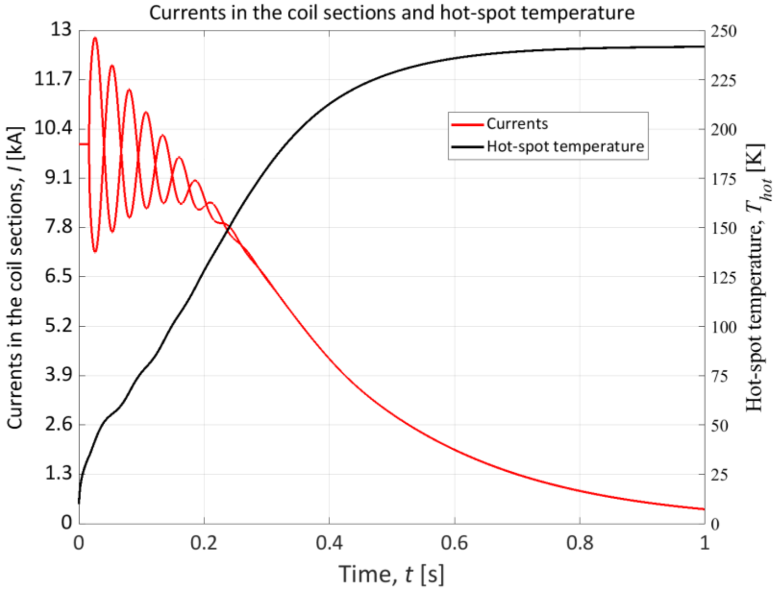
Current reference cross-sections
Common-coil

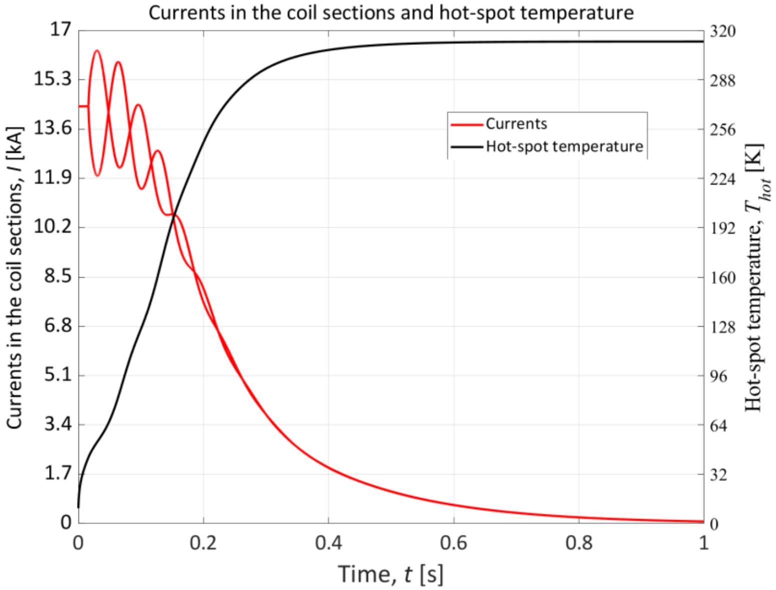
- No internal structure in innermost layer
- Coils vertically separated by horizontal plates
  - Vertical stress management
- HTS and LTS separated by vertical ribs
  - Horizontal stress management
- Stress almost in spec
- Challenge: pole turns
  - Avoidable with asymmetric coils

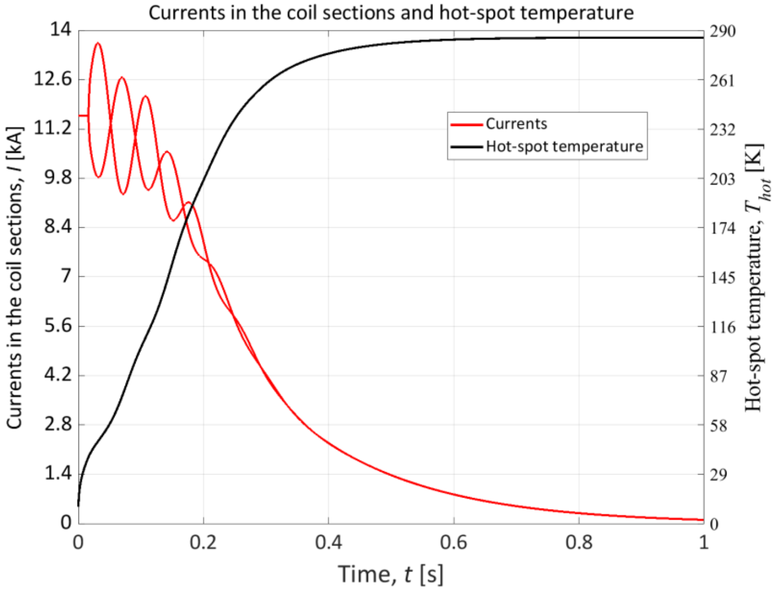


Current reference cross-sections
Quench protection (1 m long magnet)

Block-coil V1	Common-coil V5	Cos-theta V28_137







Block-coil V1

Hot-spot temperature	Peak voltage to ground	Peak CLIQ current
242	Not optimized yet	5670

Common-coil V5

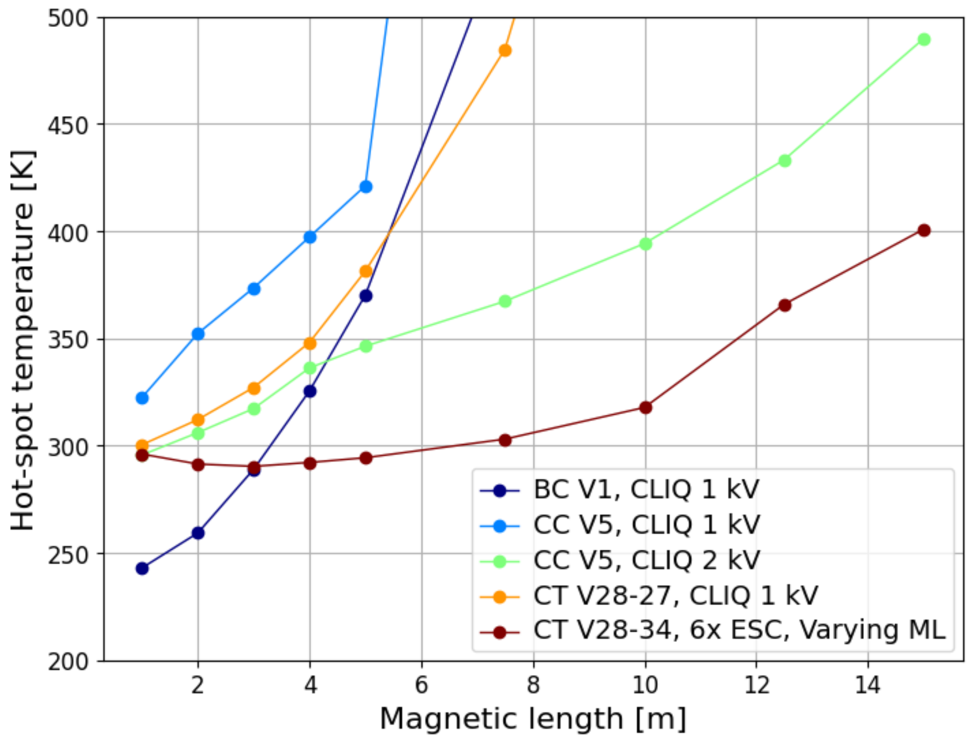
Hot-spot temperature	Peak voltage to ground	Peak CLIQ current
313	501	4329

Cos-theta V28_137

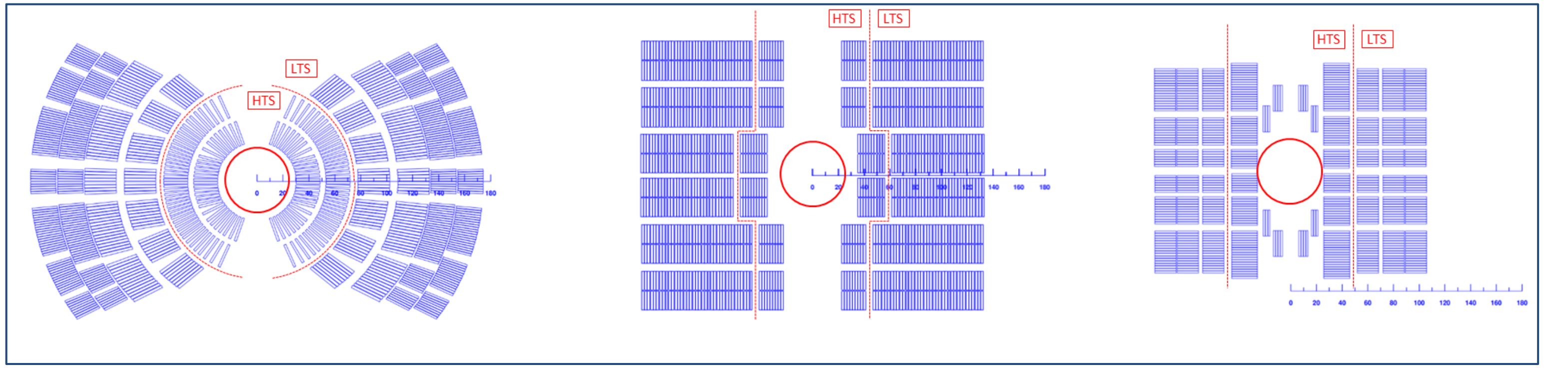
Hot-spot temperature	Peak voltage to ground	Peak CLIQ current
286	570	3810

Current reference cross-sections
Quench protection (more than 1 m length)

- Without new solutions, hard to go beyond 3-4 m
- Longer lengths protectable with ESC (Energy Shift with Coupling)

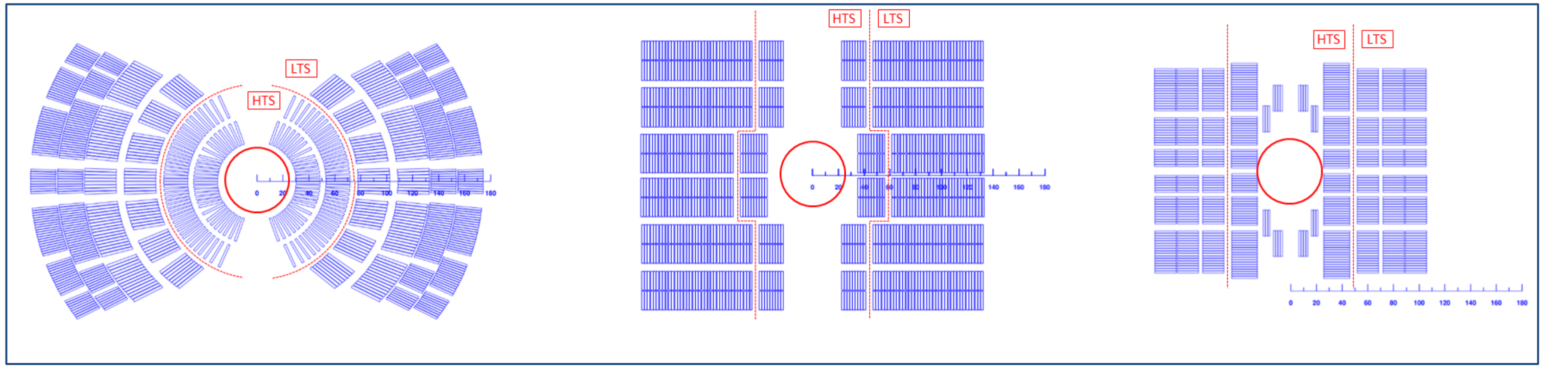


Current reference cross-sections
Summary



- For now, CT and CC most analyzed: for 1 m, they meet the criteria (still some work on the corner peaks)
- More work required on BL for fair comparison
- Different results depending on the approach: minimum HTS (in this case CT), or minimum coil (in this case, CC)
- Mechanics: stress management required in all directions; still very high stress in the mandrel/ribs
- Quench protection seems ok for 1 m magnets in all 3 designs
  - For longer new solutions to be considered

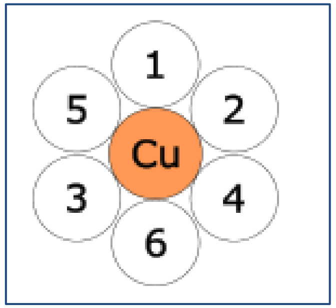
Current reference cross-sections Summary

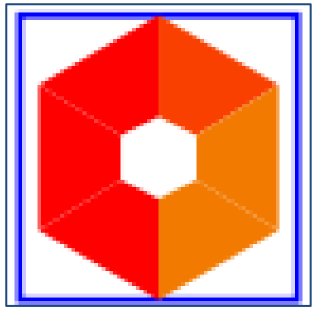


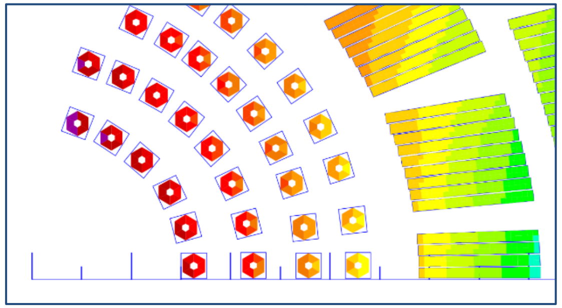
- Some assumptions under discussion
  - CT and BL with only double-layer coils? Too conservative? How about single layer, at least in the outer-most coils?
  - No internal support of innermost CC coils?
  - Pole coils to be studied
- The assumptions related to fabrication seems to have a major impact: we do as usual or we assume something new?
- 3D effects not yet considered (splice of the BL, pole coil in the CC)
- An finally, the REBCO……

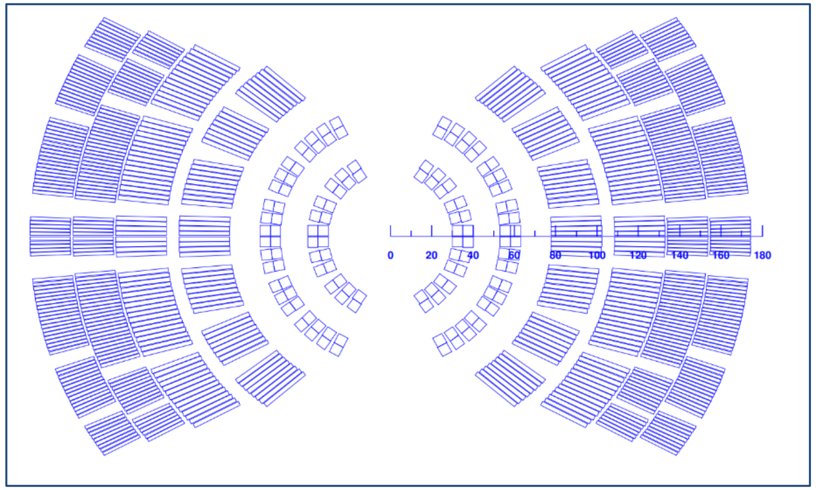
Additional designs under study
REBCO hybrid

- STAR 6-around-1 cable

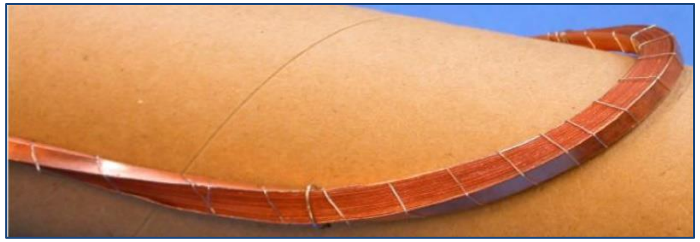


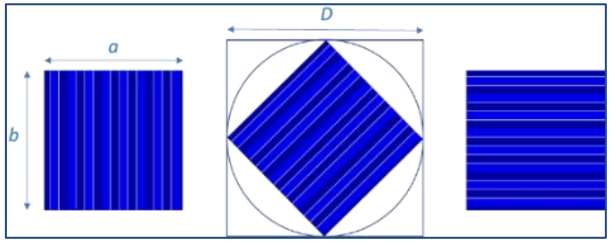


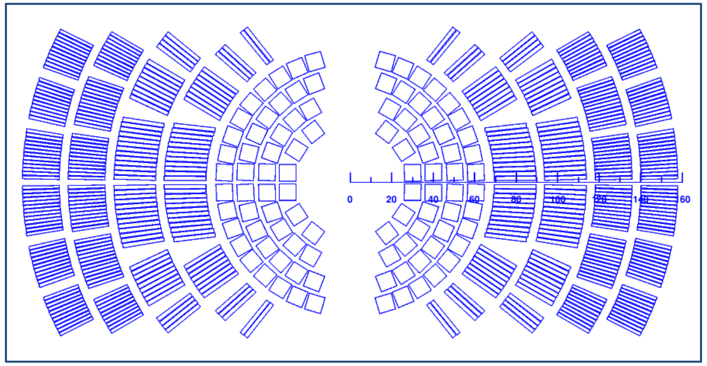




- REBCO twisted-stack cable







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  - Why hybrid and why 20 T
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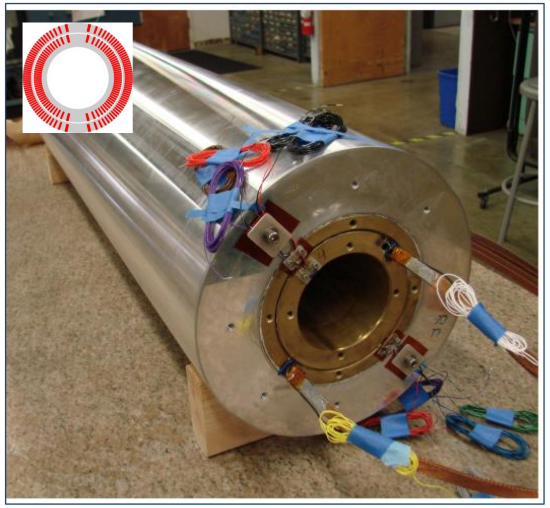
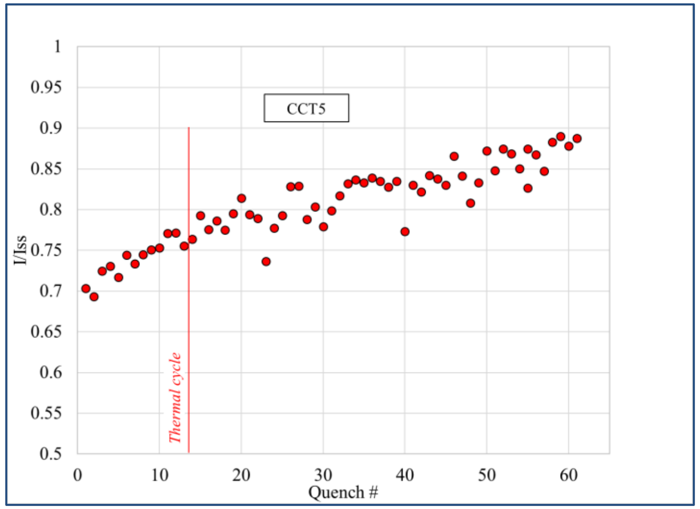
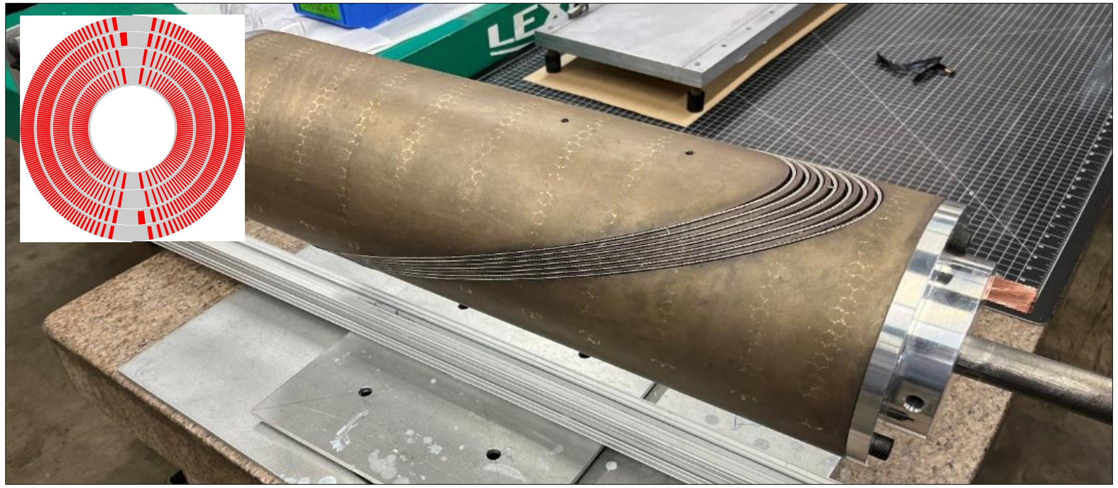
  - Nb_3Sn outserts
  - HTS inserts
- Conclusions

Nb_3Sn outserts
Canted-Cosθ: CCT5 and CCT6

- CCT5
  - Tested in 2019
  - 8.5 T in 90 mm ap.
  - Ready to be used as outsert
- CCT6
  - Mandrel under fabrication
  - LD1 (HD2) and MQXF cable
  - Design: 15 T (1.9 K, 80% I_{ss}) in 120 mm aperture

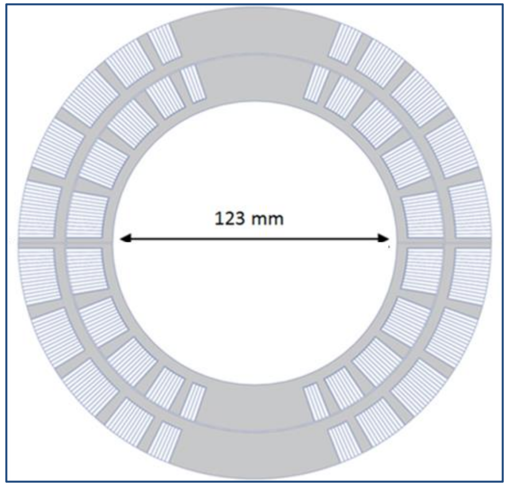


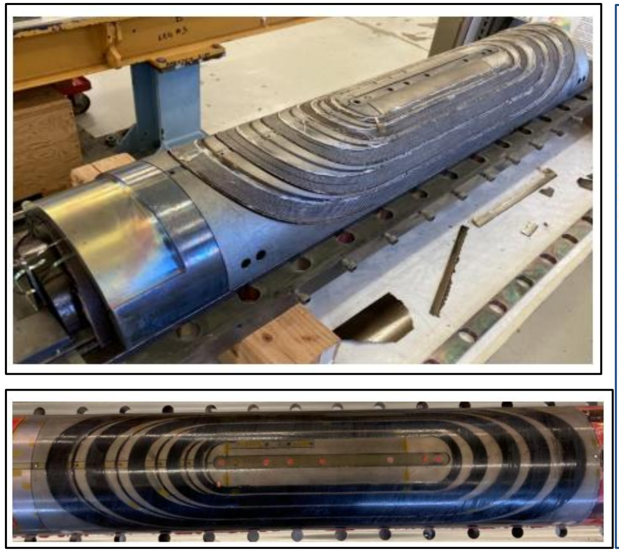


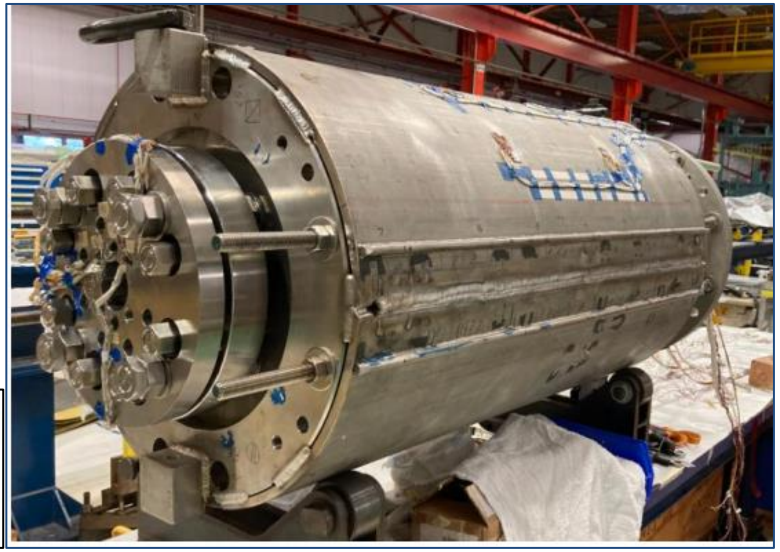


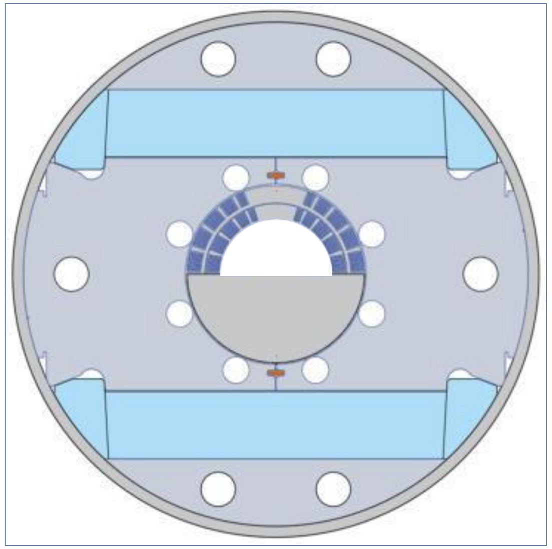
Nb_3Sn outserts
Stress Management Cosθ (SMCT)

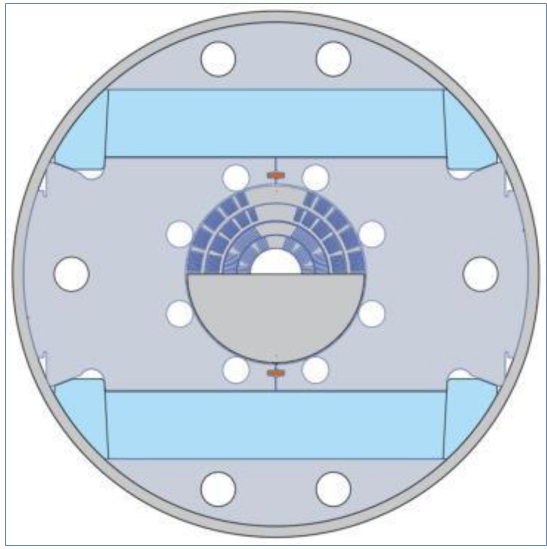
- SMCT
  - Stress management at the conductor-block level
  - Target: 11 T in 120 mm aperture
  - Coil tested in mirror, both with and without inner coil of the MDPCT1







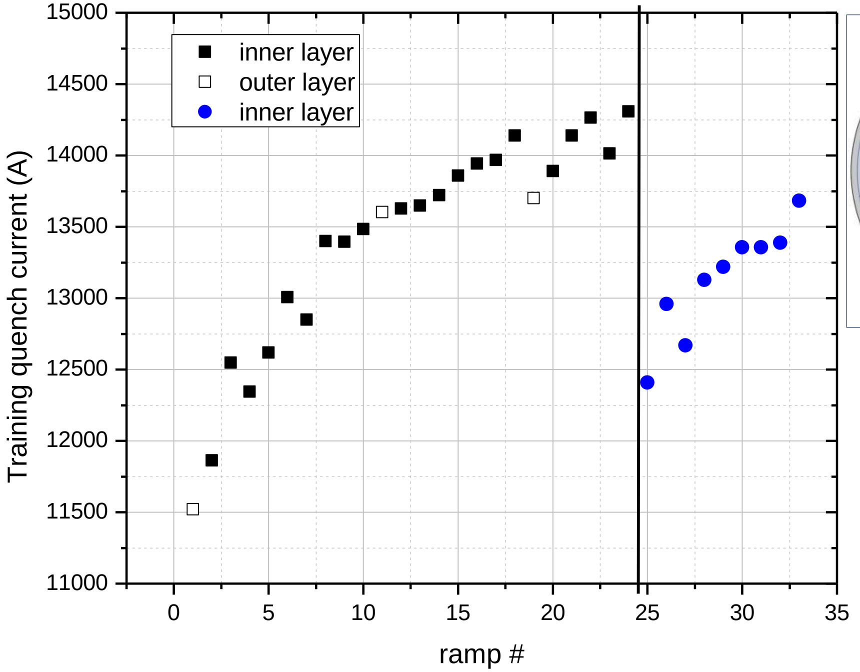


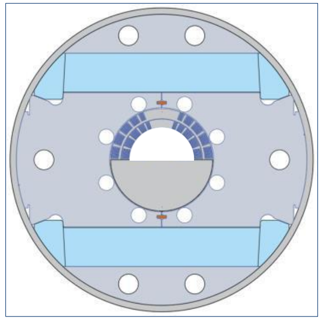


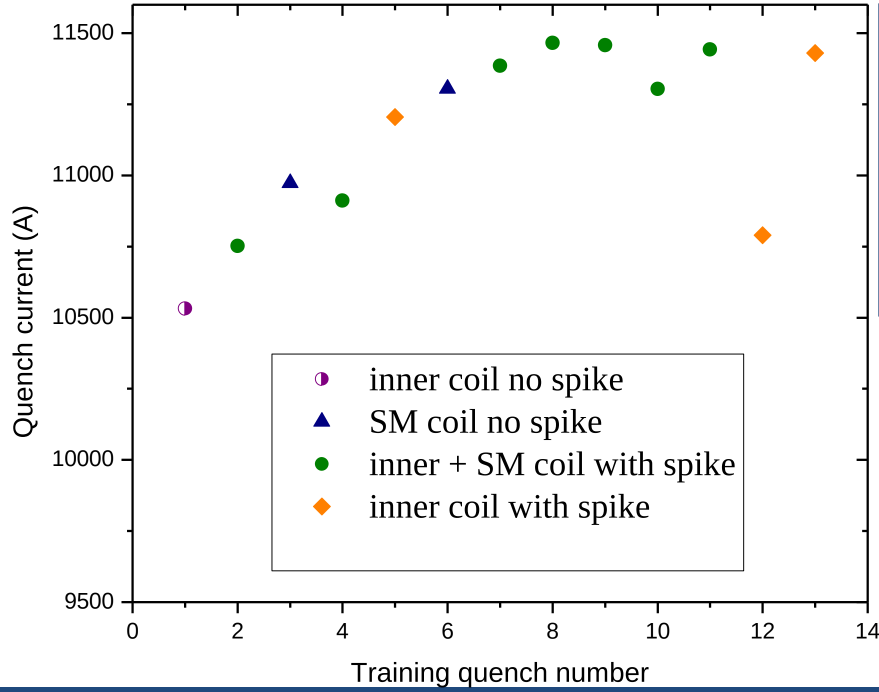
Nb_3Sn outserts
Stress Management Cosθ (SMCT)

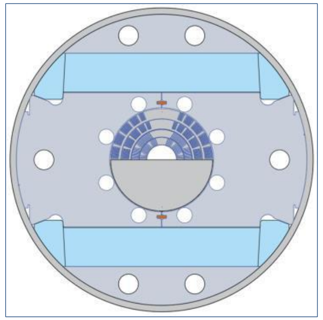
- SMCTM1
  - 14.3 kA, 87 % I_{ss} reached in 24 quenches
  - 12.7 T conductor peak field
  - No memory after thermocycle

- SMCTM1b
  - Highest current was 11.46 kA, 82 % I_{ss}
  - 14.5 T conductor peak field in the inner coil





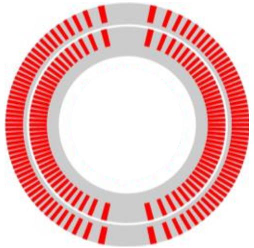




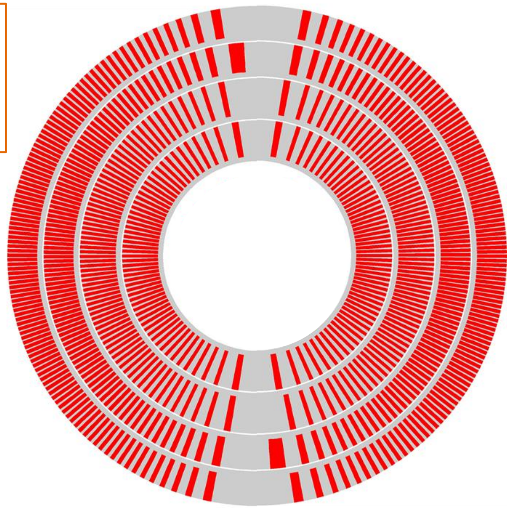
Nb_3Sn outserts
Summary

in scale

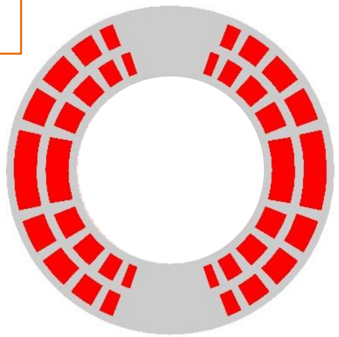
CCT5
90 mm
8.5 T

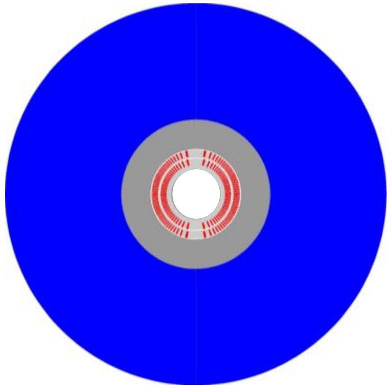


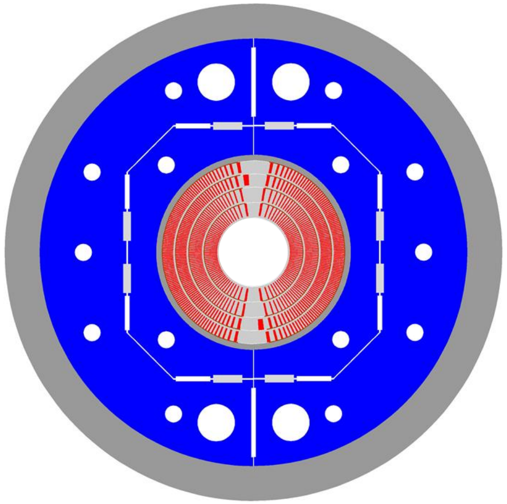
CCT6
120 mm
15 T
(design)

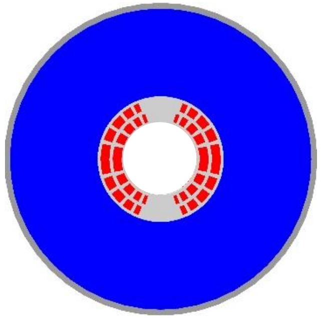


SMCT
120 mm
11 T
(design)









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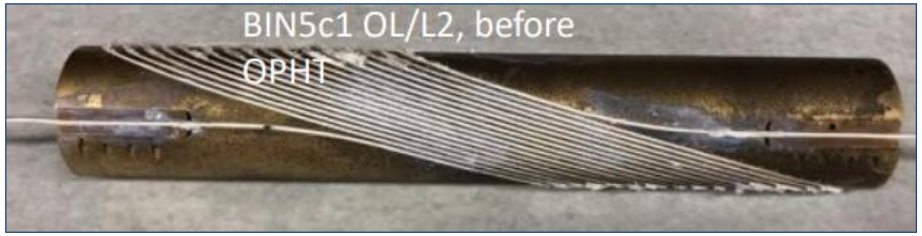
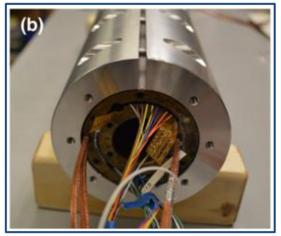
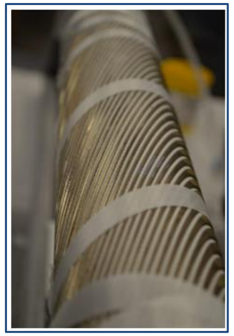
Bi2212 inserts
Canted-Cosθ: Bin5, BiCCT1, and BiCCT2

- Bin5
  - 1.6 T in 31 mm aperture
  - Successfully tested in stand alone
  - Ready to be tested in CCT5
- BiCCT1
  - 5 T in 40 mm aperture
  - Coil wound and ready for reaction
  - To be tested in CCT6
- BiCCT2
  - 7 T in 40 mm aperture
  - 12 mm cable fabricated
  - To be tested in CCT6

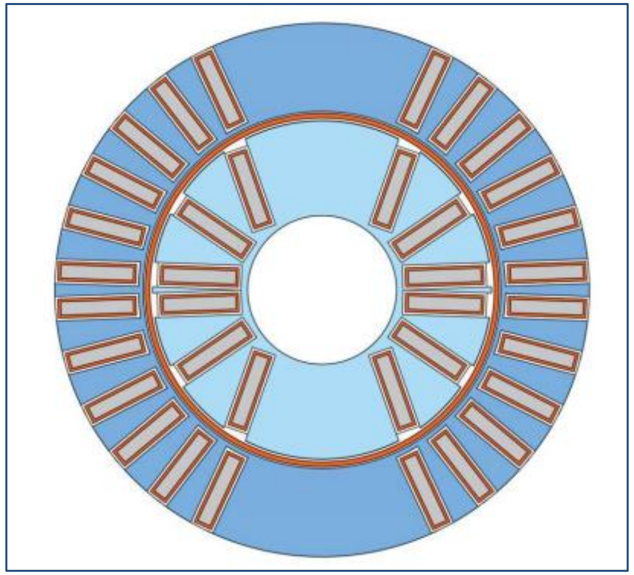


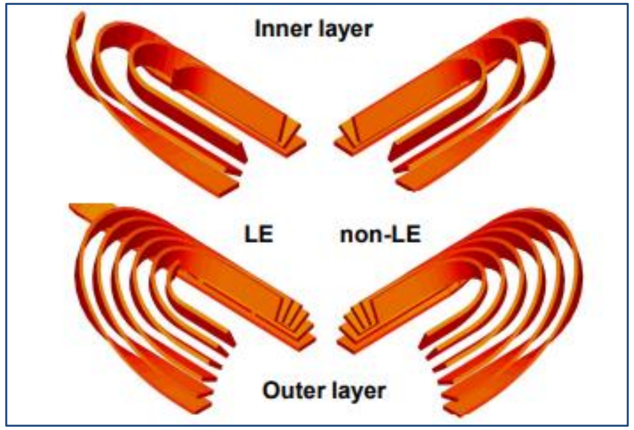


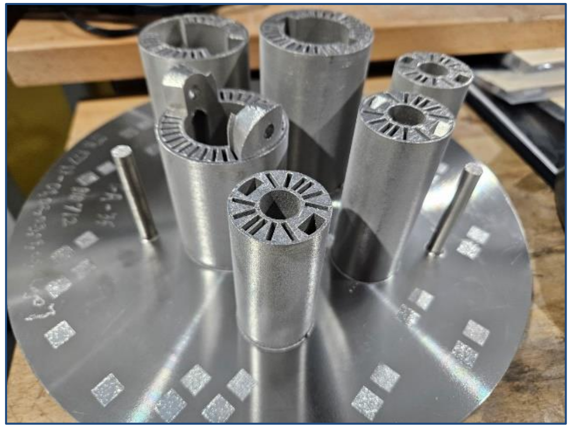


Bi2212 inserts
Stress Management Cosθ (SMCT)

- Bi2212 SMCT
  - 1-2 T in 15 mm aperture
  - Winding test performed with plastic parts
  - Fabrication of Inconel 3D printed mandrel in progress
  - To be tested in a 4L (CT from 15T magnet + SMCT coil)

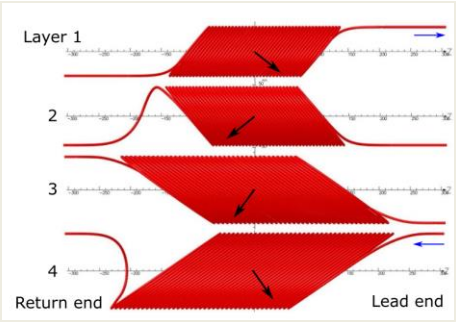


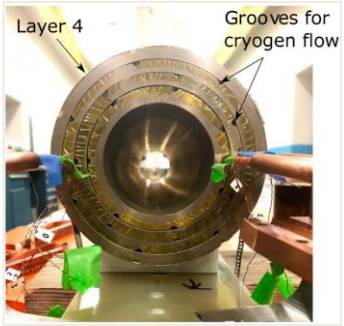




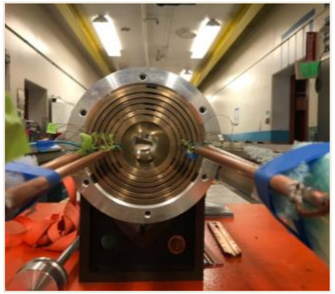
REBCO inserts
Canted-Cosθ ("C" series)

- C2: stand-alone test in 2020
  - 2.9 T in 65 mm aperture
  - Fundamental step towards development CORC CCT inserts



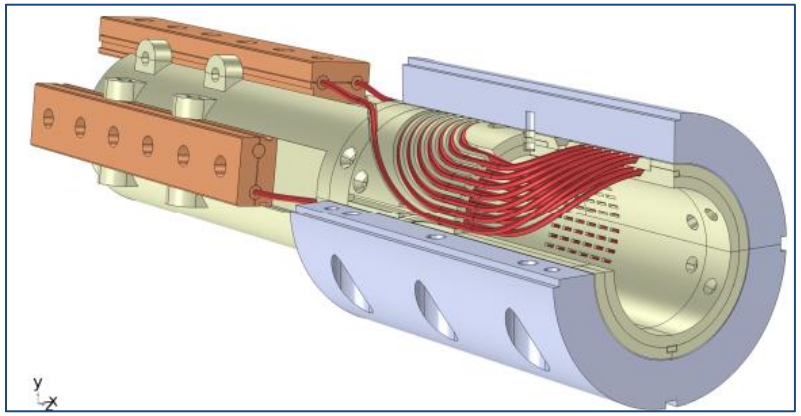


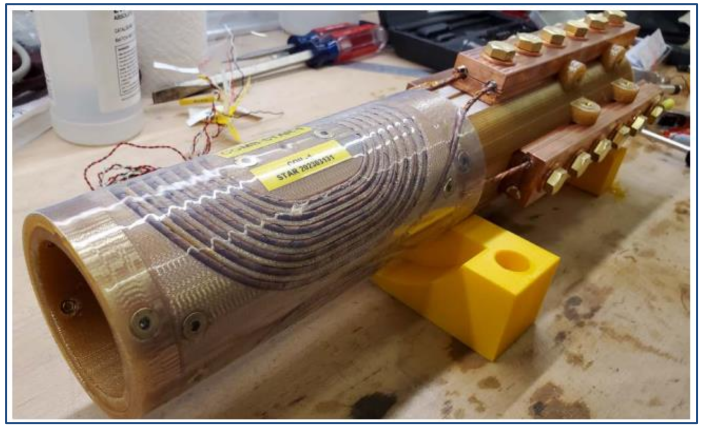
- Next step: C3
  - Target: 5 T in 60 mm aperture
  - Under fabrication



REBCO inserts
The COMB (Conductor on Molded Barrel) series

- COMB insert
  - Target: 2-3 T in 100 mm aperture with CORC® wire
  - To be tested in SMCT after stand alone test
  - Test with STAR® wire at both 77 K and 4.5 K
    - 1.5 T bore field reached



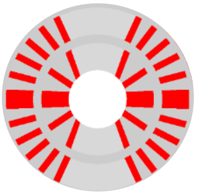


Bi2212 and REBCO inserts
Summary

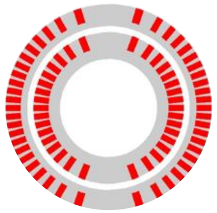
in scale

Bi2212

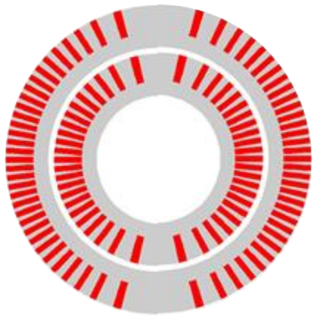
SMCT
15 mm
1-2 T
(target)



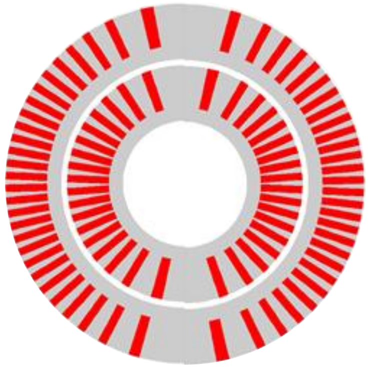
Bin5
31 mm
1.6 T



BiCCT1
40 mm
3 T
(target)

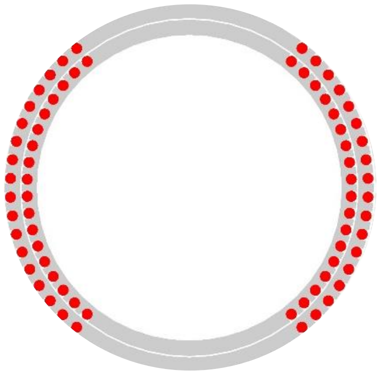


BiCCT2
40 mm
5 T
(target)



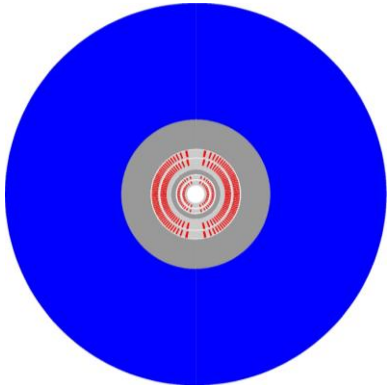
REBCO

COMB
100 mm
2-3 T
(target)

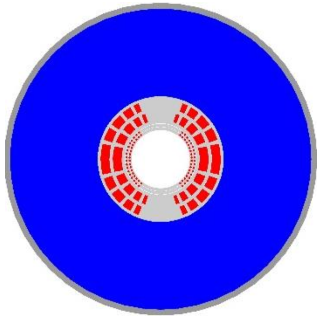


Overview of planned MDP hybrid magnets

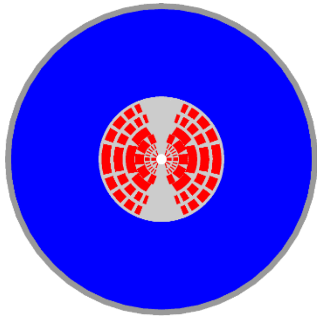
CCT5-Bin5
30 mm
9-10 T



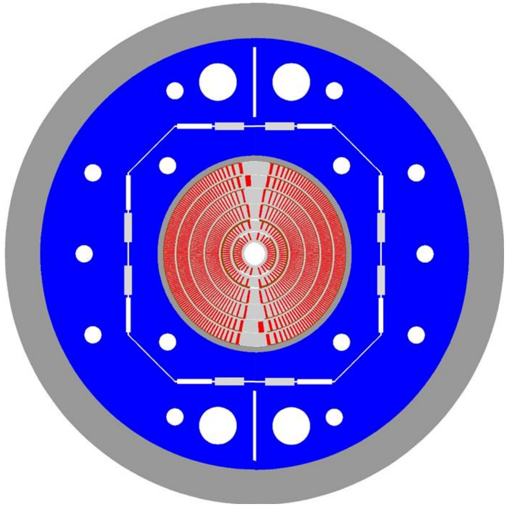
COMB-SMCT
100 mm
11-12 T



11T-Bi SMCT-SMCT
15 mm
14-16 T



CCT6-BiCCT1-2
40 mm
14-16 T



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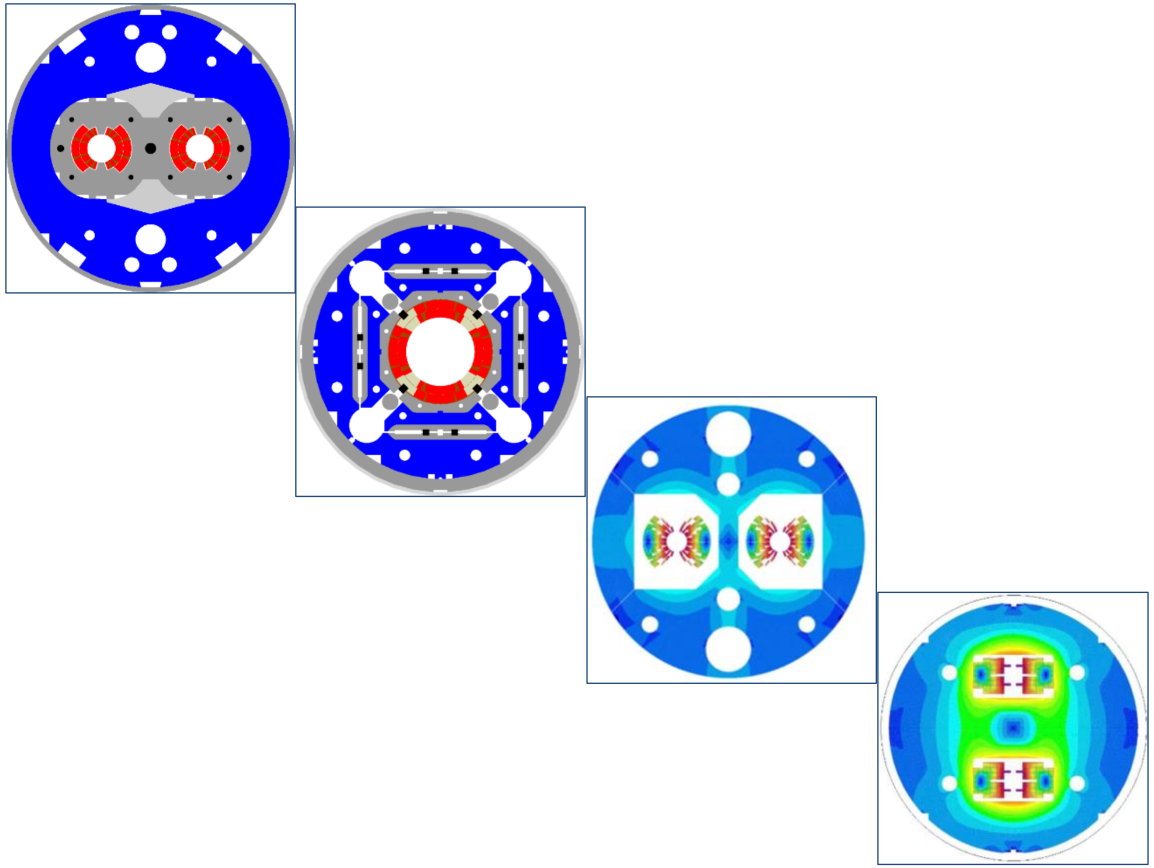
Conclusions

- US MDP pursuing an LTS-HTS hybrids magnets program towards 20 T
  - Excellent tool to perform R&D on various materials and magnets
- 20 T design study
  - Coil size ranging from 120 to 160 mm OR depending on design options and assumptions (HTS vs overall)
  - Stress management required in particular in the innermost layers
  - Up to 3-4 m length can be protected, beyond new solutions required
- Large aperture Nb_3Sn outserts under development with stress management concepts
  - CCT: “5” is ready, “6” under develop.,
  - SMCT first coil being tested in mirror configuration
- HTS inserts
  - Successful test of Bi2212 Bin5
  - Both REBCO CCT and COMB insert designs validated with CORC® and STAR® wires
- First hybrid test (9-11 T field level) expected in 2024

Appendix

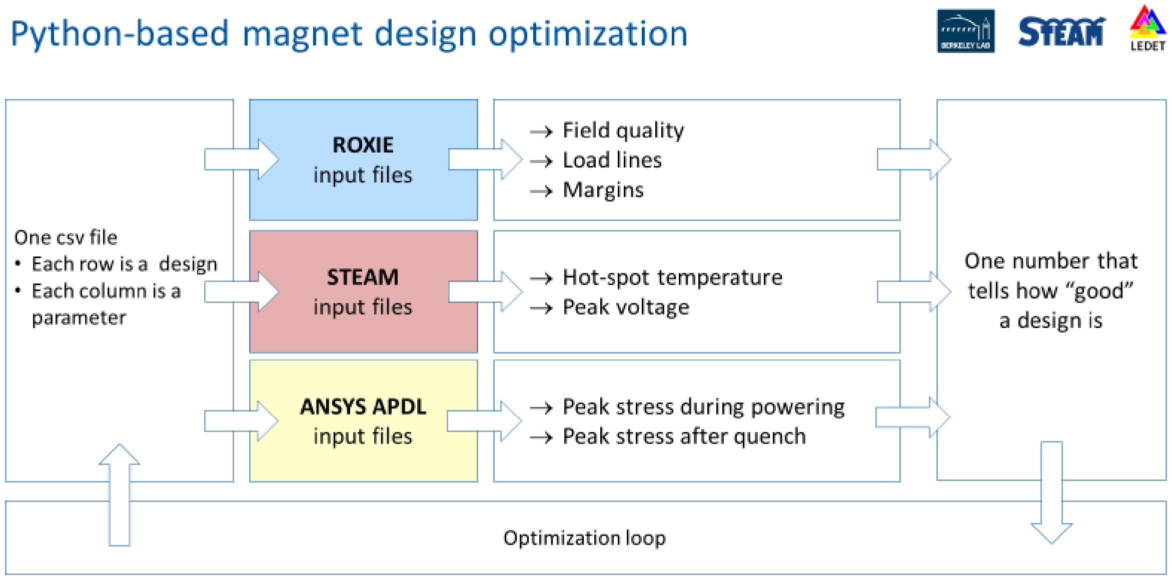
Motivations of a 20 T hybrid design

- …also….the “4 T step”
  - 8 T
    - Nb-Ti “limit” (LHC)
  - 12 T
    - Nb_3Sn (HL-LHC)
  - 16 T
    - Limits of Nb_3Sn
  - 20 T
    - HTS



Current reference cross-sections
Optimization process

Python-based magnet design optimization



Developed with G. Vallone (LBNL)

Emmanuele Ravaioli – Quench protection of 20 T HTS+LTS dipole magnets – 2024/04/30 13

Cos-theta magnet variants – Qualitative evaluation

#	Efficiency HTS/LTS	Margin	Field Quality	Mechanics HTS/LTS	Quench Protection (1 m)	Quench Protection (15 m)
26	~/x	√	√	~/~	x	x
28	x/x	√	√	√/~	x	x
28_14	√/~	x	~	√/√	x	x
28_17	~/√	~	√	√/√	~	x
28_20	√/x	~	√		√	x
28_22	~/x	√	~		x	x
28_27	x/√	√	~	~/√	√	x
28_28	~/√	√	~	√/~	√	x
28_53	√/~	~	~	√/x	√	x
28_56	√/~	√	x		√	x
28_58	√/~	~	√	x/x	~	x
28_60	√/~	√	√	x/√	√	x
28_63	x/√	x	~	x/√	~	x
28_65	x/√	x	x	~/√	x	x

More details on the mechanics in M. D'Addazio's presentation

Emmanuele Ravaioli – Quen… …s – 2024/04/30 12

Critical current versus transverse stress

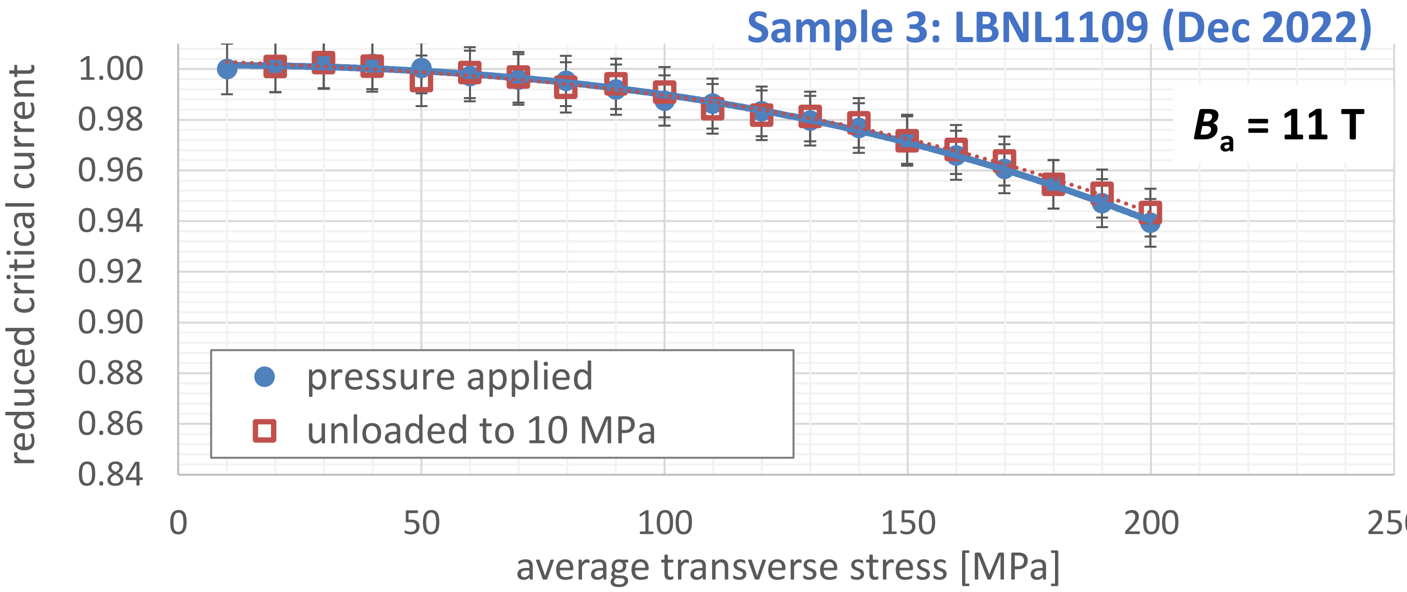
Applied field 11 T, data normalized to initial I_c of 2.70 kA (sample 3), and 4.07 kA (sample 4)

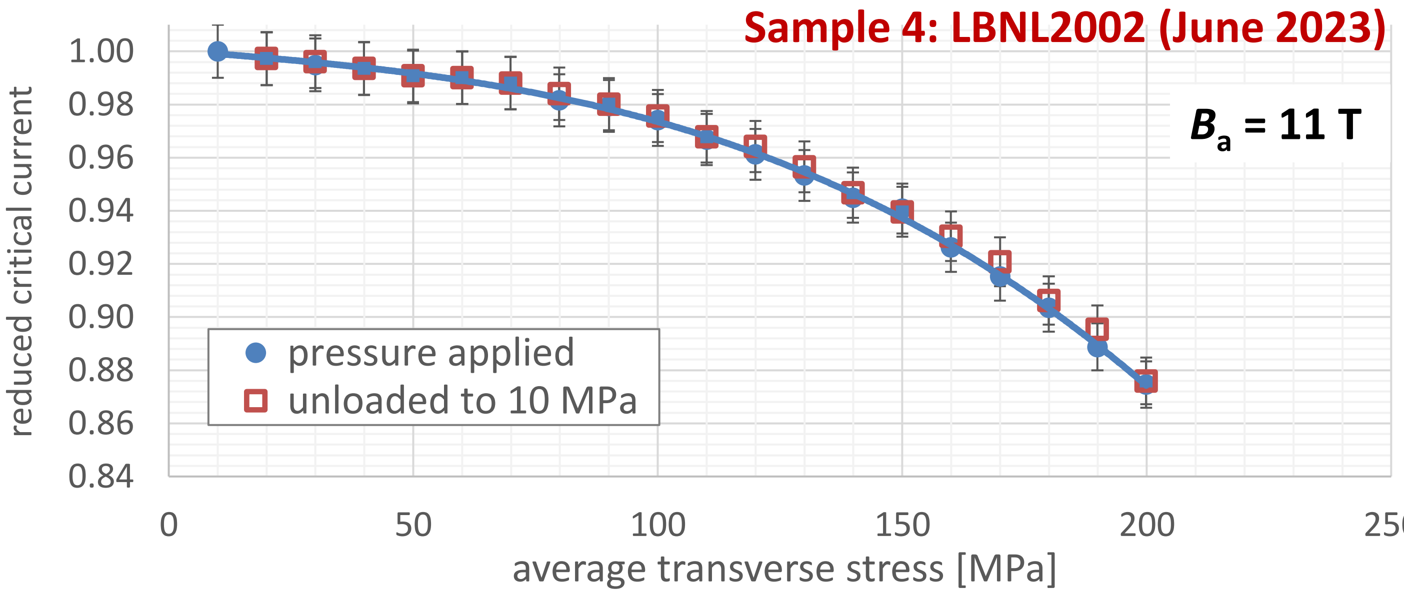
- Measurement sequence:
  - 10 MPa
  - 20 MPa
  - 10 MPa
  - 30 MPa
  - 10 MPa
  - 40 MPa
  - etc.

- **5% degradation reached at:**

  170-200 MPa in sample 3 and

  120-150 MPa in sample 4





Appendix

CT	C28_137				
		HTS	LTS1	LTS2	MQXF
Strand D	mm	0.9	0.8	0.7	0.85
Cu/SC		4	0.8	1.6	1.2
Astrands	mm2	0.636	0.503	0.385	0.567
N strands		32	50	50	40
Cable width	mm	14.872	22.164	19.392	18.15
Cable thick in	mm	1.620	1.440	1.260	1.462
Cable thick out	mm	1.780	1.593	1.400	1.588
Cable thick mid	mm	1.700	1.516	1.330	1.525
Thick comp		0.94	0.95	0.95	0.90
Width comp		1.03	1.11	1.11	1.07
Insulation thick	mm	0.15	0.15	0.15	0.145
Ins Cable width	mm	15.1721	22.46364	19.69219	18.44
Ins Cable thick in	mm	1.92	1.74	1.56	1.752
Ins Cable thick in	mm	2.08	1.892727	1.7	1.878
Ins Cable thick mid	mm	2	1.816364	1.63	1.815
Area cable	mm2	25.28257	33.60813	25.79161	27.67875
Area ins cable	mm2	30.3442	40.80213	32.09827	33.4686
N turns		37	76	104	50
A ins turns	mm2	1123	3101	3338	1673
A ins turns HTS	mm2	1123			
A ins turns LTS	mm2	6439			
A ins turns tot	mm2	7562			1673
Current	A	11584	11584	11584	16230
Bbore	T	20	20	20	
Bpeak	T	20.46	16.12	13.06	
J0	A/mm2	382	284	361	484.9321
Je_strands	A/mm2	569	461	602	715.0408

BL	V1			
		HTS	LTS1	MQXF
Strand D	mm	1	1.13	0.85
Cu/SC		4	1.15	1.2
Astrands	mm2	0.785	1.003	0.567
N strands		28	24	40
Cable width	mm	14.7	14.7	18.15
Cable thick in	mm	1.8	2.03	1.462
Cable thick out	mm	1.8	2.03	1.588
Cable thick mid	mm	1.8	2.03	1.525
Thick comp		0.9	0.90	0.90
Width comp		1.05	1.08	1.07
Insulation thick	mm	0.15	0.15	0.145
Ins Cable width	mm	15	15	18.44
Ins Cable thick in	mm	2.1	2.33	1.752
Ins Cable thick in	mm	2.1	2.33	1.878
Ins Cable thick mid	mm	2.1	2.33	1.815
Area cable	mm2	26.46	29.841	27.67875
Area ins cable	mm2	31.5	34.95	33.4686
N turns		56	210	50
A ins turns		1764	7340	1673
A ins turns HTS	mm2	1764		
A ins turns LTS	mm2	7340		
A ins turns tot	mm2	9104		1673
Current	A	10275	10275	16230
Bbore	T	20	20	
Bpeak	T	20.83	16.05	
J0	A/mm2	326	294	485
Je_strands	A/mm2	467	427	715

CC	V5				
		HTS	LTS1	LTS2	MQXF
Strand D	mm	0.85	0.9	0.9	0.85
Cu/SC		4	1.8	2.5	1.2
Astrands	mm2	0.567	0.636	0.636	0.567
N strands		43	34	34	40
Cable width	mm	19.73	16.15	16.15	18.15
Cable thick in	mm	1.52	1.6	1.6	1.462
Cable thick out	mm	1.52	1.6	1.6	1.588
Cable thick mid	mm	1.52	1.6	1.6	1.525
Thick comp		0.89	0.89	0.89	0.90
Width comp		1.08	1.06	1.06	1.07
Insulation thick	mm	0.15	0.15	0.15	0.145
Ins Cable width	mm	20.03	16.45	16.45	18.44
Ins Cable thick in	mm	1.82	1.9	1.9	1.752
Ins Cable thick in	mm	1.82	1.9	1.9	1.878
Ins Cable thick mid	mm	1.82	1.9	1.9	1.815
Area cable	mm2	29.9896	25.84	25.84	27.67875
Area ins cable	mm2	36.4546	31.255	31.255	33.4686
N turns		47	35	70	50
A ins turns		1713	1094	2188	1673
A ins turns HTS	mm2	1713			
A ins turns LTS	mm2	3282			
A ins turns tot	mm2	4995			1673
Current	A	14380	14380	14380	16230
Bbore	T	20.00	20.00	20.00	
Bpeak	T	20.60	13.16	11.82	
J0	A/mm2	394	460	460	485
Je_strands	A/mm2	589	665	665	715

Emmanuele

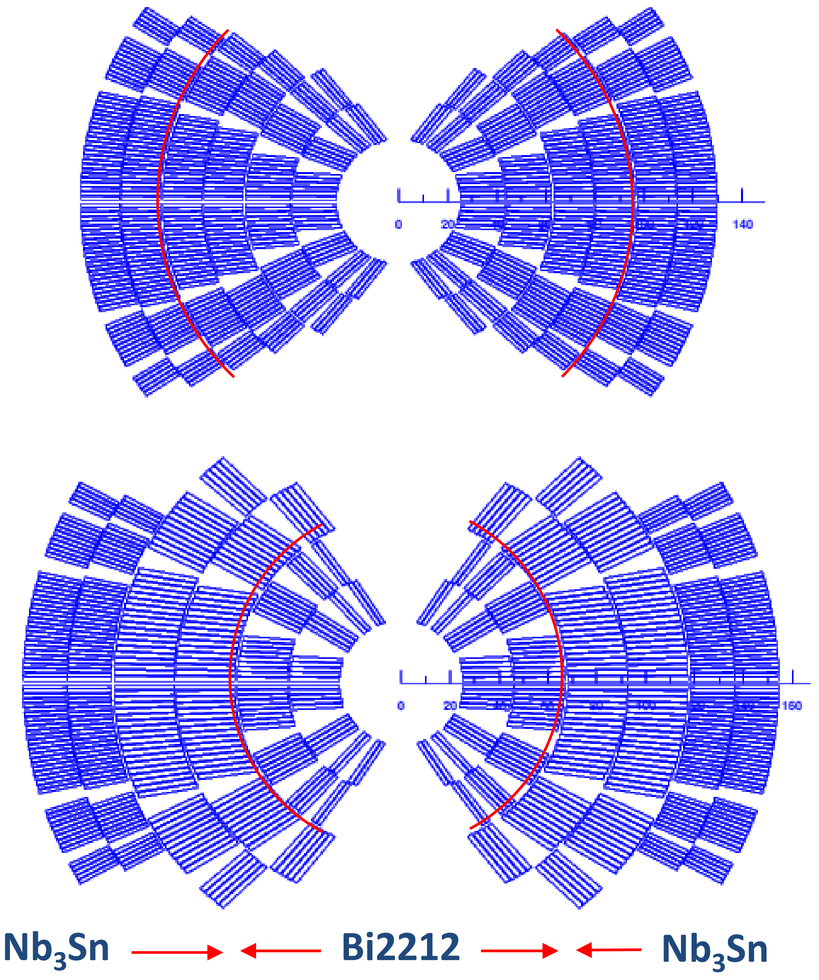
#	B_bore HTS+LTS	B_bore HTS	B_bore LTS	B_bore HTS wo/ iron	B_bore LTS wo/ iron	B_bore HTS 15% margin	B_bore LTS 15% margin
V28_69	20.0	6.3	14.1	5.9	12.5	8.8	16.6
V28_17	20.0	7.4	13.1	6.9	11.5	9.7	14.4
V28_63	20.0	9.4	11.6	8.3	9.8	11.1	12.9

CCT5_Bin5: coil_OR_329
CCT5_Bin5: magnet_coil_OR_76

CCT6-BiCCT2 : coil_OR_158
CCT6_BiCCT2 : magnet _OR_430

Magnetic analysis
"Traditional" Cosϑ (without stress management)

- See talk from V. Marinozzi
- 6 layers, with cables 13 mm to 21 mm wide
  - Double-layer coils with internal splice and not graded
- Two options considered
  - 4 layer HTS, 2 layer LTS or 2 layer HTS, 4 layer LTS
- Field quality requirements met
  - Margin to be optimized
- Quench protection addressed (*J* in Cu)
- Stress requirements partially addressed
  - Accumulated σ_ϑ → 150-160 MPa
  - Accumulated σ_r → approaching 200 MPa



R&D towards Nb_3Sn outserts Canted-Cosθ: subscales

- Development of sub-scale CCT for material/training study
  - 5.5 T in 50 mm aperture
  - Focus on impregnation material
- Sub_2 to Sub_6: from Mix-61 to wax
  - Excellent training (no training) performance
  - Stable plateau and holding
- Currently under development: Sub_7
  - Filled wax
    - Based on PSI box test, same training performance as wax, better mech properties
    - Better candidate for higher stress outsert magnets
  - Coil fabricated, magnet assembly in progress, test expected in the summer