U.S. MAGNET DEVELOPMENT PROGRAM

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

P. Ferracin

Applied Superconductivity Conference (ASC 2024)
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U.S. DEPARTMENT OF ENERGY | Office of Science

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Acknowledgement

- Members US MDP 20 T hybrid magnet working group
  - BNL: M. Anerella, J. Cozzolino, R. Gupta, F. Kurian, B. Yahia
  - FNAL: G. Ambrosio, M. Baldini, E. Barzi, S. Gourlay, V. Kashikhin, V. Marinozzi, I. Novitski, G. Velev, A. Zlobin
  - 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
  - NHMFL: K. Amm, L. Cooley, D. Larbalestier

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

Outline

- Introduction and motivations
  - US Magnet Development Program and the 20 T hybrid magnet working group
  - Why hybrid magnets and why stress managed coils
- Overview of hybrid activities
  - Nb_3Sn outserts
  - HTS inserts
    - Bi2212
    - REBCO
  - First hybrid magnet
- Towards a 20 T hybrid magnet
- Conclusions

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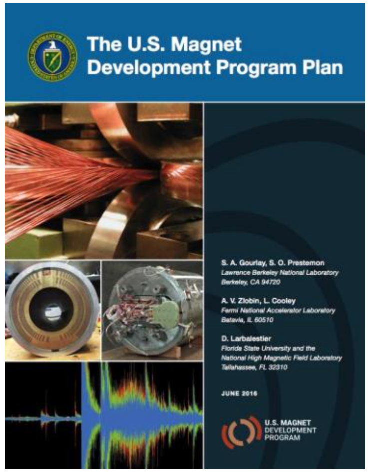
US Magnet development program

- 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
  - Probing stress management structures
  - Perform R&D on HTS accelerator magnets
  - Develop LTS/HTS hybrid magnets
  - Investigate fundamental aspects of magnet design and technology



https://arxiv.org/abs/2011.09539

MDP 20 T hybrid working group

- Established in 2020 to
  - Perform a conceptual design of a 20 T hybrid HTS-LTS magnet
    - Medium-long term goal of the roadmap
  - 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
- Road-map to be updated by the end 2024 (following 2023 P5 report)

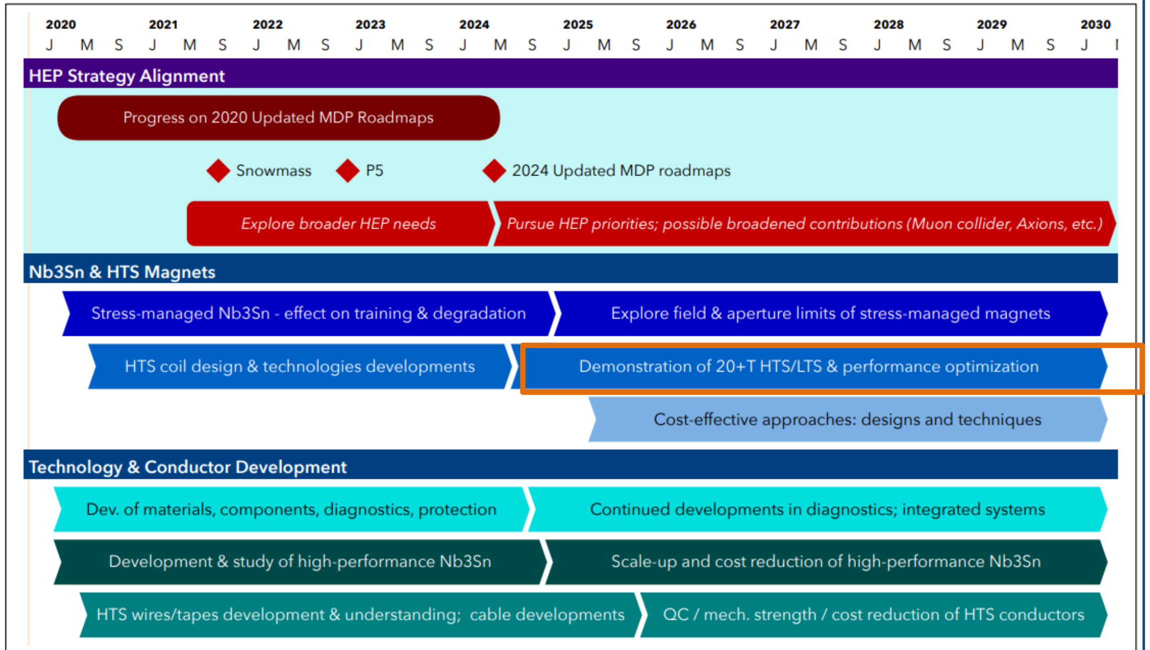


Figure 8. A high-level ten-year roadmap for the US Magnet Development Program, designed to align with the US Physics community planning process.

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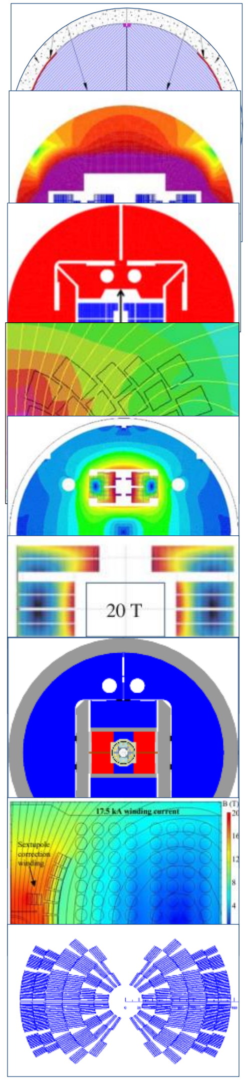
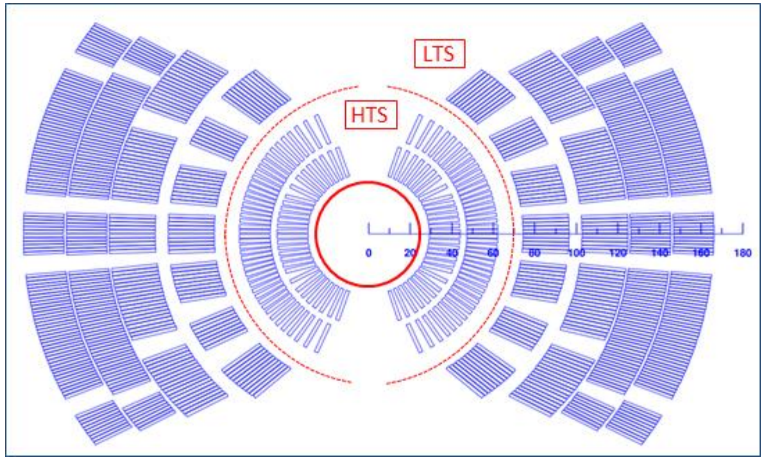
HTS/LTS hybrid magnets
Previous work

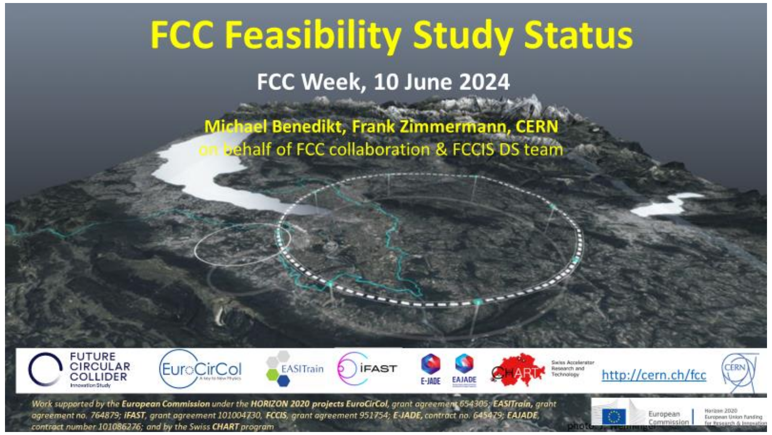


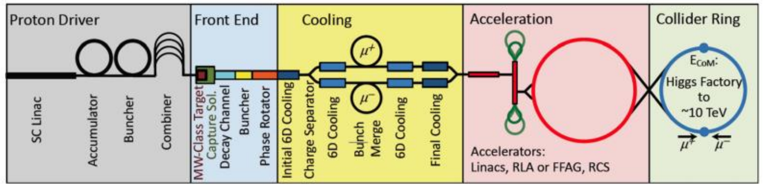
- 2005, P. McIntyre, *et al.*, 24 T hybrid for LHC tripler (TAMU)
- 2011, 2014, E. Todesco, *et al.*, 20 T hybrid for LHC upgrade (CERN)
- 2015, G. Sabbi, *et al.*, 20 T hybrid for SPPC China and FCC (LBNL)
- 2015, R. Gupta, *et al.*, 20 T hybrid for LHC upgrade (BNL)
- 2016, Q. Xu, *et al.*, 20 T hybrid 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 design studies (US MDP)

HTS/LTS hybrid magnets

- The hybrid “concept”: use HTS only where it is needed
  - **HTS insert**: innermost part of the coil, in high field
  - **LTS outsert:** outermost part of the coil, in low field
- So far, it is an economically viable option
  - To explore the very high bore fields → 16+ T range
  - To test Nb_3Sn conductor in large bore and high field magnets
    - → high stress
  - To test HTS in high background fields
- Relevant to…
  - FCC-hh
    - “high-field superconducting magnets: 14-20 T”
  - Muon colliders
    - Large aperture (100-160 mm), 12-16 T
    - IR quadrupole magnets (20 T)







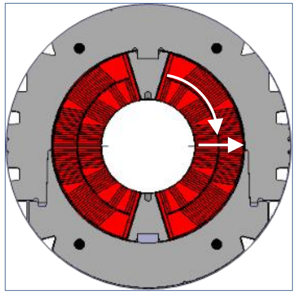
HTS/LTS hybrid magnets

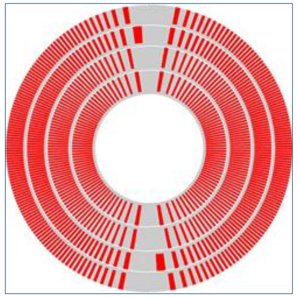
- In summary, from the MPD perspective, the HTS/LTS hybrid is a very effective tool
  - To perform R&D on a broad spectrum magnets similar to those considered for FCC-hh or Muon Colliders
  - To test HTS in high field
- On a side note (but still important)
  - It forces HTS and LTS teams to work together (and learn from each others) on integrated designs
  - It is a very interesting and fun problem for magnet designers and excellent case study for “workforce development”
    - It contains almost everything: different SC materials…different cable geometries…magnetics… mechanics…quench detection and protection…..

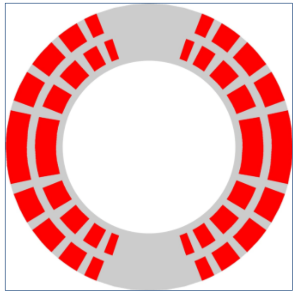
Stress managed coil designs

- In traditional cos-theta design
  - Accumulation of Lorentz forces, both azimuthally and radially, resulting in high coil stress
- In stress managed cos-theta design
  - Lorentz forces are intercepted by mechanical “stoppers”, both azimuthally and radially
    - Originally proposed by P. McIntyre for block-design in 1997

- Two options consider by MDP
  - Canted Cos-theta design (CCT)
    - Each turn on a groove, separated by spars and ribs, in a tilted solenoid configuration
  - Stress management cos-theta (SMCT)
    - Traditional cos-theta with individual conductors or blocks in a groove





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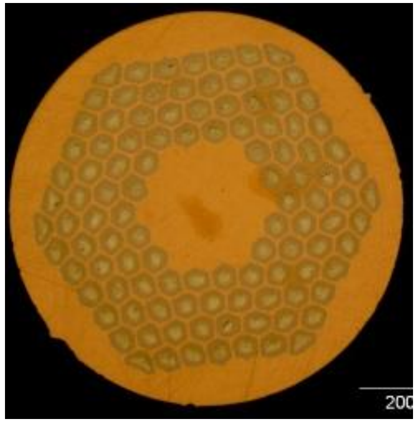
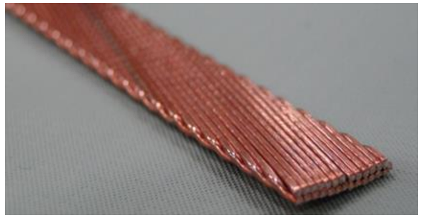
Nb_3Sn wires and cables

- Strands
  - Bruker-OST RRP 108/127 or 150/169
  - Diameter ranging from 0.6 mm (CCT subscales) to 0.85 mm
- Cables
  - Rutherford cable with 11 to 51 strands
  - Width from 4 mm to 22 mm
  - SS core (MQXF cable)
- Insulation
  - S2 glass braided

Bruker-OST RRP 108/127





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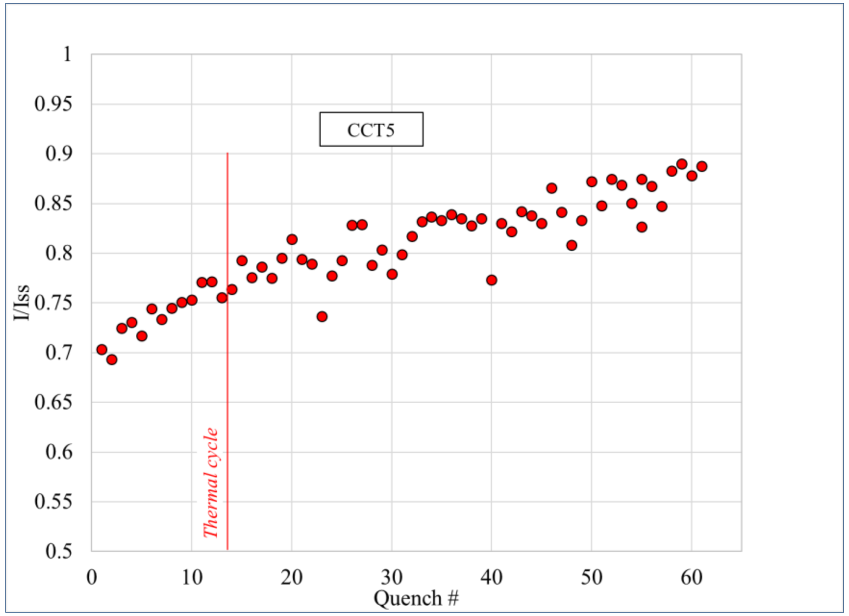
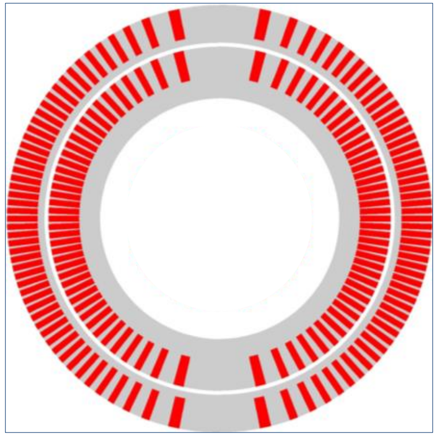
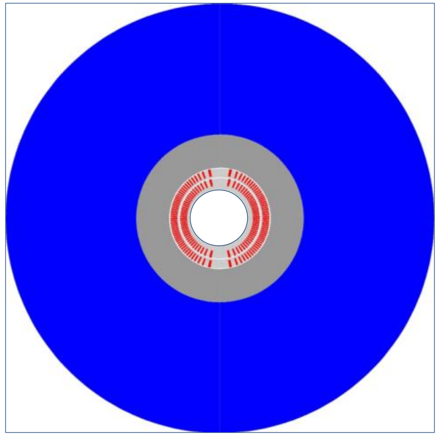
Nb_3Sn CCT outserts

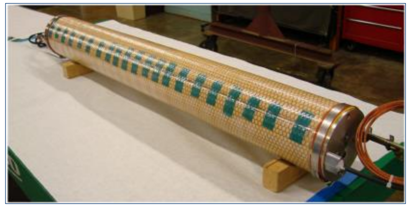
D. Arbelaez, *IEEE Trans. Appl. Supercond.*, VOL. 32, NO. 6, Sep. 2022, 4003207.

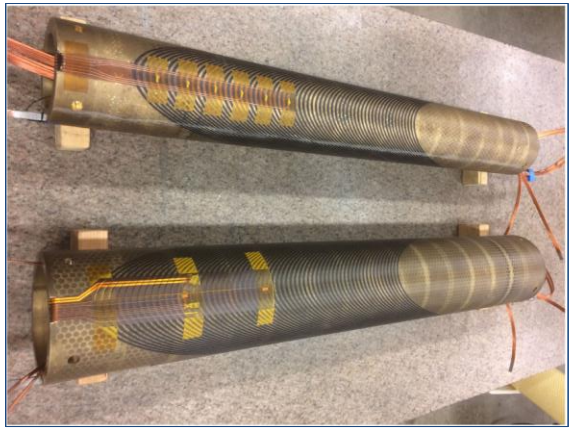
- CCT5 (tested in 2019)
  - 2 layer with 10 mm wide cable
  - **90 mm** clear bore, 1 m length
  - About 60 quenches to 90%, good memory after TC
  - B_{bore} max: **8.5 T;** B_{peak} max: 9.7 T

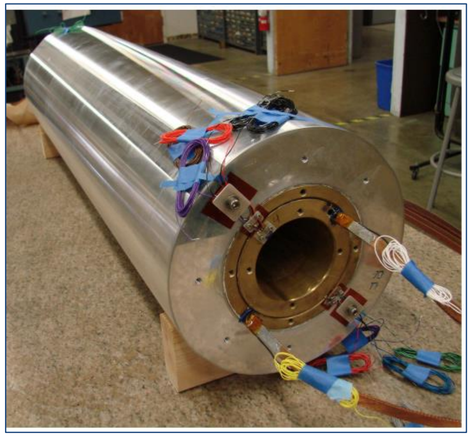












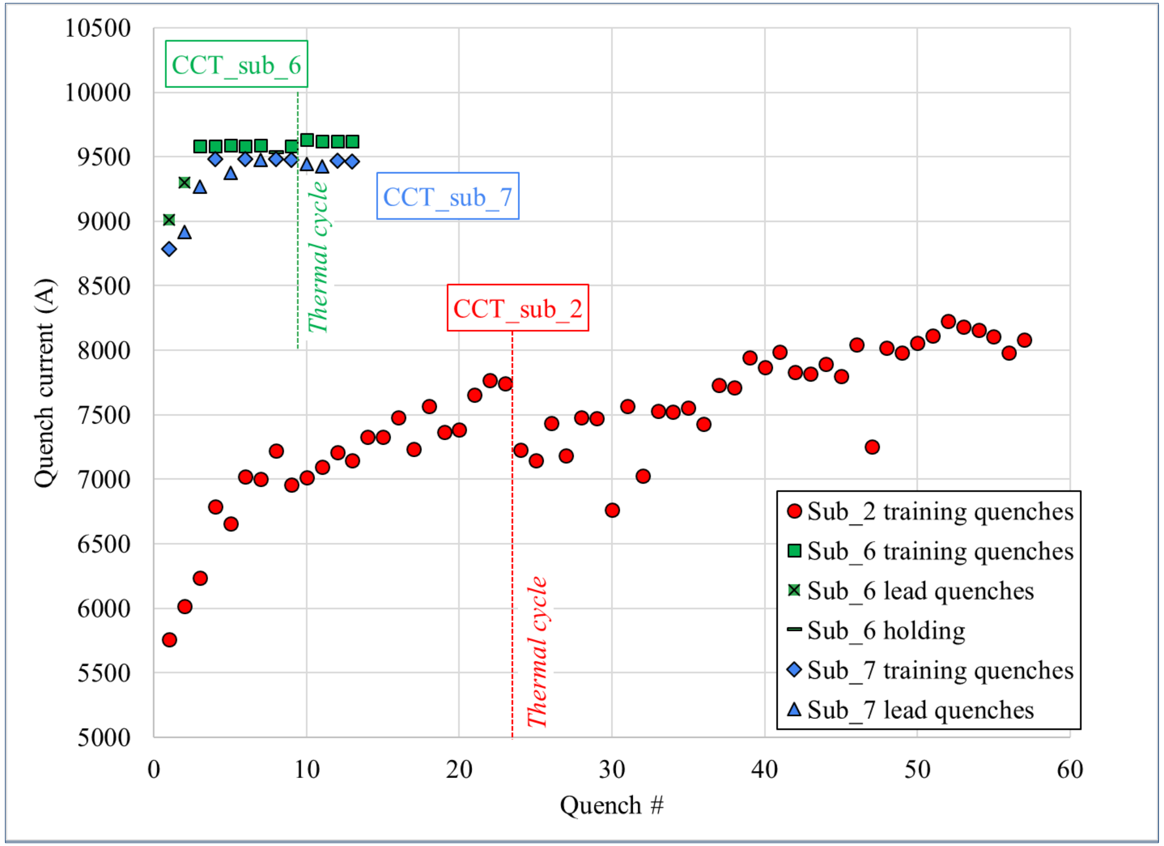
Nb_3Sn CCT outserts

D. Arbelaez, *et al.*, **2LOr2E-04**

J. L. Rudeiros-Fernandez, *et al.*, **4LOr2E-02**

G. Vallone, *et al.*, **5LOr2B-02**

- In parallel, development of sub-scale CCT for material/training study
  - 5.5 T in 50 mm aperture, 0.7 mm length
- Very similar training as CCT5 (good!) → fast turnaround for studies
- Following BOX tests at PSI*, subscales were impregnated with:
  - Wax: CCT_sub_6
  - Alumina particle filled wax: CCT_sub_7
  - Either no or minimal training, stable plateau at I_{ss}, perfect memory, and holding current



*M. Daley, *Supercond. Sci. Technol.* 34 (2021) 115008

Nb_3Sn CCT outserts

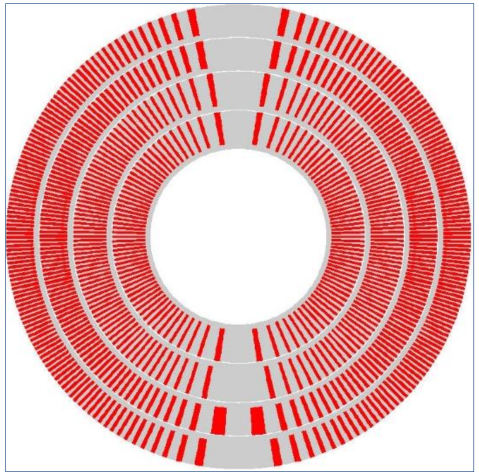
D. Arbelaez, *et al.*, **2LOr2E-04**

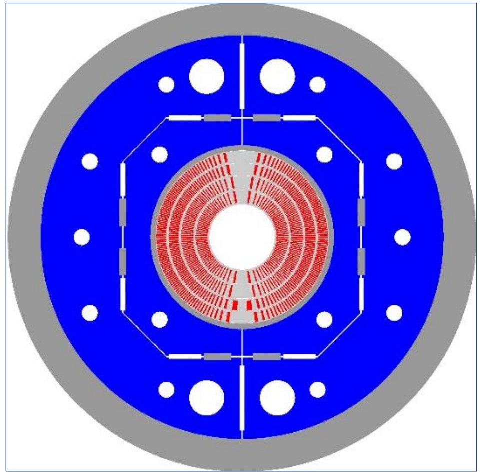
J. L. Rudeiros-Fernandez, *et al.*, **4LOr2E-02**

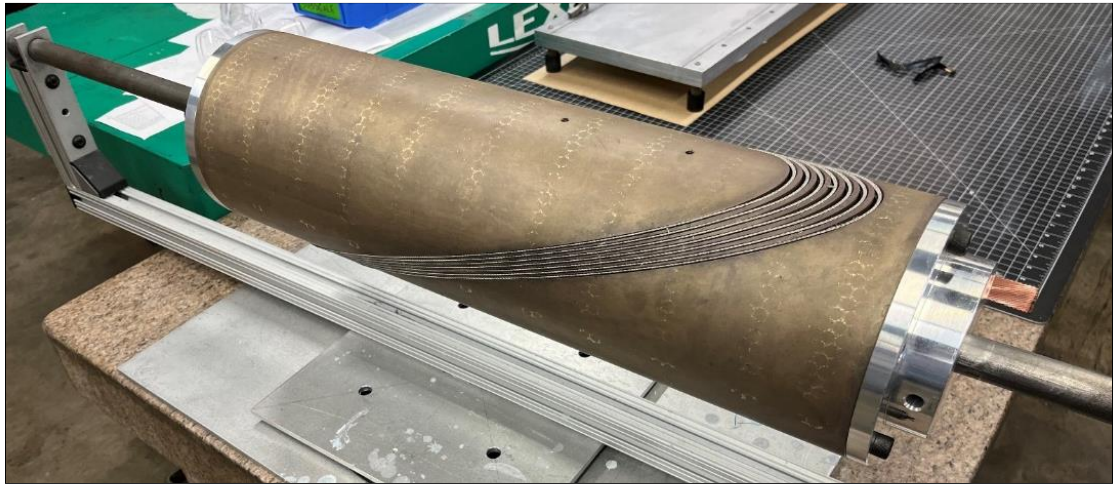
- Next steps
  - CCT5 with filled wax (in fabrication)
    - Targeting B_{bore} of 9.7 T (at I_{ss}), 90 mm bore, with minimal training and stable plateau
    - Conductor in higher stress than sub-scale, more representative of high field magnets
  - Continue R&D with sub-scale on new impregnation materials (Telene)

E. Barzi, *et al.*, **2LOr1E-01**

- And then….CCT6: 4 layers with 21 and 18 mm wide cables
  - Design: 15 T (1.9 K, 80% I_{ss}) in 120 mm aperture







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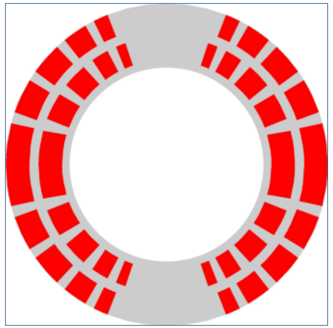
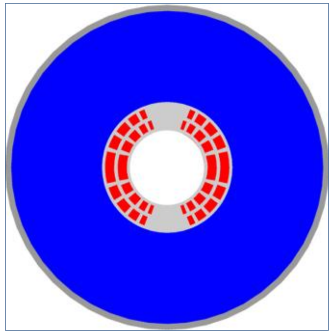
Nb_3Sn SMCT outserts

E. Barzi, *et al.*, **4LOr2E-01**

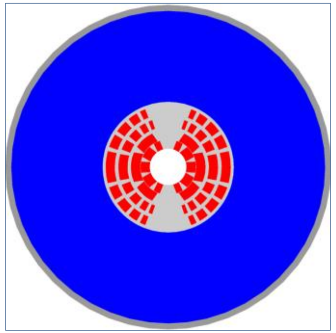
- SMCT coils
  - Conductor-blocks in groove
  - One coil fabricated and tested in a mirror configuration
- SMCTD1 2L dipole
  - Target: **11 T** in **123 mm** aperture
- SMCTD1 4L dipole
  - SMCT outer coils + MDPCT1 inner layer
  - Target: **14-15 T** in **60 mm** aperture



SMCTD1 2L



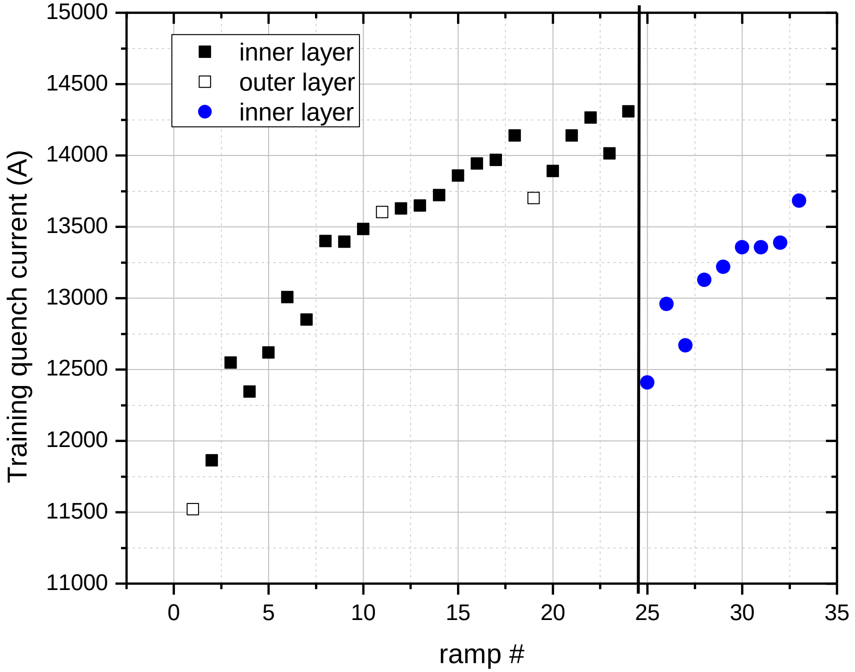
SMCTD1 4L

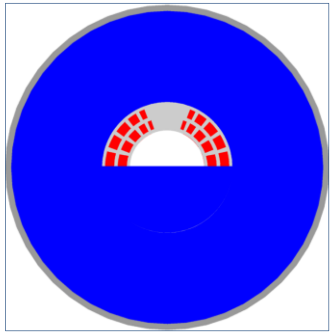


Nb_3Sn SMCT outserts

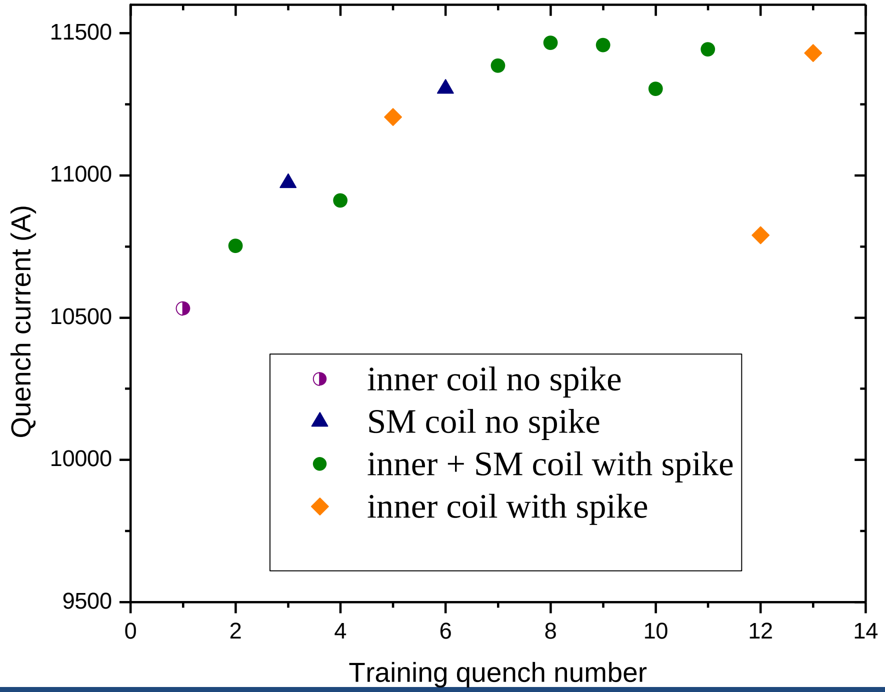
E. Barzi, *et al.*, **4LOr2E-01**

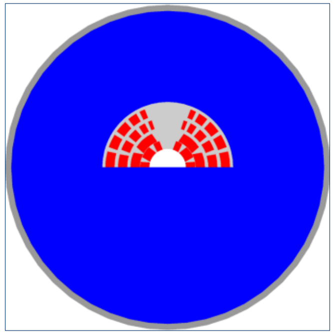
- SMCT coil tested in mirror SMCTM1, both with and without inner coil of the MDPCT1
- SMCTM1a
  - 14.3 kA, 87 % I_{ss} reached in 24 quenches
  - 12.7 T conductor peak field
  - Poor memory/no degradation after TC
- SMCTM1b
  - Highest current was 11.46 kA, 82 % I_{ss}
  - 14.5 T conductor peak field in the inner coil
  - 12.6 T conductor peak field in SMCT coil





SMCTM1a





SMCTM1a

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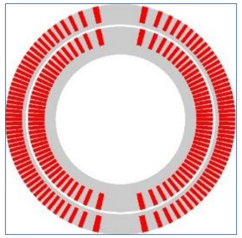
Nb_3Sn outserts
Summary

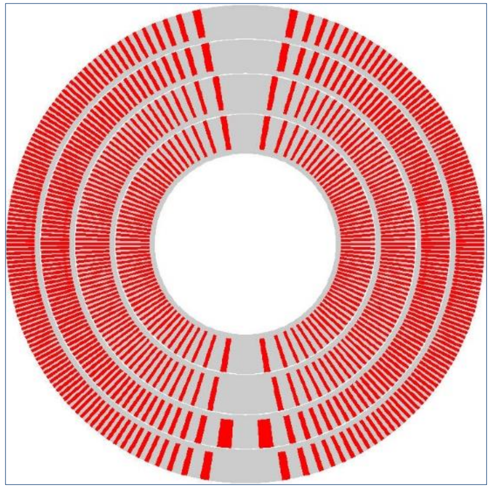
CCT5
ID: 90 mm; OD: 152 mm
8.5 T

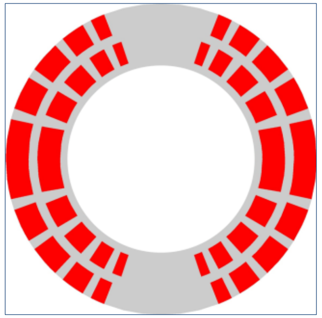
CCT6
ID: 120 mm; OD: 316 mm
Target: 14-15 T

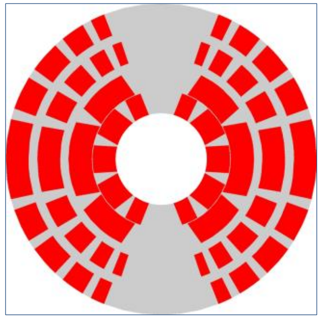
SMCT
ID: 122 mm; OD: 205 mm
Target: 11 T

SMCT+ MDPCT1
ID: 60 mm; OD: 205 mm
Target: 14-15 T









in scale

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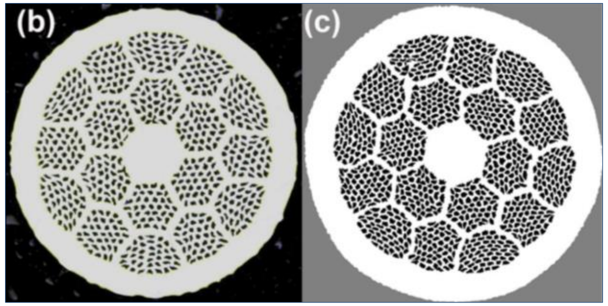
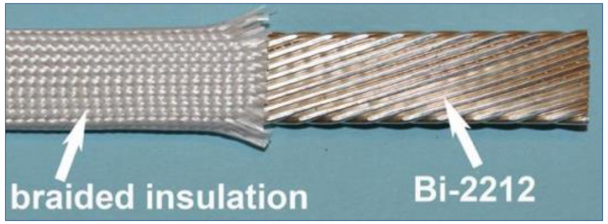
Bi2212 wires and cables

Tengming Shen, *et al.*, **3MOr1A-01**

- Isotropic, multifilamentary round wire
  - *Bruker-OST* architecture 37×18 or 55×18
  - 50 bar overpressure heat treatment (OPHT) in Ar-O_2 or O_2 at 885-900 °C
  - J_e ~ 750 A/mm^2 at 20 T, 4.2 K
- Rutherford cable
  - Bin5
    - **4 mm wide**, 9-strand, 0.8 mm strand
  - BiCCT1
    - **7.8 mm wide**, 17-strand, 0.8 mm strand
  - BiCCT2
    - **12.3 mm wide**, 22-strand, 1.0 mm strand
  - Insulation: combination of a TiO_2 coating with a mullite sleeve
    - To prevent electrical shorts between turns and reduce ceramic leakage
- "Renegade" furnace under commissioning at NHMFL
  - Homogeneous hot zone: 250 mm diameter, 1 m long





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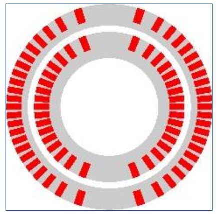
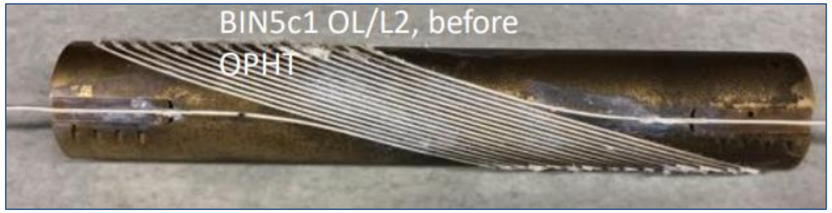
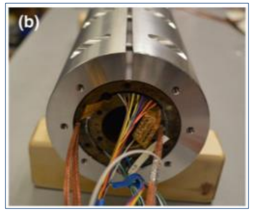
Bi2212 CCT inserts

Tengming Shen, *et al.*, **3MOr1A-01**

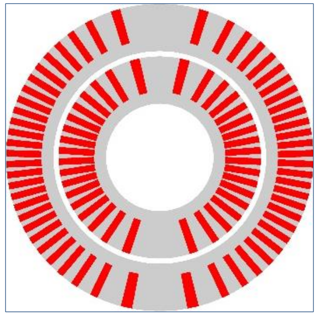
- Bin5
  - **1.6 T** in **31 mm** aperture
  - Successfully tested in stand alone
  - Ready to be tested in CCT5

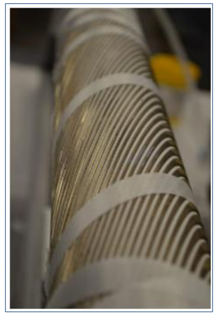




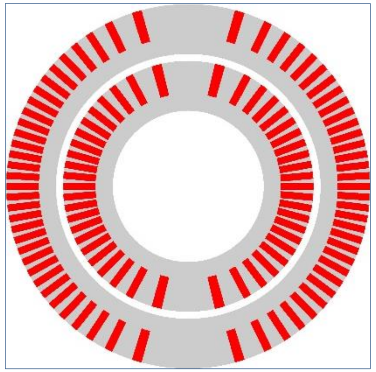


- BiCCT1
  - Target: **5 T** in **40 mm** aperture
  - Coil wound and ready for reaction





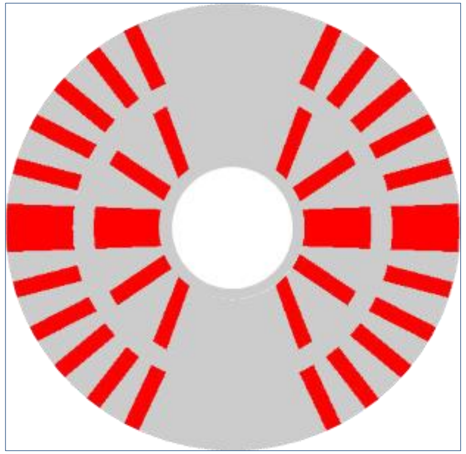
- BiCCT2
  - Target: **7 T** in **40 mm** aperture
  - 12.3 mm cable with 1 mm strand fabricated

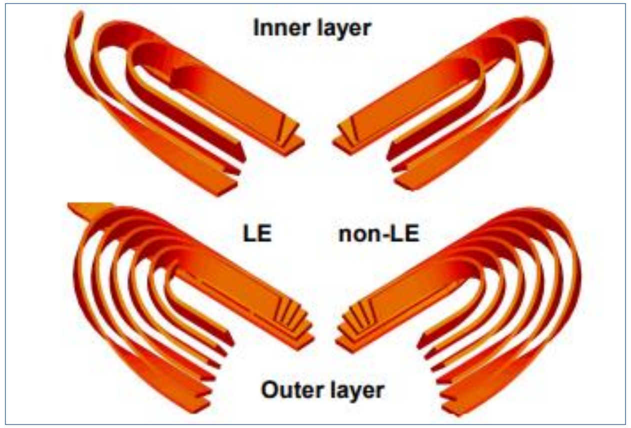


Bi2212 SMCT inserts

Emanuela Barzi, *et al.*, **4LOr1B-03**

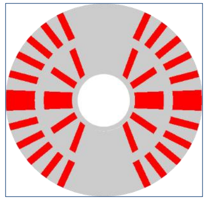
- Bi2212 SMCT
  - Target: **1-2 T** in **15 mm** aperture
  - Winding test performed with plastic parts and Nb-Ti cable
  - Fabrication of Inconel 3D printed mandrel completed
  - To be tested stand-alone and in a 4L SMCTD1



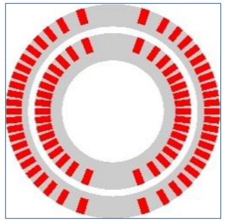


Bi2212 CCT and SMCT inserts

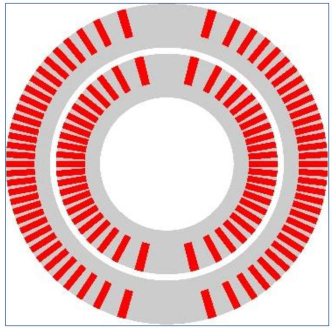
BiSMCT
ID: 15 mm; OD: 58 mm
Target: 1-2 T



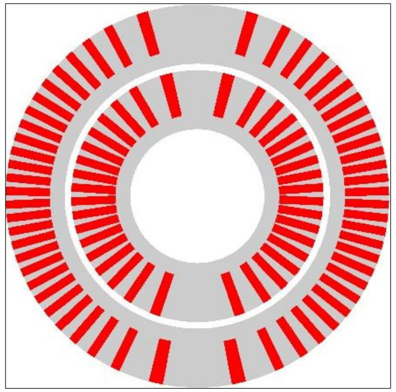
Bin5
ID: 30 mm; OD: 64 mm
1.6 T



BiCCT1
ID: 40 mm; OD: 96 mm
Target: 5 T



BiCCT2
ID: 40 mm; OD: 114 mm
Target: 7 T



in scale

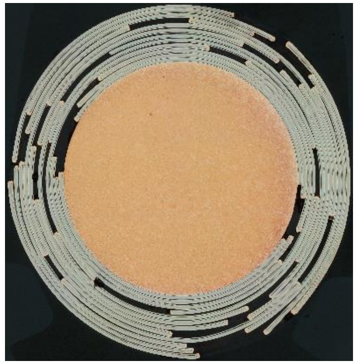
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

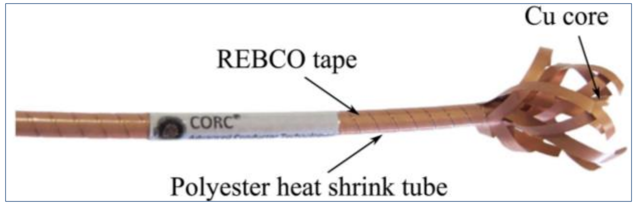
Outline

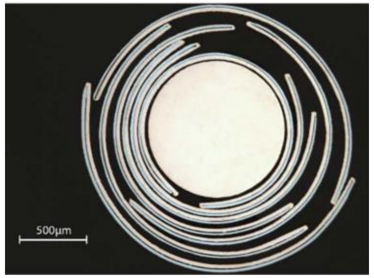
- Introduction and motivations
  - US Magnet Development Program and the 20 T hybrid magnet working group
  - Why hybrid magnets and why stress managed coils
- Overview of hybrid activities
  - Nb_3Sn outserts
  - HTS inserts
    - Bi2212
    - REBCO
  - First hybrid magnet
- Towards a 20 T hybrid magnet
- Conclusions

REBCO wires and cables

- Conductor on Round Core CORC® (***ATC LLC***)
  - 24-30 tapes in 12 layers (2-3 tapes per layers)
  - Tape: ~2 mm wide, 30 µm thickness
  - Cu core of 2.5 mm diameter
  - Total diameter: 3.7 mm including 30 µm polyester jacket
- Symmetric Tape Round STAR® (***AMPeers***) wire
  - 8-12 tapes on 8-12 layers
  - Tape 1.8-2.6 mm wide, 18-30 µm thickness
  - Cu core of 0.8+ mm diameter
  - 1.7-2.5 mm total diameter
- 6-around-1 STAR® cable (work in progress)



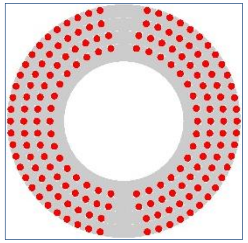
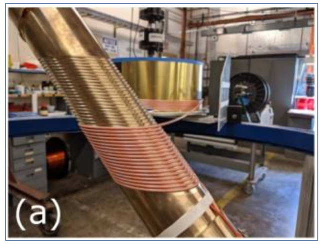


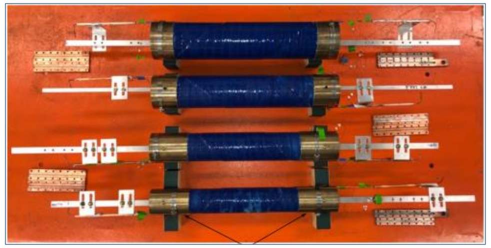


Atik Chavda, *et al.*, **4LPo1H-05**

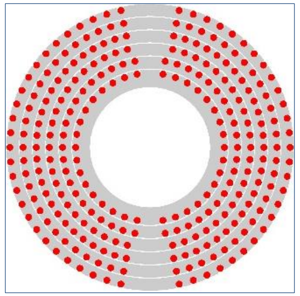
CCT CORC inserts

- The “C” series:
  - **C2**: first “accelerator” quality insert (CCT)
    - Successful 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 **65 mm aperture**
    - Under fabrication
  - Both magnets are “stand-alone”
    - OD lager than 120 mm, due to minimum bending radius requirements

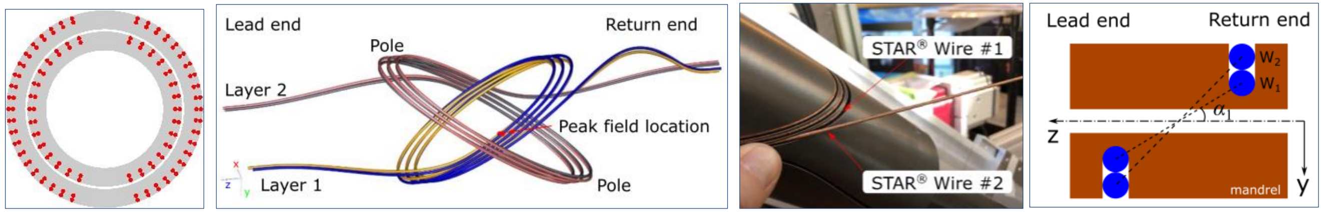


X. Wang, *et al.*, **Supercond. Sci. Technol.** 34 (2021) 015012.

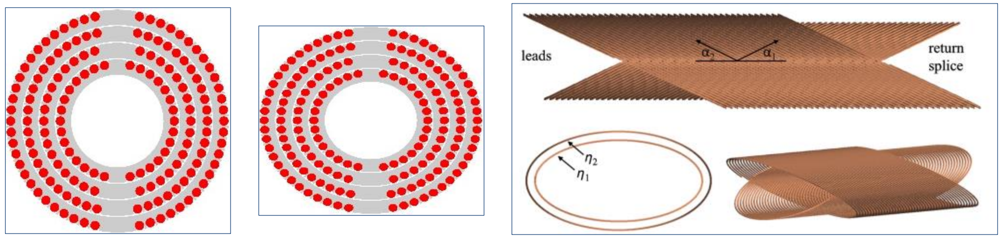


CCT/Uni-layer CORC/STAR inserts

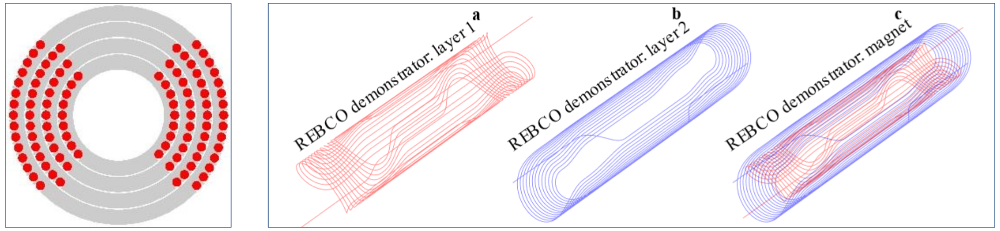
- Several options under study for a 90 to 120 mm OD insert
  - The “S” series (CCT with STAR wire)
    - CCT with 2 STAR wires per groove
      - Preliminary 3 turns coil fabricated and tested
      - Currently under design: S1
  - CORC Round or Elliptical CCT
    - New elliptical design to reduce minimum bending radius, by a reduction of the vertical aperture
  - CORC Uni-layer
    - Design to maximize field (CT cross-section) and minimize bending radius



X. Wang, *et al.*, **Supercond. Sci. Technol.** 35 (2022) 125011.



Yufan Yan, Lucas Brouwer, *et al.*, **1LPo1H-09**

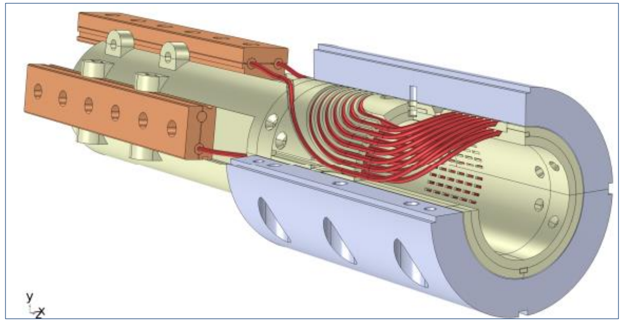


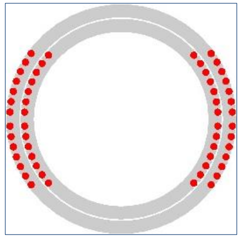
J.L. Rudeiros Fernandez, , *et al.*, **3LOr2B-03**

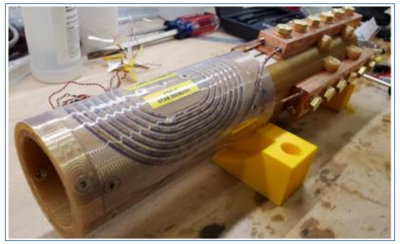
COMB REBCO inserts

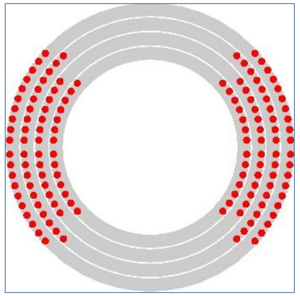
V. Kashikhin, , *et al.*, **3LOr2B-02**

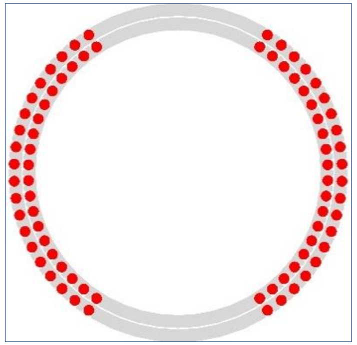
- The COMB (Conductor on Molded Barrel) series
  - SMCT with single conductor in groove
  - Double-layer coils with layer jump
- Fabrication and test of COMB-STAR-1
  - **1.5 T bore field** reached in **60 mm bore**
- Next step
  - Fabrication of COMB-STAR-2 and COMB-CORC-1
    - Targeting **5 T** in **60 mm bore**

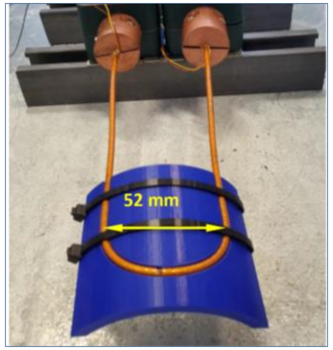












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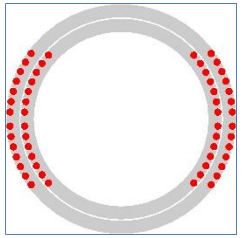
Bi2212 and REBCO outserts Summary

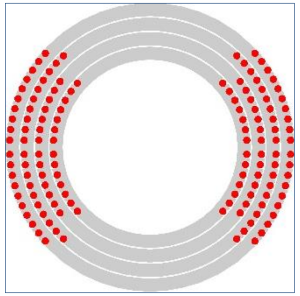
in scale

REBCO COMB Series

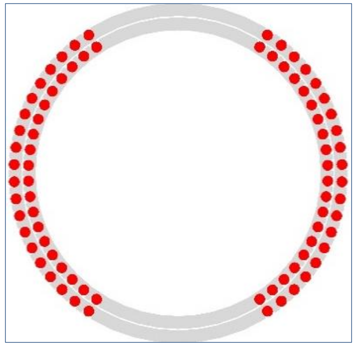
COMB-STAR1
ID: 60 mm; OD: 80 mm
1.6 T



COMB-STAR2
ID: 60 mm; OD: 100 mm
Target: 3-5 T

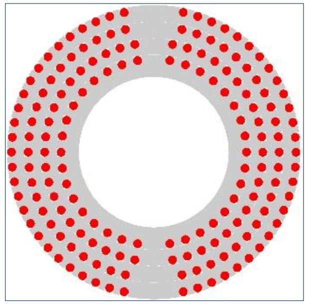


COMB-CORC-1
ID: 100 mm; OD: 120 mm
Target: 3-5 T

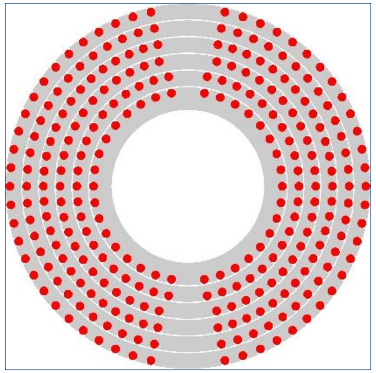


REBCO CCT-Unilayer Series

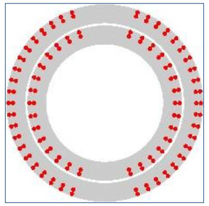
C2 (stand-alone)
ID: 65 mm; OD: 127 mm
2.9 T



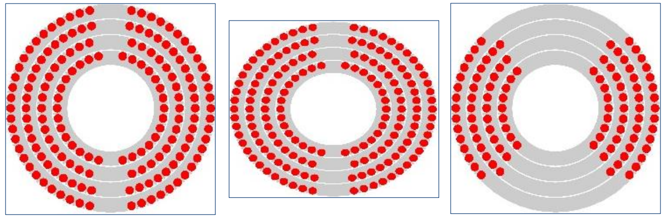
C3 (stand-alone)
65 mm; OD: 155 mm
Target: 5 T



S1
50 mm; OD: 84 mm
Target: 1-2 T



C4 (cct, e-cct, uni-layer)
ID: 40 mm; OD: 90 mm
Target: 3-5 T



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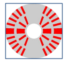
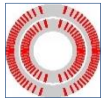
Summary of inserts and outserts

BiSMCT

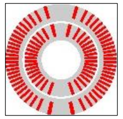


Bin5

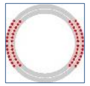
BiCCT1



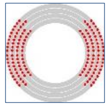
BiCCT2



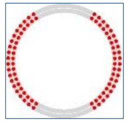
COMB-STAR1



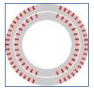
COMB-STAR2



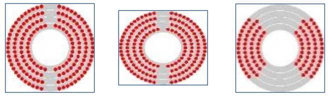
COMB-CORC-1

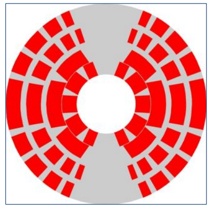


S1

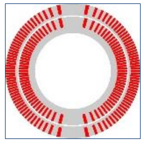


C4 (cct, e-cct, uni-layer)

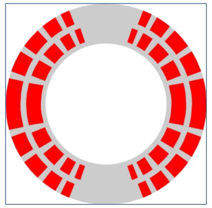




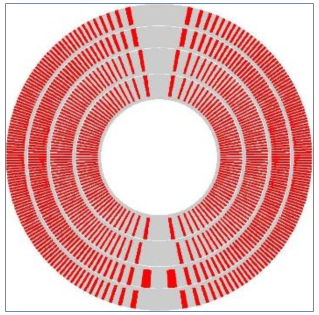
SMCT+ MDPCT1



CCT5



SMCT



CCT6

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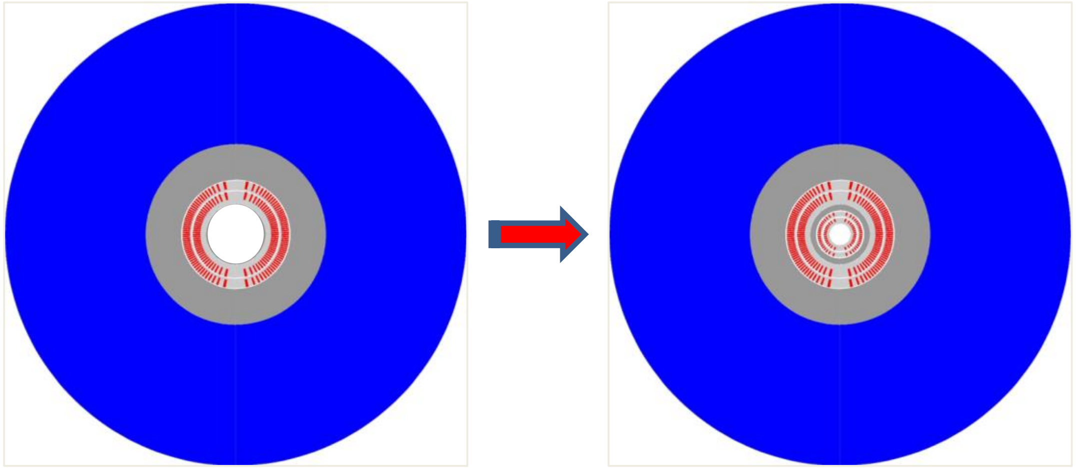
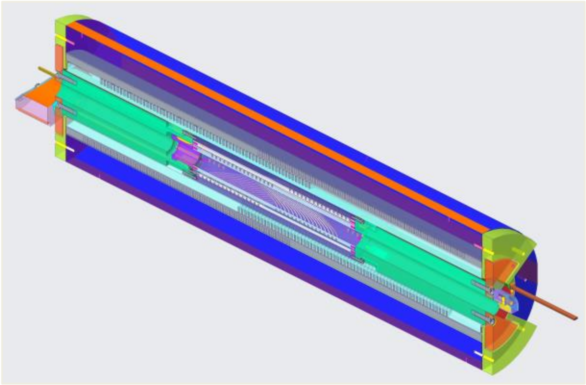
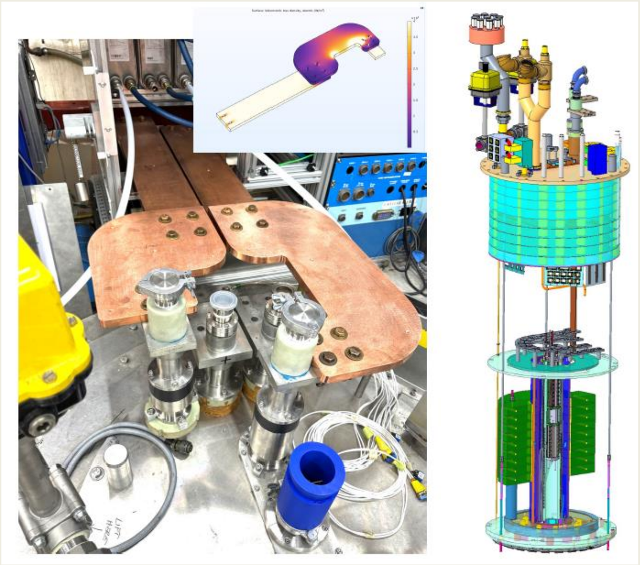
Hybrid Bin5-CCT5

R. Teyber, , *et al.*, **5LOr2D-02**

- Work ongoing to combine **CCT5** with **Bin5** in hybrid configuration
  - Lesson learned: not simple insertion, but rather an **integrated design**
- Test expected by end of 2024: **first hybrid magnet** at **10 T field level**
  - Relatively “low field”, but very important milestone towards higher field
- Upgrade of the LBNL test facility for hybrid testing: commissioning completed
  - Challenge: **two independent facilities** (PS, quench protection, header) in one facility







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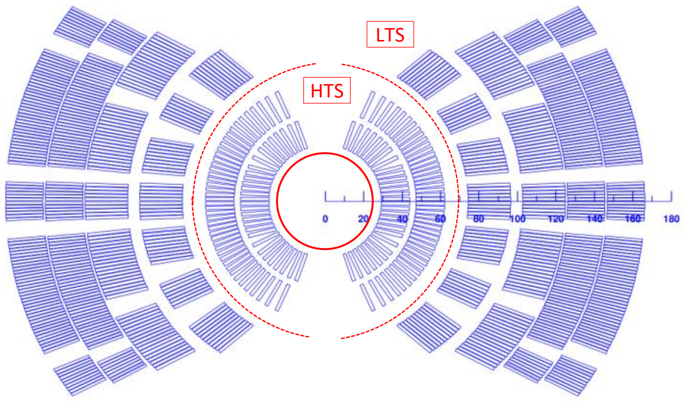
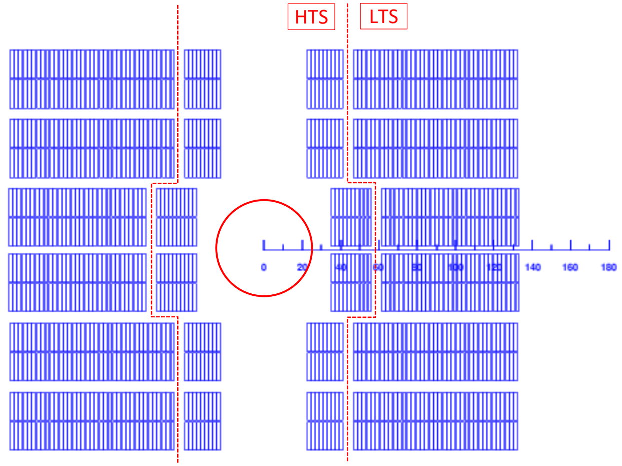
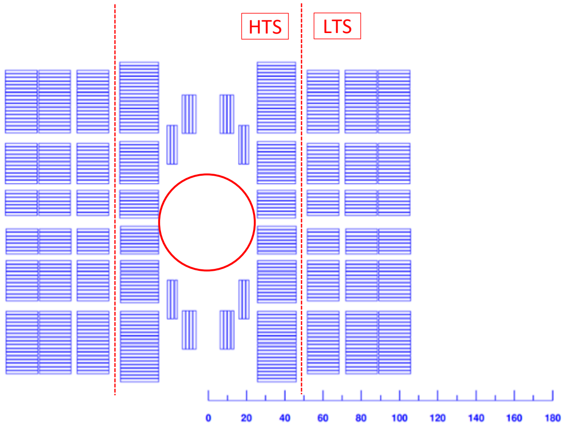
Towards 20 T hybrid magnet Overview







- Three options considered (Cos-Theta, Block, Common-coil), all with a Bi2212 insert
- Iterative process: magnetic, mechanical, and QP analysis
- More focus on Cos-theta: MDP inserts and outserts current design
- …and on common coils

  R. Gupta and D. Martins Araujo, *et al.*, **4LOr2B-02**

  – Only preliminary design with block
- Quench protection of the 3 designs carried out

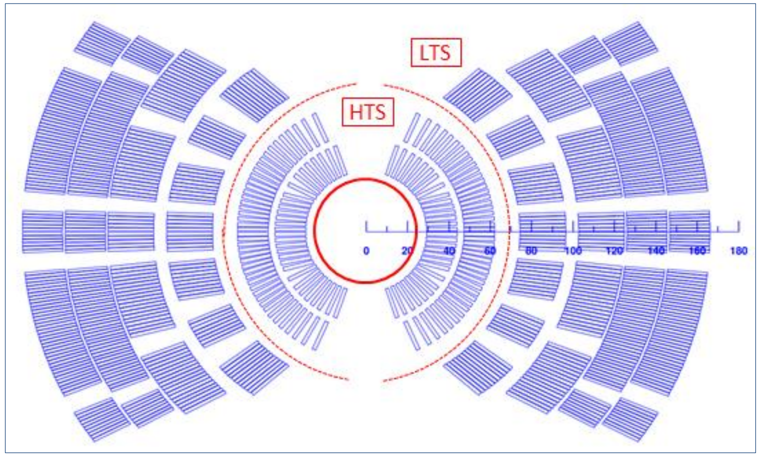
  Emmanuele Ravaioli, , *et al.*, **4LOr1B-06**

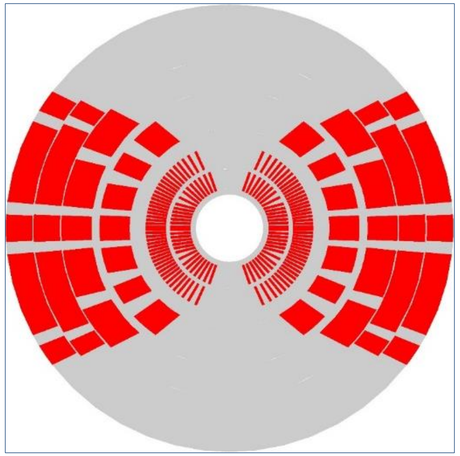
  – Quench protection ok for 1+ m long magnet, for the 10-15 m length new solutions to be considered

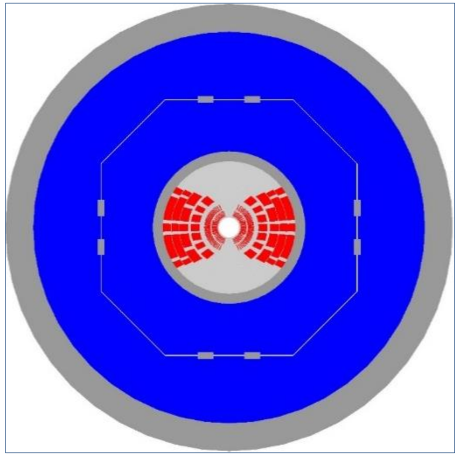
Towards 20 T hybrid magnet
Cos-theta option

- Magnetic:
  - 2 layer HTS, 4 layer LTS, field quality and margin in spec, OR coil: 165 mm
- Mechanics:
  - Stress management required in all directions
    - First 2 layers (HTS) with single cable in grove, second 2 layers (LTS) with single block in grove, last 2 layers traditional CT
  - Coil stress acceptable, but very high stress in the mandrel (Inconel or Nitronic?)
  - Large mechanical structure: 1120 mm.
    - Pre-load provided by bladder and key support structure to reduce peak field in conductor.

Marika DAddazio, , *et al.*, **4LOr2B-03**







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Conclusions

- US MDP pursuing an LTS-HTS hybrids magnets
  - Excellent tool to perform R&D on various HTS magnets, Nb_3Sn magnets
    - All relevant to future colliders
- Large aperture Nb_3Sn outserts under development with stress management concepts
  - CCT: “5” is ready, “6” under develop.,
  - SMCT first coil successfully tested in mirror configuration
- HTS inserts
  - First Bi2212 CCT coil Bin5 ready to be tested in hybrid; others to come
  - Both REBCO CCT and COMB insert designs validated with CORC® and STAR® wires
- First hybrid test (9-11 T field level) expected in 2024

- 20 T design study
  - Stress management required in particular in the innermost layers
  - Up to 3-4 m length can be protected, beyond new solutions required
  - Large coils, large magnets…overall challenging, but no showstoppers

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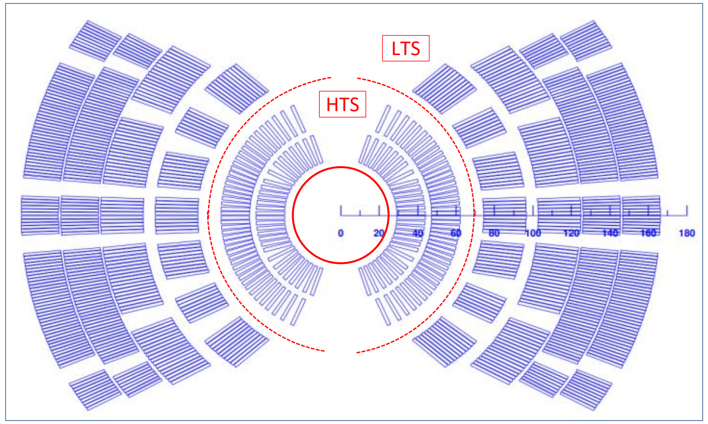
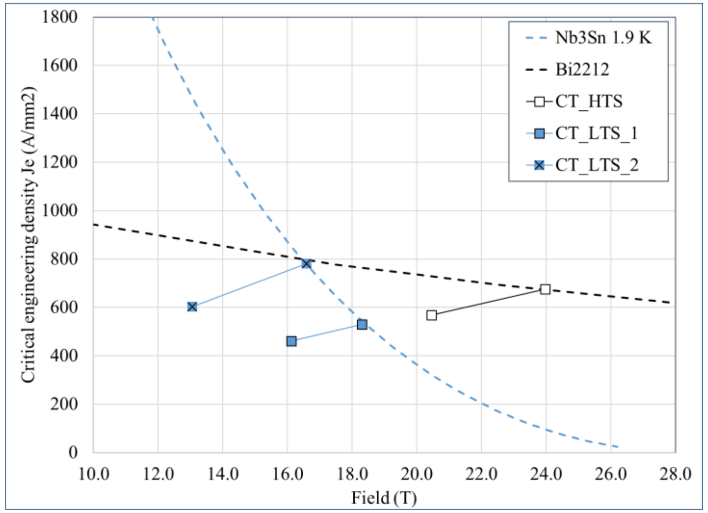
Towards 20 T hybrid magnet
Cos-theta magnetics and quench protection

- 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
- 1 m long magnet protectable with CLIC only
  - Peak temperature 270 C

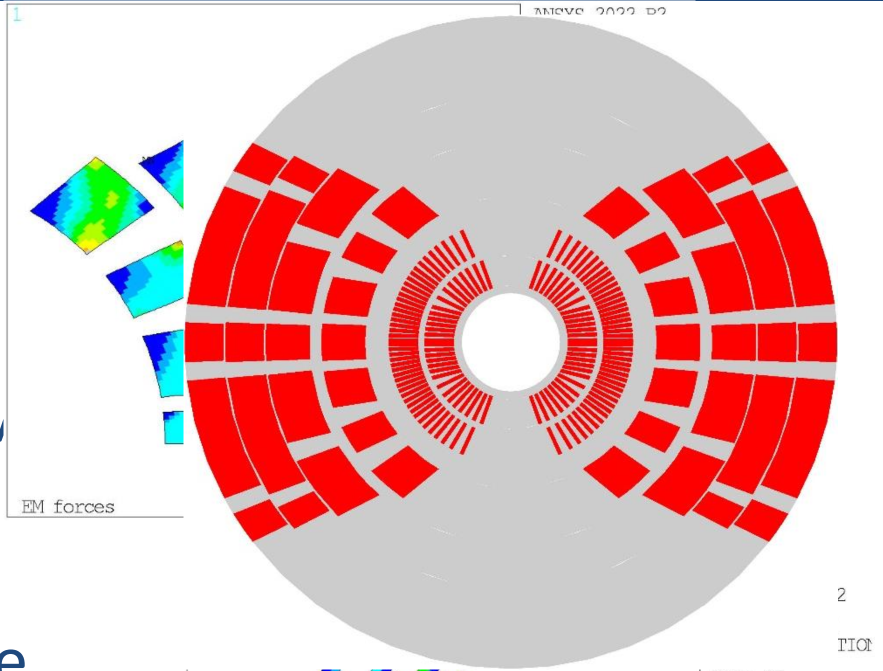


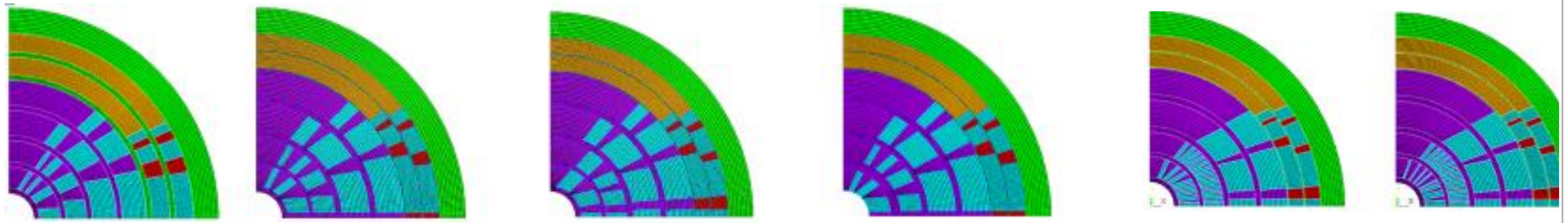


Emmanuele Ravaioli, *et al.*, **4LOr1B-06**

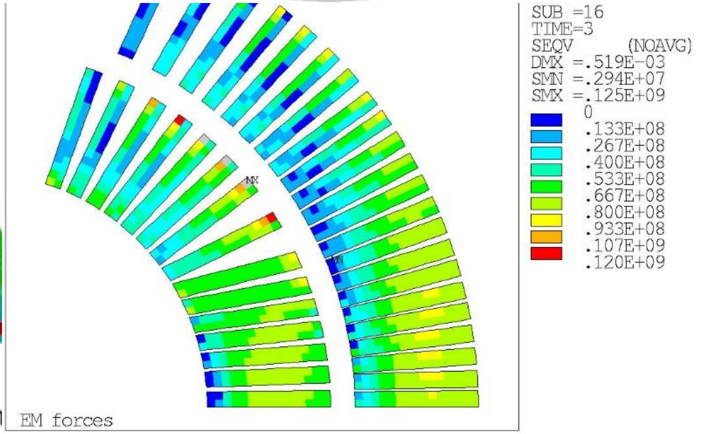
Current reference cross-sections
Cos-theta mechanics

- 4 out of 6 layers with stress management
  - Result of several iterations
- First two layers (HTS) with single cable in grove, ribs and spar
- Second two layers (LTS) with single block in grov with ribs and spar
- Last two layers traditional CT
- Coil stress acceptable, 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 Turn



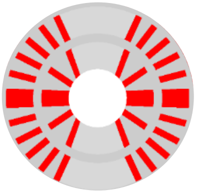
P. Ferracin, "Development of HTS/LTS Hybrid Dipole Magnets by the US Magnet Development Program"

Bi2212 and REBCO outserts Summary

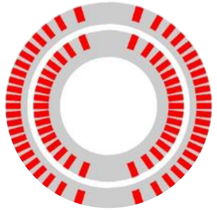
in scale

Bi2212

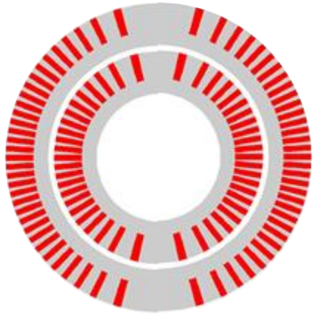
SMCT
15 mm
1-2 T
(target)



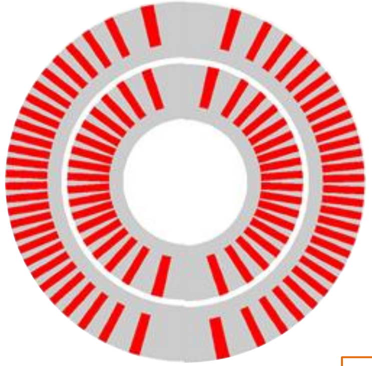
Bin5
31 mm
1.6 T



BiCCT1
40 mm
3 T
(target)

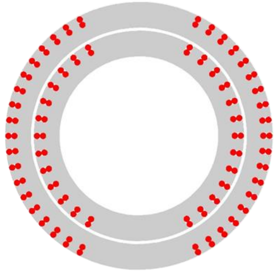


BiCCT2
40 mm
5 T
(target)

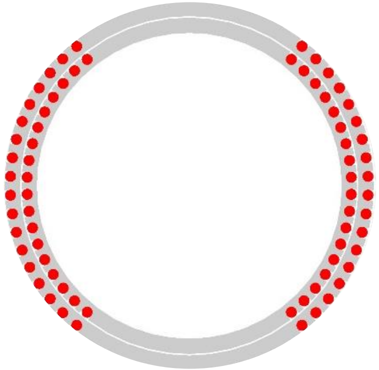


REBCO

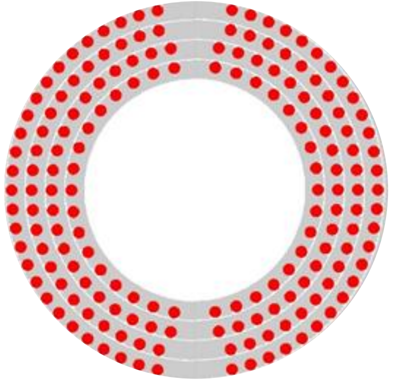
S1
50 mm
1-2 T
(target)



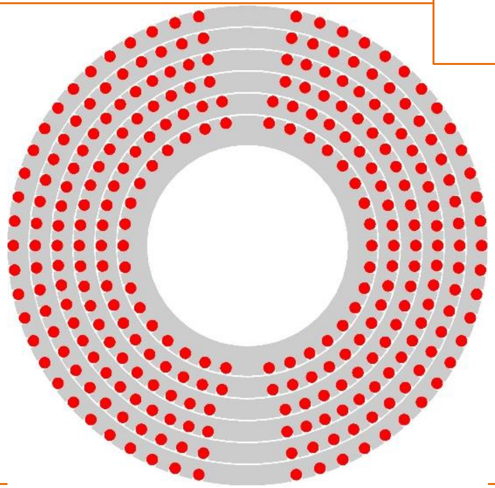
COMB
100 mm
2-3 T
(target)

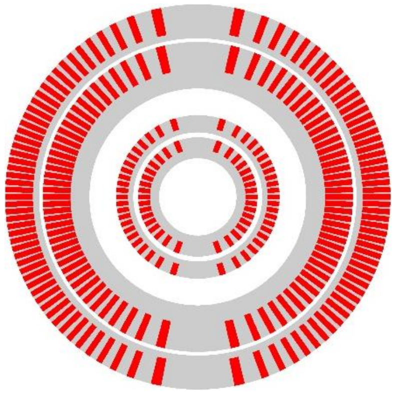


C4
70 mm
5 T
(target)



C3
ID: 65 mm
OD: 155 mm
5 T
(target)





Appendix

Design criteria

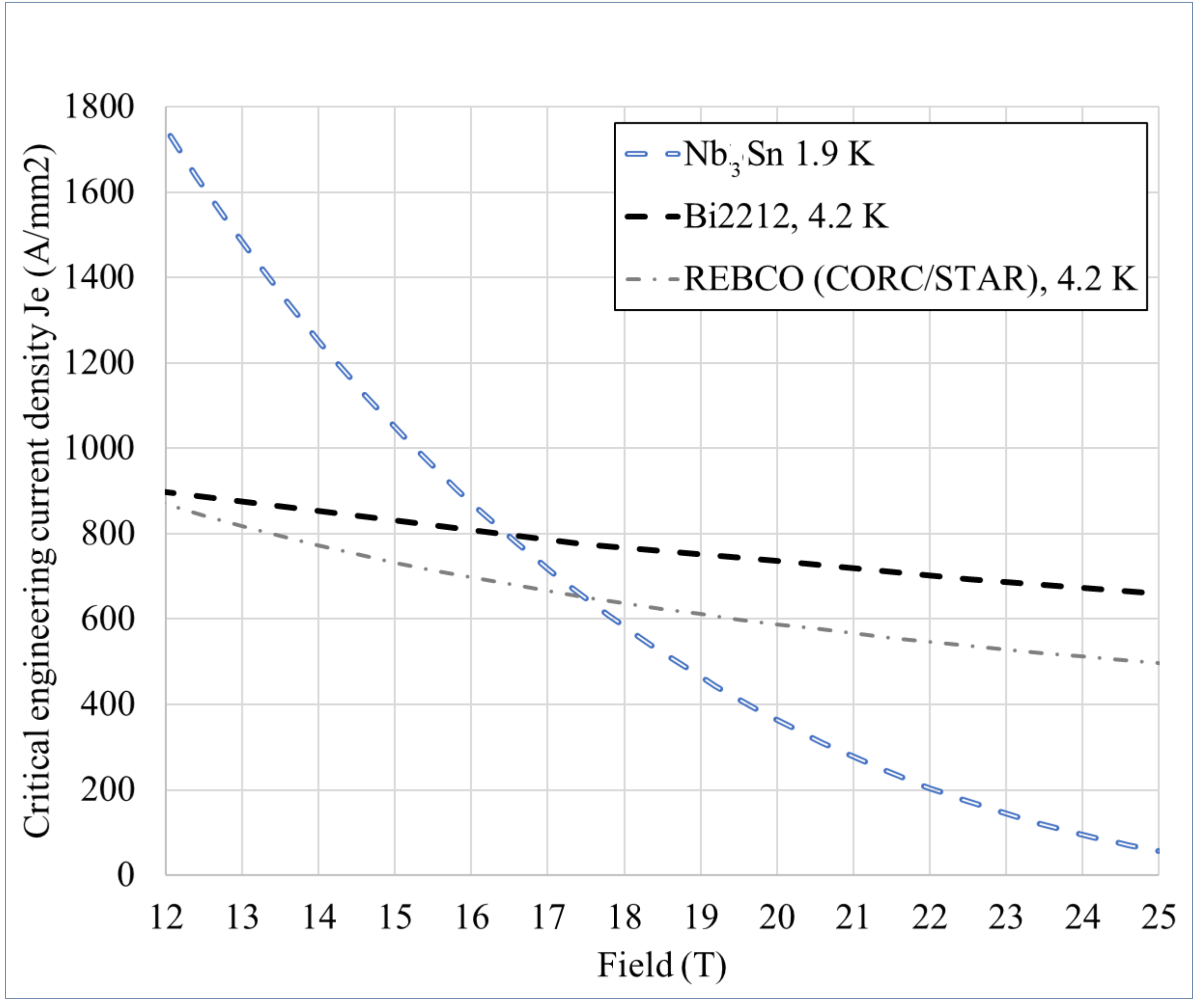
- Coil and magnet parameters
  - Free coil aperture (diameter) — 50 mm
  - Operational bore field — 20 T
  - load-line fraction @ 1.9K: I_{op}/I_{ss} — <= 87 %
  - 2D Geometrical harmonics — b_n<3 units for n<10 (at R_{ref}=17 mm)
- Quench protection
  - All coils powered in series
  - Maximum hot spot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

Superconducting materials: J_e and J_o

- Assumptions for magnetic analysis
  - J_e = Strand current / strand area
    - *J_{e_LTS} = 875 A/mm^2 (1.9 K, 16 T, 5% degrad.)*
      - *3000 A/mm^2 J_c (4.2 K, 12 T, virgin)*
    - *J_{e_HTS} = 740 A/mm^2 (20 T)*
      - Bi2212 value

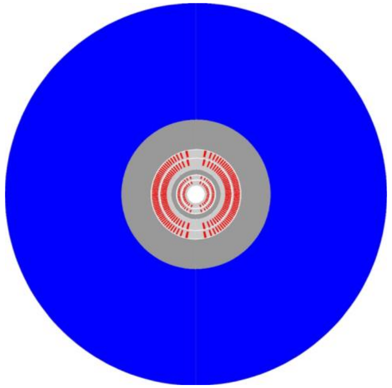
- Nb_3Sn and HTS cross at 16.5 T

- CORC/STAR wire still lower in J_e *(600 A/mm^2, 20 T)*

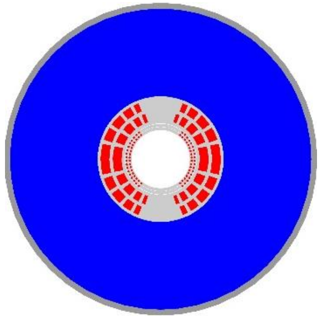


Overview of planned MDP hybrid magnets

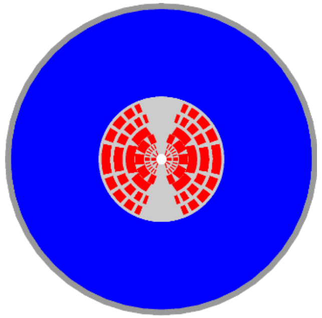
CCT5-Bin5
30 mm
9-10 T



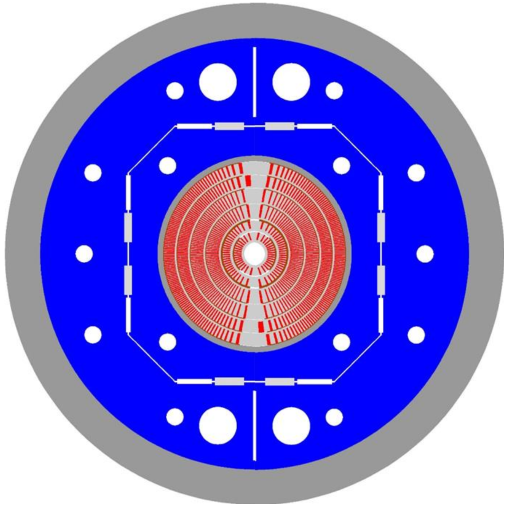
COMB-SMCT
100 mm
11-12 T



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



CCT6-BiCCT1-2
40 mm
14-16 T



IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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