U.S. MAGNET DEVELOPMENT PROGRAM

Status of US MDP

P. Ferracin

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Outline

- US Magnet Development Program and 2025 updated road map
- Nb_3Sn magnets, HTS magnets, and hybrid magnets
- Modeling and Diagnostics
- New Areas
- Conclusions

US Magnet Development Program

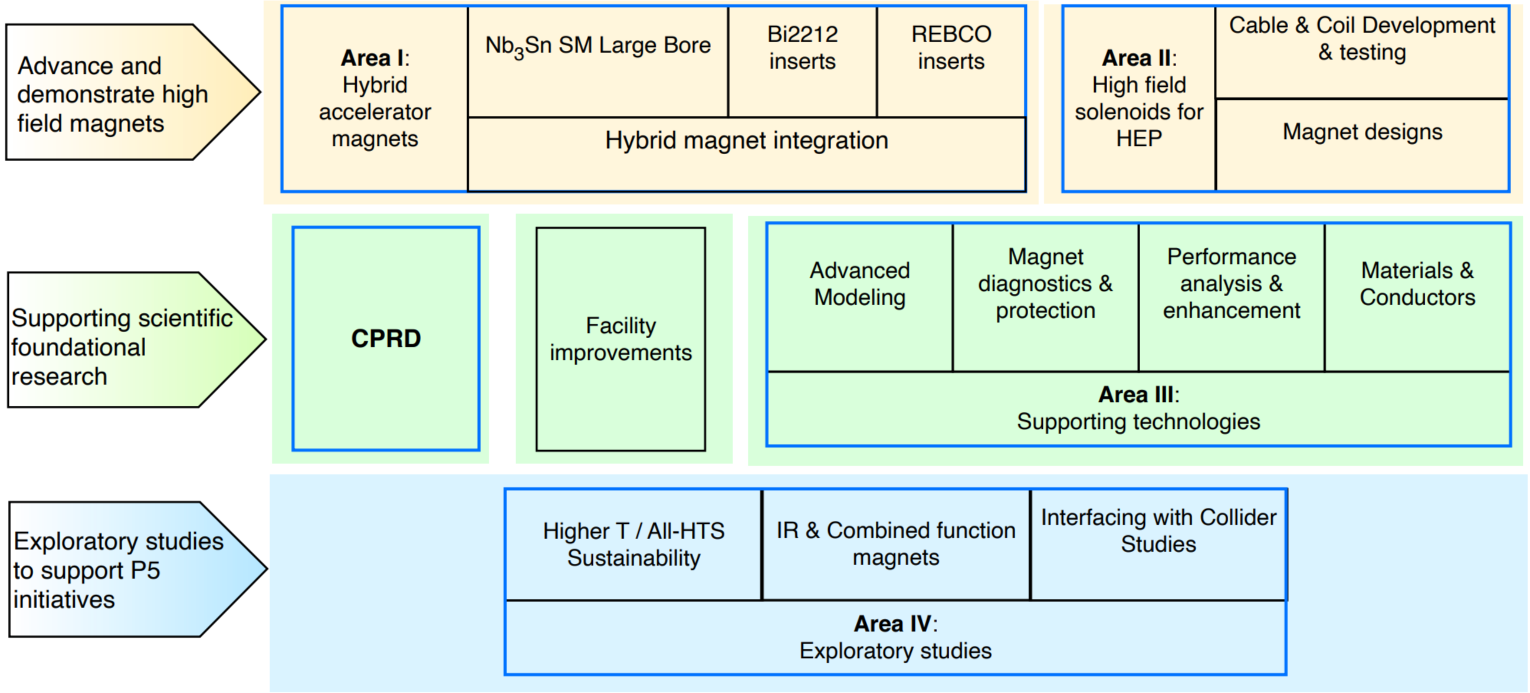
- US MDP is a collaboration among 4 US laboratories (BNL, FNAL, LBNL, NHMFL) established in 2016 as a result of the 2013 P5 report

- 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
  - Perform R&D on HTS accelerator magnets
  - Develop LTS/HTS hybrid magnets
  - Investigate fundamental aspects of magnet design and technology
  - Workforce development

US Magnet Development Program

- Road map updated in 2025, as a result of 2023 P5 report
  - Priority for 10 TeV pCM colliders like FCC-hh and Muon colliders
- Activities organized in four Areas (two new areas defined)



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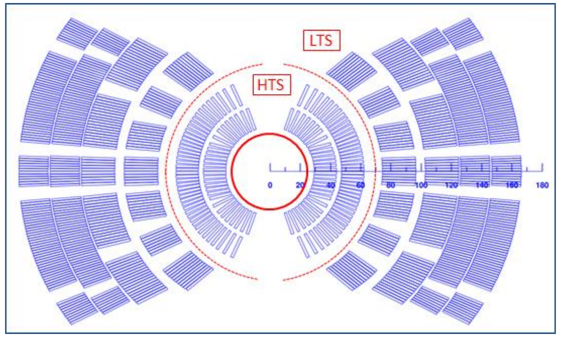
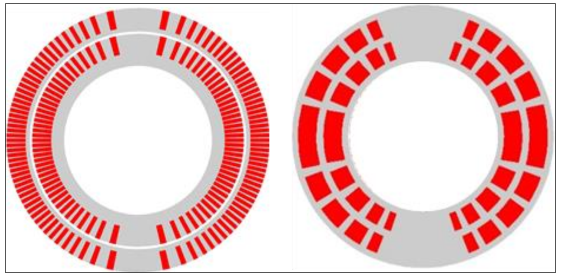
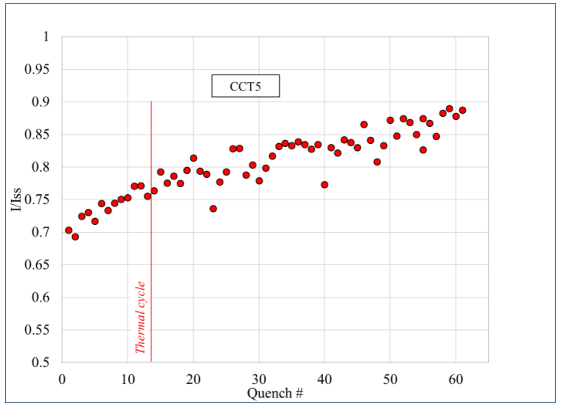
Nb_3Sn magnets R&D focus

1. Large aperture Nb_3Sn magnets (90-120 mm)
   – To test Nb_3Sn conductor in large bore and high field magnets → high stress → relevant to both FCC and MC
   – To test HTS in high background fields → hybrid LTS/HTS
2. Stress managed structures
   – Coil including structural elements
      • Radially: mandrels; Azimuthally: ribs
3. Training studies
   – New impregnation materials, modeling and diagnostics

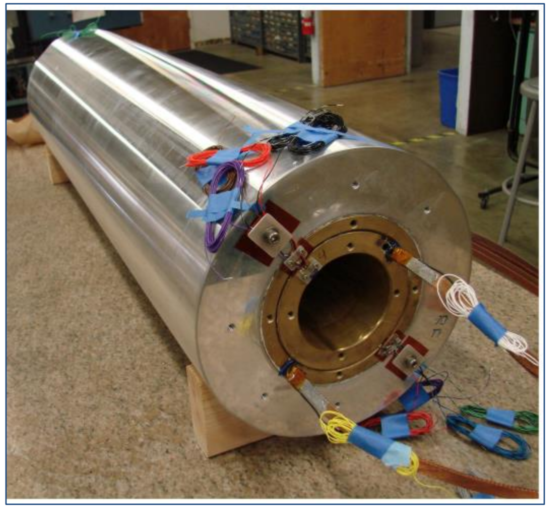


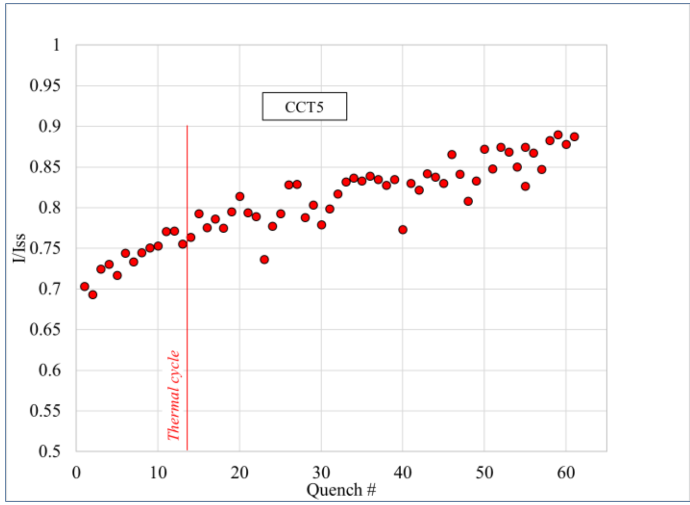




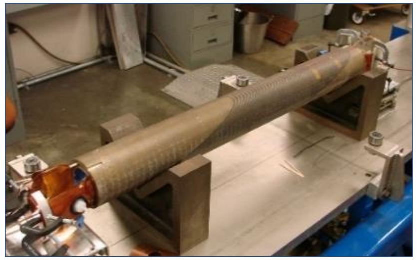
Nb_3Sn magnets
Canted-Cosθ (CCT) magnet development

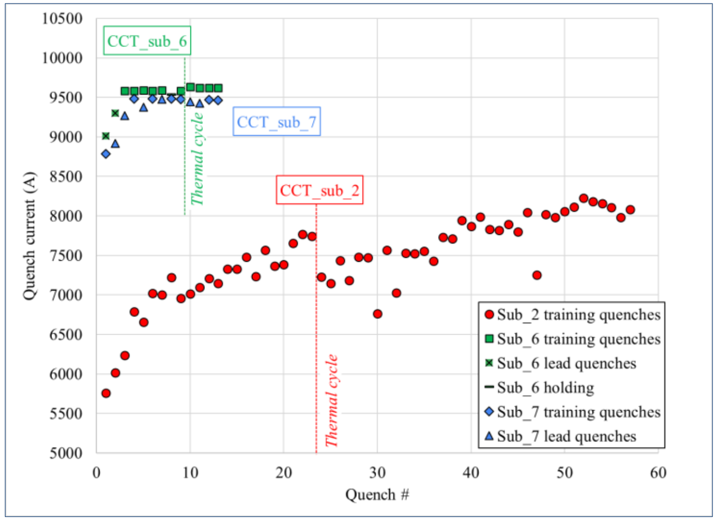
- CCT5 (tested in 2019)
  - 1 m coil length
  - B_{bore} max: 8.5 T, 90 mm bore
  - About 60 quenches to 90%
    - Good memory after TC





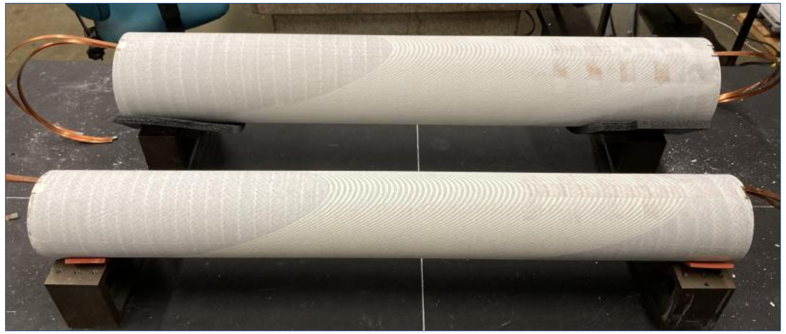
- Sub-scale CCT (6 tests in 2019-2025)
  - 5.5 T in 50 mm aperture, 0.7 mm length
  - Similar training as CCT5 with epoxy
  - No/minimal training with wax or filled wax
  - Next: Telene (tested on undulator) subscale being fabricated at FNAL

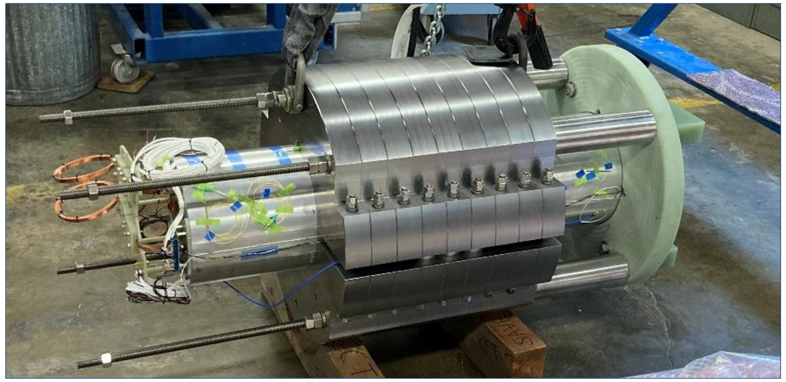




Nb_3Sn magnets
Canted-Cosθ (CCT) magnet development

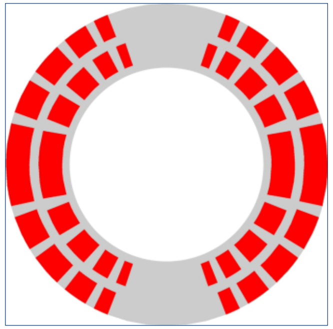
- Next steps
  - CCT5 with filled wax (CCT5w)
    - Goal: ~10-11 T in 90 mm aperture with minimum/no training
      - Exploring filled wax in higher field and stresses
    - Magnet built a shipped to FNAL for test in June 2025
  - CCT6
    - Goal :12-14 T in 120 mm aperture
    - Status: L1 mandrel under fabrication after several few turns tests
      - 1.5 m long mandrel, ~2-3 month machining process



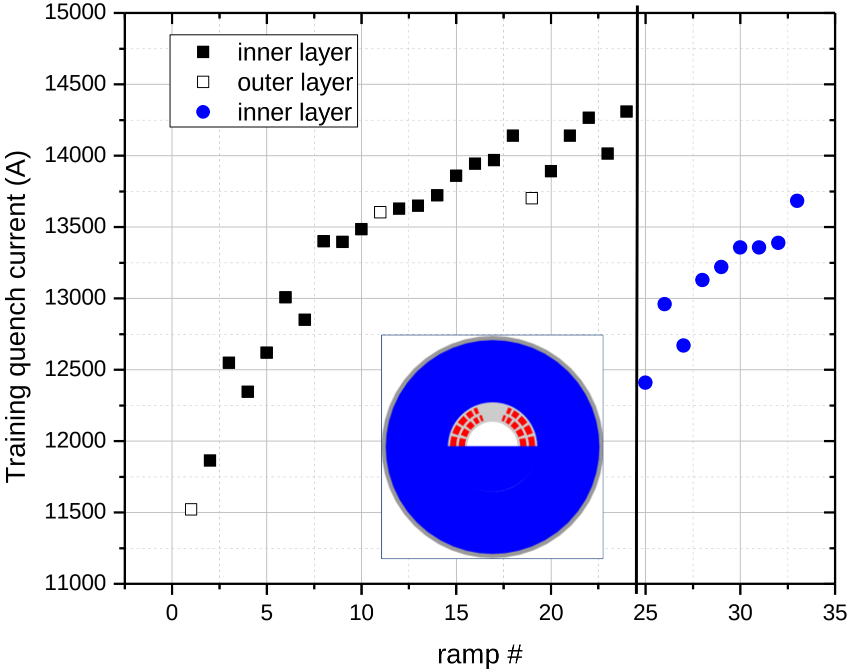


Nb_3Sn magnets
Stress-Management-Cosθ (SMCT) magnet development

- One coil fabricated and tested in mirror configuration



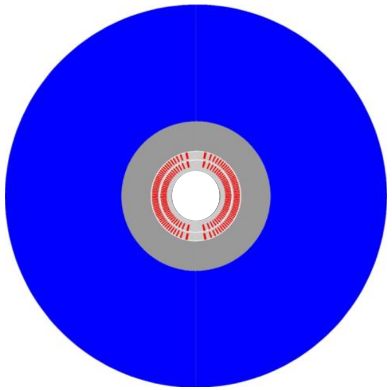
- SMCTM1a (tested in 2024)
  - 12.7 T in 120 mm bore (half)
  - 87 % I_{ss} reached in 24 quenches
  - Poor memory/no degradation after TC



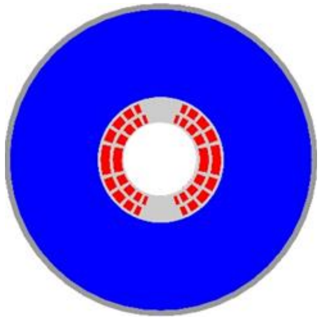
- Second coil under fabrication

Nb_3Sn magnets
In summary, coming up

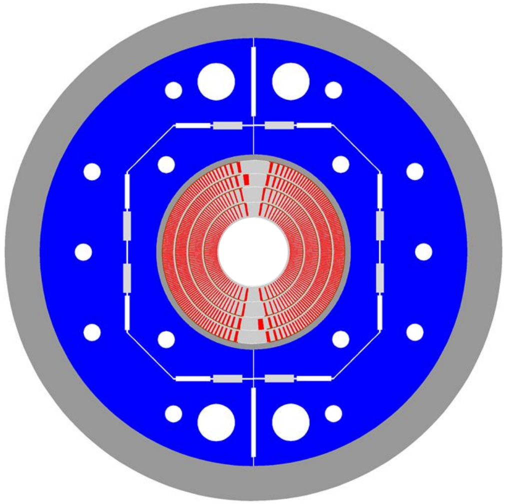
CCT5w
90 mm, ~10 T (target)
Fabrication completed
Test in 06/2025



SMCT
120 mm, ~11 T (target)
Fabrication on going
Target 2026-2027



CCT6
120 mm, ~12-14 T (target)
Fabrication on going Target
2026-2027



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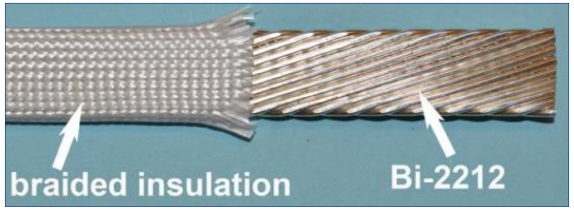
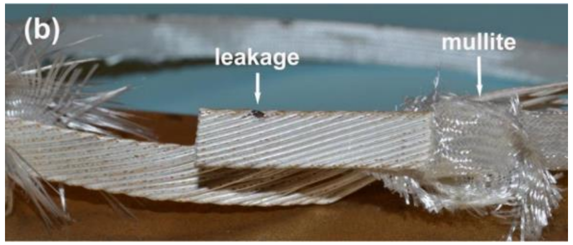
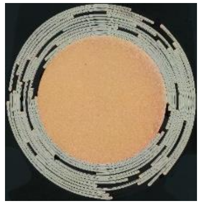
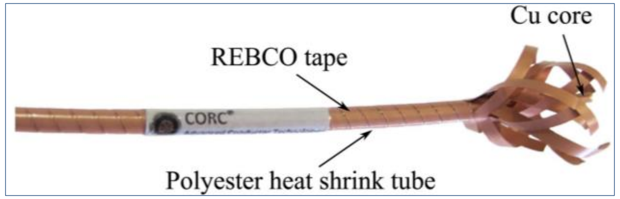
HTS magnets
Conductor and cables

- Bi2212
  - Rutherford cable, heat treatment 50 bar in O_2 at 885-900 °C
  - Challenges: leaks/degradation and furnace
- REBCO
  - 3 options considered
    - Conductor on Round Core CORC® (***ACT LLC***)
      - 24-30 tapes, total diameter: 3.7 mm
    - Symmetric Tape Round STAR® (***AMPeers***) wire
      - 8-12 tapes, 1.7-2.5 mm total diameter
    - 6-around-1 STAR® cable (work in progress)
  - Challenges: degradation during coil fabrication

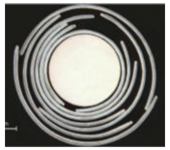








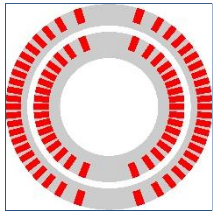
Advanced Conductor Technologies LLC
www.advancedconductor.com

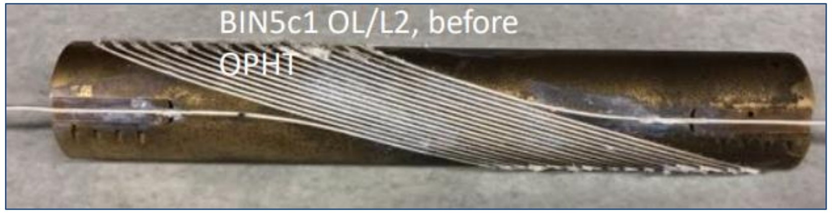


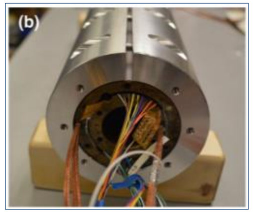
Bi2212 magnets
Development of racetracks, CCT and SMCT magnets

- RC7n8 (2019)
  - 4.7 T reached in with racetrack coils configurations
    - Highest field so far in “no bore” design

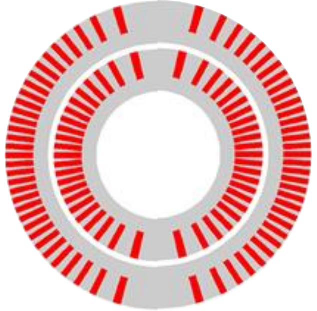
- Bin5 (2021)
  - 1.6 T in 31 mm aperture
  - Ready for first hybrid test

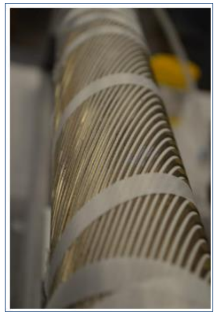


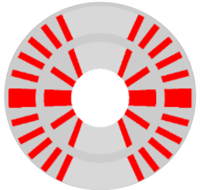




- Next steps
  - Bi-CCT1-1
    - Target: 3-5 T in 40 mm aperture
  - Bi-SMCT-1
    - Target: 1-2 T in 15 mm aperture

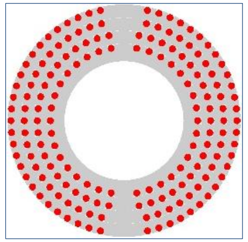
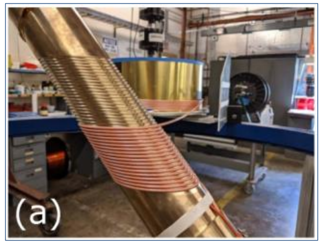


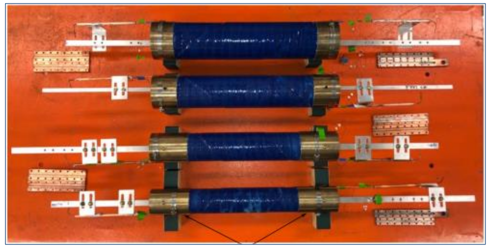
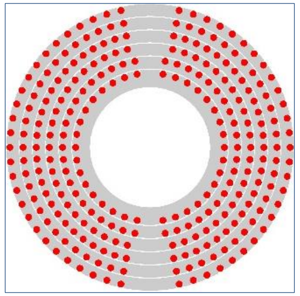


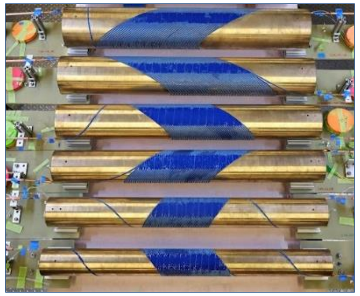
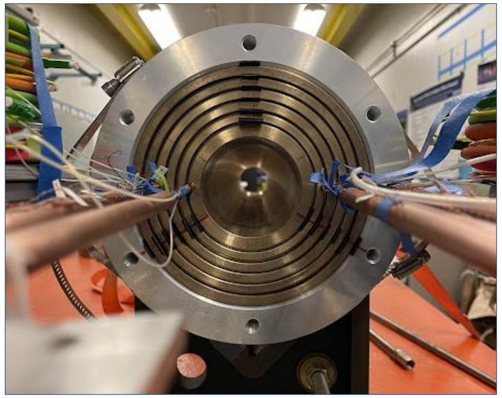


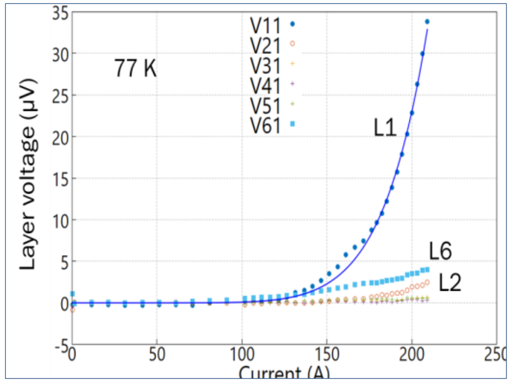
REBCO magnets
Development of CCT magnets

- C2 (2020)
  - 2.9 T in 65 mm aperture
- C3 (2025)
  - 5.2 T in 65 mm aperture
    - Highest field so far with apert.
  - We stopped at 40 μV (no quench onset)
  - Next test: field quality, and ramp to higher current

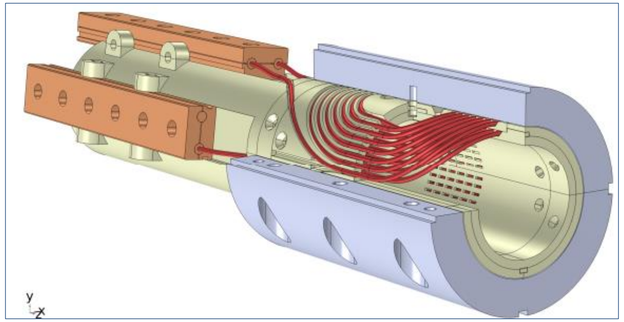



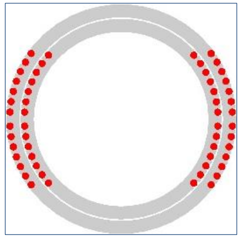



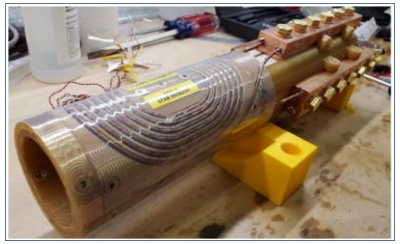


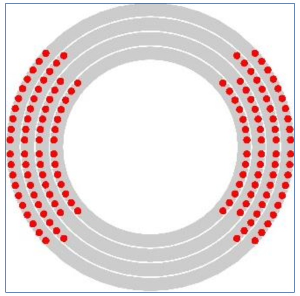
REBCO magnets
Development of COMB magnets (FNAL)

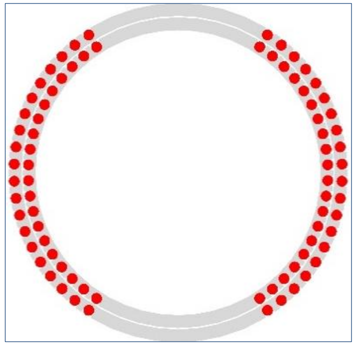
- The COMB (Conductor on Molded Barrel)
  - SMCT with single conductor in groove
  - Double-layer coils with layer jump
- COMB-STAR-1 (2024)
  - 1.5 T field in 60 mm bore
- Next step
  - Fabrication of COMB-STAR-2 and COMB-CORC-1
    - Targeting 5 T in 60 mm bore

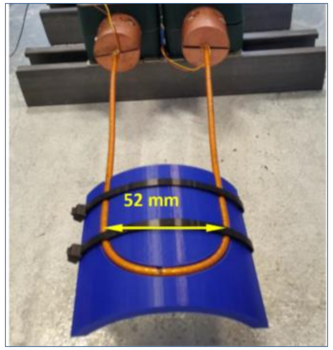












HTS magnets
In summary, coming up

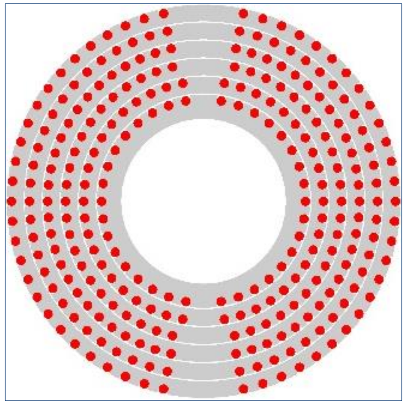
REBCO C3
65 mm, 5.2 T
Re-test in 2025

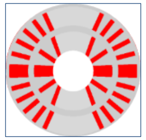
Bi-SMCT-1
15 mm, 1-2 T (target)
Fabrication on going
Test 2025

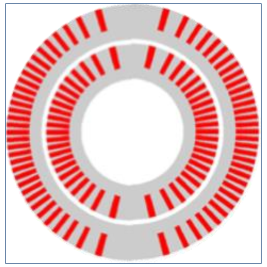
Bi-CCT-1
40 mm, 3-5 T (target)
Fabrication on going
Test 2025-2026

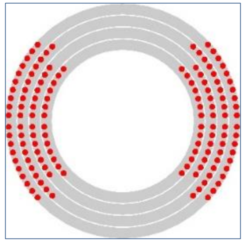
COMB-STAR-2
60 mm, ~5 T (target)
Fabrication on going
Target 2026-2027

Nb_3Sn magnets









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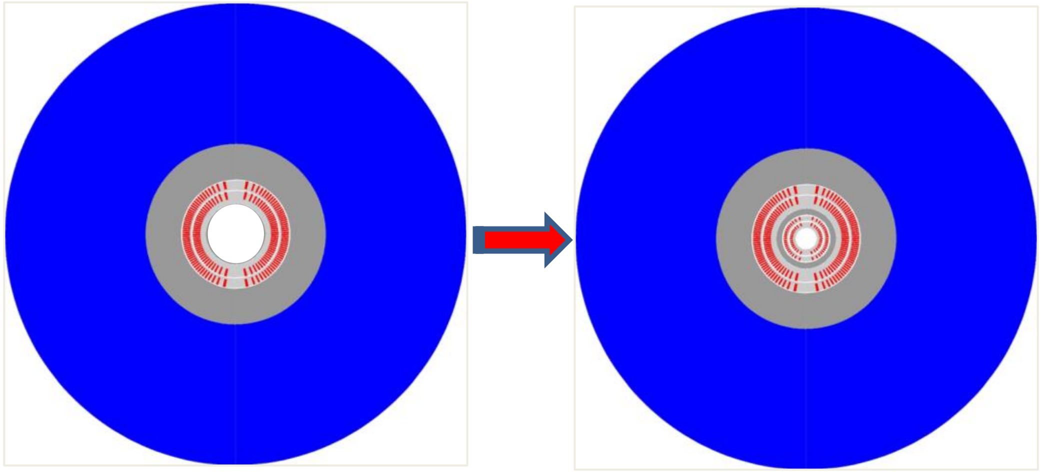
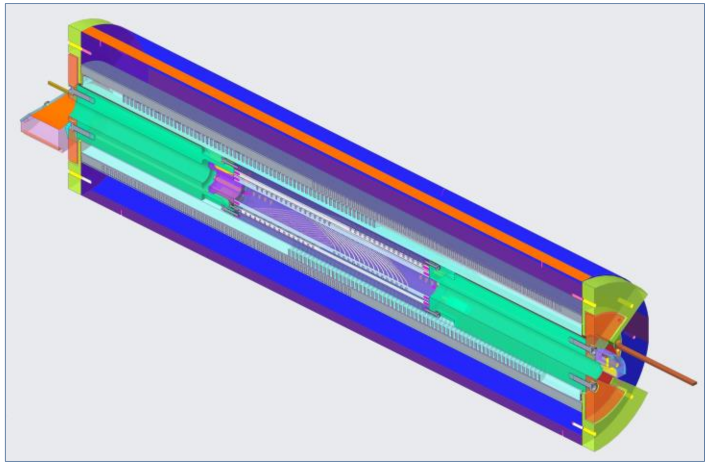
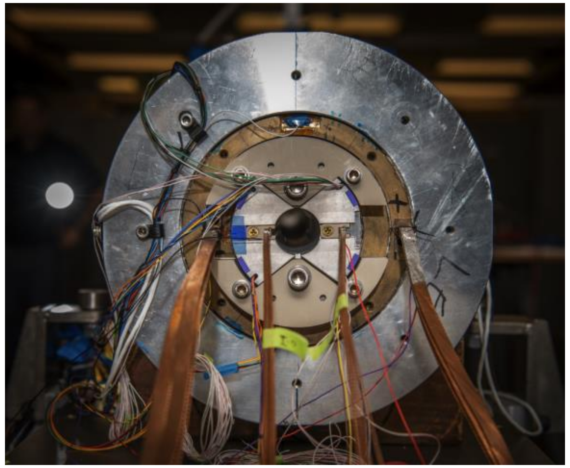
Towards high field LTS/HTS hybrid magnets

- Combining LTS and HTS magnets is a very effective way to reach high field
- Hybrid magnets have became a key goal for the US MDP
- Work ongoing to combine CCT5 with Bin5 in hybrid configuration: HM1
- Test expected by June 2025: first hybrid magnet at 10 T field level
  - Again, still relatively “low field”, but first milestone towards higher field







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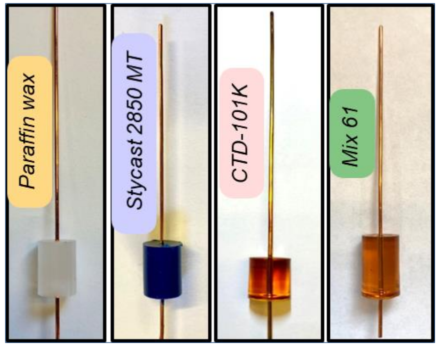
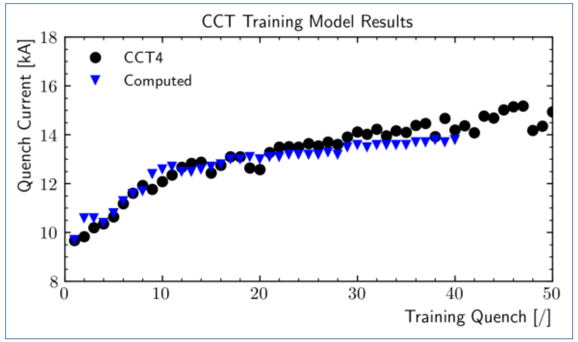
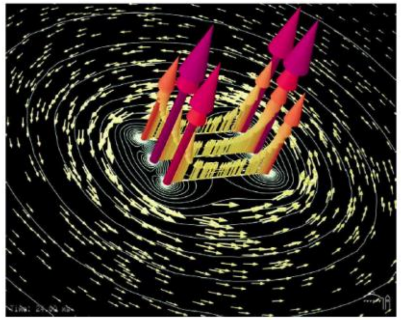
Modeling and diagnostics

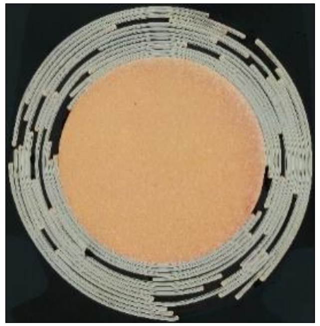
- **Training** studies with
  - Debonding strength measurements
  - Finite element models



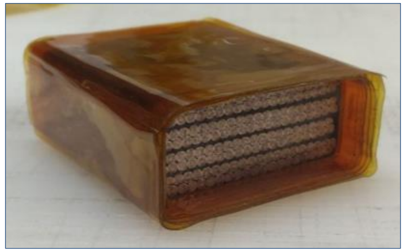


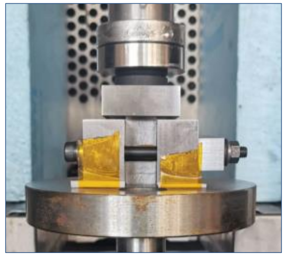
- **Modelling (BELFEM)** of current sharing during/after a quench in REBCO cables

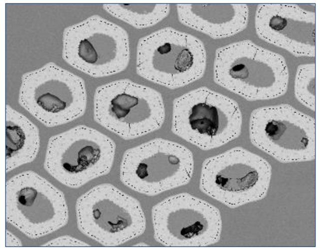


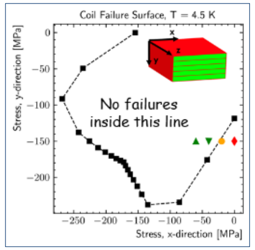


- Measure and compute **failure criteria** in Nb_3Sn
  - How do we pre-load magnets to minimize conductor degradation?



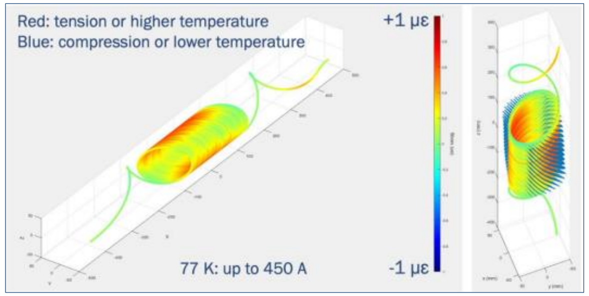


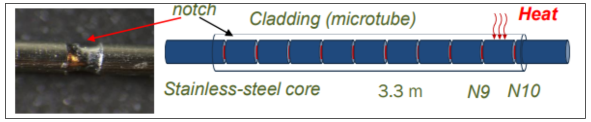


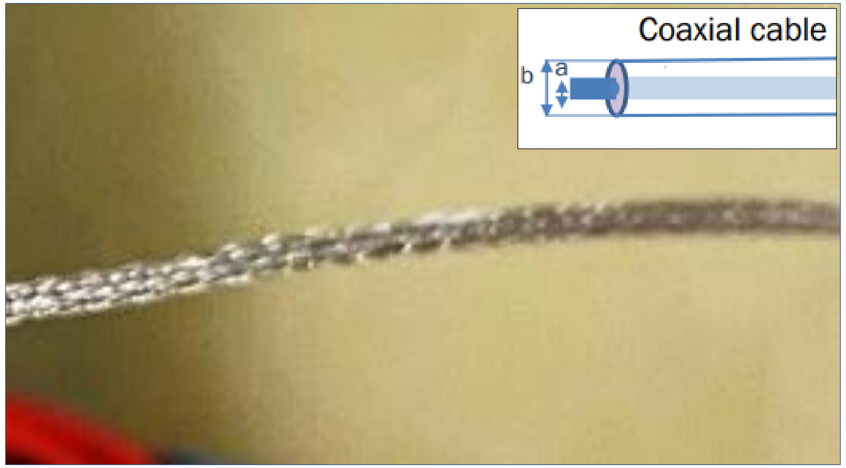


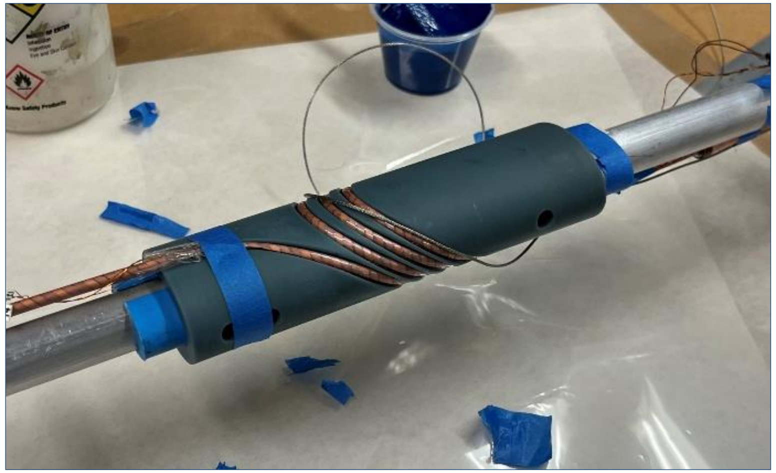
Modeling and diagnostics

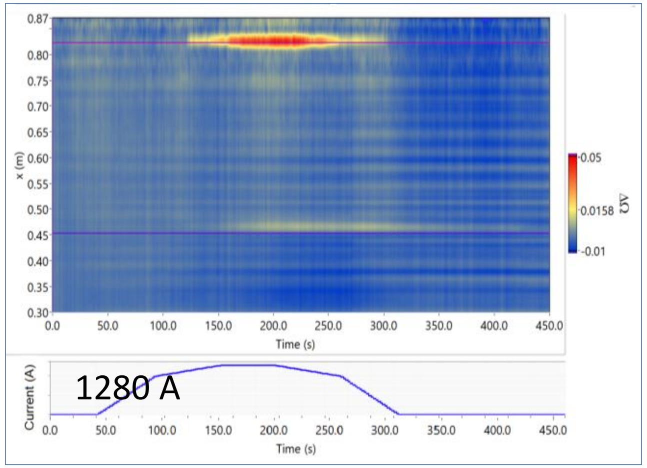
- Advanced diagnostics are developed to detect *T* rise in HTS
  - Optical fibers
    - Most developed technologically, but sense both *T* and strain
  - Ultrasonic waveguides for hot spot localization
    - Very robust (all metal), but fairly large diameter (~1 mm) signal attenuation at long lengths (>10 m)
  - RF time-domain reflectometry sensors
    - Combine best features of fiber-optic and ultrasonic sensing.









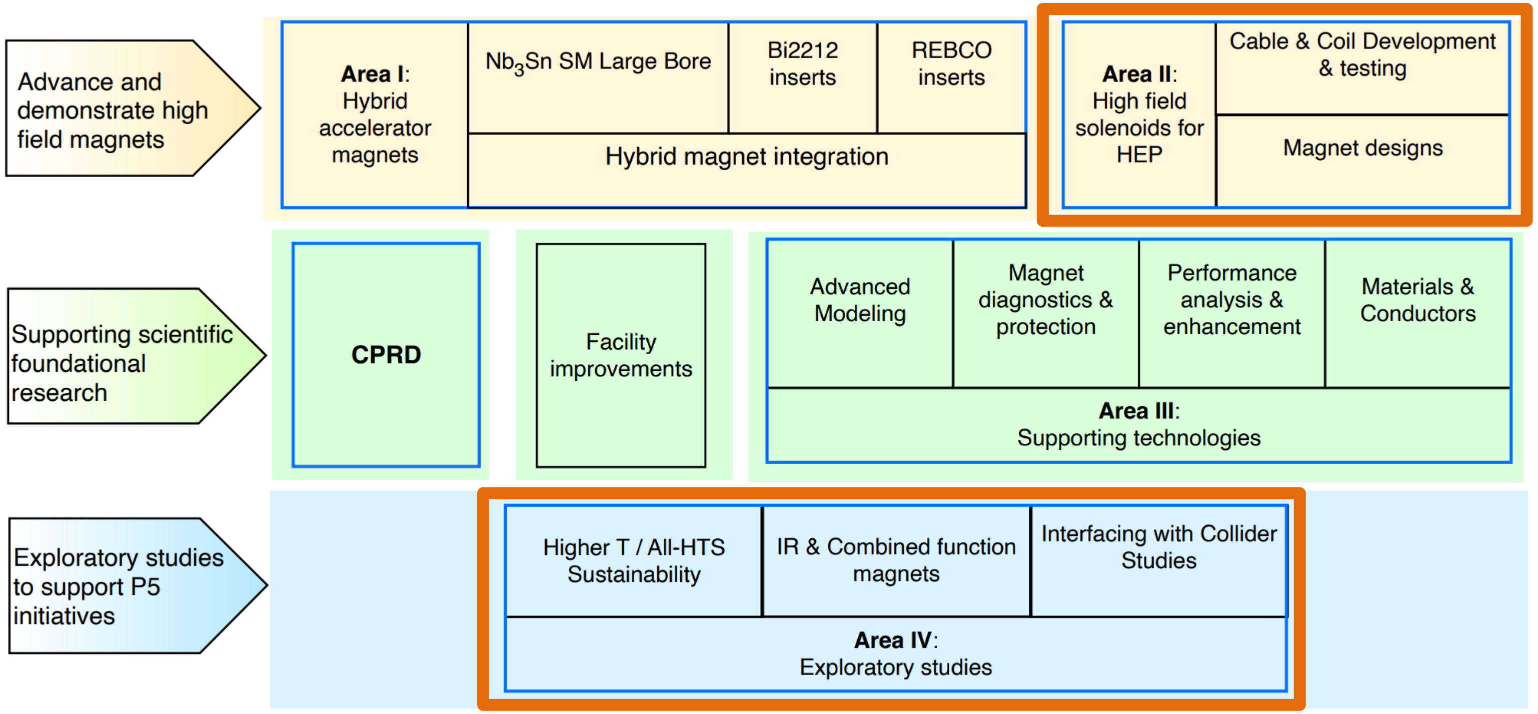


Outline

- US Magnet Development Program and 2025 updated road map
- Nb_3Sn magnets, HTS magnets, and hybrid magnets
- Modeling and Diagnostics
- New Areas
- Conclusions

Two new areas in new roadmap

- Area II: Solenoids for Muon Colliders
- Area IV: Exploratory studies on all HTS at 20 K, IR, combined functions



Outline

- US Magnet Development Program and 2025 updated road map
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Conclusions

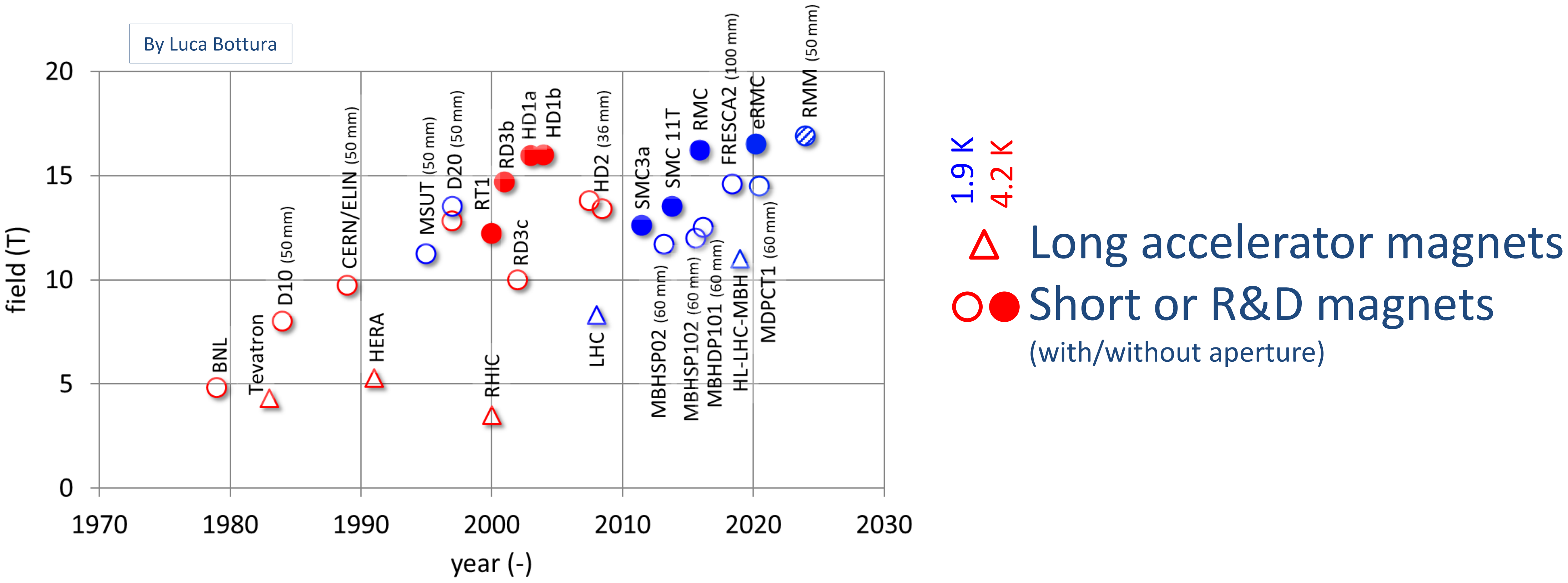
- The US MDP program carries out basic R&D to address P5 call for next generation of colliders

- Research focus and achievements
  - Nb_3Sn magnet limits and performance
    - Stress management coils, training-free subscale → CCT5w, SMCTM1a mirror test, development on going of 120 mm high field magnets
  - HTS inserts in the 1-3 T field range with Bin5, C2, COMB-STAR-1 and 5.2 T with C3
  - Assembly and testing of hybrid magnets: effective tool to perform R&D on both LTS and HTS
    - First hybrid HM1 to be tested in June 2025
  - New modelling of training and Nb_3Sn degradation, and new diagnostics (ultrasonic sensors, RF) for detecting quenches in HTS

- More details at the MDP Collaboration meeting next week in Berkeley, CA.

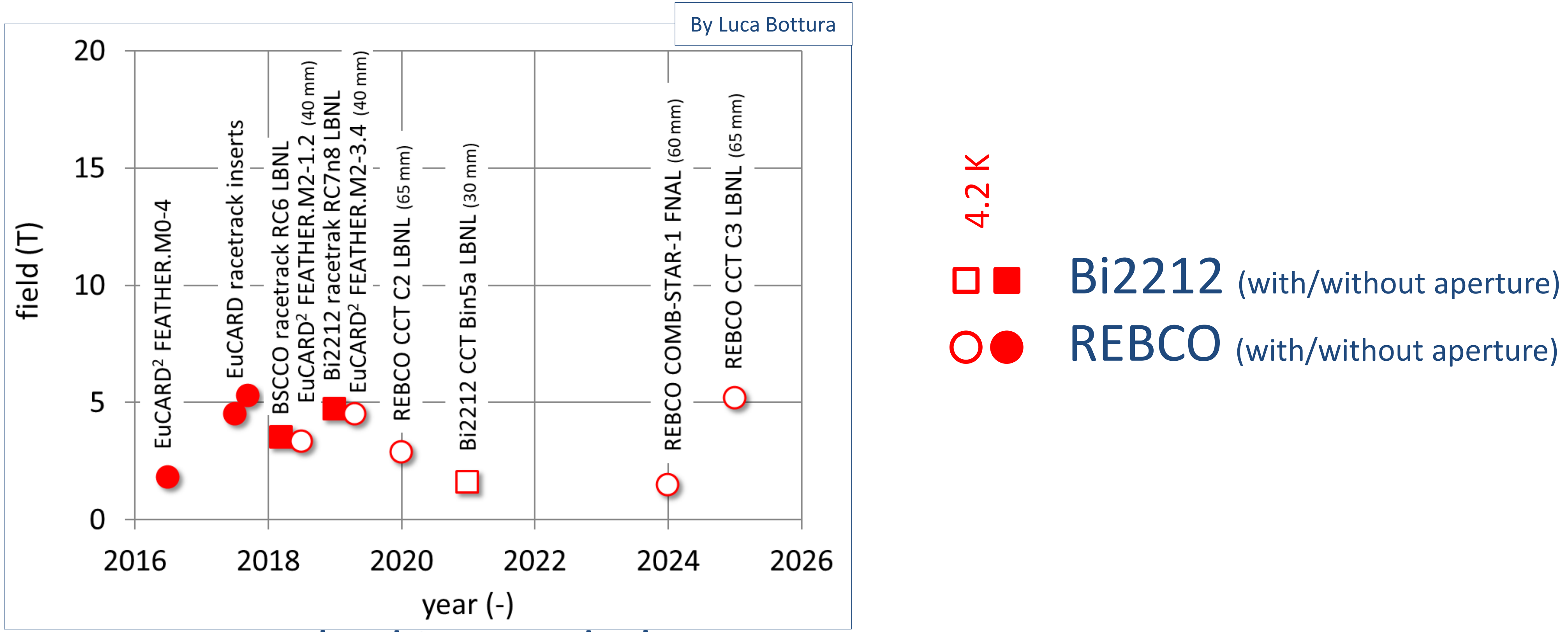
Appendix

Status of magnets with low temperature superconductors



- Nb_3Sn accelerator magnets up to 11-12 T
- 14-16 T reached on short R&D magnets

Status of magnets with high temperature superconductors

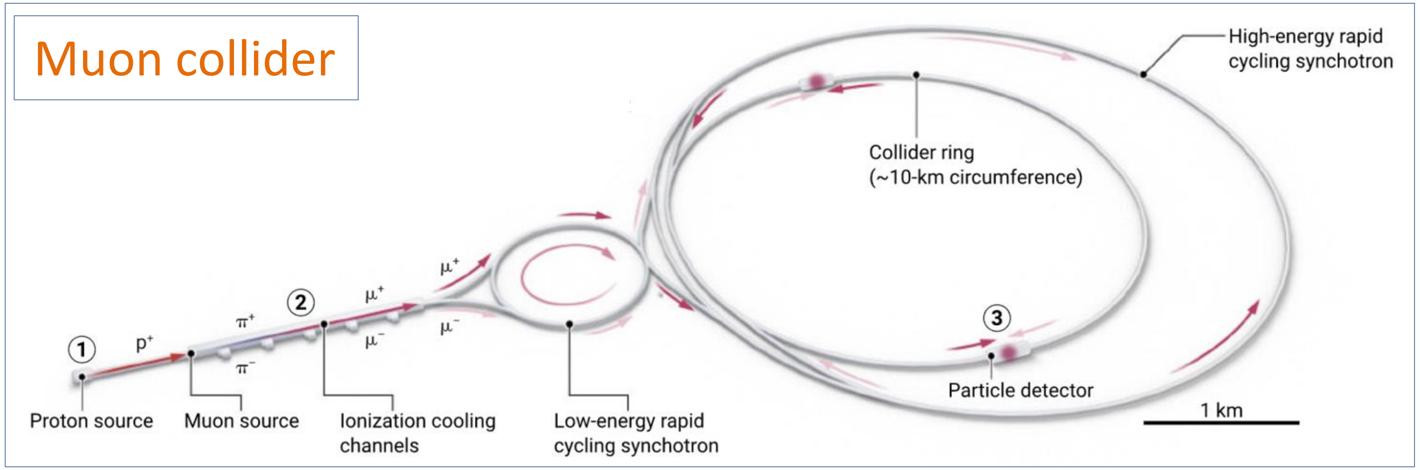


- 5 T with aperture reached in stand-alone test
- Relatively low, however potentially 2-3 T in high background field

  → possibility to push beyond the Nb_3Sn limits in hybrid configuration

Future colliders

- From 2013 and 2023 P5 report, call to maximize field and minimize cost
  - Priority for 10 TeV pCM colliders like

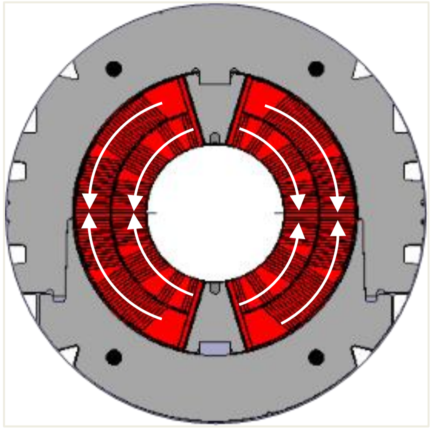


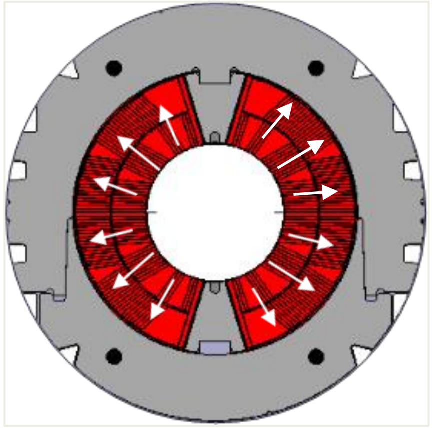
- 90.7 km tunnel, Energy c.o.m. 85-120 TeV
- Dipoles from 14 T (Nb_3Sn) to 20 T (all HTS or hybrid)
- Temperature from 1.9 K to 20 K
- Ramped magnets

- Cooling solenoids with up to 20-40 T and large apertures (HTS)
- Collider dipoles with 5-14 T (Nb-Ti, Nb_3Sn and HTS)
- HTS IR quadrupoles
- Temperature from 4.5 K to 20 K
- Steady state

Nb_3Sn magnets R&D focus
2) Stress management designs

- In a traditional dipole designs, e.m. forces accumulate on mid-plane and radially
  - In the 15-20 T range, stress of the order of 150-200 MPa
- Nb_3Sn is brittle and strain sensitive
  → Performance degradation with about ≥ 150 MPa





- MDP has being focusing on the development of stress managed structures
  - The coil includes structural elements
    - Radially: mandrels
    - Azimuthally: ribs
  - Interception of e.m. forces
    → Risk reduction of conductor degradation