APS-TD Magnet Research and Development

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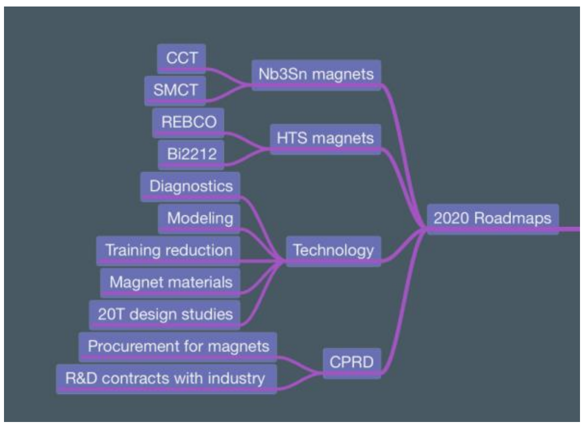
11 July 2024

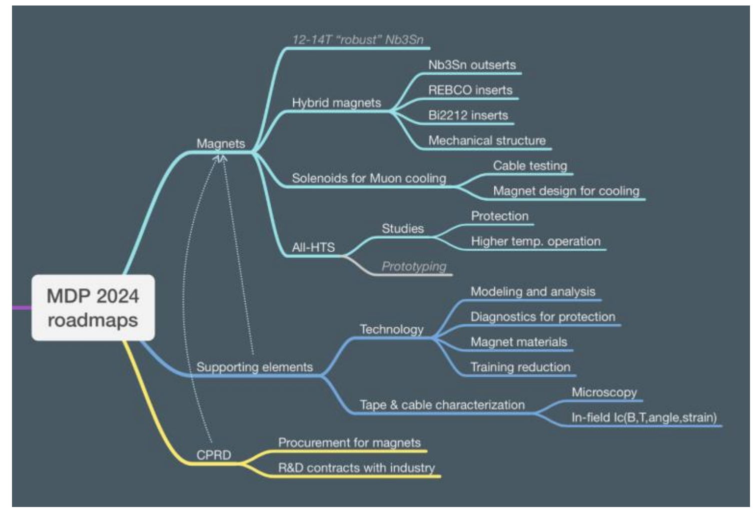
Magnet R&D at APS-TD

- Superconducting magnets
  - Based on low and high temperature superconductors (LTS and HTS)
  - Conductor dominated (high-field) for proton and muon machines
  - Iron-dominated (low field) for electron machines
- Material studies
  - Artificial Pinning Centers in Nb_3Sn to increase critical current
  - High-Cp materials to increase the stability and reduce training
  - Coil impregnation with advanced resins and potentially thermo-plastics
- Innovative diagnostics
  - Fiber-optics for quench detection
  - Acoustic sensors and quench antennae for quench characterization
- Synergetic activities
  - Undulators (collaboration with ANL)
  - EIC support (collaboration with BNL)
  - Fusion support (collaboration with PPPL)
- Funding sources: GARD, SBIR, LDRD, US-Japan collaboration, early-career grants…

US Magnet Development program

- The US Magnet Development program has been the driving force behind the superconducting magnet R&D in the US
- Fermilab is an active MDP player along with LBNL, BNL and NHMFL
- The program is in the process of re-alignment with P5 recommendations…

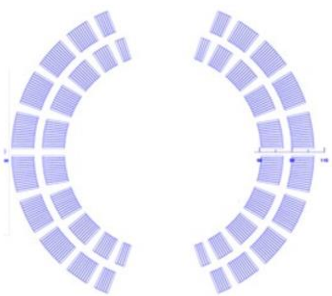




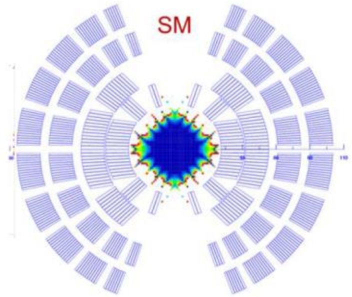
May	June	July	August	September	October	November

Data gathering: ***P5***: - opportunities & priorties ***Structure***: - what works well what can be improved	**Detailing structure** - identify Areas & priorities - identify milestones - timelines, resource needs	**Finalizing document & internal discussions**	**Review with HEP**	**Publish updated MDP Roadmap**

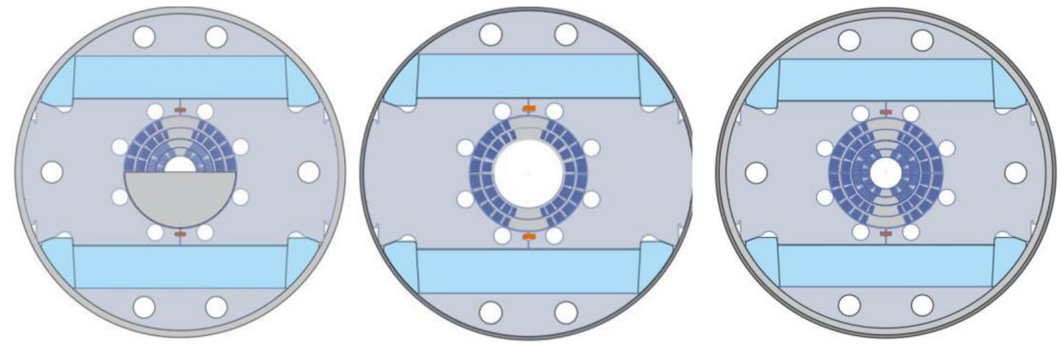
Stress-Managed Cos-Θ (SMCT) magnet development



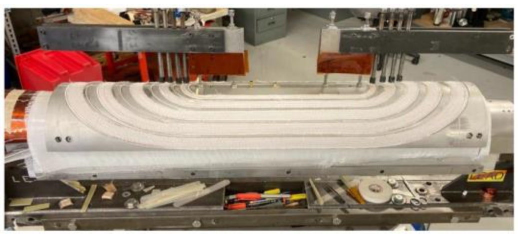
ID=120 mm, B_{des}~11 T



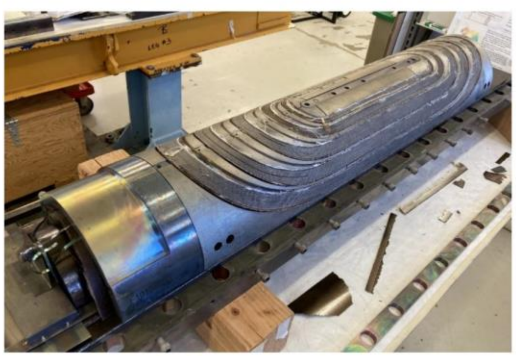
ID=60 mm, B_{des}~17 T



Cos-theta dipole coils with stress management



Coil after winding



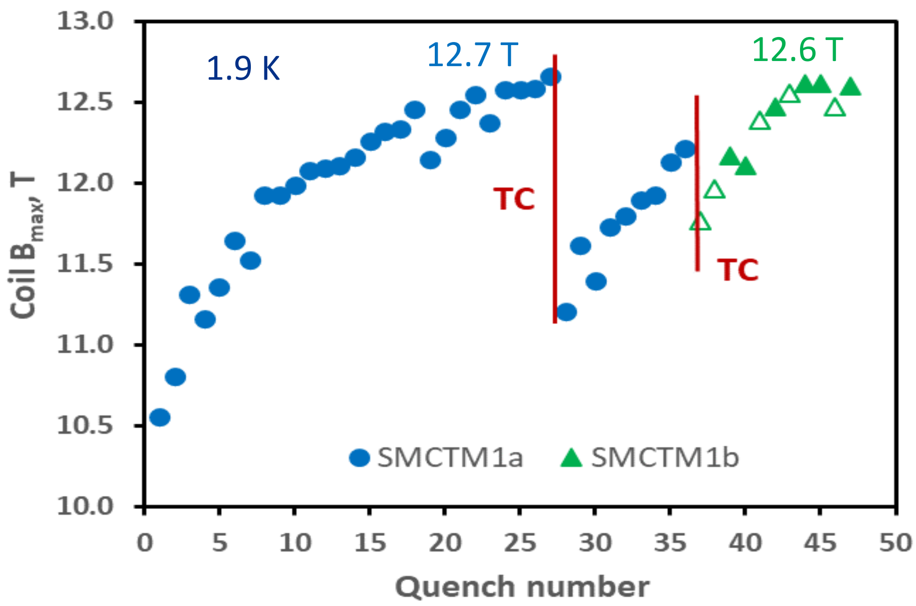
Coil after reaction

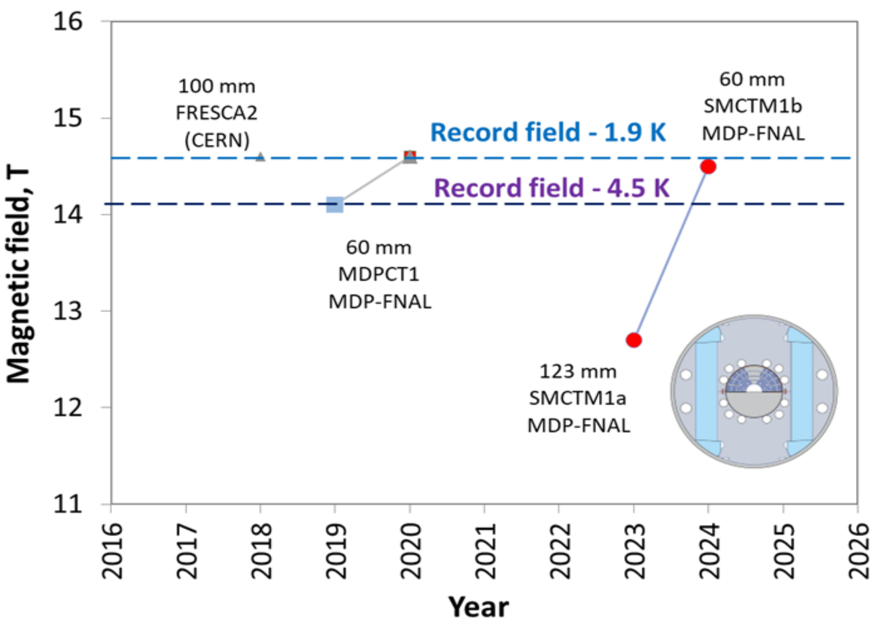
Coil after impregnation with epoxy

- The 123-mm stress-managed Nb_3Sn cos-theta (SMCT) coil is a new concept being developed at Fermilab for high field and/or large aperture accelerator magnets based on LTS and HTS
- The SMCT structure is used to reduce large coil deformations under Lorentz forces and, thus, the excessively large strains and stresses in the coil

Nb_3Sn SMCTM1a/b test summary

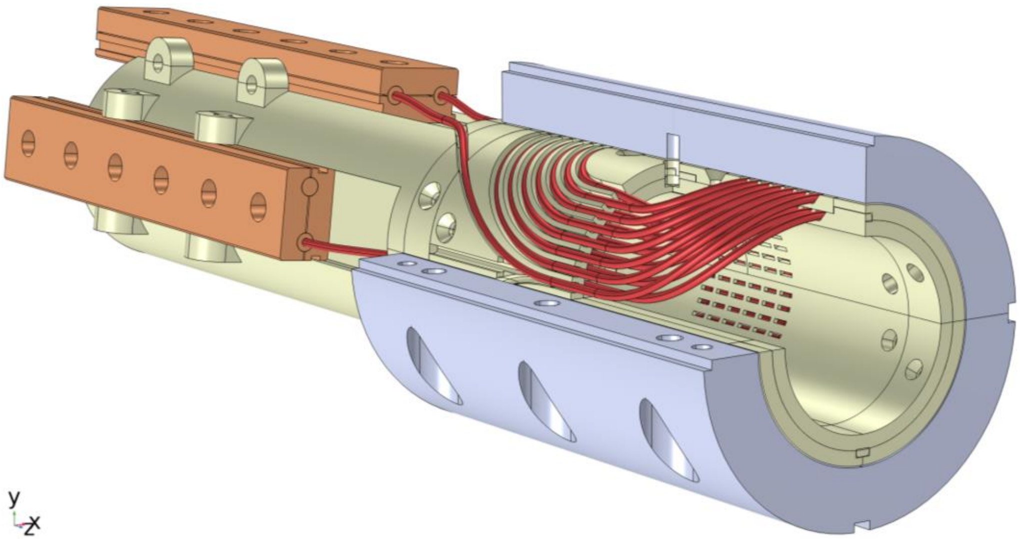
- The 1st SMCT coil has been designed, fabricated and tested at Fermilab in 2022-2024
  - the record field of ~12.7 T was achieved in 123-mm aperture dipole coil made of brittle Nb_3Sn cable in both 2L and 4L configurations

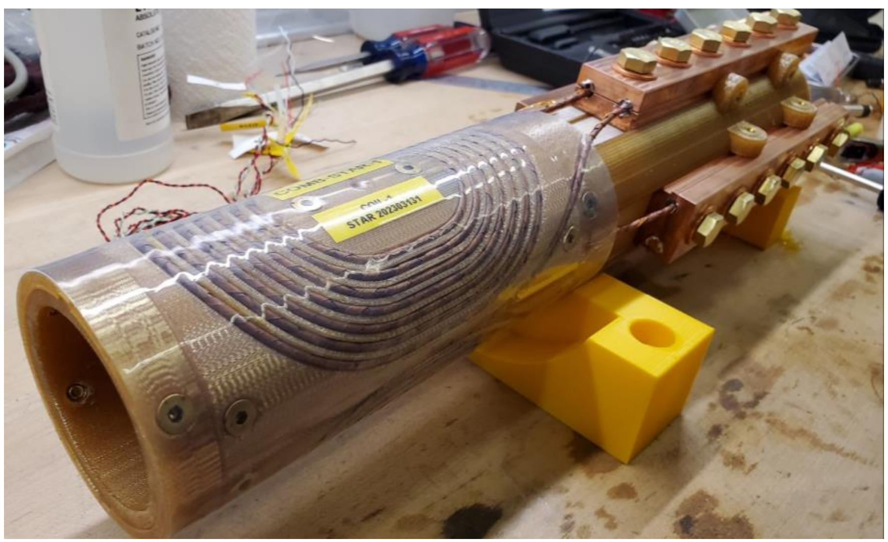




- The 123-mm SMCT coil was built upon the experience with construction of the 60-mm dipole, which achieved 14.6 T in 2020
- Fabrication of the 2nd SMCT coil and its test independently and in two-coil configuration with the 1st SMCT coil and MDPST1 inner coils are planned to further study the potential of the SMCT technology

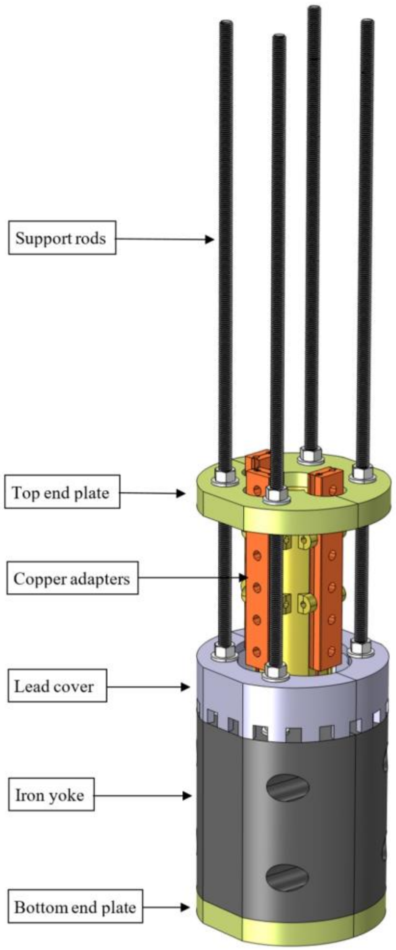
HTS COMB-STAR-1 dipole magnet design

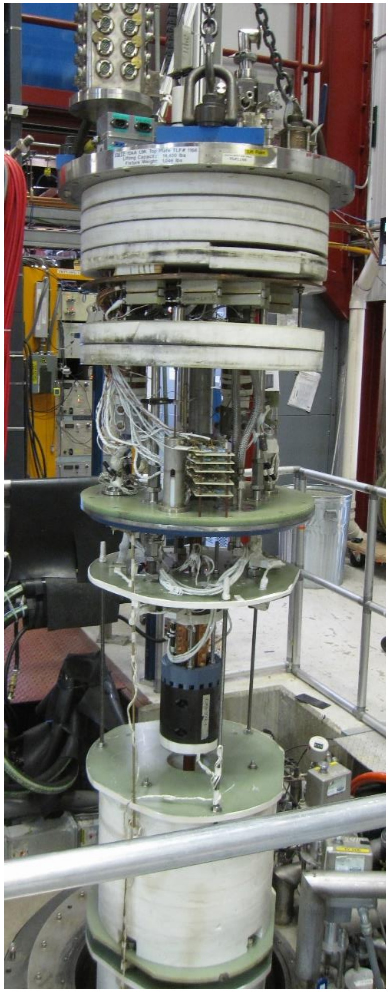


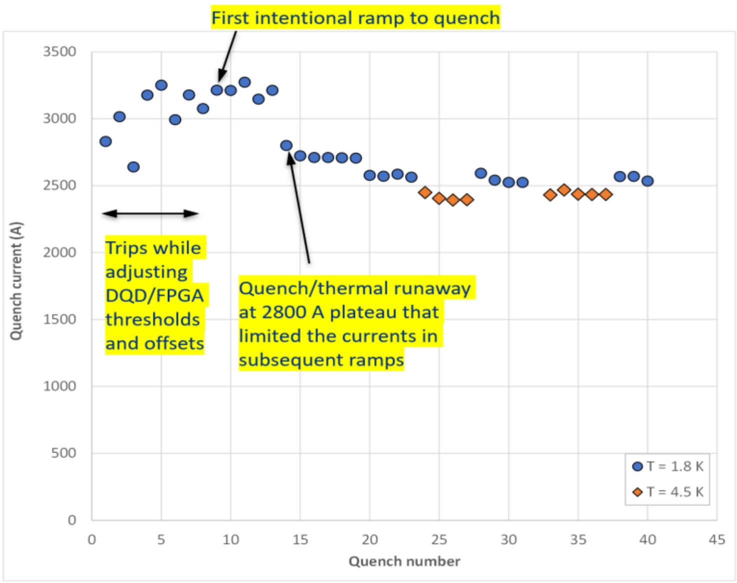


- Based on Conductor on Molded Barrel (COMB) technology proposed at Fermilab in 2019
- 60 mm clear bore
- Two half-coils made with two layers of round REBCO STAR® wire
- The cable is wound into a continuous channel without internal splices
- Coil support structures 3D printed from ULTEM
- The leads are terminated at 3 copper adapters that allows to test each coil individually
- Redundant voltage taps co-wound with the conductor into the support structure to minimize the noise

COMB-STAR-1 magnet testing

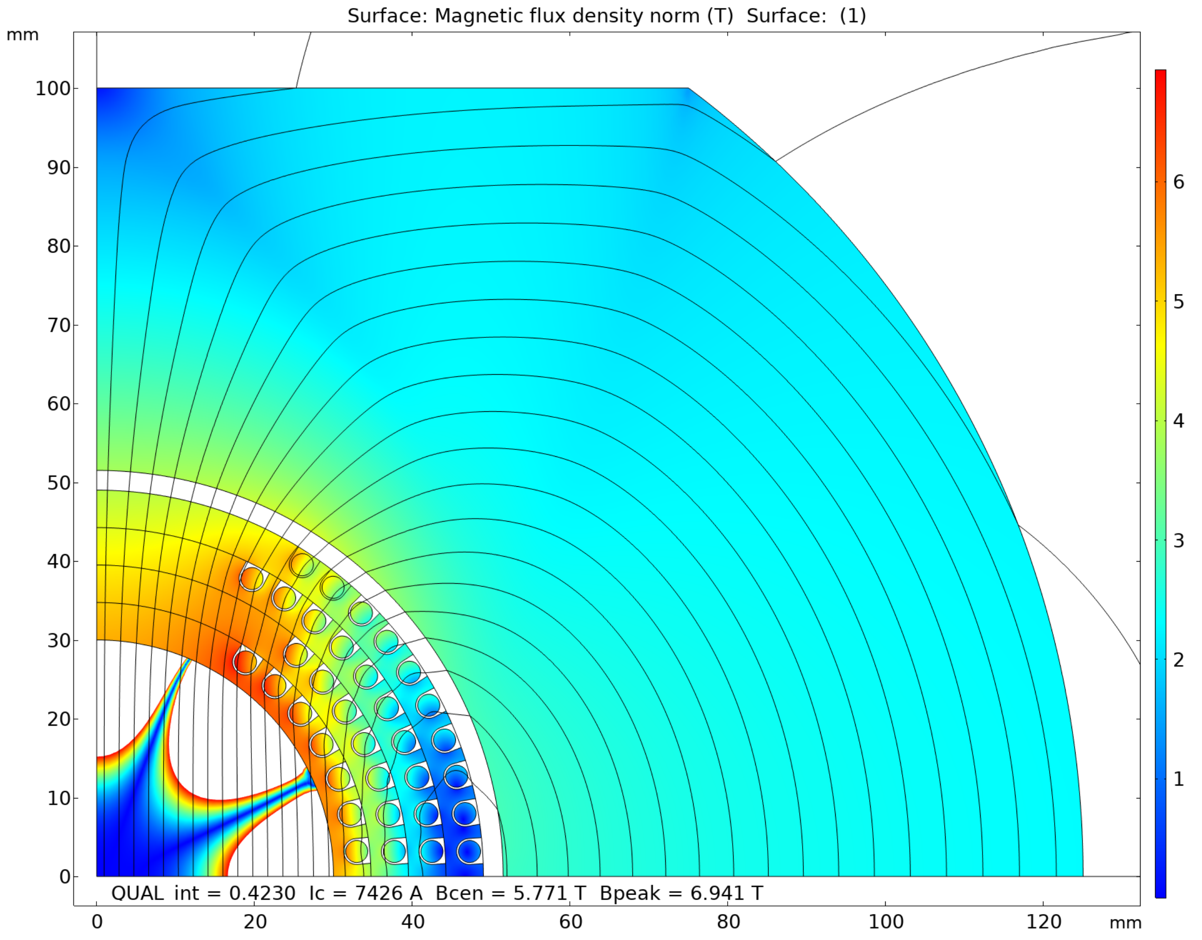






- Fabricated and tested in liquid nitrogen in 2023 and in liquid helium in 2024
  - The critical current retentions for the coils in LN_2 were in 93-99% range, which exceeded the goal
  - Achieved 1.5 T bore field @ 3.3 kA in LHe
- It was the first experimental demonstration of a multi-layer COMB magnet fabricated with REBCO cable
  - Next magnets will target 5 T bore field

Next COMB-STAR magnet (2025)



- The coil will consist of at least four layers (with six layers also being considered) of STAR wire with each turn placed into a channel in a dedicated COMB structure
- Based on the virgin STAR tape performance in liquid helium measured previously, the magnet should reach ~5.8 T bore field and 6.9 T peak coil field at 7.4 kA current in the 4-layer version
- These numbers will be confirmed by the cable testing in a background field at the liquid helium temperature

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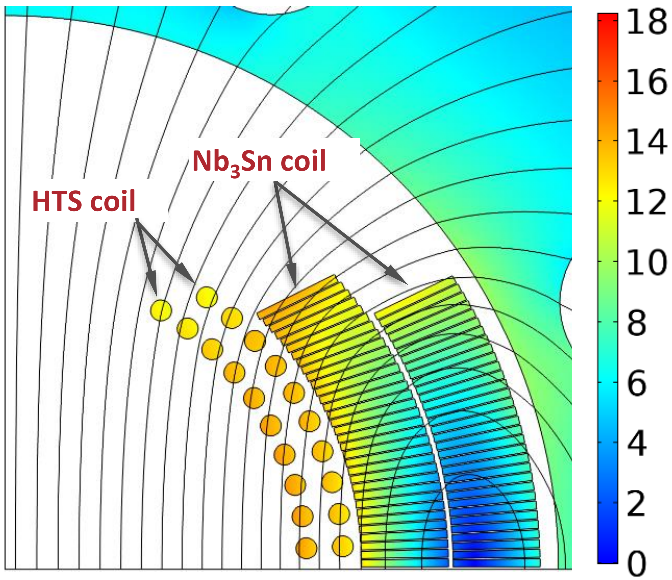
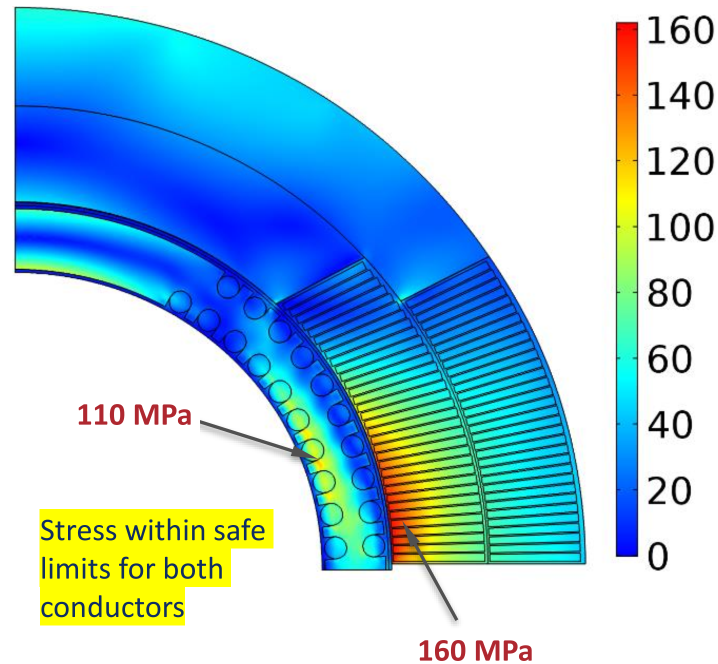
Hybrid HTS/LTS magnet test (2025-2026)

Magnetic field (T)



Equivalent stress (MPa)

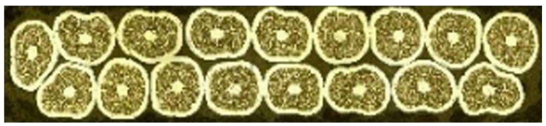


- REBCO insert in a Nb_3Sn magnet
  - ~100 mm clear bore
  - 2 layers of a larger CORC cable
  - Existing Nb_3Sn coil from a previous project
- The goal is to demonstrate a reliable hybrid HTS/LTS operation
- Will need substantial test facility upgrades

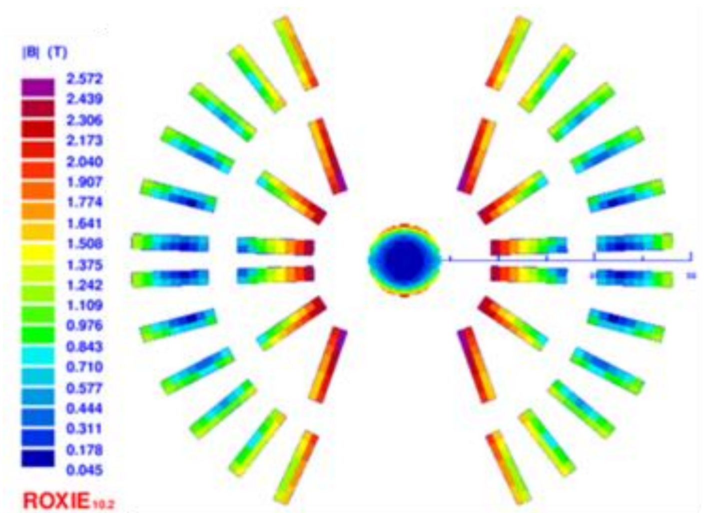
HTS coil concept with Bi-2212 Rutherford cable

The HTS coil technology based on a Bi-2212 cable and SMCT coil design is being developed at Fermilab in collaboration with LBNL/NHMFL

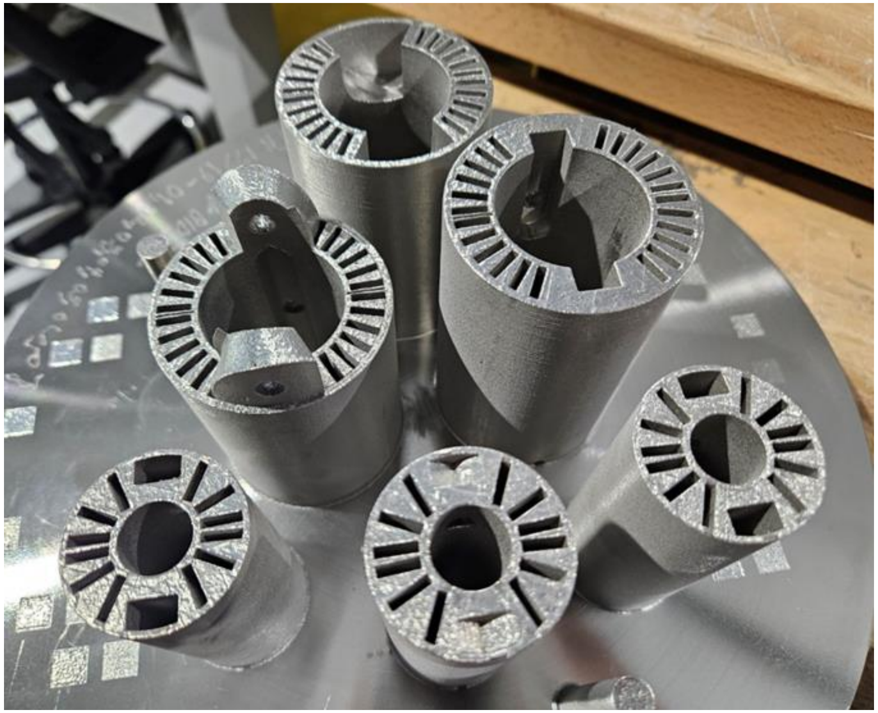
Bi2212 composite wire, Rutherford cable and coil cross-section



- **0.8 mm Bi2212 wire (BOST)**
- **17-strand cable 7.8×1.44 mm^2 (LBNL)**



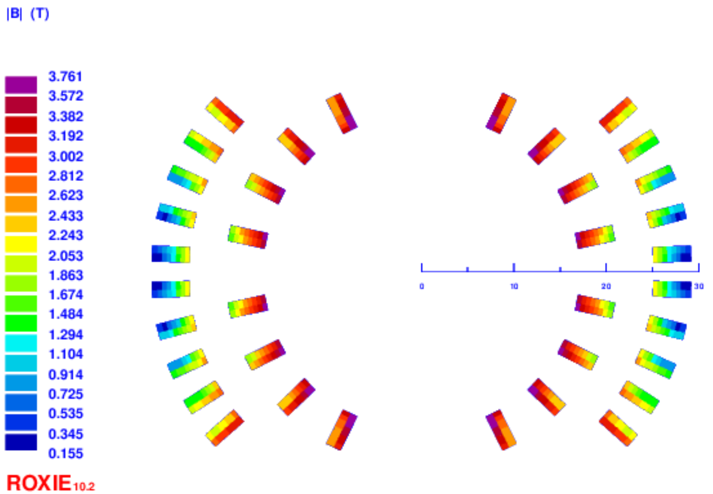
Coil structure parts printed from Inconel 718

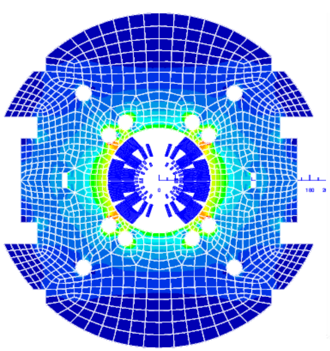


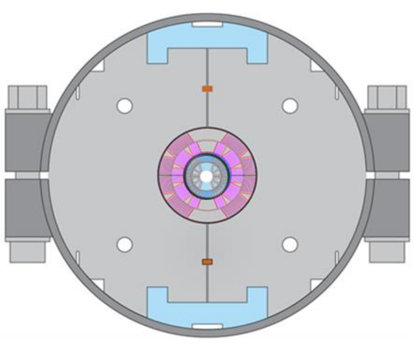
REBCO coil concept based on TST cable

An HTS coil based on a Twisted Stack (TST) cable made of REBCO tapes – an alternative to round REBCO cable technology

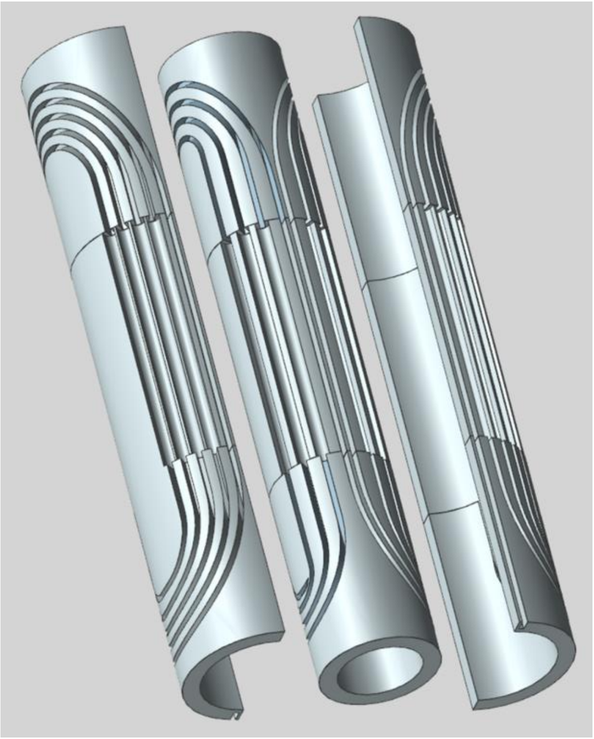
Coil and magnet cross-section







Coil structure

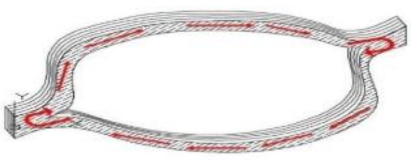


Practice coil

Practice coil uses 3D-printed plastic parts and 12-tape stack cable made of 4 x 0.1 mm^2 SS tape

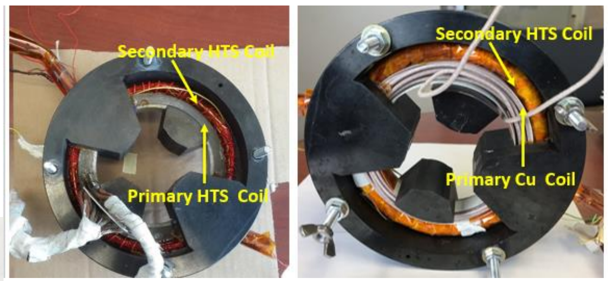
Iron-dominated (low-field) HTS models

A novel concept was investigated based on coils assembled from the parallel HTS loops without splices

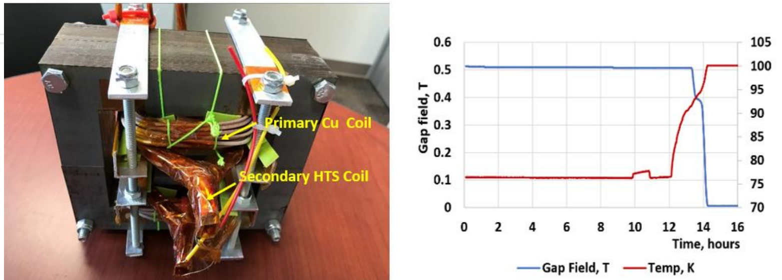


Coil configuration

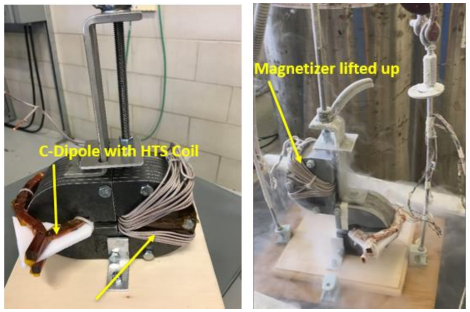
Coil from 100 parallel HTS loops



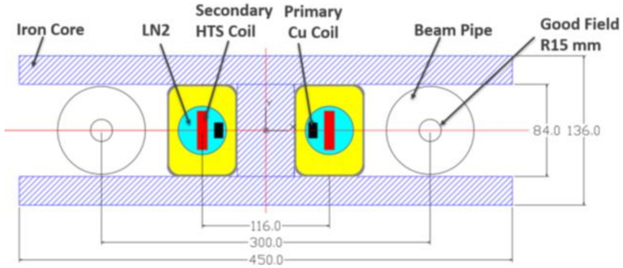
HTS Quadrupoles (2019-2021)



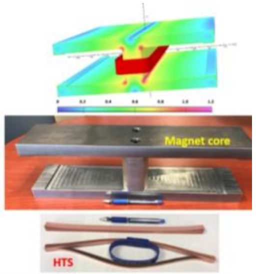
HTS Dipole (2022). 4 kA current in HTS coils circulated 12 hours without decay and a power source



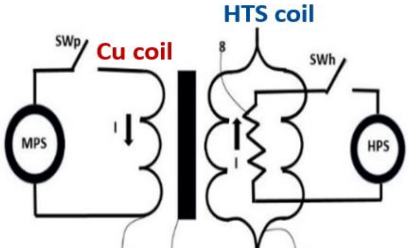
HTS Dipole with Mechanical Energy Transfer. Current circulated 12 hours (2023)



FCC-ee HTS dipole concept presented at FCC Week (2024)



FCC-ee model parts (2024)



Current transformer to energize HTS coil

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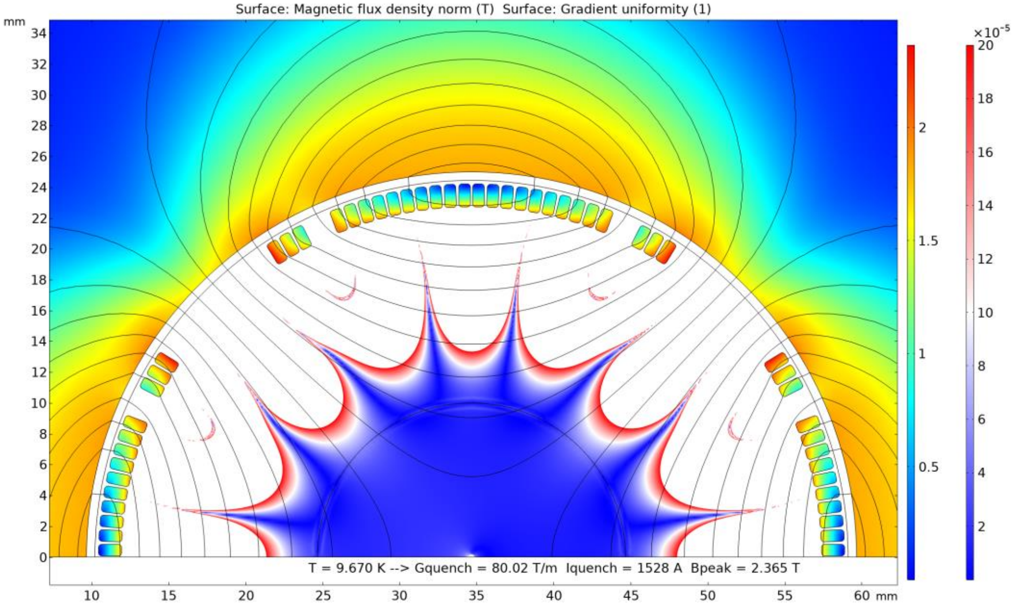
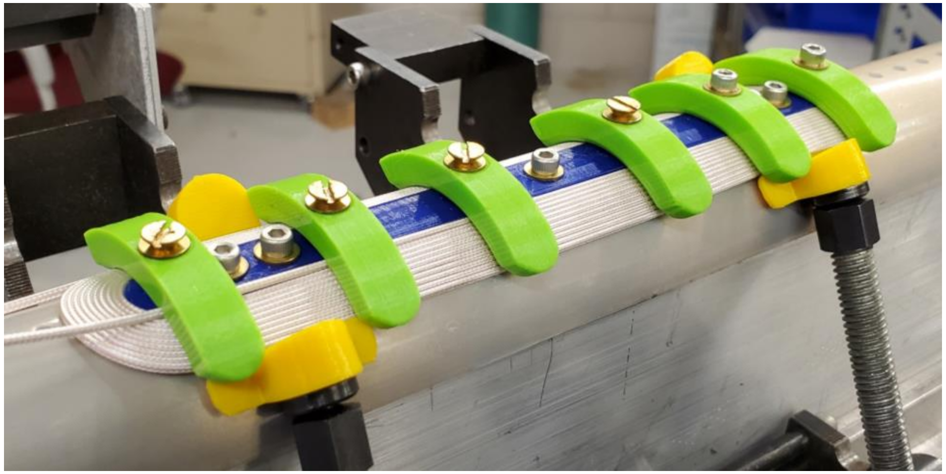
SuperKEKB IR upgrade

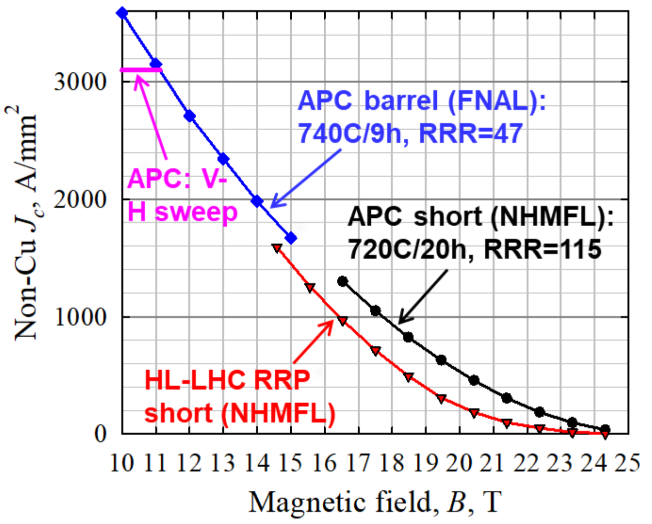


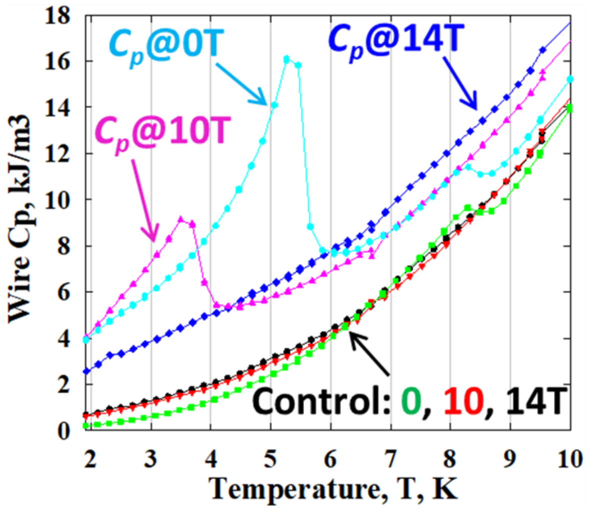


- The idea is to upgrade the existing NbTi IR quads with Nb_3Sn coils…
  - to make them thinner and increase the thermal margin
  - to move them closer to the IP
  - to increase the luminosity
- Joint effort between Fermilab and KEK under the US-Japan collaboration
  - KEK provided the Nb_3Sn conductor
    - Special order with 2.3 μm filaments to control the coil magnetization
  - Fermilab made the magnet design and fabricated several practice coils
- The prototype and the actual magnets are to be fabricated in 2025-2028

Advanced material R&D

- Nb_3Sn with artificial pinning centers (APC)
  - The APC Nb_3Sn developed at FNAL (Xu et al.) is the only Nb_3Sn conductors that meet the FCC-hh conductor J_c specification.
  - The instability issue has been holding back scaling up of APC wires. Significant progress has been made to solve the issue recently. Now instability is not a big concern for APC wires anymore. Now preparing for making long APC wires.
- Nb_3Sn with high specific heat (C_p)
  - A problem with Nb_3Sn magnets is the long training, which leads to high cost and long test time. FNAL (Xu et al.) has been developing Nb_3Sn conductors with high C_p and thus higher energy margin, which may help to reduce the magnet training.
  - Previous high-C_p wires had drawability issue, preventing scaling up. After optimizing the wire design, the drawability issue has been solved. A long wire (1.6 km long) has been produced. Ready to be fabricated into a model dipole magnet for testing the training performance.





Fermilab

Summary

- A vibrant magnet R&D program building upon 25 years of advanced magnet and material development (post NbTi)
  - Record fields achieved by Nb_3Sn magnets in the last 5 years
  - HTS magnets are still in their baby stages, but growing quickly
  - State-of-the-art material research
  - Collaborative efforts and synergetic activities augmenting the program breadth and quality
- The program is in the process of re-alignment with P5 recommendations
  - The focus is shifting towards HTS magnets that come in different flavors
    - Standalone and hybrid, dipoles/quadrupoles and solenoids, REBCO and Bi-2212…
  - For Nb_3Sn - a “robust” 12-14 T design should be developed
  - The magnet development is accompanied with supporting elements, including advanced diagnostics, material studies, modeling and analysis