



U.S. MAGNET
DEVELOPMENT
PROGRAM

US efforts towards HTS accelerator magnets

Soren Prestemon
US Magnet Development Program
Lawrence Berkeley National Laboratory
On behalf of the US MDP Collaboration

- The US Magnet Development Program
 - Context within Department of Energy
- The MDP HTS program
 - REBCO magnet developments
 - Instrumentation and diagnostics
 - Modeling and analysis
- Next major milestones for the program
- Opportunities to join forces: initiatives in HEP, FES, and High-Field Magnets



The US MDP is a technology development program

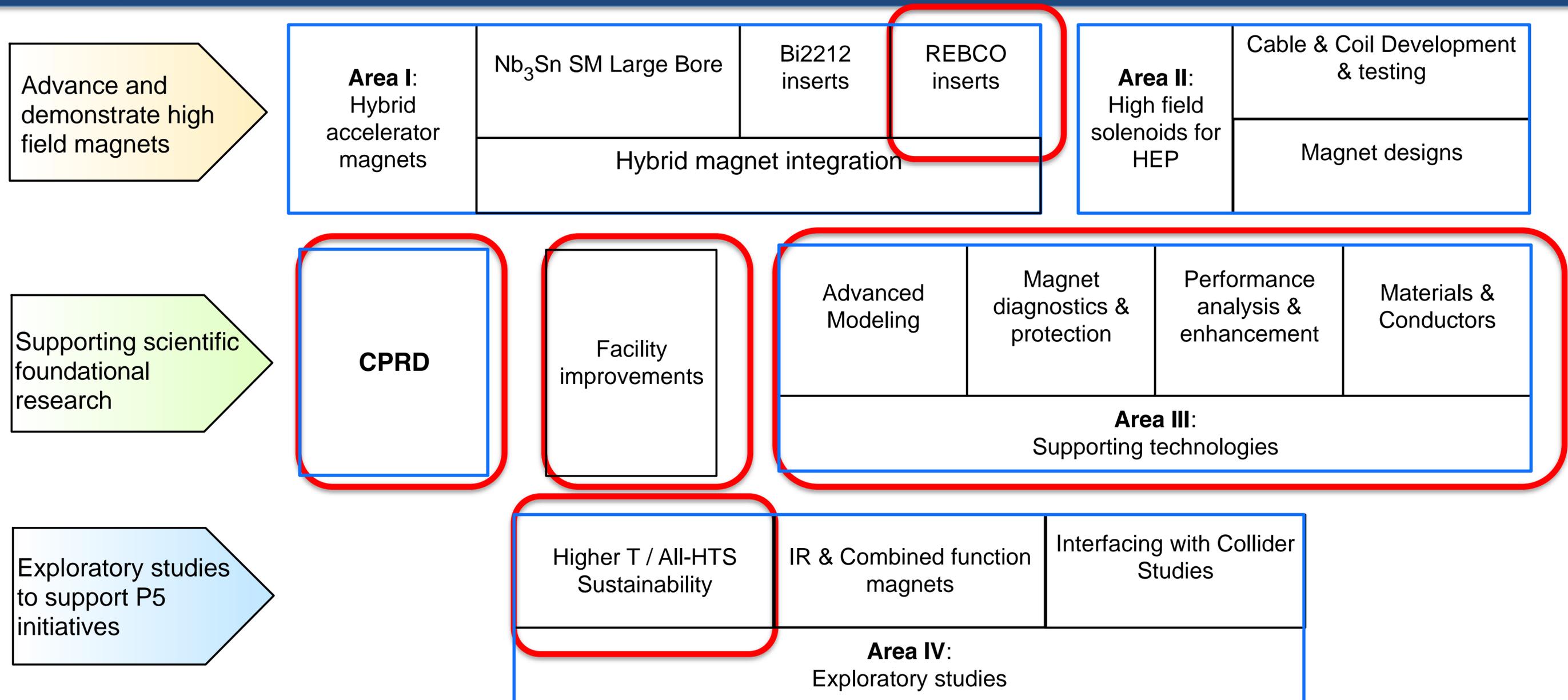
•Goals:

- . Explore and define the performance limits of superconducting accelerator magnets
- . Develop, understand and demonstrate high field HTS magnet technology
- . Investigate and understand the fundamental science of magnet design and performance
- . Pursue conductor R&D to achieve properties that align with accelerator magnet goals
- . Support the development of advanced workforce for superconducting magnet technology

•Furthermore, MDP has the goals of:

- . Integrating the teams across the partner laboratories for maximum value and effectiveness to the program
- . Identifying and nurturing HEP and cross-cutting / synergistic activities and opportunities with other programs to more rapidly advance progress towards our common goals.

Our program has been reviewed and revised to align with P5 recommendations

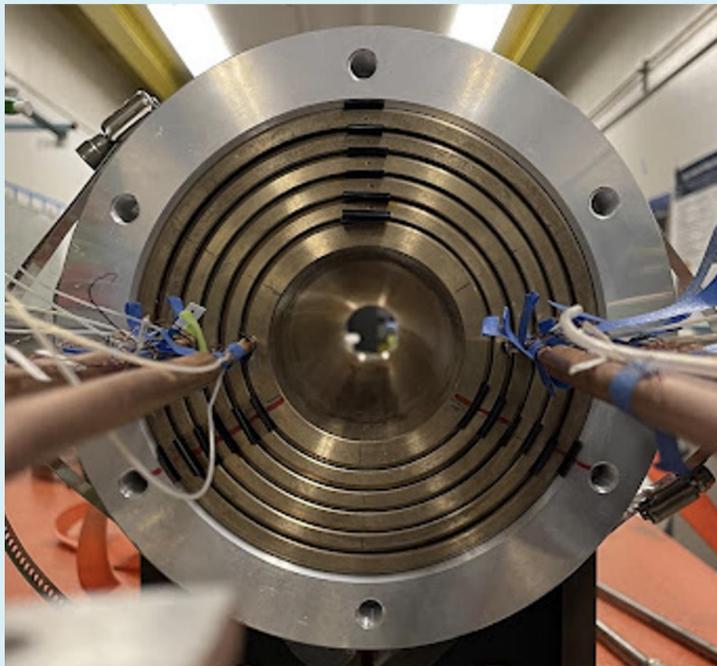


Further build collaborations, leverage synergies with fusion and with the NHMFL

REBCO is actively pursued at all MDP laboratories

LBNL:

- Exploring CORC and STAR wires – developing technology
- Focus primarily (not solely) on CCT



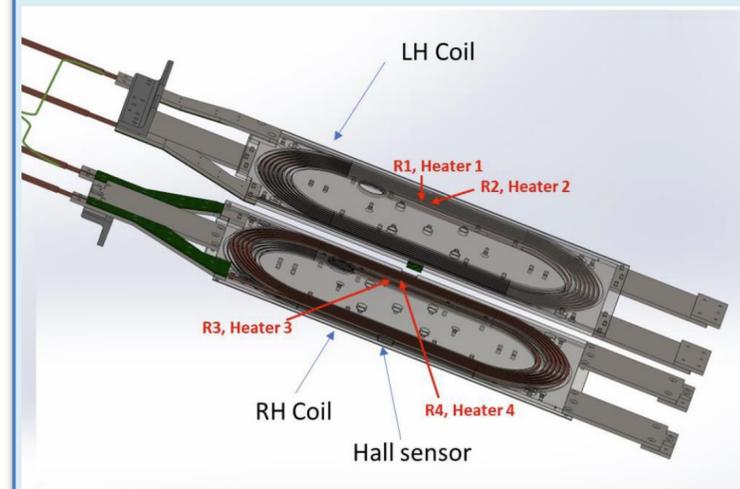
FNAL:

- Exploring CORC and STAR wires
- Focus primarily (not solely) on COMB design



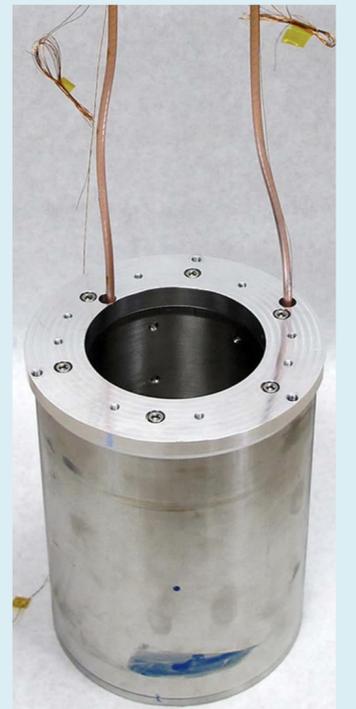
BNL:

- Testing REBCO in 10T common coil
- Measure magnetization, AC losses
- Significant synergy with fusion collaborations

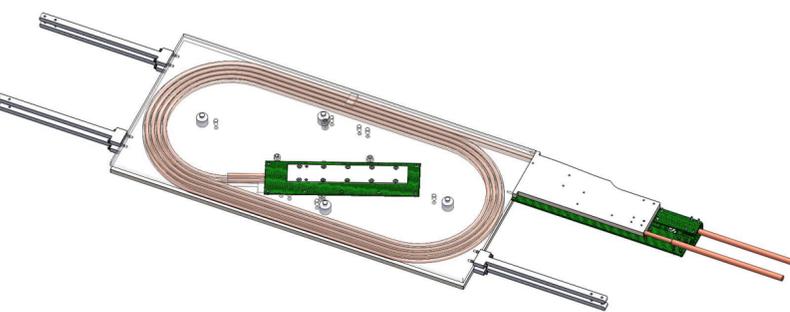
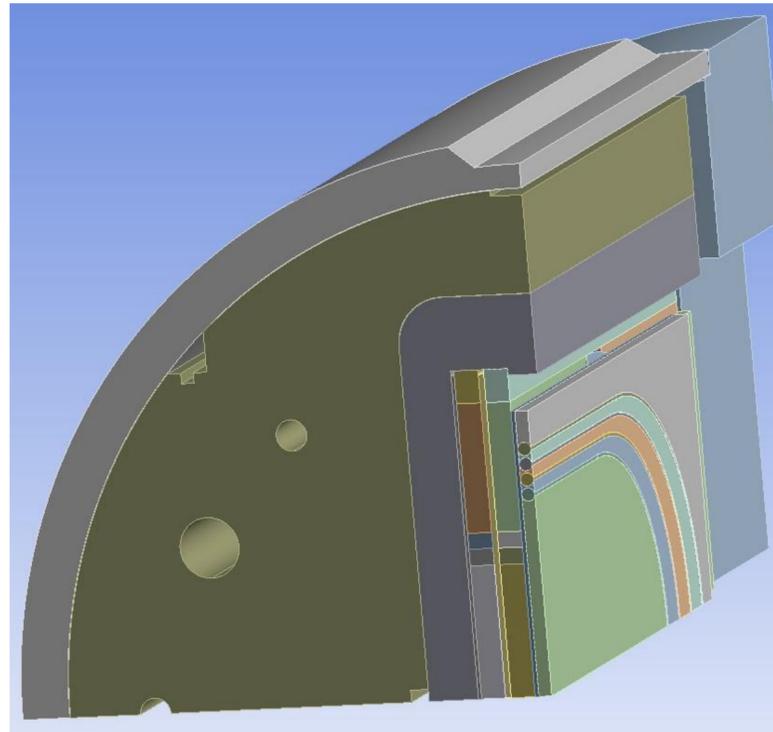


ASC/NHMFL:

- Evaluating conductors and CORC and STAR wires
- Solenoid fabrication and testing in background field



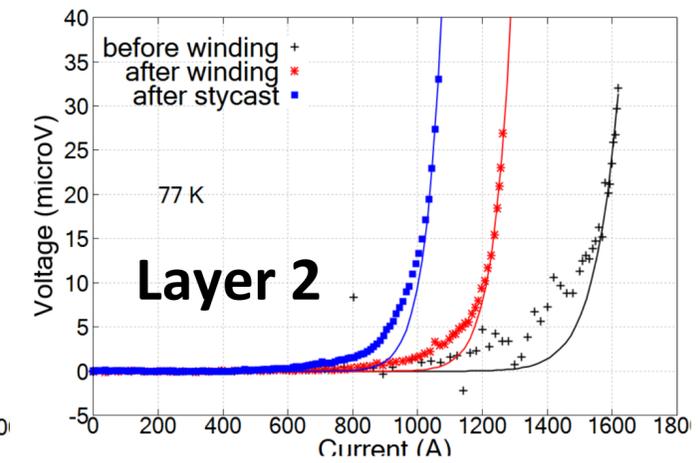
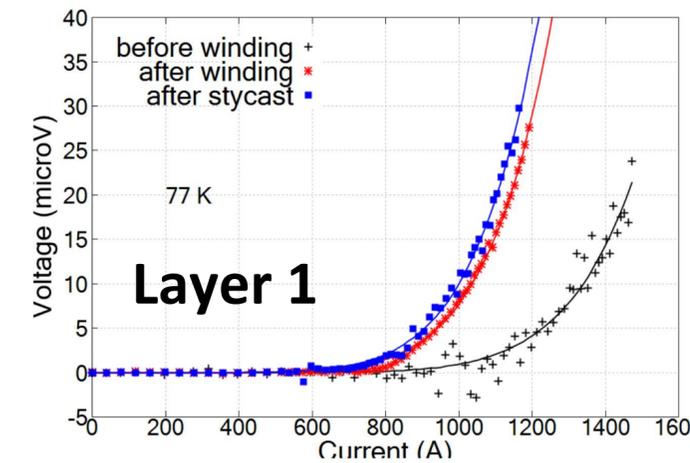
Test cables in-field at BNL in the common-coil test facility



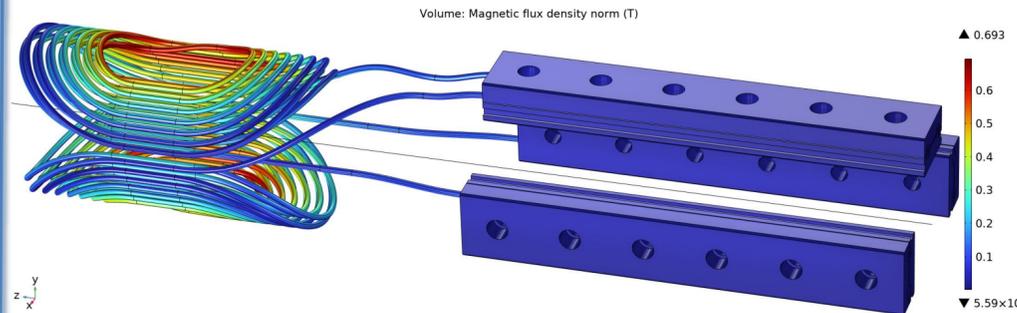
Major 2025 deliverable – “C3”

- Target >5 T
- 6-layer CCT using CORC® wires

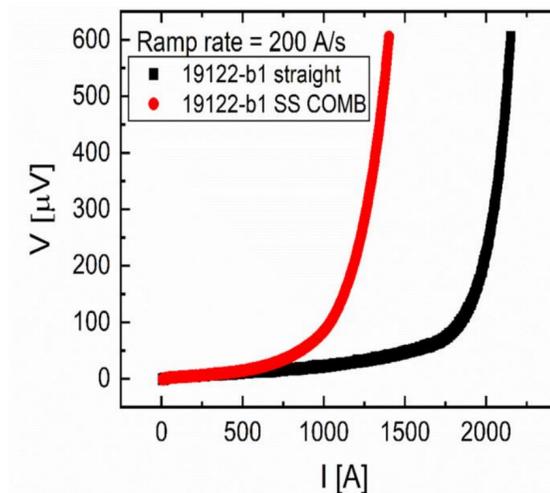
3-turn practice
windings were
made for each layer



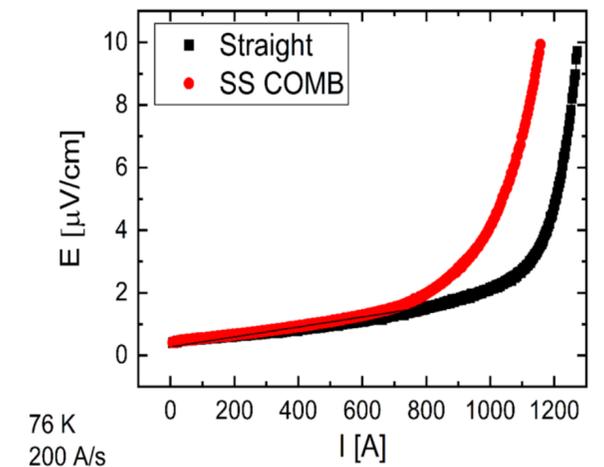
“COMB” design advancing as a test platform



“Early” CORC



Improved CORC



C3 is a 6-layer CCT magnet using CORC conductor

Xiaorong Wang

- 145 m of CORC® wires in six pieces, maximum piece length 35 m
- Specified the minimum tape I_c for HM tapes

Aluminum shell

Layer 6

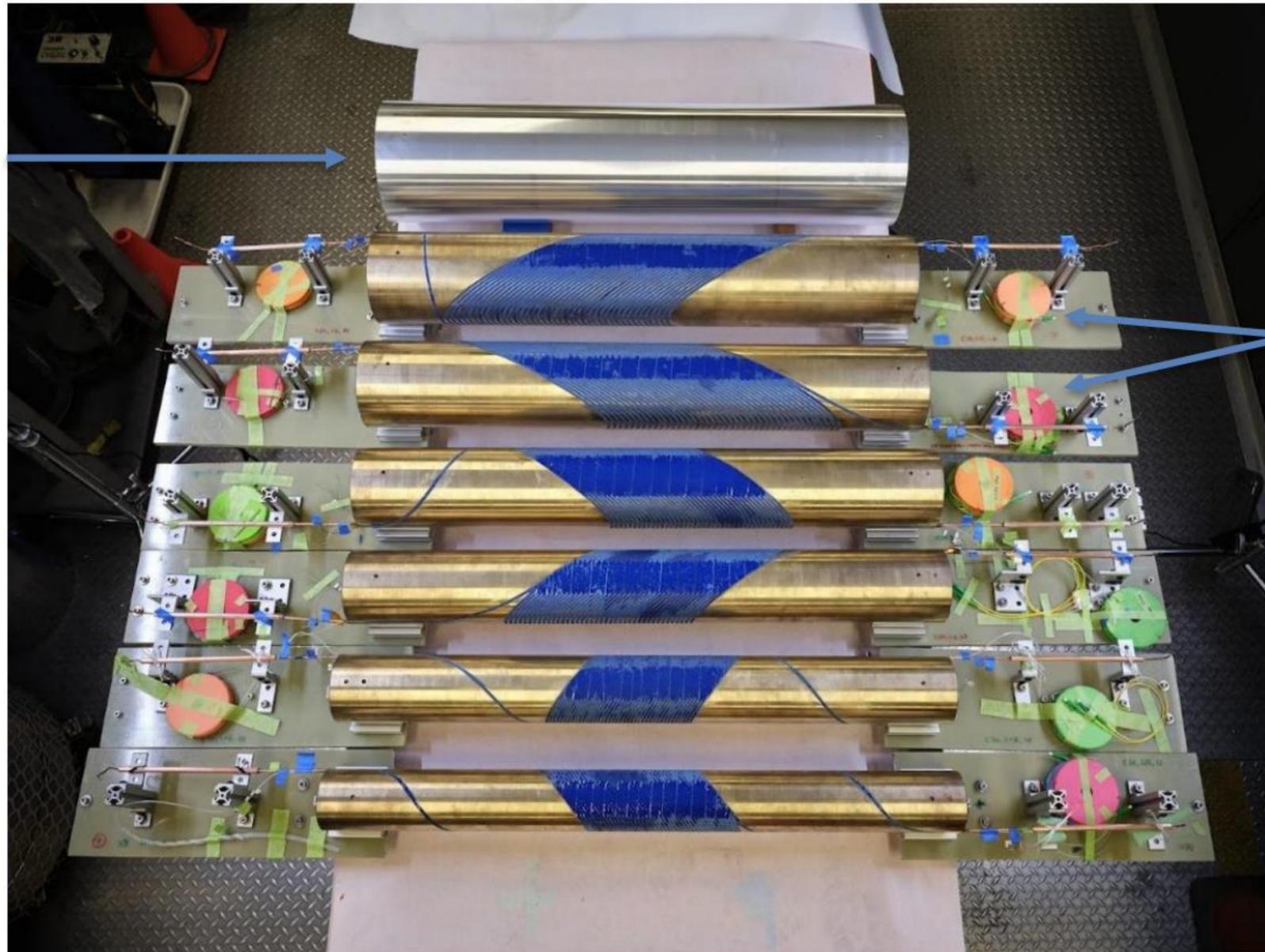
5

4

3

2

1



Optical-fiber spool

Image courtesy of Andy Lin

C3 was designed to achieve 4-5T => major goal of the 2020 MDP roadmap

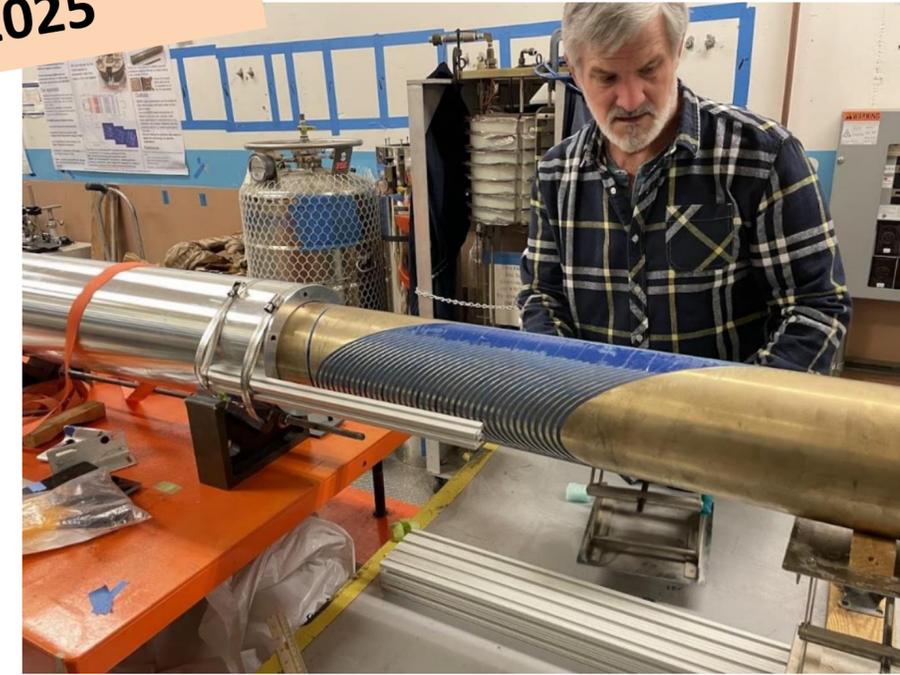
- First 4.2K test took place last week

- Achieved 5.2T in 65mm bore, with <25 microvolt/layer

- Future tests will explore magnetization, losses, and higher field

- Fiber optics in each layer – all survived test

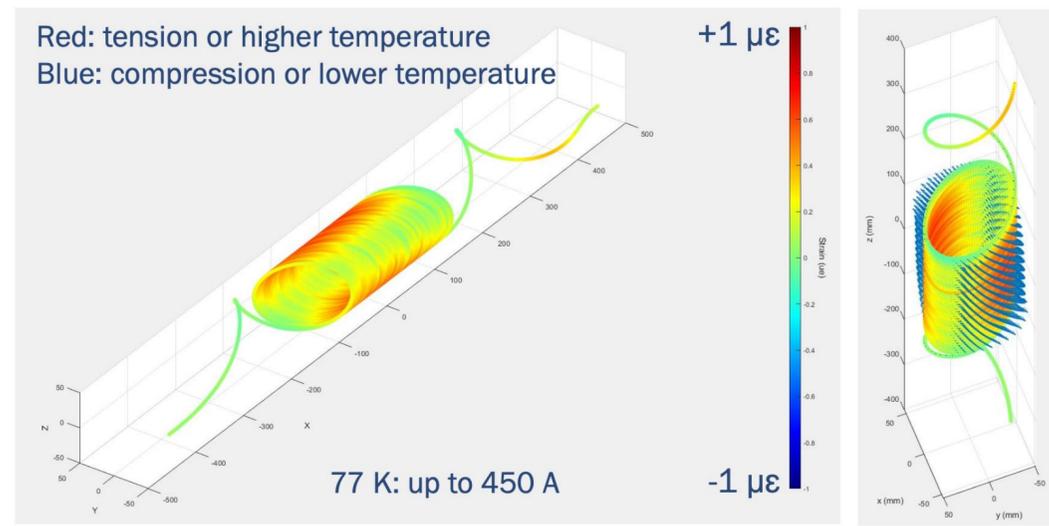
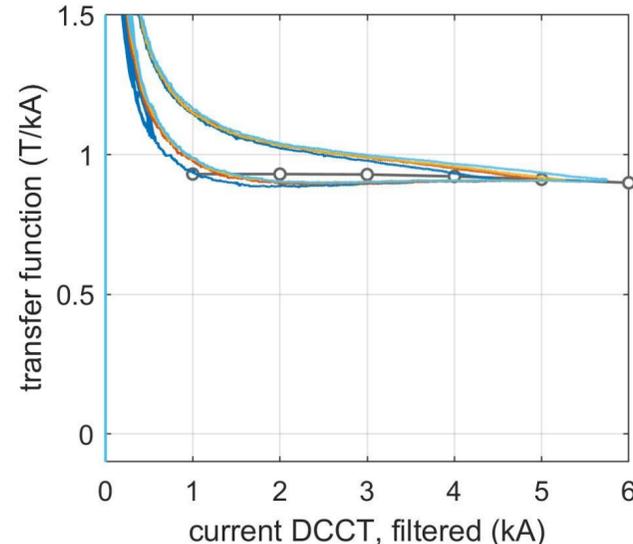
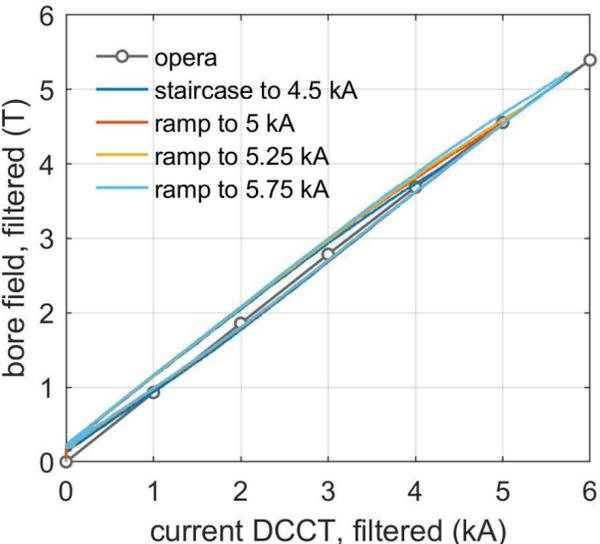
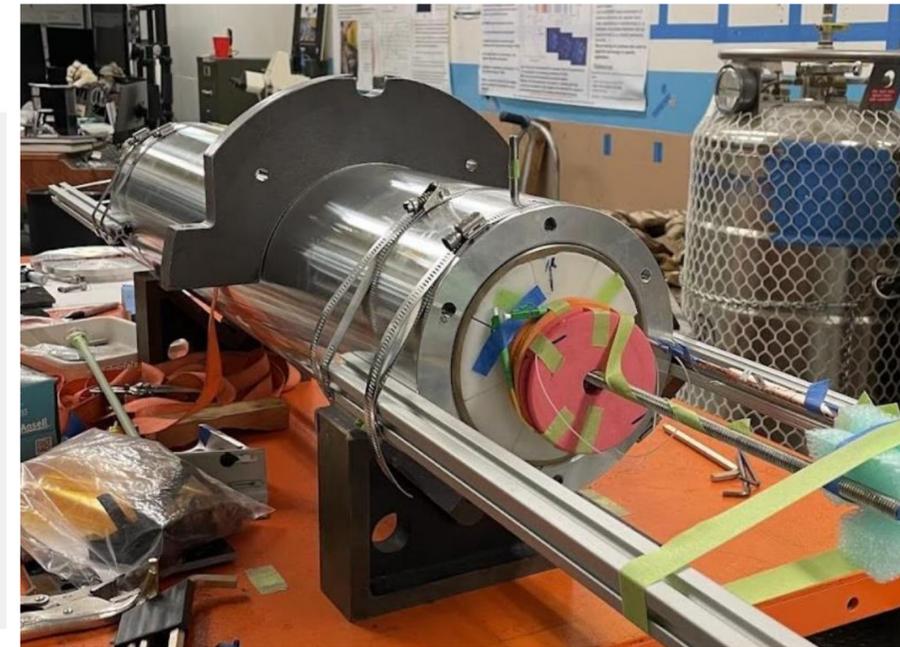
New result!
March 4th, 2025

Raw data on transfer function from various ramp scenarios

Strain measured via distributed optical fiber – test at 77K shown here

- *Linqing Luo et al 2025 SUST 38 035029*

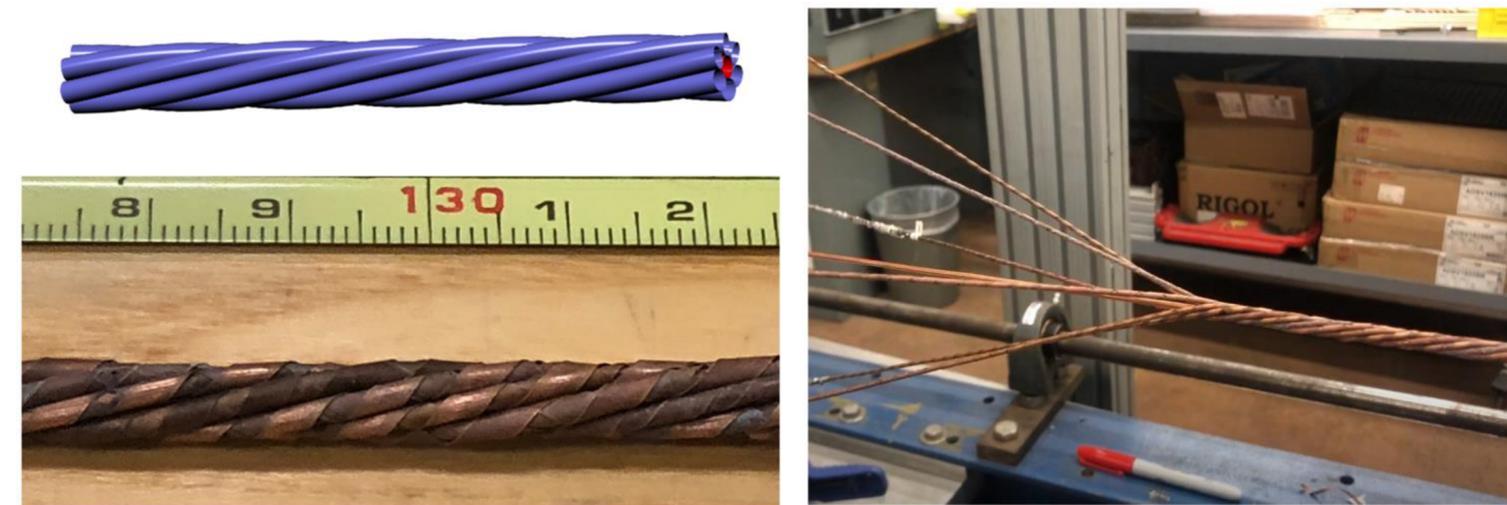


We study STAR[®] wires to keep conductor options open

Xiaorong Wang et al 2022 Supercond. Sci. Technol. 35 125011

- Next step is S1 magnet, a longer version of [s0](#),
 - 2 layers, 40 turns, 2-wire ribbon cable, 1 – 2 T dipole field at 4.2 K
 - Will fit inside CCT5 as an insert test
 - 90 m STAR[®] wires ordered and delivered by AMPeers
- Driving questions for S1
 - Can we make longer STAR[®] wires with uniform geometry and I_c ?
 - Can we impregnate the bare STAR[®] wires?
 - Impregnation with filled wax cause negligible degradation.
 - How does the magnet perform? What further magnet and conductor development is needed?

- Develop 6-around-1 cable toward a magnet conductor
 - Transposed configuration
- Supported by an SBIR Phase II project with AMPeers
 - Leveraging LBL cabling infrastructure and expertise
 - Project will provide 10 m long cable to make a 3-turn magnet within the next 18 months. If successful, an order can follow

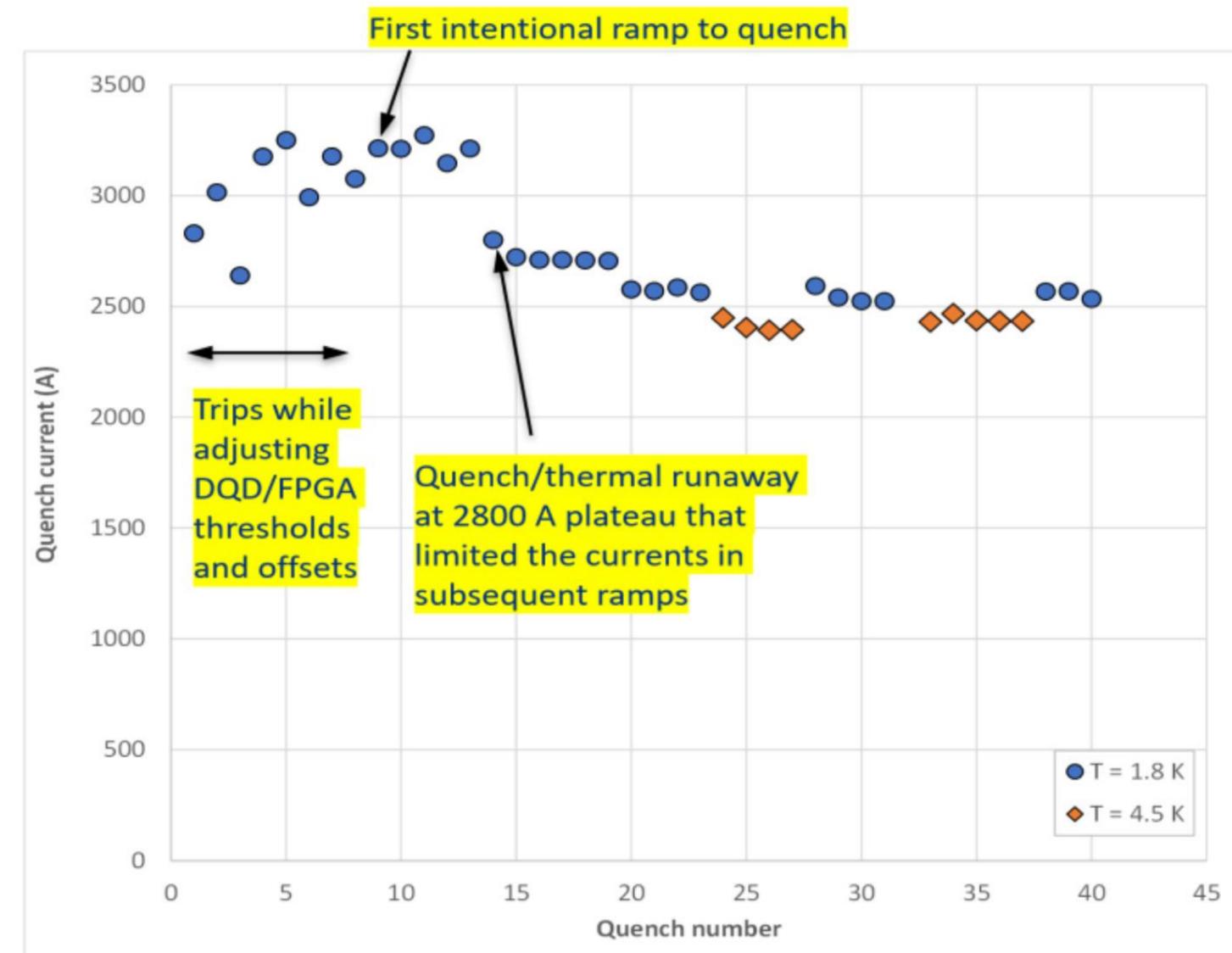
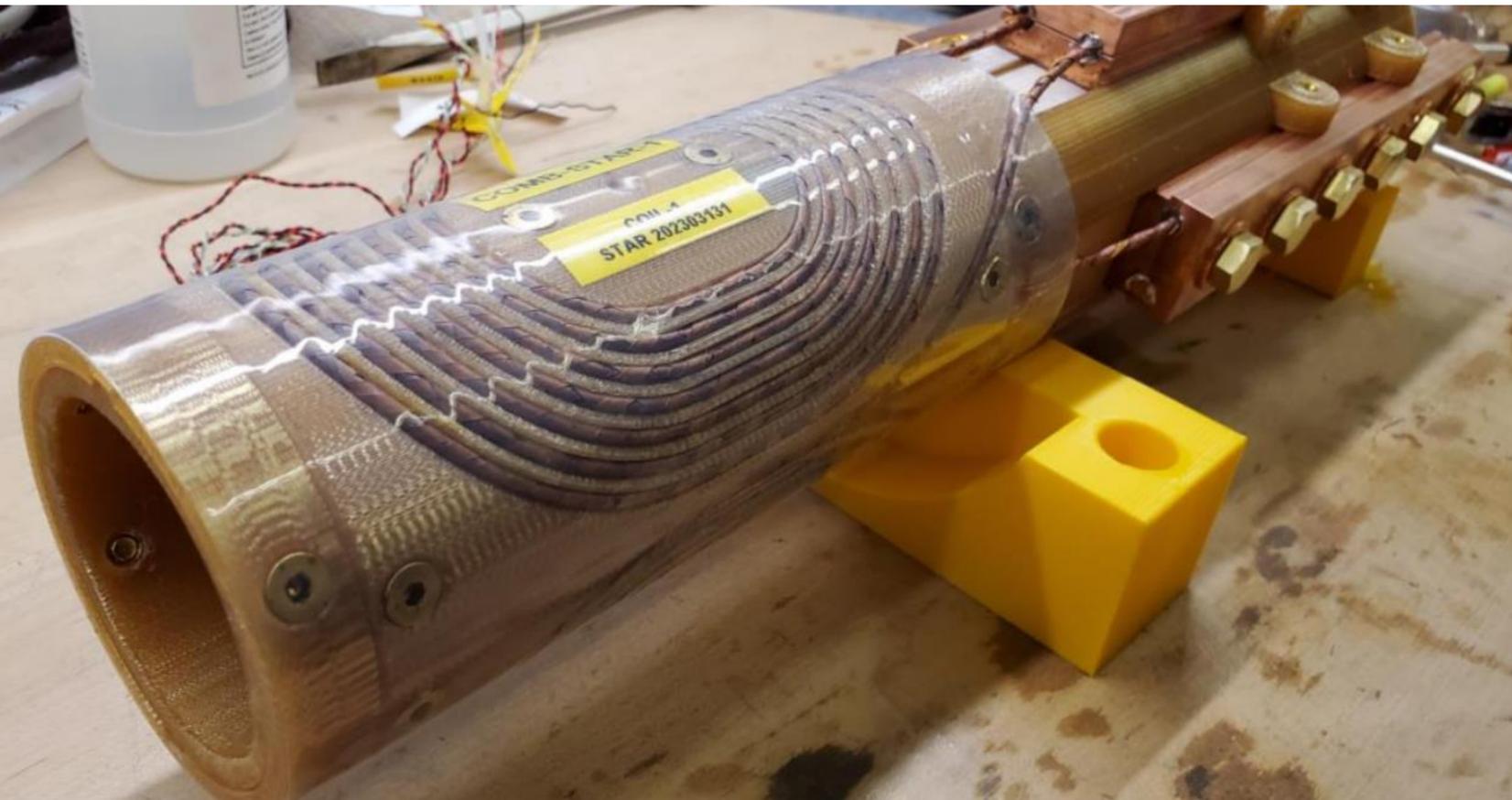


N. Castaneda et al. 2024. "A 6-around-1 Cable Using High-Temperature Superconducting STAR[®] Wires for Magnet Applications." SuST 37 (3): [035009](#).

COMB concept incorporates stress management with cos-theta current distribution

- COMB-STAR-1 magnet (2023-24) Achieved 1.5 T bore field @ 3.3 kA in LHe
 - o Degradation in one coil explored vi micro-CT scan

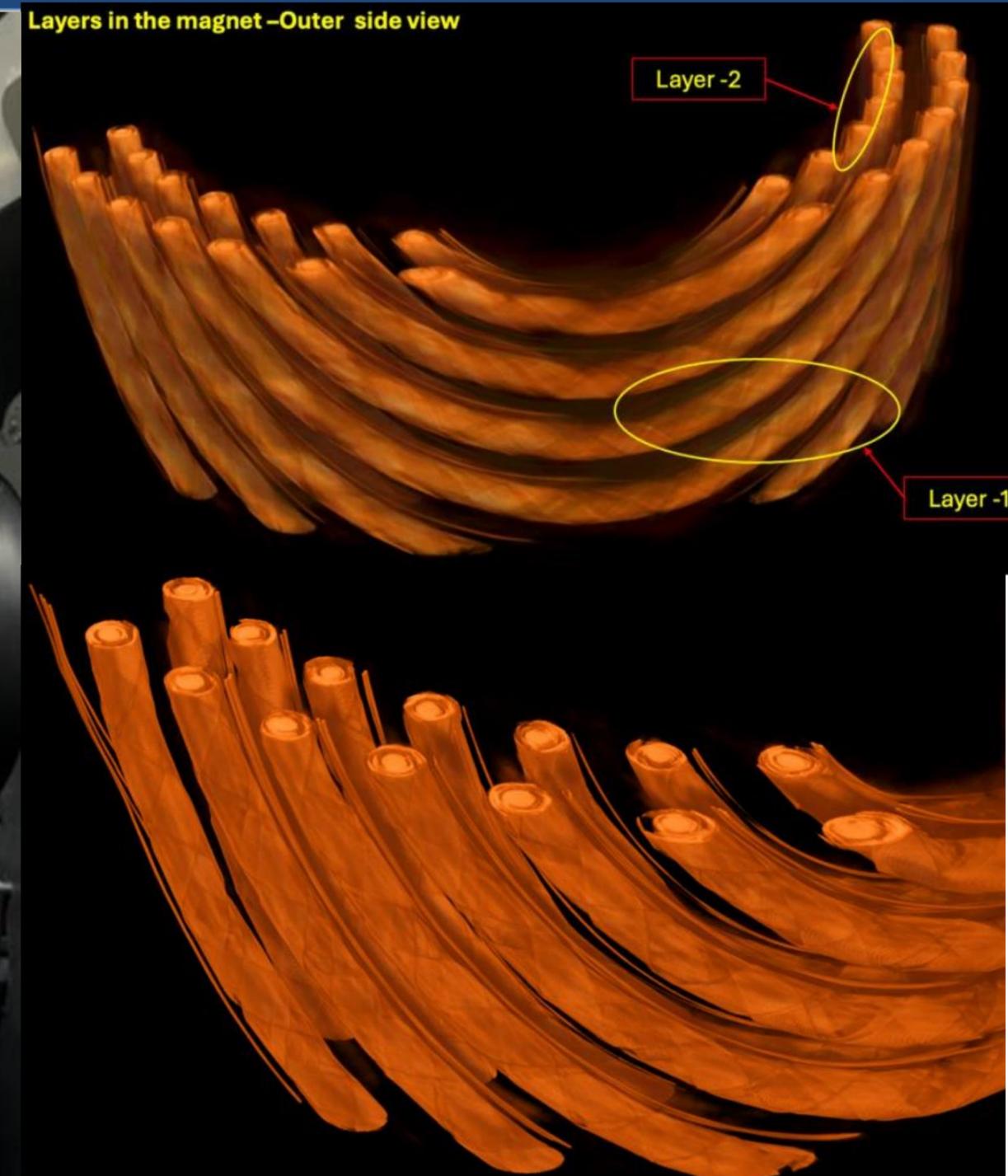
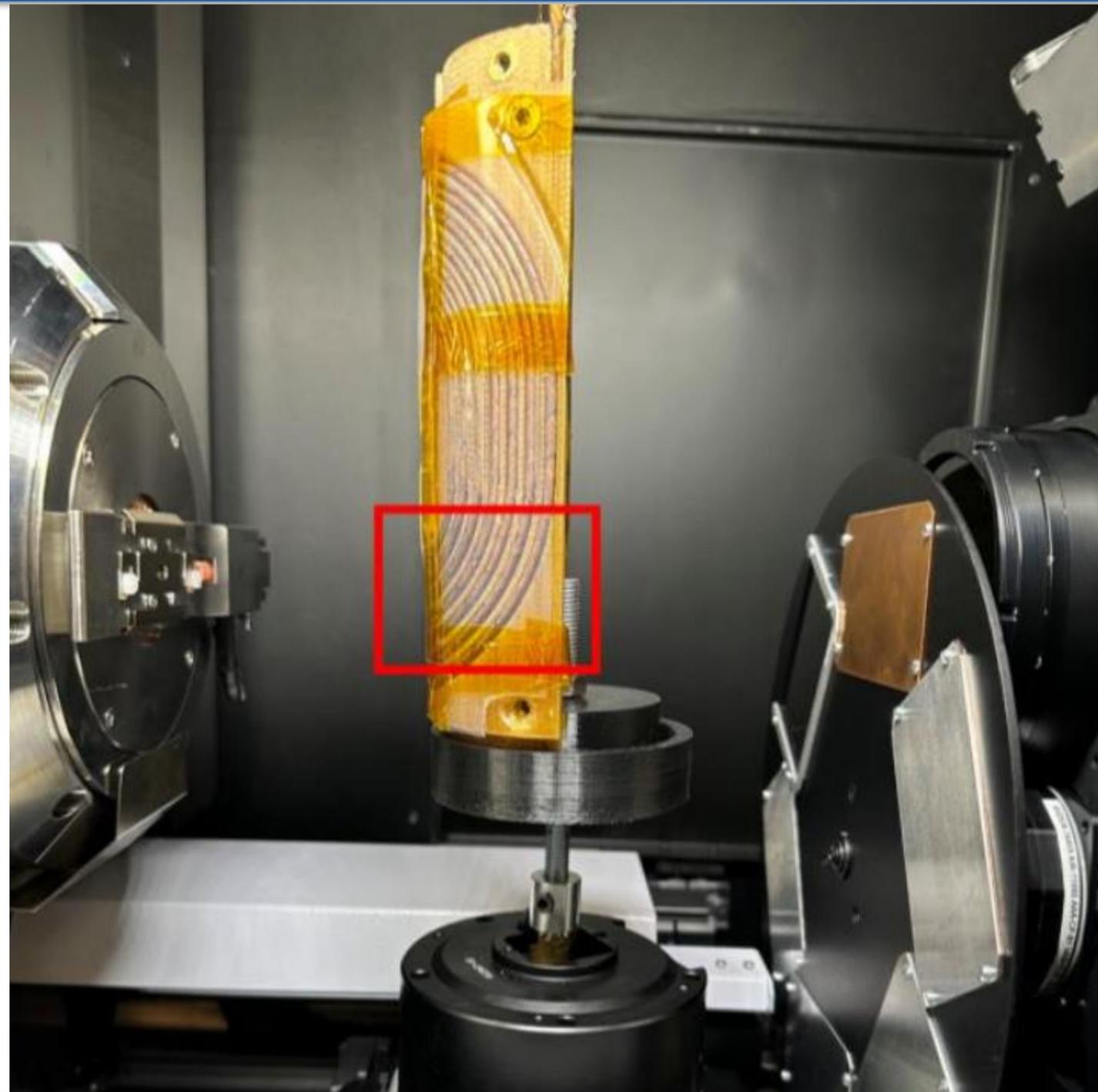
Vadim Kashikhin



Disassembly/autopsy/micro-CT scan performed on the half-coil

The technique shows promise, but resolution cannot distinguish fine details in the wire

No evidence of wire damage apparent

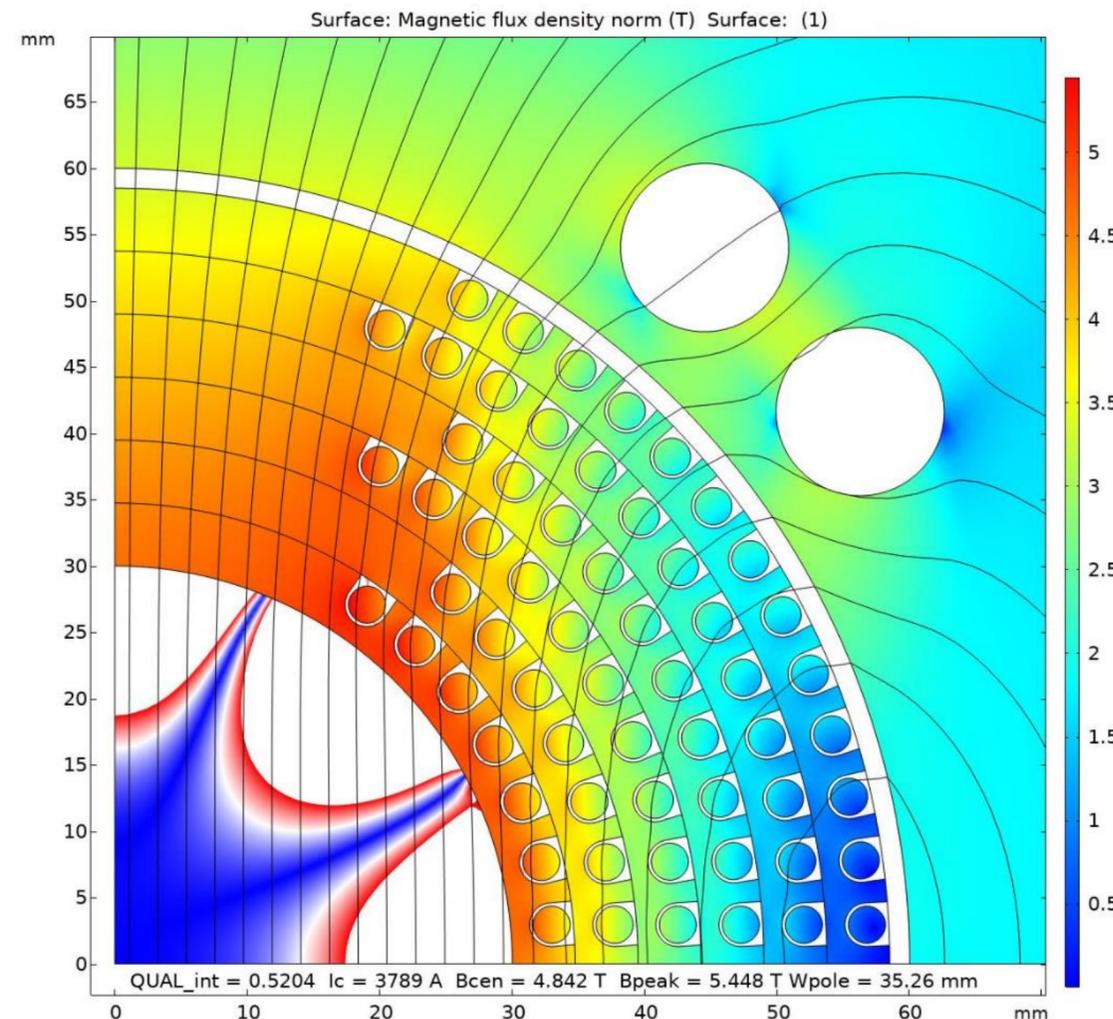


Designs for the next STAR and CORC COMB magnets are progressing

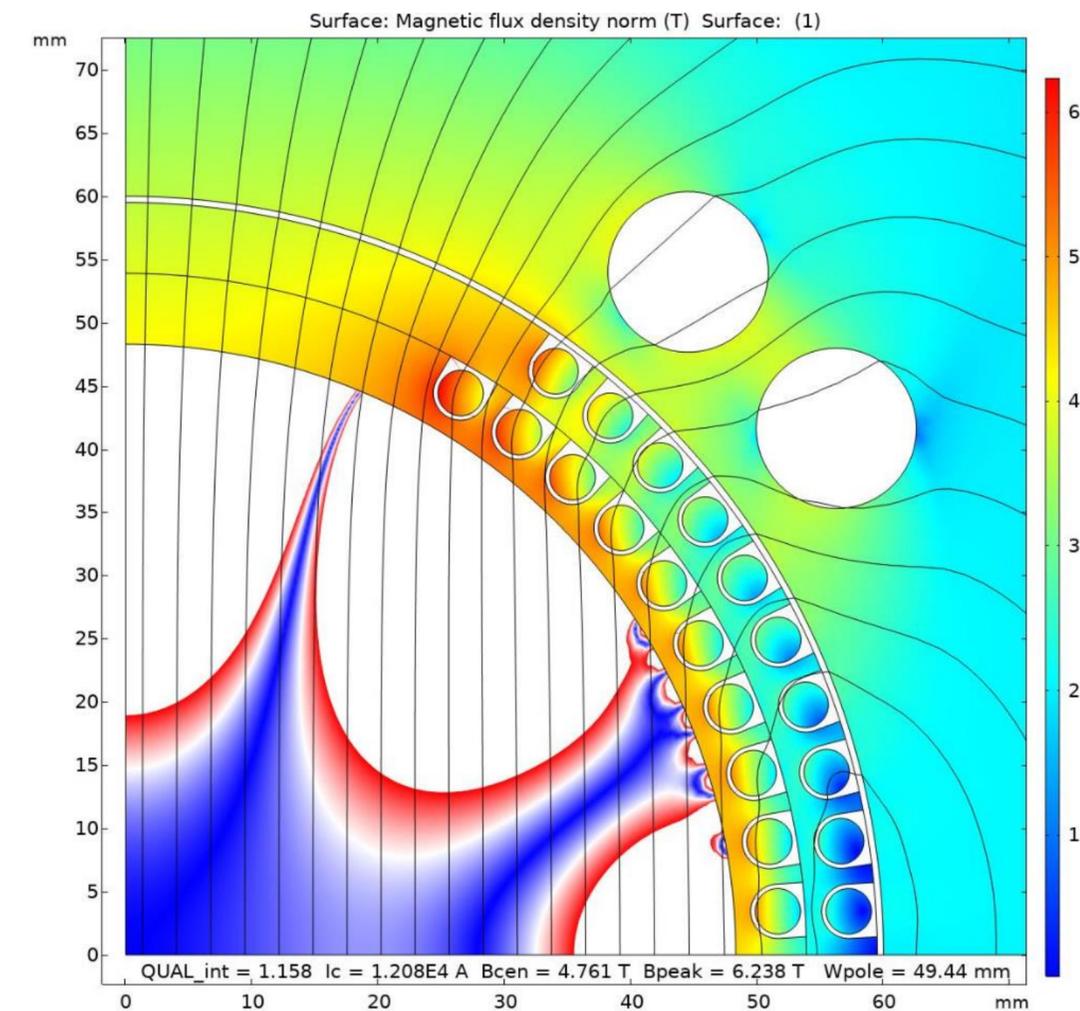
- STAR™ allows for smaller bend radius => 60mm bore, 6 layers, may consider grading
- CORC™ allows higher current but limited bending => ~97mm bore, 2 layers

- STAR wire: 12 layers of AMPEER tape, 1 tape/layer; wire OD 2.6mm
- CORC: 24 Superpower HM tapes, 2 tapes/layer; wire OD 3.8mm
- 4.8T bore field with 120mm OD

COMB-STAR-2



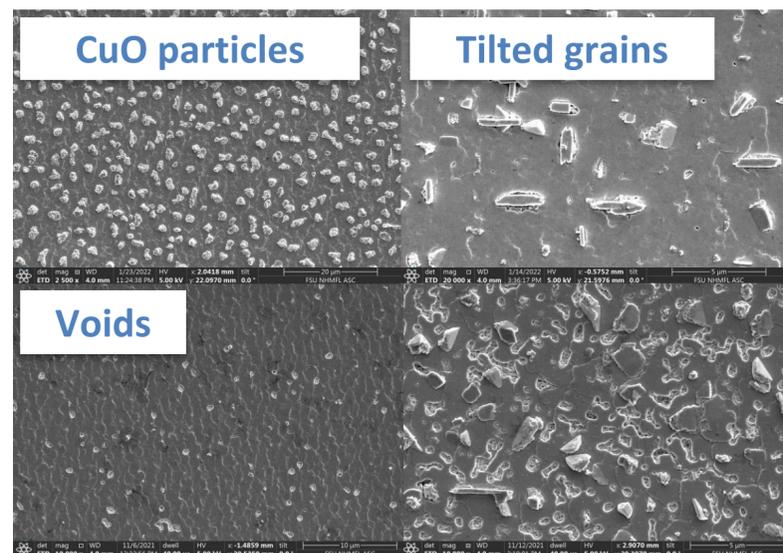
COMB-CORC-1



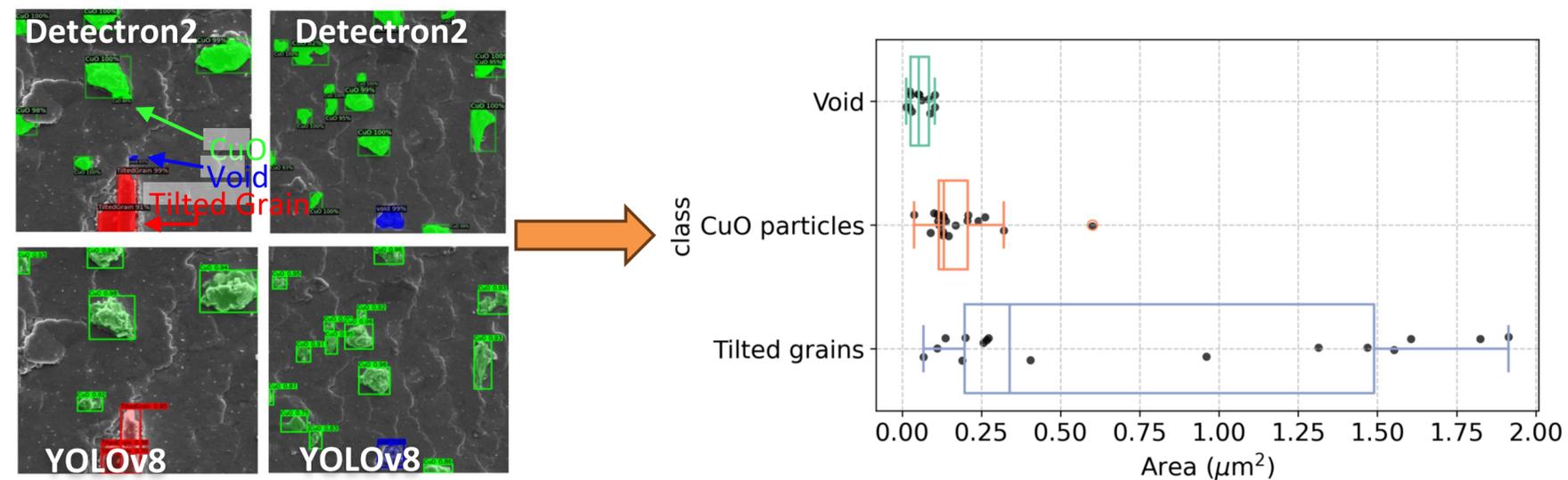
Materials research and procurements in support of magnet developments

- Conductor Procurement and R&D (CPRD) is a dedicated element of MDP
 - Primary goals of a) supporting magnet R&D needs, and b) investing in specific industry efforts that have particular potential for MDP
- University and lab materials research:
 - Expertise in materials characterization
 - Supports industry through innumerable collaborations
 - Supports magnet R&D by quantifying material properties, performance risks, etc.

Top surface SEM imaging using Thermo Fisher Helios G4 UC at FSU



From Poster by N. Menon et al "Machine Learning for Image Analysis: Accelerating Image Segmentation to Survey Larger Regions and Parameter Spaces"



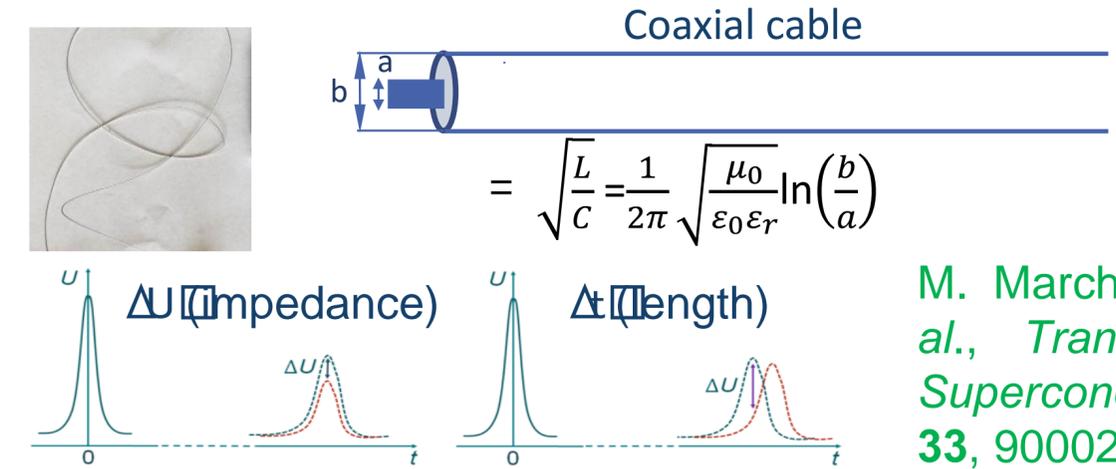
Diagnostics are envisioned to be central to HTS magnet protection

Maxim Marchevsky

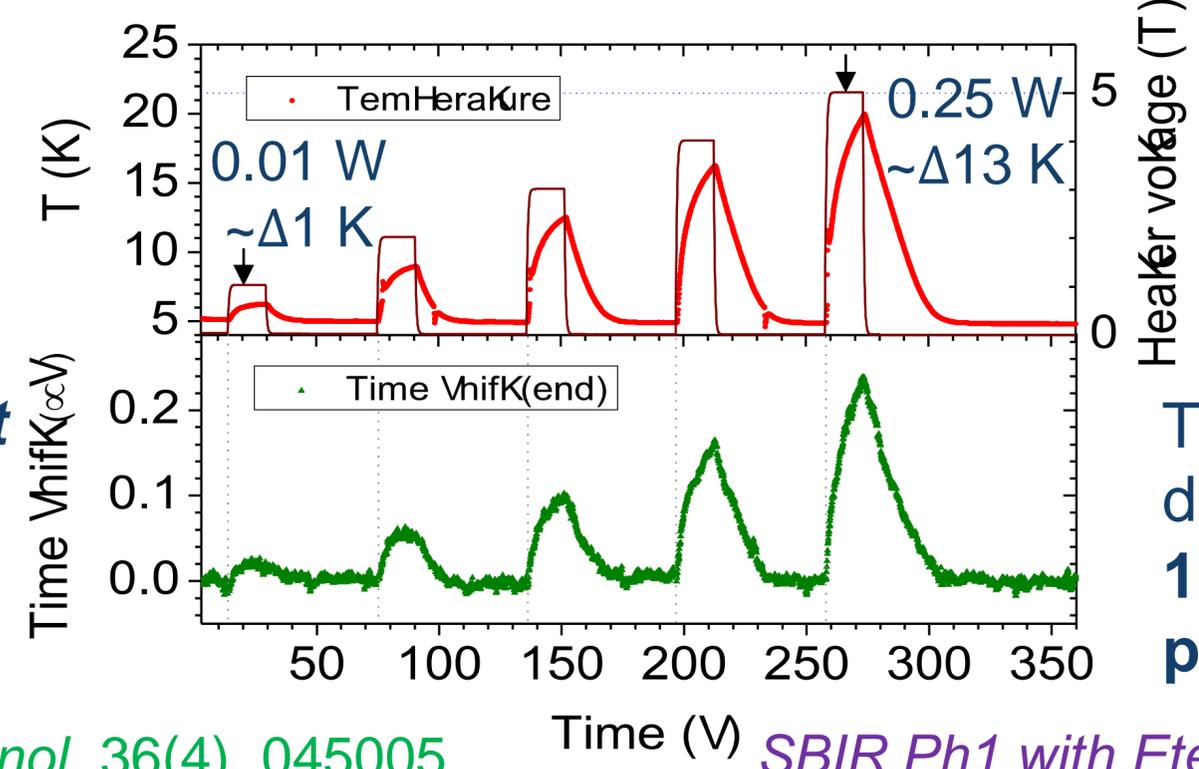
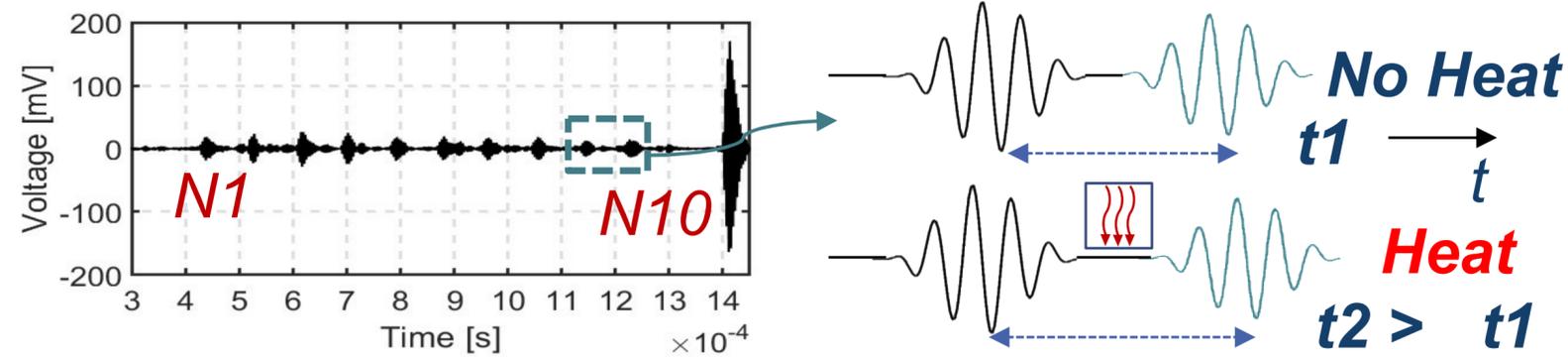
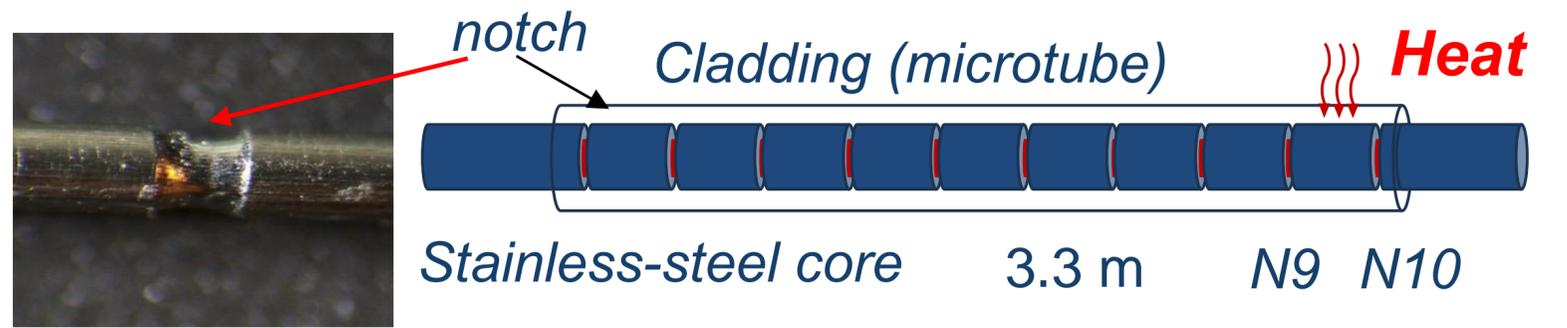
- We are pursuing multiple avenues – fiberoptics, Hall sensors, cryo-electronics, etc.

Core idea:

- A new protection paradigm for HTS magnets has emerged, aiming at avoiding quenching altogether
- We will detect the dissipative regime using advanced non-voltage diagnostics and estimate proximity to the runaway



M. Marchevsky *et al.*, *Trans. Appl. Supercond.*, 2023, **33**, 9000206.



Time shift is detectable at **T = 1K** and heater power of **0.01 W**.

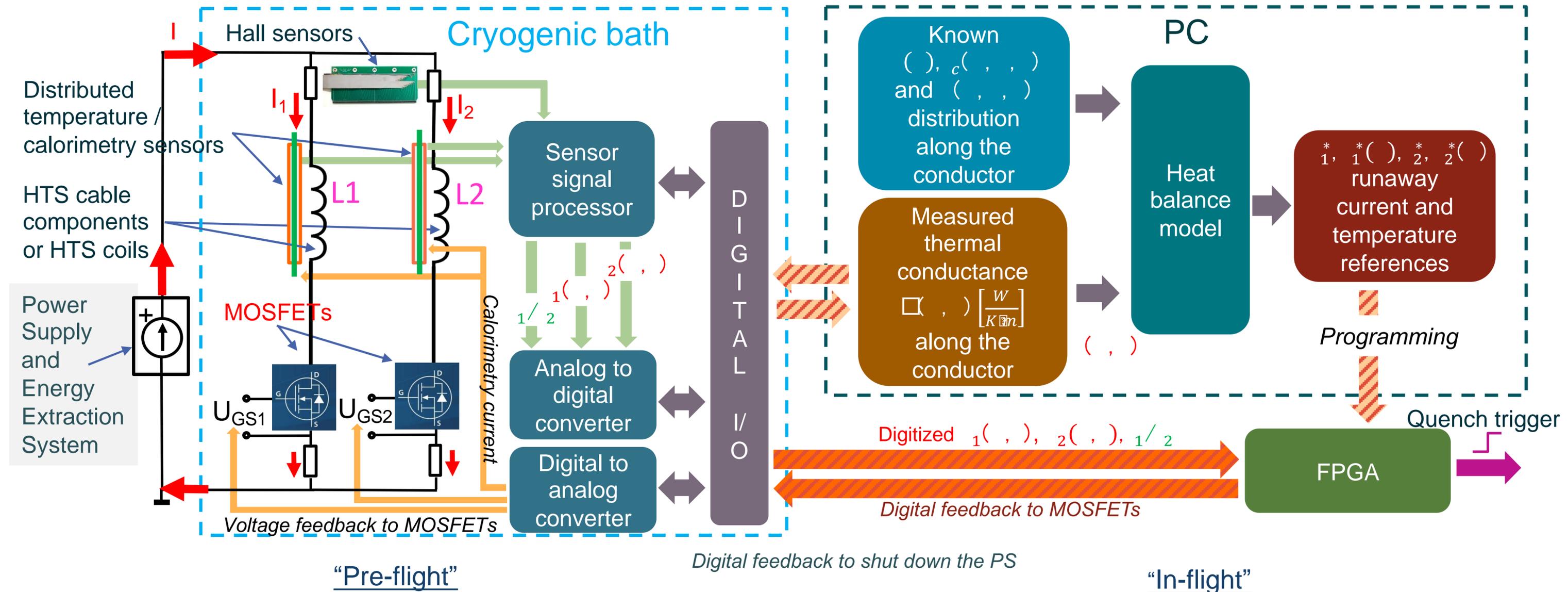
M. Marchevsky and S. Prestemon, 2023, *Supercond. Sci. Technol.* 36(4), 045005

SBIR Ph1 with Etegent Technologies

A vision for protection: : a functional block diagram for protecting a two-component HTS conductor or a two-coil system (L1, L2)

M. Marchevsky

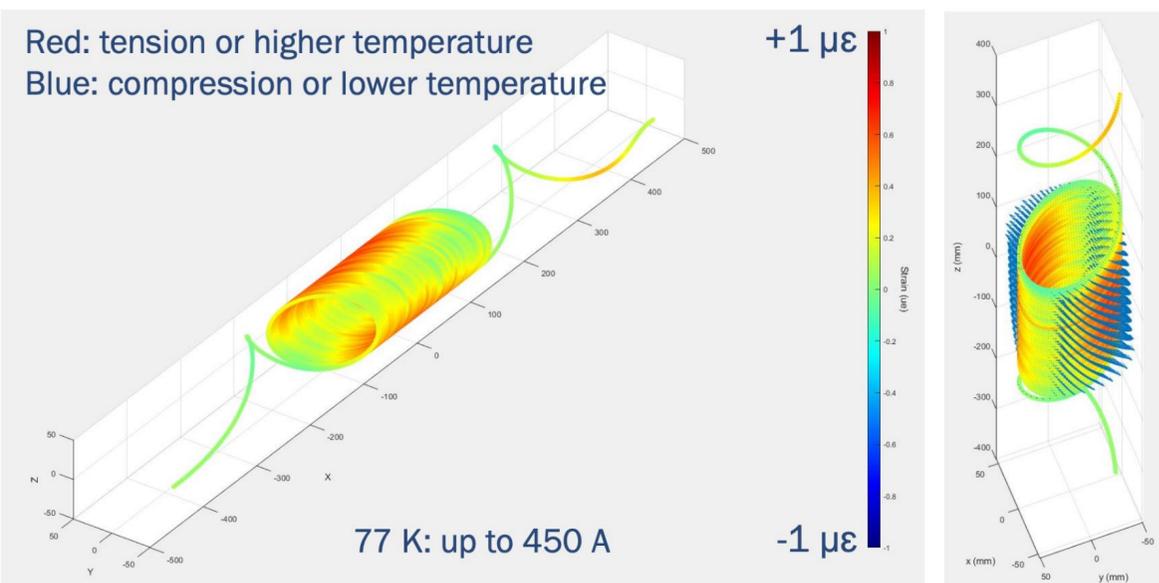
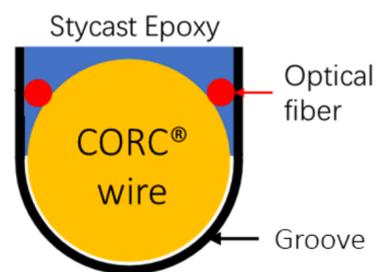
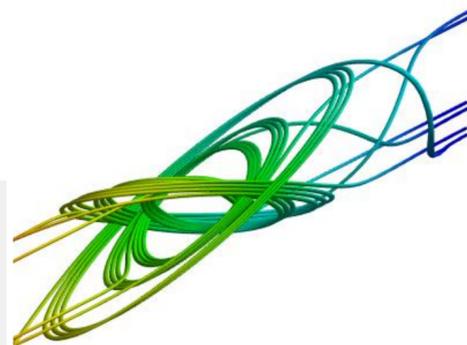
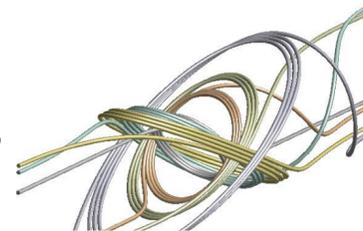
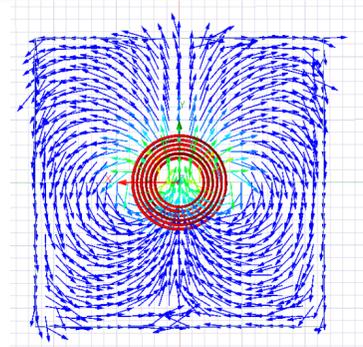
Integrate advances in sensors, cryo-electronics, modeling, conductor characterization, and controls



1. Using the PC, measure $(,)$ with calorimetric sensors
2. Calculate runaway $*(,), *(,)$, program into the FPGA
3. Monitor $_1(,), _2(,), _1/_2$, compare them to $*, (,), *(,)$
4. Generate feedback to MOSFET boards, send a quench trigger

Groove: an automated modeling framework for 'conductor in groove' designs

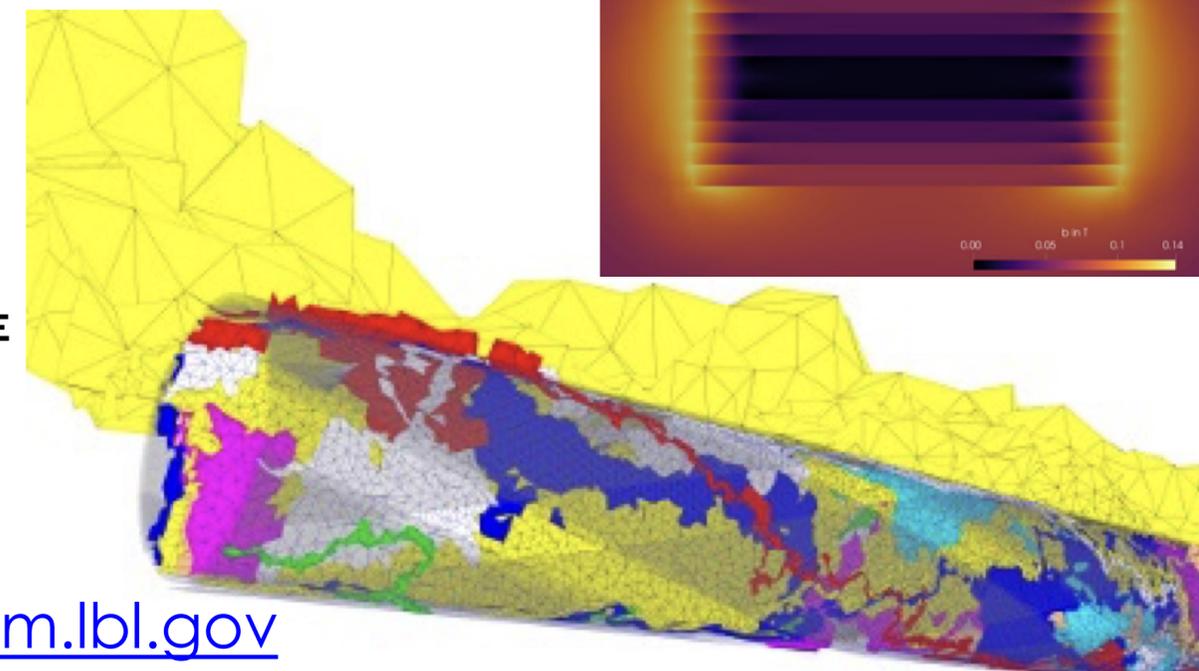
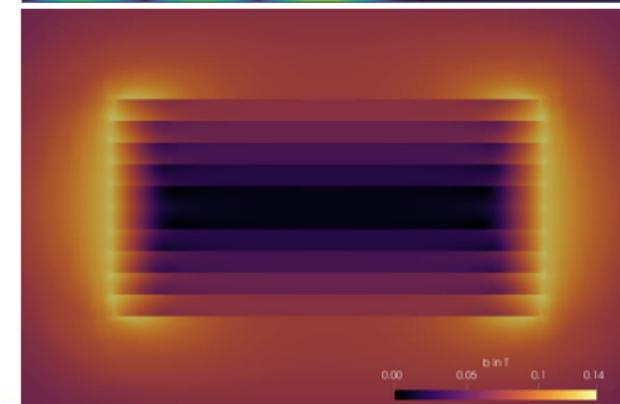
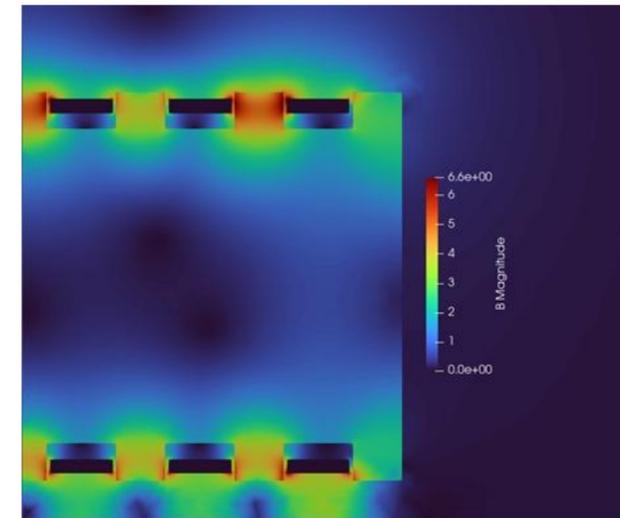
- Python code base generating geometry and magnetic/mechanical models ready
- For the moment, focused on CORC/STAR magnets (REBCO area)
- Nice validation provided by the extremely clean distributed fiber optic measurements on the 3 turns prototype C3a
- Developed model is qualitatively matching the measurements



Berkeley Lab Finite Element Framework for High Temperature Superconductors

BELFEM:

- Goal: predict quench propagation along three-dimensional thin shells
- Strong collaboration with Polytechnique Montréal
- Use state of the art numerical models and solver libraries (h-phi & STRUMPACK)



<https://belfem.lbl.gov>

There are significant synergies between Fusion and HEP magnet research – especially muon collider

DOE Offices of HEP & FES jointly funding a large-bore cable test facility

- Will provide 15T dipole field over 750mm good-field, 1.9-50K on-sample
- Cryostat will enable testing of high-field hybrid magnets
- *Will be a user facility located at FNAL*

HFVMTF Cable Test Facility: First Workshop on User Interfaces

Registration
Event Registration

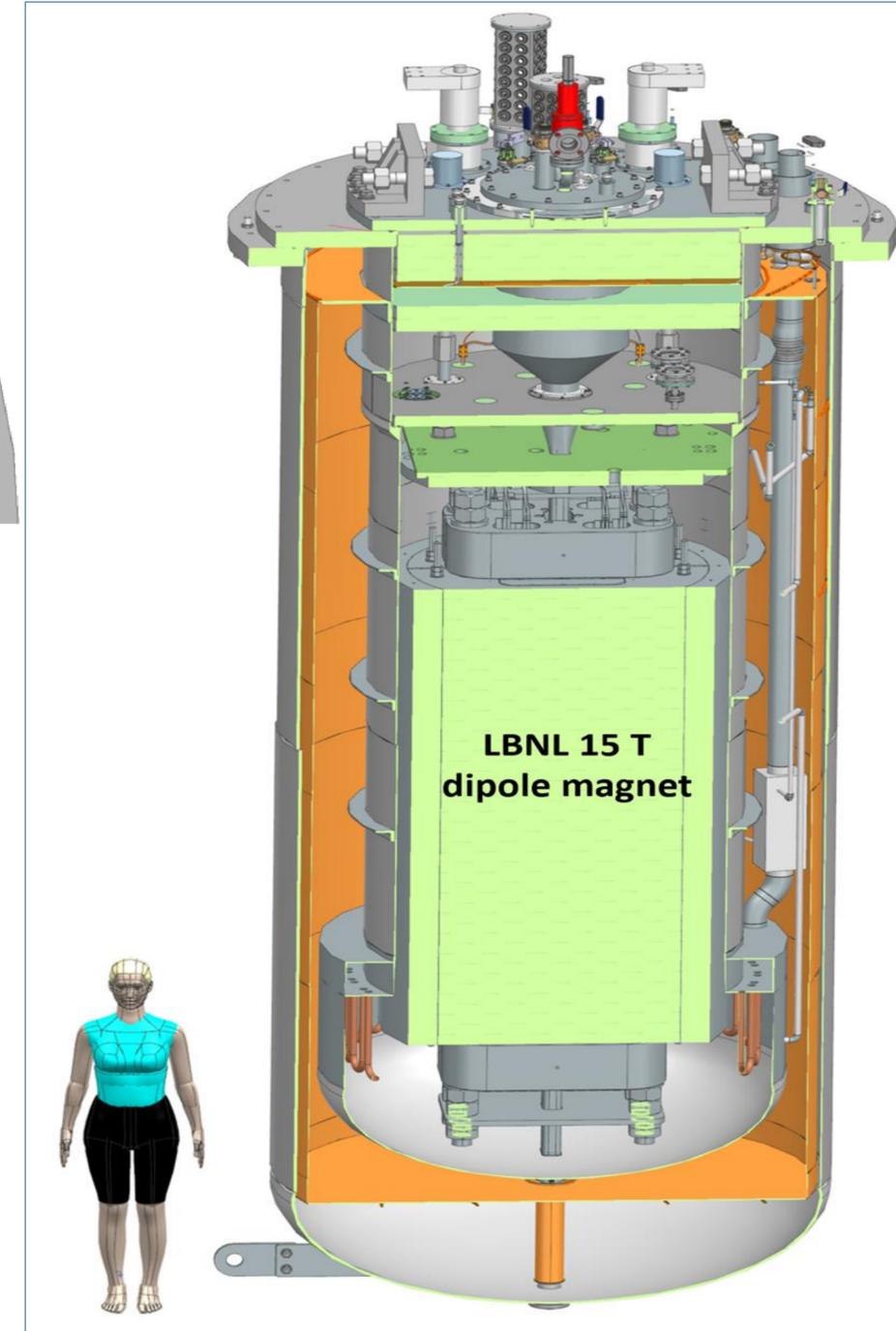
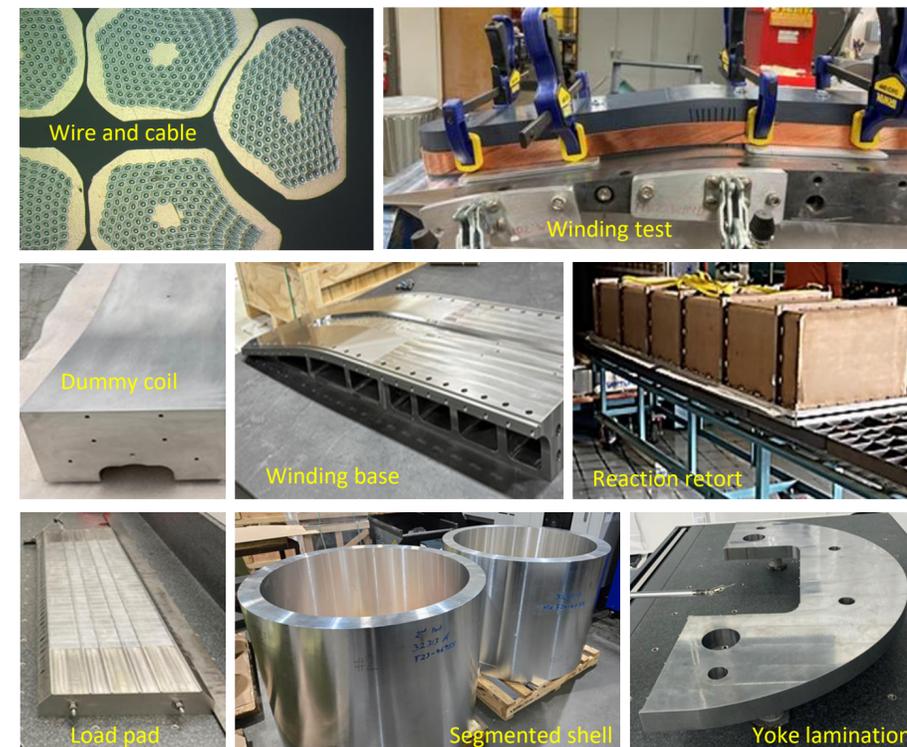
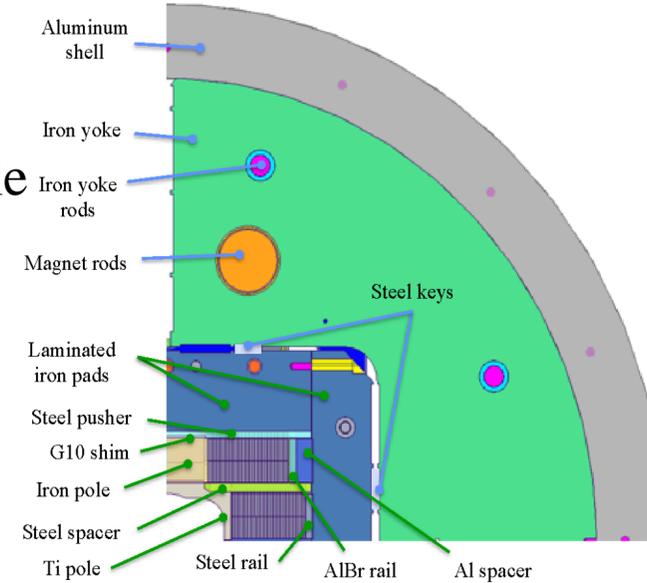
Contact info
velev@fnal.gov

2ND FUSION MAGNET COMMUNITY WORKSHOP

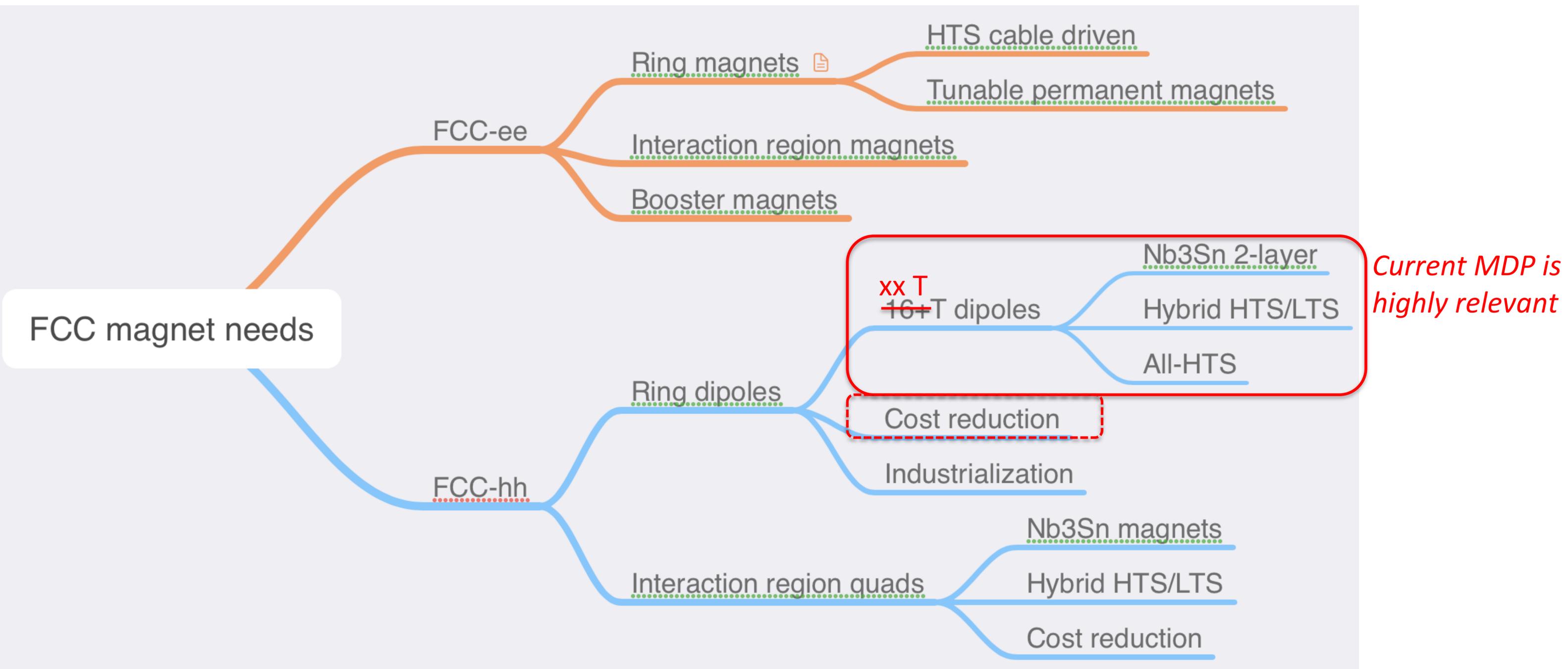
The Applied Superconductivity Center at the National High Magnetic Field Lab in Tallahassee, Florida held its second Fusion Magnet Community Workshop from January 21 to 23, 2025.

Overview

This workshop aims to better define R&D gaps and research objectives of the U.S. fusion magnet community. The workshop will include fusion companies, public fusion program participants, and universities in the U.S. fusion magnet community. Significant technology maturation efforts are underway to demonstrate the compact high field approach for commercial fusion. Given recent progress in superconducting magnet technology driven by the private fusion sector, Fusion pilot plant (FPP) concepts and supporting magnet technologies are being developed in parallel to meet aggressive U.S.



The US MDP currently pursues research addressing a – critical – subset of the magnet needs for a future FCC hadron collider



Current MDP is highly relevant

A muon collider will require critical advances in magnet technology – ripe for synergies with other applications

• Radiation is a major consideration:

- Study tradeoff in aperture/bore+shielding vs magnet radiation hardness
- Further advance understanding of radiation hardness of superconductors and magnet materials

• Rapid acceleration is critical:

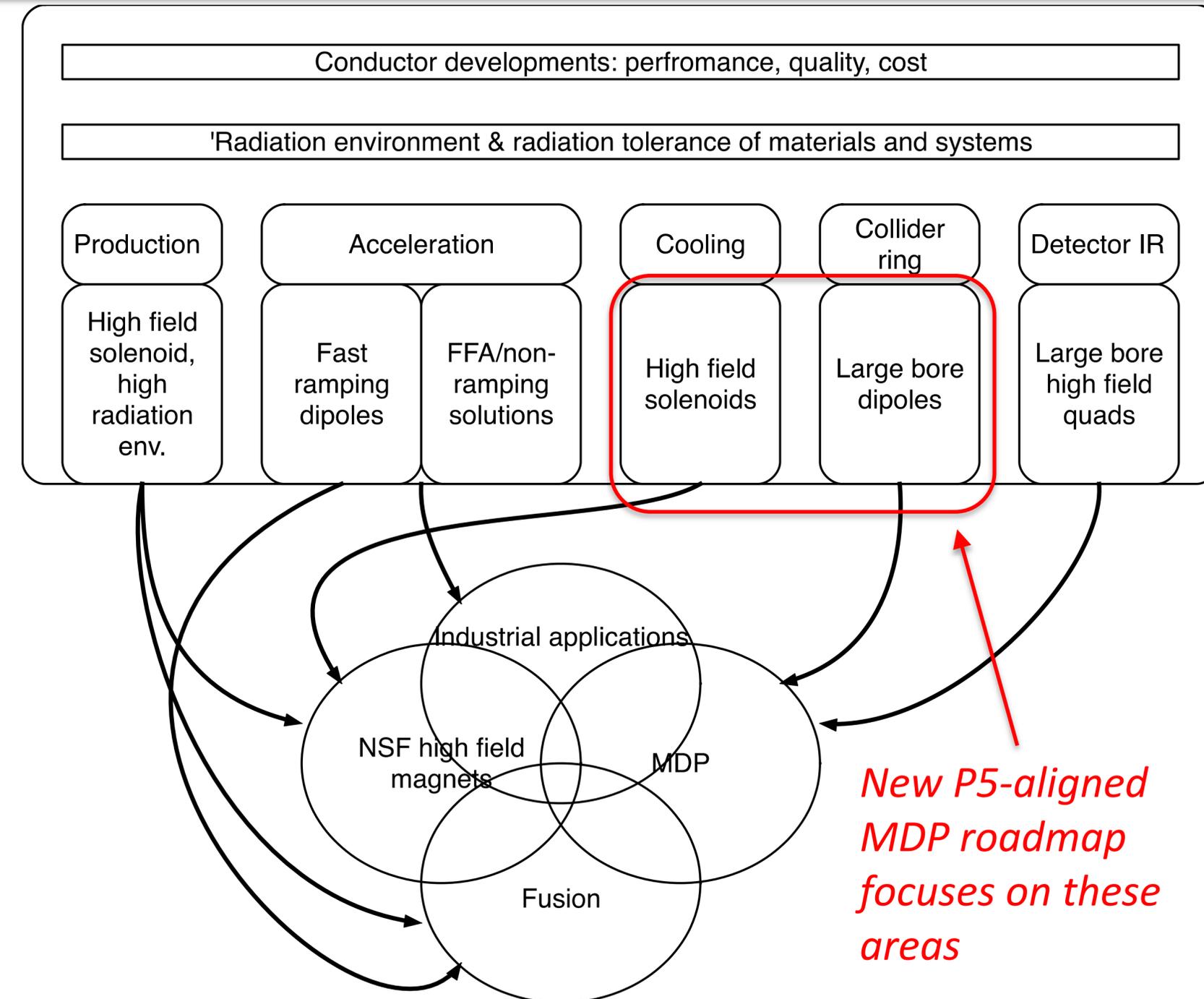
- Study fixed-field booster options where applicable
- Further investigate high dB/dt magnet concepts
- Evaluate acceleration (particularly low-energy) schemes in an integrated approach

• Large thermal loads suggest higher-temperature operation

- Explore all-HTS option
- Explore facility and operational cost models

• Leverage strong synergies with fusion and High-Field magnets (e.g. condensed matter):

- Fastest development path for very challenging target and cooling magnets



Thank you!



New paradigms: quench-free HTS magnet designs?

Traditional superconducting magnet design ensures magnet can survive quenches

Motivation:

- spontaneous quenches => lack of reliable precursor, not controllable
- Training => potential for improved performance after quenching

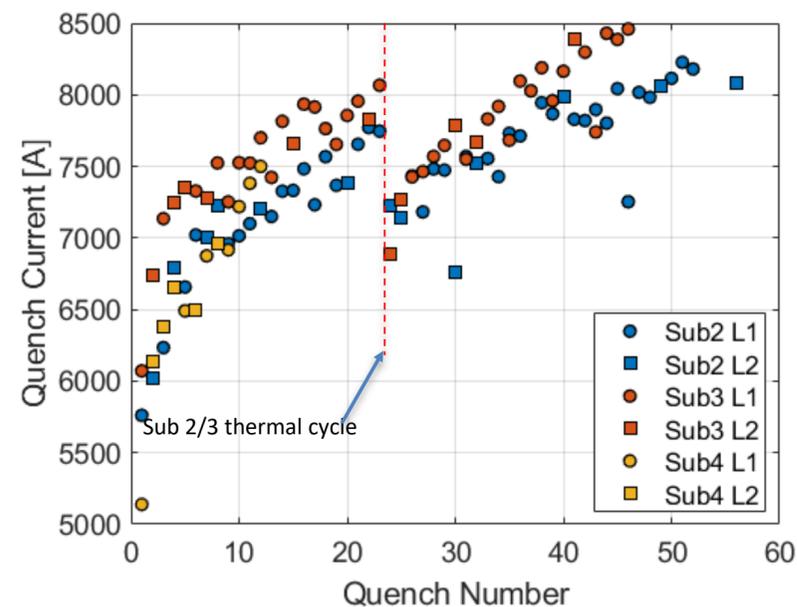
Can we contemplate a new paradigm for HTS?

- Higher MQE => not (?) susceptible to spontaneous quenches => no “random” behavior
- So far no indication that HTS magnets exhibit training => no performance enhancement

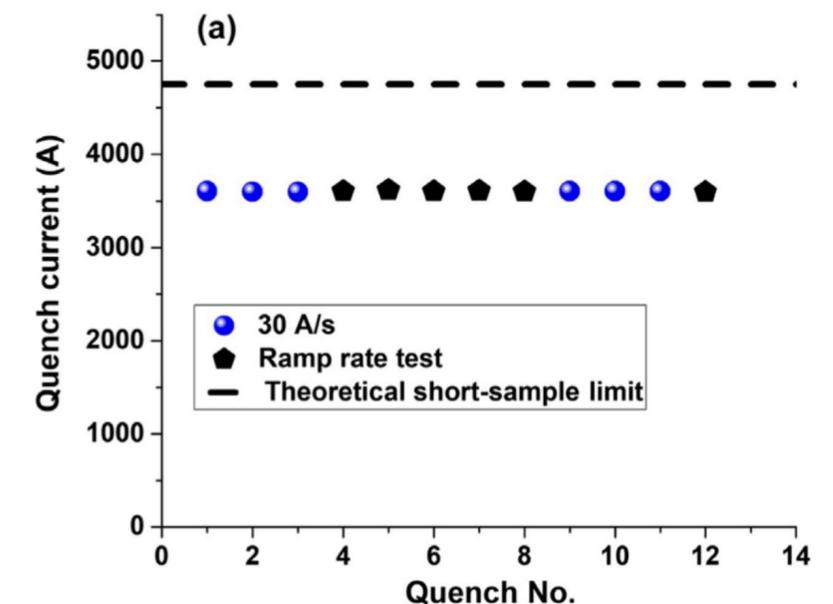
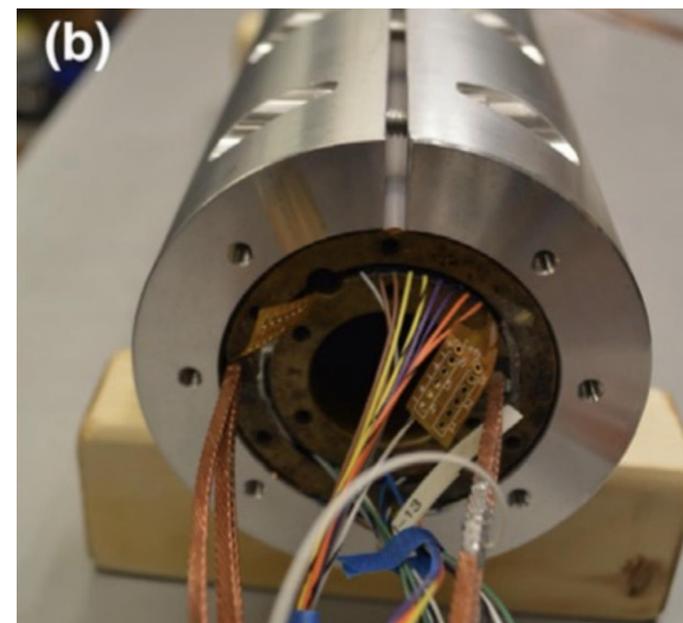
Design to eliminate run-away quenching !?

T. Shen et al., PHYS. REV. ACCEL. BEAMS 25, 122401 (2022)

“Typical” Nb₃Sn CCT magnet training



- “Rapid” training to ~75% short-sample, then rate changes
- “Fair” memory after thermal cycle



New paradigms: Liquid hydrogen cooled collider?

- **Hydrogen has critical advantages:**
 - Plentiful => not supply limited
 - Carnot + liquefaction efficiency => dramatic improvement in "wall-plug efficiency"
 - Strong investments from other societal uses => cost, storage/shipping evolving rapidly
- **But there are concerns/issues:**
 - Safety => highly combustible in presence of oxygen
 - Materials compatibility => some restrictions due to embrittlement/corrosion
 - Limits superconductor option => only REBCO maintains significant transport current at 20K

Sustainability will be a driving consideration in any future international physics experiment - our community needs to make a strong, dedicated effort to explore liquid hydrogen for future colliders