Fermilab Capabilities in Support of Fusion Technology Development

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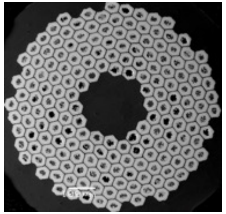
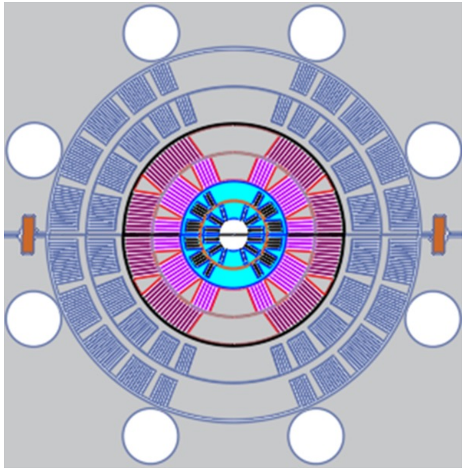
Infrastructure and Capabilities Relevant to Fusion Energy Research

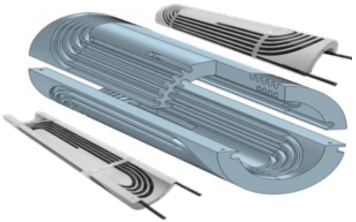
- Superconducting Materials
  - Nb_3Sn
  - REBCO
  - Bi-2212
- Magnet Fabrication Facilities
  - Normal and Superconducting
- Magnet Technology Development
  - Advanced Instrumentation and Diagnostics
  - Modeling and Simulation
  - New materials (epoxy, insulation
- Superconducting Magnet Test Facilities





Superconducting Materials

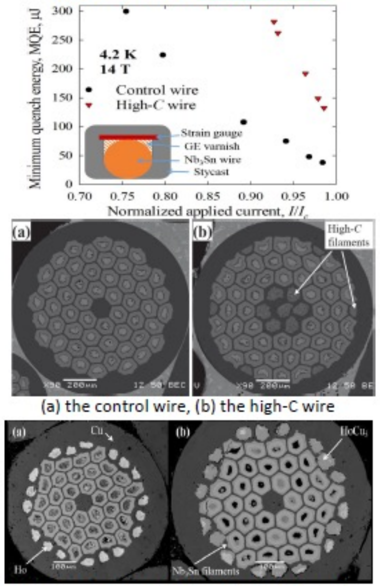
- Nb_3Sn conductor
  - Artificial Pinning Centers and High-Cp optimization and industrialization
- Nb_3Sn magnets
  - 15 T dipole;
  - Stress management (SM) structures for coils in magnets above 16T
- Bi-2212 material and process improvement
- REBCO cables and magnet development
- Measure performance of superconductors
  - Test samples of individual strands and cables with varying temperature, pressure, field, strain, measuring J_C, RRR dependencies



Nb_3Sn wire and cable improvements

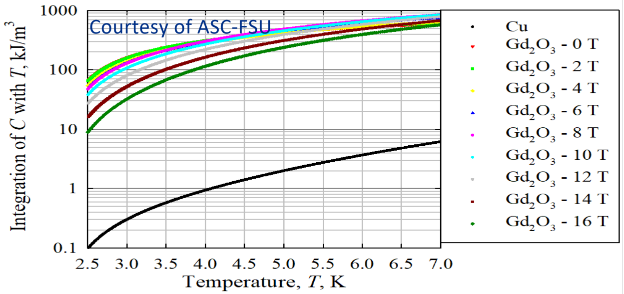
- Increase wire/cable C_p to reduce magnet training
- Increase wire J_c to optimize magnet efficiency and cost

X. Xu *et al.* on high-Cp wire



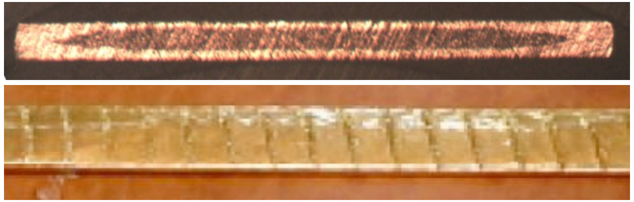
(a) the control wire, (b) the high-C wire

(a) unreacted wire with Ho-powder filaments,
(b) the wire after reaction at 640 °C for 120 hrs.

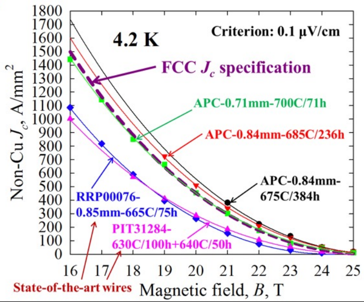


E. Barzi *et al.* on high-Cp cable

Increase cable C_p up to tenfold using a Cu tape doped with Gd_2O_3 powder.



Xingchen Xu *et al.* on Artificial Pinning Center

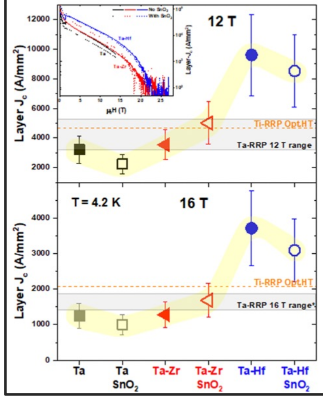


Internal oxidation of Nb-1%Zr
⇒ ZrO_2 particles
⇒ point pinning
⇒ enhance Jc

Exceptional Jc achieved, but stability <16T compromised; further optimization required

Nb_3Sn ha untappe

Shreyas Balachandran *et al.* on Hf alloying of Nb-Ta



550°C/100h+ 670°C/100h

- Nb-Ta-Hf alloy maintains the irreversibility field (4.2K) of 23.5T
- Fine-grain Nb_3Sn can be obtained without O additions
=> Nb or NbTa rods can be replaced by Nb-Ta-Hf alloy

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Fermilab

Developing high-C_p Nb_3Sn conductors to reduce magnet training

- A possible way to reduce training is to increase the energy margin of Nb_3Sn conductors by increasing their specific heat (C_p).
- Fermilab is developing high-C_p Nb_3Sn conductors by adding high-C_p materials into them.
  - Utilize standard manufacturing process.
  - Demonstrated much higher minimum quench energy
  - Producing long lengths (> 2km)

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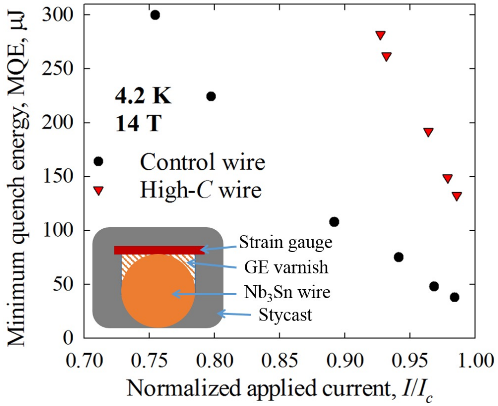
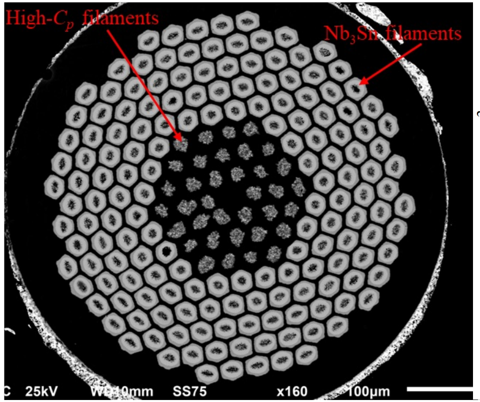
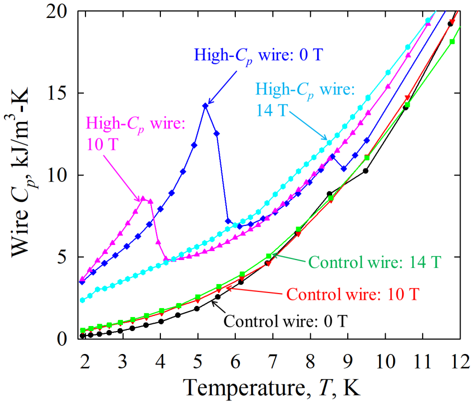




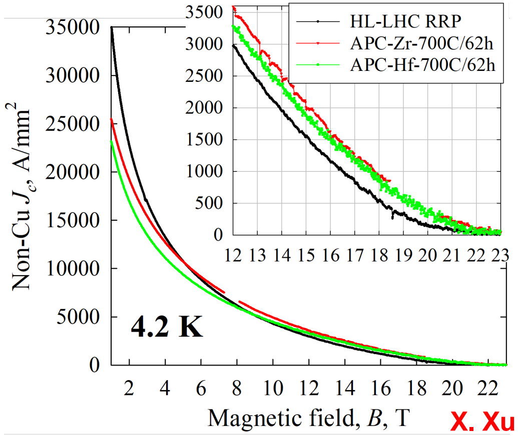


X. Xu, P. Li, A. Zlobin, X. Peng, *Supercond. Sci. Technol.* 31, 03LT02, 2018.

X. Xu *et al.*, *IEEE Trans. Appl. Supercond.*, to be published

APC Nb_3Sn conductors to boost high-field J_c and reduce low-field magnetization

- APC strands with low d_{eff} can be produced w/o issue.
- The high-field J_c of APC conductors has surpassed the state-of-the art and the J_c specification needed by the proposed Future Circular Collider (FCC).
- APC conductors have higher non-Cu J_c at high fields (e.g., 30-40% higher at 16 T) and also lower non-Cu J_c and magnetization (for the same d_{eff}) at low fields (e.g., ~30% lower at 1 T) than state-of-the art



X. Xu *et al.*, submitted

- Presently working to make APC conductors ready for magnet use.
- Expect to take 1-2 years.

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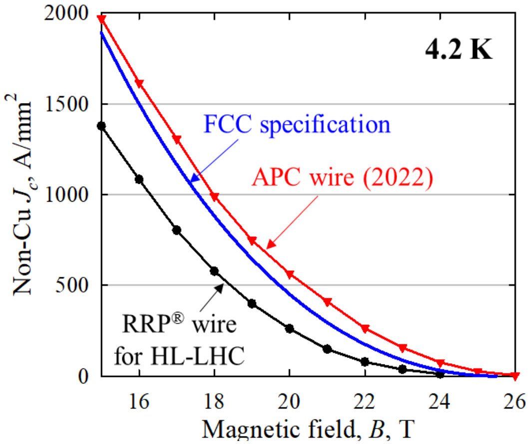

X. Xu *et al.*, *Supercond. Sci. Technol.* 36, 035012, 2023

Fermilab

Strand & Cable Testing Lab

4 cryostats with 15T SC solenoids, cold bores between 64 and 147 mm, test temperature 1.8-100K.

- 2 kA PS and DAQ system
- 28 kA SC transformer
- I_c (B,T, e,…), RRR, magnetization, stability measurements

5 ovens up to 1250°C for heat treatment in Argon and in Oxygen.

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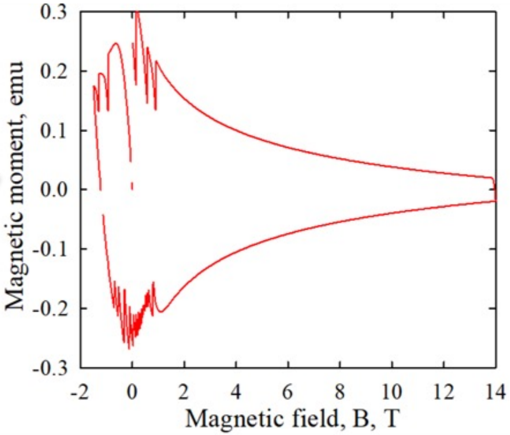
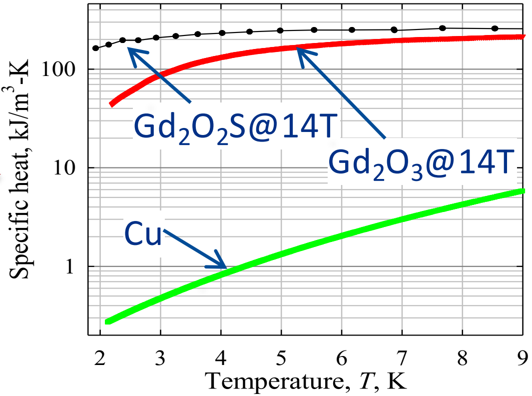
A Variety of Measurement Capabilities - example PPMS

- Temperature range: 1.9 K to 400 K
- Magnetic range: -14 T to 14 T
- Functions: vibrating sample magnetometer (VSM), heat capacity, resistivity, thermal conductivity

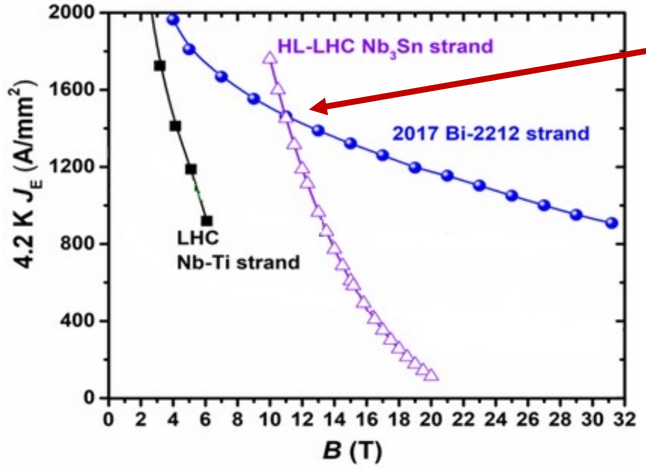
Magnetic moment versus field (*M-H*) loops measured by the PPMS:



Specific heat values measured by the PPMS:

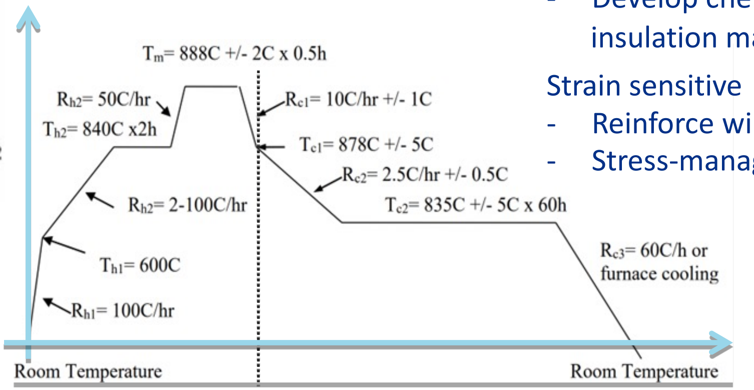


Exploring the use of high temperature superconductors for accelerator magnets and other high field magnet applications



Bi-2212 exceeds performance of Nb_3Sn for fields above 12 T

Complex Heat Treatment
888^0C, O_2 atmosphere at 50bar



Simplify reaction by split melt process

Proposed work to improve performance

Susceptible to damage during cabling
- Optimize sub-element geometry

Leaks during reaction
- Develop chemically compatible insulation materials

Strain sensitive
- Reinforce wire and/or cable
- Stress-managed support structures

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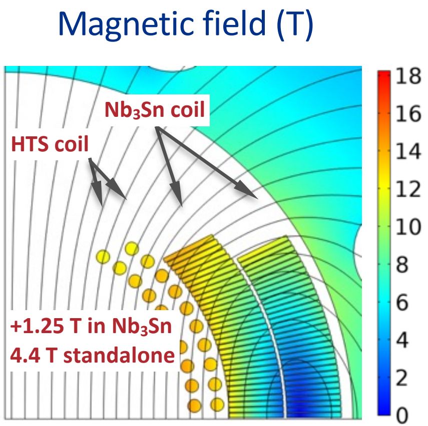
HTS: A novel magnet technology - Conductor On Molded Barrel (COMB)

Hybrid magnet demonstrator



- Short sample studies to determine the bending degradation.
- Performance demonstration to reach 5 T self field using CORC® cable.
  - Test expected in 2023.

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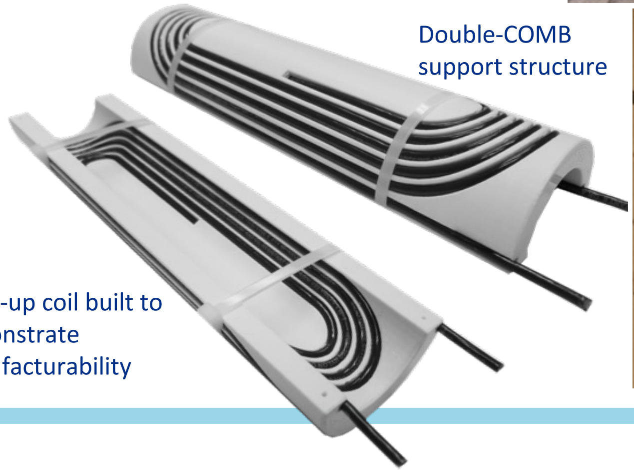
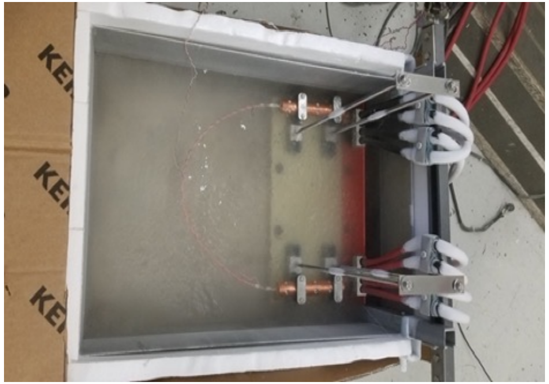
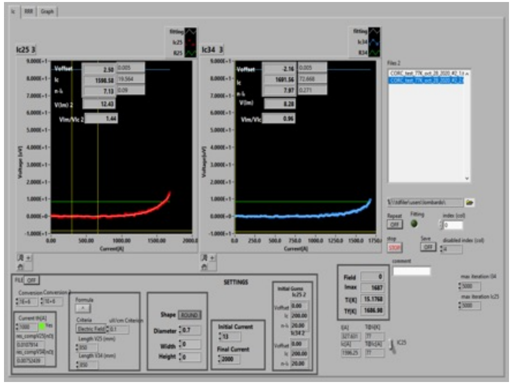
V. Lombardo (lombardo@fnal.gov)



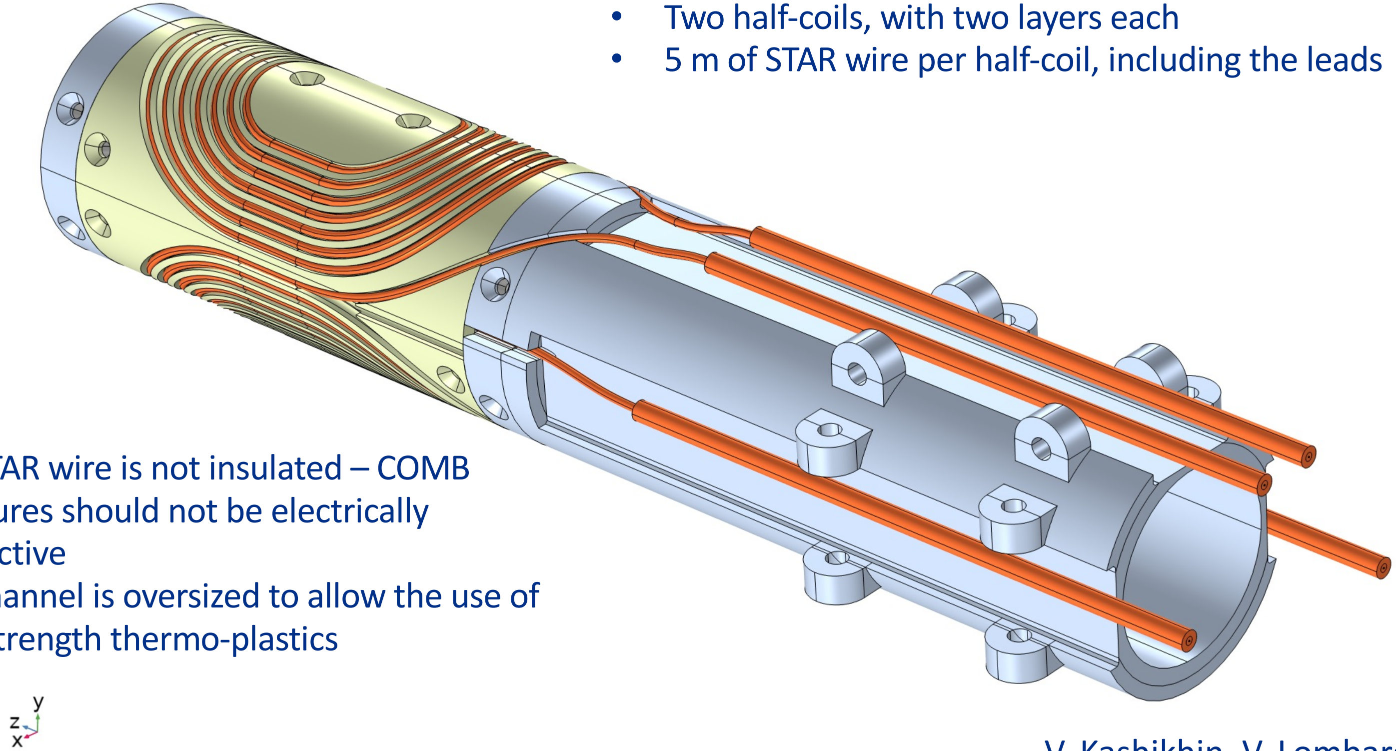
Mock-up coil built to demonstrate manufacturability





REBCO COMB* magnet with STAR® wire

- 60 mm clear bore
- Two half-coils, with two layers each
- 5 m of STAR wire per half-coil, including the leads

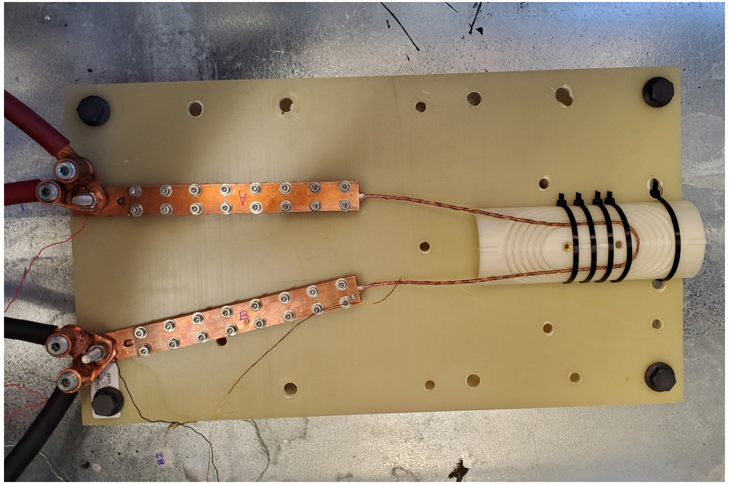


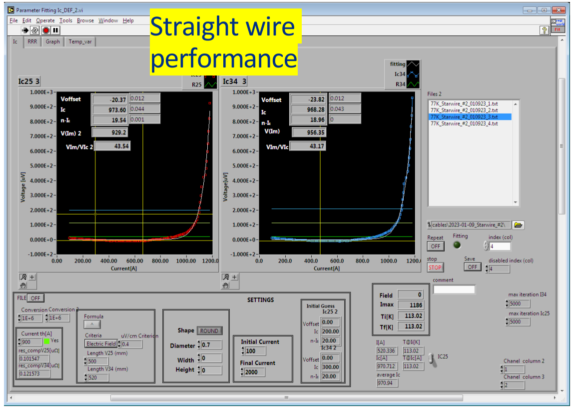
- The STAR wire is not insulated – COMB structures should not be electrically conductive
- The channel is oversized to allow the use of high-strength thermo-plastics

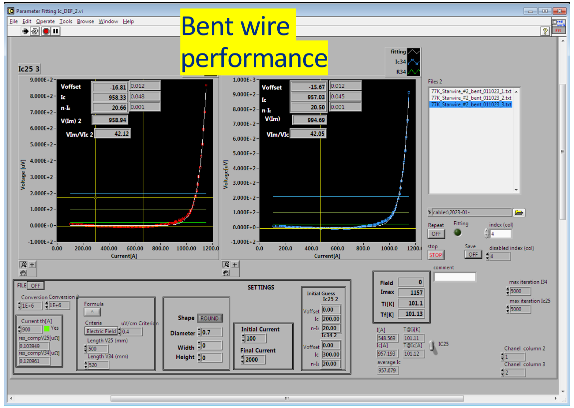
*Conductor on Molded Barrel

V. Kashikhin, V. Lombardo, FNAL

REBCO STAR® Wire Testing







- A short piece or STAR wire was tested in liquid nitrogen before and after bending around the 33-mm wide pole in the COMB structure (the tightest bend in the coil)

- ~98% critical current retention was observed (not corrected for self field), which essentially means no degradation due to bending

V. Kashikhin, V. Lombardo, FNAL

Fermilab

Superconducting Magnet Fabrication Facilities

- Supporting projects and R&D
- The capabilities currently include:
  - Manufacturing SC cables;
  - Coil winding, curing, reaction, epoxy impregnation;
  - Assembling multiple coils into a magnet cold mass;
  - Instrumentation

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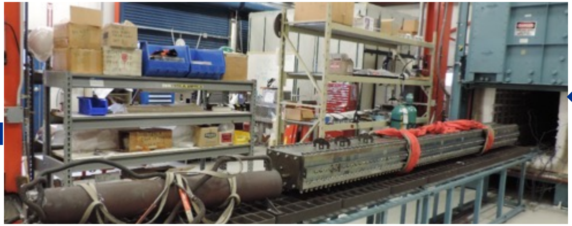
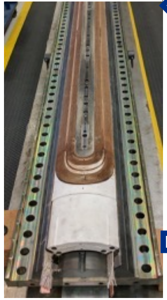
Coil winding

7.7 m curing press



6 m Reaction Oven &Coil Tooling

Reacted Coil



7 m long vacuum oven, VPI

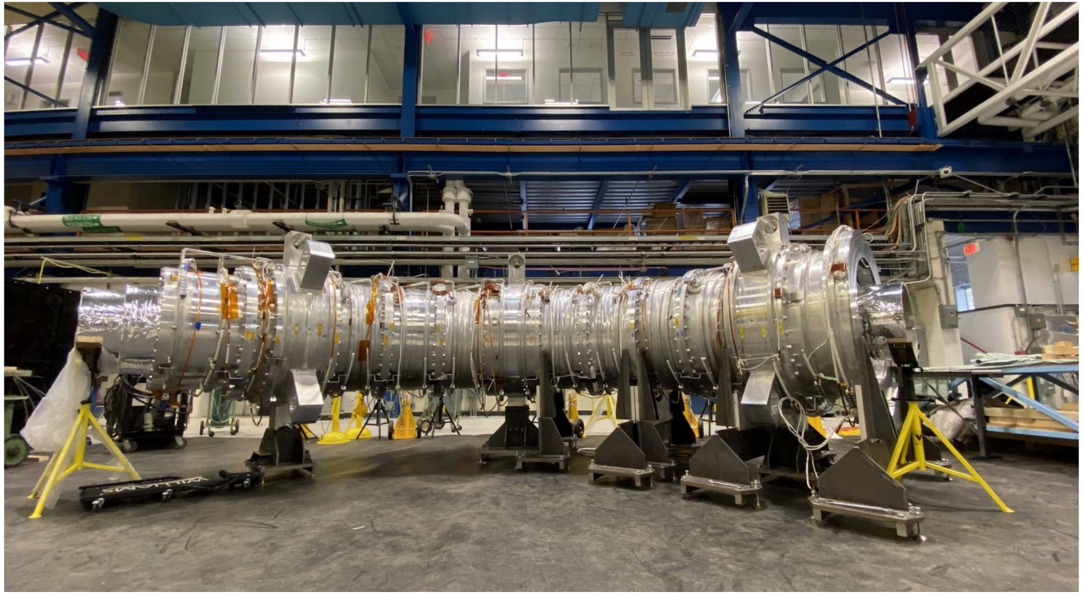
Final Coil

Cold Mass Assembly/Fabrication for the LHC Hi-Lumi Upgrade

- Large scale assembly facility for LHC cryoassemblies
  - Expertise in magnet inspection, cryostating, alignment

Facilities for Large Scale Magnet Test and Assembly

Superconducting Solenoids for the Fermilab Mu2e Experiment



Designed and Fabricated in partnership with Industry

Magnet Test Facilities at Fermilab

- MTF is an ensemble of comprehensive capabilities and facilities that enable Magnet Science and Technology R&D and support of projects at Fermilab
- State-of-the-art superconducting magnet test facilities to support of DOE programs and projects
- World-class magnet testing capabilities include
  - Room Temperature Magnet Measurements
  - Superconducting Magnet Testing
    - Vertical Magnet Test Facility
    - Stand 4 Horizontal Test Stand
    - Stand 3 (HTS leads, small R&D magnets)
    - Stand 7 cryostat for small cryo-cooled magnets

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- HEP projects for the next decade
- Support testing of LTS and HTS conductors for Fusion and HEP
- Support complex R&D for future lepton and hadron colliders
- Develop cutting-edge test systems and stands

Approximately 45 staff members (scientists, engineers, technicians) with extensive experience and critical skills in magnet design, fabrication and test - deep roots in Tevatron, SSC, LHC IR quadrupole projects and High Field magnet R&D

Vision for Fermilab's MTF

- Fermilab has the potential to become a cryogenic temperature test facility/center for the DOE National Labs
- Currently, we are building a HTS cable-testing facility jointly for the US DOE Offices of High Energy Physics and Fusion Energy Sciences
- Fermilab possesses all the necessary expertise to support such a center:

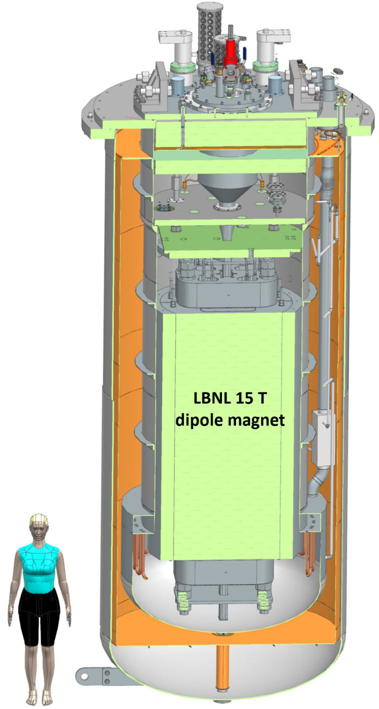
  Cryogenic expertise

  High current and high-power supplies experts

  Quench protection for devices with large stored energy

  Qualified personnel to test cryogenic devices for projects and R&D

High Field
HTS cable test facility



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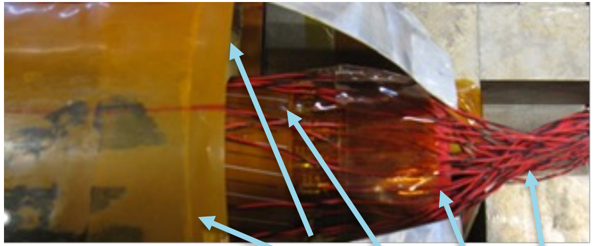
Magnet Technology Development

- Training and diagnostics
  - Fibers as strain gauges, training studies and mitigation
- Instrumentation and quench protection
  - New accurate quench antennas, fibers for HTS QP
- Material studies
  - New epoxy and insulation material tests, high-Cp materials in cable and epoxy
- Modeling and simulation
  - New tools (STEAM, AI for Nb_3Sn training prediction)

High Resolution Quench Antenna

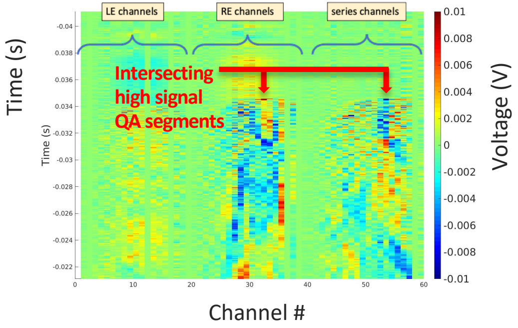
- High spatial and temporal quench location resolution based on flexible quench antenna arrays



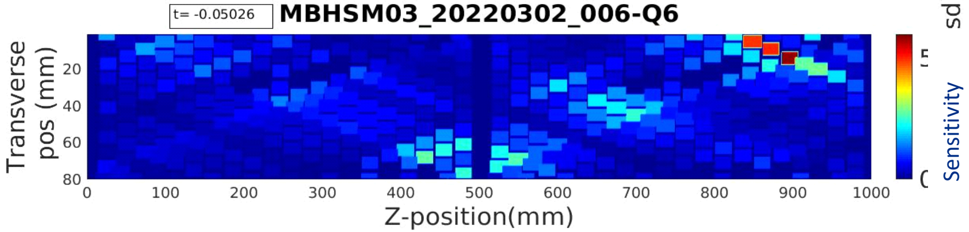
Crossing sensors

Achievable combined
(with voltage tab measurements)
resolution down to ~ 1 mm

Example quench



Visualization of quench or event activity development in a magnet
by correlated variables (yield proportional to the product of multiple signals)



- (Off-line) Monitoring of electro-magnetic activity during magnet powering
  - Acoustic activities are separately monitored but at lower spatial resolution

Warm Test Stand (WTS) for Pick Up Coils

- Ability for specialized quench antenna or magnetic measurement probe development relying on room-temperature test stand, a.k.a. WTS, emulating real magnet (or chosen) conditions

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Investigating QA designs/boards pre- or post- “cold” tests.

Flux variation source positioning (loop holder)

(the loop plane is perpendicular to the QA board plane and along the QA’s length)

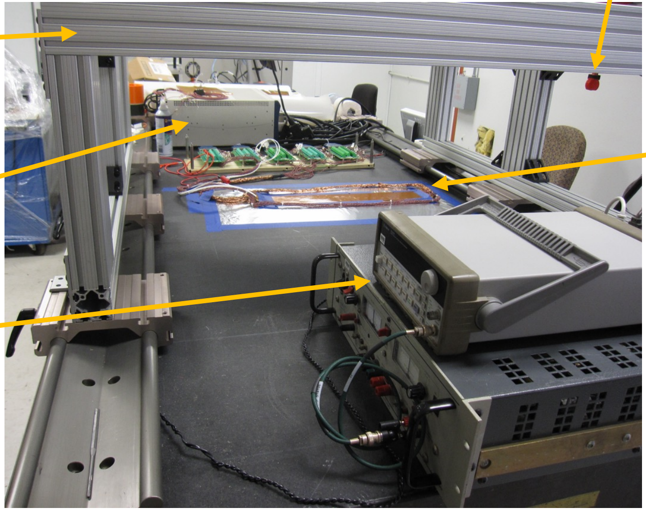
WTS (positioning system) frame

(positioning to within tens of microns)

DAQ
(100 kHz)

Current generator

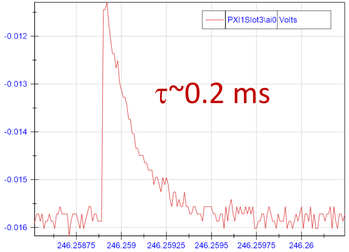
(square waves, 100 Hz, ±12 A)



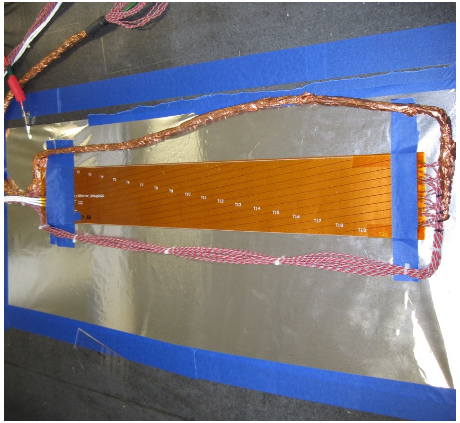
Flex-QA

(over grounded aluminum foil)

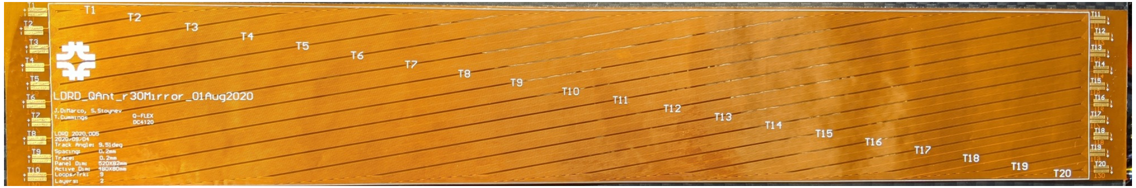
QA response to a pulse

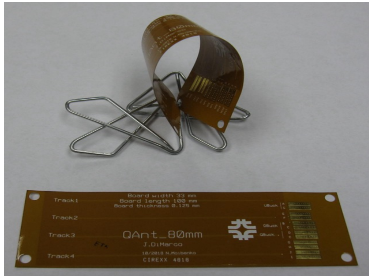


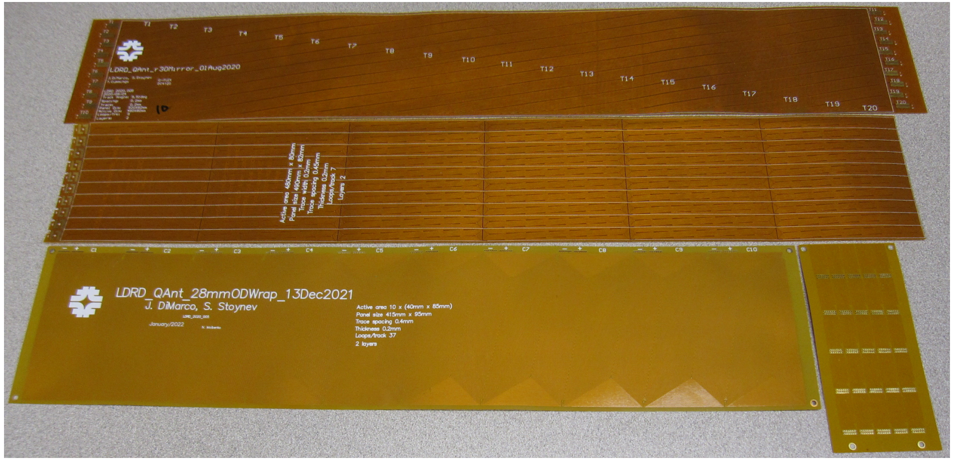
QA set up for measurements



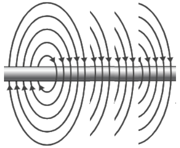
Experienced in the Use of High-Quality Flexible PCB Instrumentation

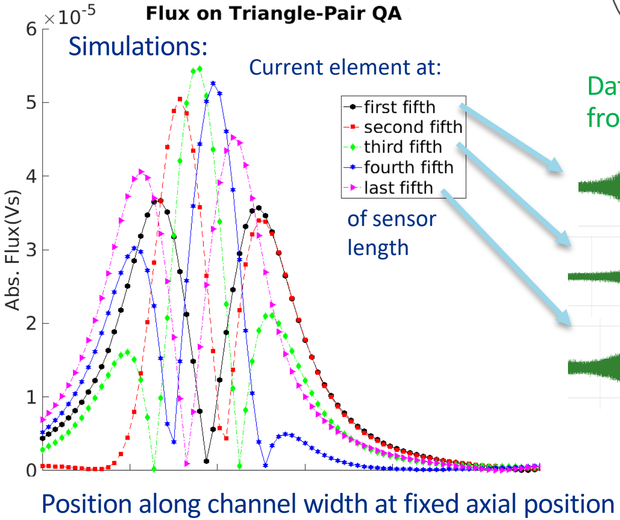




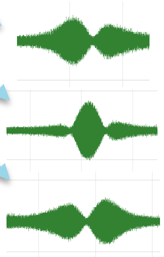


Adequate simulations of QA response (data are dual-polarity)





Data shapes from WTS:



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Ultra Sensitive V-I Measurement Capability

- Multi-channel nano-voltmeter, a.k.a. MUX, for monitoring/investigating superconductor degradation
- Internal noise /stability/ at low-tens of nano-V level
- Protected from voltage surge up to 1.5 kV

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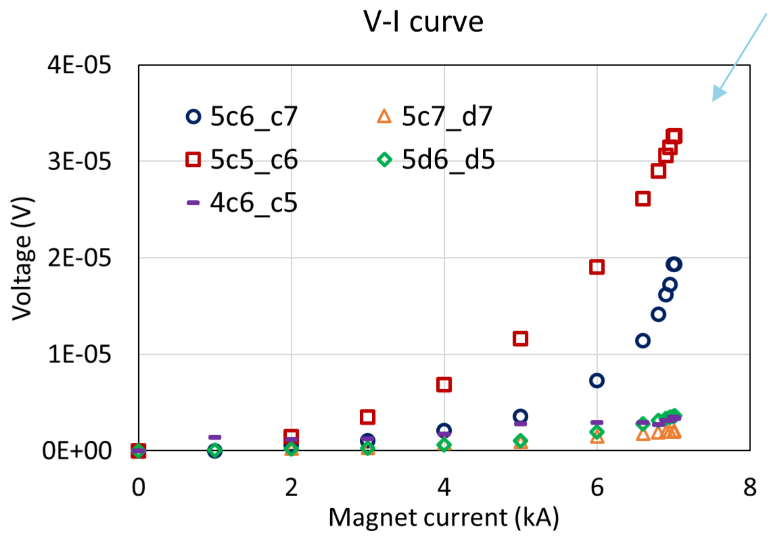
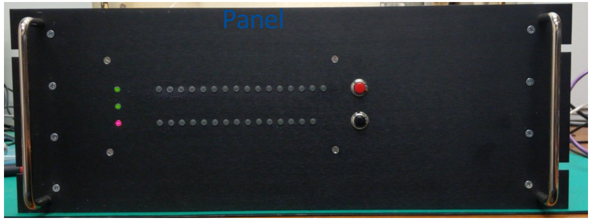
"15 T" dipole magnet data

This indicates severe conductor degradation

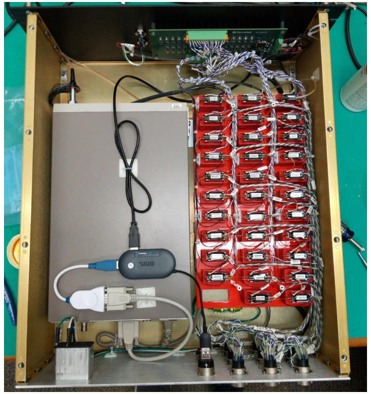


Front Panel



Back Panel

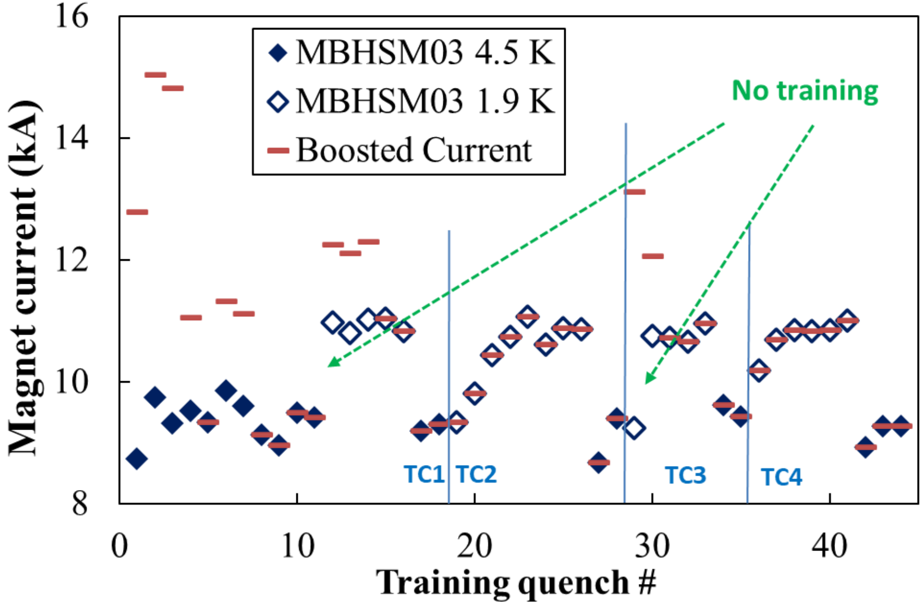
Internal View



Quench Current Boosting Device (QCD)

- Novel device for “eliminating” training in superconducting magnets
  - Capacitor based (0.4 F, up to 1 kV)
  - Meaningful for up to ~ 20 mH magnets

Data from “11 T” mirror magnet



QCD was not applied in thermal cycle two (TC2) and TC4

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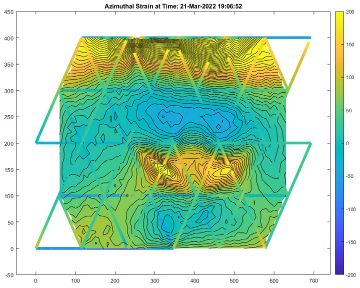
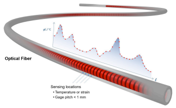
Optical Fiber Strain Measurement System

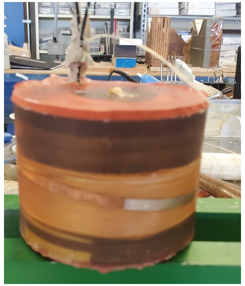
Strain map obtained using distributed Rayleigh sensors during the welding of the stainless-steel shell of a magnet cold mass

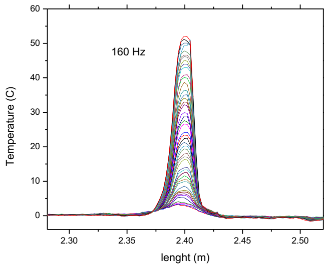




- For a 20 m fiber there are ~30,000 individual sensing regions
- Strain map obtained covers an area approximately 100,000 times standard gage

Next step: obtain for the first time a strain map of a superconducting coil during magnet training





Tests in LN_2 have been successfully performed using:

- A 5m fiber encapsulated in a Teflon tube wound in a small solenoid and discharging a capacitor.
- Produces quench evolution profile in Nb_3Sn coils over a temperature range of 180K in 60ms.

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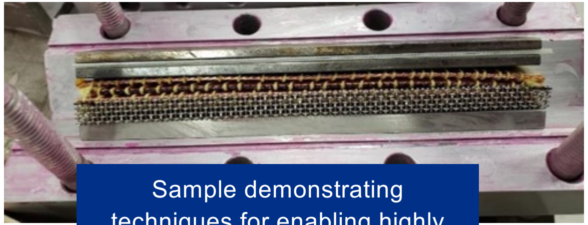
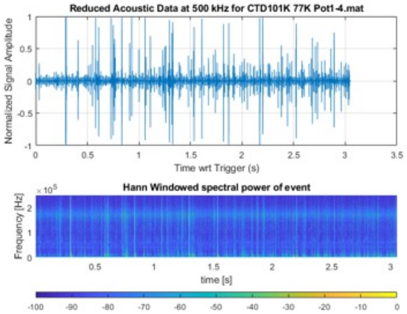
Composite Materials R&D

- Develop insulation systems that reduce or eliminate magnet training
- Build quiet magnets, eliminate training
- Quantify energy release events under actual loading conditions
- Develop techniques for enabling different classes of magnet impregnation systems

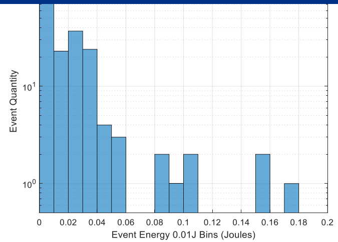


Sample demonstrating techniques for enabling highly viscous resins



Thermal Shock sample demonstrating poor thermal shock resistance

Load and acoustic data: Enabling quantification and measurement of behavior in magnet like configuration (with LBNL help)



Energy Spectrum during sample testing: Use this to target quench mitigation actions

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