Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Applied Physics and Superconducting Technology Directorate

Ram C. Dhuley, PhD

56th Users Meeting

28 June 2023

APS-TD – Mission

- **Pursue highly innovative R&D program** in superconducting magnets and SRF for accelerators and quantum technology to advance the lab's scientific mission and to help in defining the lab's future direction
- **Operate accelerator test facilities** to maximize the lab's scientific productivity and impact
- **Develop and build next generation accelerators and detectors** using cutting-edge technologies
- **Educate and train the next generation of physicists and engineers**

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APS-TD – Overview

https://td.fnal.gov/

Divisions

- Design, Fabrication, and Metrology
- Magnet Technology
- Cryogenic Technology
- SRF Technology and Material Science

Research and Development

- Superconducting RF
- Superconducting Magnet
- Quantum Technologies

Capabilities

- Cryogenics
- Machine shop, QA/QC
- SRF; Magnets

Programs and Projects

- PIP II
- LCLS-II and LCLS-II HE
- High Luminosity LHC Accelerator Upgrade Project (HiLumi AUP)
- Mu2e
- SRF Program
- Magnet Development Program
- Accelerator Support
- Compact SRF accelerator (IARC at Fermilab)

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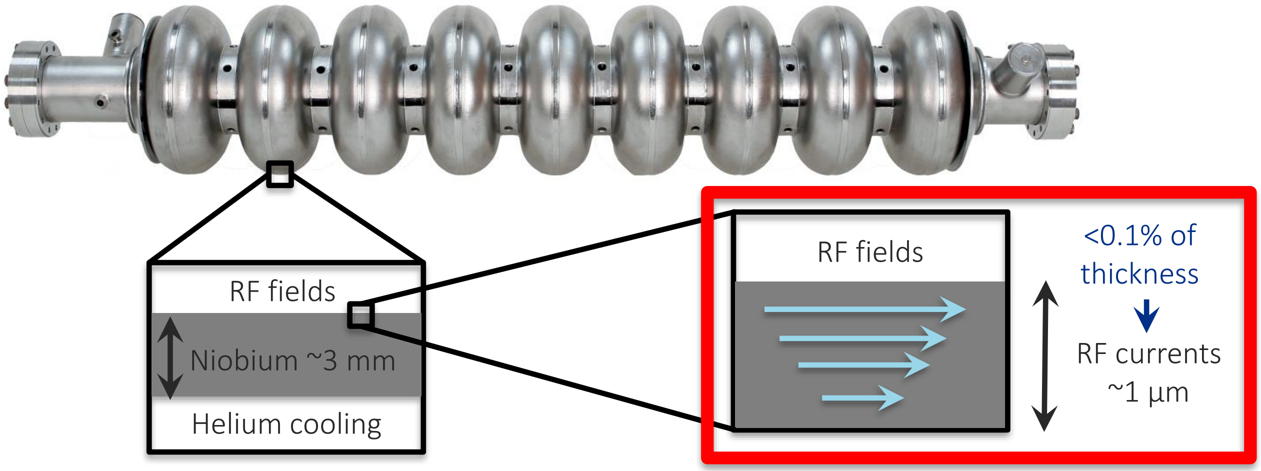
Superconducting RF R&D

https://td.fnal.gov/srf-rd/



Final treatment is crucial to performance

Ongoing research topics:

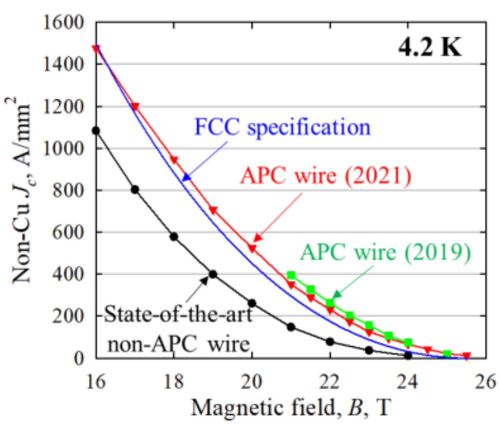
- Improving Nb_3Sn Cavity Performance Using Centrifugal Barrel Polishing, E. Viklund
- Thermal Stability of Nb_3Sn Surface Oxide, A. Cano
- Comparing the Effectiveness of Low Temperature Bake in EP and BCP Cavities, H. Hu
- Characterization of Nb films at low temperatures, B. Abdisatarov
- Electropolishing study on nitrogen-doped niobium surface, V. Chouhan
- Single-spoke cavity plasma processing, P. Berrutti
- PI Loop Compensation for 2.6 GHz Cavity Dark Photon, C. Contreras-Martinez

Superconducting materials/magnet R&D

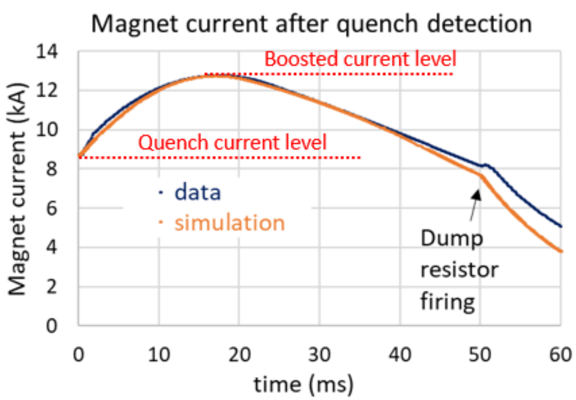
https://td.fnal.gov/magnets-rd/

Ongoing research themes:

- Nb_3Sn conductor with artificial pinning centers (APC), X. Xu
- Quench Current-boosting Device (QCD), M. Baldini, S. Feher, S. Stoynev , et al.
- Quench antenna arrays, J. DiMarco et al.
- Multiplexed nano-voltmeter for superconductor damage assessment, T. Cummings et al.



Nb_3Sn conductor with APC meeting FCC spec



QCD enabled boosted current level

Internal view of the newly developed MUX

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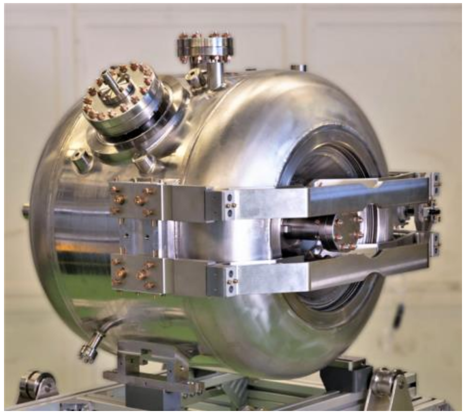
Proton Improvement Plan II (PIP II) https://pip2.fnal.gov/

- **High-power proton accelerator**, an essential enhancement to the Fermilab Accelerator Complex
  - Power the world's most intense high-energy neutrino beam for DUNE
- First particle accelerator built in the U.S. with significant contributions from several **international partners**
- **APS-TD role:**
  - SRF cavities and cryomodules – HWR, SSR, elliptical
  - 2 K cryogenics for cooling the SRF cavities

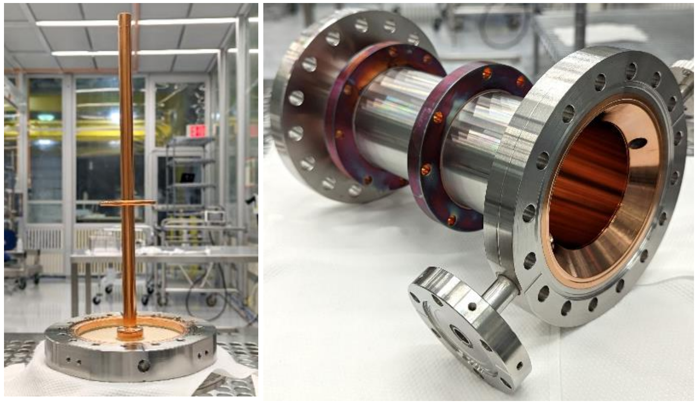
PIP II – SSR major advancements

- **Pre-production SSR-2**
  - Completed manufacturing of all high-power couplers and 3 ppSSR2 cavities
- **Production SSR-1**
  - Cavity fabrication in progress, Cryomodules at the final design stage

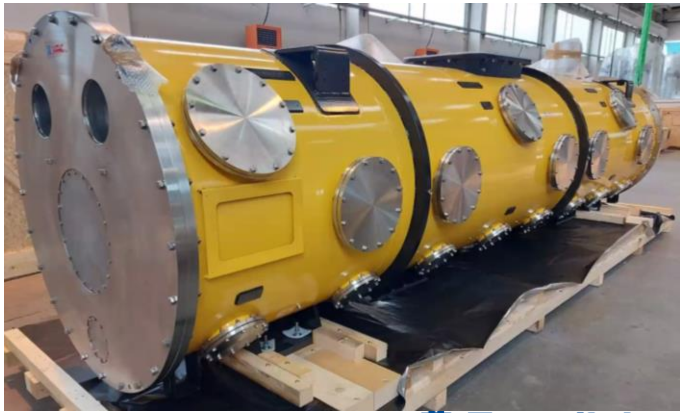
ppSSR2 cavity with Tuner



ppSSR2 Coupler Antenna and Vacuum End

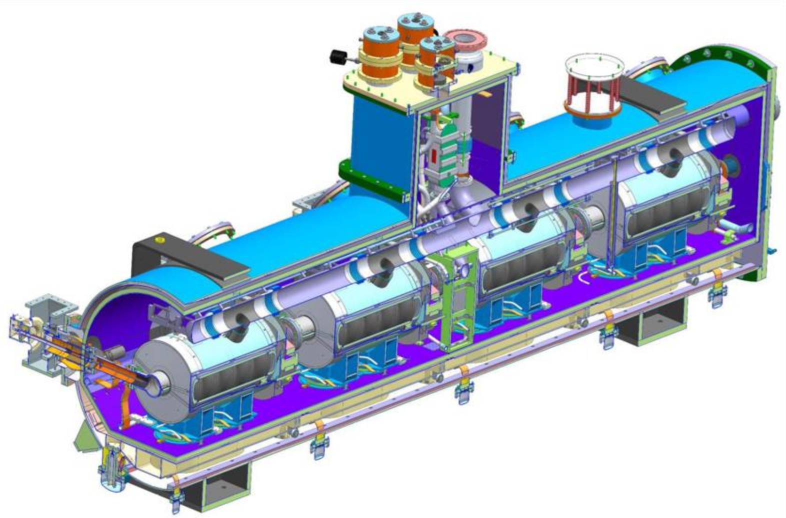


ppSSR2 Vacuum Vessel

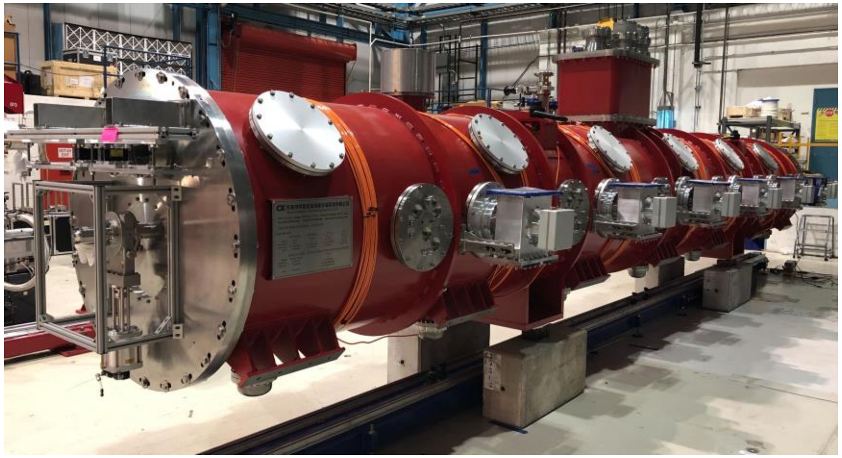


PIP II – 650 MHz major advancements

- **Low β 650 MHz**
  – Completed qualification of pre-production cavities
  – Finalized the design of pre-production cryomodules
- **High β 650 MHz**
  – Completed construction, assembly, and testing of the prototype cryomodule



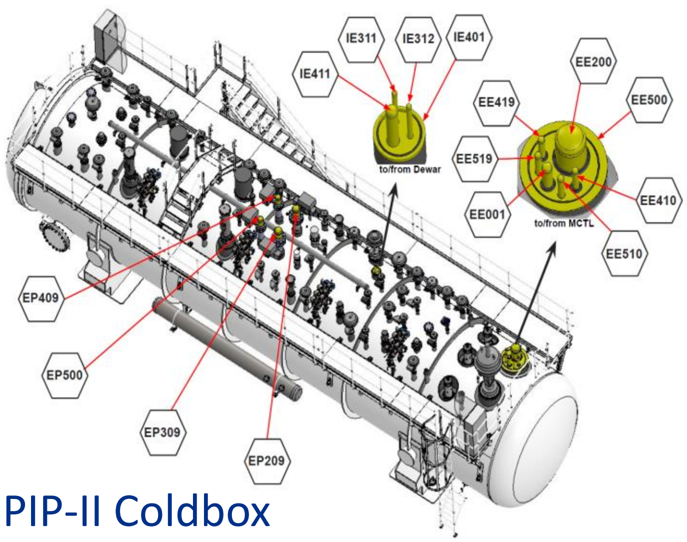
Low Beta pre-production cryomodule final design



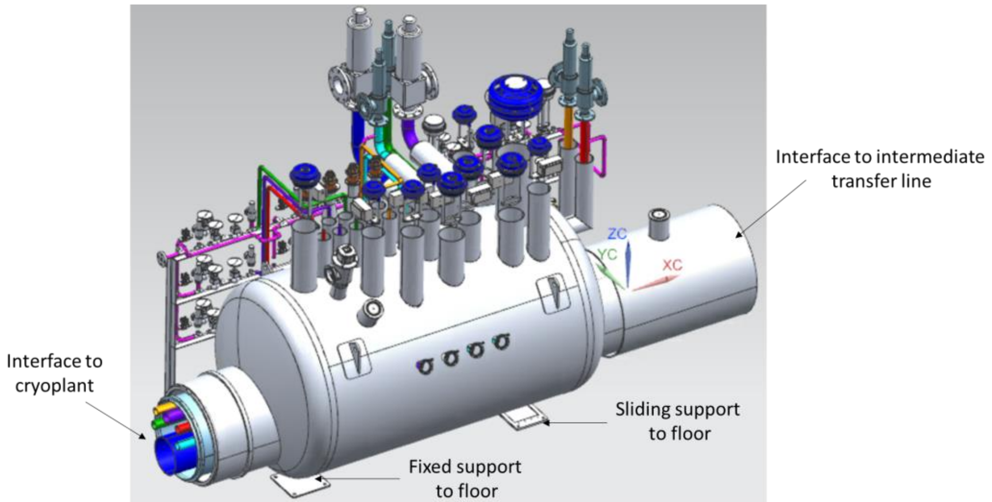
Completed HB650 cryomodule

PIP II – Cryogenics major advancements

- **Cryoplant**
  - Building construction complete, beneficial occupancy granted
  - Coldbox is in the final design phase
- **Cryogenic distribution system**
  - Began procurement of vacuum-jacketed multi-transfer lines



PIP-II Coldbox



PIP-II Distribution Valve Box

LCLS-II HE

https://lcls-ii.fnal.gov/

- **LCLS-II HE is the high energy upgrade of the LCLS-II SRF linac at SLAC**
  - Electron energy 4 GeV → 8 GeV
  - **SRF linac** uses 1.3 GHz elliptical cell SRF cavities, operating **cryogenically** near 2 K
- **APS-TD role:** Produce world class cryomodules for; support cryogenic distribution system design

LCLS-II HE – major achievements

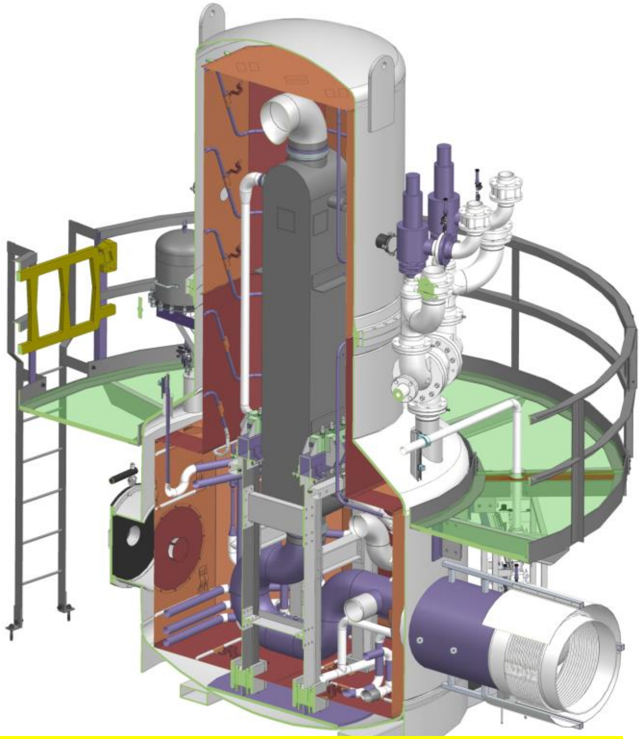
- Verification Cryomodule (vCM) achieved a cw V_{acc} >200 MV under full module operation; delivered 4 CMs to SLAC
- Cryogenic Distribution Box final design is complete; procurement in progress

vCM at SLAC

F22 at SLAC

F21 at SLAC

F23 at SLAC



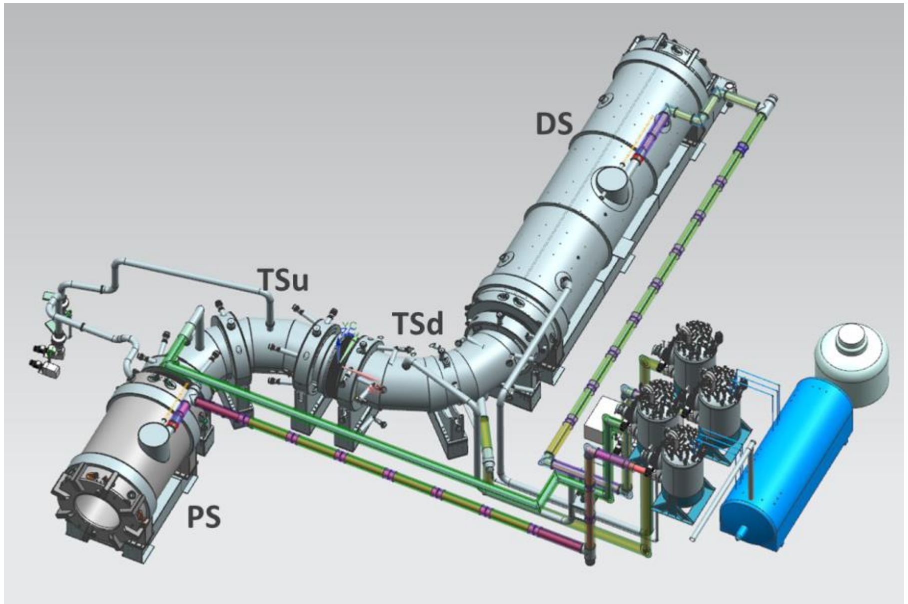
LCLS-II HE Distribution Box, vendor model

Mu2e

https://mu2e.fnal.gov/

- **Experiment at Fermilab** to search for the charged lepton flavor violating process $\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$

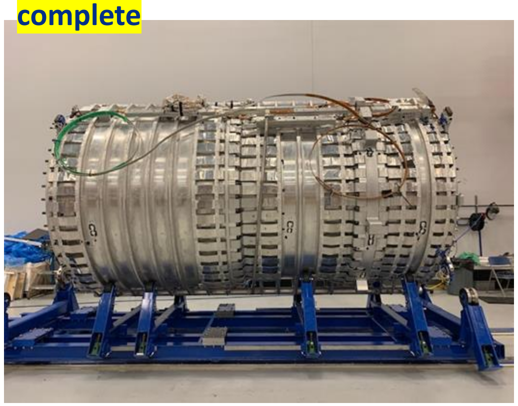
- Heart of experiment is **4 large superconducting solenoids**
  - Production Solenoid: built in industry
  - 2x Transport Solenoid: coils built in industry, assembled at FNAL
  - Detector Solenoid: built in industry

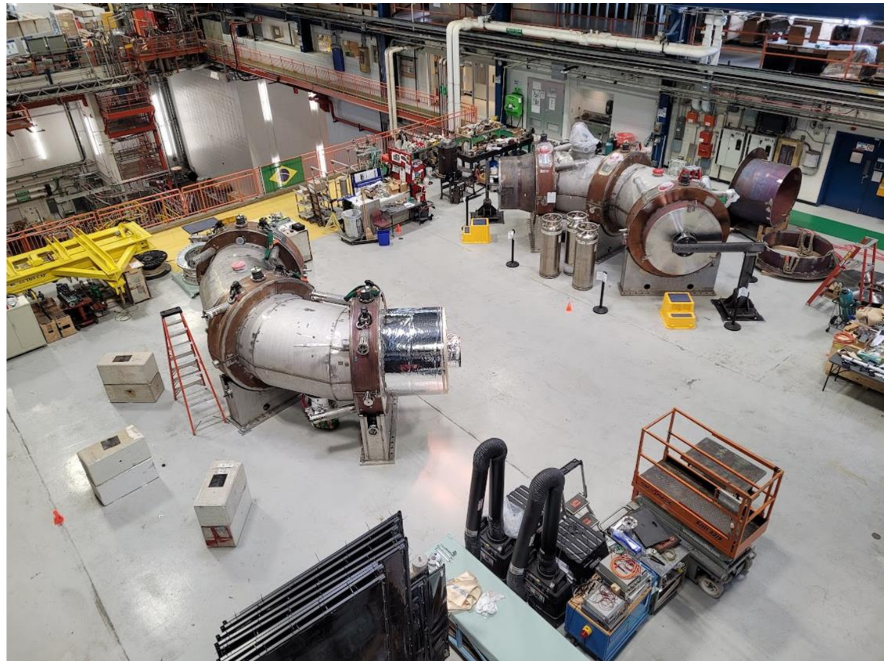


- **APS-TD leads effort** to deliver solenoids and build local infrastructure (cryogenics etc.) to power them

Mu2e – major achievements

Production Solenoid cold mass complete

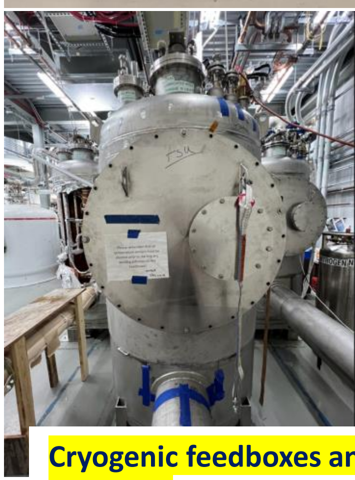




Transport Solenoids in final assembly stages

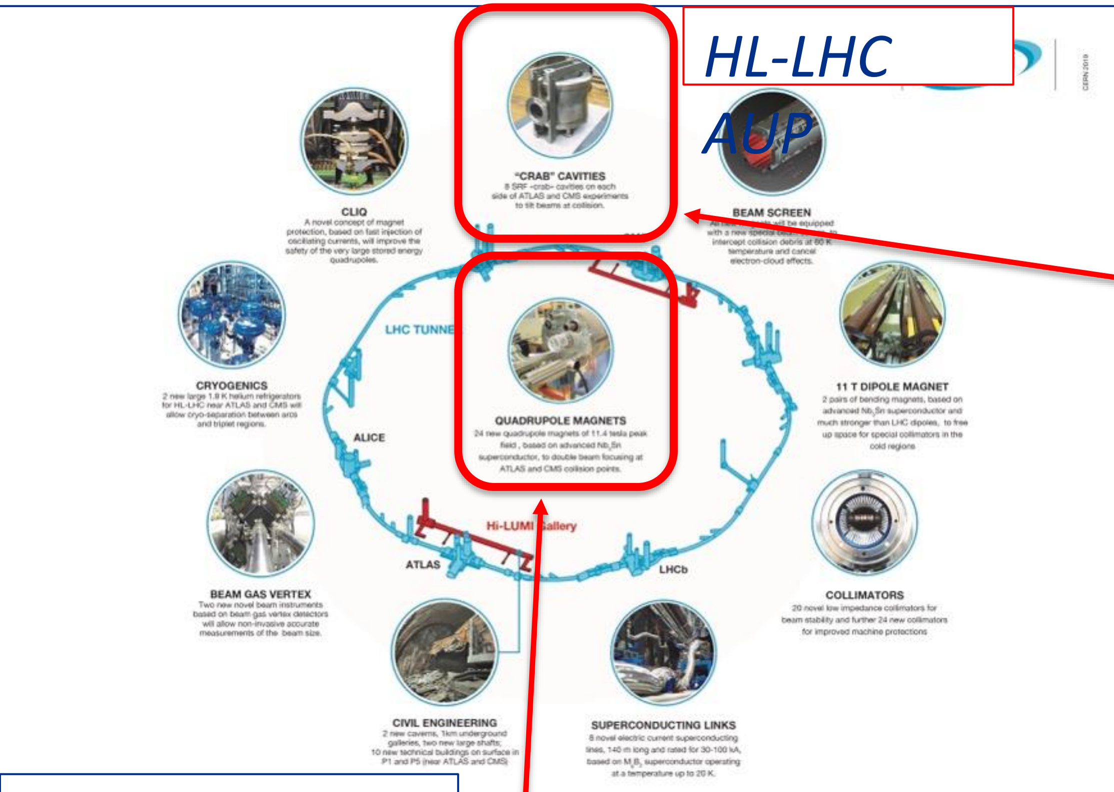
Last Detector Solenoid coil winding complete

Quench detection system assembled



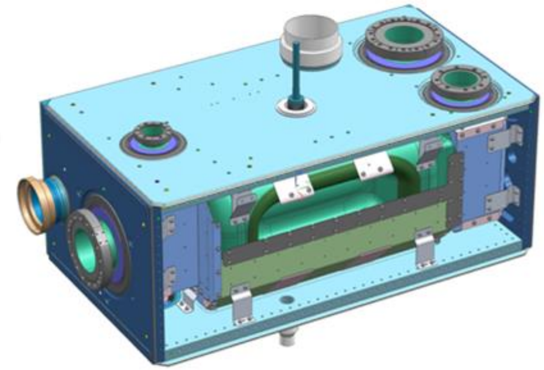
Cryogenic feedboxes and transfer line installations complete

HiLumi LHC Accelerator Upgrade Project (AUP)



From HL-LHC Project Leader
O. Bruning - CERN

- **10 Dressed RFD**



Dressed RFD Cavity
(front wall removed to show internal components)

- **10 Q1/Q3 Cryoassemblies (with 20 magnets)**

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AUP – major achievements

Vertical test prep of MQXFA (BNL)

- Successful vertical test of 7 magnets
- Pre-Series Bare Cavities are in final stages of manufacturing
- Horizontal Test of Cryoassembly #1 reached Acceptance Current during 1st thermal cycle

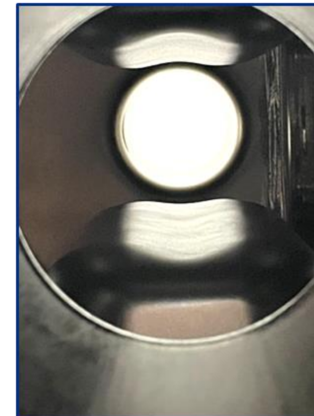
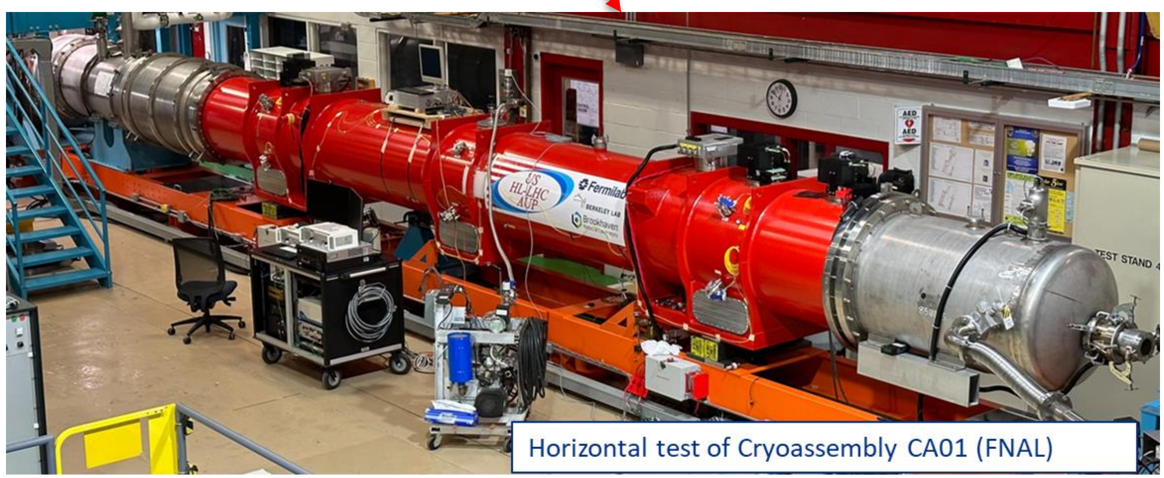


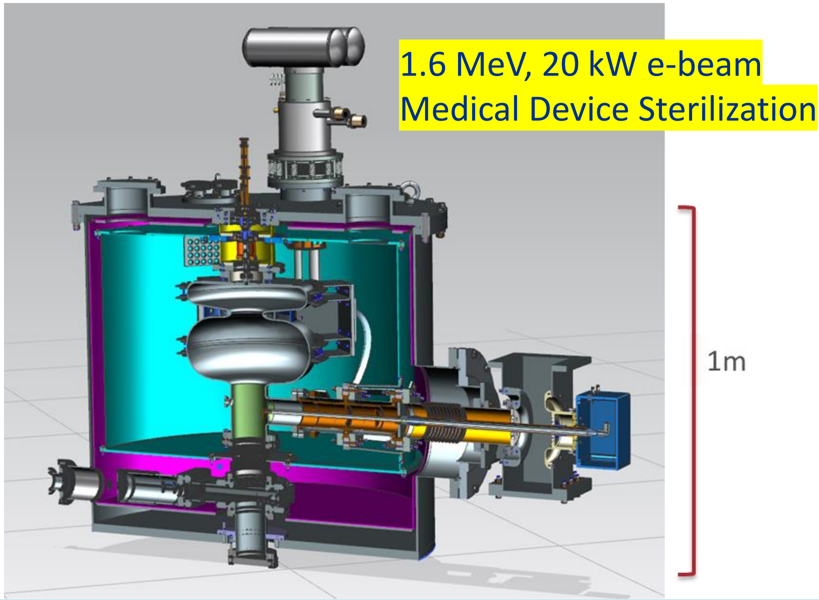
Photo of cavity interior with deflecting poles visible

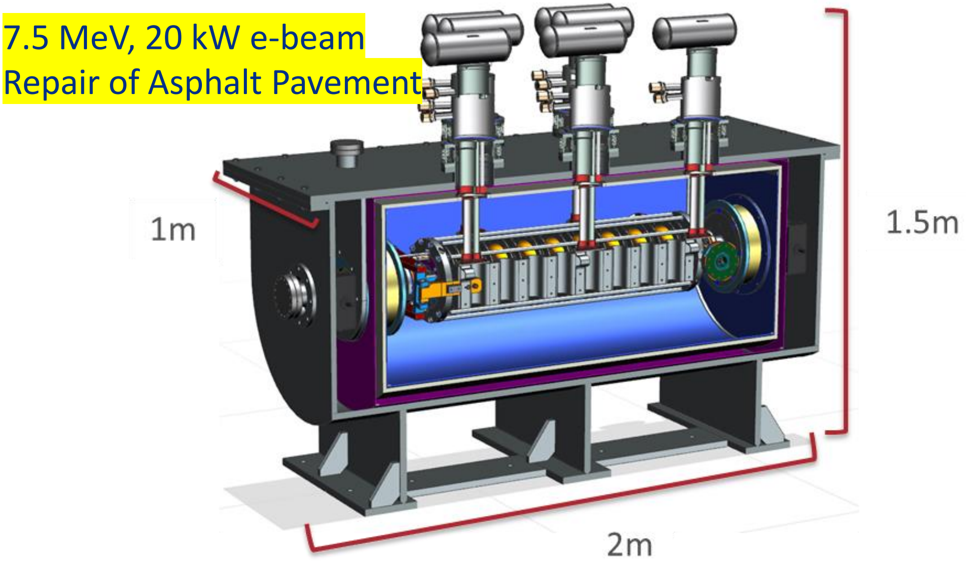


Horizontal test of Cryoassembly CA01 (FNAL)

SRF accelerators for industrial applications

- **APS-TD is lending SRF and cryogenics expertise** to *IARC at Fermilab* for developing high-power e-beam accelerators for industrial applications https://iarc.fnal.gov/superconducting-rf-accelerators/
- These accelerators will use cryocooler conduction cooled Nb_3Sn SRF cavities (no liquid helium)
- Two e-beam accelerators are currently under development





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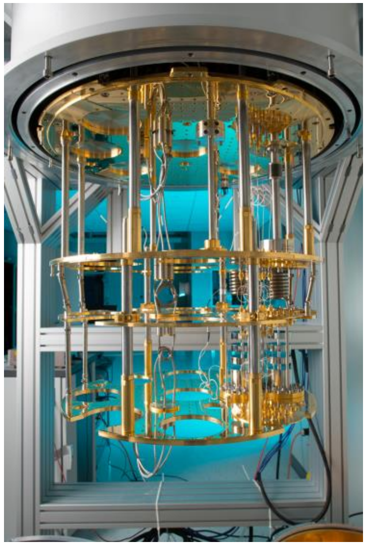
APS-TD Cryogenic capabilities

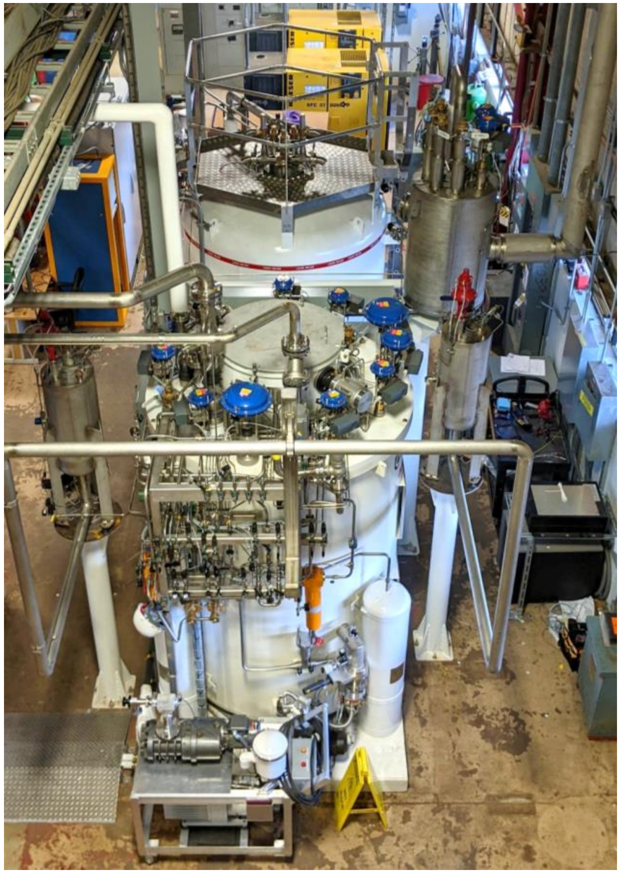
APSTD supports the laboratory cryogenic engineering and operational requirements

- Helium 4.5 K and 2 K Facilities
  - Physics experiments (Mu2e and more)
  - Test facilities (CMTF, VTS, HFVMTF)
  - Superconducting Linac (PIP II)
- mK Facilities
  - Quantum computing
  - Detector development
- Support to LAr experiments/projects
  - LAr bubble chamber
  - DUNE Near Detector

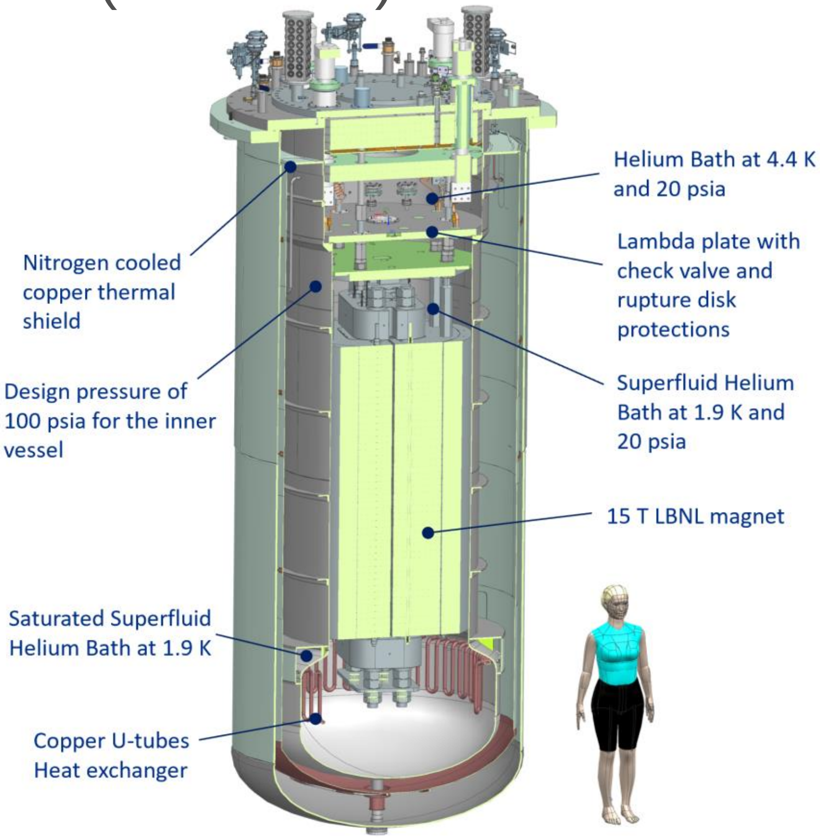


APS-TD Cryogenics – major ongoing activities

Upgrade of IB1 helium refrigerator coldbox and storage dewar



New IB1 double bath 4.5 K/1.9 K superfluid helium cryostat designed to test HTS magnets in high magnetic fields (DOE FES)



Design, fabrication, metrology capabilities

Machine Shop

- Serving FNAL experiments and operations with high tolerance rapid prototype and small run machined parts
- Certified welding processes
  - GTAW (Tungsten), FCAW (Flux core), PAW (Plasma Arc), GMAW (Mig)

Design and drafting

- Provide extensive 3D modeling and drawing/drafting support to lab-wide projects

Quality and Materials Department

- Support projects with
  - estimating costs and providing expertise on manufacturing and quality engineering issues
  - incoming inspection services
  - storage and inventory control
  - metrology and fabrication procurement services

Concluding Remarks

- APS-TD is at the forefront of R&D of superconducting RF and magnets that continues to impact ongoing and future particle accelerators and detectors development.
- Several projects at Fermilab as well as other accelerator labs worldwide continue to benefit from APS-TD's technical leadership in superconducting and cryogenic technologies.

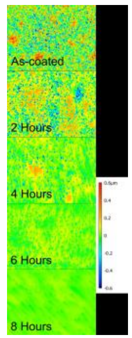
- **Thank you to all who provided material for this talk!**
- **Apologies for not been able to cover the numerous other APS-TD activities in this talk.**

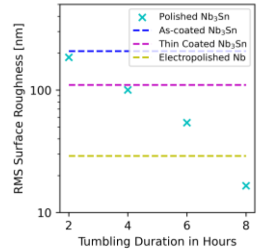
Backup slides

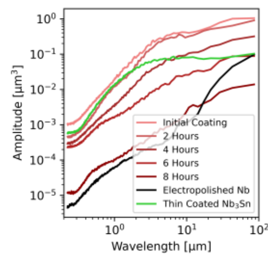
Examples of R&D activities for current and future accelerators

Improving Nb3Sn Cavity Performance Using Centrifugal Barrel Polishing, Eric Viklund, Ph.D. candidate

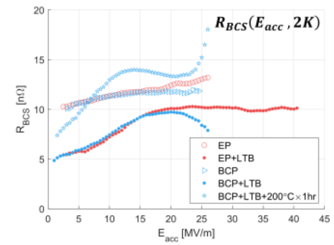
- Centrifugal barrel polishing (CBP) is an effective method of polishing Nb_3Sn coated cavities.
- Nb_3Sn films polished using CBP can achieve less than 20 nm surface roughness with minimal material removal.
- Reduced surface roughness contributes to achieving high gradients in SRF cavities.

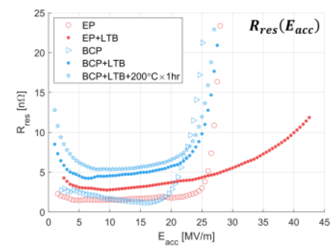




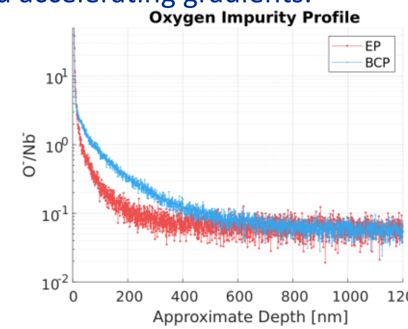


Comparing the Effectiveness of Low Temperature Bake in EP and BCP Cavities, Hannah Hu, Ph.D. candidate





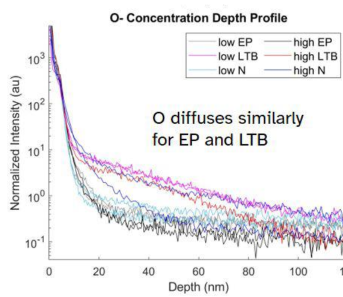
- LTB cures HFQS in EP cavities? Why is LTB not effective on BCP?
- Understanding and optimizing surface treatment will improve quality factors and accelerating gradients.



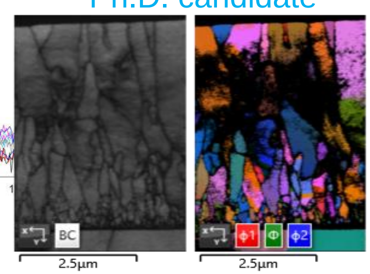
The Collaborative Effects of Intrinsic and Extrinsic Impurities in Low RRR SRF Cavities, Katrina Howard, Ph.D. candidate

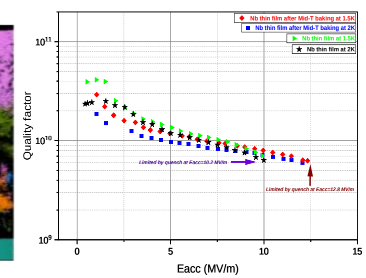
What role intrinsic impurities serve?

- Understanding of intrinsic impurities will enable future high Q_0 / high gradient surface treatments
- High quality factors and high gradients will improve the efficiency and the energy reach of future accelerators.



Characterization of Nb films at low temperatures, Bektur Abdisatarov, Ph.D. candidate





Understanding RF loss mechanisms in niobium thin films, which is applicable to both SRF cavities for accelerators and qubits for quantum computing research.

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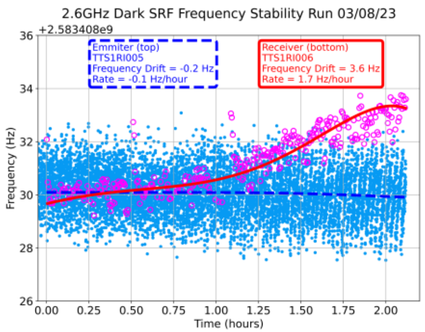
More examples of R&D activities

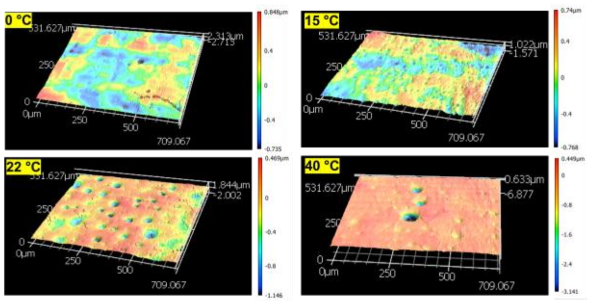
PI Loop Compensation for 2.6 GHz Cavity Dark Photon, Crispin Contreras-Martinez



- For dark photon search, light-through-the-wall experiment, two SRF cavities must operate at almost the same frequency.
- Proportional-integral algorithm development significantly improved cavity frequency matching (10 Hz/hr to 0.1 Hz/hr), allowing for faster searches with better statistics.

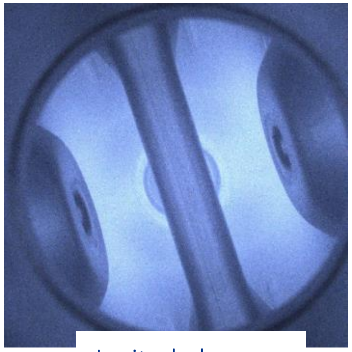
Electropolishing study on nitrogen-doped niobium surface, Vijay Chouhan

Effect of temperature (at 18 V)



- The nitride layer enhances the risk of small pits on the surface. - The study shows how to eliminate the pitting risk on the Nb surface.
- This optimization leads to higher and more reproducible accelerating gradients in SRF cavities.

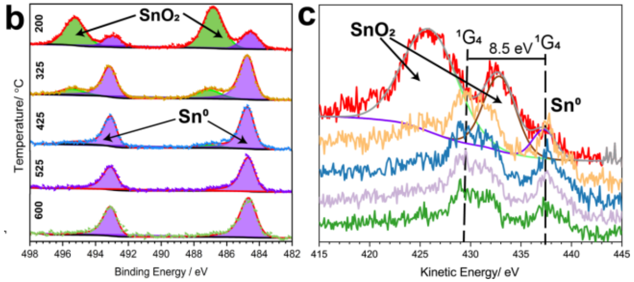
Single-spoke cavity plasma processing, Paolo Berrutti



Ignited plasma in spoke cavity
6/28/2023

- Plasma cleaning has been proven effective in eliminating multipacting and in preserving the field emission free performance of the LCLS-II HE vCM.
- HOMs ignition is applied to different SRF cavities making plasma processing possible for any cavity geometry, including spoke resonators like the SSR1 for PIP-II.

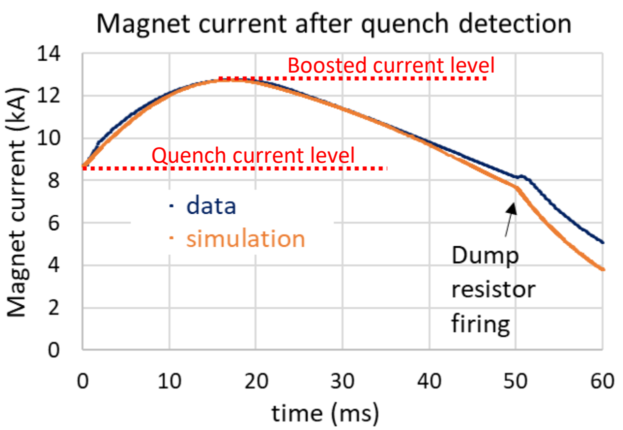
Thermal Stability of Nb3Sn Surface Oxide, Arely Cano

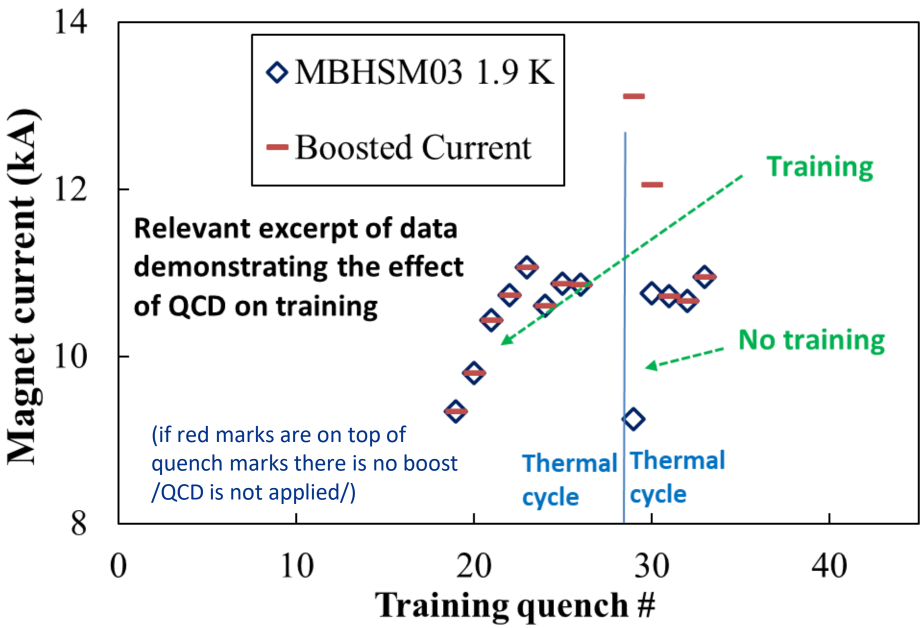


- The development of thermal treatments to effectively remove the native oxide layer in Nb3Sn. The objective is to address intrinsic energy losses, minimize surface resistance, and ultimately maximize the Q-factor at high fields.

VERSION 4 Magnet training: QCD (Quench Current-boosting Device)

We have designed and commissioned a device (QCD) which "boosts" the magnet current above its quench current level effectively pushing the quench current up:





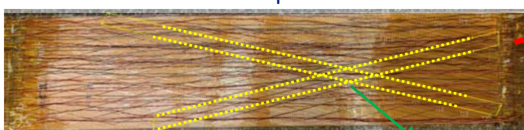
By applying sufficiently large current boost **training in superconducting magnets can be eliminated.**

Results finalized and published

SC magnet measurements with QA

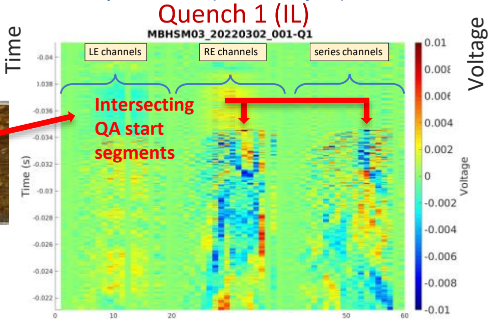
Quench antenna arrays (flex-QA) were demonstrated to give excellent precision and sensitivity for quench characterization

Superimposed images of the stacked QA panels along with the responding channels in the first quench

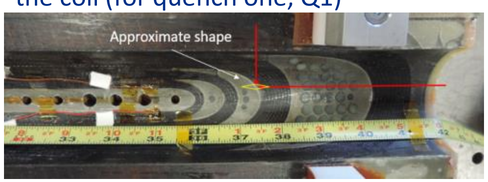


The diagonals of the rhombus formed are 8.1 mm and 48 mm (its side is 24.6 mm)

Data from all channels around quench time for quench 1 (inner layer)



Projection of the flex-QA response area on the coil (for quench one, Q1)

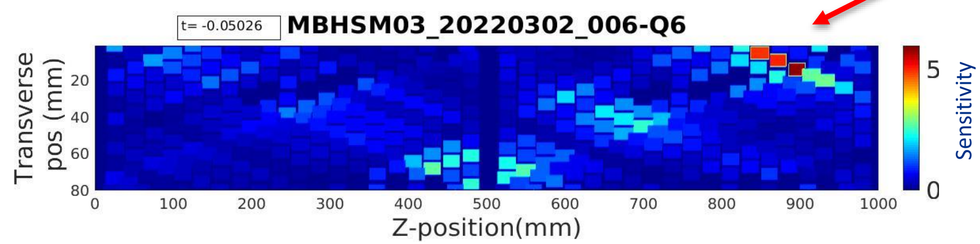


We are confident about location to within 2 mm; the quench location is consistent with voltage tap segment and acoustic measurements

The flex-QA arrays are a new powerful improvement to QA techniques for quench analysis and may be applicable for quench detection as well.

Data from an outer layer quench (QA saw all of them)

We can visually see where a quench starts and how it develops over time



This is a single time slice of data (100 kHz DAQ rate)

Color-map plots are useful to spot features and patterns, along with start of quenches. Variations of those (integrated, normalized, relative to standard deviation, etc.) can show particular features better or worse.

Flex-QA saw all quenches even before voltage tap voltage started rising.

Results finalized and published