FERMILAB-SLIDES-21-084-QIS-TD
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

# Applied Physics and Superconducting Technology

Bianca Giaccone

54th Annual Users Meeting

3 August 2021

# APS-TD Mission

- Pursue **highly innovative R&D program in SC 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**

# APS-TD: Departments, R&D, Programs and Projects

Departments:

- **Cryogenics**
- **Machine Shop**
- Magnet Systems
- Quality and Materials
- SRF Department
- Test & Instrumentation

R&D:

- **Superconducting RF**
- **Superconducting Magnets**
- Quantum Technologies

Projects:

- **PIP II**
- **LCLS-II and LCLS-II-HE**
- **High Luminosity LHC Accelerator Upgrade Project**
- **Mu2e**

Programs:

- SRF Program
- Magnet Development
- Accelerator Support

Capabilities:

- **Cryogenic**
- Magnet
- SRF

# APS-TD: Departments, R&D, Programs and Projects

Departments:

- **Cryogenics**
- **Machine Shop**
- Magnet Systems
- Quality and Materials
- SRF Department
- Test & Instrumentation

R&D:

- **Superconducting RF**
- **Superconducting Magnets**
- Quantum Technologies

Projects:

- **PIP II**
- **LCLS-II and LCLS-II-HE**
- **High Luminosity LHC Accelerator Upgrade Project**
- **Mu2e**

Programs:

- SRF Program
- Magnet Development
- Accelerator Support

Capabilities:

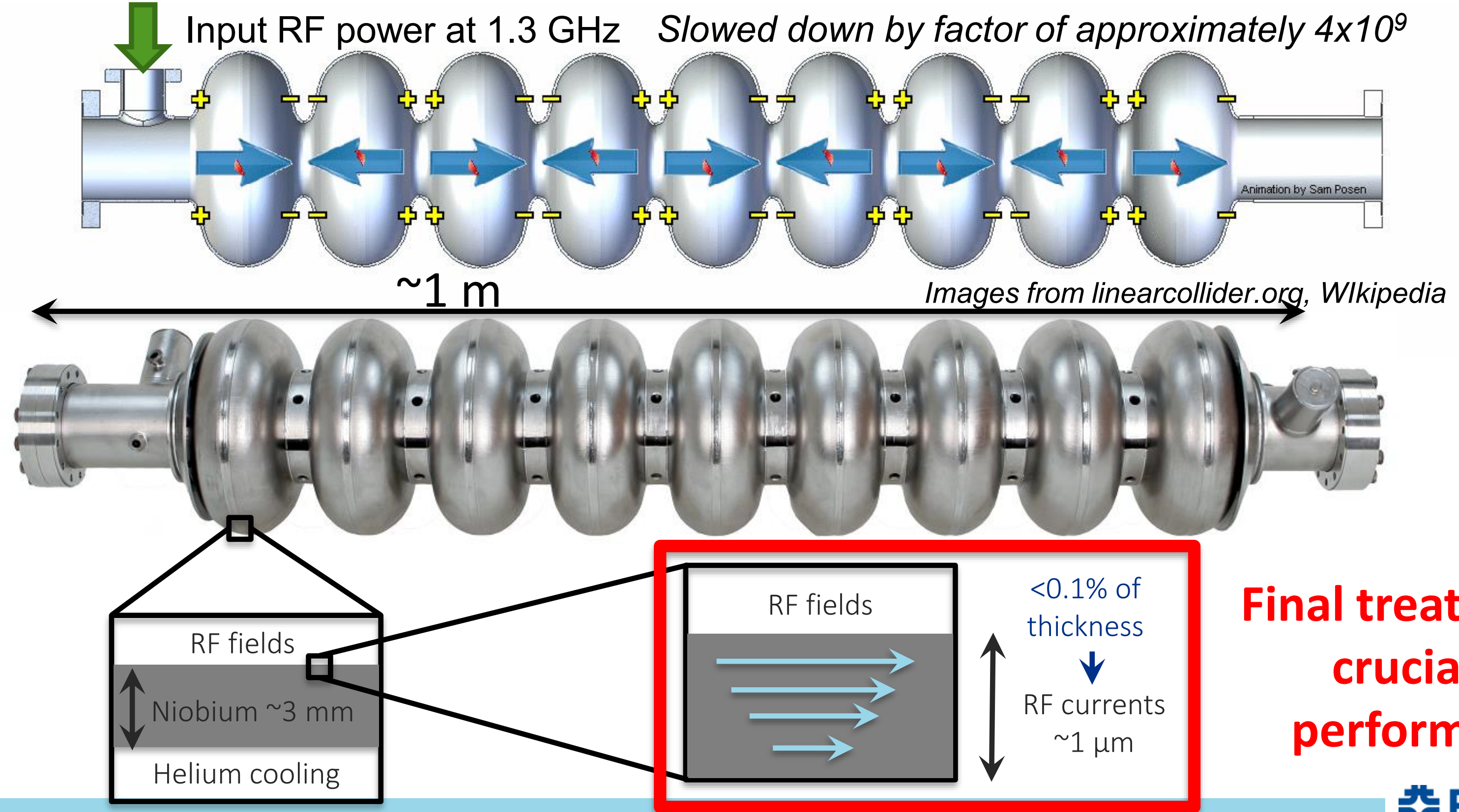
- **Cryogenic**
- Magnet
- SRF



Fermilab

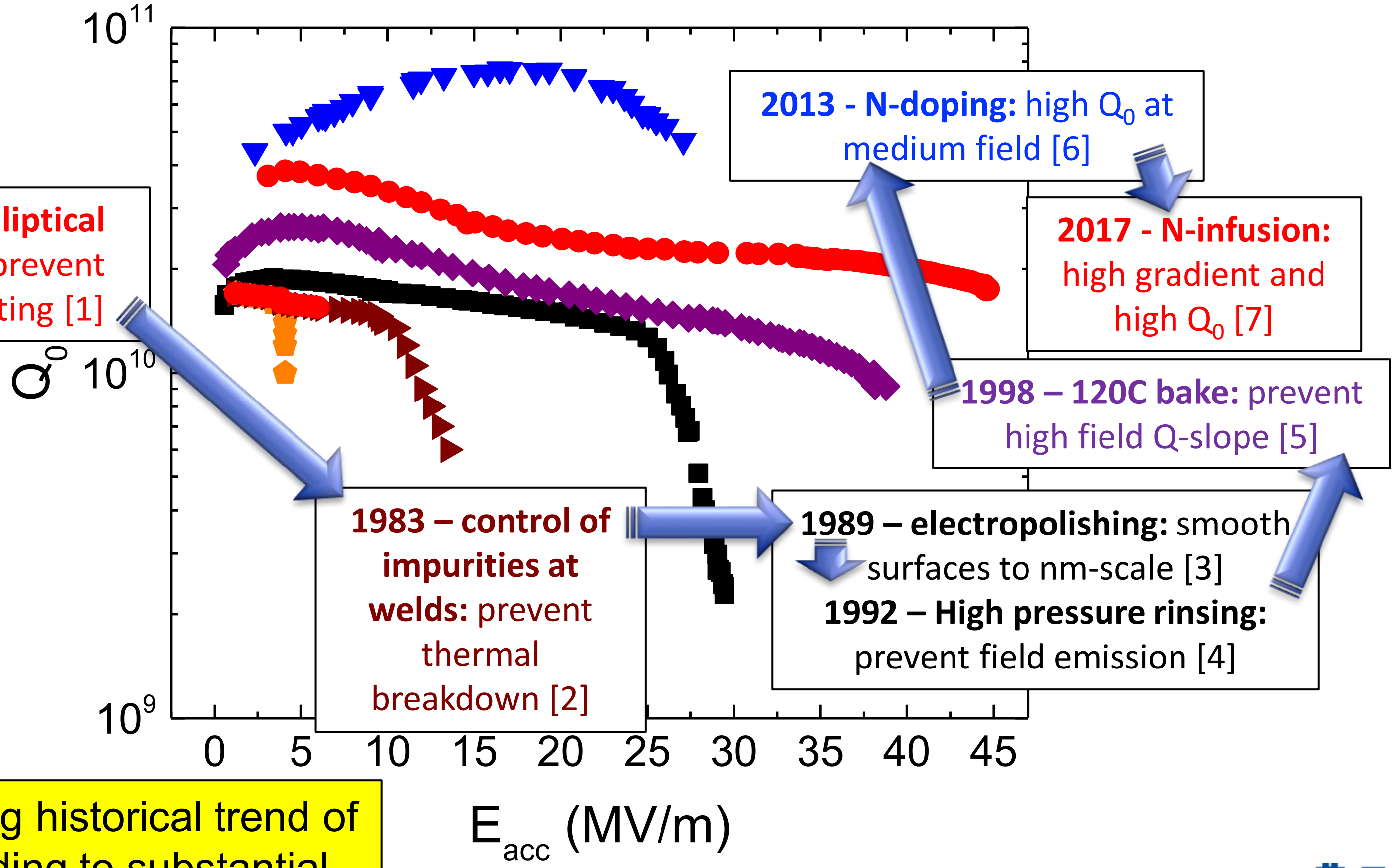
# R&D: Superconducting RF sector

- SRF cavities: fundamental component of linac, high quality EM resonators ($Q_0>10_{10}$)




**Final treatment is crucial to performance**

# R&D: Superconducting RF sector

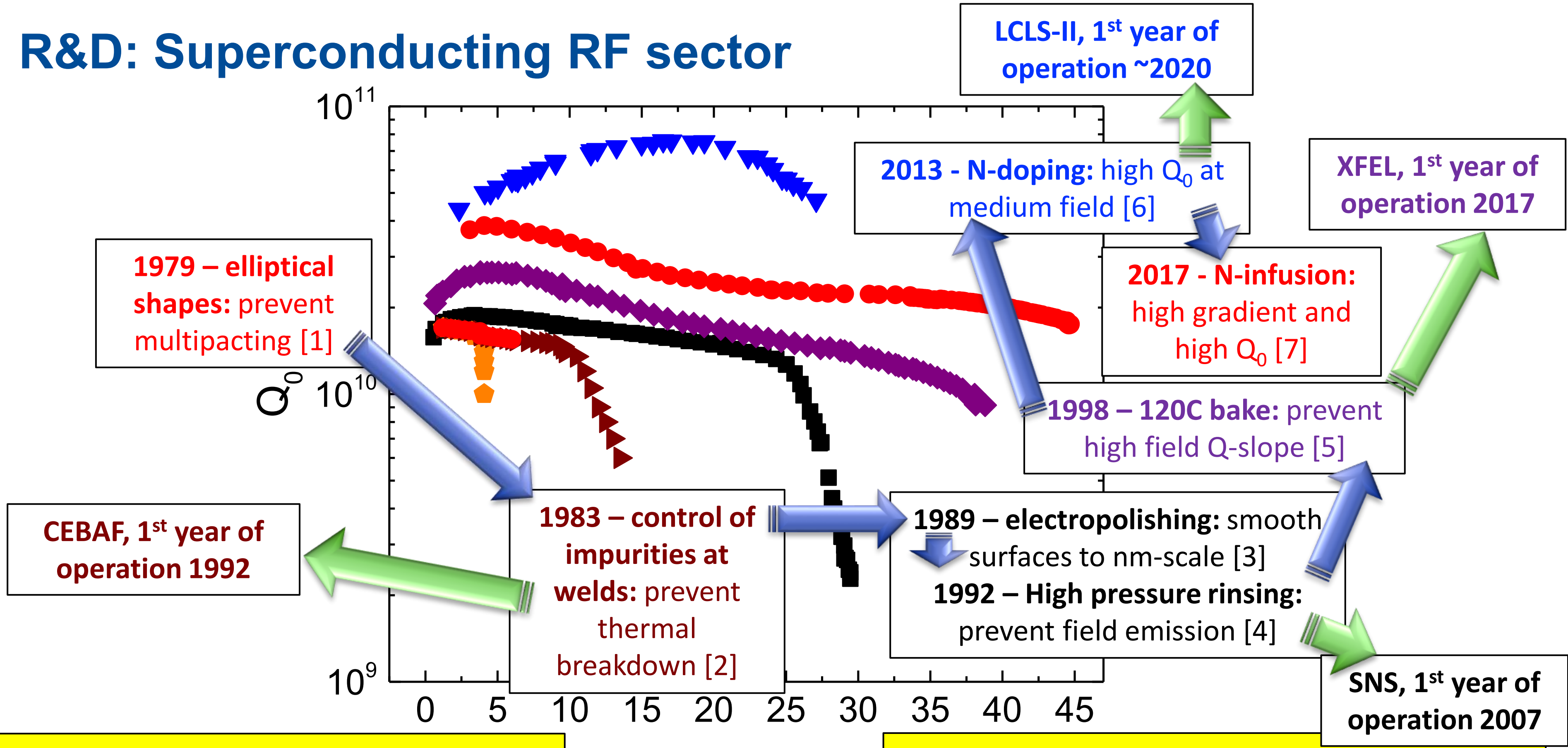



There is a strong historical trend of SRF R&D leading to substantial advances in cavity performance



Fermilab

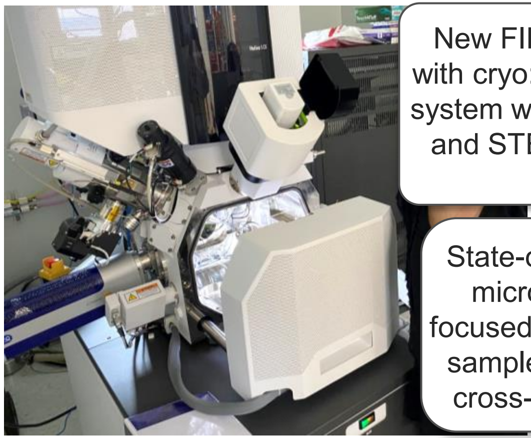
# R&D: Superconducting RF sector




There is a strong historical trend of SRF R&D leading to substantial advances in cavity performance

Stronger performance improves the feasibility of building new accelerators with unprecedented scientific reach

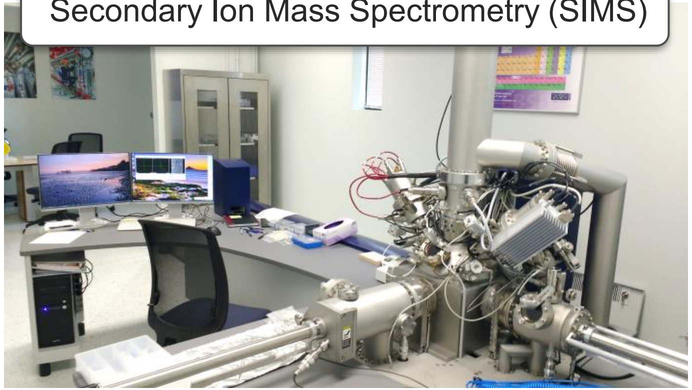
# Material Science instruments



New FIB/SEM/STEM system with cryo: FEI Helios Dual beam system with Oxford EDS, EBSD, and STEM detector, cryo and heating stage

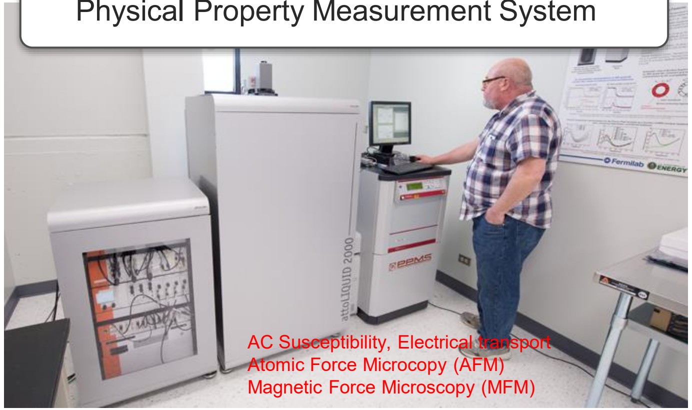
State-of-the-art electron microscope with the focused ion beam for TEM sample preparation and cross-sectional studies

Secondary Ion Mass Spectrometry (SIMS)



Quality Tests: Instron Testing apparatus and Eddy current Scanner

Physical Property Measurement System



# Examples of R&D activities from the Material Science group

## Irradiation studies on bulk Nb samples, Tiziana Spina

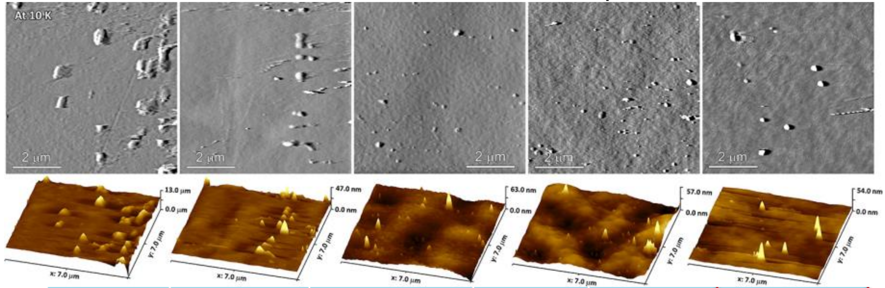

Hydride size reduction due to enhancement of radiation induced nucleation centers (v-H)

What is the effect on HFQS?

- Irradiation experiment on Nb 1.3GHz cavity ongoing

## Surface features on cavity cut-out samples, Zuhawn Sung

Hot Spot | + 800C HT | 120C Baked | N-doped | N-Infused

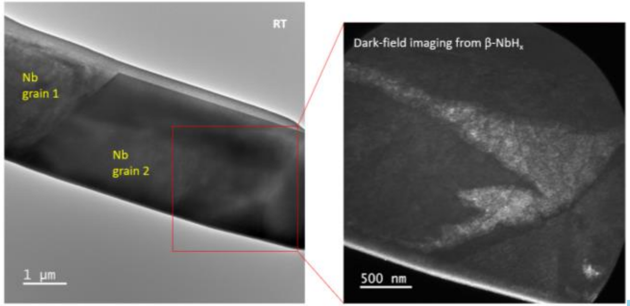



| | No. of NbH precipitations | Total projected area* (abs. [µm²]) | Avg. Height [nm] | Avg. Diameter [nm] | Total NbH volume [$10^{-3} \times \mu m^3$])† |
|---|---|---|---|---|---|
| Hot Spot | 59 | 3.58 | 30.0 | 687.3 | 337.7 |
| 800C HTed | 36 | 0.99 | 6.12 | 397.3 | 22.3 |
| 120C Baked | 24 | 0.46 | 20.1 | 305.1 | 14.2 |
| N-Doped | 40 | 0.56 | 17.9 | 272.1 | 13.3 |
| N-Infused | 16 | 0.58 | 32.1 | 496.4 | 12.8 |

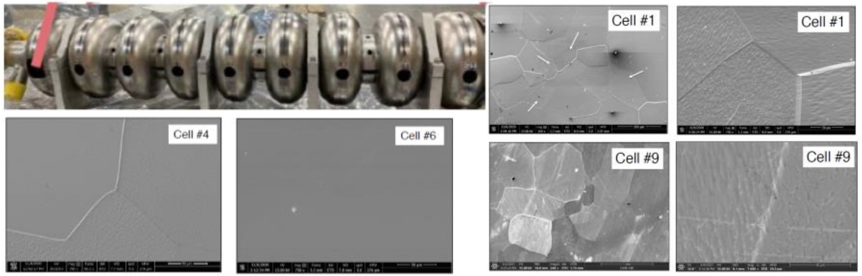
H trapping by N →

## Microstructural control of superconductors for better performance, Jae-Yel Lee

Nb SRF cavities: analyzing hydrides as a source of Q-slope and quench




## Nature of surface defects found in 2/0 N-doped 9-cell cavity, Arely Cano



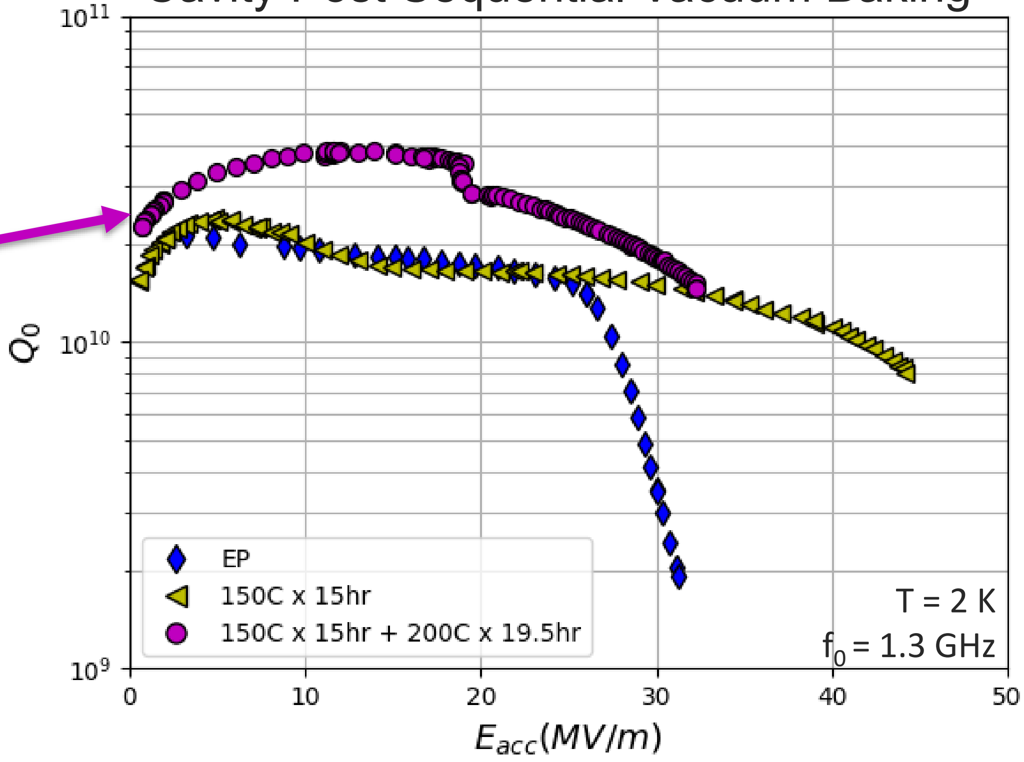

Cell #1 & 9: identified as quench inducers, show high density of defects; Cell #1: correlation between preferential attack with grain orientation in (111) planes


Fermilab

# Research Towards High $Q_0$/High Field in Bulk Nb SRF Cavities

- Breakthrough: oxygen diffusion in Nb SRF cavities is critical in enabling:
  - Ultra-high gradients
  - **NEW: High $Q_0$**
    - **→ Discovery of "oxygen doping"?**
- Enables "tuning" of performance for high $Q_0$ or gradient by simply tailoring oxygen profiles *via* diffusion
- Utilizing findings to design Nb surface engineering protocols that **combine high $Q_0$ and high field**

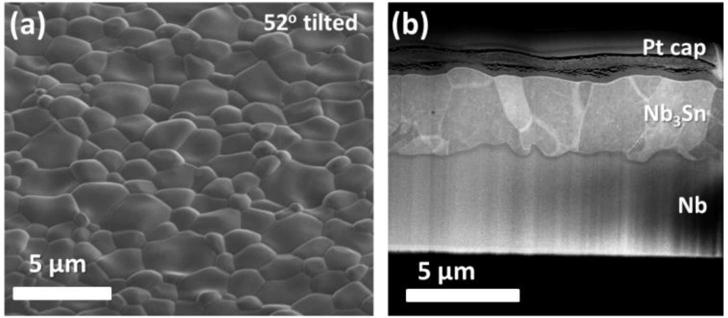
Performance Evolution of a Bulk Nb SRF Cavity Post Sequential Vacuum Baking



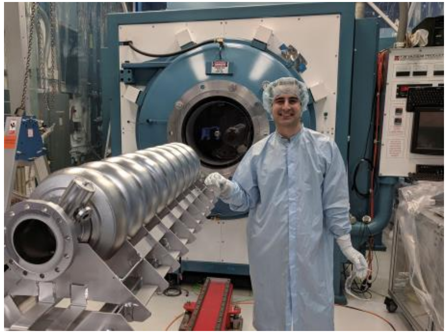

Daniel Bafia, Alex Romanenko, Anna Grassellino

# New SRF Material: $Nb_3Sn$

- Current state of the art superconductor for SRF cavities is niobium
- $Nb_3Sn$ coated cavities can operate at 4.4 K to reduce cost of cryogenics and enable new compact accelerator applications; in addition, theory predicts maximum gradient 2x niobium
- Fermilab $Nb_3Sn$ SRF R&D highlights:
  - First ever 9-cell cavity made with $Nb_3Sn$ – key technical demonstration for accelerators for industry, universities, and beyond
  - World record accelerating gradient for non-niobium cavities
  - Development of understanding of $Nb_3Sn$ materials science in collab w/ Northwestern




*SEM images of $Nb_3Sn$ film coated on Nb: a) surface, b) cross section*



*First $Nb_3Sn$ 9-cell cavity – relevant structure for accelerator applications*

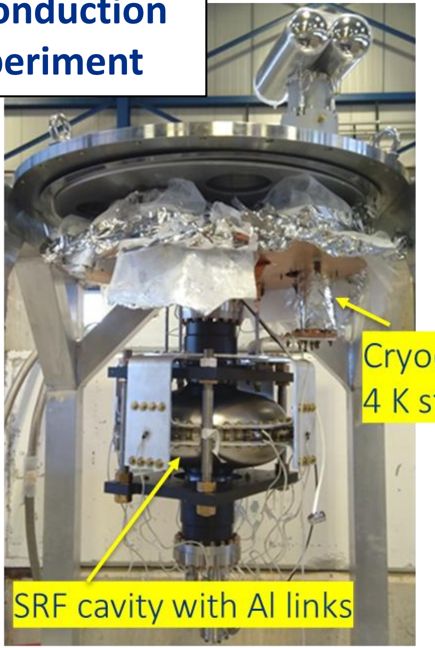
# Fermilab Compact Accelerator Development using $Nb_3Sn$ SRF


R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136

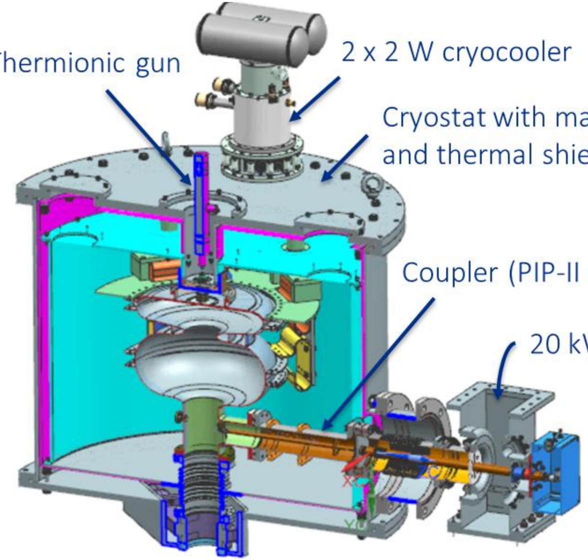
R.C. Dhuley et al., ***IEEE Trans. Appl. Supercond.***, 2019, https://ieeexplore.ieee.org/abstract/document/8651336

R.C. Dhuley, M.I. Geelhoed, J. Thangaraj, ***Cryogenics***, 2018, https://doi.org/10.1016/j.cryogenics.2018.06.003


**Successful conduction cooling experiment**




**New Prototype Compact Accelerator under Development**




**Courtesy Ram Dhuley, Fermilab**

# APS-TD: Departments, R&D, Programs and Projects

Departments:

- **Cryogenics**
- **Machine Shop**
- Magnet Systems
- Quality and Materials
- SRF Department
- Test & Instrumentation

R&D:

- **Superconducting RF**
- **Superconducting Magnets**
- Quantum Technologies

Projects:

- **PIP II**
- **LCLS-II and LCLS-II-HE**
- **High Luminosity LHC Accelerator Upgrade Project**
- **Mu2e**

Programs:

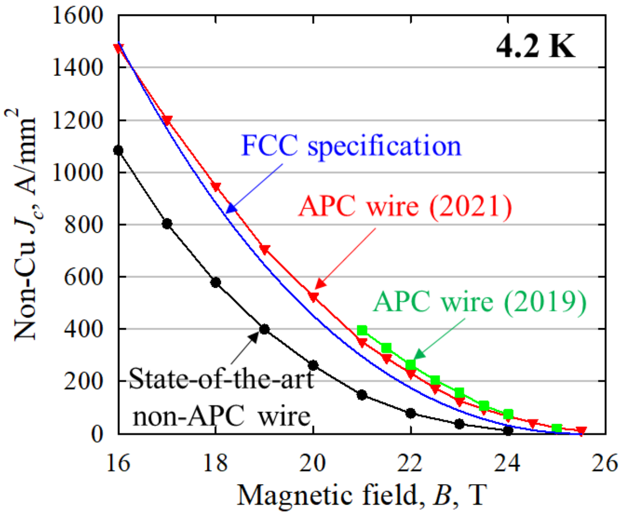
- SRF Program
- Magnet Development
- Accelerator Support

Capabilities:

- **Cryogenic**
- Magnet
- SRF

# $Nb_3Sn$ superconductor R&D

- Future energy-frontier hadron colliders (such as FCC-hh outlined in European Strategy Update) will require $Nb_3Sn$ superconductors with performance – particularly critical current density ($J_c$) – much above state of the art.
- **FNAL R&D (by X. Xu et al.) is developing $Nb_3Sn$ conductors with artificial pinning centers (APC). Such conductors have achieved the challenging FCC $J_c$ specification**.
- Recently, **great progress** has been made in pushing the APC conductors **toward readiness for use in magnets**, such as improvement of stability, development of 217-stack wires with small filament size, development of wires with good performance after rolling, paving the way for making cables.
- Recent studies also show that the APC conductors have the **extra benefit of much lower low-field magnetization**, which is very desirable for accelerator magnets.




Xingchen Xu, *et al.*

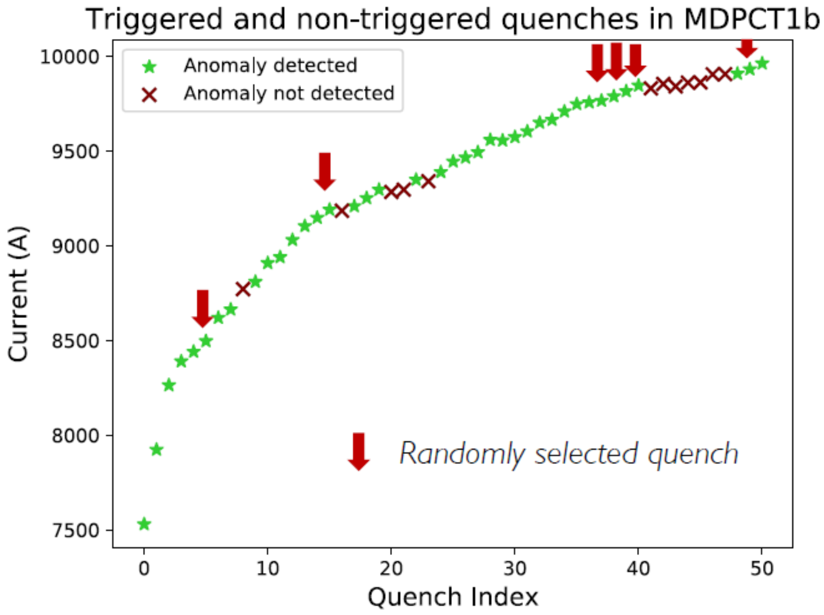


Fermilab

# AI for detection of quench precursors in SC magnets

AI advantages compared to standard quench detection:

- System with 0 delay time -> more performing magnet design
- System independent on quench propagation velocity -> HTS
- System is able to predict quench ->
  - no hot spot anymore
  - eliminate/reduce magnet training
- Compact, fast data acquisition system able to collect all diagnostic data in magnets

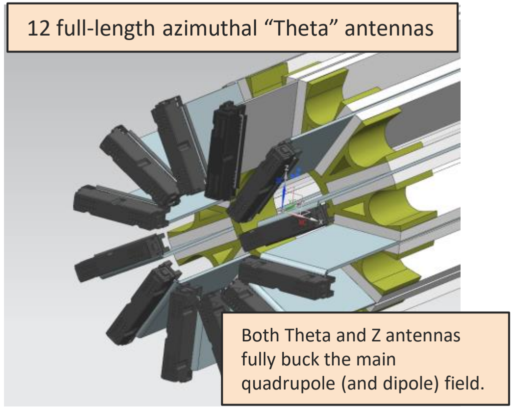


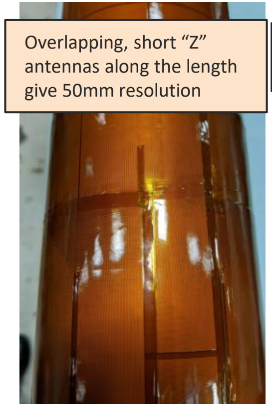

Triggered on 77% of the quenches starting from 15 s before a quench

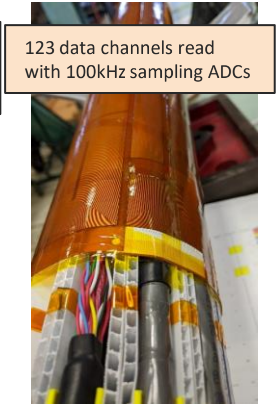
Vittorio Marinozzi

# Full–length Quench Antenna Array

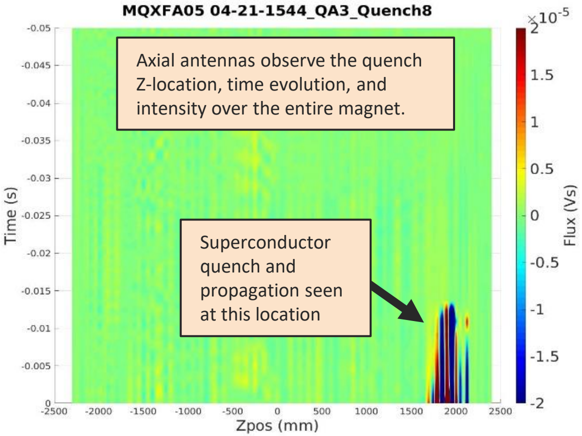
Used for determining the location of quenches in MQXFA superconducting magnets during production series testing for the Hi-Lumi Accelerator Upgrade Project

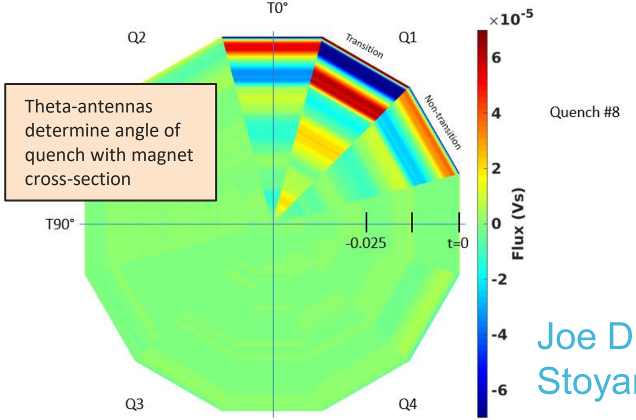








Joe DiMarco, Stoyan Stoynev

# APS-TD: Departments, R&D, Programs and Projects

Departments:

- **Cryogenics**
- **Machine Shop**
- Magnet Systems
- Quality and Materials
- SRF Department
- Test & Instrumentation

R&D:

- **Superconducting RF**
- **Superconducting Magnets**
- Quantum Technologies

Projects:

- **PIP II**
- **LCLS-II and LCLS-II-HE**
- **High Luminosity LHC Accelerator Upgrade Project**
- **Mu2e**

Programs:

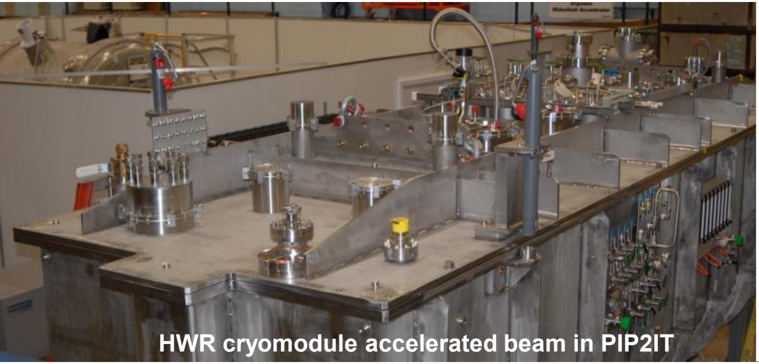
- SRF Program
- Magnet Development
- Accelerator Support

Capabilities:

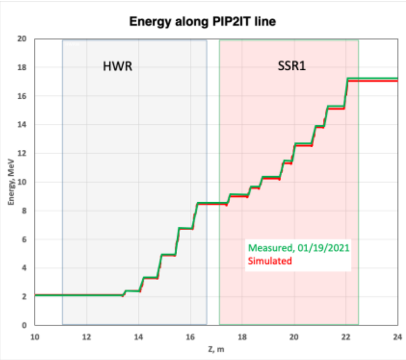
- **Cryogenic**
- Magnet
- SRF

# Proton Improvement Plan - II

## A year in acceleration



HWR cryomodule accelerated beam in PIP2IT





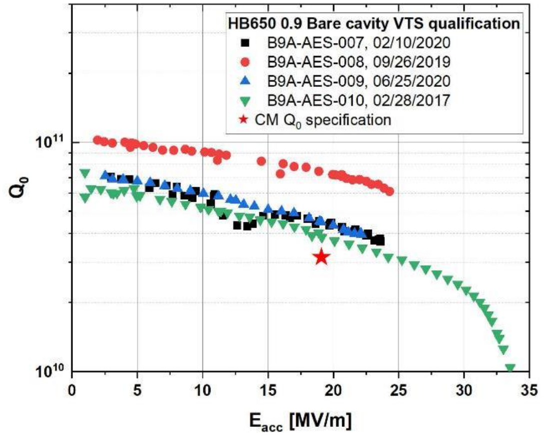
Prototype SSR1 cryomodule accelerated beam in PIP2IT

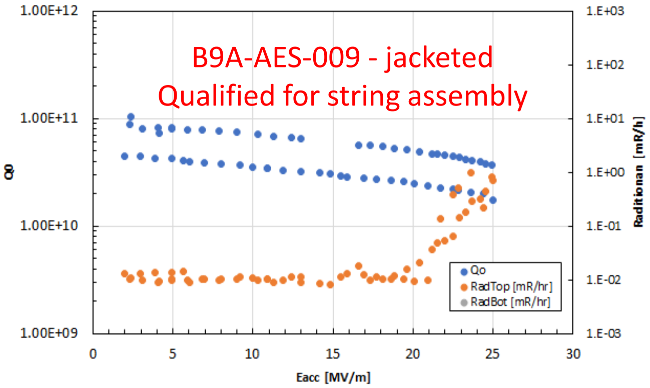
The HWR and the prototype SSR cryomodules accelerated beam in PIP2IT as expected from simulations and at the first shot, nearly at full transmission.

The prototype SSR1 is the first cryomodule fully designed by Fermilab and is the basis for the other PIP-II cryomodule types (HWR excluded).

The characterization of these two units in PIP2IT allows to transfer all lessons learned to production cryomodules.

More info on PIP-II @ L. Lari's talk




The recipe for HB650 cavities has been finalized. N-Doping will be used to boost the Q0 and reach the unprecedented specification.

Six prototype cavities (of which 3 from India) are being prepared for the string assembly of the HB650 cryomodule which is planned in the fall.

One LB650 cavity from INFN is being characterized and qualified.

SSR2 cavities are being manufactured and will be at Fermilab early next year.

More info on PIP-II @ L. Lari's talk

# Fermilab LCLS-II Cryomodule Production Completed

- Fermilab developed nitrogen-doping technique that allowed cavities to reach world-record performance.
  - Cryomodule performance exceeded specifications and twice the previous state of the art
- 18 Fermilab-built cryomodules are installed as part of LCLS-II linac + 2 spares
- LCLS-II extended Fermilab's SRF capabilities to include high-performance cryomodules in a production environment


All CMs delivered to SLAC


All CMs installed in SLAC tunnel

# LCLS-II-HE at Fermilab

- Upgrade to LCLS-II that will enable the production of x-rays at higher energies https://lcls.slac.stanford.edu/lcls-ii-he
- After success of LCLS-II, SRF cavity goals higher for HE
- HE cavities are treated with Fermilab-developed 2N0 process to improve gradient
- Verification cryomodule (vCM) was assembled and tested at FNAL: Outstanding performance

  (see more on next slide)
- Start CM production – Summer 2021: Fermilab will assemble, test & ship 14 CM to SLAC

vCM at cryomodule test stand

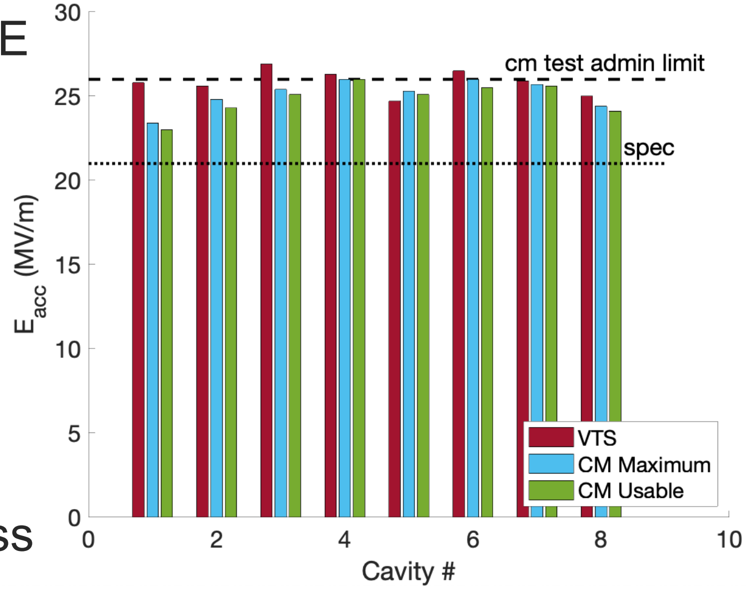
Transportation to Fermilab cryomodule test facility



Fermilab

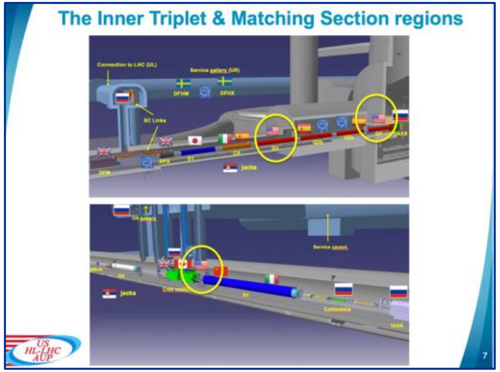
# LCLS-II-HE vCM Results at Fermilab

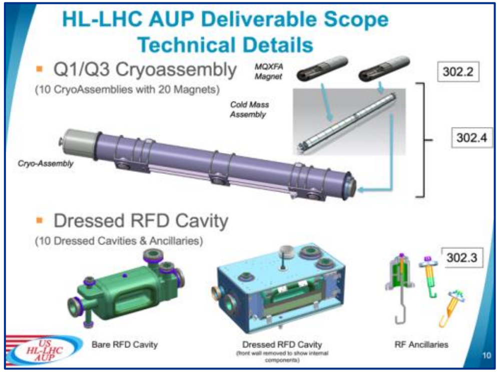
- Gradient and $Q_0$ in all 8 cavities exceeds LCLS-II-HE specification
- 2N0 cavity fabrication recipe/protocol is verified
- No field emission observed at any gradient in any cavities after processing - Very clean assembly, crucial for accelerator performance
- This is an excellent demonstration of what is now possible in a CW cryomodule thanks to SRF R&D, meticulous assembly, and many teams of world class experts. This is an incredible and world record cryomodule!




| | $E_{acc}$ Spec | $E_{acc}$ avg | $Q_0$ Spec | $Q_0$ avg |
|---|---|---|---|---|
| **HE vCM (8 cavities)** | **21 MV/m** | **25 MV/m** | **$2.7 \times 10^{10}$** | **$3.0 \times 10^{10}$** |
| LCLS-II prod'n (280 cavities) | 16 MV/m | 19 MV/m | $2.7 \times 10^{10}$ | $2.9 \times 10^{10}$ |

# High Luminosity LHC Accelerator Upgrade Project




- AUP fulfills the "***highest near-term priority***" as identified by the U.S. HEP Community through the 2016 Snowmass/P5 process
- APS-TD together with other US Labs & Universities (BNL, LBNL, JLAB, SLAC, ODU, UF) contributing expertise in $Nb_3Sn$ High Field magnets (focusing quadrupoles) and SRF Crab Cavities for the interaction regions to deliver 3000 $fb^{-1}$ to ATLAS/CMS.

Managerial Status

- Project executed under Order 413.3b and received DOE approvals for CD-1 (Cost & Schedule Range), CD-2 (Baseline) and CD-3 (Construction Approval)
- AUP is at ~50% of its execution, with a TPC of ~250M$

Technical Status

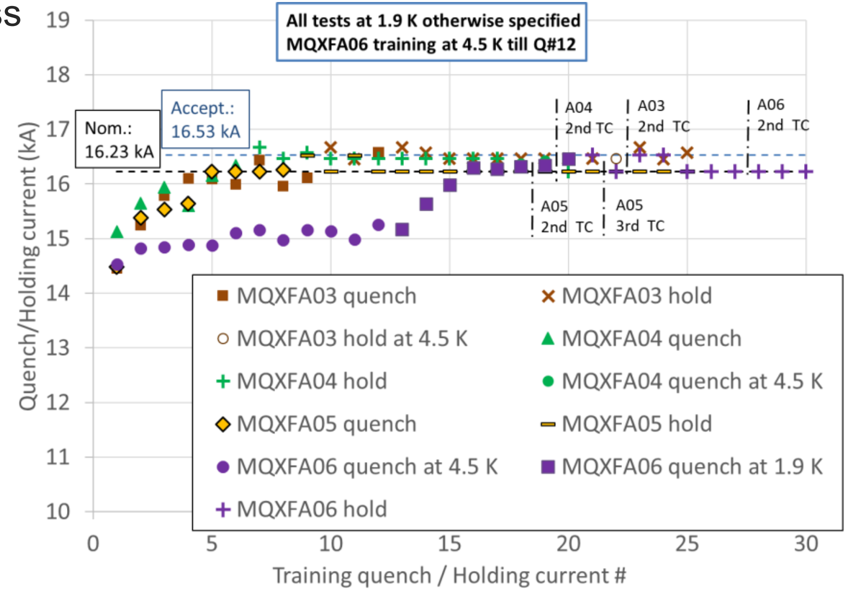
- Magnets Assembly
  - Reached 50% completion of coils
  - 5 (out of 20) magnets assembled, 4 tested successfully so far.
- Cold Mass (CM) and CryoAssembly (CA)
  - $1^{st}$ CM under fabrication. CA kits received from CERN
- SRF Cavities
  - 2 Prototypes built: $1^{st}$ prototype met HL-LHC requirements, $2^{nd}$ prototype is under test.

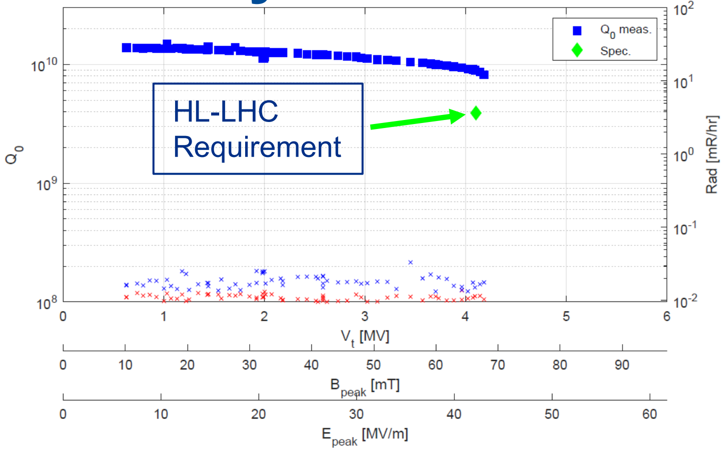
More info on HL LHC @ D. Berry's talk

# AUP magnets performance and CRAB cavity

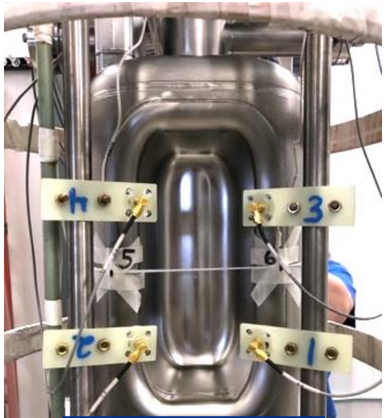
## Magnet Vertical Tests:

- Magnets MQXFA03, MQXFA04, MQXFA05 and MQXFA06 met all requirements tested at BNL (4 out of 4 !)
- MQXFA03 and MQXFA04 accepted for use in 1st Cold Mass
- MQXFA05 and MQXFA06 to be accepted shortly for 2nd Cold Mass




VTS Preparations

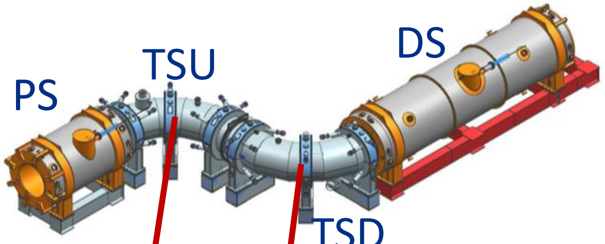


Second Sound Instrumentation

# Mu2e Solenoids

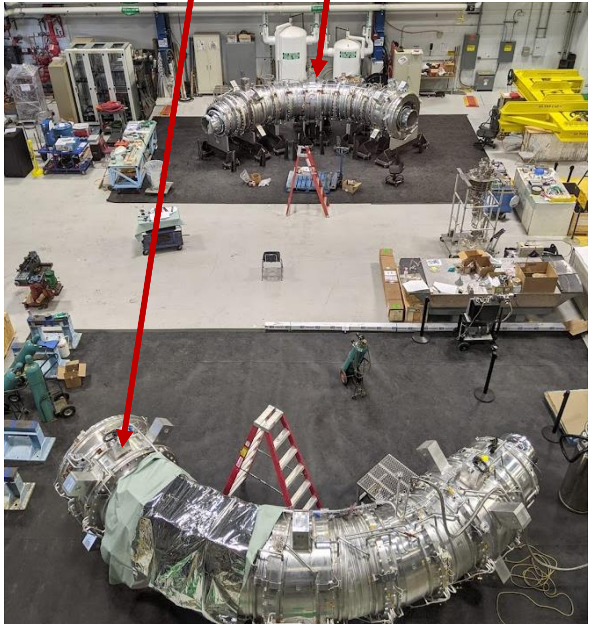
https://mu2e.fnal.gov/

- All Transport Solenoid units have been tested, accepted, and assembled in HAB!
  - TSU thermal shield at FNAL, TSD thermal shield nearly finished at vendor
- Production and Detector Solenoid being fabricated at General Atomics
  - All 3 of the Production Solenoids have been wound
  - 3 of 11 DS solenoids wound




PS3 Complete

DS 10 Shell



TS Assembly in HAB

More info on Mu2e @ M. Yucel's talk

# APS-TD: Departments, R&D, Programs and Projects

Departments:

- **Cryogenics**
- **Machine Shop**
- Magnet Systems
- Quality and Materials
- SRF Department
- Test & Instrumentation

R&D:

- **Superconducting RF**
- **Superconducting Magnets**
- Quantum Technologies

Projects:

- **PIP II**
- **LCLS-II and LCLS-II-HE**
- **High Luminosity LHC Accelerator Upgrade Project**
- **Mu2e**

Programs:

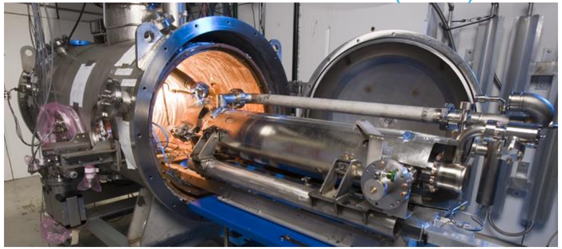
- SRF Program
- Magnet Development
- Accelerator Support

Capabilities:

- **Cryogenic**
- Magnet
- SRF

# Helium Cryogenic Based Test Facilities

- New Muon Lab (NML)
  - Supports Fermilab Accelerator Science and Technology (FAST)
- Meson Detector Building (MDB)
  - Supports SRF dressed single cavity horizontal testing
- Cryomodule Test Facility (CMTF)
  - Supports cryomodule acceptance testing
- Industrial Building 1 (IB1)
  - Vertical dewar magnet and SRF cavity testing, power lead and sensor calibration testing, horizontal magnet acceptance testing
- Muon Campus (MC)
  - Supports Muon g-2 and Mu2e experiments
- Heavy Assembly Building (HAB)
  - Supported Mu2e solenoid testing. Support of large dilution refrigerator initiative


Horizontal Test Stand (MDB)


New IB1 Liquefier


FAST Cryomodule (NML)


Cryomodule Test Stand (CMTF)

# Machine Shop

Provides:

- High tolerance prototype
- Small run machined parts
- Certified welding processes
- High tolerance EDM wire capability

Equipped with:

- Manual lathes
- Milling machines
- Computer Numerical Control horizontal and vertical machines
- Water jet cutting capabilities

The welder team is certified to weld a variety of metals

Status Update:

The Machine and Weld shops remain busy as usual working with all projects across the Lab. In particular, ND APA Hangers and lifting apparatus. The shops have also participated in the APS-TD Axion Cavity production.

APA Lifting Assy

Axion Cavities

# Summary

- SRF and Magnet R&D:
  - MSL is equipped with many state of the art microscopes, allowing microscopic understanding of the cavity surface and performance
  - New insight on the $O_2$ role in Nb near surface region may help combining high Q with high field
  - Successfully achieved conduction cooling with $Nb_3Sn$ SRF cavity
  - Great progress in $Nb_3Sn$ APC, achieving challenging FCC $J_c$ specification
  - Interesting application of AI to study of quench precursors
  - Full length-quench antenna array: azimuthal and theta antennas identify the position and progress of the quench in MQFXA SC magnets
- PIP-II:
  - HWR and prototype SSR CMs accelerated beam in PIP2IT nearly at full transmission at the first shot
  - SSR2 cavities are being manufactured
  - Recipe for High-beta 650MHz cavities finalized, prototype cavities are being prepared
- LCLS-II CM production at FNAL has been completed
- LCLS-II-HE vCM has been assembled and tested achieving world record performance!
- HL-LHC AUP:
  - Magnets: produced 50% of the coils, 5/20 magnets and tested 4
  - CRAB cavities: 2 prototypes built, 1st tested and met HL-LHC requirements
- Mu2e Solenoids: all transport solenoids tested and assembled, production and detector solenoid are being fabricated

# I'd like to thank all the authors who kindly provided material and input for this talk and to apologize to the numerous activities not covered here

LCLS-II
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
PIP-II
Particle Accelerator Project
March 15, 2019 Groundbreaking
CERN
Fermilab
Jefferson Lab
Mu2e
US HL-LHC AUP
U.S. DEPARTMENT OF ENERGY | Office of Science
HiLumi HL-LHC PROJECT