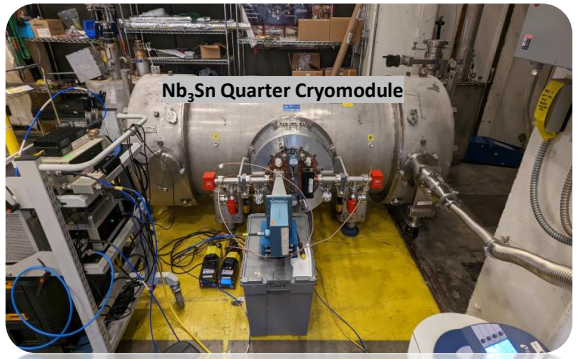
First Nb_3Sn coated CEBAF style quarter cryomodule



Anne-Marie Valente-Feliciano

On behalf of

U. Pudasaini, G. Ciovati, C. Reece, J. Fisher, M. Drury, M. McCougan, M. Weaks, R. Rimmer, T. Reilly, R. Geng and SRF Technical Staff.

G. Eremeev, S. Posen, B. Tennis

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

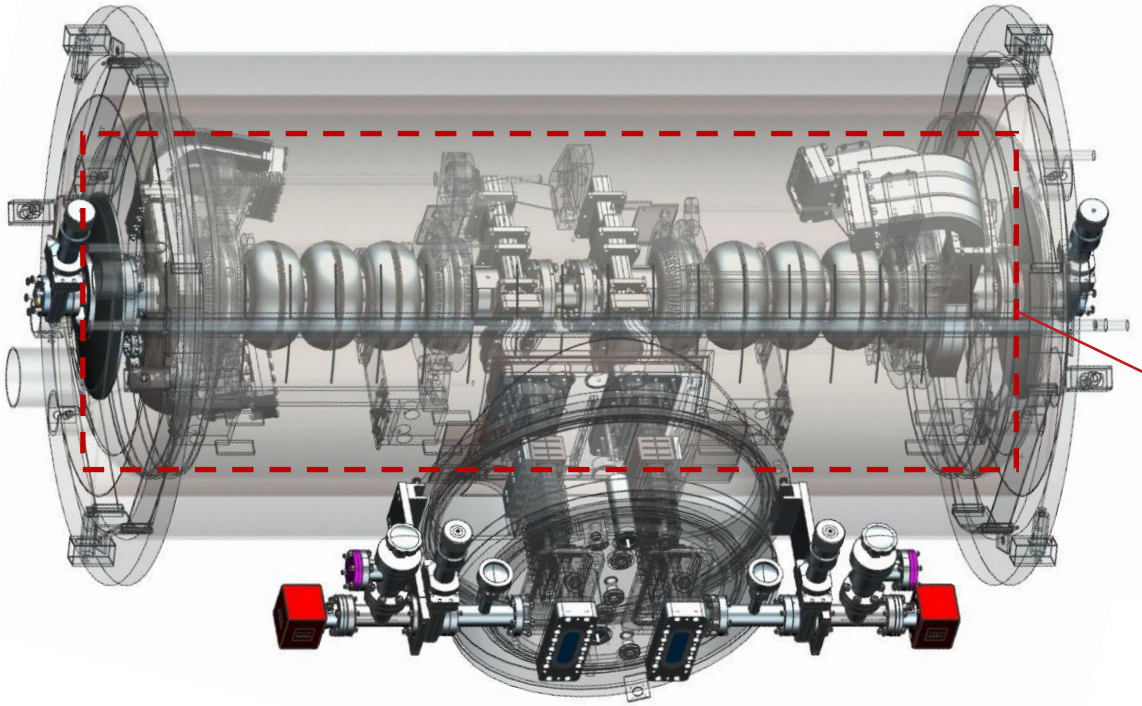
JSA

Outline

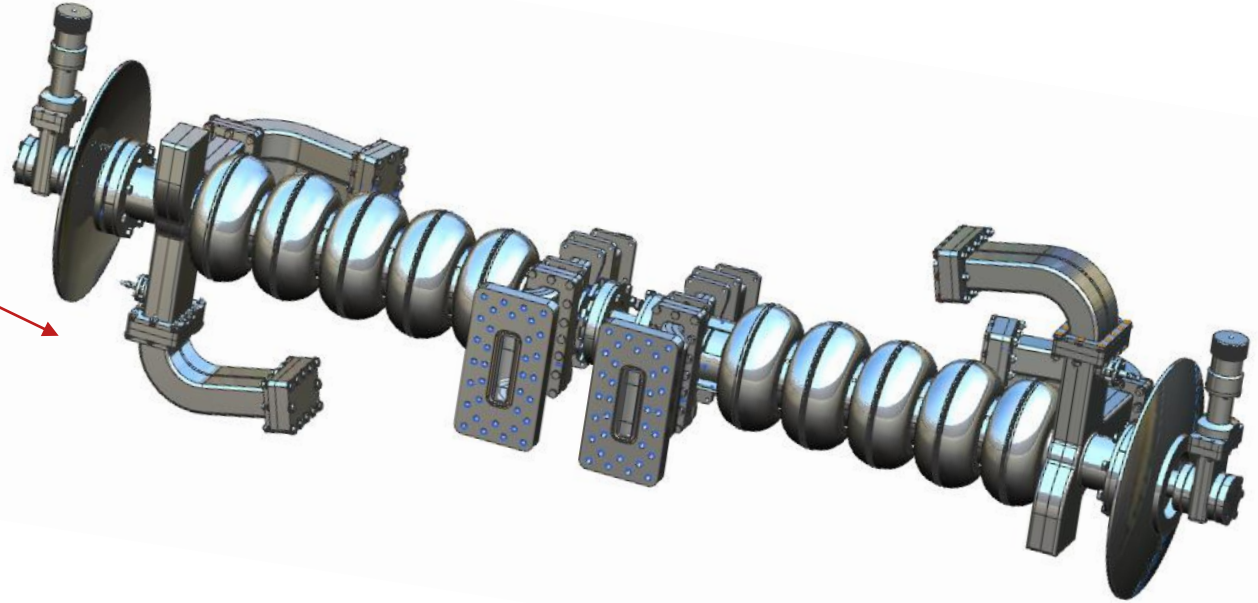
- Introduction
- Technique & coating facilities
- Development & qualification of Nb_3Sn coated 5-cell cavities
- Nb_3Sn cryomodule development
- RF test of completed cryomodule
- Next step
- Lessons learned
- Summary & outlook

Introduction

Goal: develop a quarter cryomodule with Nb_3Sn-coated cavities with an average gradient of 10 MV/m per cavity.



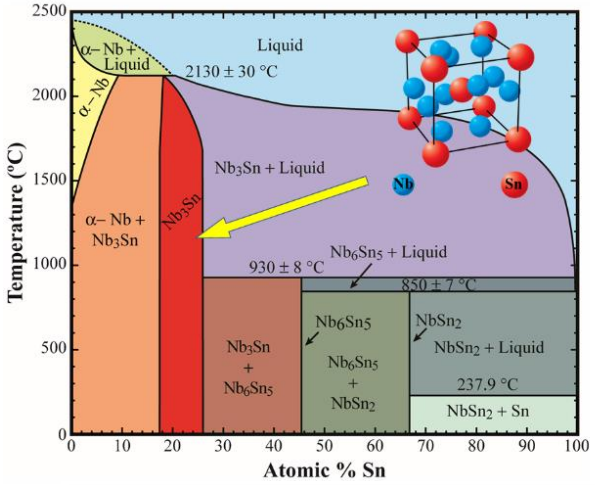
Based on:
1.5 GHz CEBAF C75 (low-loss) 5-cell cavities

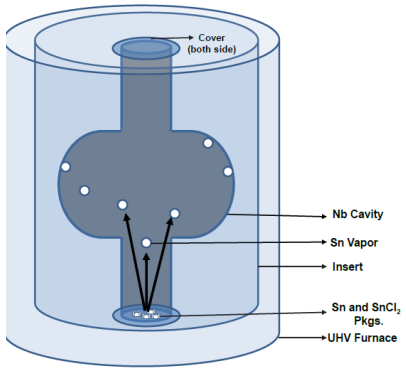


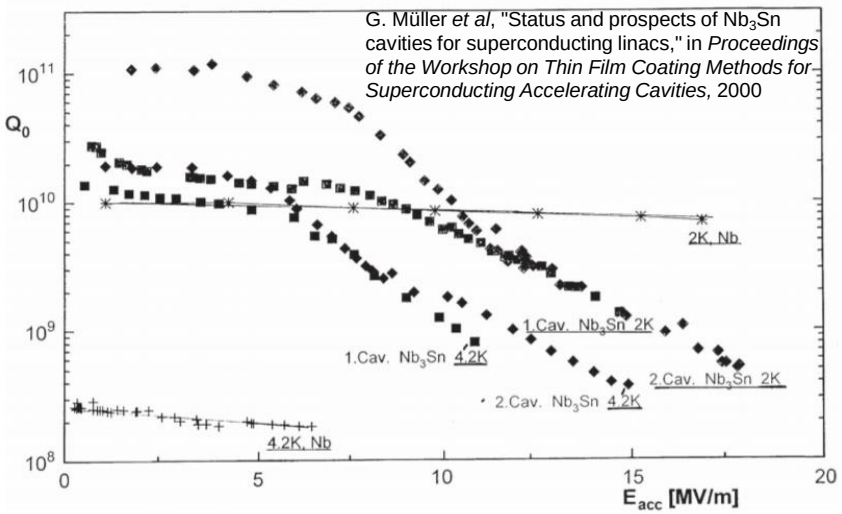
In the framework of G. Eremeev's ECA : "Formation of Superconducting Nb3Sn Phase for Superconducting Radio Frequency (SRF) Cavities "

Vapor Diffusion – "*The*" current mainstream technique

- since 1970s (*Siemens*)
- so far 'THE' technique producing practical Nb_3Sn cavities

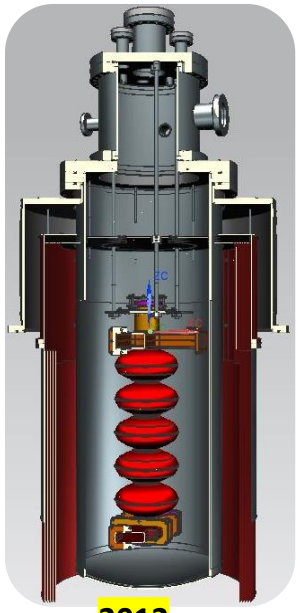






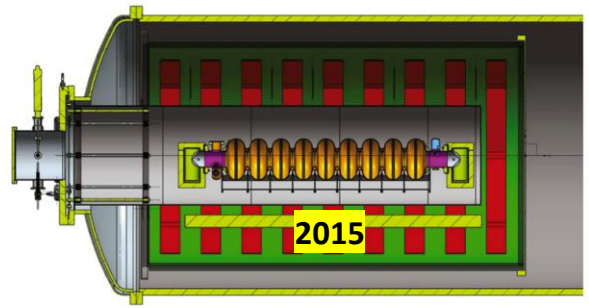
G. Müller *et al*, "Status and prospects of Nb_3Sn cavities for superconducting linacs," in *Proceedings of the Workshop on Thin Film Coating Methods for Superconducting Accelerating Cavities*, 2000

Vapor diffusion coating facilities around the world



2012

Jefferson Lab



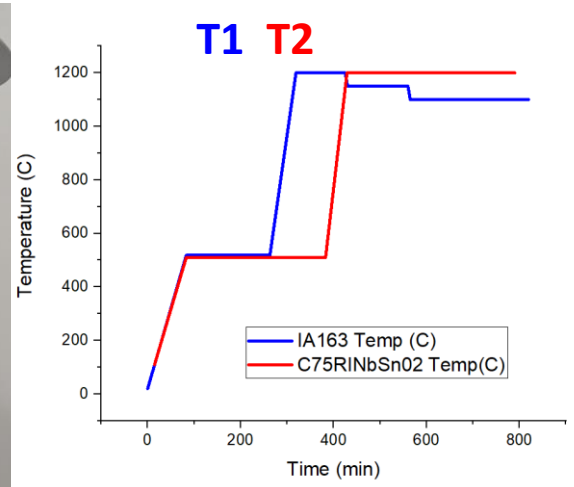
2015

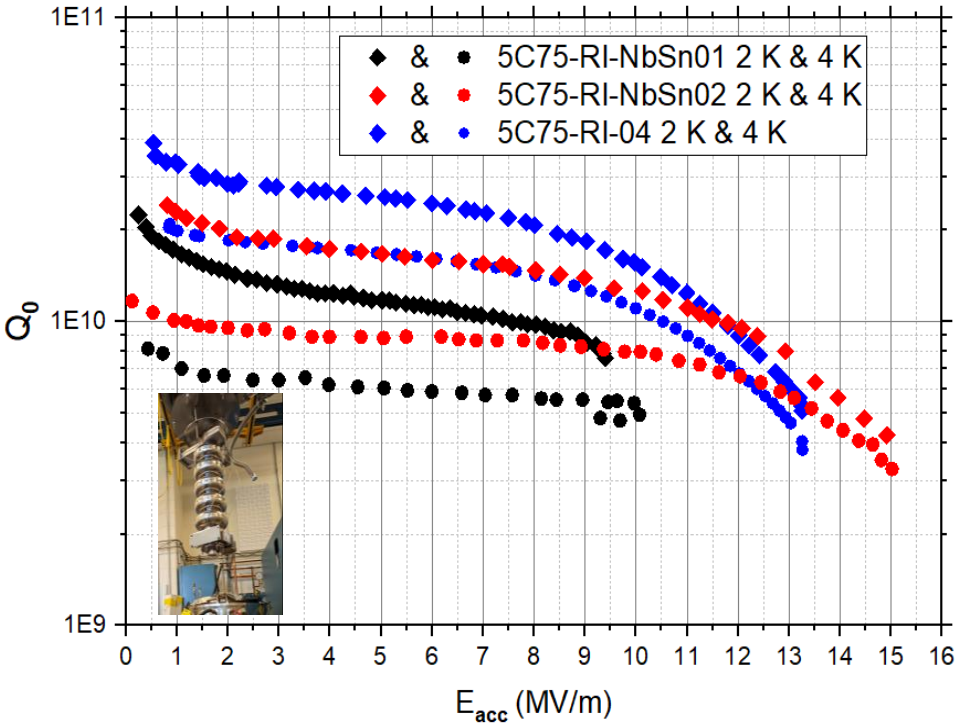
Fermilab

Jefferson Lab

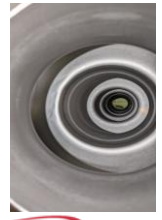
Multi-Cell Coating at Jefferson Lab

- Process development based on witness samples coated with multi-cell cavities
  - 1.5 GHz 5-cell and 1.3 GHz 3-cell
- Sn source(s) and temperature profile optimization
- Q_0 and E_{max} suitable for accelerator applications





Witness sample in each run.	Sn consumption (g)				
	1st coating	2nd Coating	3rd Coating	5C75-RI-NbSn02 02	5C75-RI-NbSn02 02
Primary	3.6	2.50	2.79	3.05	**2.42**
Secondary 1	1.7	1.50	1.42	1.50	**1.48**
Secondary 2	---	1.60	1.43	1.51	**1.48**
Total	5.3	5.60	5.64	6.06	**5. 38**
Setup	S1-T1	S2-T1	S3-T2	S2-T1	**S3-T2**



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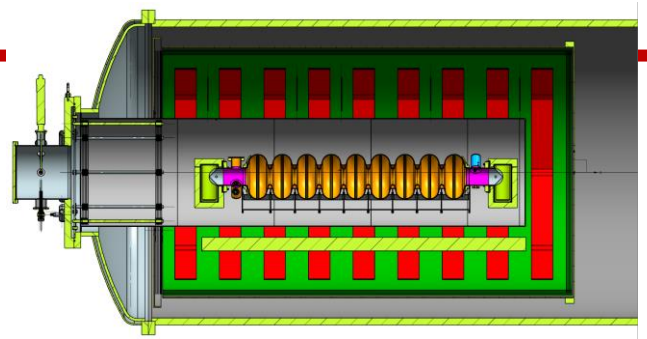
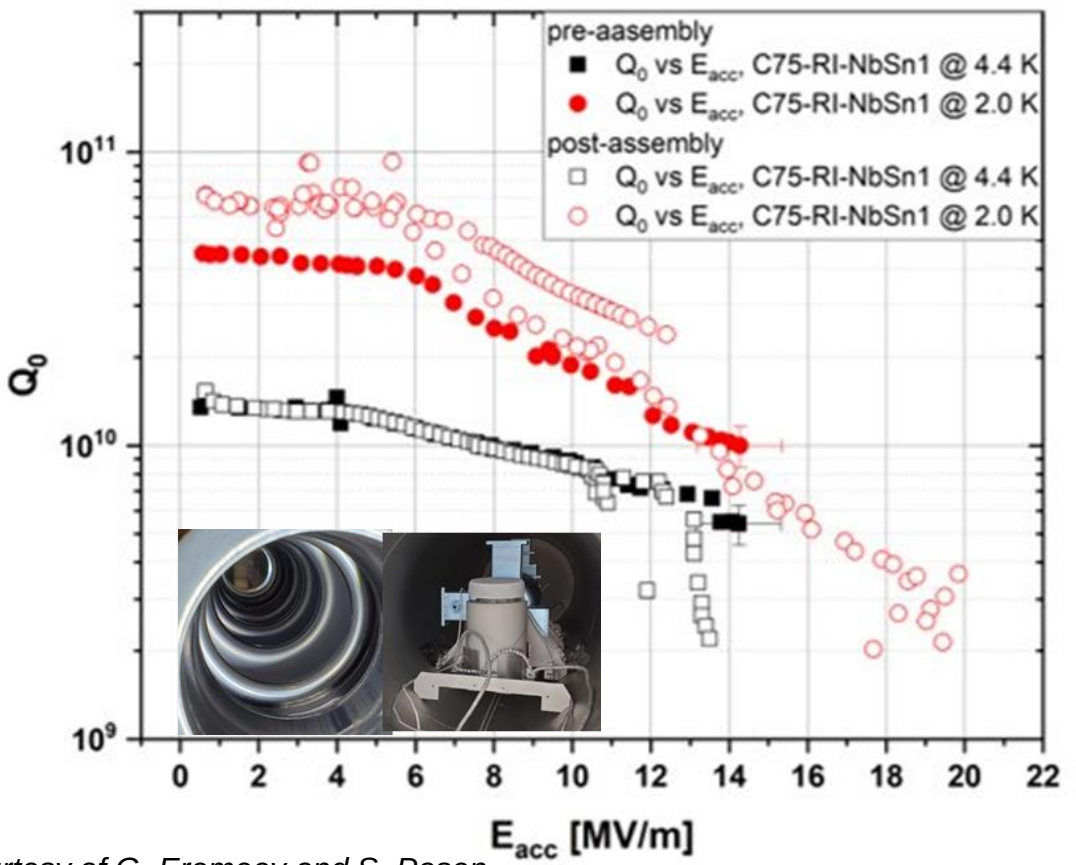
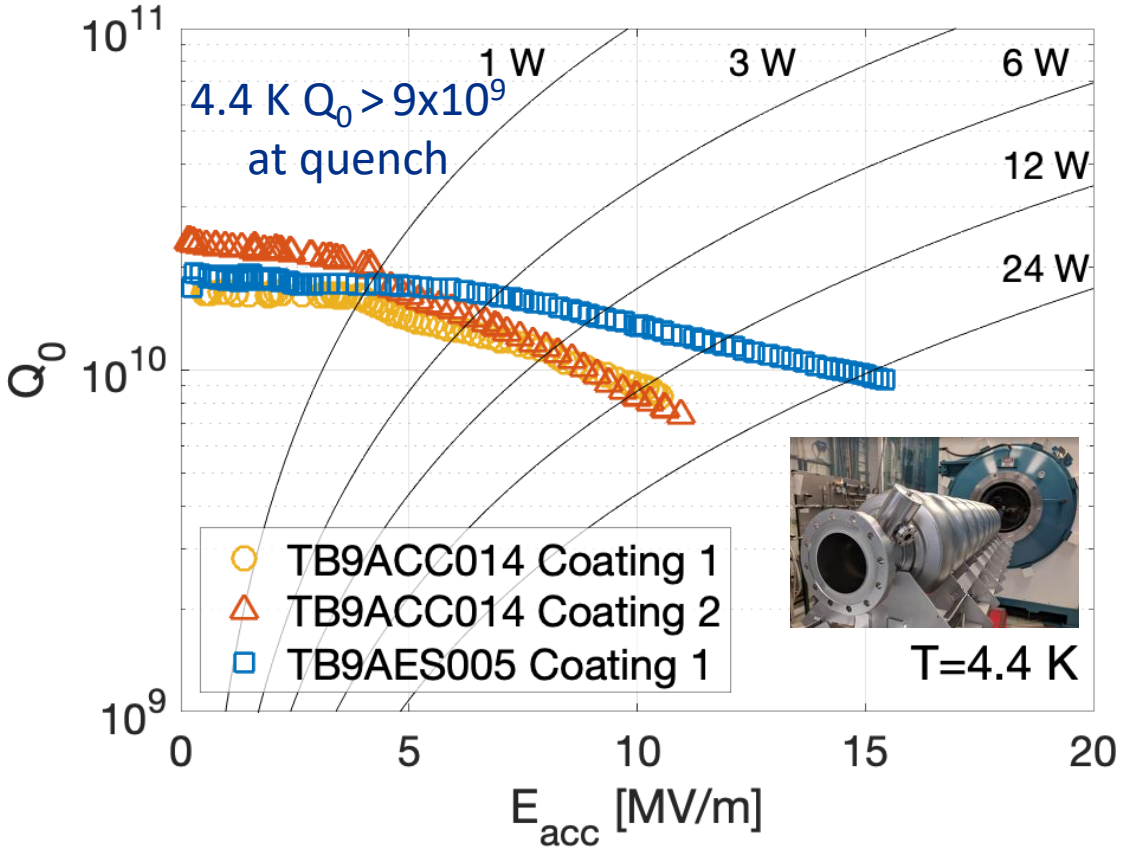
Multi-cell Cavity Coating at Fermilab

- Coatings of multicell accelerator structures for various projects
- E_{acc} > 15 MV/m, Q ~ 1x10^{10} at 4.4 K





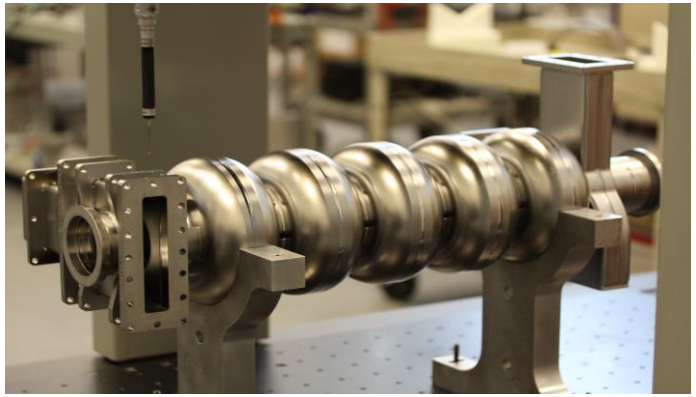


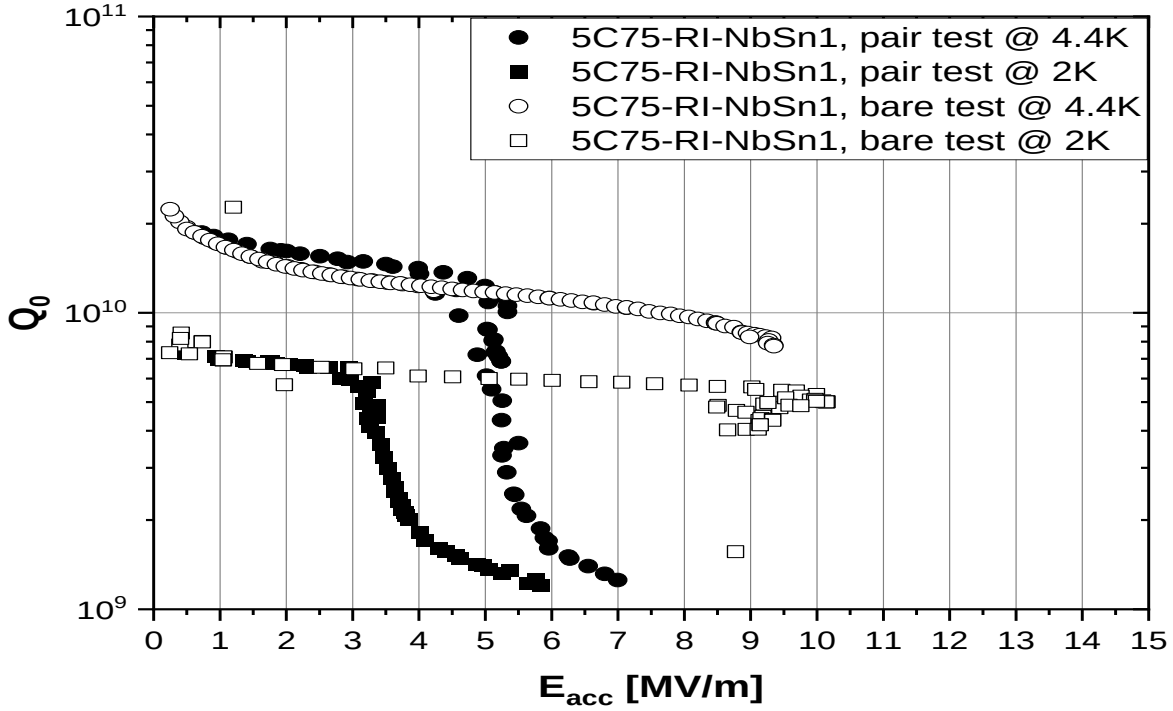
Courtesy of G. Eremeev and S. Posen

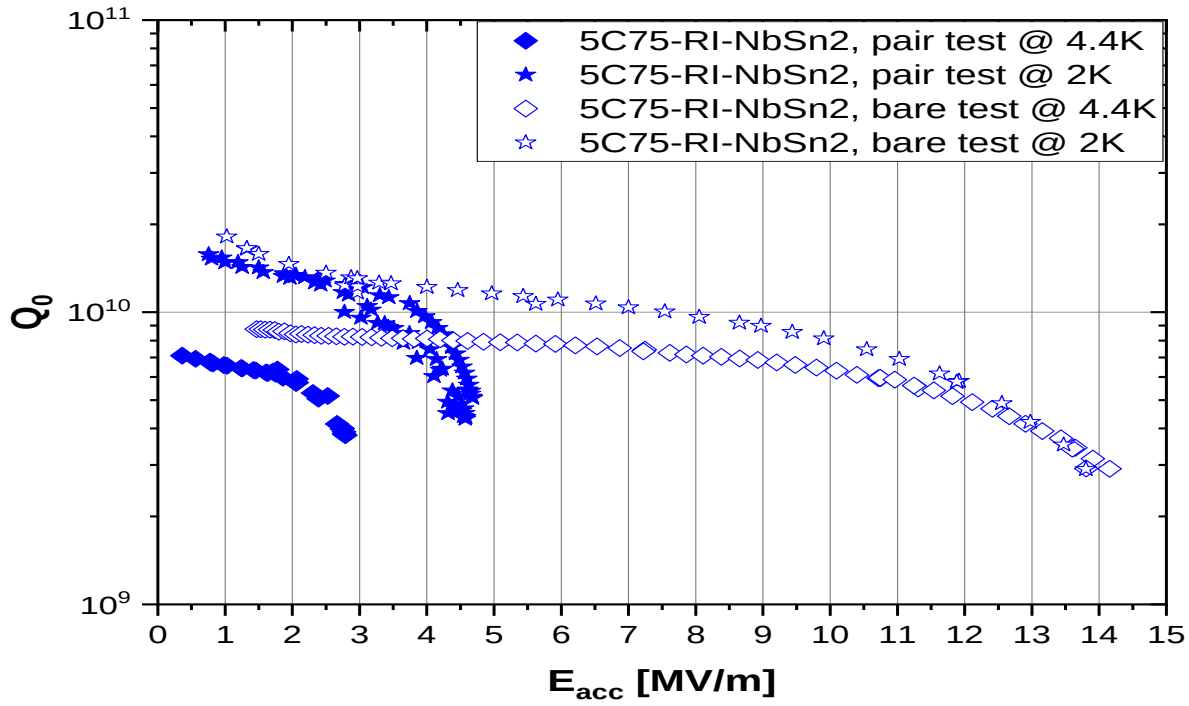
Qualification of Nb_3Sn-coated C75 5-cell cavities at JLab

- Two five-cell Nb_3Sn-coated cavities qualified in 2019 with E_{max} of 12 and 14 MV/m
- Degraded to below 5 and 7 MV/m during the vertical pair test
  - Mechanical stress due to vertical pair assembly & hanging
- both cavities required reprocessing and re-coating

G. Eremeev, U. Pudasaini, Tesla Collaboration Meeting 2022, Aomori Japan





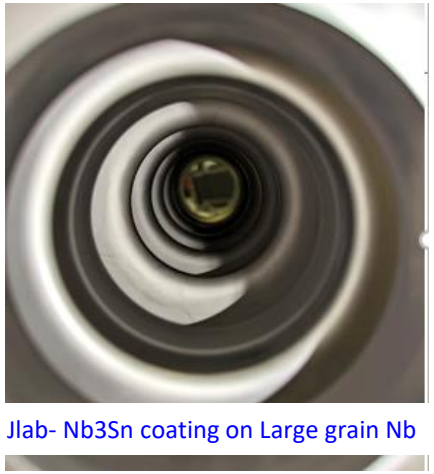


*Work-based on G. Eremeev's Early Career Award at Jefferson Lab.

Jefferson Lab

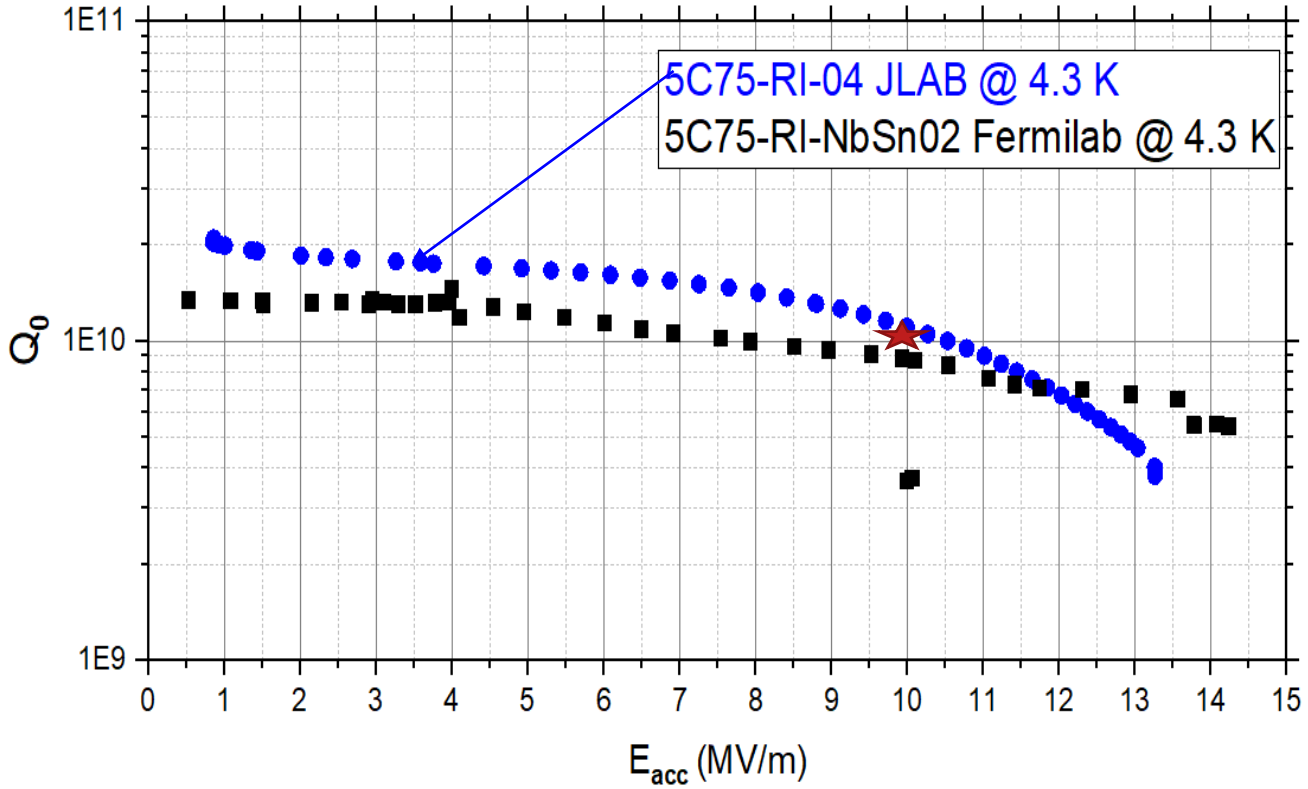
Re-Qualification of Nb_3Sn-coated Cavities

- One cavity coated at JLab and another at Fermilab
- Both cavities reached >13 MV/m with Q~10^{10} at 10 MV/m



Jlab- Nb_3Sn coating on Large grain Nb

Fermilab- Fine Grain Nb Cavity



- Pair subjected to disassembly due to a leak in a RF window

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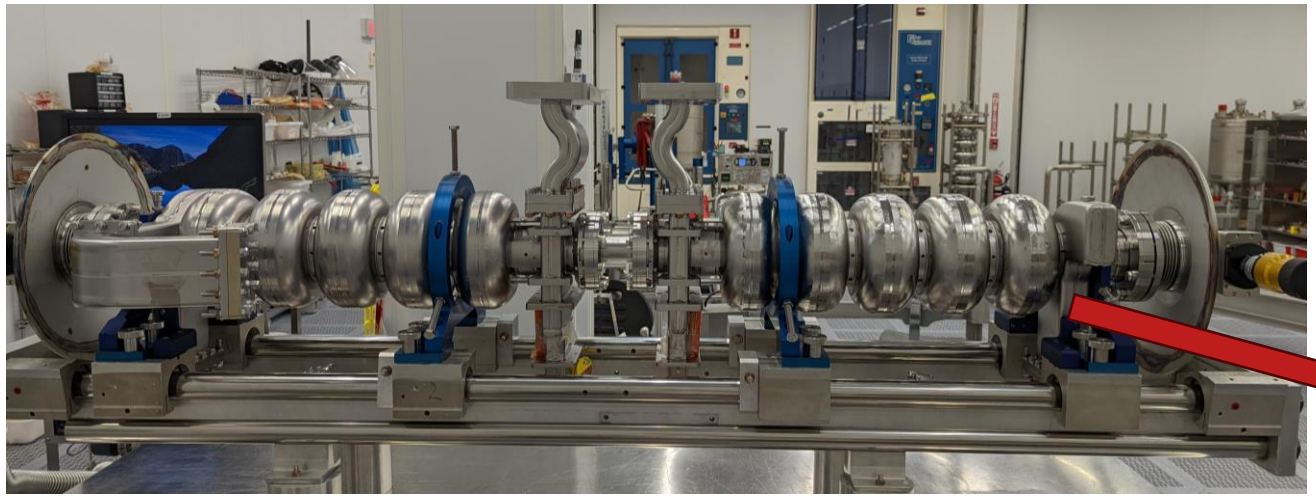
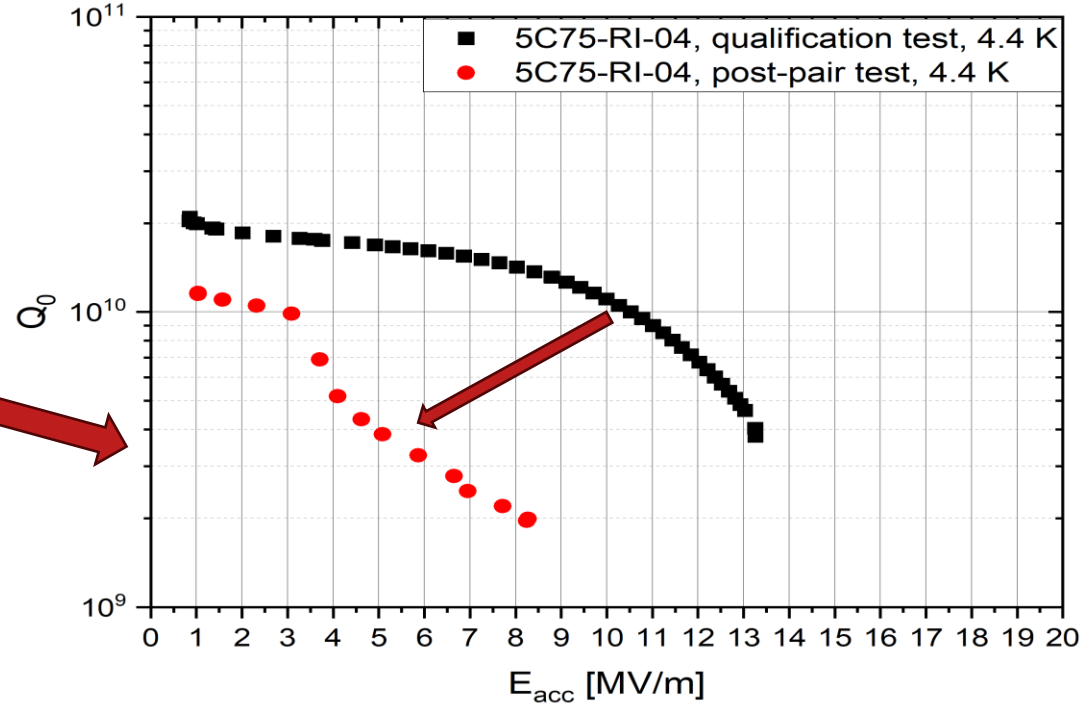
Re-Qualification of Nb_3Sn-coated Cavities

- Cavities were re-tested independently – degraded one cavity
- Pair successfully assembled again
- Skipped vertical test of the pair to avoid mechanical degradation





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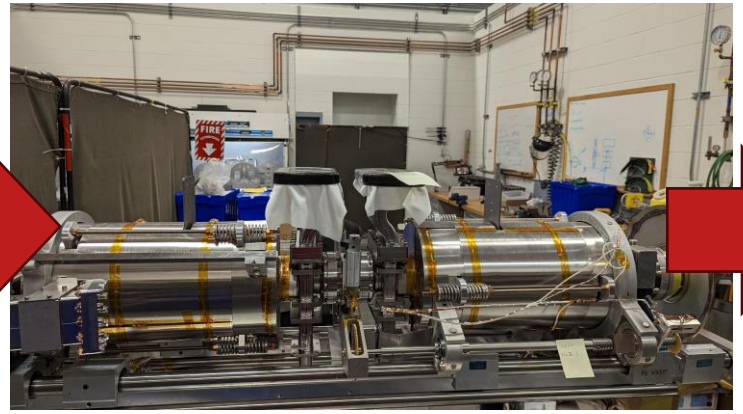
Cryomodule Assembly

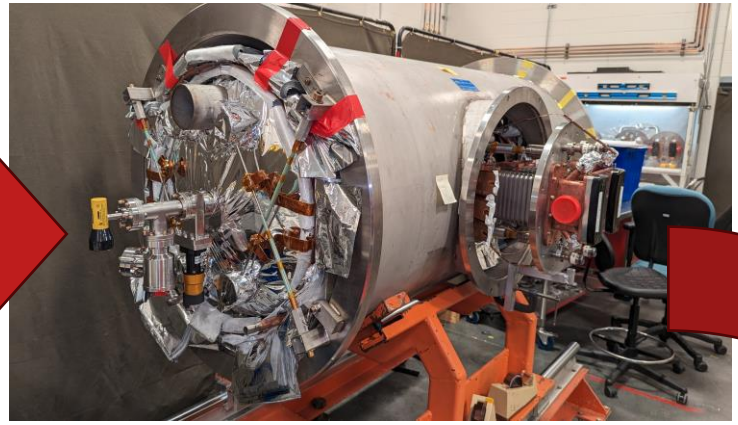
- **Several assembly steps required modifications to avoid mechanical strain on the cavities.**

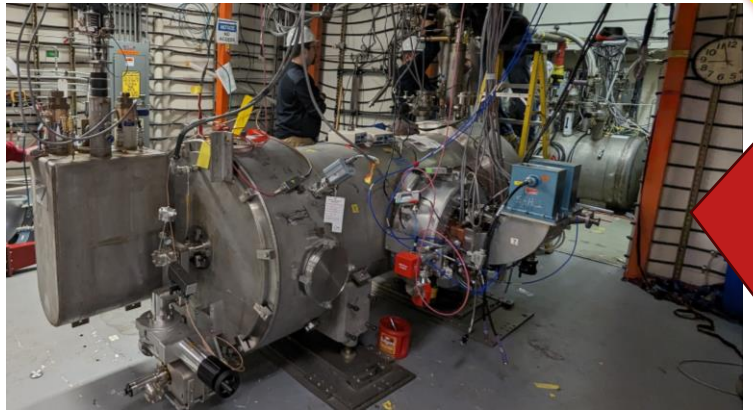
April 2023

May 2023

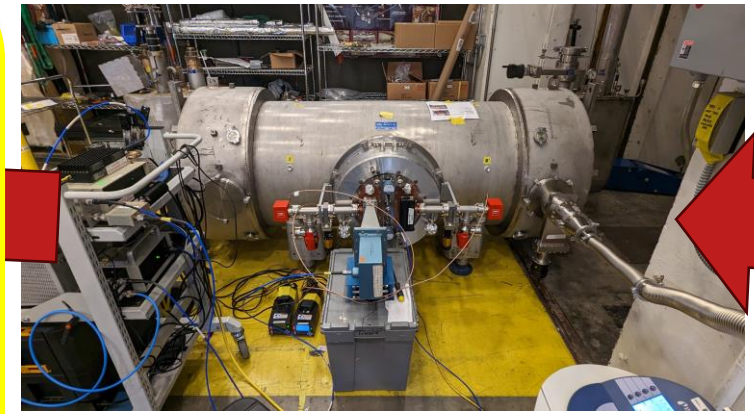


July 2023

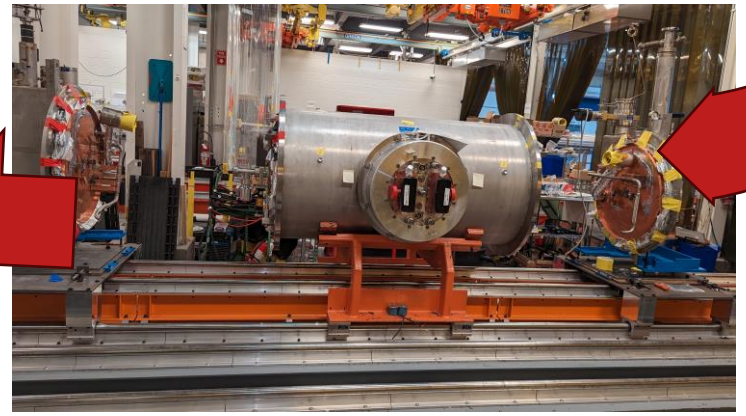




April 2024



November 2023



August 2023

Slow cooldown with temperature gradient ~ 0.3 K across the cryomodule.

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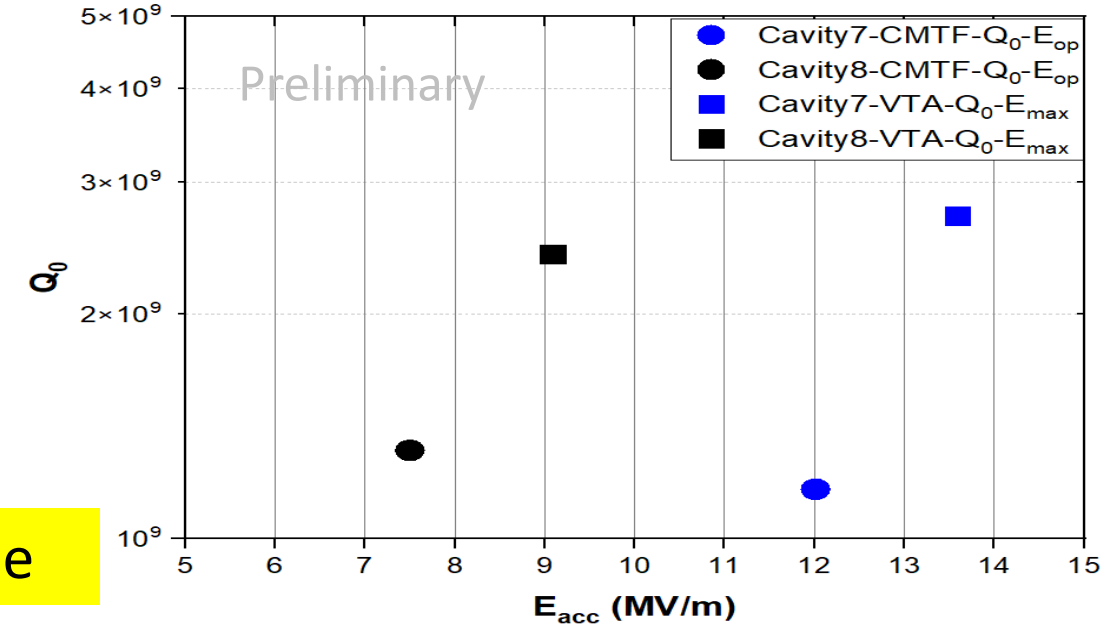
QCM Preliminary Qualification Test Results

Cavity	CMTF f(MHz) @ 4 K	CMTF f(MHz) @ 2 K	VTA Emax (MV/m) @ 4 K	CMTF Emax (MV/m) @ 4 K	Eop (MV/m) 1 h run @ 4 K FE-free	VTA Emax (MV/m) @ 2 K	CMTF Emax (MV/m) @ 2 K	Eop (MV/m) 1 h run @ 2 K FE-free
5C75-RI-NbSn01	1496.56	1496.59	13.6	13.3	12.6	18.5	13.2	12.4
5C75-RI-04	1496.41	1496.44	9.0	7.9	7.5	9.2	8.7	8.5

- Accelerating gradients close to vertical test at 4 K
- Frequency difference between two cavities ~150 kHz
- Second cavity tuned to match the first one at 2 K– no degradation

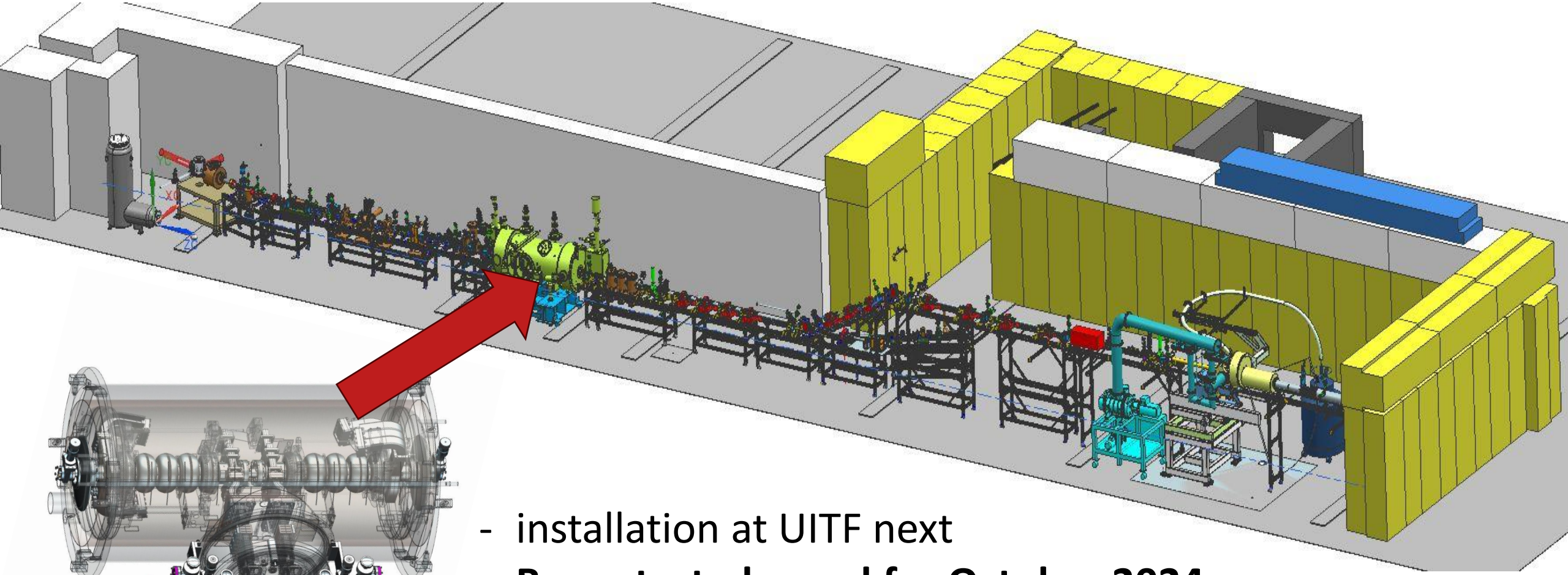


First demonstration of >**10 MeV** Nb_3Sn cryomodule

Fermilab Jefferson Lab

What's next?

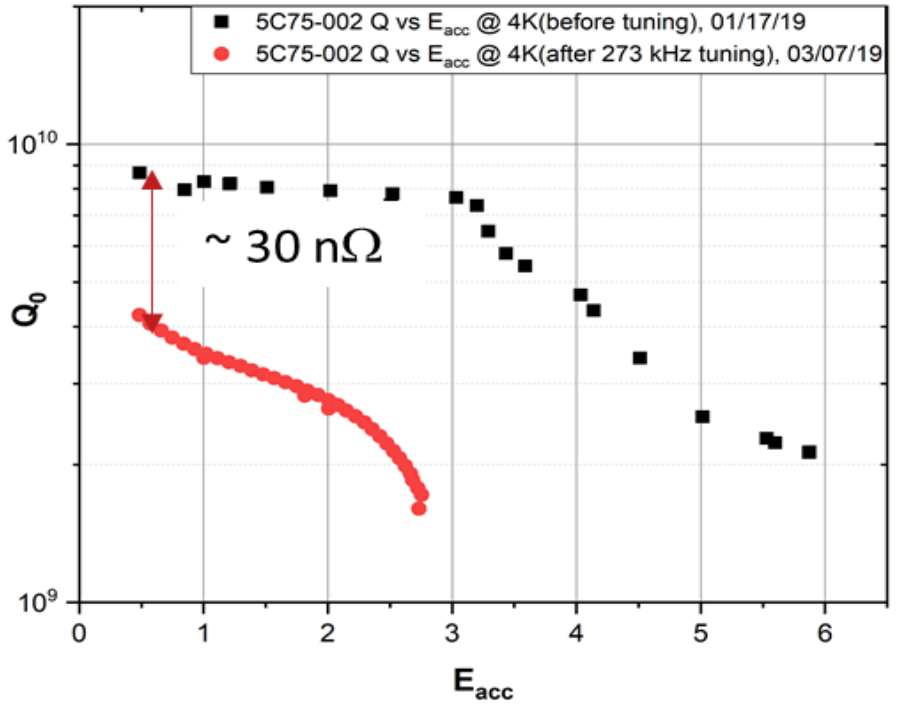
Upgraded Injector Facility at Jefferson Lab

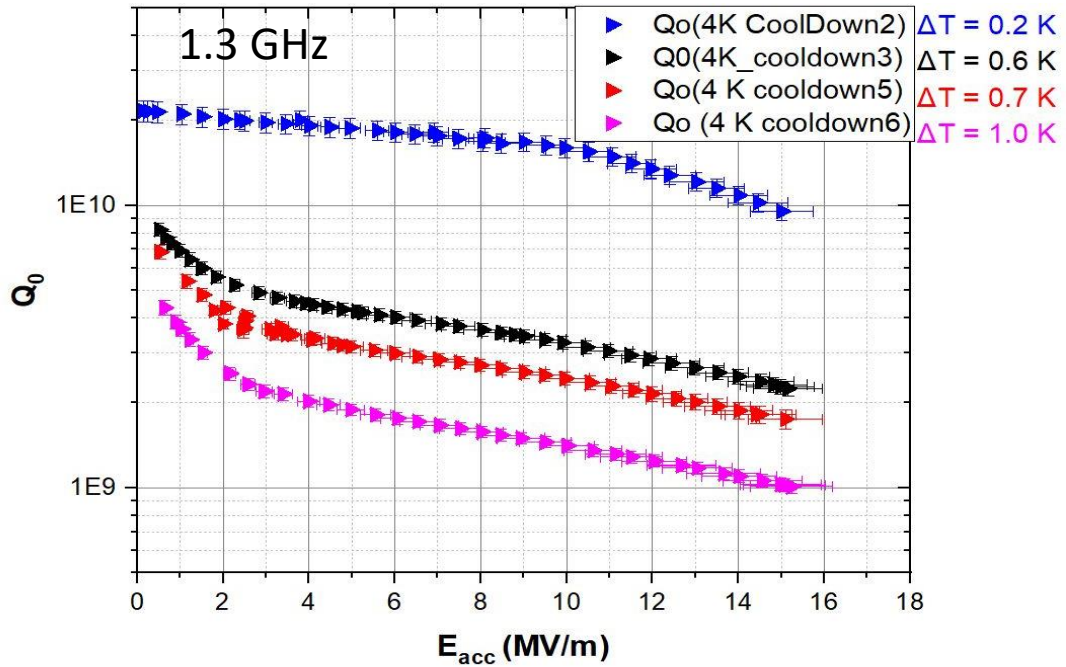


- installation at UITF next
- **Beam test planned for October 2024.**

Stay Tuned.

Lessons Learned





Challenges in Deploying Nb_3Sn Cavities for Accelerators

- Mechanical vulnerability of brittleness of the material – Need for specific procedures
  - Risks associated with handling and assembly
  - Tuning sensitivity
- Bi-layer material
  - Thermal current during the cooldown resulting in Q-degradation

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Summary & Outlook

- First-ever 10 MV/m gradient achieved in Nb_3Sn cryomodule with multi-cell cavities
- Material brittleness poses challenges in maintaining performance from fabrication to installation
- Developing alternative techniques to enable Nb_3Sn deposition on Cu substrates

  HiPIMS as energetic condensation to form A15 phase at temperatures compatible with the substrate

  Cylindrical cathode, new flange material
- Successful exercise highlighting the potential of Nb_3Sn, but further efforts needed for reliable deployment of Nb3Sn based cavities in cryomodules