MSU/FRIB Accelerator Physics and Engineering Seminars

First Beam Test of Niobium-Tin SRF Cavity Cryomodule at JLAB and Next Step

December 5, 2025

Rongli Geng

Jefferson Lab

U.S. DEPARTMENT of ENERGY

Outline

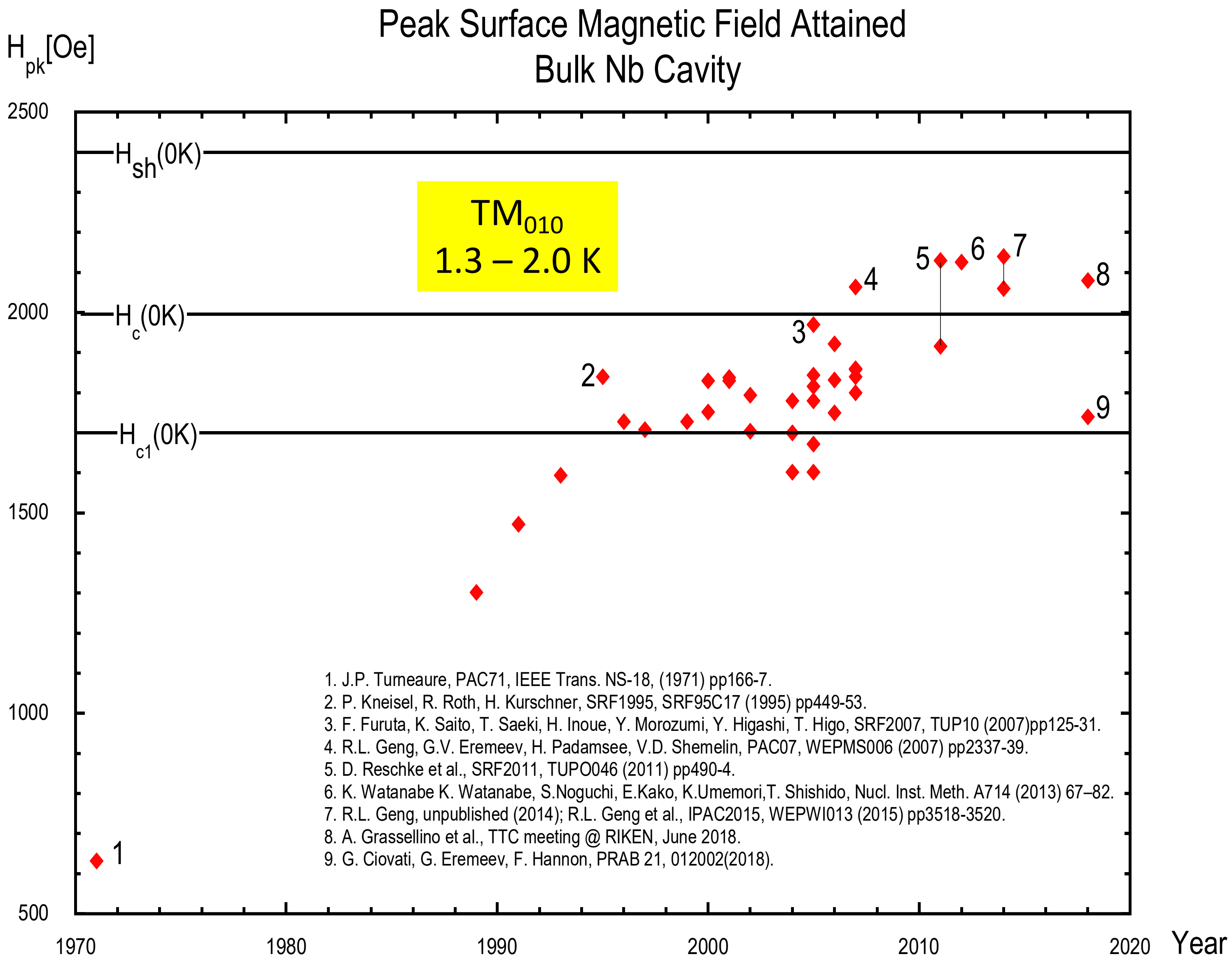
- Motivation for niobium-tin material for SRF
- Niobium-tin SRF cavity development at Jefferson Lab
- UITF facility and cryomodule/cavity design
- Cavity coating and cryomodule assembly
- Cryomodule preparation, check out, and beam test
- Next steps
- Conclusion

Motivation for Niobium-Tin Material for SRF

- Relative to niobium (Nb), incumbent SRF material, Nb_3Sn (Niobium-tin) possesses superior properties
  - Superconducting transition temp. (Tc) twice as high
  - Superheating field strength (H_{sh}) nearly doubled
- Consequences and impacts
  - Enables SRF Nb_3Sn cavity operation at 4 K at an RF heat dissipation on par with that for Nb cavity at 2 K, leading to enormous saving in electricity for cryoplant infrastructures supporting large-scale SRF accelerators.
  - Eliminates the need for a 2 K cold box, leading to a simplified cryoplant architect, hence a significant improvement in the facility uptime and reliability.
  - Enables much higher acceleration gradient (more than 100 MV/m), significantly shrinking footprint of SRF accelerators.
  - Enables compact 10 MeV level SRF accelerator and table-top 1 MeV level SRF instruments, cooled by commercial cryo-coolers as opposed to special cryoplants.

Material	Nb	Nb_3Sn
T_c [K]	9.25	18.3
ρ_n [μΩcm]	0.1	~ 5
$H_{sh}(0)$ [Oe]	2400	~ 4500
Δ [meV]	1.45	~ 3.1
Q^{BCS} @ 2K	$\sim 5\cdot10^{10}$	$\sim 5\cdot10^{14}$
Q^{BCS} @ 4K	$\sim 5\cdot10^{8}$	$\sim 5\cdot10^{10}$
E_{acc} [MV/m]	~ 50	~ 100

Adapted from G. Eremeev et al., “Achieving 10 MV cryomodule with Nb_3Sn cavities”, Invited talk THYN02, NAPAC2025.



Data Point	material	Freq [GHz]	# of cells	Treatment
1	Nb	1.3	1	HT+LTB
2	Nb	1.3	1	BCP
3	Nb	1.3	1	EP+LTB
4	Nb	1.3	1	EP+LTB
5	LG Nb	1.3	9	EP+LTB
6	Nb	1.3	2	EP+LTB
7	LG Nb	1.5	1	EP+LTB
8	Nb	1.3	1	EP+M-LTB
9	Nb	3.0	1	EP+LTB

Nb: Fine-grain nNb
LG Nb: large grain ingot Nb
HT: UHV firing 1800 °C
CP: Buffered chemical Polishing (HNO_3+HF+H_2O)
EP: Electropolishing (HF+H_2O+H_2SO_4)
LTB: Low temperature bake 100-120 °C
M-LTB: Modified LTB (75°C + 120 °C)

Nb3Sn cavity potential 100 MV/m

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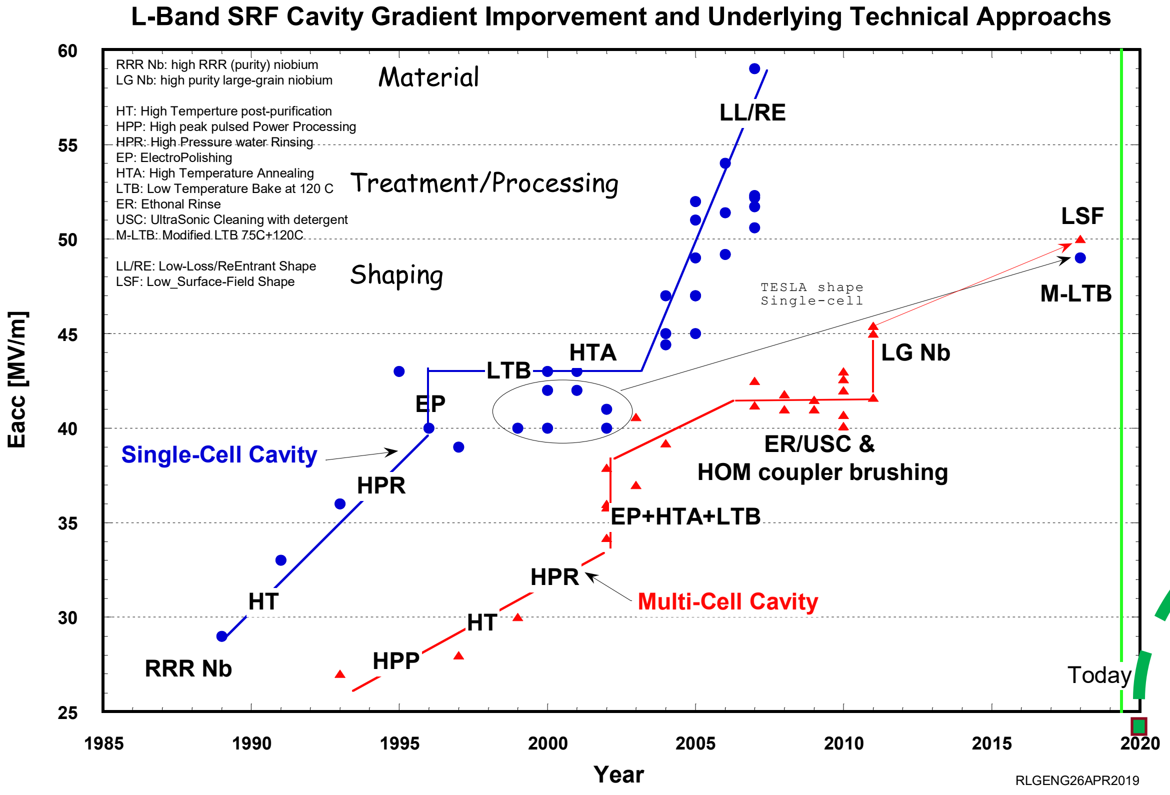
Cavity shaping led to gradient breakthrough in bulk Nb cavities reaching 45 - 59 MV/m in 1-cell cavities

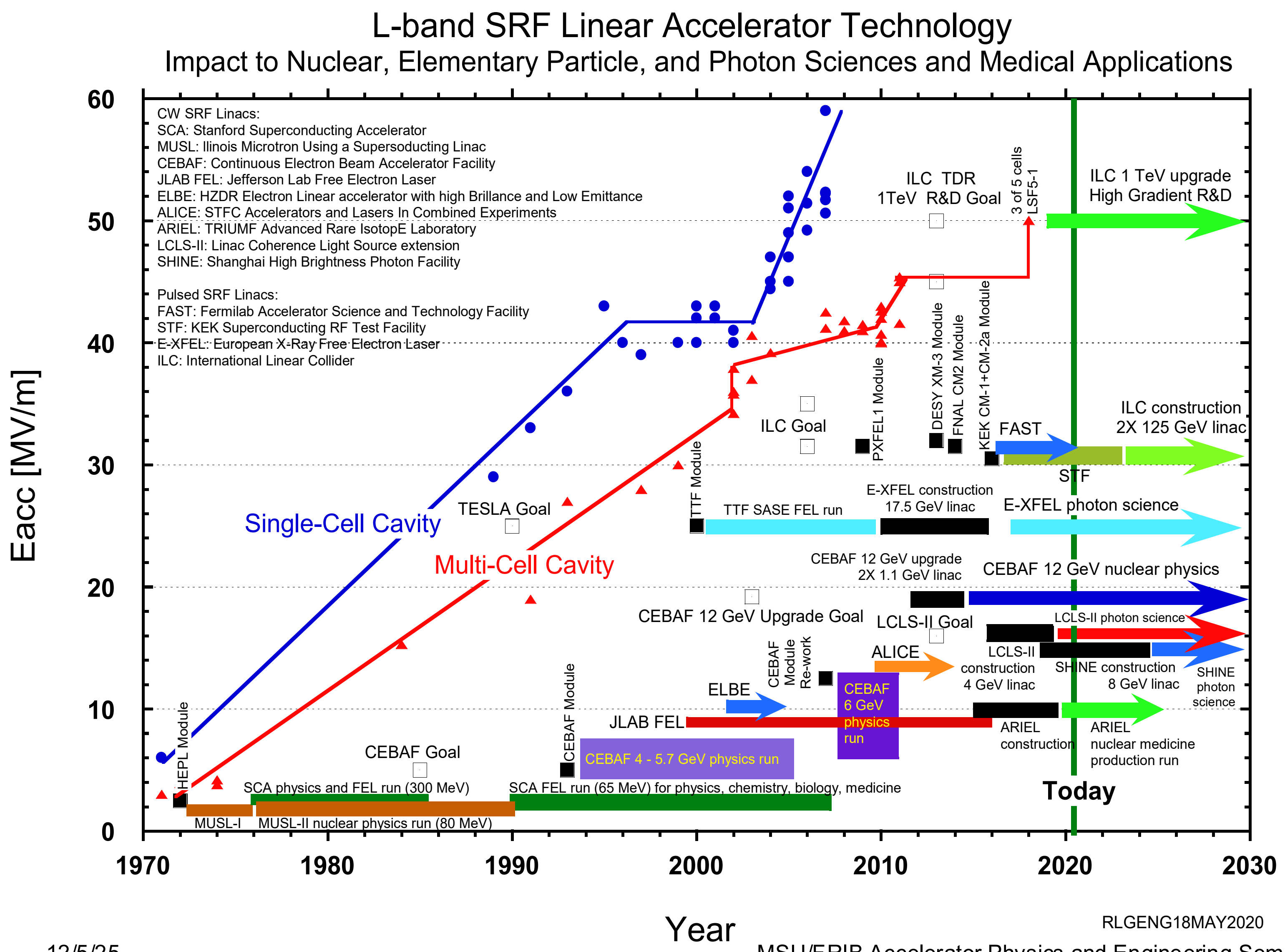


24 MV/m observed in today's best Nb3Sn 1-cell cavity

New learning curve for SRF Nb_3Sn cavity

- Growing interest and development in Nb_3Sn cavities
  - Current best approach is Sn vapor diffusion with bulk Nb cavity
  - Work is under way seeking to put Nb_3Sn on Cu cavity

Gradient Frontier of SRF Cavities and Accelerators

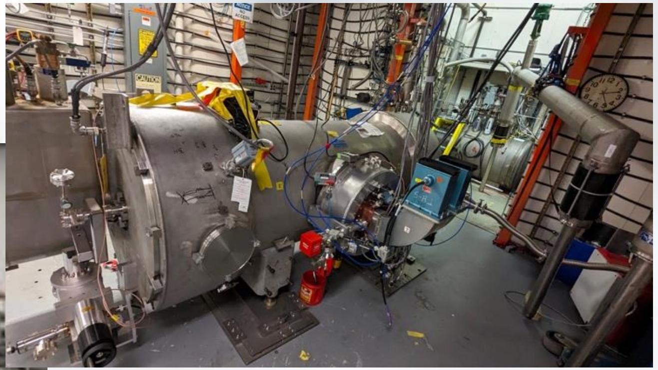


- Steady SRF gradient progress in Nb cavities drove broad applications over past five decades.
- Last decade saw an intensive interest and progress in Nb cavity Q_0 to lower losses.
- Nb_3Sn the next SRF material to breakthrough 60 MV/m gradient and to transform application landscape?

Niobium-Tin SRF Cavity Development at JLAB

Jefferson Lab

- G. V. Eremeev, W. A. Clemens, K. Macha, H. Park, and R. S. Williams, “Development of Nb3Sn Cavity Vapor Diffusion Deposition System”, in *Proc. SRF'13*, Paris, France, Sep. 2013, paper TUP071, pp. 603-606.
- G. V. Eremeev, W. A. Clemens, K. Macha, H. Park, and R. S. Williams, “Commissioning Results of Nb3Sn Cavity Vapor Diffusion Deposition System at JLab”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3512-3514. doi:10.18429/JACoW-IPAC2015-WEPWI011
- G. V. Eremeev, “Results from the First Single Cell Nb3Sn Cavity Coatings at JLab”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3509-3511. doi:10.18429/JACoW-IPAC2015-WEPWI010
- G. V. Eremeev, M. J. Kelley, C. E. Reece, U. Pudasaini, and J. Tuggle, “Progress With Multi-Cell Nb3Sn Cavity Development Linked With Sample Materials Characterization”, in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper TUBA05, pp. 505-511.



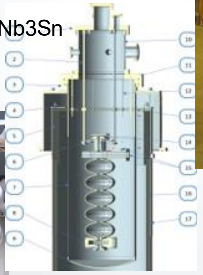
2024

Demonstration of two 5-cell CEBAF-style Nb_3Sn coated cavities in a CEBAF-style quarter cryomodule in 2024

- ✓ 13 MV/m and 8 MV/m
- ✓ Cavity coating at FNAL & JLAB

2023

2018

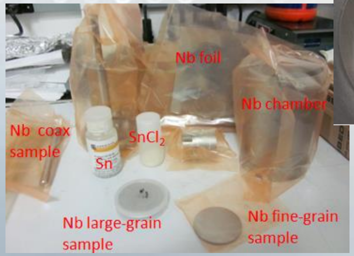


2017

Major boost by DOE NP ECA to Grigory Eremeev in 2016

2015

2014



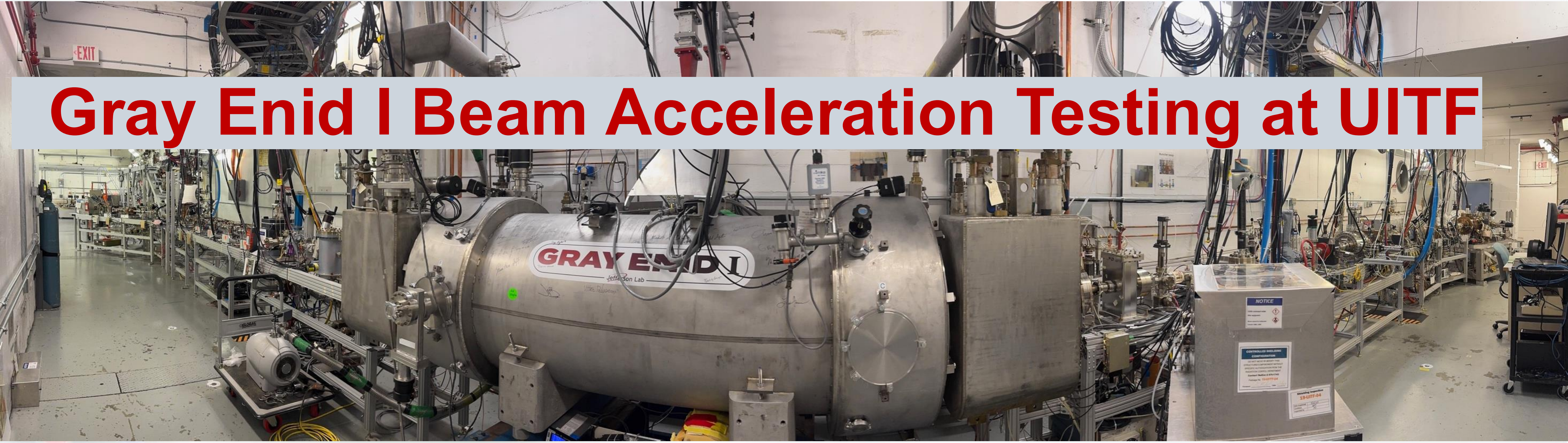
2010-2012

- DOE BES inverse Compton light source development
- DOE NP Advanced Technology Research and Development

- U. Pudasaini *et al.*, “Nb3Sn Multicell Cavity Coating at JLab”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1798-1803. doi:10.18429/JACoW-IPAC2018-WEYGBF3
- G. V. Eremeev and U. Pudasaini, “Development of Nb3Sn Multicell Cavity Coatings”, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3070-3073. doi:10.18429/JACoW-IPAC2019-WEPRB111
- U. Pudasaini *et al.*, “Recent Results From Nb3Sn Single Cell Cavities Coated at Jefferson Lab”, in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 65-70. doi:10.18429/JACoW-SRF2019-MOP018
- U. Pudasaini, G. V. Eremeev, M. J. Kelley, and C. E. Reece, “Recent Developments of Nb3Sn at Jefferson Lab for SRF Accelerator Application”, in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 713-716. doi:10.18429/JACoW-NAPAC2019-WEPLM52
- G. V. Eremeev *et al.*, “Preservation of the High Quality Factor and Accelerating Gradient of Nb_3Sn-Coated Cavity During Pair Assembly”, presented at the SRF'23, Grand Rapids, MI, USA, Jun. 2023, paper TUPTB010.
- G Eremeev et al, “Demonstration of E_{acc} = 10 MV/ m with Nb_3Sn cavities in a cryomodule”, 2025 Supercond. Sci. Technol. 38 07LT01, DOI 10.1088/1361-6668/ade82d.

November 20, 2024 Jefferson Lab
Niobium-Tin Cavity Cryomodule Dedication: Gray Enid I

Gray Enid I Beam Acceleration Testing at UITF

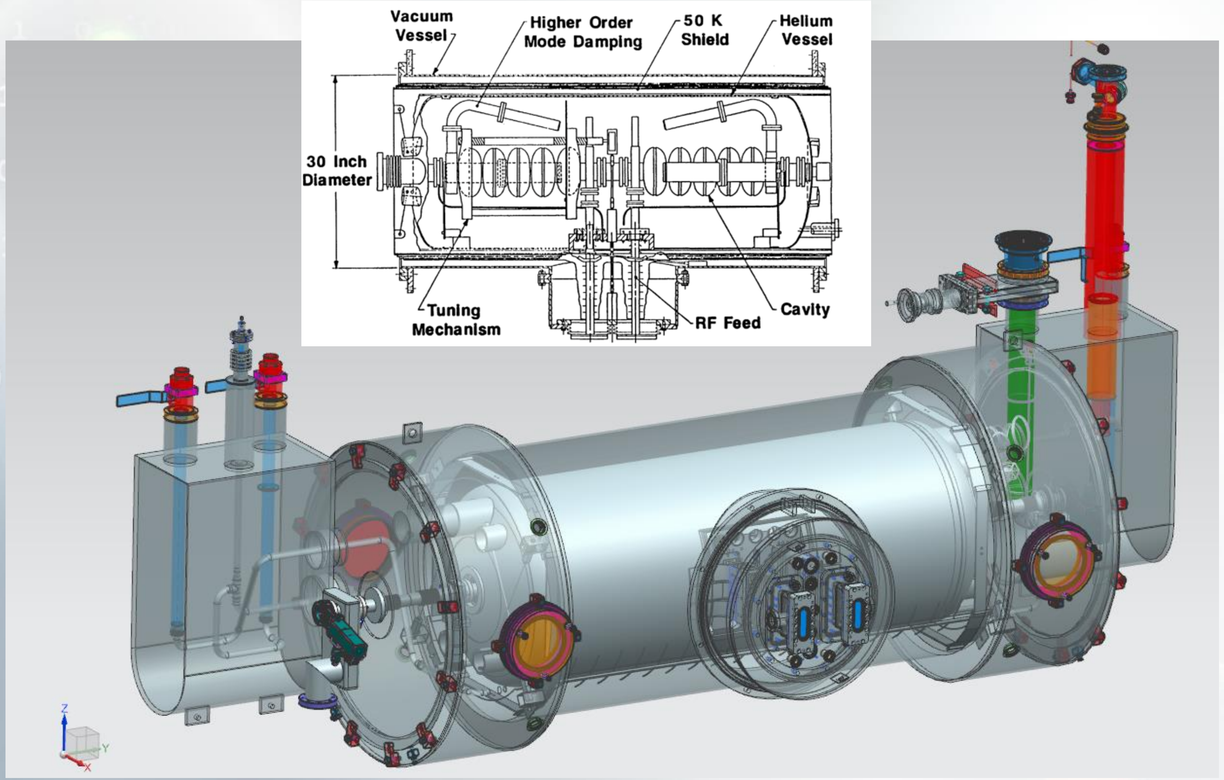


- Upgraded Injector Test Facility (UITF): a test bed that can be quickly reconfigured for testing new accelerator technologies.
  - Test cryomodules, RF cavities, photocathodes, and polarimeters.
  - Provide venue to perform low energy physics experiments with polarized electron beam.
- 200 keV beam from photocathode in DC gun.
- Laser pulse length 35 ps, rep rate 1497 MHz nominal and adjustable
- Cryomodule interfaces
  - Cryomodule installation and connection to beamline
  - RF waveguide connection to upstairs 5 kW Klystrons
  - Cryogenic lines connection to Cryogenic Test Facility

Cryomodule and Cavity Design

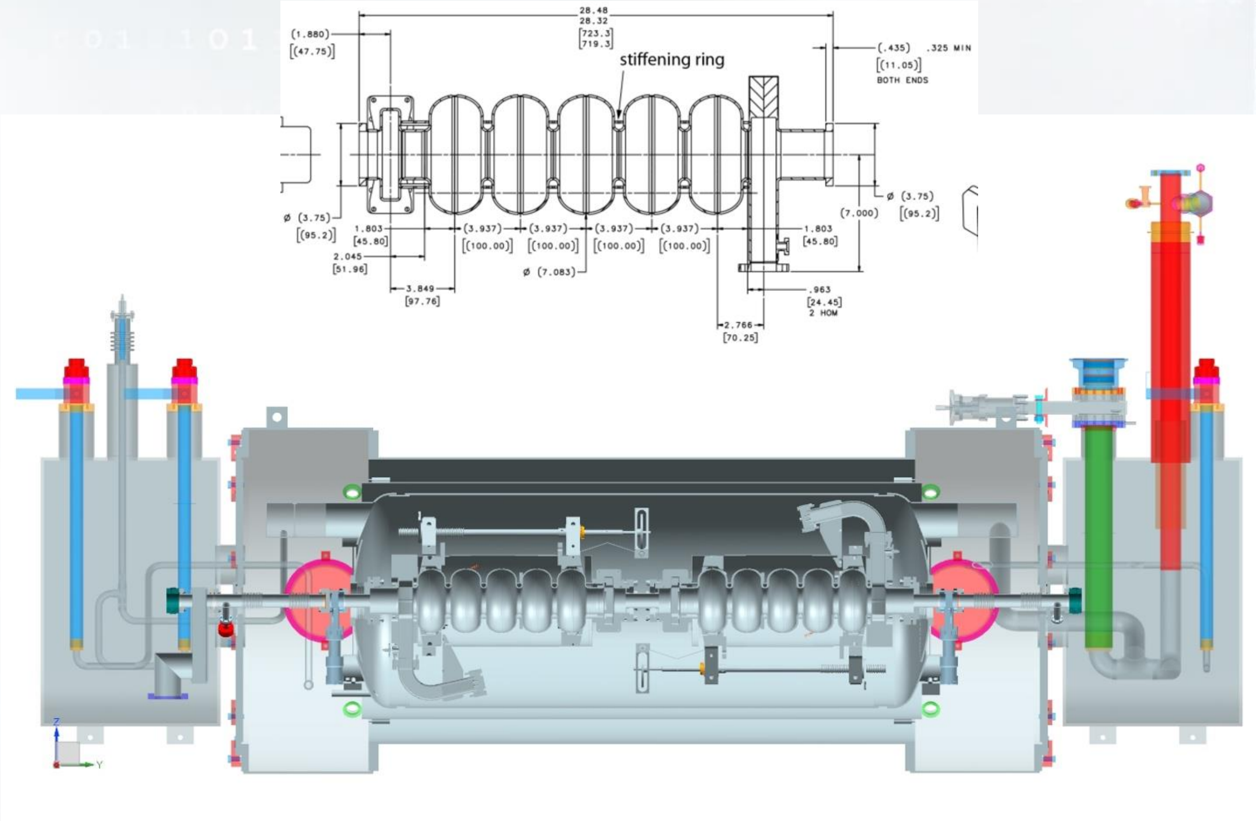
- An existing CEBAF-style quarter cryomodule

https://proceedings.jacow.org/srf87/papers/srf87a09.pdf
https://proceedings.jacow.org/SRF91/papers/srf91a02.pdf

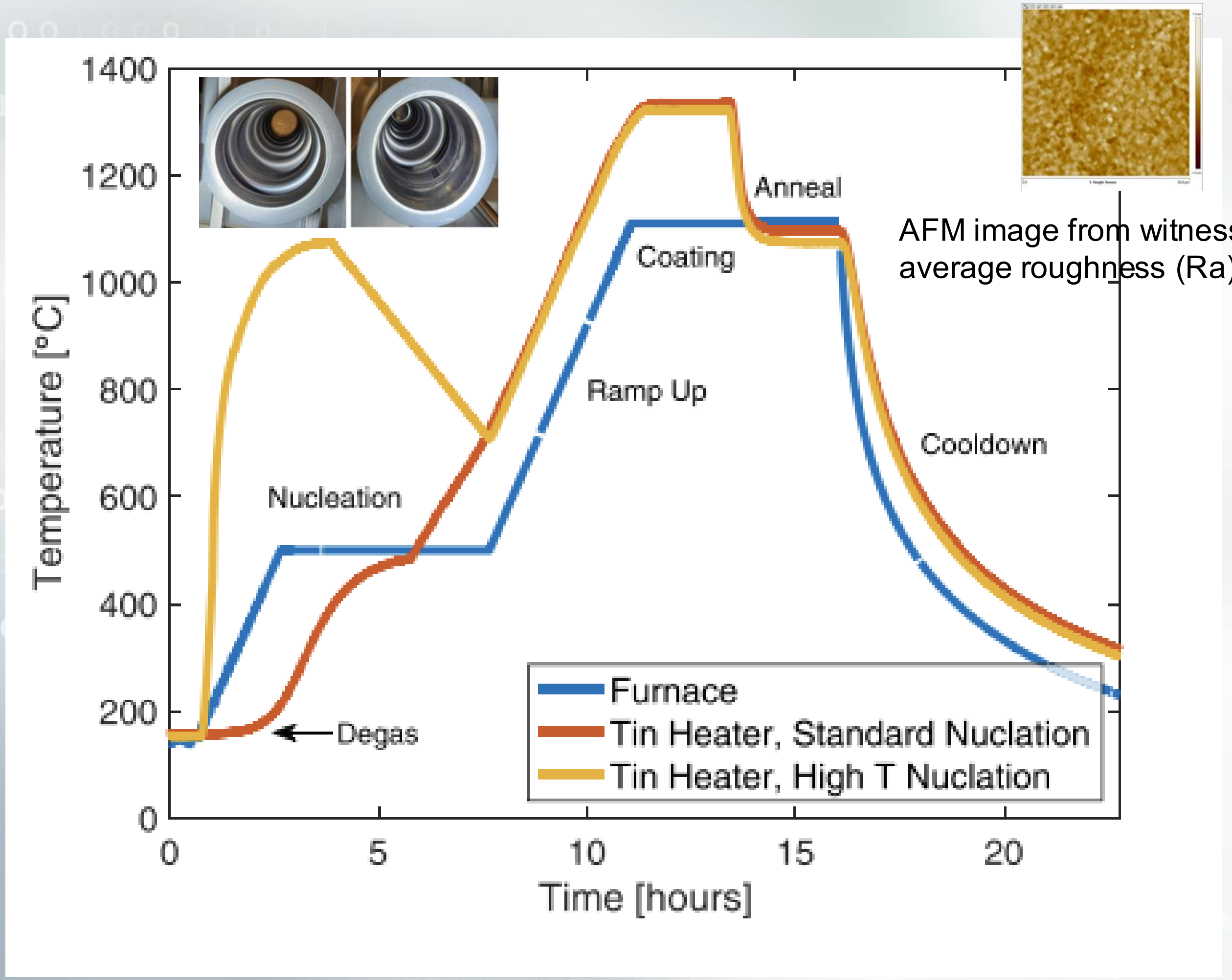


- Two CEBAF-style 5-cell cavity (new cavity cells)

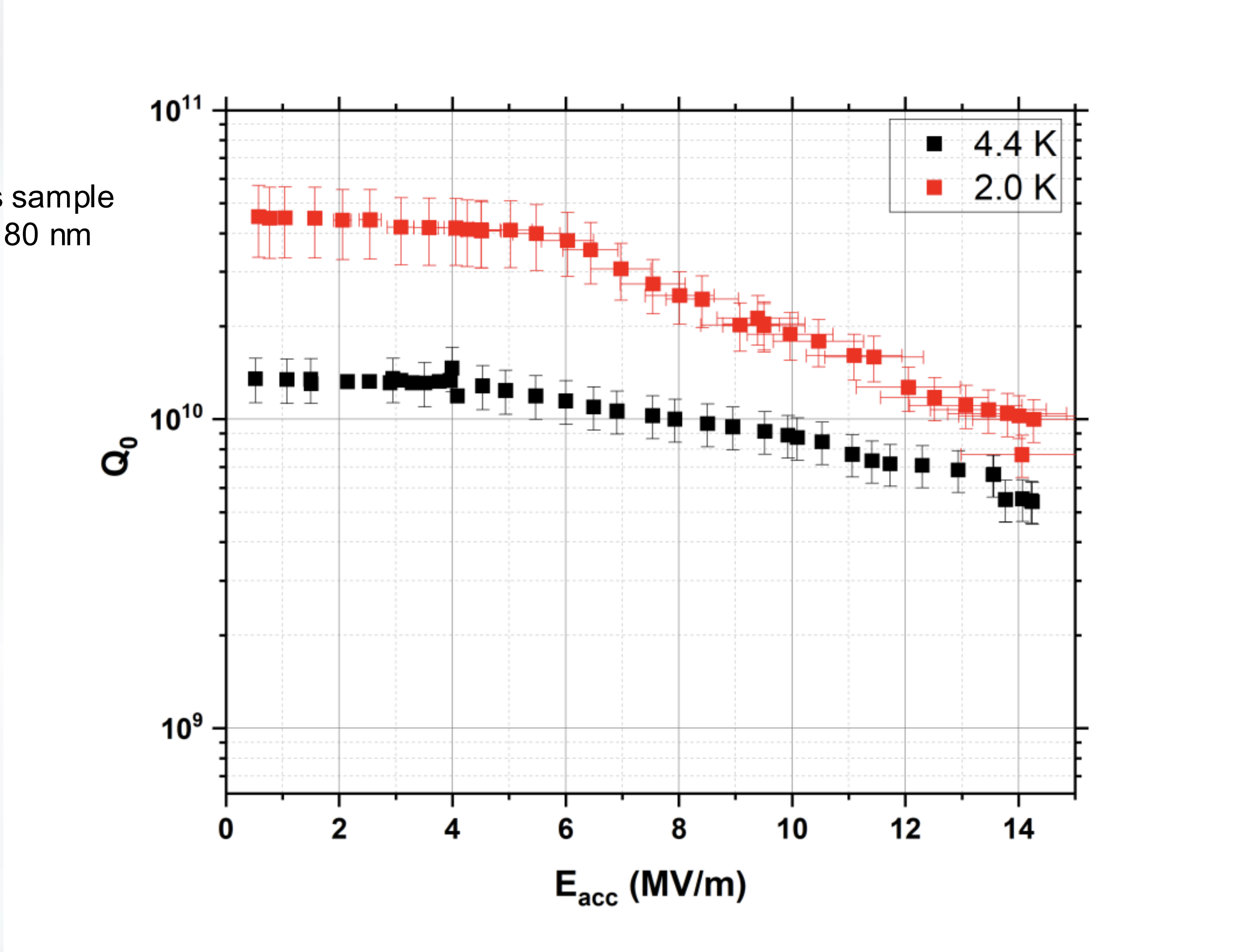
F. Marhauser et al., JLAB-TN-17-055



Cavity 1 Coating and Qualification Test at FNAL

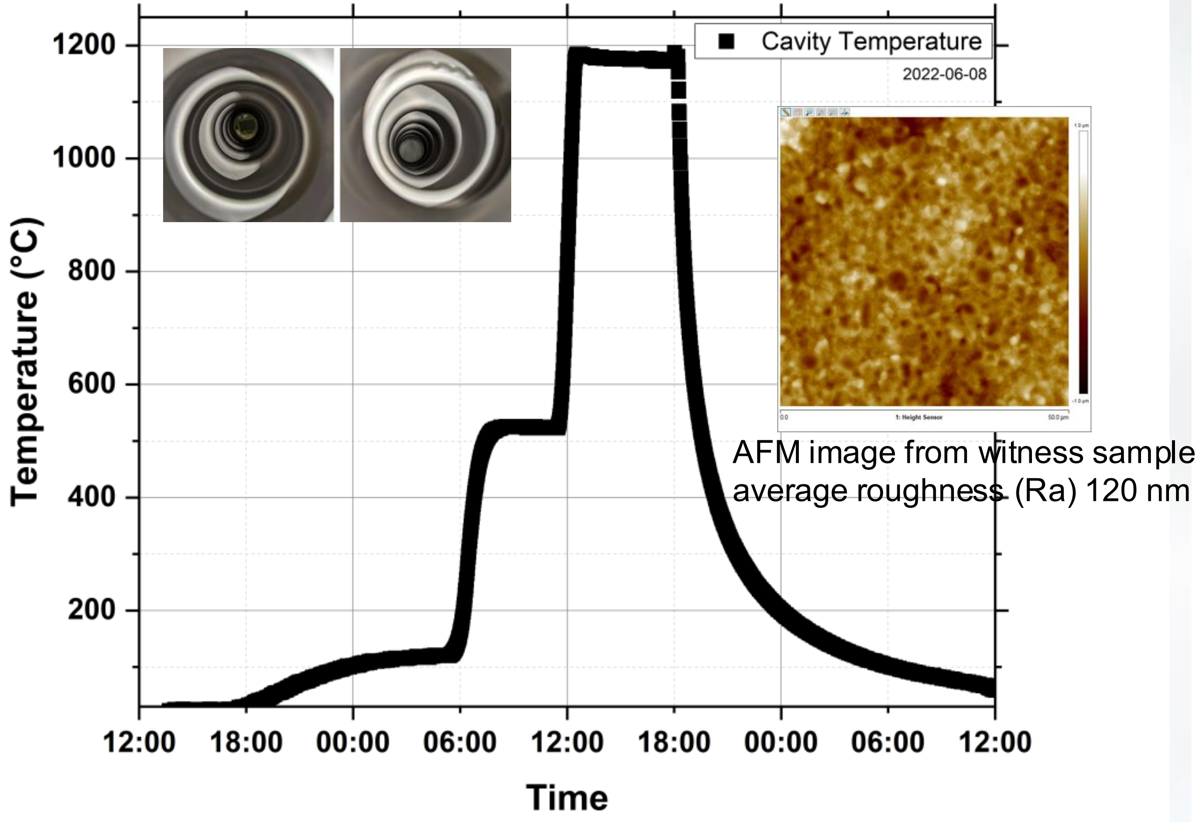


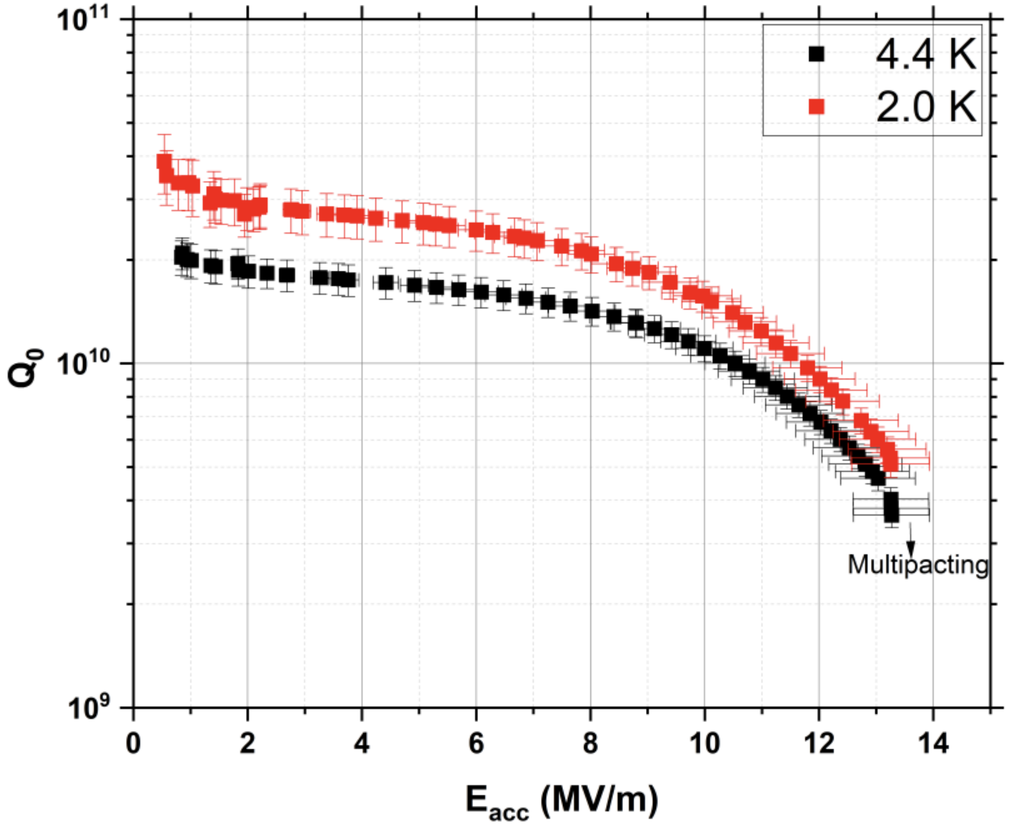
AFM image from witness sample
average roughness (Ra) 80 nm



U.Pudasaini et al., “First cryomodule with Nb3Sn cavities for beam acceleration test at Jefferson Lab”, JLAB-TN-24-052.

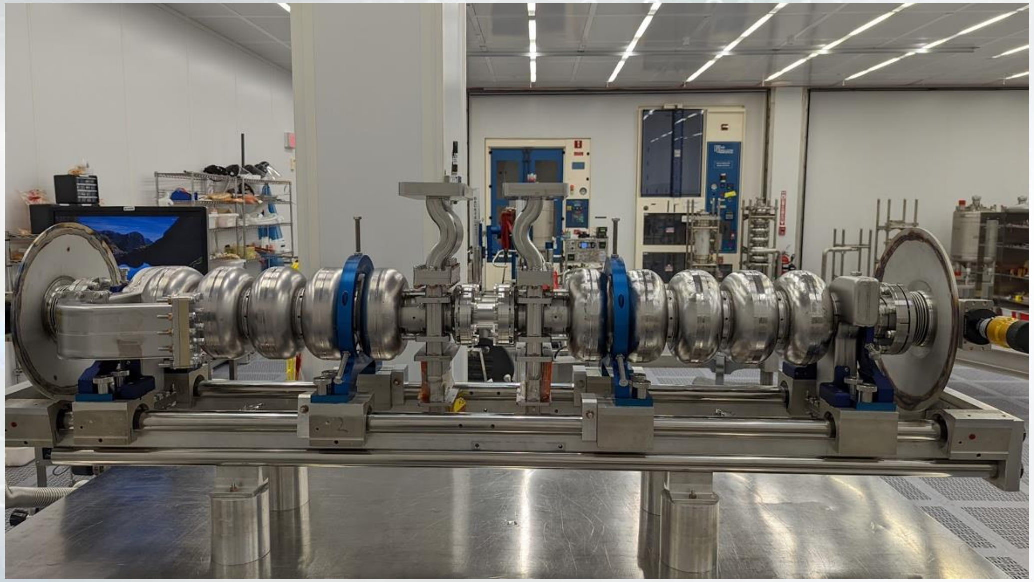
Cavity 2 Coating and Qualification Test at JLAB

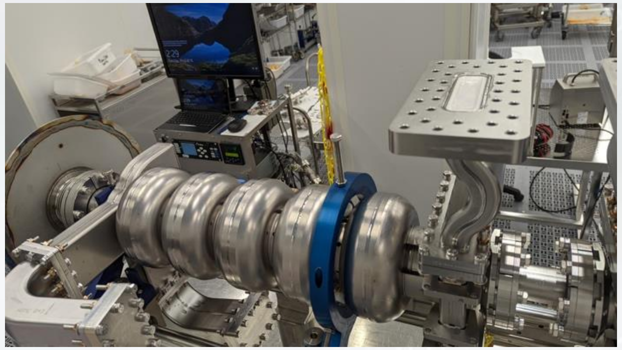




U.Pudasaini et al., "First cryomodule with Nb3Sn cavities for beam acceleration test at Jefferson Lab", JLAB-TN-24-052.

Cavity Pair Assembly

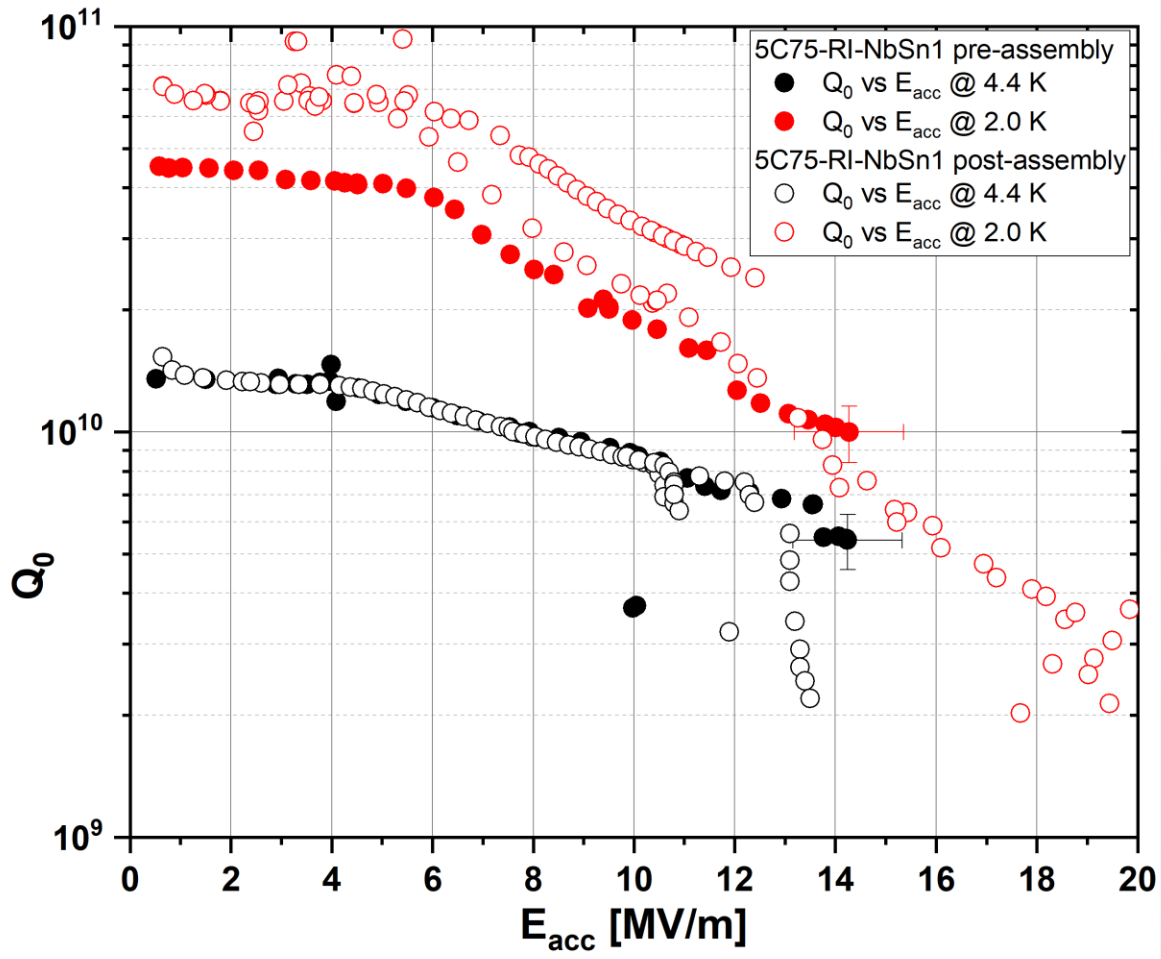


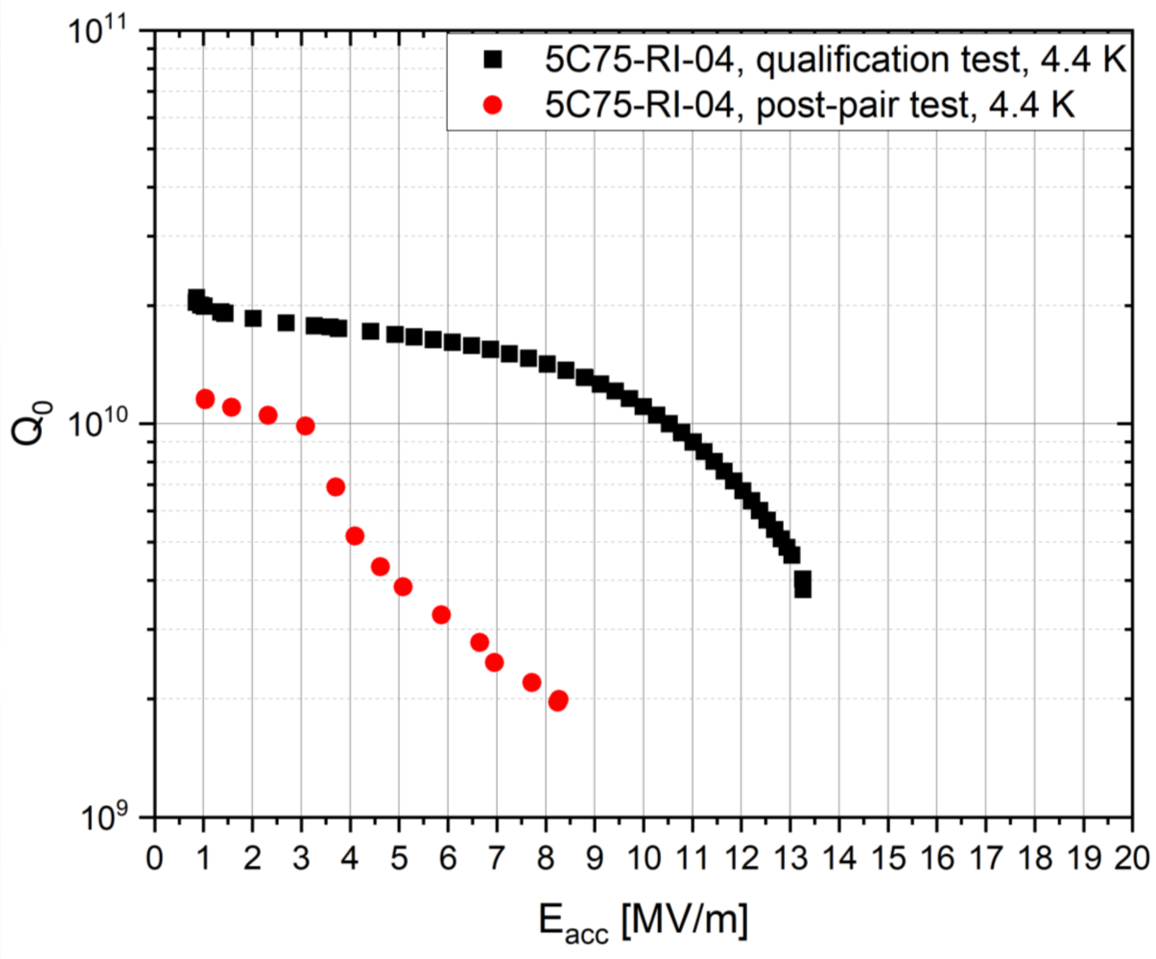


- Due to a leak in one of the dogleg, the pair had to be disassembled.
- The re-work provided the opportunity to test the cavities after the pair assembly.

G. Eremeev et al., "Achieving 10 MV cryomodule with Nb_3Sn cavities", Invited talk THYN02, NAPAC2025.

Cavity Performance Post Pair Disassembly



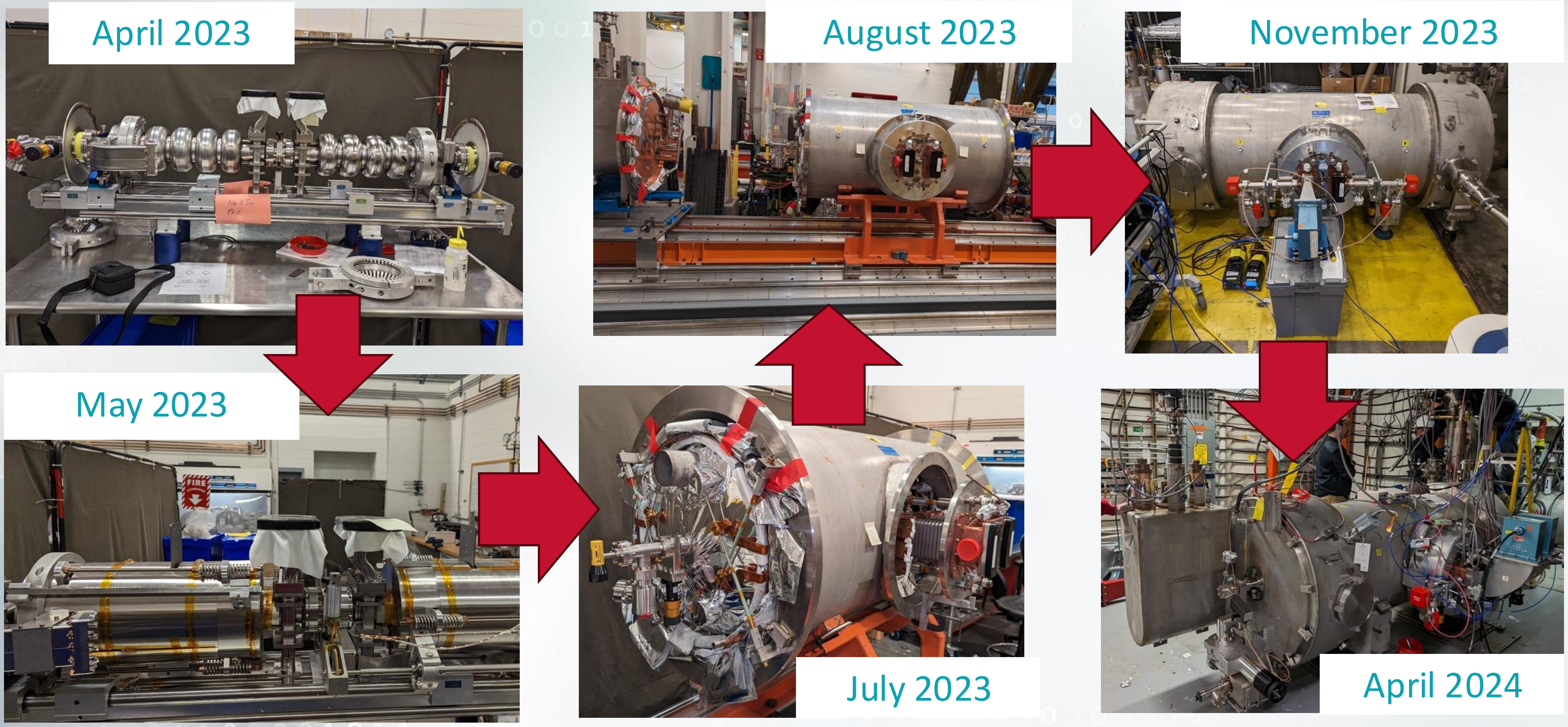


G. Eremeev et al., “Achieving 10 MV cryomodule with Nb_3Sn cavities”, Invited talk THYN02, NAPAC2025.

Cryomodule Assembly

Jefferson Lab

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



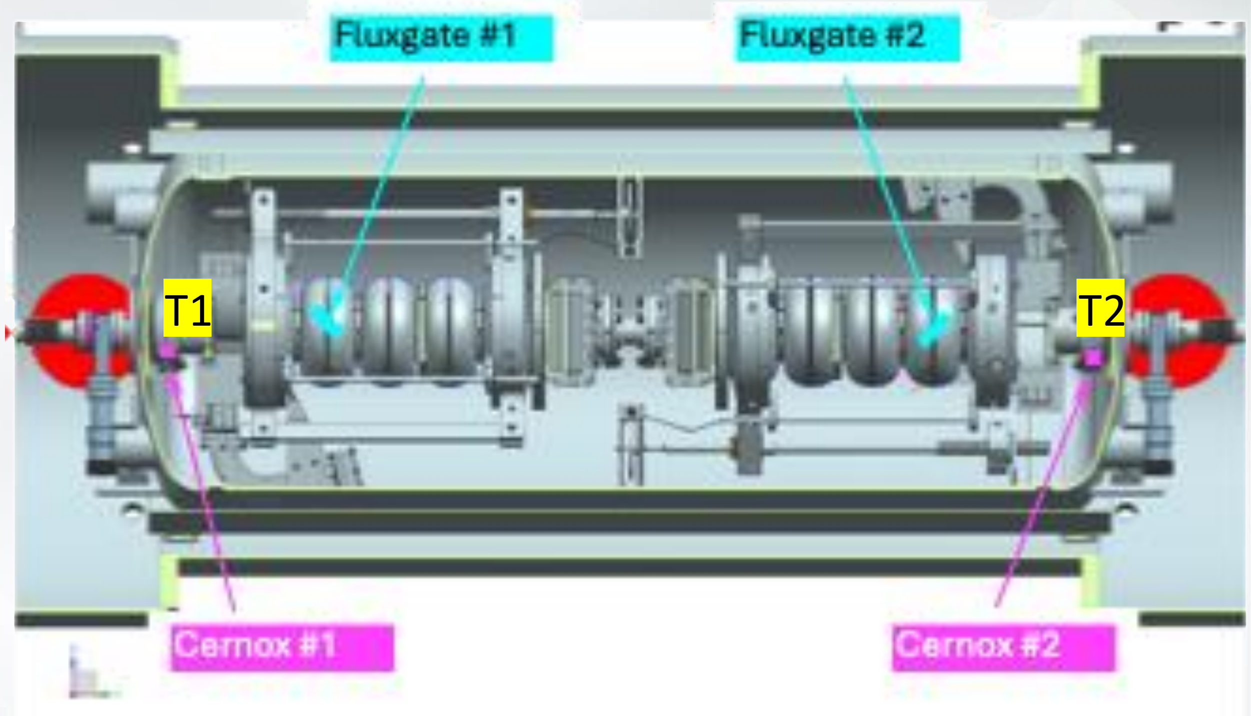
G. Eremeev et al., “Achieving 10 MV cryomodule with Nb_3Sn cavities”, Invited talk THYN02, NAPAC2025.

Cryomodule Cooldown

- Ambient magnetic field in cavity space monitored with two fluxgate magnetometer.
  - < 5 mG
- Slow cooldown with uniform temperature distribution across the length of the cavity pair during the normal conducting to superconducting transitioning period.

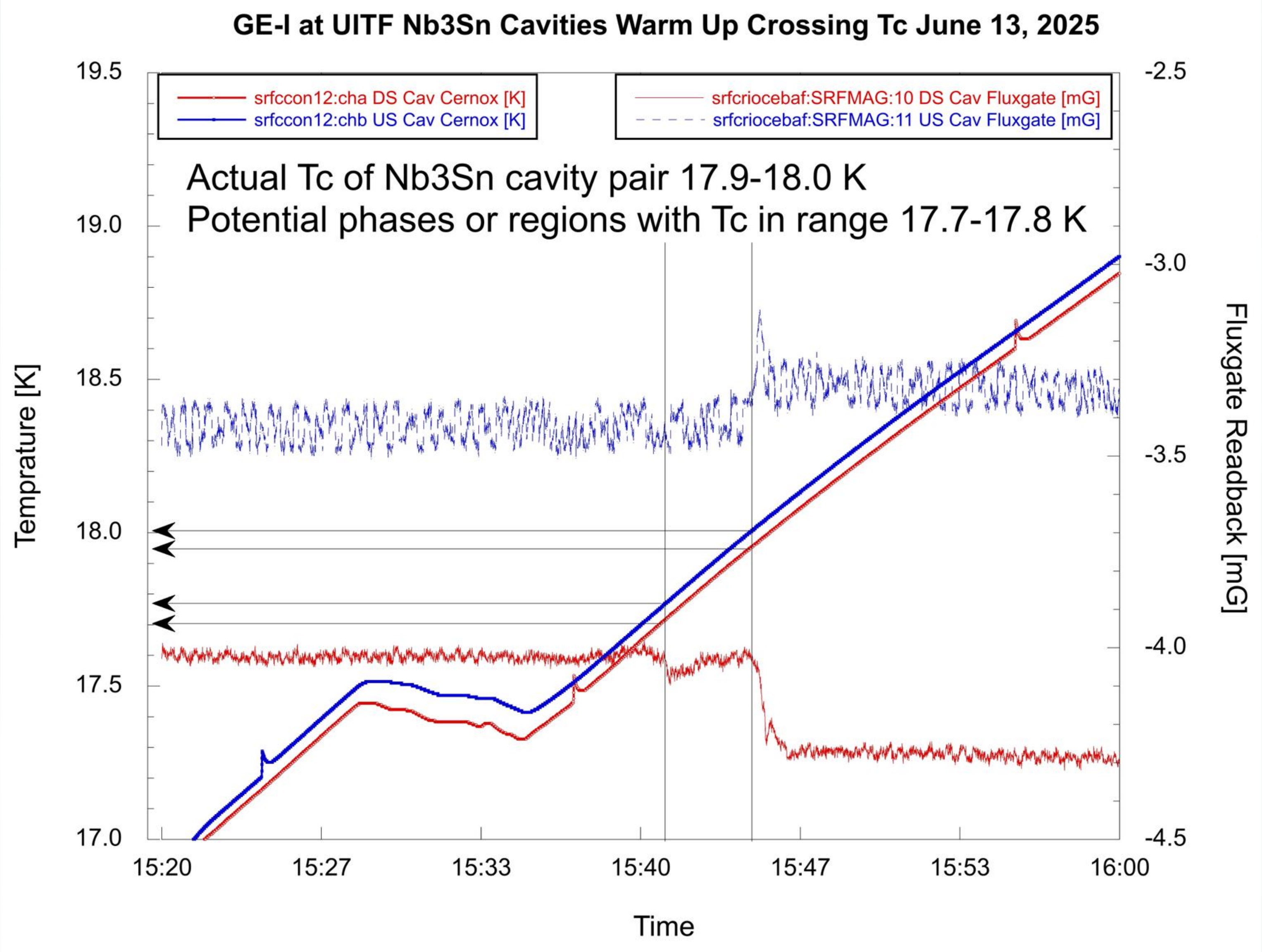
Requirement: T2-T1 <= 0.3 K
Staring time: When T1 reaches 18.5 K
Ending time: When T2 reaches 17.5 K

After T2 is lower than 17 K, cooldown can proceed at larger rate

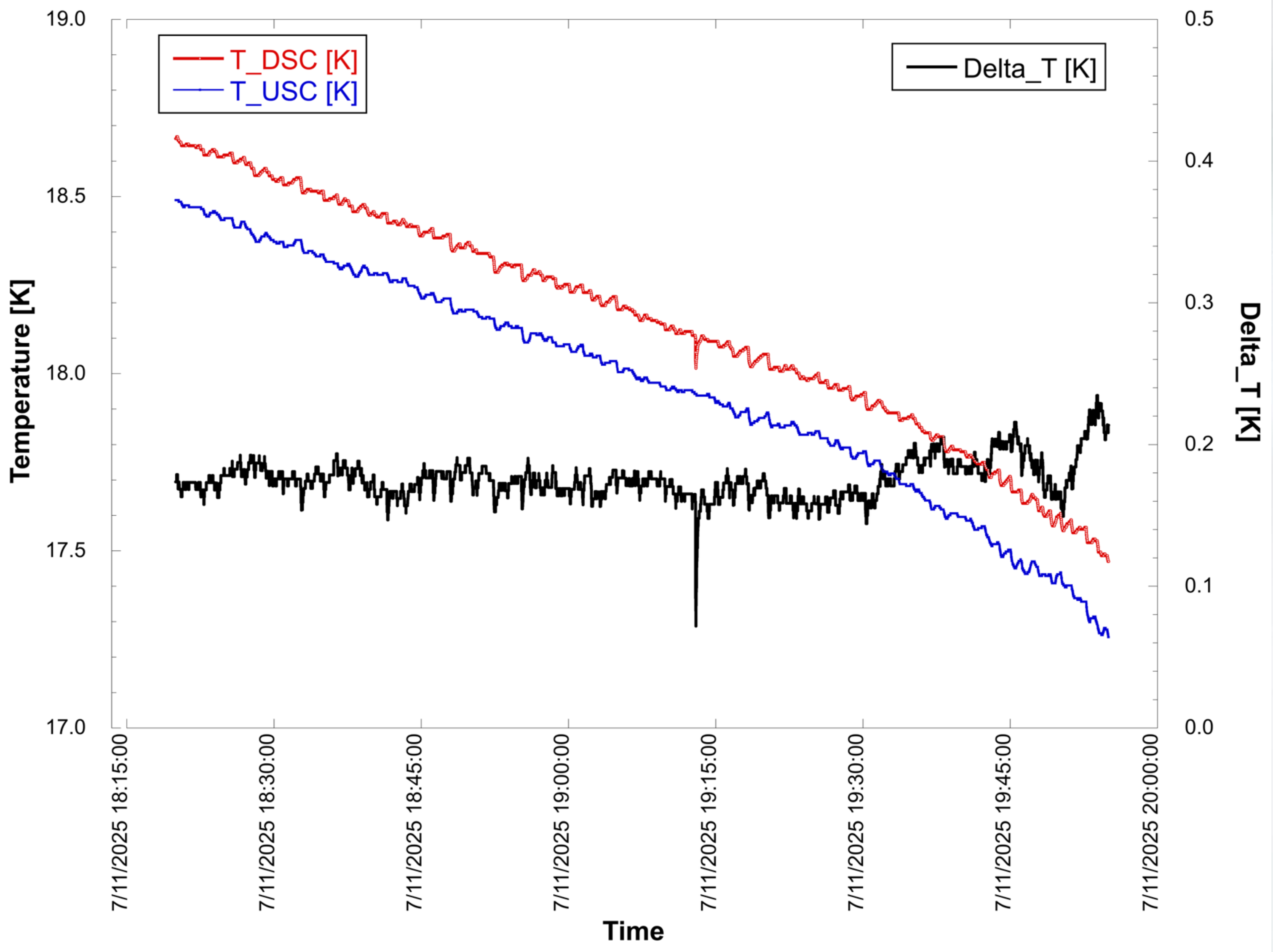


Magnetic fluxgate and Cernox sensors for monitoring ambient magnetic fields and controlling the cooldown process.

- Cooldown requirement chosen with measured Tc
- Tc determined by flux jumps during warmup process
  - Stable temperature rise
  - Uniform temperature distribution



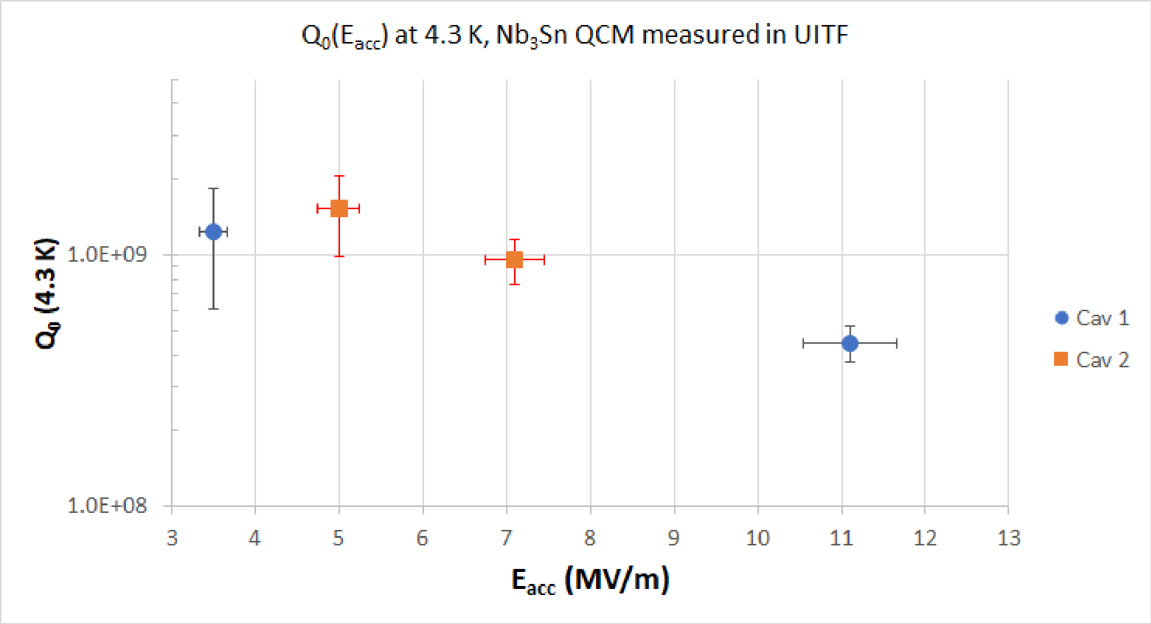
- Best Achieved Delta_T 0.17 K
- Process optimization
- Understanding attributes of the integrated system of cryomodule, cryo-lines, and cryo-plant

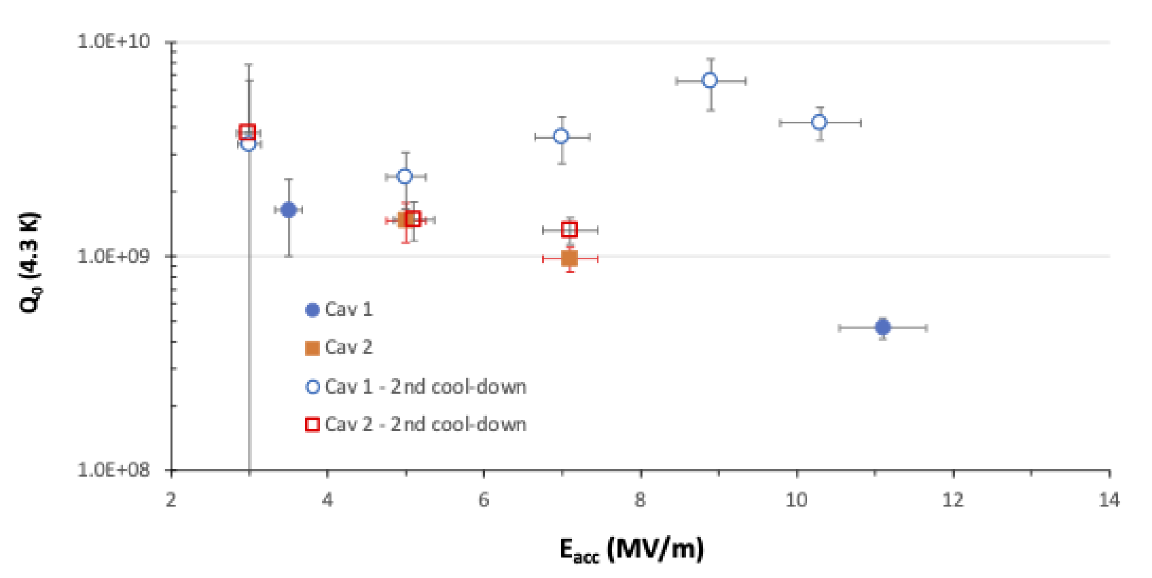


Cryomodule Cold Checkout

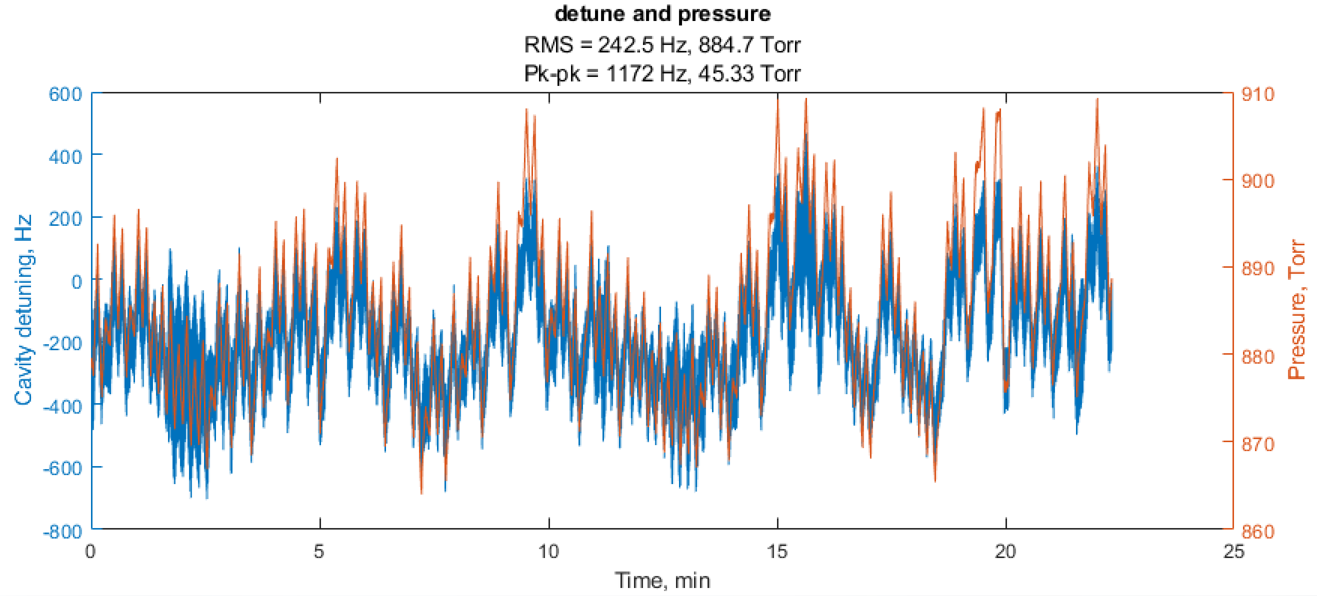
	Unit	Cavity 1/ Upstream Cav	Cavity 2/Downstream Cav
Landing frequency at 4K	MHz	1496.545	1496.405
Qext – Incident RF power coupler	-	1.37E7	1.75E7
Qext – Field probe	-	5.13E11	9.18E11
Emax, 4 K	MV/m	11.8	7.4
Eops, 4 K	MV/m	11.3	7.0
Emax, 2 K	MV/m	12.6	7.5
Eops, 2 K	MV/m	11.0	7.0

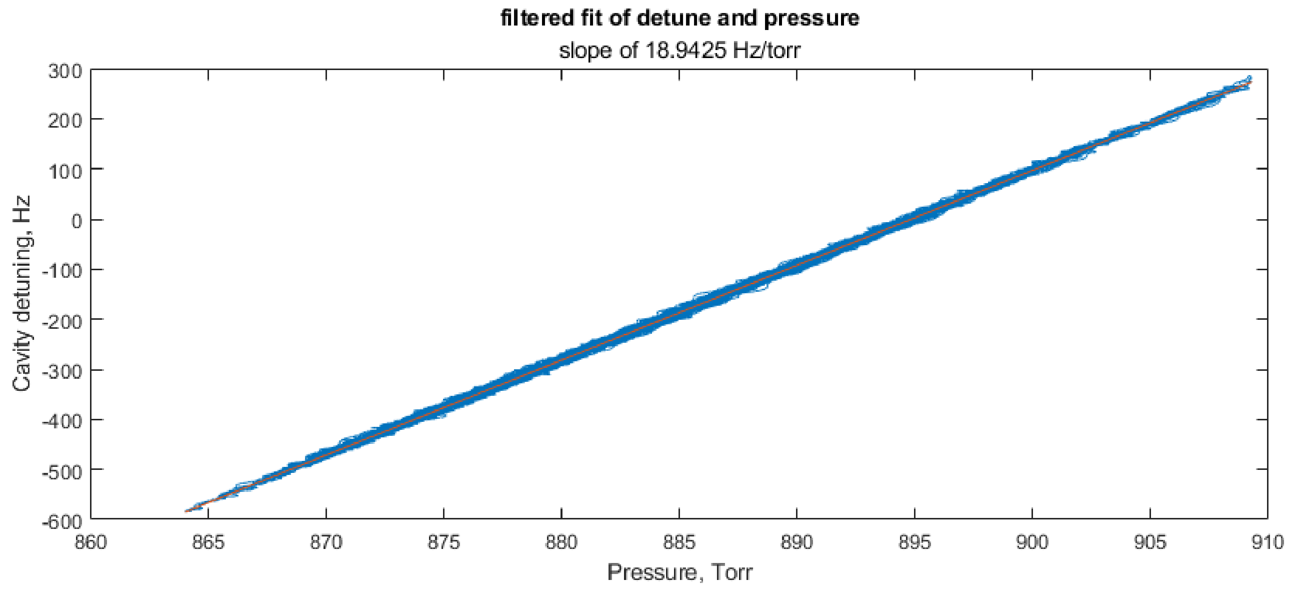
- 4 K Q0 1-2E9 at low field
  - Measurements done post certain number of quench events during the initial power rise for determining Emax
  - 0.17 K Delta_T cooling across Tc
- A 30 K thermal cycle was carried out, larger 4 K Q0 values were then observed: 3-4E9 at low field
  - 0.33 K Delta_T cooling across Tc



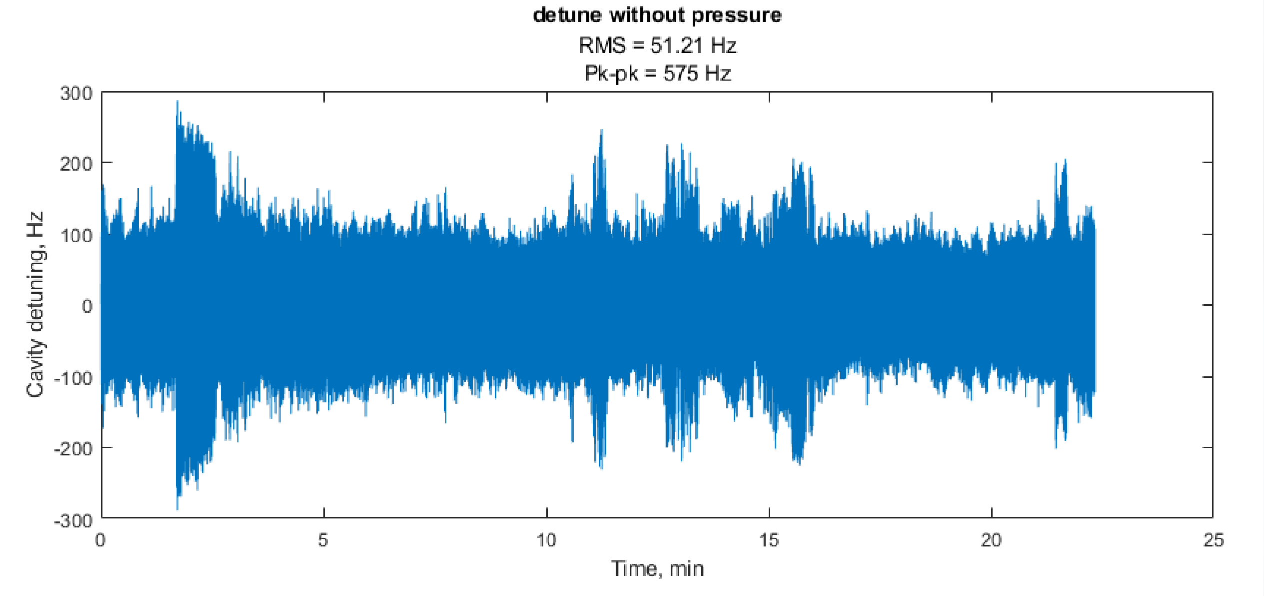


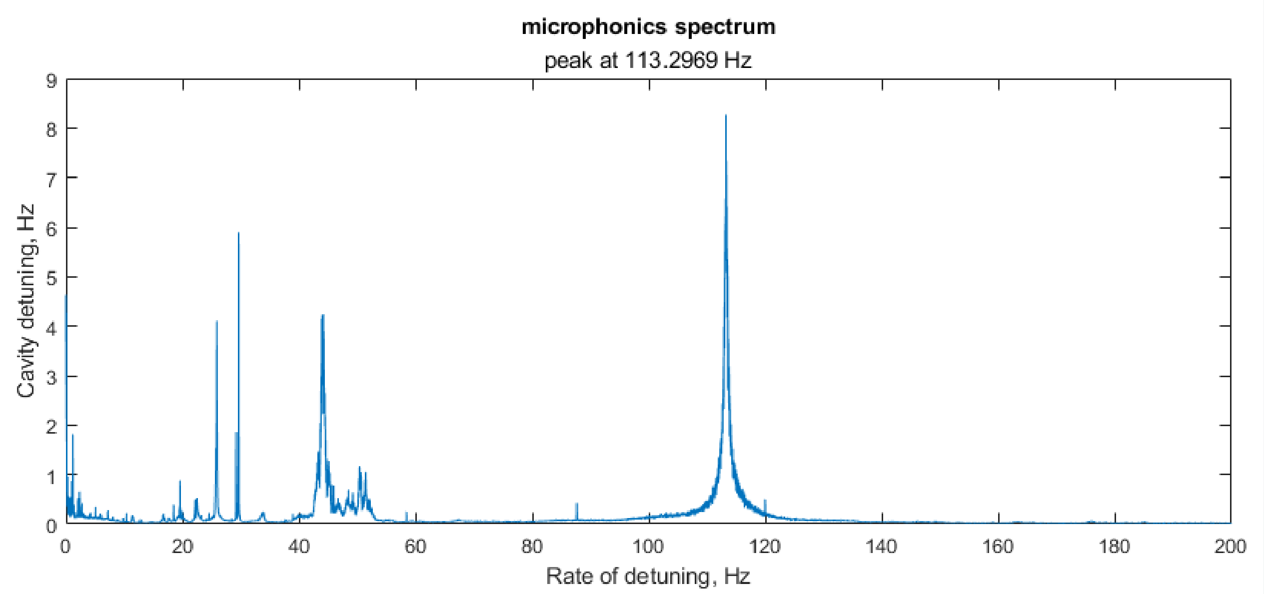
- Helium pressure fluctuation at 4 K peak-to-peak 45 Torr
  - 3.2 Torr at 2 K
- Filter fit of detuning against pressure gives df/dp = 19 Hz/Torr for upstream cavity (cavity 1)





- Fast detuning with “slow” detuning from pressure removed: peak-to-peak 575 Hz for upstream cavity
- Fourier transform spectrum reveals the leading mode at 113 Hz.





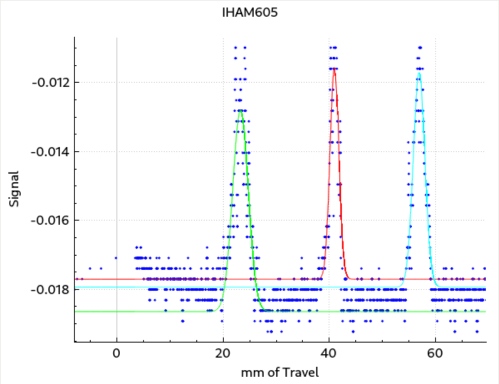
Beam Acceleration Test at UITF

Both cavities tuned by ~ 50 kHz to common frequency of 1496.500 MHz. Laser pulse rate at 1496.500 MHz as well

- Cavity 1 compressed by tuner
- Cavity 2 stretched by tuner

2 K

Metric	Value
Beam energy	6.9 MeV
Cavity 1 Eacc	10 MV/m
Cavity 2 Eacc	6 MV/m

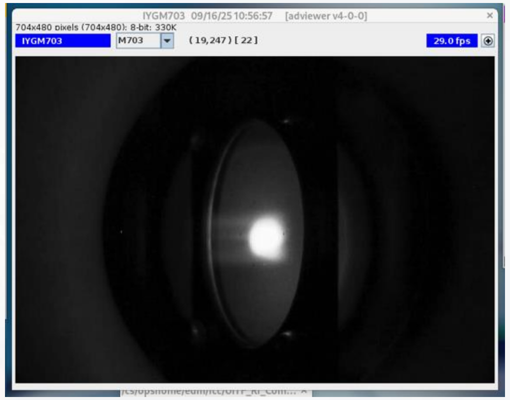


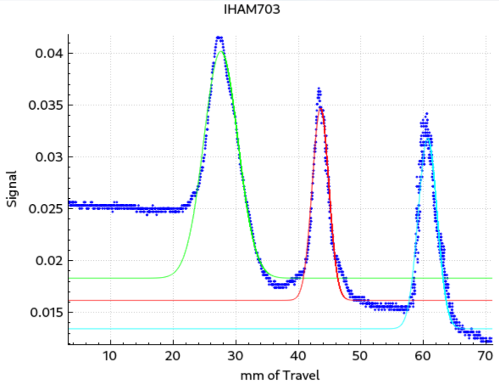
Beam spot on viewer

Beam cross-section profiles

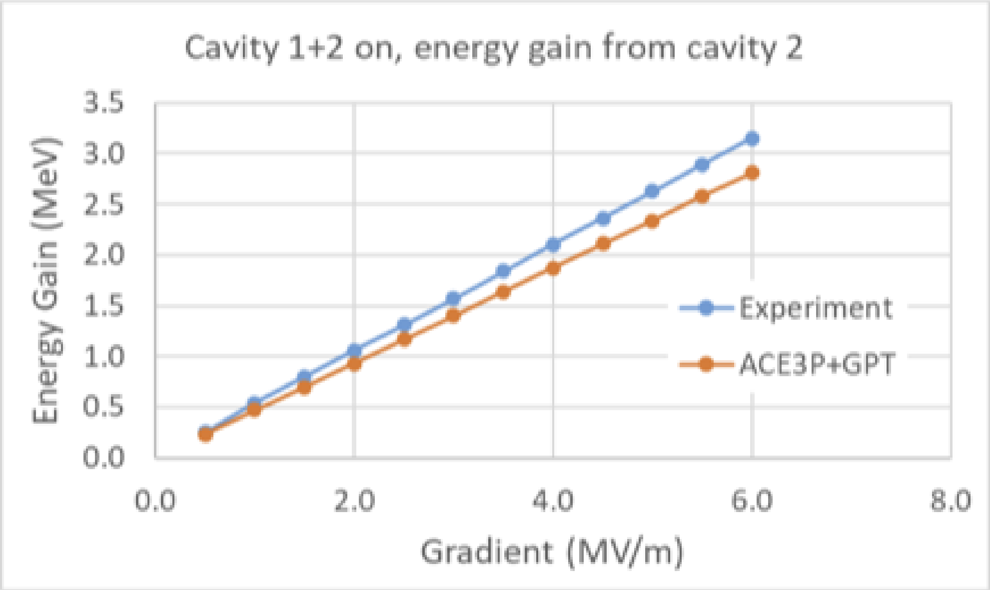
4 K

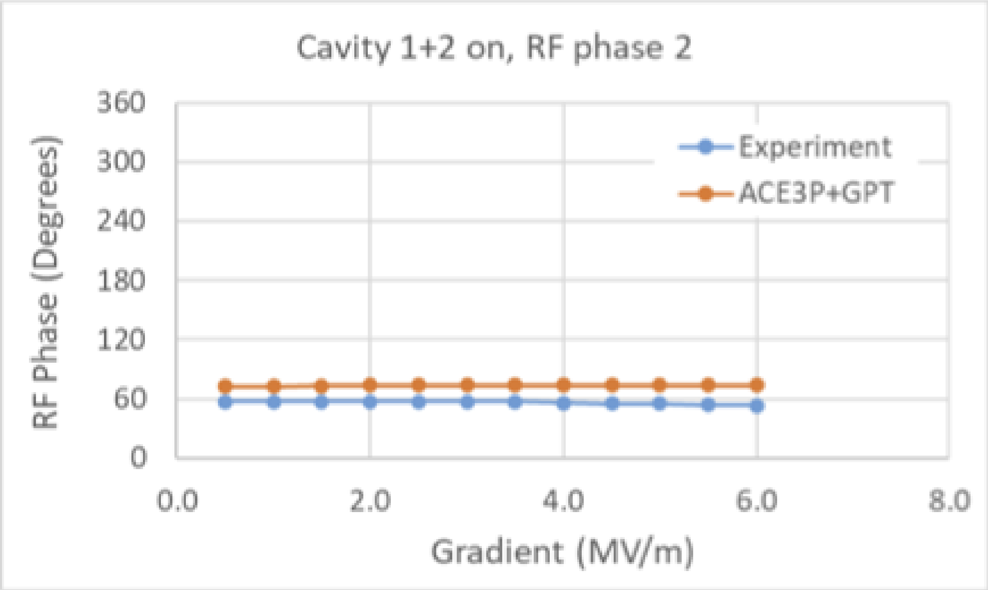
Metric	Value
Beam energy	5.1 MeV
Cavity 1 Eacc	7 MV/m
Cavity 2 Eacc	4 MV/m



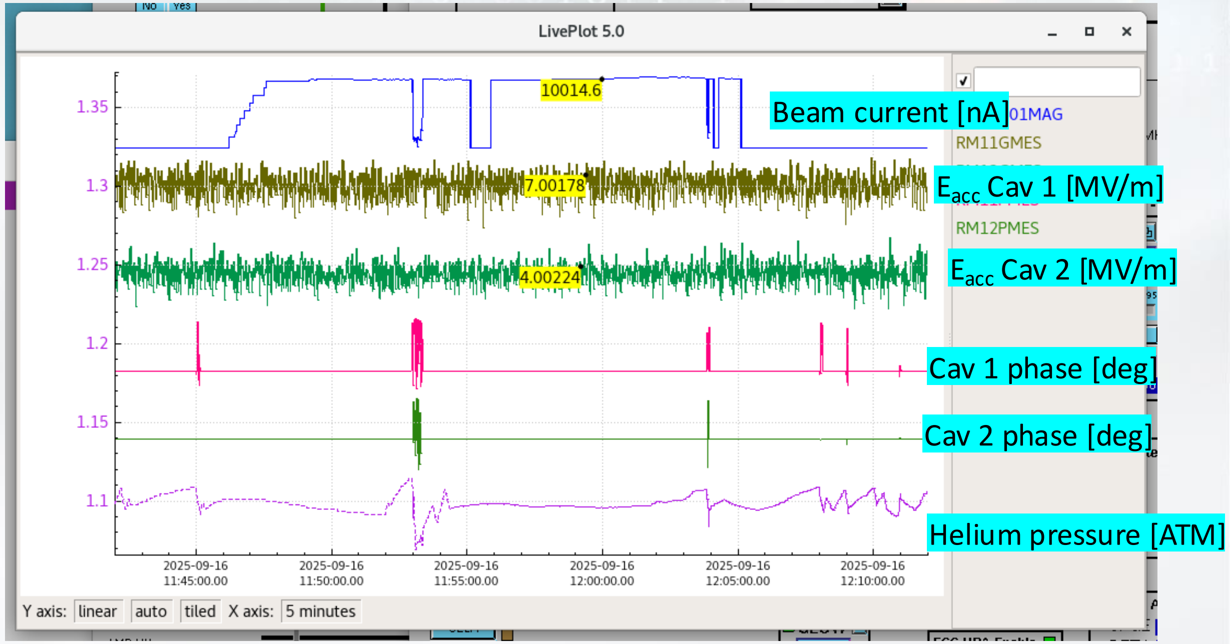


- Beam energy was measured with varying cavity gradient set point at 2 K
  - Cavity 1 held at fixed gradient and phase
  - Cavity 2 gradient and phase scanned
- Cavity phase was optimized for maximum beam energy
- Simulation results are compared with experimental results
  - Field map by ACE3P
  - Beam dynamics by GPT





- Cavities regulated by LLRF for amplitude & phase
  - Cavity phase instability problem was initially encountered and more pronounced at 4 K relative to 2 K
  - Apparent correlation with fast helium bath pressure fluctuations
- This problem was mitigated by
  - Cryomodule thermal cycle to 30 K followed by uniform cooldown (Delta_T 0.3K)
  - Adjustment of JT control and return valve control
  - Optimization of tuner step motor control
- Cavity gradient capability at 4 K (LLRF regulates only the amplitude)
  - Cavity 1: 10 MV/m
  - Cavity 2: 6 MV/m

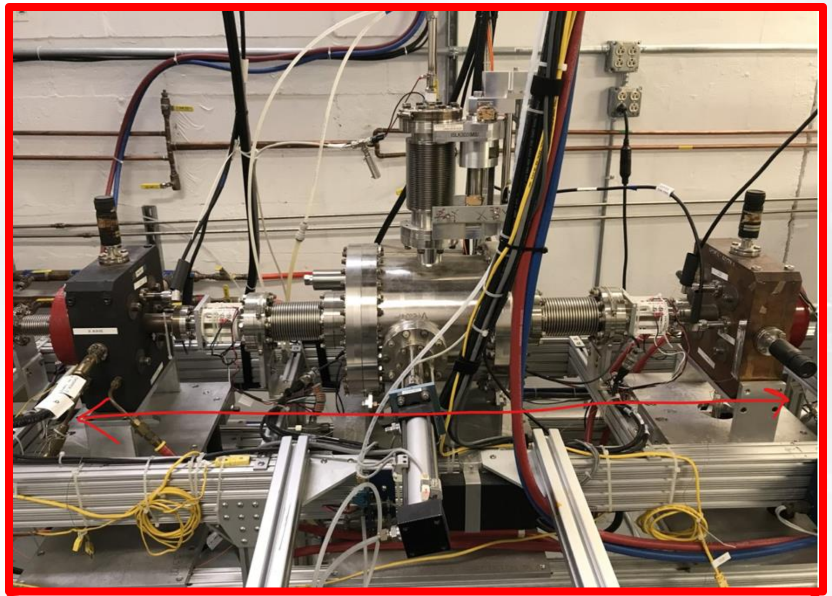


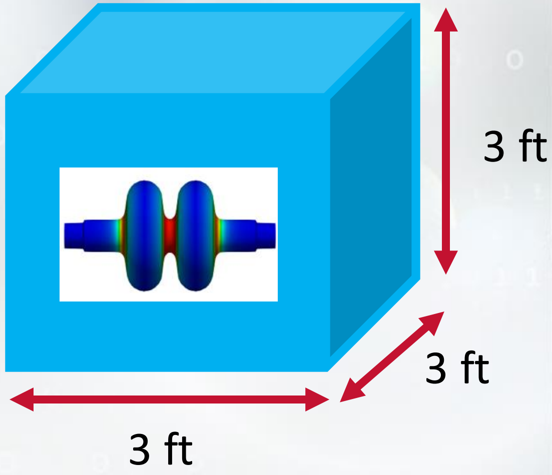
Summary of Beam Test Results

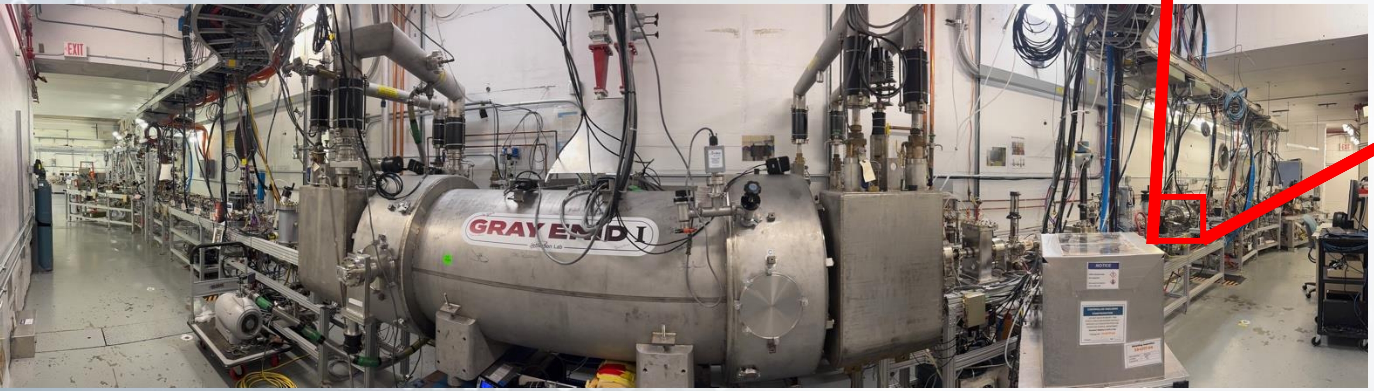
Metric	Value		Unit
	4 K	2 K	
Beam energy	5.1	7.1	MeV
Beam current	10	0.1	μA
Beam mode	CW		
Bunch rep rate	1496.500		MHz
Cavity 1 E_{acc}	7	10	MV/m
Cavity 2 E_{acc}	4	6.5	MV/m

What's Next?

- Deliver beam for target irradiation experiment in early 2026 with beam energy 5 MeV.
- Install Gray Enid II to extend the beam energy to 10 MeV







Gray Enid II

A 3'x3'x3' box cryomodule with conduction-cooled 2-cell 1.5 GHz cavity cooled by cryo-coolers and powered by a solid-state amplifier

Conclusion

- First electron beam acceleration was accomplished with two 5-cell CEBAF-style Nb_3Sn coated SRF cavities hosted in a CEBAF-style cryomodule, Gray Enid I, installed in JLAB's UITF.
- Integration of Nb_3Sn cavities and cryomodules in an accelerator systems, including beamlines, high-power RF sources, and cryo-plant went well.
- Gradient performance of both Nb_3Sn cavities was preserved in UITF accelerator relative to that measured at CMTF. E_{acc} 10 MV/m with a CW beam current 100 nA was demonstrated at 2 K.
- Stable CW beam at 4 K demonstrated with a beam current of 10 μA and beam energy 5.1 MeV with amplitude and phase regulated operation of two 5-cell Nb_3Sn cavities at E_{acc} 7 and 4 MV/m, respectively (previously published record beam acceleration E_{acc} 2.3 MV/m, Z. Yang et al., SUST 38(2025) 015009).
- Unloaded quality factor Q_0 3-4E9 demonstrated at low field at 4 K (previously published record 7E7 at 4 K in a 3-cell 8 GHz Nb_3Sn cavity, G. Arnolds et al., IEEE Tran. Nucl. Sci., NS26, (1979)3775-73).
- Plan to deliver beam with Gray Enid I for a target irradiation experiment in early 2026.
- Plan calls for installation of a conduction-cooled Nb_3Sn cryomodule to double the 4 K beam energy from 5 MeV to 10 MeV by end of 2026

Acknowledgements

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QUESTIONS?