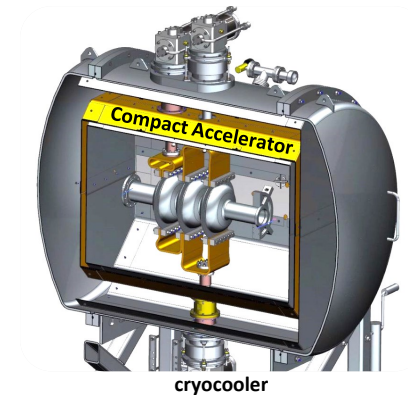
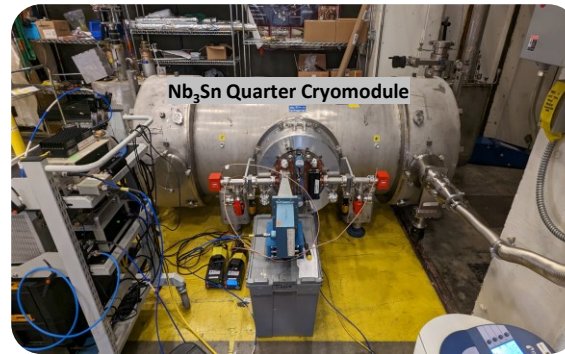


Nb₃Sn SRF cavities from R&D to real accelerator

Overview of recent developments



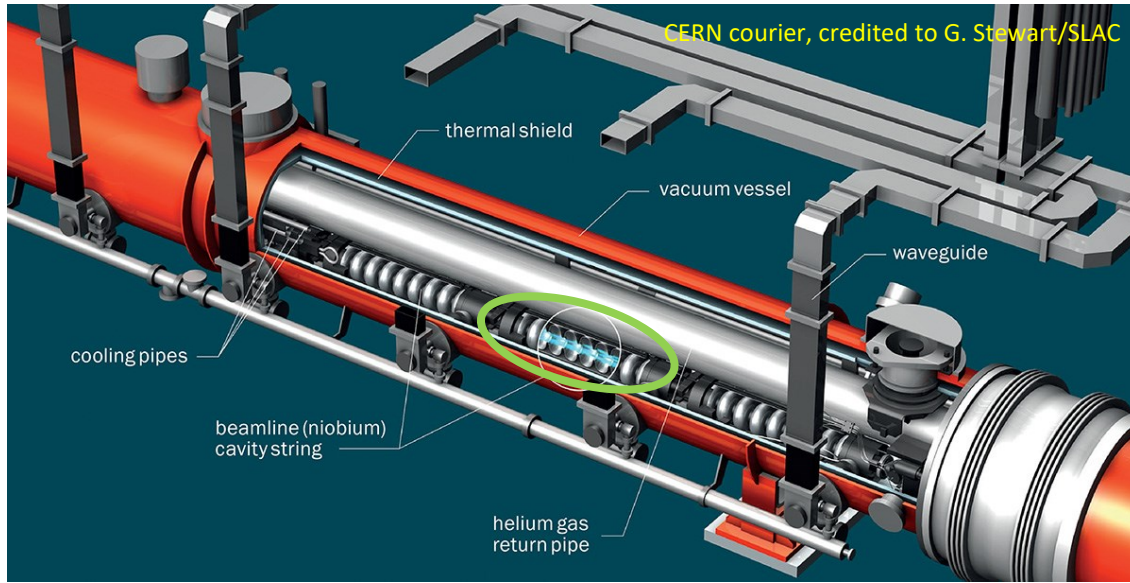
Uttar Pudasaini

Tuesday, May 28, 2024

Outline

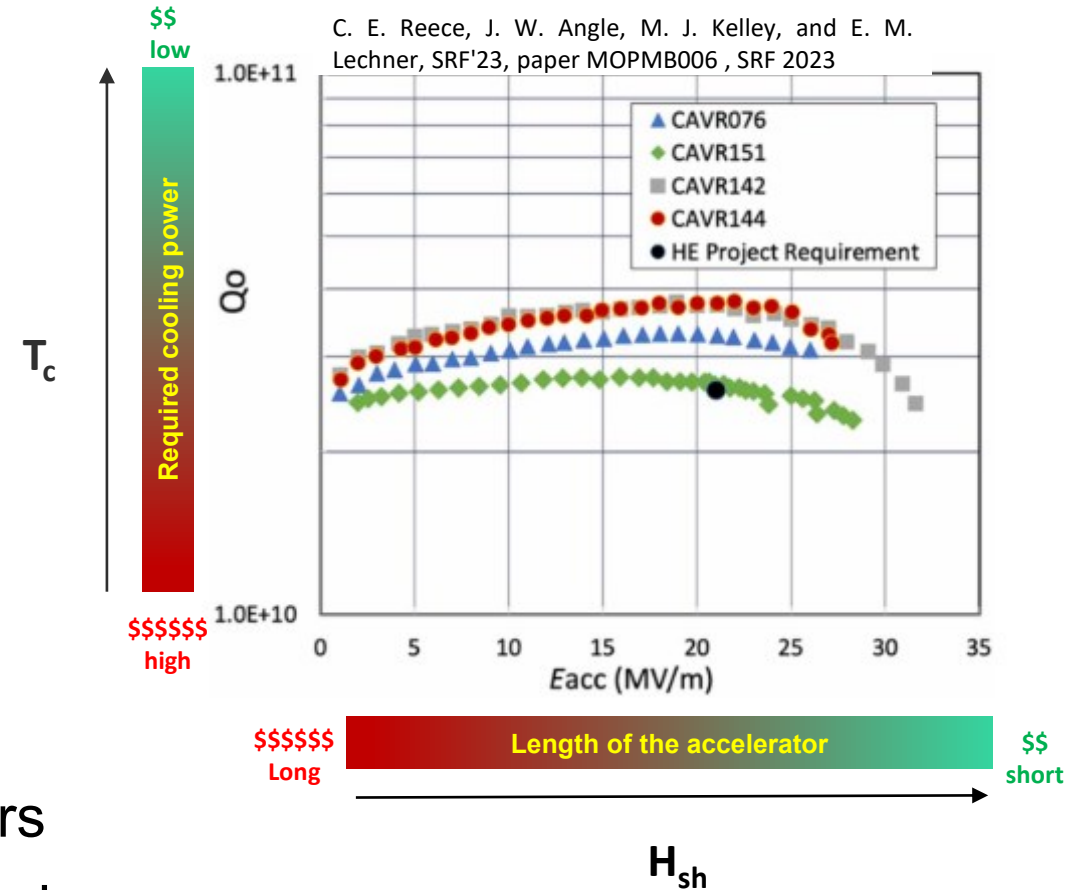
- Potential of Nb₃Sn
- Status of Nb₃Sn cavity R&D
- State-of-the-art Nb₃Sn cavities
- Nb₃Sn cryomodule development
- Nb₃Sn cavities for conduction-cooled compact accelerators
- Current Challenges
- Summary and Outlook

SRF Cavities and their Meaning for Accelerators

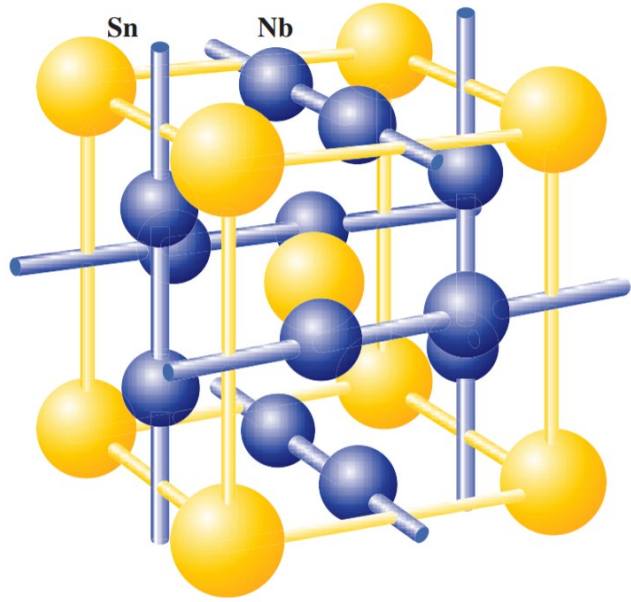


cutaway showing the LCLS-II cryomodule

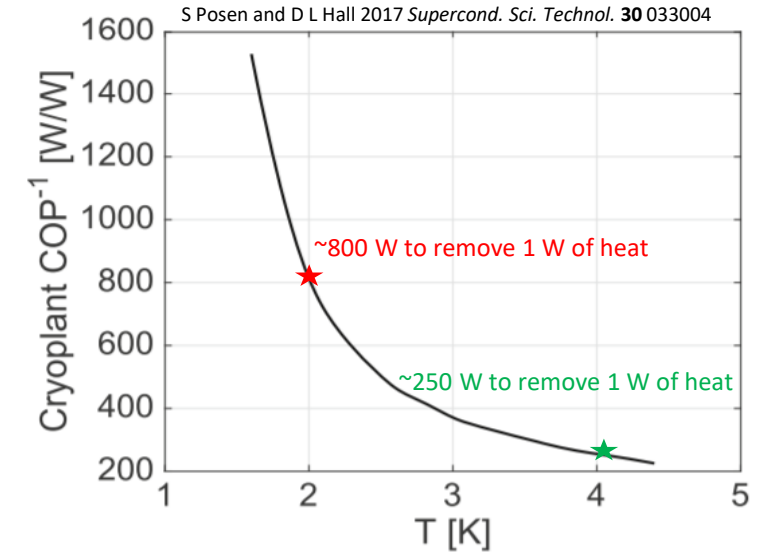
- SRF cavities → Integral part of particle accelerators
 - Niobium → Element of choice for cavity manufacturing
 - BUT cavities performance closing in on intrinsic material limits
 - PLUS → Optimal performance at 2 K requires complex cryogenic facility
- ↪ What's next?



Nb₃Sn and its Potential for SRF Cavities



	Nb	<i>Approximate values</i> Nb₃Sn
T_c (K)	9.25	18.3
H_{sh} (mT)	220	425
Q^{BCS} at 2 K	5×10^{10}	5×10^{14}
Q^{BCS} at 4 K	5×10^8	5×10^{10}
E_{acc} (MV/m)	50	100



- better RF performance → higher Q_0 and E_{acc}
- potential for 4K operation → performance like Nb cavities @ 2K
- simplify cryogenic systems → conduction-cooling with cryocoolers
- transformational technology → enables new application of SRF accelerators & reduces costs
- challenge(s) → brittleness & low thermal conductivity mandate use in thin-film form only

Current Nb₃Sn Coating Techniques in R&D

- Diffusion Techniques

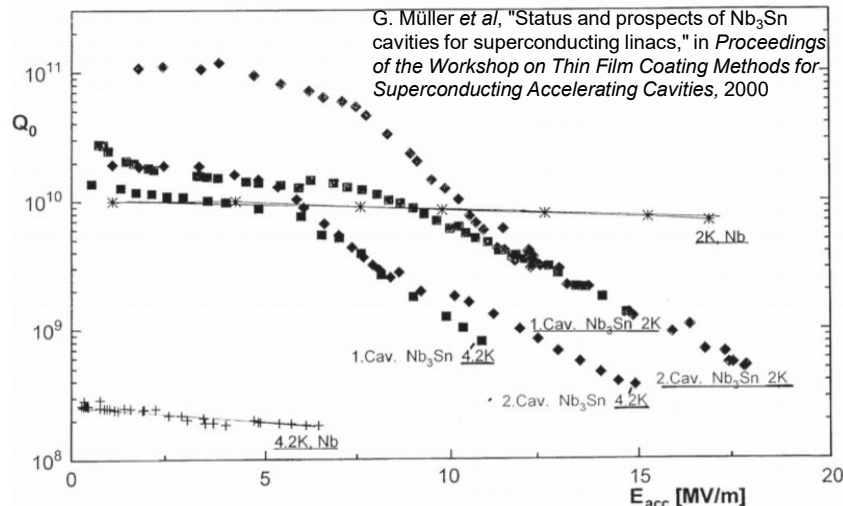
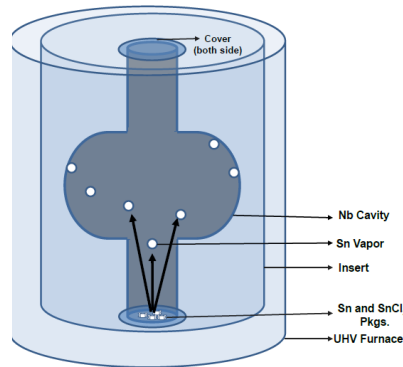
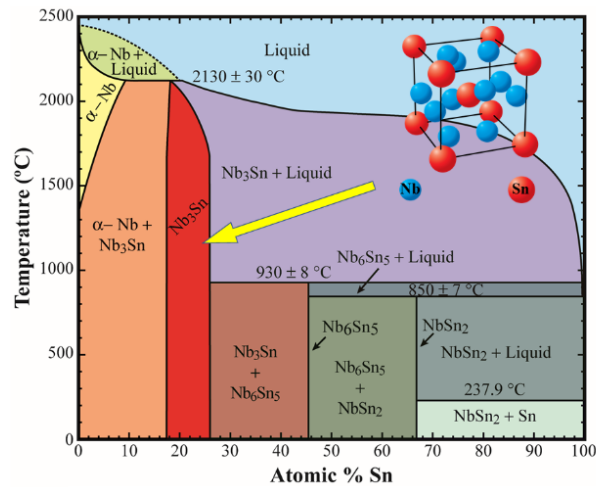
- Vapor diffusion (Cornell U., JLab, Fermilab, KEK, IMP, Peking U., SARI) for Nb₃Sn/Nb cavity
- Sn-plating followed by thermal diffusion (Cornell U.) for Nb₃Sn/Nb cavity
- Liquid Sn diffusion (INFN) for Nb₃Sn targets
- Chemical vapor deposition (Ultramet, Cornell U.) for Nb₃Sn/Cu cavity
- Bronze technique (IMP, e2P, MagLab, Peking U.) for Nb₃Sn/Cu cavity

- Magnetron Sputtering

- DC magnetron sputtering (ODU, JLab, CERN, INFN, Cornell U., Peking U.) for Nb₃Sn/Cu cavity
- High-Intensity Pulse Impulse Magnetron Sputtering (CERN, JLab, STFC) Nb₃Sn/Cu cavity

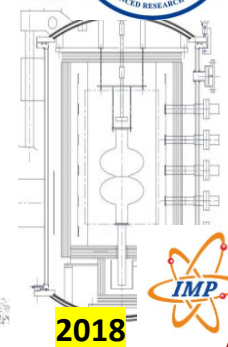
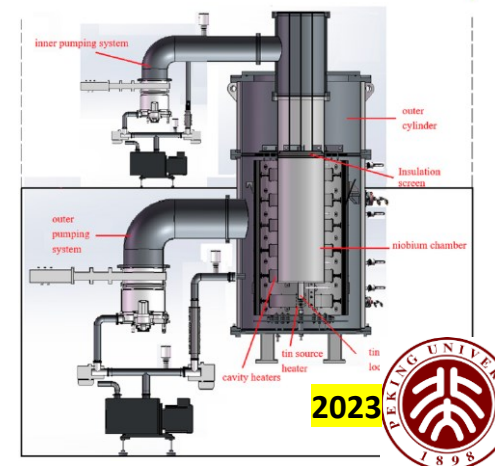
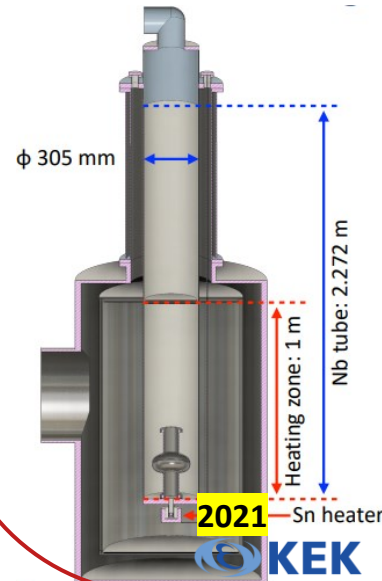
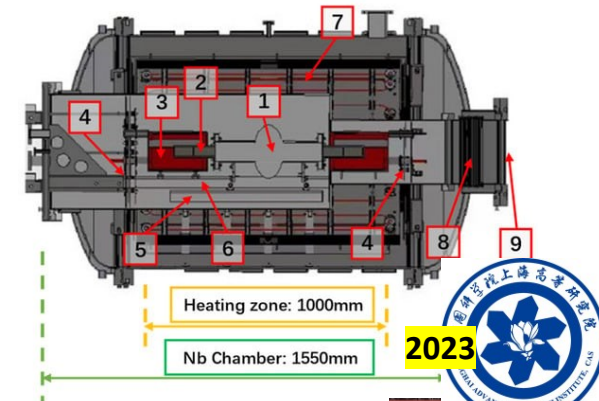
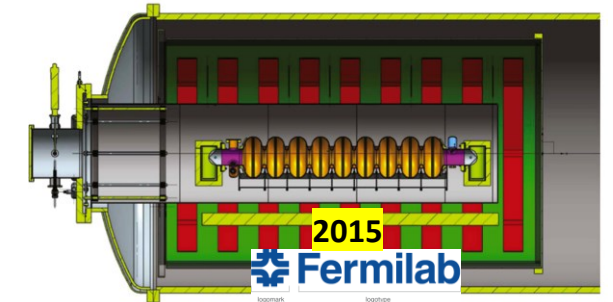
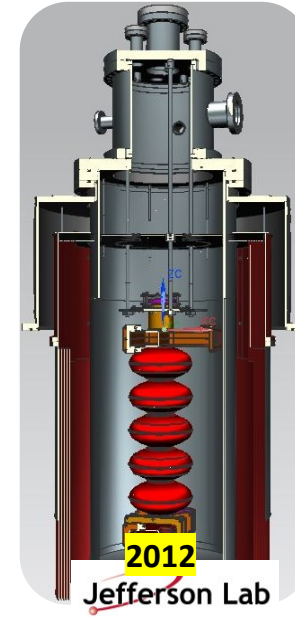
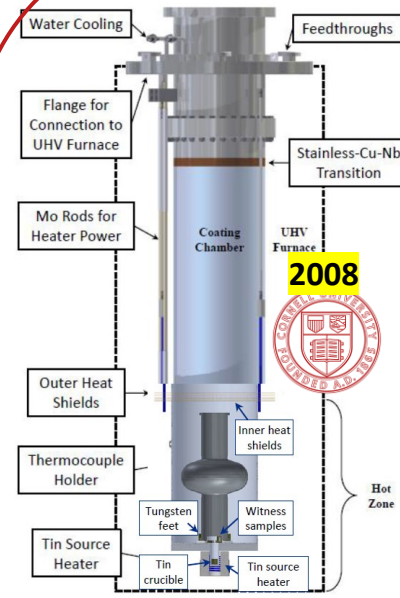
Vapor Diffusion – The current mainstream technique

- since 1970s (*Siemens*)
- so far 'THE' technique producing practical Nb₃Sn cavities

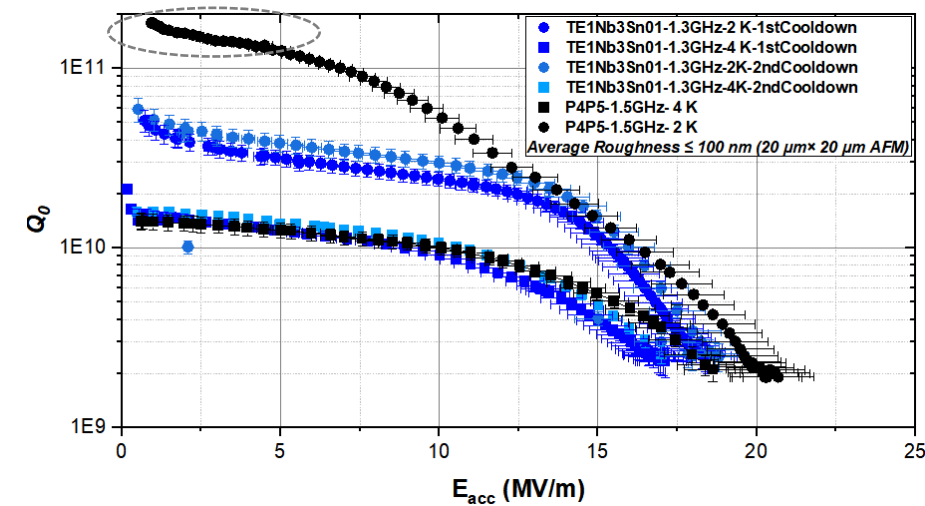
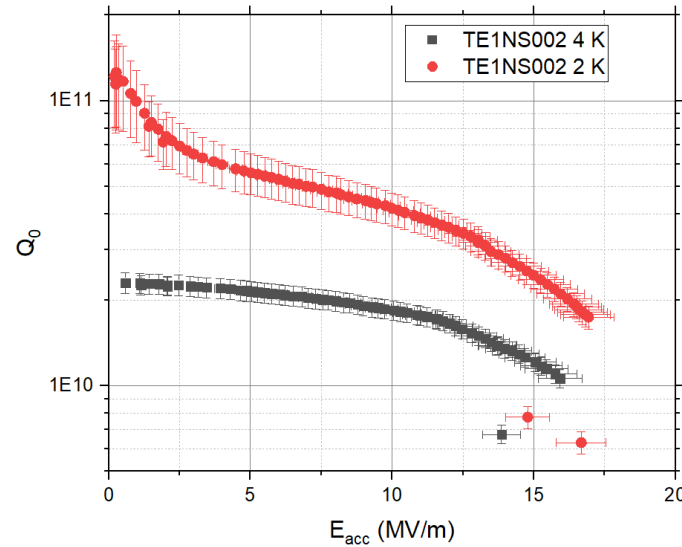
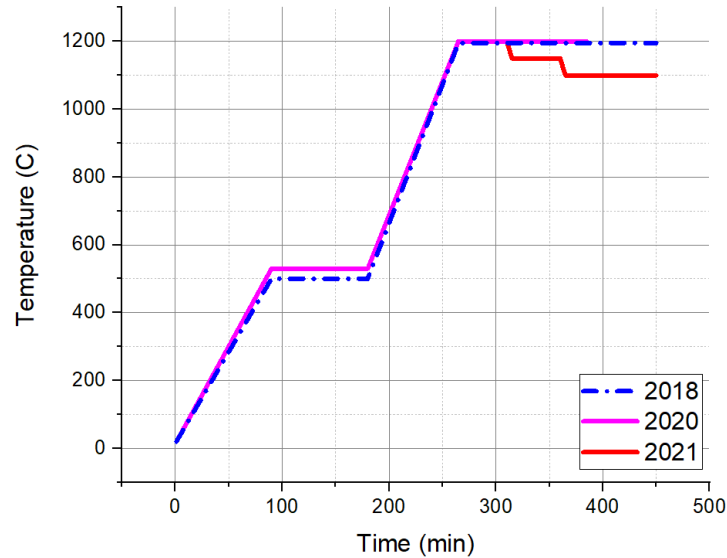


G. Müller *et al*, "Status and prospects of Nb₃Sn cavities for superconducting linacs," in *Proceedings of the Workshop on Thin Film Coating Methods for Superconducting Accelerating Cavities*, 2000

Vapor diffusion coating facilities around the world



Single-Cell R&D at JLab



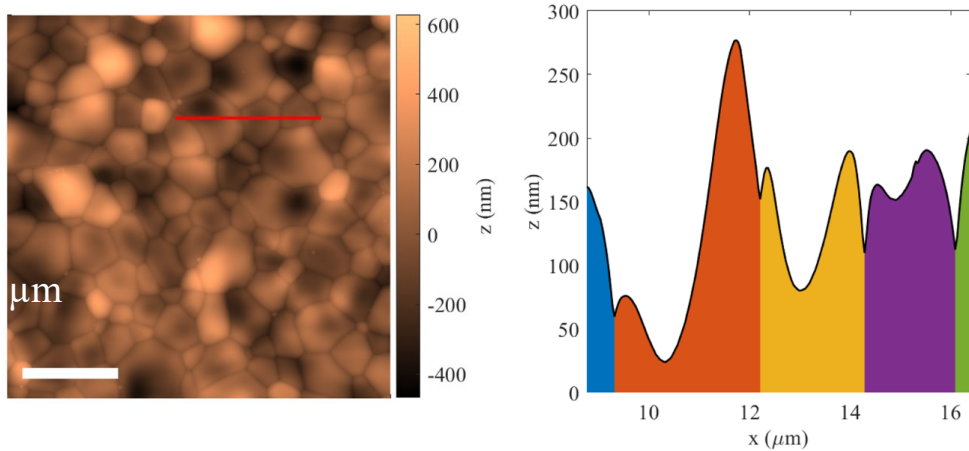
- $Q_0 > 10^{10}$ at accelerating gradient > 15 MV/m
- Coating profile continuously updated with feedback from witness sample analysis
- ~ 20 MV/m achieved but Q-slope observed
 - Sn-residue?

Cavity	Low field Q at 4.3 K	E_{acc} with Q $> 10^{10}$ at 4.3 K	Max E_{acc} (MV/m)	Witness sample Ra (nm)
RDT7	3×10^{10}	15.5	15.5	57 ± 4
TEN1S002	2.5×10^{10}	16.5	17.5	68 ± 3
P4P5#	1.3×10^{10}	10	20.7*	98 ± 4
TE1NS001	1.6×10^{10}	11	18.9	87 ± 4
TE1NS001	2.3×10^{10}	9.5	16	102 ± 16
TE1NS001	1.7×10^{10}	9	16.5	154 ± 10
TE1NbSn01	1.3×10^{10}	7.5	19.2*	77 ± 1
TE1NbSn02	1.4×10^{10}	8	18.8*	80 ± 10

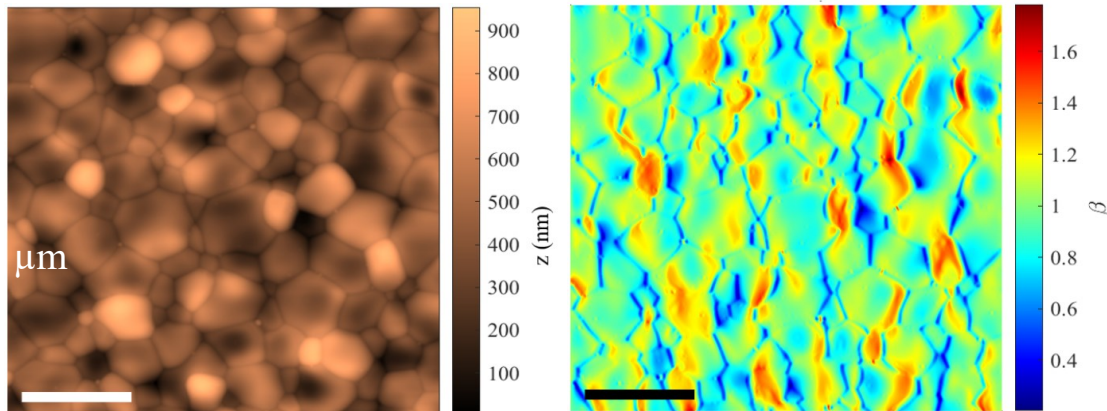
#P4P5 – 1.5 GHz cavity

* Limited by input power

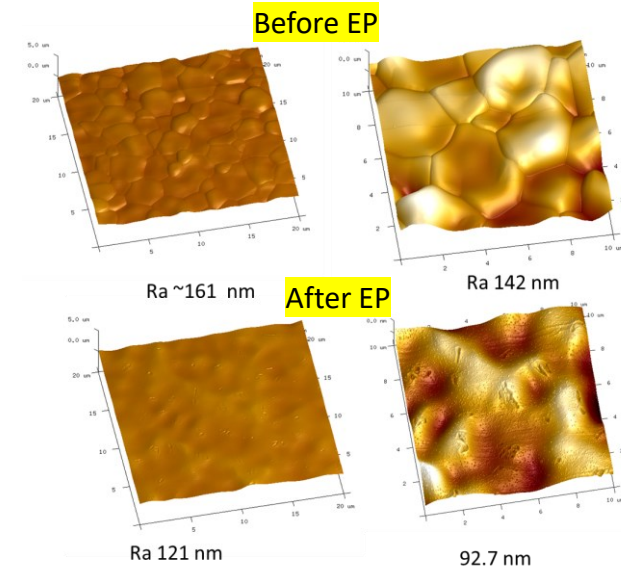
The Importance of Surface Roughness



- Inherently imperfect topography characterized by undulating intragranular topography and thermally grooved grain boundaries
 $\hookrightarrow$ Enhance magnetic field leading to degraded high field performance or thermal instability.



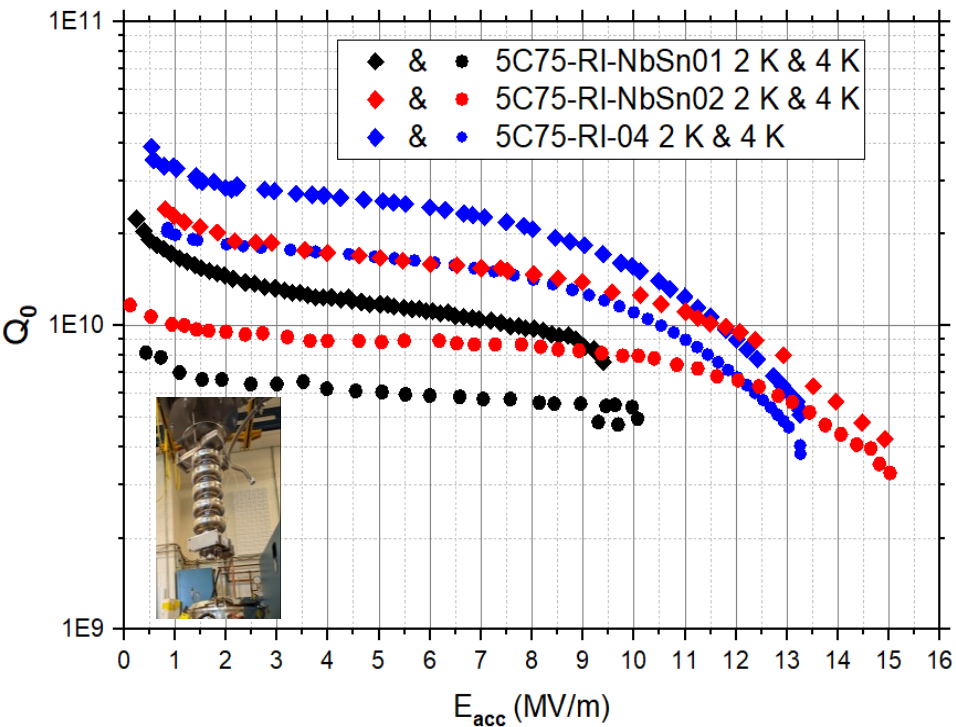
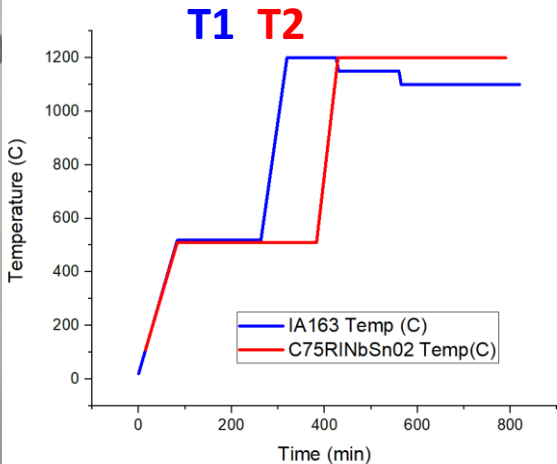
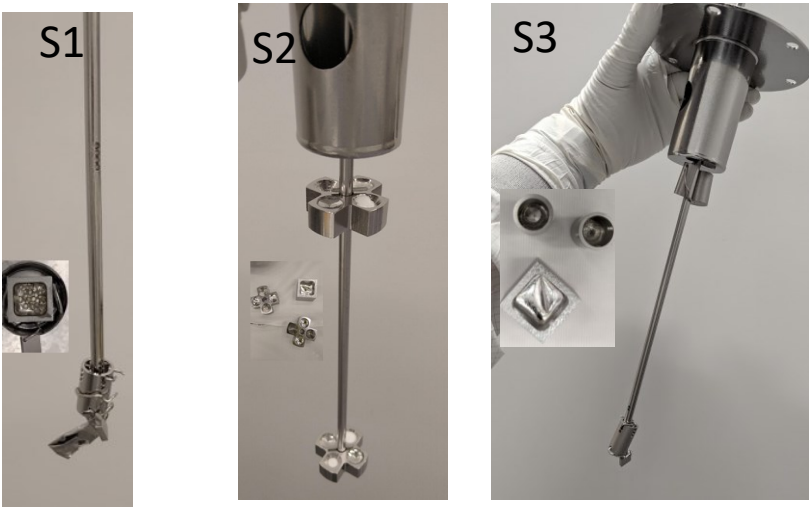
- Can post processing methods be applied to reduce the effect of surface roughness?
- control roughness during the coating stage by
 - tuning the temperature profile
 - improving upon the Nb-Sn nucleation at early stage of the thin film growth
- work in progress



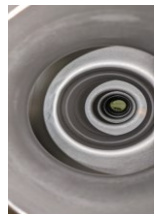
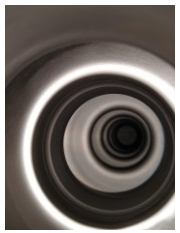
Expt	1200 °C	1150 °C	1100 °C	R_a (nm)	Grain size (μm)	Thickness (μm)
01	10 min	45 min	85 min	69 ± 3	0.93	1.3
02	10 min	45 min		40 ± 1	0.75	1.0 ± 0.2
03	10 min			27 ± 2	0.55	0.75
04	10 min		85 min	43.5 ± 1.5	0.6	1.02

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

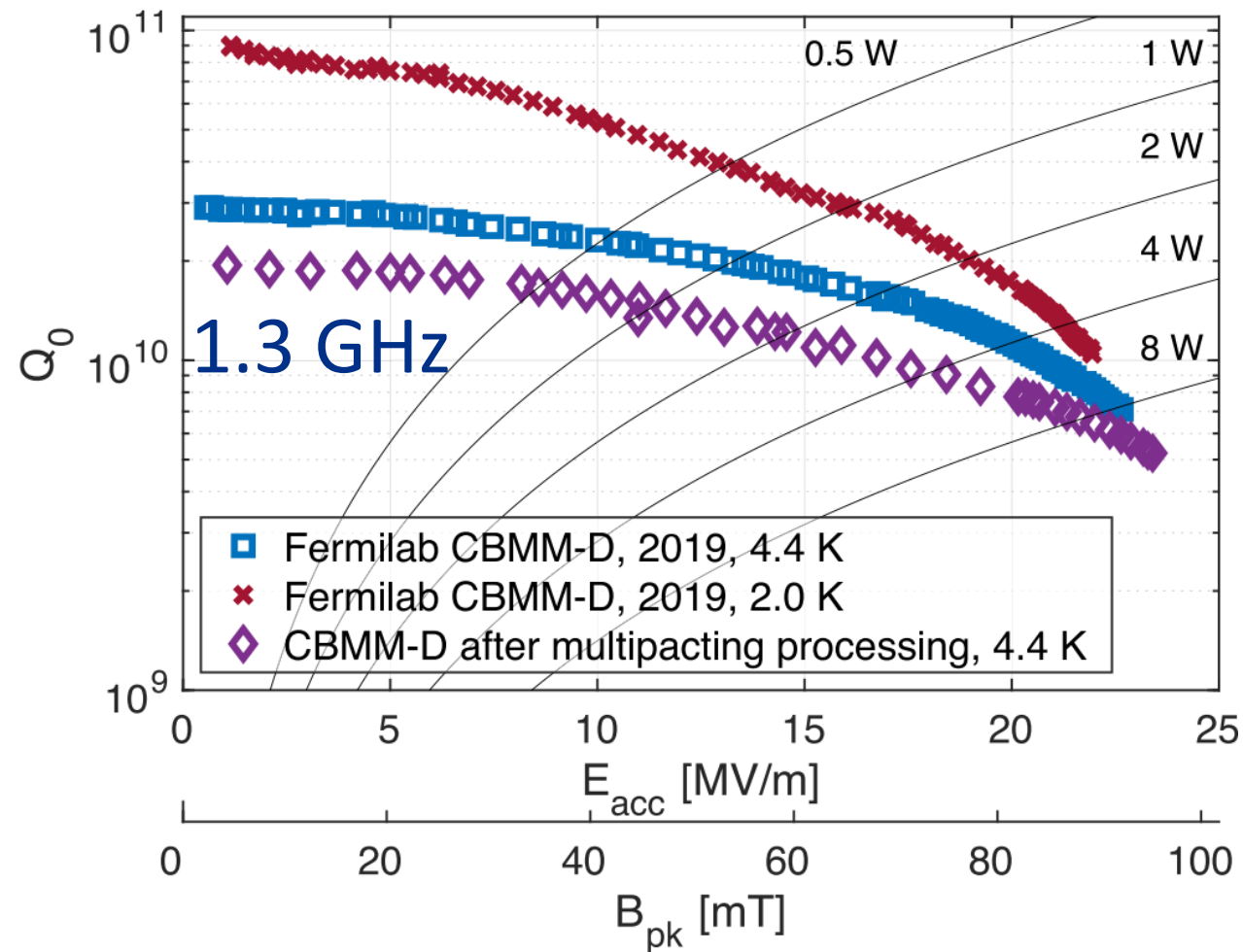
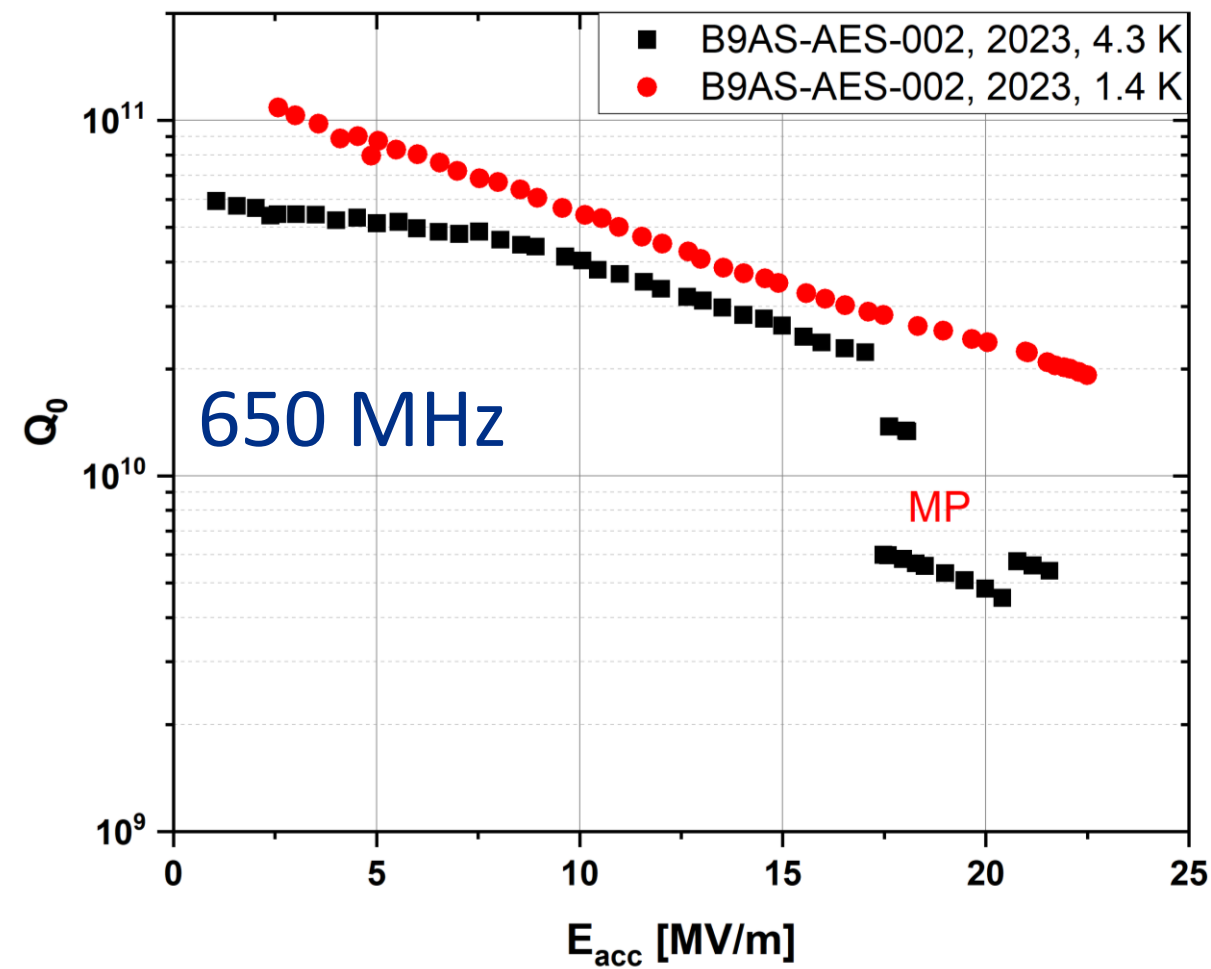


Witness sample in each run.		Sn consumption (g)			
	1 st coating	2 nd Coating	3 rd Coating	5C75-RI-NbSn02 02	5C75-RI-NbSn02 02
Primary	3.6	2.50	2.79	3.05	2.42
Secondary 1	1.7	1.50	1.42	1.50	1.48
Secondary 2	---	1.60	1.43	1.51	1.48
Total	5.3	5.60	5.64	6.06	5.38
Setup	S1-T1	S2-T1	S3-T2	S2-T1	S3-T2



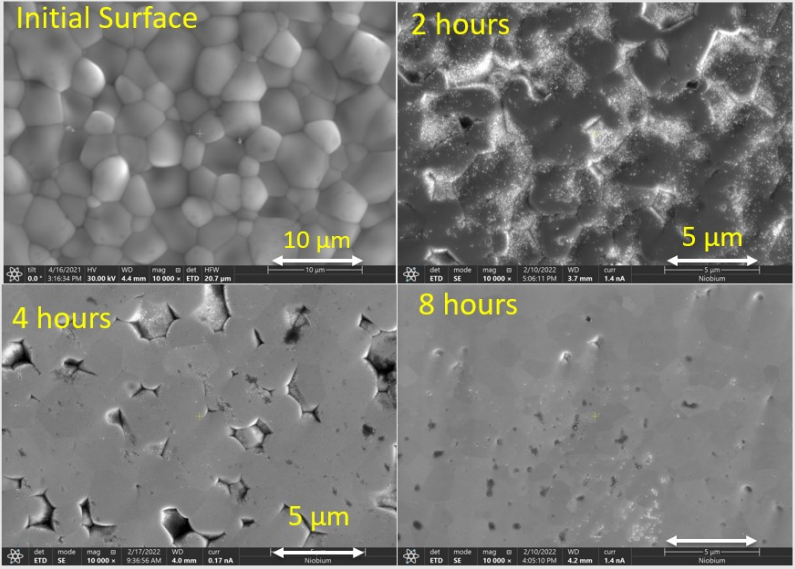
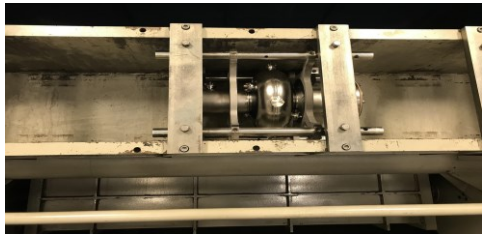
Single-cell cavity R&D at Fermilab

- Demonstration of gradients > 20 MV/m on single-cell Nb₃Sn cavities

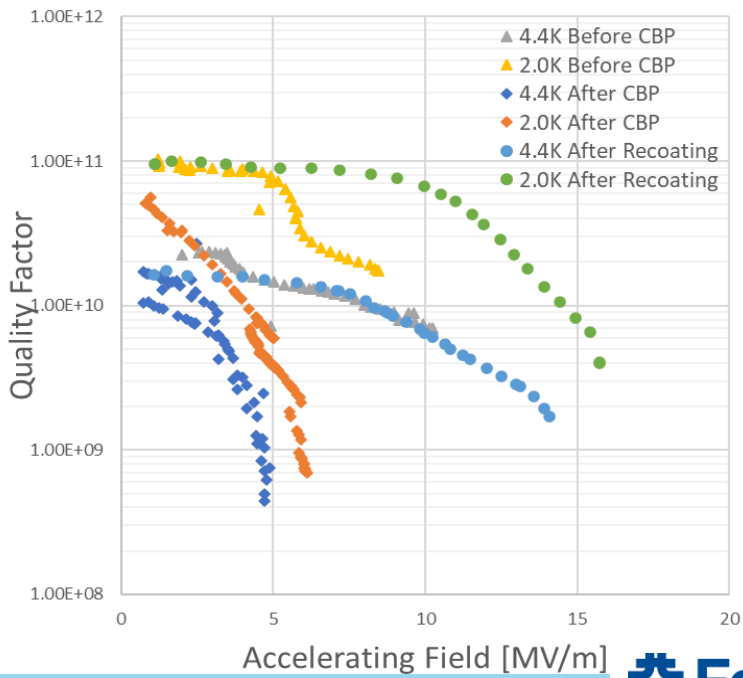


Roughness Reduction - Fermilab

- The Centrifugal Barrel Polishing method (CBP) used commonly to smooth Nb cavities has been adapted to smoothen Nb₃Sn coated cavities
- Nanoparticle abrasive suspension (40 nm silicate or 50nm alumina particles) plus (0.25" wooden ball or 0.5" felt cube)
- 120 RPM in the barrel polishing machine



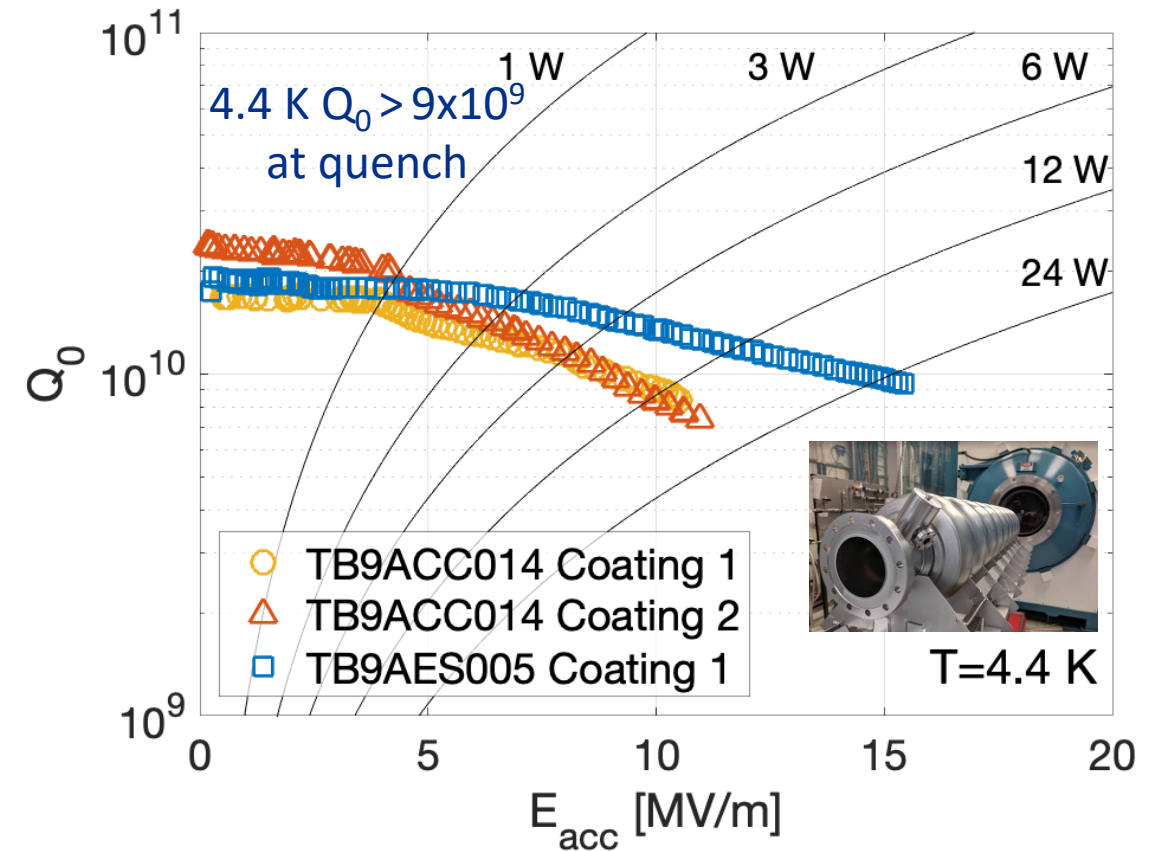
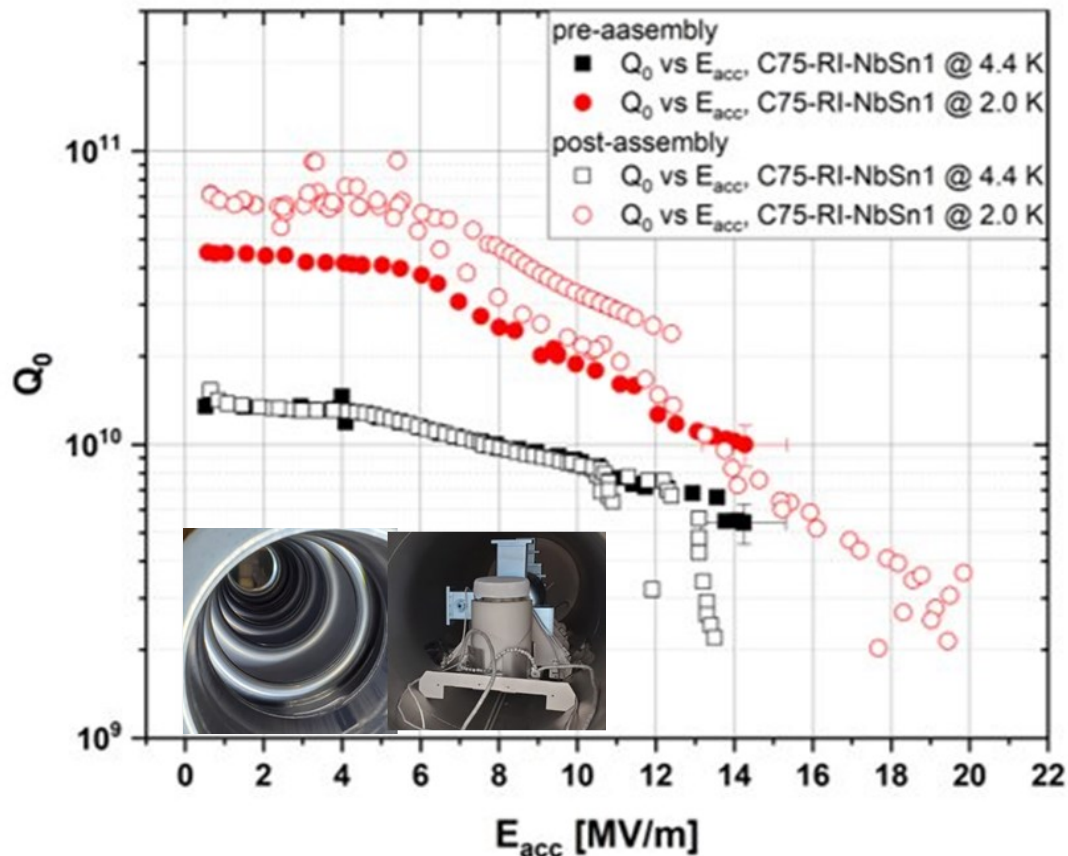
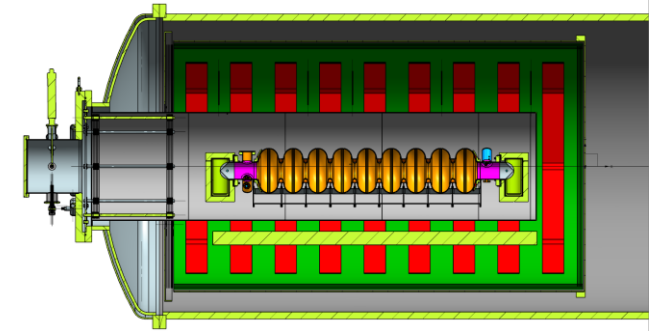
Cavity performance was improved after CBP followed by a short recoating procedure



Viklund, Eric, David N. Seidman, David Burk, and Sam Posen. "Improving Nb₃Sn cavity performance using centrifugal barrel polishing." *Superconductor Science and Technology* 37, no. 2 (2024): 025009.
Viklund, Eric, et al. "Healing Gradient Degradation in Nb₃Sn SRF Cavities Using a Recoating Method." arXiv preprint arXiv:2405.00211 (2024).

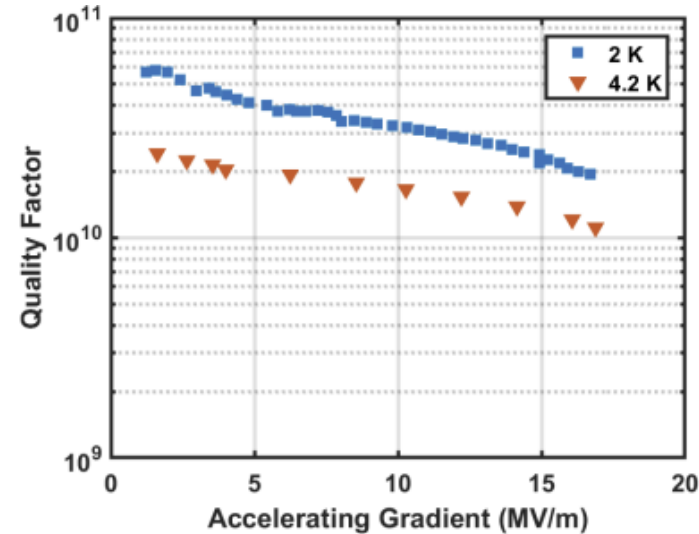
Multi-cell Cavity Coating at Fermilab

- Coatings of multicell practical accelerator structures for various projects
- $E_{\text{acc}} > 15 \text{ MV/m}$, $Q \sim 1 \times 10^{10}$ at 4.4 K



Nb₃Sn Cavity Development at Cornell University

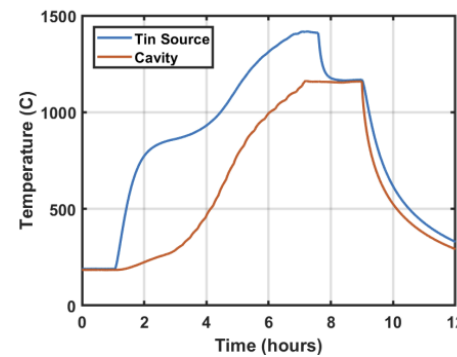
Single-cell cavity performance



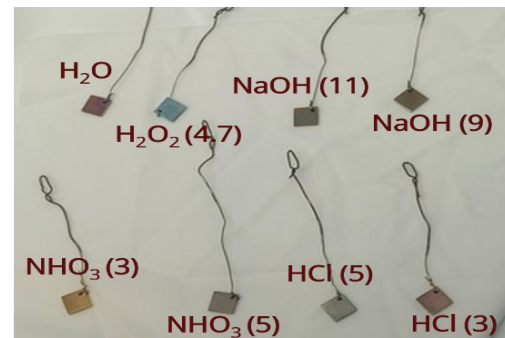
- Q₀ > 10¹⁰ at accelerating gradient > 15 MV/m in single-cell cavities prepared via vapor diffusion
- comparable performance demonstrated for 1.3 GHz, 2.6 GHz, and 3.9 GHz cavities

Standard Sn diffusion Optimization

- new coating profile for smoother coating
 - low BCS resistance but higher residual resistance

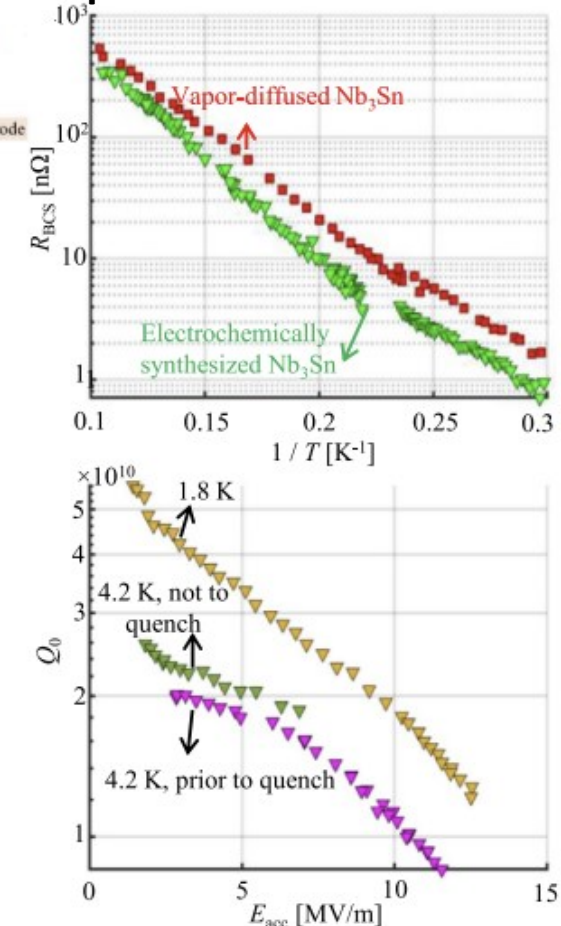
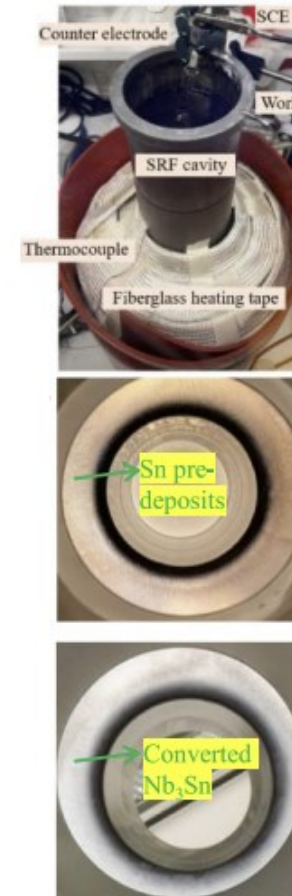


Nucleation Studies



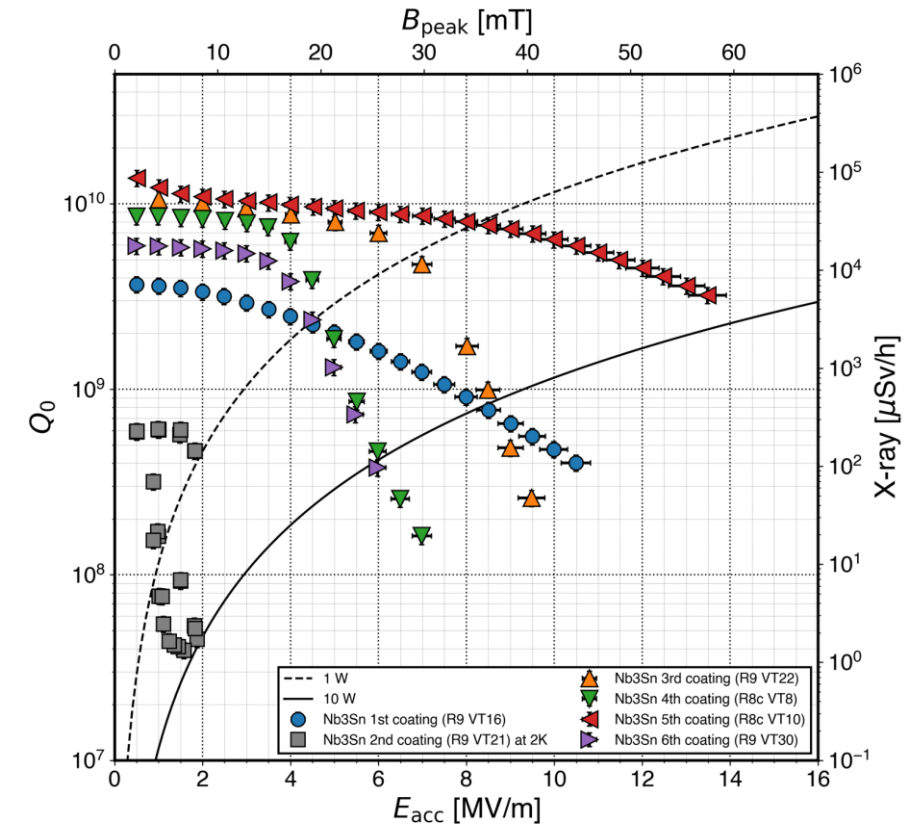
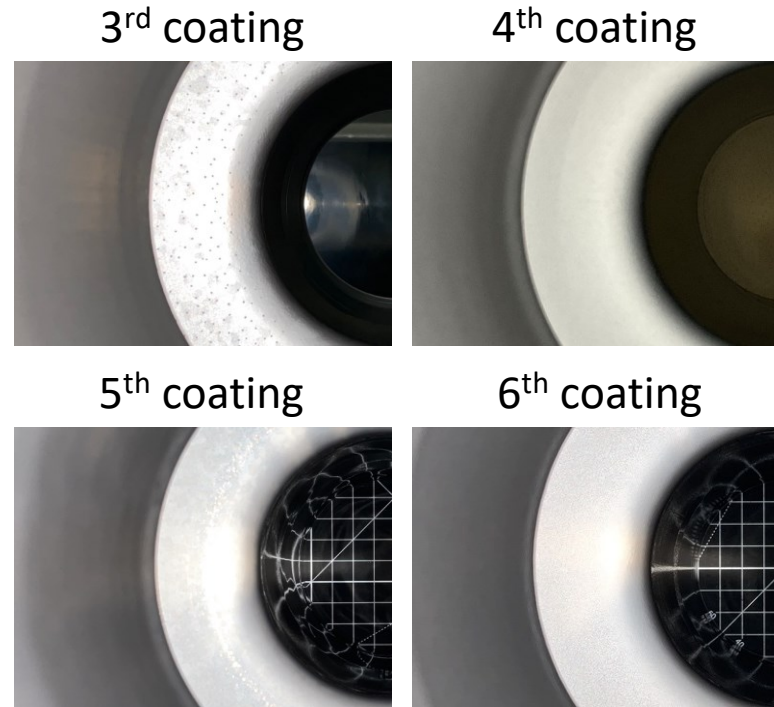
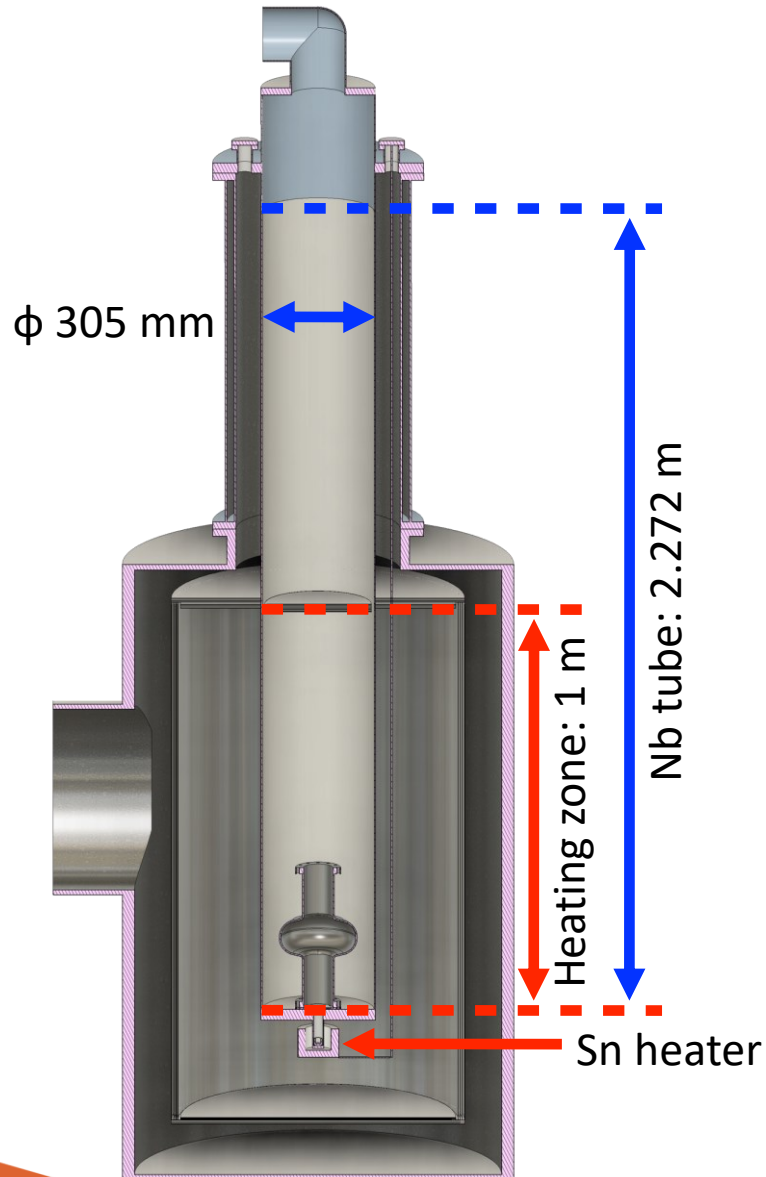
- surface chemistry treatments to optimize nucleation for smoother films

Nb₃Sn via thermal diffusion of electrodeposited Sn



- smooth, homogeneous, high-purity Nb₃Sn

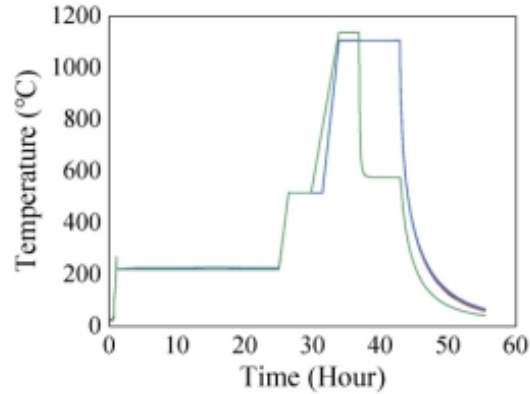
Nb₃Sn cavity development at KEK



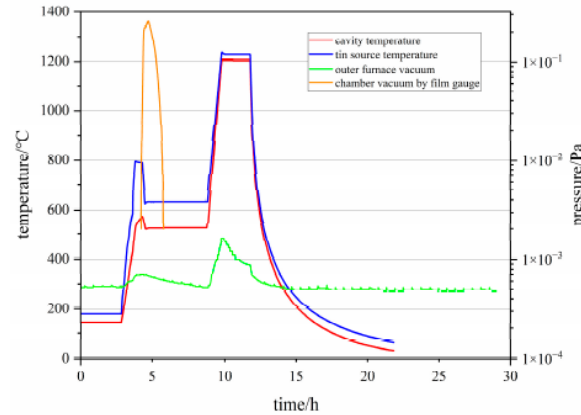
- Nb₃Sn deposition on single-cell Nb cavities via Sn vapor diffusion
- Achieved Q_0 exceeding 10^{10} at 4.2 K in some cavities
- Addressing strong Q-slope at high accelerating gradients

Nb₃Sn Cavity R&D in China

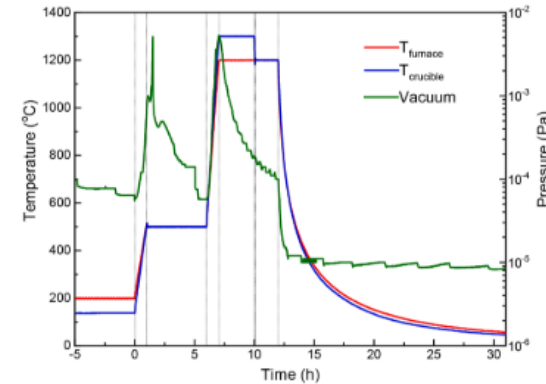
IMP, Lanzhou



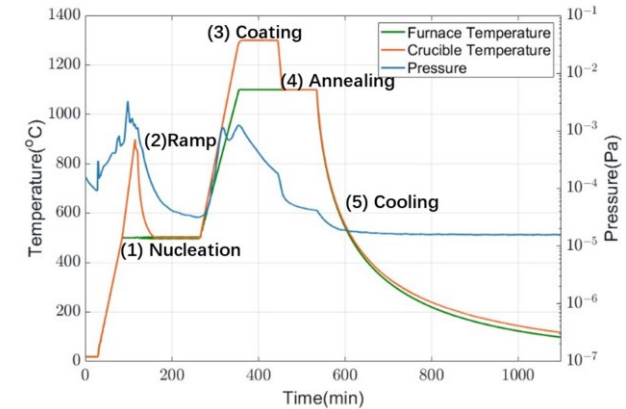
Peking University, Beijing



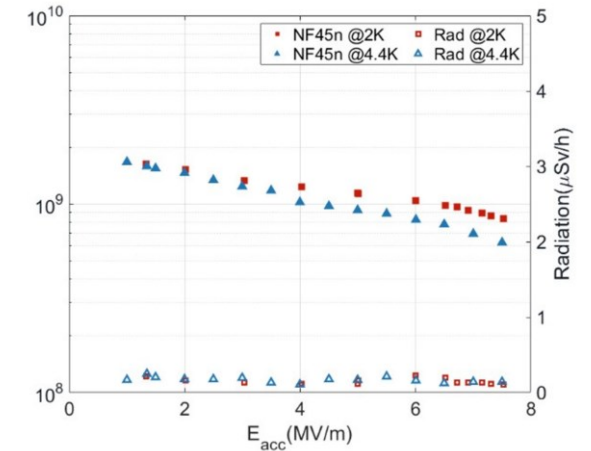
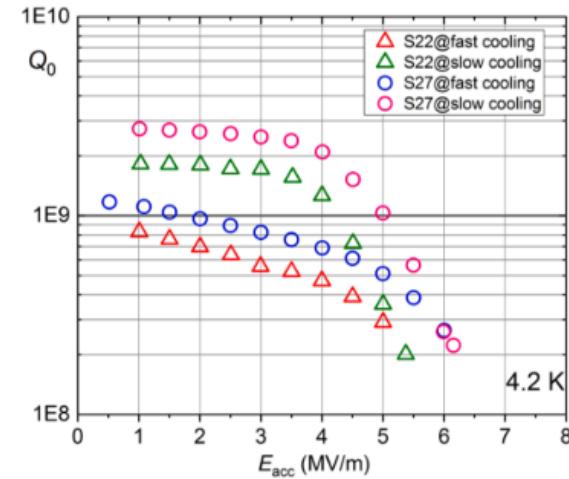
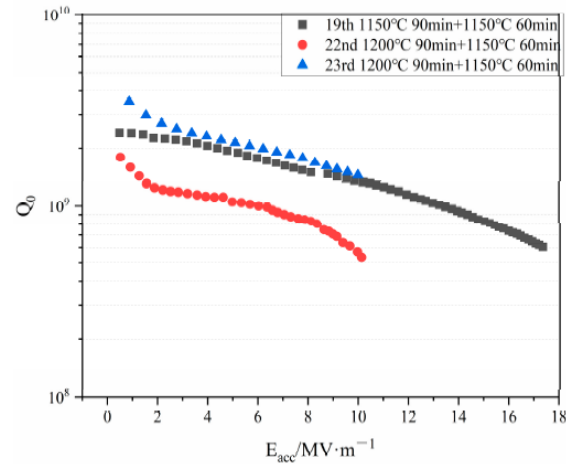
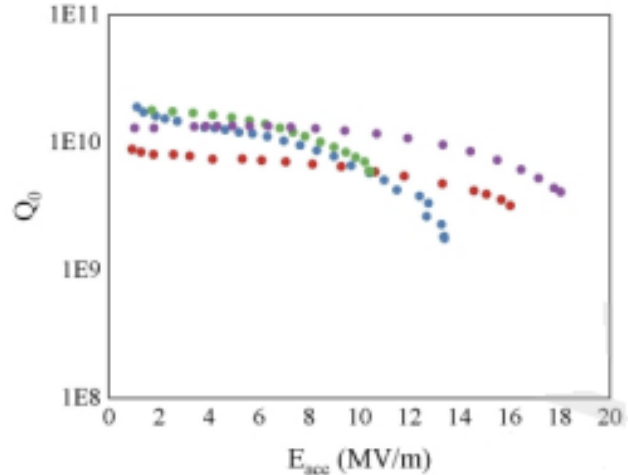
IHEP, Beijing



SARI, Shanghai



— Cavity-T1 — Cavity-T2 — Cavity-T3 — S



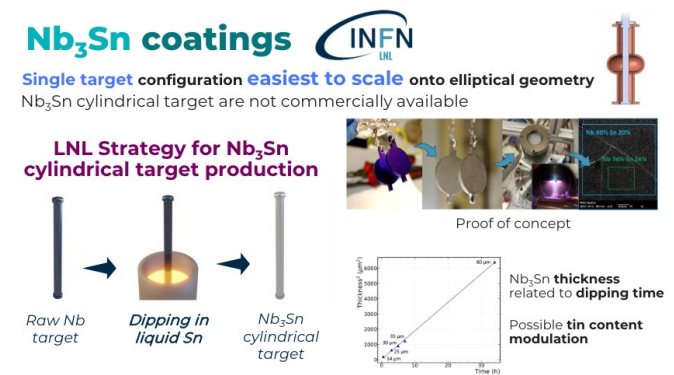
• Process (1) • Process (2) • Process (3) • Process (7)

- Results from 1.3 GHz single-cell cavities at 4 K
- Coating process like FNAL or Cornell
- Coating process optimization in progress

C. Dong et al. "Preliminary Research of Niobium Cavity Coating with Nb₃Sn Film at IHEP." *Physica C: Superconductivity and its Applications* 600 (2022): 1354107.
 G. Jiang, et al. "Understanding and optimization of the coating process of the radio-frequency Nb₃Sn thin film superconducting cavities using tin vapor diffusion method." *Applied Surface Science* 643 (2024): 158708.
 G. Wang et al. "Nb₃Sn Cavities Coated by Tin Vapor Diffusion Method at Peking University." *Applied Sciences* 13.15 (2023): 8618.
 Q. Chen et al. "First Results of Nb₃Sn Coated Cavity by Vapor Diffusion Method at SARI." *Coatings* 14.5 (2024): 581

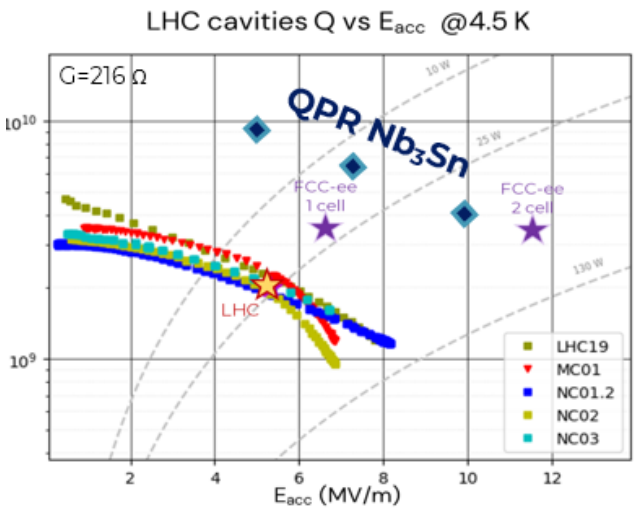
Development of Nb₃Sn in Europe

Target development and Nb₃Sn sputtering at INFN



PRELIMINARY RESULTS FROM Nb PLANAR RESONATOR

Courtesy of C. Pira

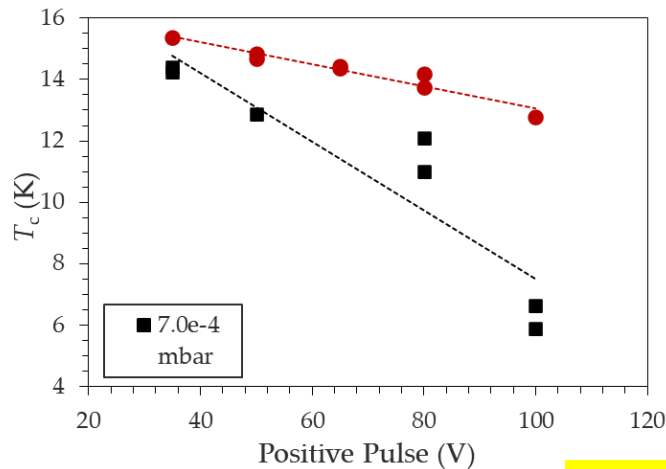


Nb₃Sn on bulk Nb to validate coating performance on 1.3 GHz Elliptical Cavities (2025)

C. Pira et al., "Progress in European Thin Film Activities", in Proc. 21th Int. Conf. RF Supercond. (SRF'23), Grand Rapids, MI, USA, Jun. 2023, pp. 607-614. doi:10.18429/JACoW-SRF2023-WECAA01

Nb₃Sn/Cu Development at CERN

- Choice to move to bi-polar HiPIMS 
- Q-slope mitigation proven on Nb/Cu
 - Detrimental to long-range order parameter (bombardment energy)



Courtesy of G. Rosaz

- T_c: still lower than the theoretical value
- Sn composition: OK
- Cu surface contamination is a key issue

Very encouraging recent RF measurements of Nb₃Sn/Cu
QPR measurements at 4.5 K and at 400, 800 and 1200 MHz show a surface resistance reduction by a factor 2 compared to that of Nb/Cu.

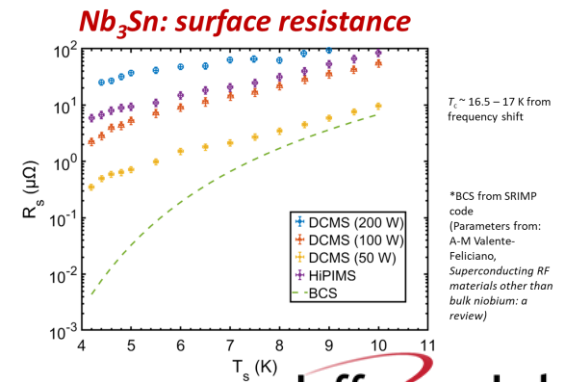
Nb₃Sn/Cu Development on STFC



- 3 DCMS, 1 HiPIMS
- **Aim:** investigate effect of target power/deposition method
 - **Substrate preparation:**
 - Diamond turned Cu disks – 10 cm diameter, 3 mm thick
 - Average roughness ~ 2-3 nm
 - **Sample preparation:**

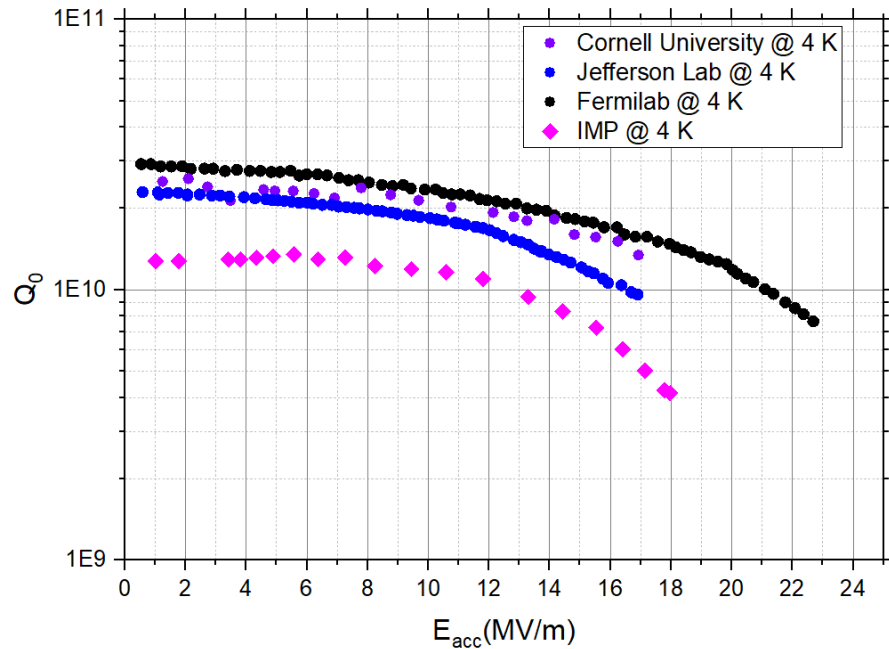
Parameter	DCMS	HiPIMS
Substrate heater current (A)	35 (~ 650 °C)	35 (~ 650 °C)
Target power (W)	200, 100, 50	100
Expected thickness (μm)	2.6	2.6

Courtesy of R. Valizadeh



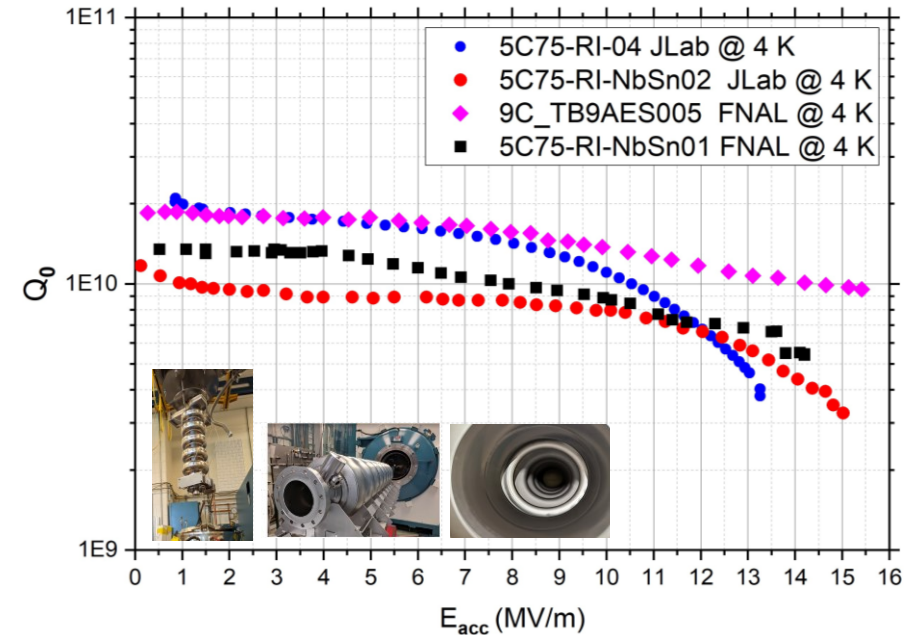
Performance of vapor-diffused Nb₃Sn grown on Nb

R&D 1.3/1.5 GHz single-cell cavity performance



- 1.3/1.5GHz single-cell cavities attain an accelerating gradient over 20MV/m with $Q \sim 10^{10}$.
- Cavities of various frequencies (650MHz, 952MHz, 2.6GHz, 3.6GHz) coated at different facilities show comparable performance.

Multi-cell cavity performance



- 1.5GHz five-cell and 1.3GHz 9-cell cavities were demonstrated to reach $Q \sim 10^{10}$ at 10MV/m at 4.4K.
- Maximum gradients achieved up to ~ 20 MV/m.

Nb₃Sn cavities are ready for accelerator applications!

U. Pudasaini et al. "Managing Sn-Supply to Tune Surface Characteristics of Vapor-Diffusion Coating of Nb₃Sn", presented at the SRF'21, East Lansing, MI, USA, Jun.-Jul. 2021, doi:10.18429/JACoW-SRF2021-TUPTEV013.

S. Posen et al. "Advances in Nb₃Sn superconducting radiofrequency cavities towards first practical accelerator applications" Superconductor Science and Technology. 2021 Jan 11;34(2):025007.

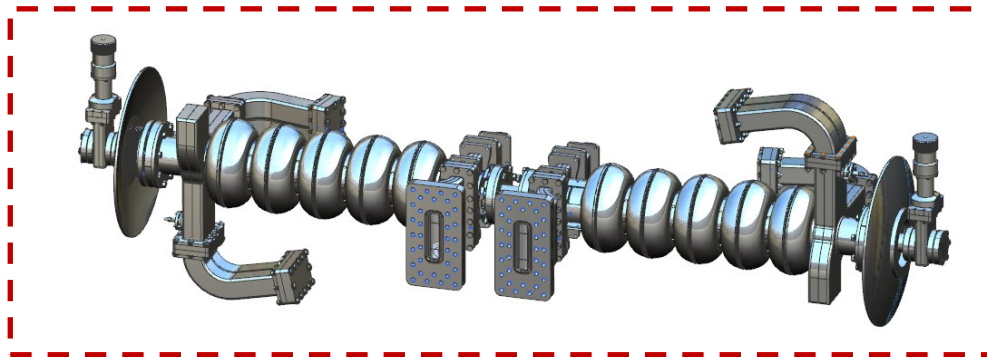
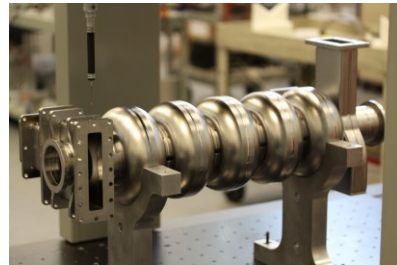
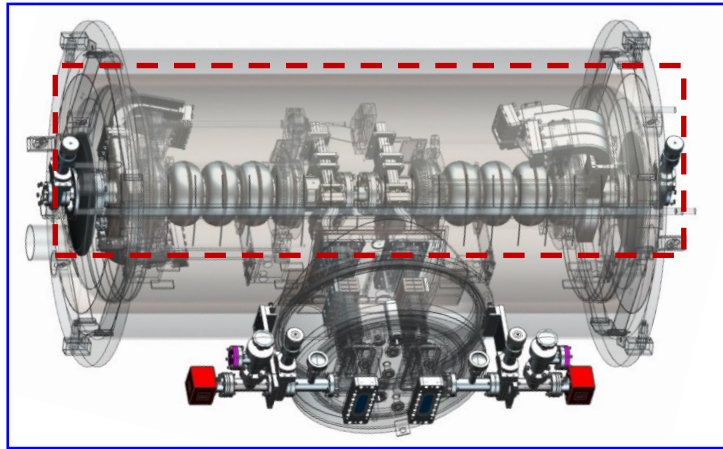
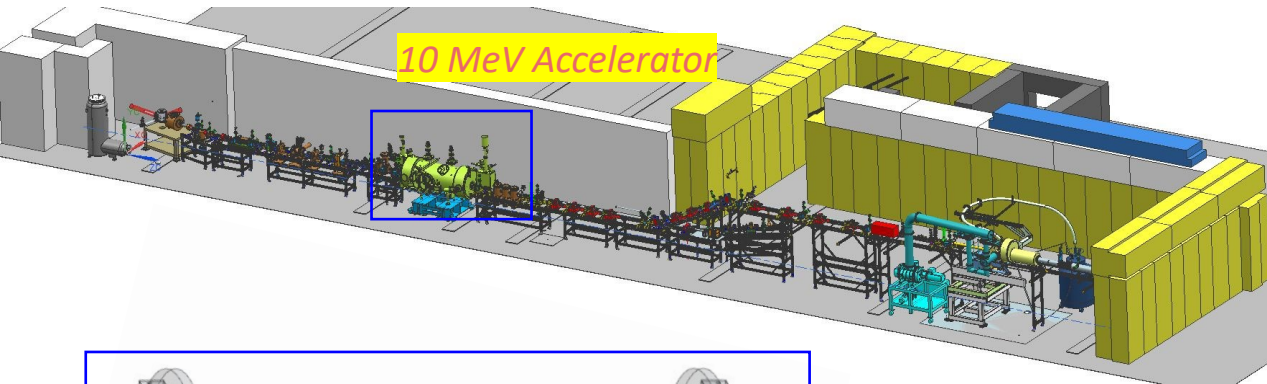
D. Hall, "New Insights into the Limitations on the Efficiency and Achievable Gradients in Nb₃Sn SRF Cavities", PhD thesis, Cornell University (2017).

G. Jiang et al., Understanding and optimization of the coating process of the radio-frequency Nb₃Sn thin film superconducting cavities using tin vapor diffusion method. Applied Surface Science. 2024 Jan 15;643:158708.

G. Ereemeev "Progress in Nb₃Sn developments for CEBAF-style quarter cryomodule" TTC-2022,

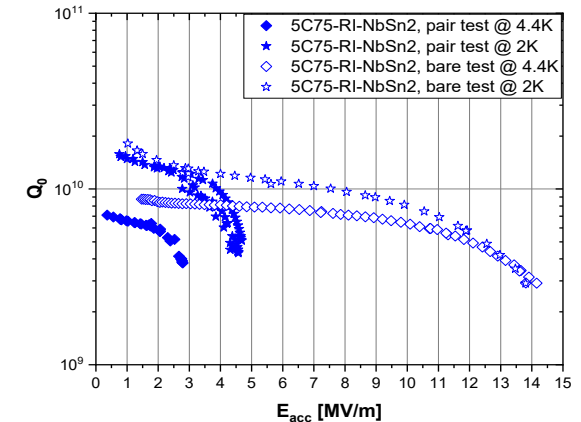
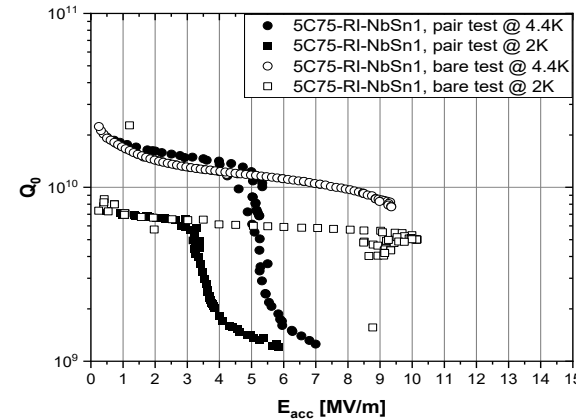
Development of CEBAF-style quarter module using Nb₃Sn-coated cavities at JLab

Upgraded Injector Facility at Jefferson Lab



- Goal: develop a quarter cryomodule with Nb₃Sn-coated cavities with an average gradient of 10MV/m per cavity.
- Two five-cell Nb₃Sn-coated cavities qualified in 2019 with E_{max} of 12 and 14MV/m but degraded to below 5 and 7MV/m during the vertical pair test
 - mechanical stress due to vertical pair assembly & hanging
- both cavities required reprocessing and re-coating

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



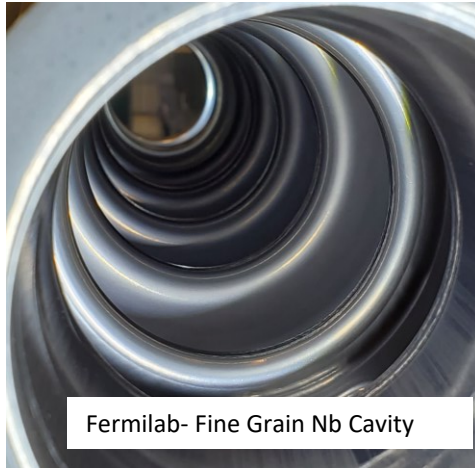
*Work-based on G. Ereemeev's Early Career Award at Jefferson Lab.

Re-Qualification of Nb₃Sn-coated Cavities

- one cavity coated at JLab and another at Fermilab
- both cavities reached >13MV/m with $Q \sim 10^{10}$ at 10MV/m
- subjected to disassembly due to a leak in a RF window

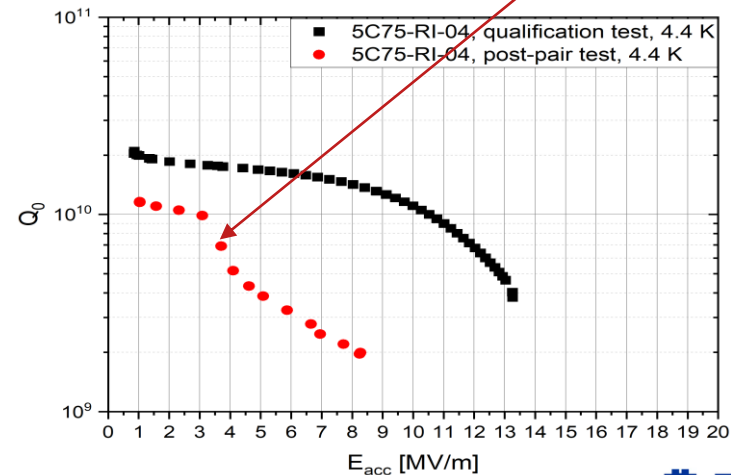
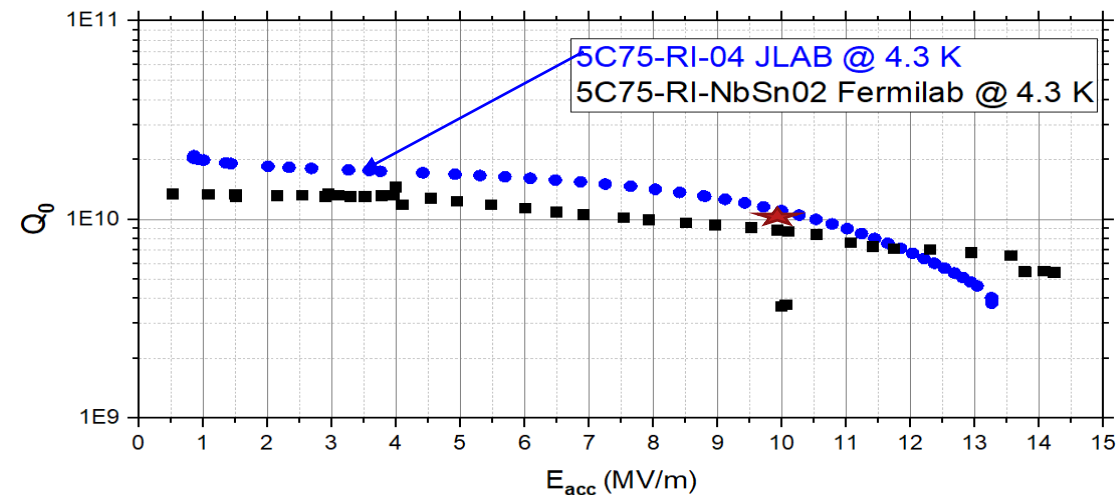
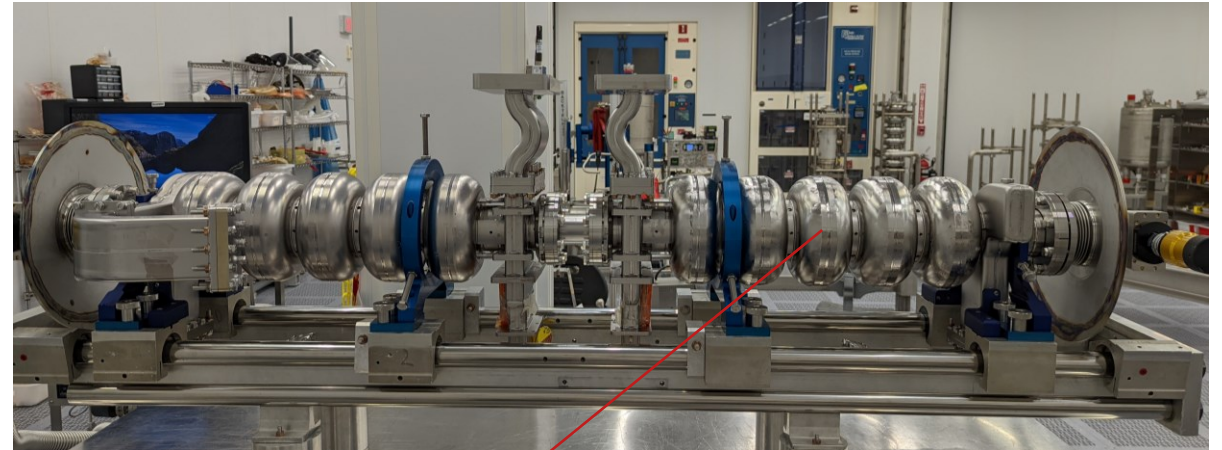


Jlab- Nb₃Sn coating on Large grain Nb



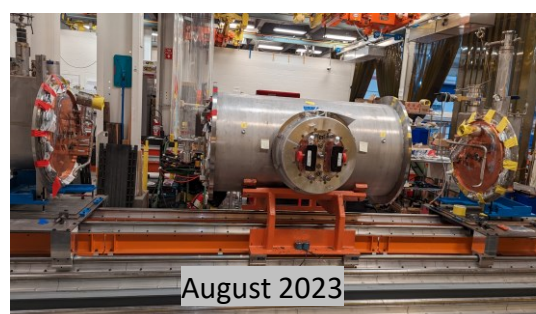
Fermilab- Fine Grain Nb Cavity

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



Cryomodule Assembly and Preliminary Qualification Test Results

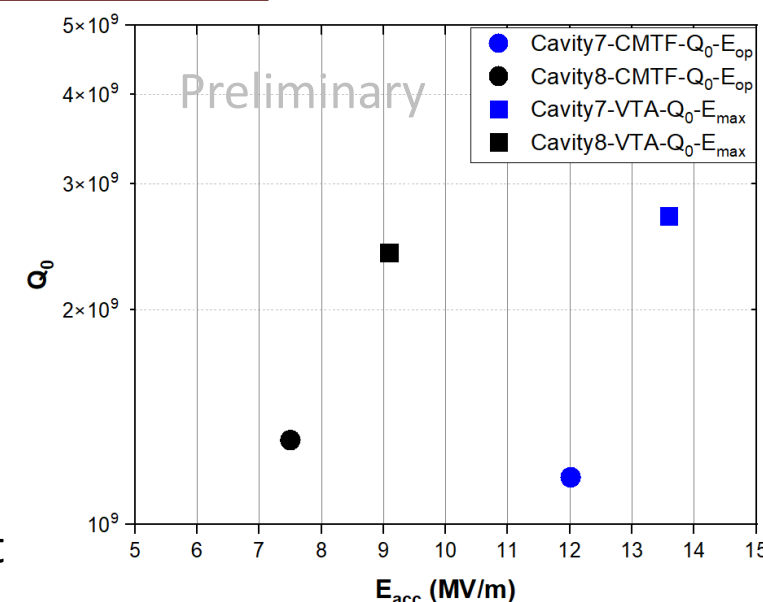
- Several assembly steps required modifications to avoid mechanical strain on the cavities.
- Slow cooldown with temperature gradient ~ 0.3 K across the cryomodule.



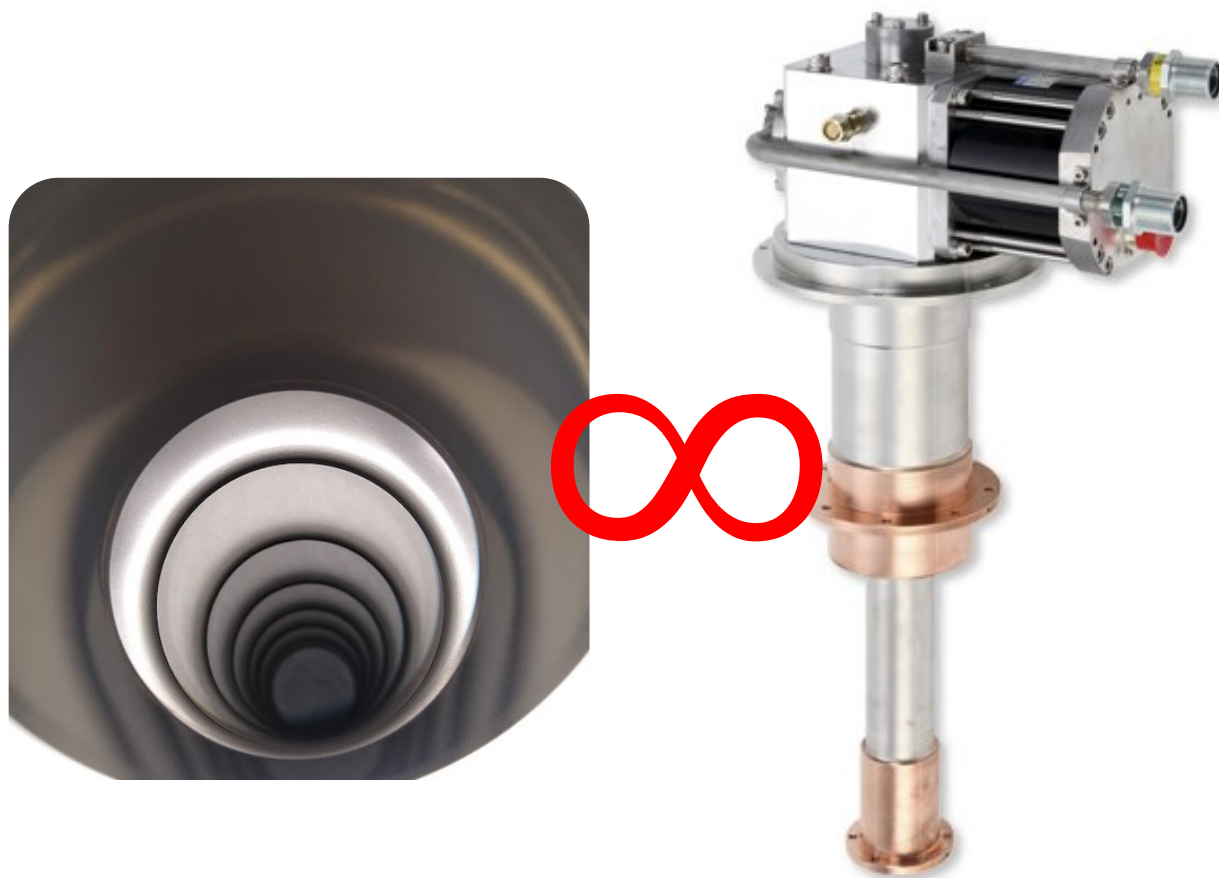
First demonstration of **10 MeV** Nb₃Sn cryomodule

Cavity	VTA f(MHz) @ 4 K	CMTF f(MHz) @ 4 K	VTA E _{max} (MV/m) @ 4 K	CMTF E _{max} (MV/m) @ 4 K	E _{op} (MV/m) 1 h run @ 4 K FE-free	VTA E _{max} (MV/m) @ 2 K	CMTF E _{max} (MV/m) @ 2 K	E _{op} (MV/m) 1 h run @ 2 K FE-free
5C75-RI-NbSn01	1496.72		13.6	13.3	12.6	18.5	13.2	12.4
5C75-RI-04	1496.40		9.0	7.9	7.5	9.2	8.7	8.5

- accelerating gradients close to vertical test
- frequency difference between two cavities ~ 150 kHz Cavity
 - ↳ tuned to match frequency
- installation at UTF next
- **beam test in October 2024. Stay Tuned.**

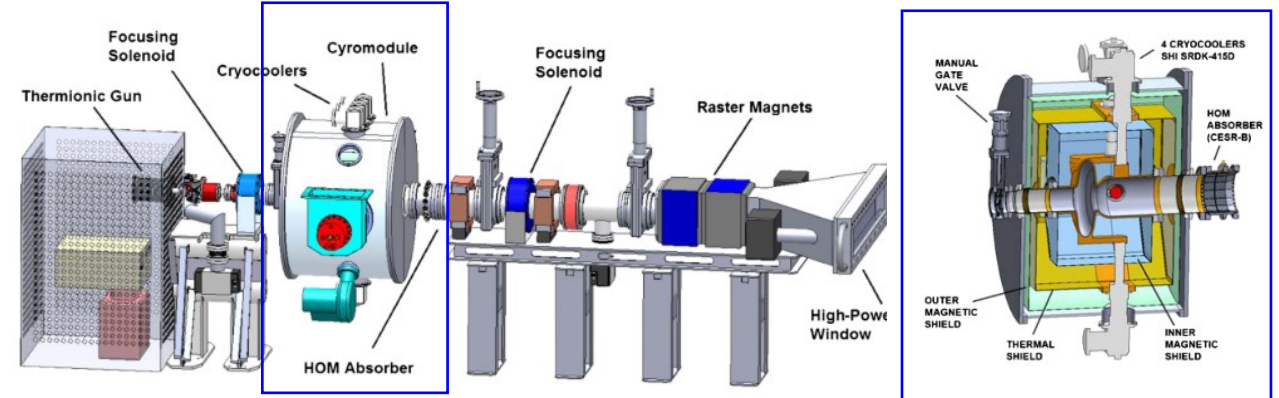


Nb_3Sn Cavities for conduction-cooled compact Accelerators

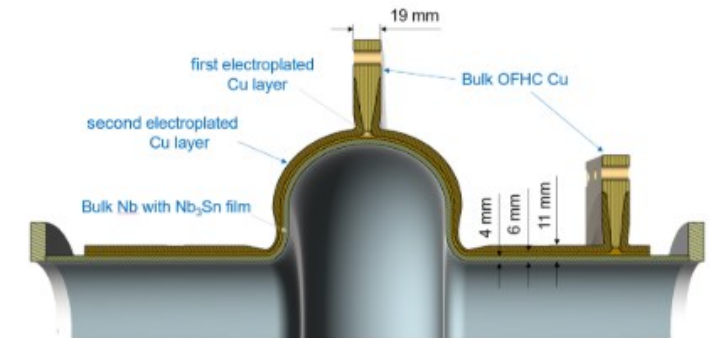
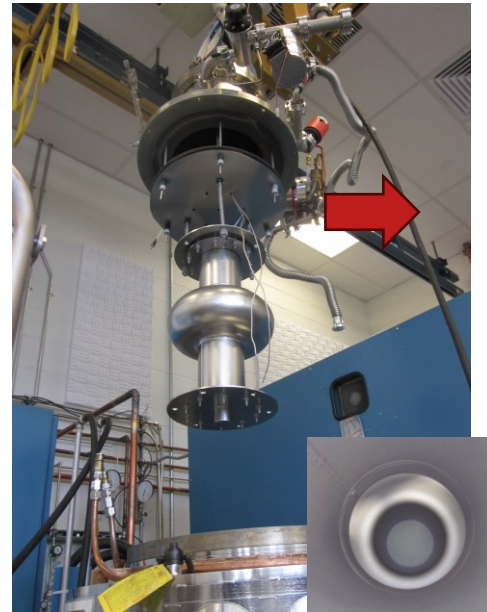


Nb₃Sn-based Conduction-cooled Compact Accelerator Development at JLab

- G. Ciovati proposed a conceptual design for a 750 MHz, CW, 1 MeV, 1 MW SRF electron Linac for environmental remediation in 2018
- frequency switched to 915 MHz for cost efficiency with commercial high-power magnetrons
- performance demonstration using 952 MHz prototype Nb cavity with conduction cooling.



G. Ciovati et al., Design of a cw, low energy, high power superconducting linac for environmental applications, Phys. Rev. Accel. Beams 21, 091601 (2018)

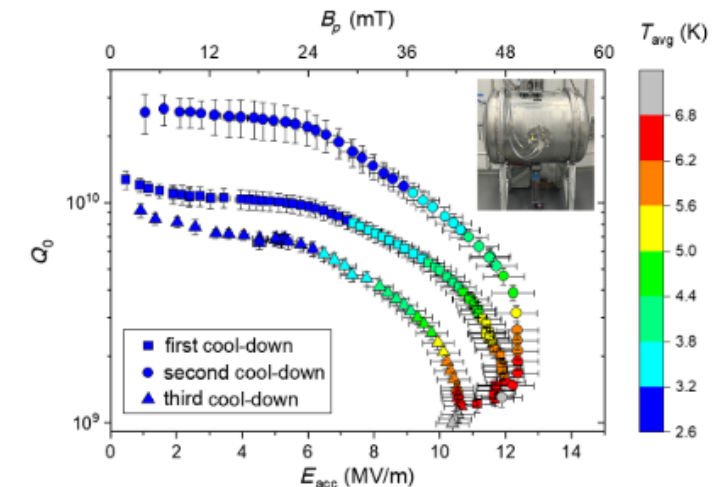
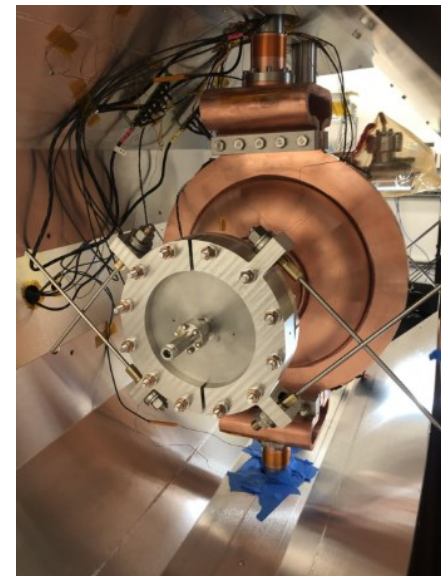
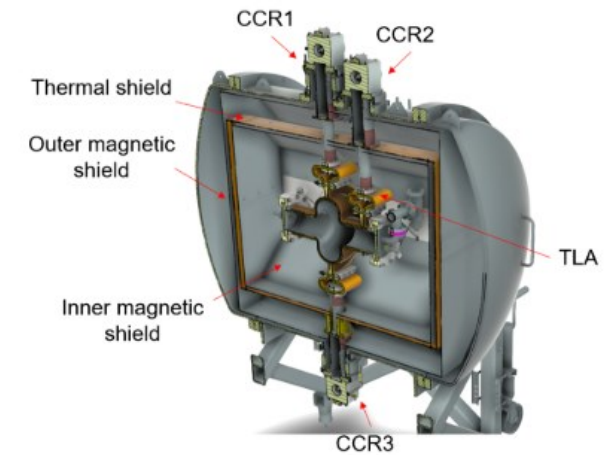
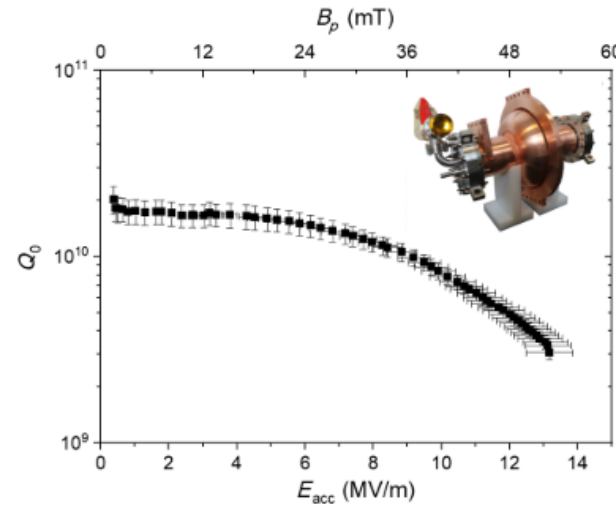


Ciovati, Gianluigi, et al. "Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators." Physical Review Accelerators and Beams 26.4 (2023): 044701.

Demonstration of Conduction-Cooled Nb₃Sn Cavity Technology for Single-Cells

- performance limited by multipacting at 53 mT
- Shipped under static vacuum to General Atomics for assembly into horizontal test cryostat
- Proof-of-concept cavity test
 - Cooled by 3 cryocoolers, achieved $B_p=50$ mT
($E_{acc} = 12.4$ MV/m)
 - highest achieved in a conduction-cooled cavity to date

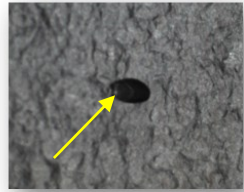
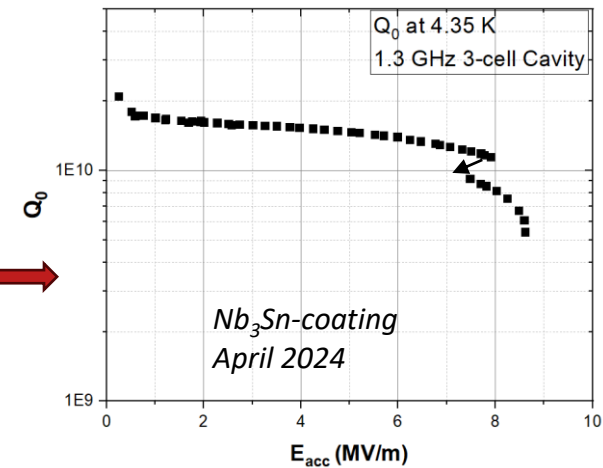
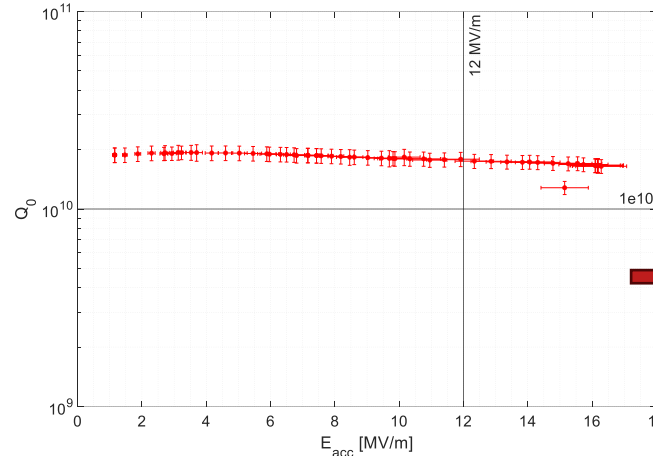
↪ What's next?



Ciovati, Gianluigi, et al. "Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators." *Physical Review Accelerators and Beams* 26.4 (2023): 044701.

Moving from 1 MeV to 10 MeV: Single-cell to Multi-cell

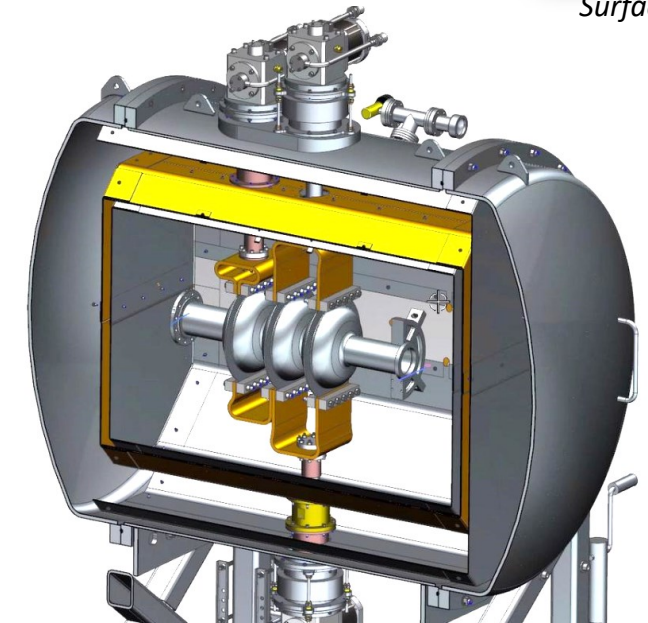
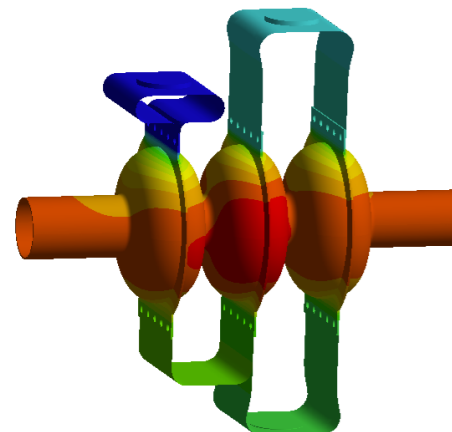
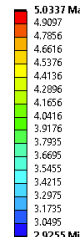
- Demonstrate conduction-cooling of a multicell cavity in horizontal test cryostat at General Atomics
- Utilize hydroformed 1.3 GHz 3-cell cavity
- Thermal links: Nb rings welded to equators
 - Cu coating and plating pre-installation in the cryostat.
- Nb₃Sn coating limited to 9 MV/m due to Nb substrate surface defect(s)
- Cryostat installation and testing planned for 2024



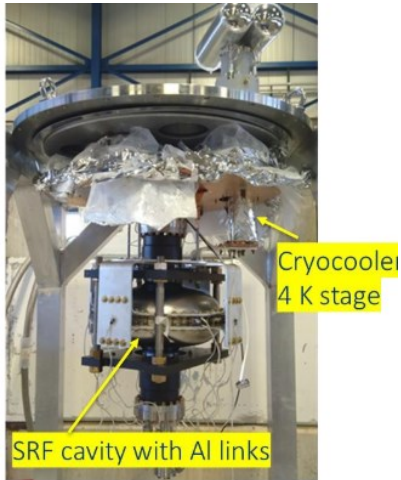
Surface defects



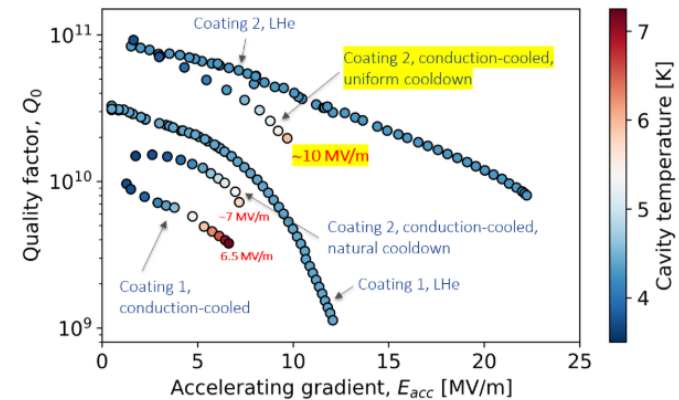
B: Rs good case Jumper
Temperature - All
Type: Temperature
Unit: K
Time: 2 s
11/11/2022 10:24 AM



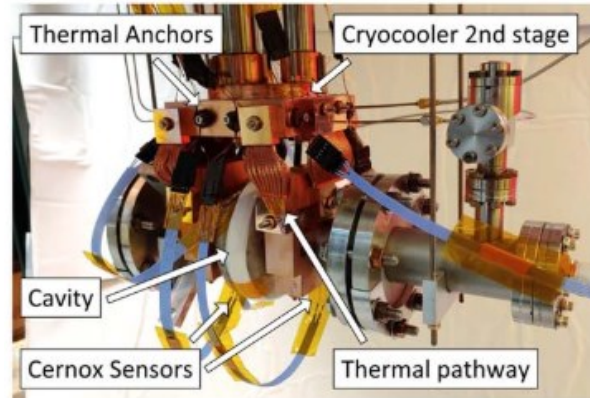
Demonstration of Conduction-Cooling of Nb₃Sn Cavities



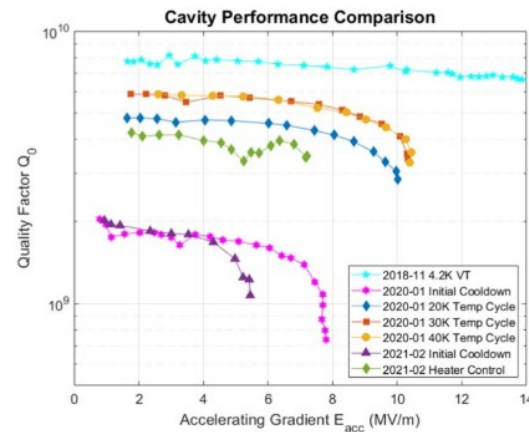
650 MHz single-cell
 $E_{acc, max} \sim 10.0$ MV/m



Dhuley, R. C., et al. "Development of a cryocooler conduction-cooled 650 MHz SRF cavity operating at ~ 10 MV/m cw accelerating gradient." IOP Conference Series: Materials Science and Engineering. Vol. 1240. No. 1. IOP Publishing, 2022.

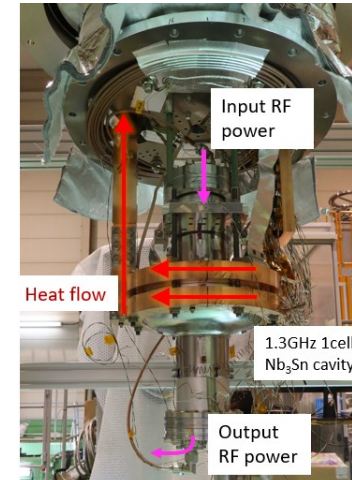


2.6 GHz single-cell
 $E_{acc, max} \sim 10.0$ MV/m

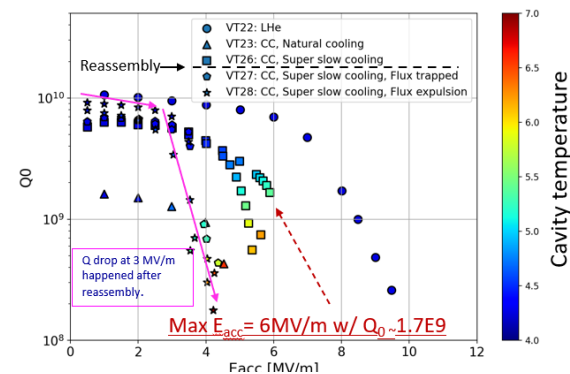


Stilin, N. A., et al. "RF and thermal studies on conduction-cooled Nb₃Sn SRF cavity." Engineering Research Express 5.2 (2023): 025078.

25



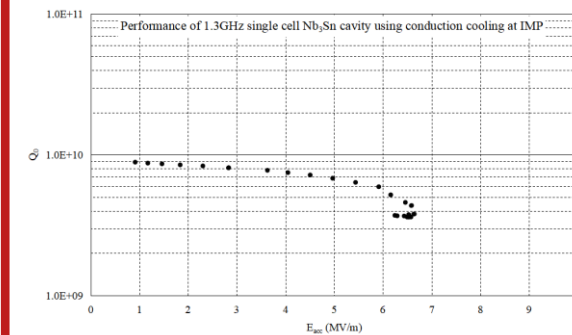
1.3 GHz single-cell
 $E_{acc, max} \sim 6$ MV/m



Courtesy of H. Ito and T. Yamada



1.3 GHz single-cell
 $E_{acc, max} \sim 6.6$ MV/m



Courtesy of Z. Yang

Jefferson Lab

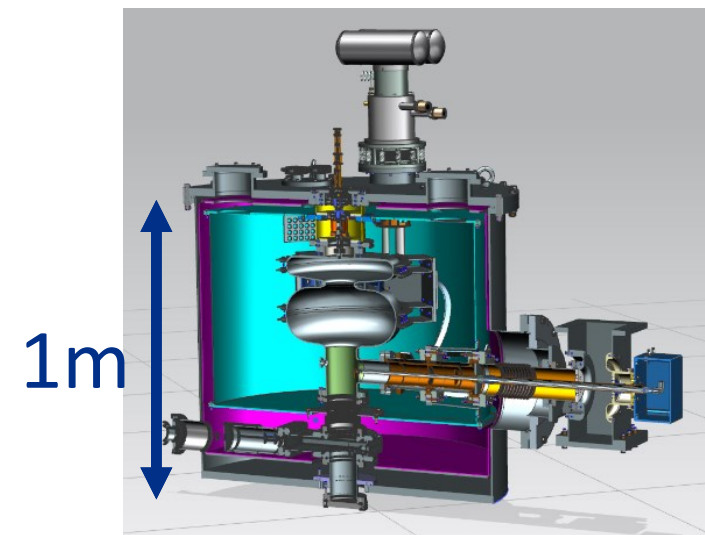
High-power X-ray prototype source development using superconducting accelerator for radiological (Co-60) source replacement

20 kW, 1.6 MeV prototype Electron Accelerator

Reduce Pillar of ORS:

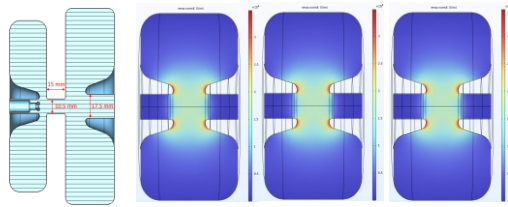
REDUCE the global reliance on radioactive sources by promoting the adoption and development of non-radioisotopic alternative technologies

- Developing compact superconducting CW RF electron accelerator
 - Provide X-ray alternative to sterilization by Cobalt-60
- Free of liquid cryogenics: more compact, less complexity, safer
 - Cryocoolers with conduction cooling
 - CW operation maximizes efficiency
- Cavity fabrication for 20 kW prototype complete
 - Nb₃Sn coating in progress
 - Commissioning to follow (mid-2025)
- Evaluating commercialization strategies

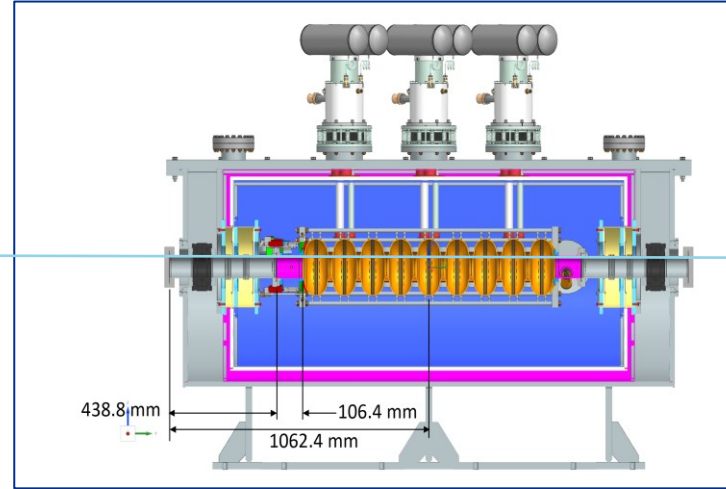


A 20 kW SRF accelerator for pavement application

Electron Injector (Normal Conducting)



Conduction cooled cryostat (Superconducting)



10 MeV

- Modular design allows parallel development – injector and cryostat are separate
- 1.3 GHz TESLA-style cavity – a mature design
- Beam loss control inside the cryostat is less stringent (losses are outside the cryostat)
- Leveraging experience from LDRD, SBIR, industry, and Fermilab SRF linac (FAST-IOTA)
- Solid State amplifiers (off-the-shelf RF systems), simple Blinky-lite control
- Mobile-friendly for pavement application
- Injector to be tested in Fall 2024

Development of practical Nb₃Sn-coated cavity for ATLAS superconducting LINAC at ANL

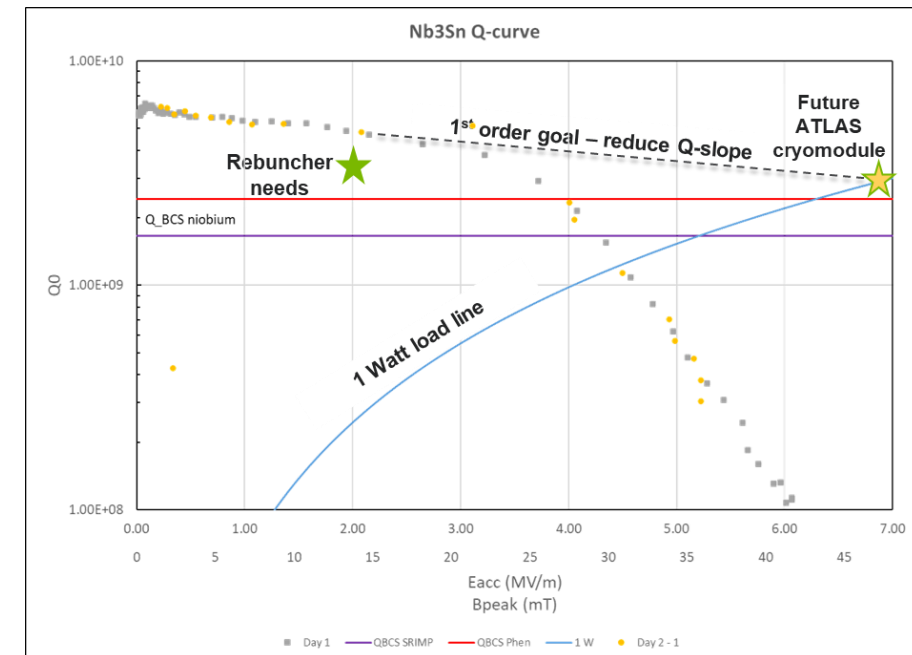
Demonstration of a Practical Nb₃Sn-coated 218 MHz Low-beta Quarter Wave Accelerator Cavity

- Fabrication and surface preparation of 218 MHz quarter wave niobium cavity at ANL



- Q at low-mid field is high: Much higher than for niobium, $R_s=7 \text{ n}\Omega$ at 4.5 K
- ATLAS Rebuncher:** Needs 0.3-0.5 MV $\rightarrow$ this performance is easily sufficient $\rightarrow$ high confidence for cavity #2
- Future accelerator cryomodules:** Need to improve Q-slope
 - Extending flat region of present curve already good
 - Even better to raise Q_0 at the same time
- At minimum two important issues will be addressed for 2nd cavity:** Plastic deformation and contamination
- Performance is good enough for rebuncher; need to resolve Q-slope for future accelerator cryomodules
- NEXT?**

- Nb₃Sn coating and testing at FNAL

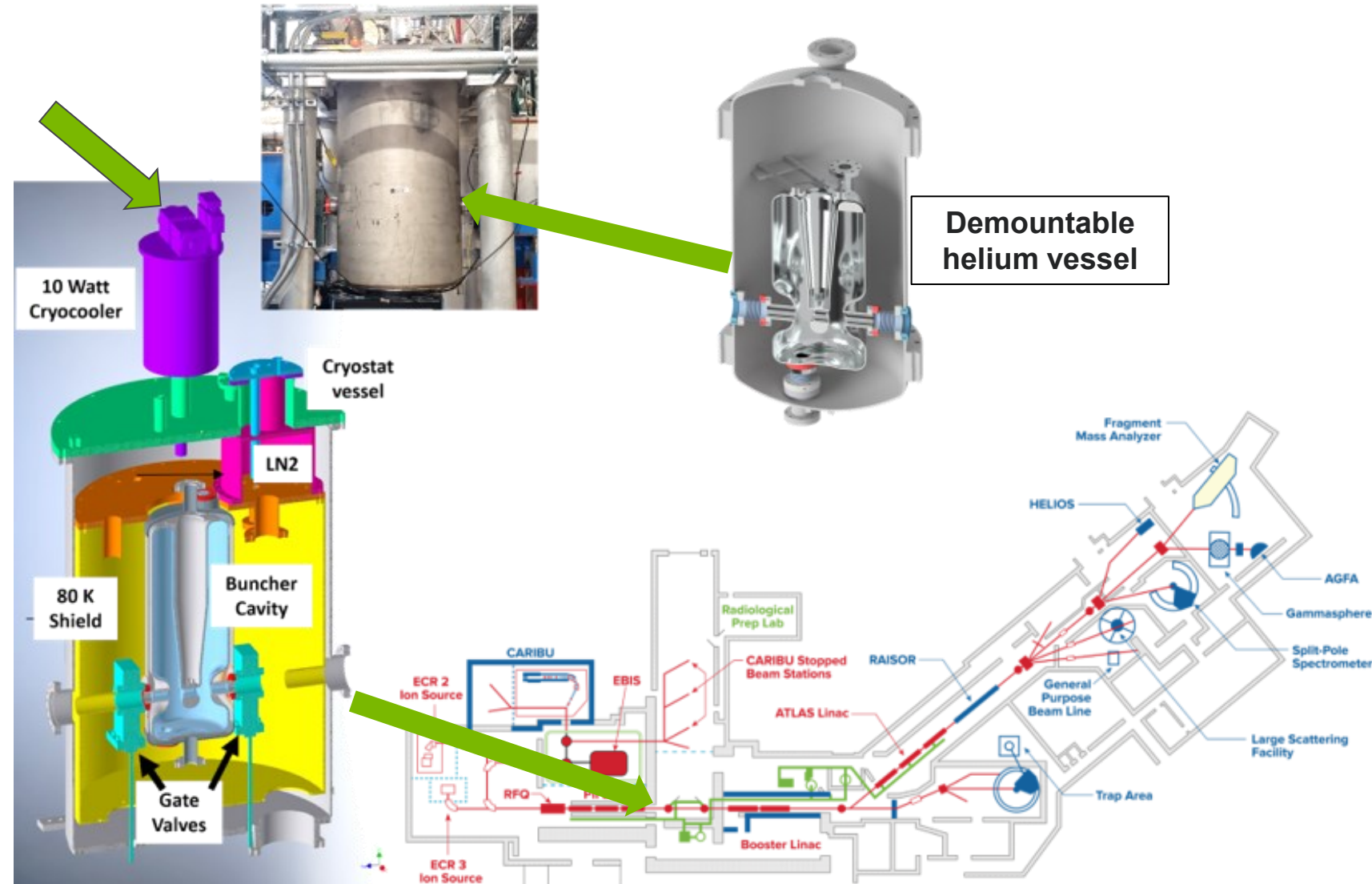


T.B. Petersen *et al.*, "Demonstration of Niobium Tin in 218 MHz Low-Beta Quarter Wave Accelerator Cavity", in *Proc. 21th Int. Conf. RF Supercond. (SRF'23)*, Grand Rapids, MI, USA, Jun. 2023, pp. 388-392. doi:10.18429/JACoW-SRF2023-TUPTB001

Plans: Installing a Nb₃Sn coated cavity in ATLAS

A rebuncher in the middle of the ATLAS provides a large benefit for high-intensity beams (N=126 factory) with moderate cavity requirements

- **Test bed:** Among the first real uses of a Nb₃Sn-coated cavity
- **Existing infrastructure:** Hardware re-use provides some cost reduction
- **10-Watt cryocooler:** Design will include compatibility with this device
- **FY2024 goal:** Develop **145 MHz** niobium-tin coated cavity course tuned for ATLAS
 - Module modifications support by ATLAS AIP

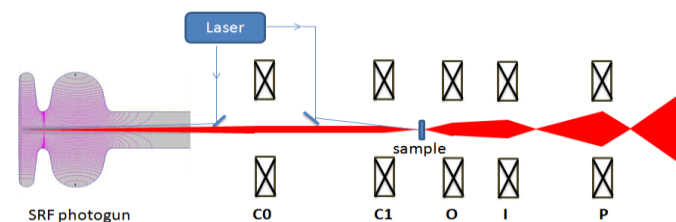
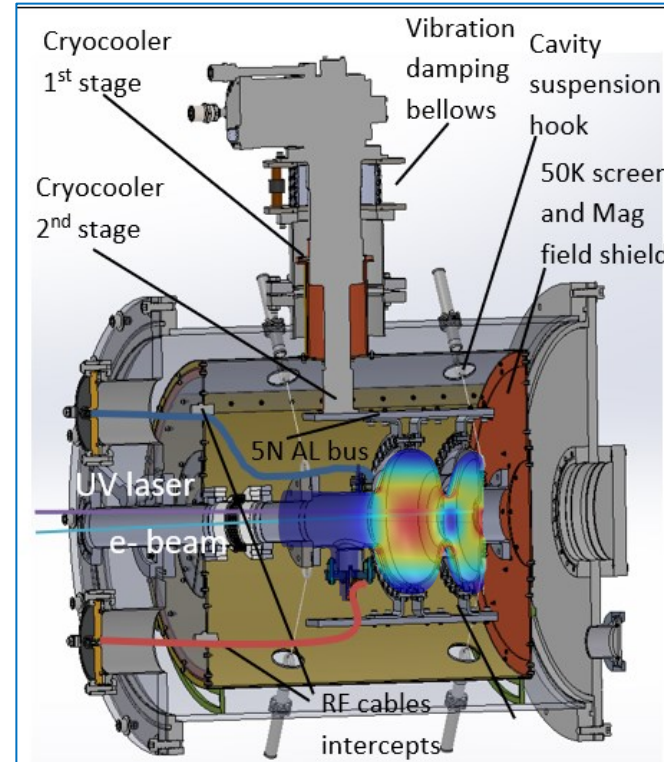


Slide courtesy of M. Kelly, ANL

SRF photogun for MeV UEM/UED*

Gun parameters

1. UEM/UED – ultrafast electron microscopy/diffraction
2. MeV beam for reduced space charge
3. Current NC record is 100Hz compared to CW operation of SRF
4. Only 2W of RF power is required
5. No need for Klystron - reduced footprint
6. One cryocooler is enough to cool Nb3Sn gun at 4K
7. Conduction cooling is simple and affordable.
8. Final goal – user facility at BNL ATF



Parameter	Value	
Application	UED	UEM
Beam energy	1.655MeV	1.655MeV
Charge	5fC	0.5pC
Laser pulse length, rms	6.4fs	6.4fs
Laser spot size	36um	180um
Beam bunch length, rms	167fs	741fs
Beam emittance	6.6nm	39nm
Energy spread (relative)	1.3e-5	6.4e-5
Frequency,	1.3 GHz	
Length	1.45cell (166.54mm)	
Q0 at 4° K (Rs = 20 nΩ)	1.16×10^{10}	
R/Q	176.9 Ω	
Geometry factor	232 Ω	
Wall Power dissipation	0.9 W	
E on axis	20 MV/m	
E max	23.5 MV/m	
B max	43.3 mT	
E acc	10 MV/m	

R.Kostin et al., "Conduction cooled SRF photogun for UEM/UED applications", UED 308081, 23-rd ATF user meeting, 2020.

Slide Courtesy from R. Kostin

Current Status

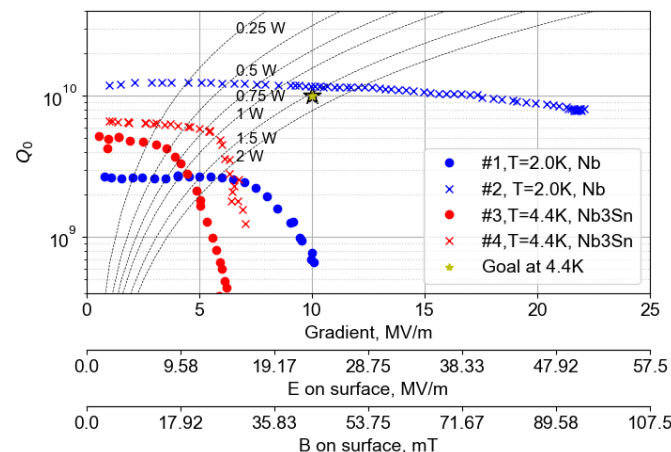
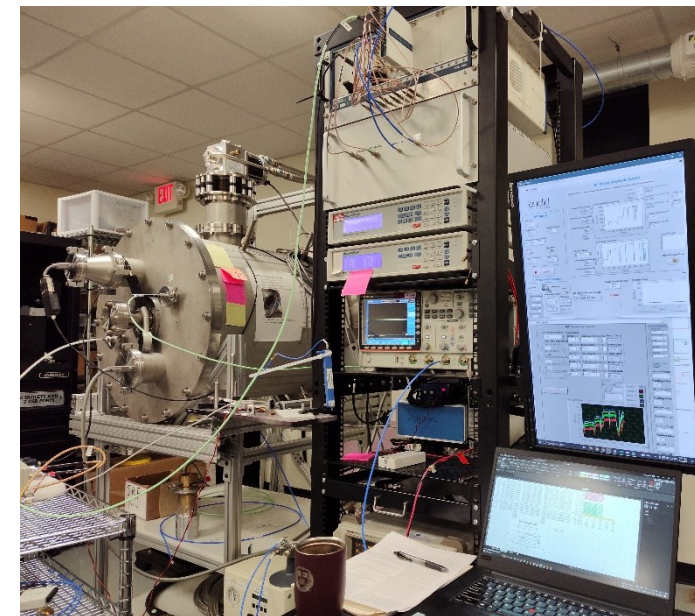
1. The cryomodule was commissioned:
 - cooled down to 2.5K;
 - magnetic field below 5mG
2. Pure Nb SRF gun was tested at 2K resulted in $Q_0=10^{10}$ and reached $E_z=47\text{MV/m}$ on axis field and $E_{acc}=22\text{MV/m}$
3. Nb_3Sn test in VTS at 4.2K revealed contamination, nevertheless was tested in conduction cooled cryomodule (CC CM).
4. $E_{acc}=4.3\text{MV/m}$ achieved in CC CM
5. Beam test at ANL AWA facility is scheduled May 2024.



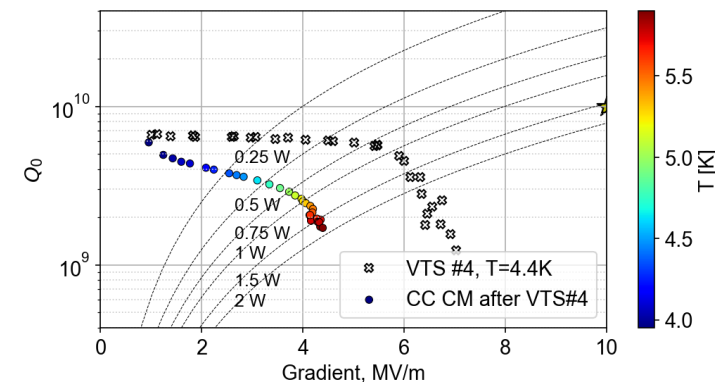
Gun surface as manufactured

Gun surface after
Rotational 140um BCP

Slide Courtesy from R. Kostin

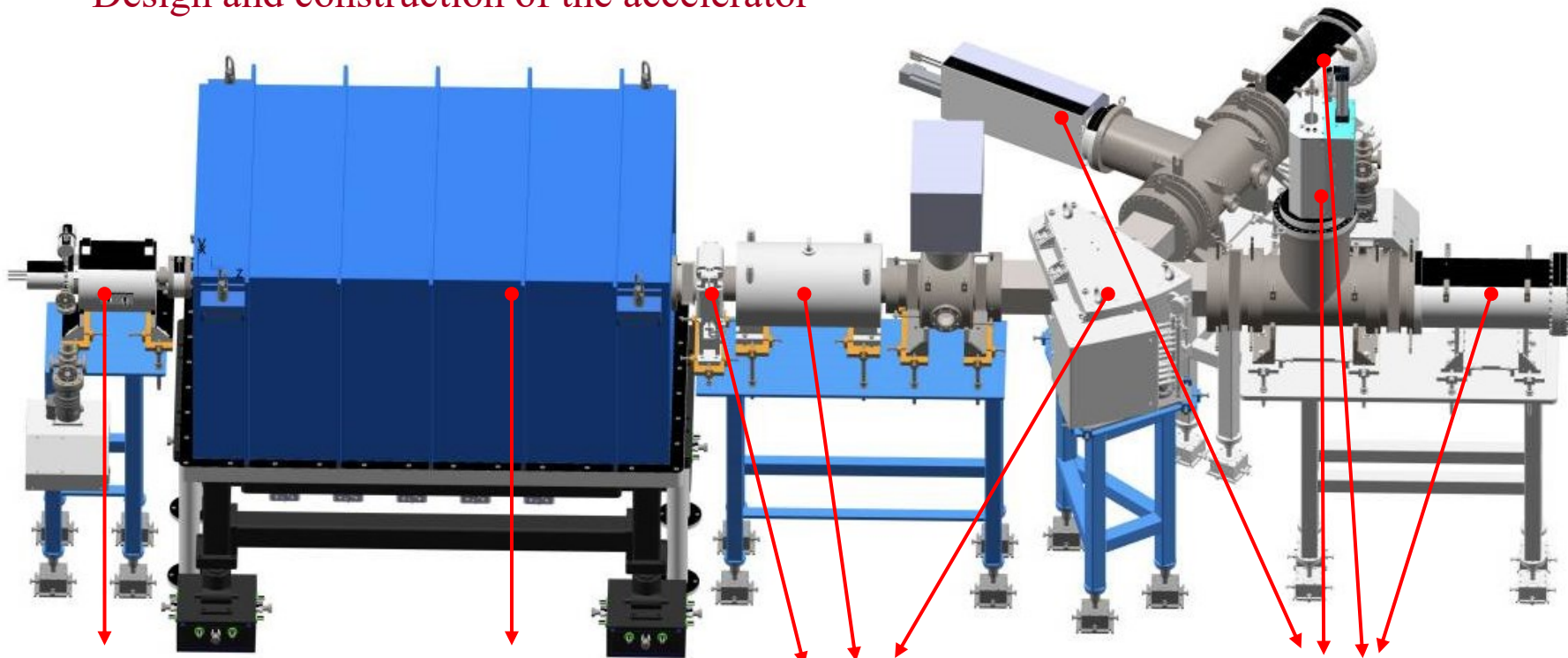


Vertical test of Nb and Nb3Sn



Nb3Sn at 4.4K in VTS and Cryomodule

- Design and construction of the accelerator



Injector:

- Gridded thermionic gun
- Cathode-anode potential: 60kV
- Macropulse length of DC beam: $0.5\text{--}2\mu\text{s}$
- Repetition rate: 1-200Hz
- Focused by solenoid and directed into the Nb_3Sn cavity

LHe-free Nb_3Sn module:

- Conduction-cooled by 10 GM cryocoolers via Cu braided tapes
- Simultaneous acceleration and longitudinal bunching in a 650MHz 5 cell elliptical cavity with $\beta=0.82$

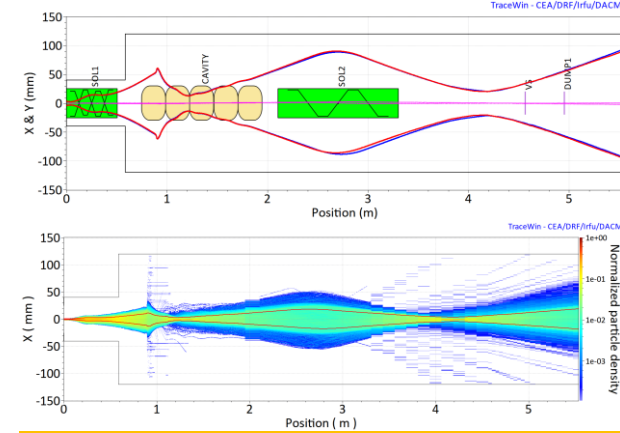
Magnets after acceleration:

- Corrector magnet
- Solenoid for focusing
- Dipole magnet for energy distribution measurement

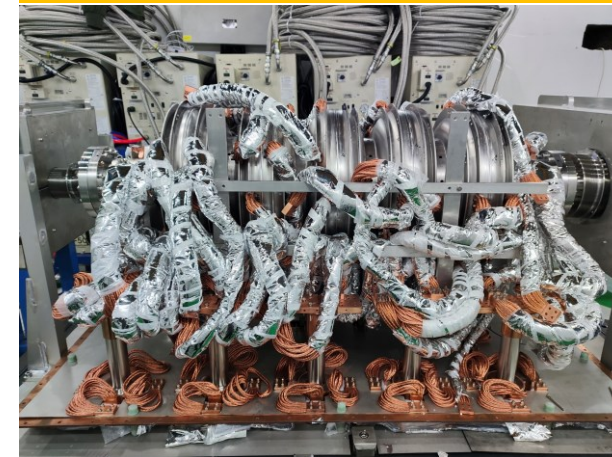
Beam diagnostic system:

- ACCT: current prior to entering the cavity
- Fluorescent target: beam spot
- DUMP1&DUMP2: beam collection
- Slit: measurement of fine energy structure near central energy

- For multiple validation considerations: Multi-cell Nb_3Sn coating, integrated assembly, horizontal test, beam acceleration experiments, pre-research for Nb_3Sn thin film SRF cavity engineering application in CiADS.

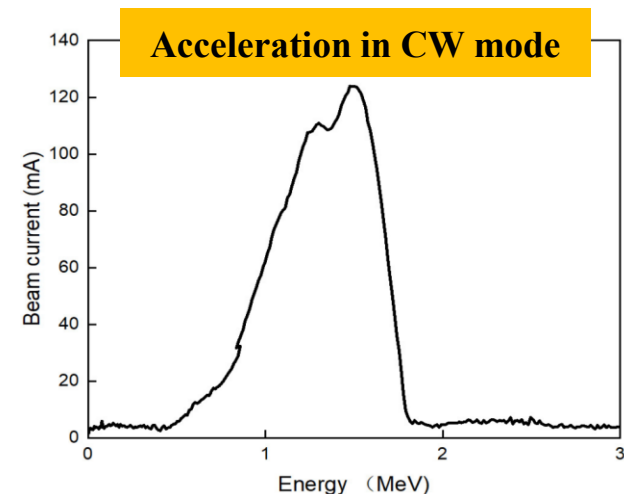
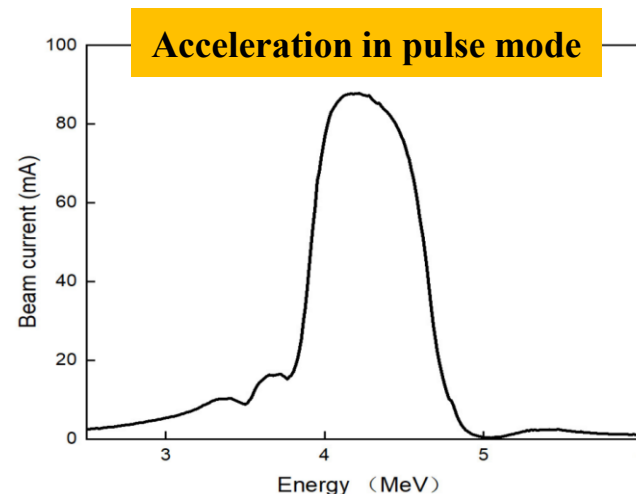
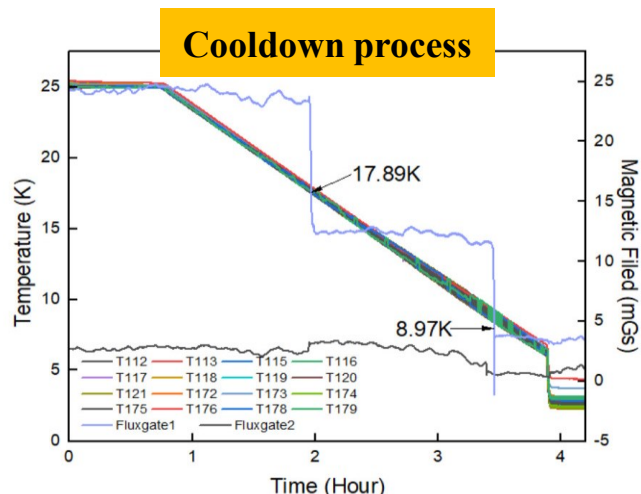


Simulation: Envelope evolution and beam loss distribution during electron beam transmission

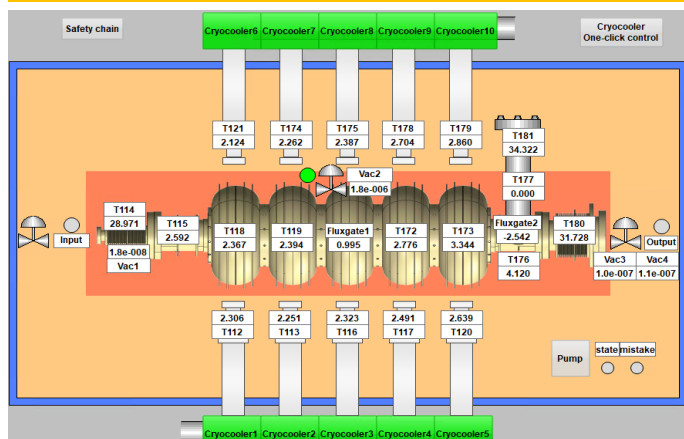


Integration of the cavity's outer surface with the second stage cold heads using copper braided tapes

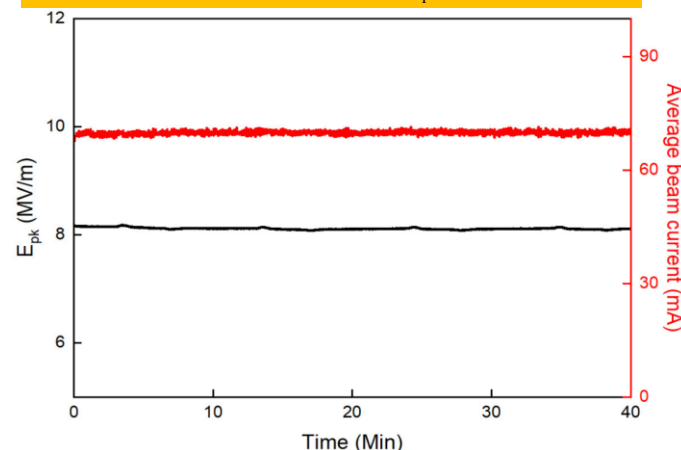
- Commissioning of the accelerator (<https://doi.org/10.48550/arXiv.2404.09187>)



Characteristic magnetic flux expulsion during cooling process

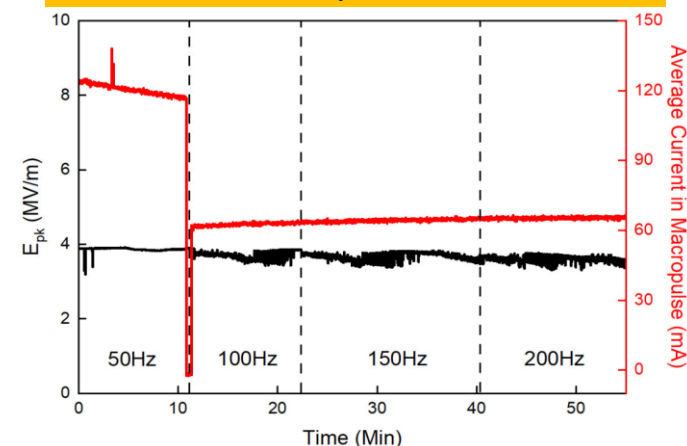


Central energy of 4.25MeV at $E_{pk}=13.78\text{MV/m}$



Stable acceleration records under 40% duty cycle and 20Hz repetition rate

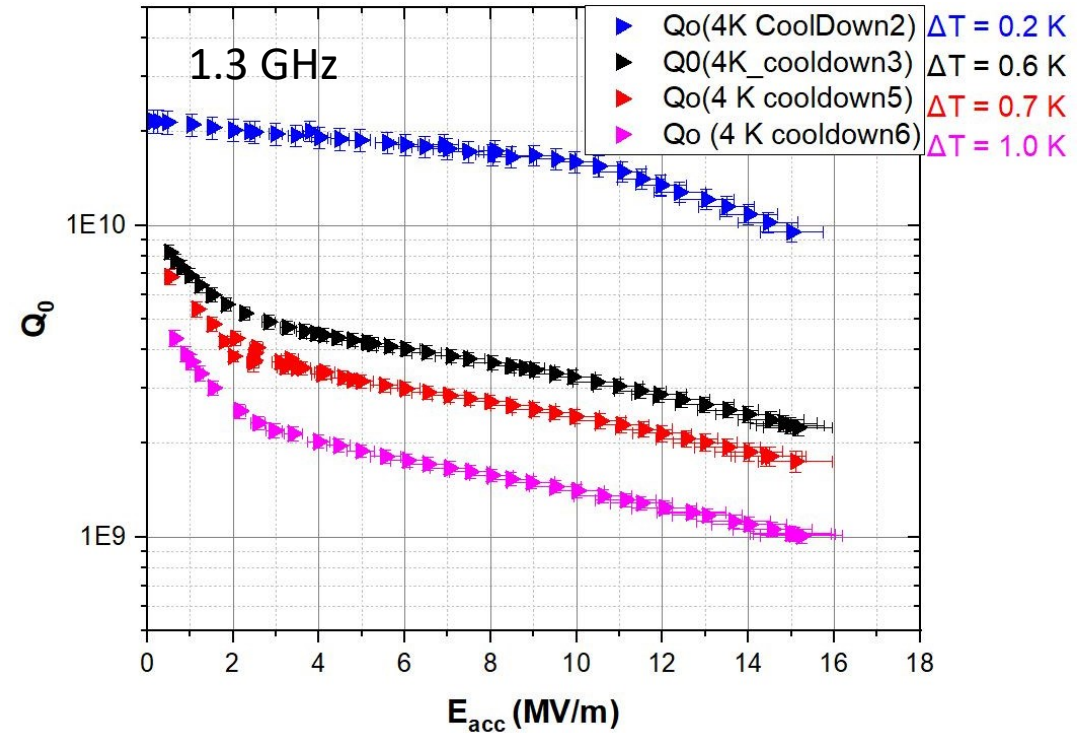
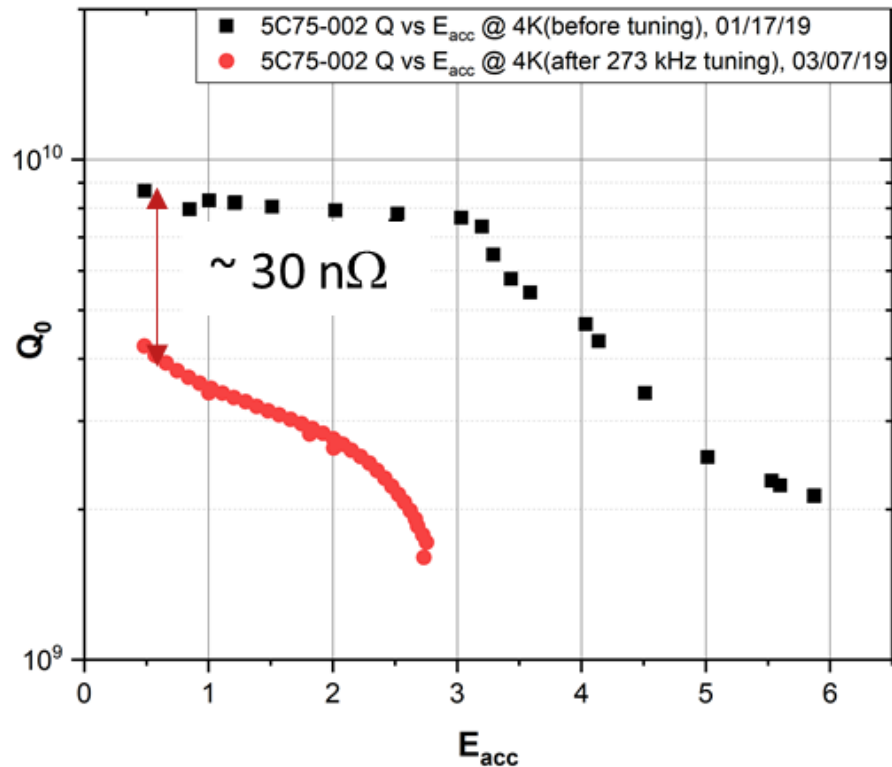
The central energy at $E_{pk}=3.91\text{MV/m}$ is 1.57MeV



Stable acceleration records in CW mode and various repetition rates up to 200Hz

- Principal validation for the engineering application of Nb₃Sn thin film cavities in SRF accelerators

Challenges in Deploying Nb₃Sn Cavities in Accelerators



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

Summary

- Single and multi-cell Nb₃Sn-coated cavities perform well for diverse accelerator applications
- First-ever 10MV/m gradient achieved in Nb₃Sn cryomodule with multi-cell cavities
- Development of multiple compact accelerators with Nb₃Sn cavities ongoing
- Debut of beam acceleration using conduction-cooled Nb₃Sn-coated cavity
- Material brittleness poses challenges in maintaining performance from fabrication to installation
- Recent encouraging successes highlight the potential of Nb₃Sn, but further efforts needed for full realization

Acknowledgements

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***Thank you for your attention.
Questions?***