Hot Topic Session: Speaker's List

Cagetory	Name	Institute	Speaker confirmed
• **Introduction**	**Gianluigi Ciovani**	JLab	yes
1. Choice of cryocoolers	1a) Tomohiro Yamada	KEK	yes
	1b) Ram Dhuley	FNAL	yes
	1c)Roman Kostin	Euclid Tech.	yes
	1d) Ziqin Yang	IMP	J. Hao
2. Thermal Link design	2a) Neil Stilin	Cornell U.	yes
	2b) Tomohiro Yamada	KEK	yes
	2c) Ram Dhuley	FNAL	yes
	2d) Roman Kostin	Euclid	yes
	2e) Thomas Proslier	CEA-Saclay	yes
3a. Nb3Sn on Cu thin-film performance	3aa) Cristian Pira	INFN	yes
	3ab) Shawn McNeal	Ultramet	yes
3b. Nb3Sn on Nb thin-film performance	3ba) Uttar Pudasaini	JLab	yes
	3bb) Jiankui Hao	PKU	yes
	3bc) Liana Shpani	Cornell	N. Stilin
4. Tunability / robustness of Nb3Sn	4a) Grigory Eremeev	FNAL	yes

3aa

Nb_3Sn on Cu:

Motivations for Cu substrate

- **Cheaper** than Nb
- Higher **thermal conductivity**
- Higher **mechanical stability**
- **PVD technology** (Nb on Cu) already used for:
  LEP, LHC, HIE-ISOLDE @ CERN
  ALPI @ INFN LNL

Different technologies under study:

- **PVD**
  - **Magnetron Sputtering**
    - **Single Target**
    - **Double Target**
  - **HiPIMS**
- **CVD**
- **Electroplating**
- **Bronze Route**

Nb$_3$Sn on Cu by PVD

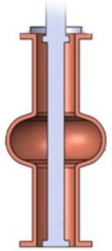
- ***R&D is Focused on Coating Parameter Optimization to get the right phase at lowest Working T possible***
- *No RF test yet on cavities available*
- *Only a couple of preliminary tests on QPR @CERN*

Multiple Challenges

- A15 are Brittle materials
- Complicated Phase Diagram
- Substrate preparation
- Low melting point substrate
- Interface diffusion
- Target Production

Strategies

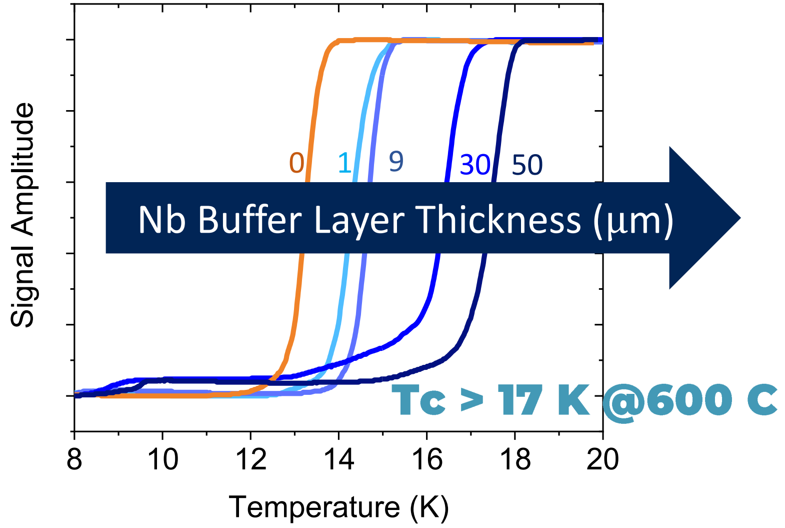
Single Target configuration easier to scale into cavities



@ *CERN and JLab* HiPIMS to densify coating

@ *STFC* DCMS-HiPIMS comparision

@ *INFN* **thick Nb buffer layer** (barrier and accommodation effect) improve dramatically Tc



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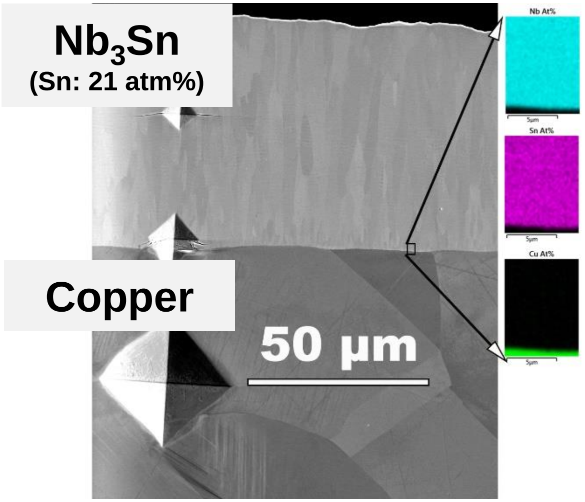
CVD Nb_3Sn Thin Film Performance

Shawn R. McNeal, Victor M. Arrieta*
Ultramet | Pacoima, California

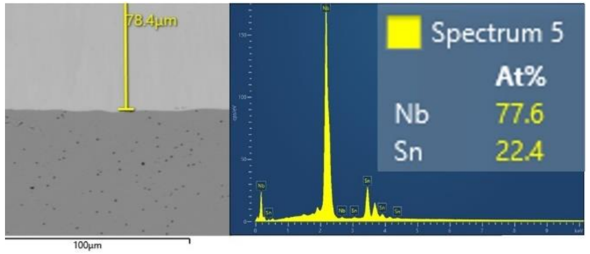
TESLA Technology Collaboration Meeting (TTC 2023)
Fermilab | Batavia, Illinois | December 5–8, 2023

PROGRESS

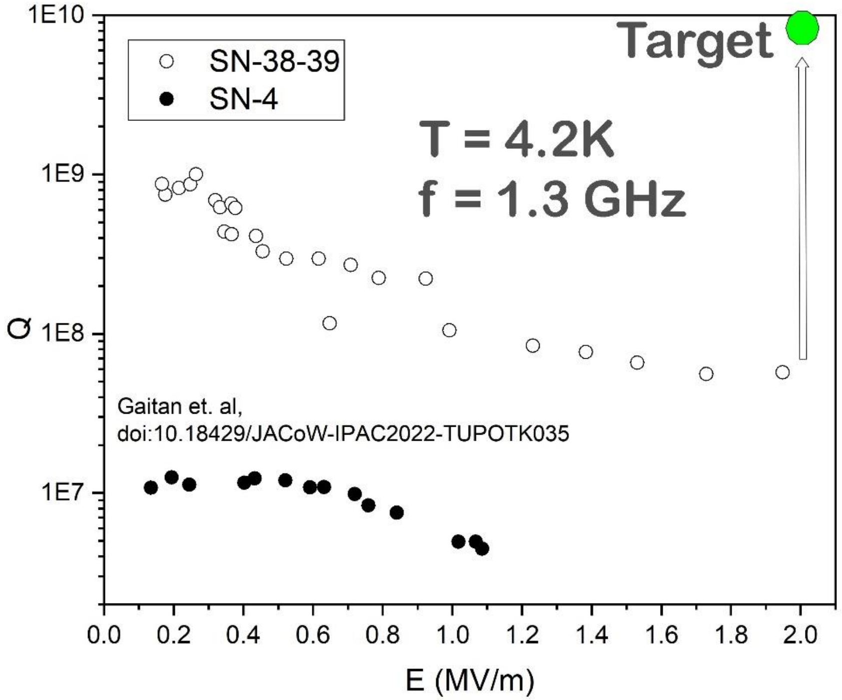
CVD Nb_3Sn coating on CVD niobium interlayer on welded (Niowave) copper cavity substrate



CVD Nb_3Sn coating on copper substrate: excellent adhesion



CVD Nb_3Sn on welded copper cavity

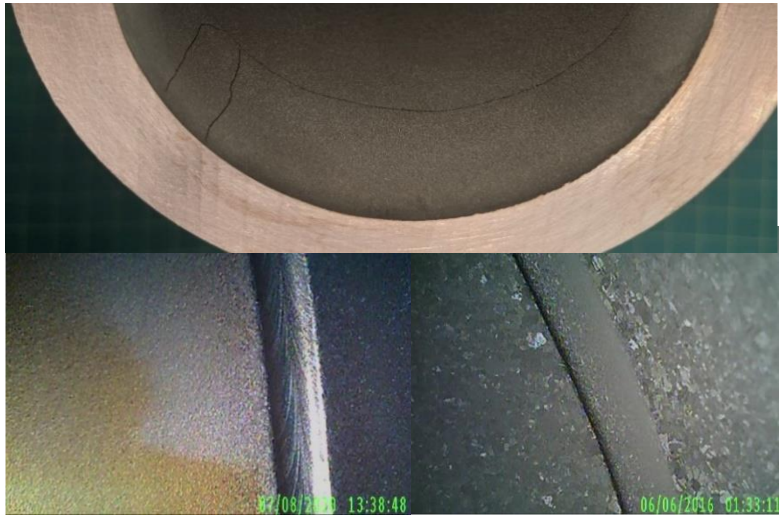


Q vs. E for first-of-kind CVD Nb_3Sn welded copper cavity SN38-39 and seamless copper cavity SN-4 with CVD Nb_3Sn coating on CVD niobium interlayer at 4.2 K

SN-4A, seamless copper cavity substrate (BTM, Inc.)

* Shawn.McNeal@ultramet.com Victor.Arietta@ultramet.com

CHALLENGES



SN38-39: ring-crack in Nb_3Sn coating on one tube (*top*); equator pre-coating (*bottom left*) and as-coated and as-tested (*bottom right*)

Left, SN-2, as-received surface roughness and anomalies; *right*, SN-4, post-etch copper and as-coated & as-tested.

What Is Needed for CVD-based Nb_3Sn/Cu Cavities

Non-Trivial Factors Impeding CVD-based Cavity Technology Growth

- **Cavity Design** Define cavity design early to enable focused, efficient, relevant process R&D for all involved
- **CVD Nb_3Sn-on-Copper Process Development & Scaling**
  - CVD reactor customization and optimization
  - CTE mismatch, thermostructural analysis, and interlayers
  - ID surface conditioning methods for bare copper and Nb_3Sn coatings
  - OD strengthening methods: AM, electrochemical, thermal spray?
- **Precursor Process Development & Scaling**
  - **Fundamental R&D:** Precursor process development leading to reliable supplier for high-quality precursors
- **Copper Cavities** Expanded domestic infrastructure & capabilities
  - **Fundamental R&D** Copper cavity substrate process R&D for high-quality cavity substrates necessary for efficient, relevant R&D leading to reliable supplier(s) (with inventory!)
- **Testing** Ready access to material and <u>cavity</u> testing
  - Ideas? Quick-check/in-process cavity test methods?
- **CVD Nb_3Sn-on-Copper Cavity Production**
  - Build-test-repeat to TRL-9

ULTRAMET
ADVANCED MATERIALS SOLUTIONS

3ba

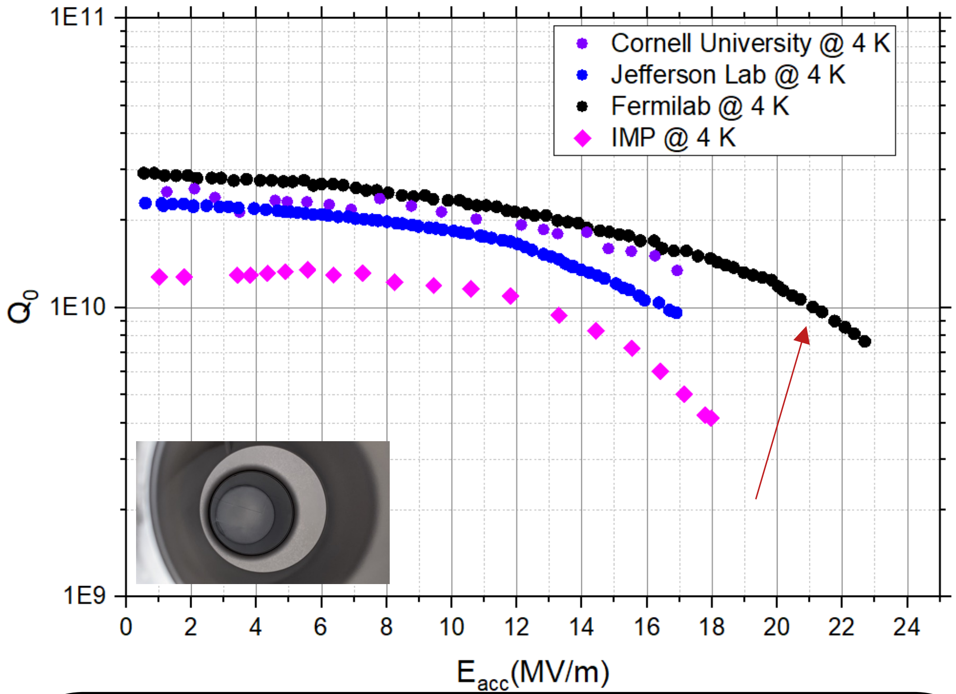
Performance of vapor-diffused Nb_3Sn grown on Nb

Uttar Pudasaini

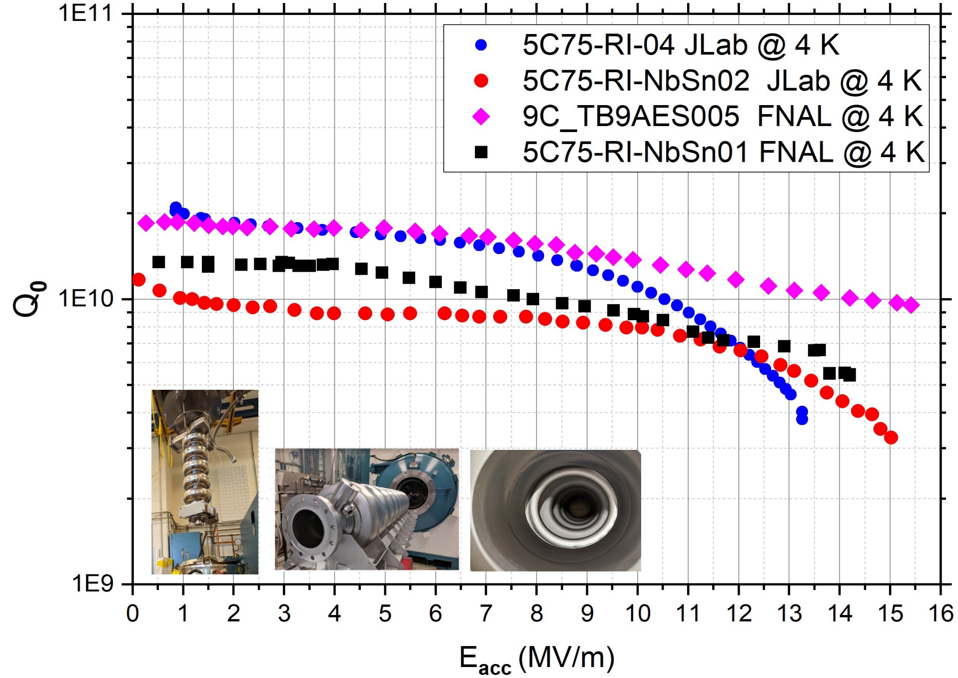
Sunday, December 3, 2023

Performance of vapor-diffused Nb_3Sn grown on Nb

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



Multi-cell cavity performance



- 1.3/1.5 GHz single-cell cavities attains accelerating gradient in excess of 20 MV/m with Q ~10^{10}.
- Cavities of various frequencies (650 MHz, 952 MHz, 2.6 GHz, 3.6 GHz) coated at different facilities show comparable performance.
- 952 MHz and 650 MHz cavities successfully operated with cryocoolers.

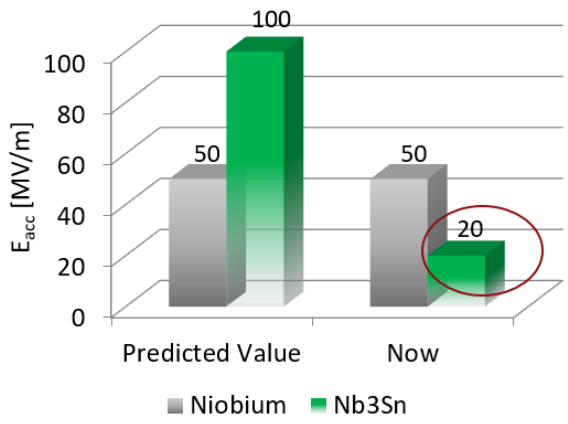
- 1.5 GHz five-cell and 1.3 GHz 9-cell cavities were demonstrated to reach Q ~ 10^{10} at 10 MV/m at 4.4 K.
- Maximum gradients achieved up to ~ 20 MV/m.
- Several projects are underway to build cryomodules with coated cavities aiming for 4 K operation with conduction cooling.

U. Pudasaini et al. "Managing Sn-Supply to Tune Surface Characteristics of Vapor-Diffusion Coating of Nb_3Sn", presented at the SRF'21, East Lansing, MI, USA, Jun.-Jul. 2021, doi:10.18429/JACoW-SRF2021-TUPTEV013.
S. Posen et al. "Advances in Nb_3Sn 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 Nb_3Sn 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.
TTC-2022

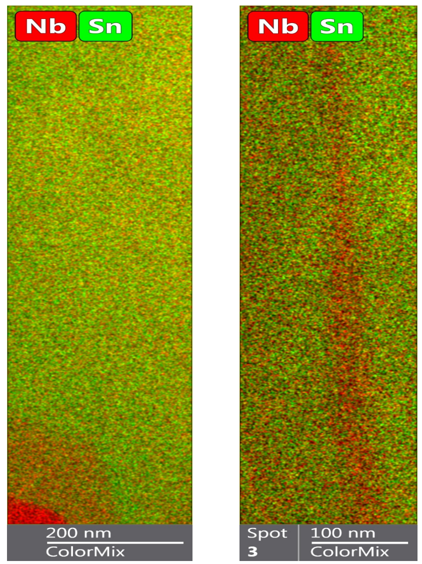
Jefferson Lab

Vapor-diffused Nb_3Sn grown on Nb: current issues

- Why is the attainable gradient limited?
  - Several approaches are being explored to push the gradient.
    - Roughness/Topography Management: Parameter optimization post-coating treatment and deposition of Sn before thermal diffusion……
    - Film thickness reduction: correlates with surface roughness reduction and improved gradient limit
    - What are the other limiting factors?



- What causes the frequent Q-slope?
  - Studies are focused on correlating material properties and RF performance
    - Grain boundary structure and compositions
    - Limitations due to local defects
    - Facility and procedure dependent: performance sensitivity to Sn residue condensation, Ti evaporation from NbTi flanges….?



TEM analysis of grain boundaries with and without Q-slope

- Feasibility for practical applications – how to preserve thin-film performance?
  - The coating process is adopted for larger/longer cavities with multiple Sn sources and coating parameter modifications.
  - How to deposit a high-quality coating on any arbitrary shape/sized cavities?
  - NbTi flanges are more practical – avoid Ti contaminations
    - Hardware to contain Ti and/or altering coating parameters?

- Reproducibility is challenging!??

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updated
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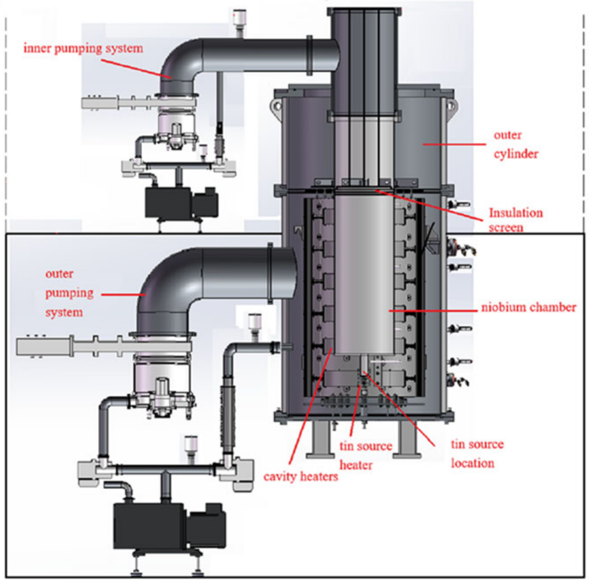
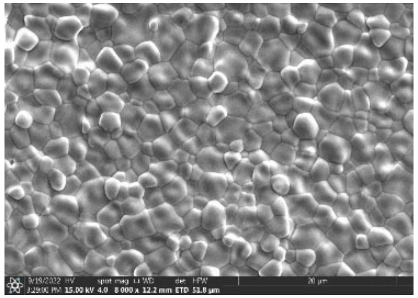
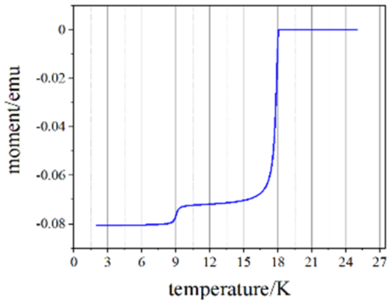
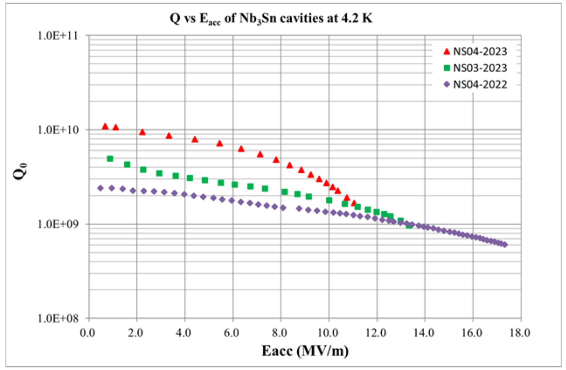
Nb_3Sn Cavities Coated by Tin Vapor Diffusion (Jiankui Hao, PKU)



3 tin sources

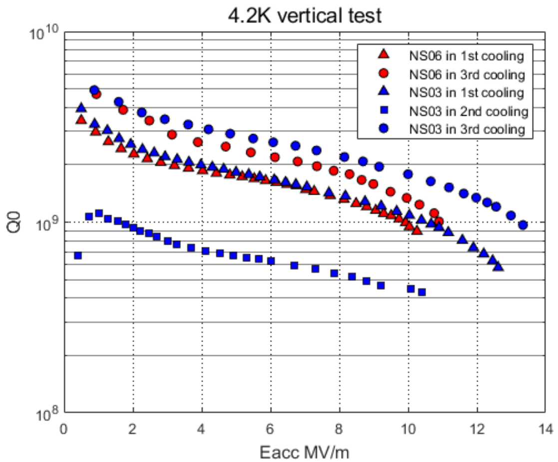






Coating: 1250°C, 120 min, Annealing: 1150 °C, 60 min

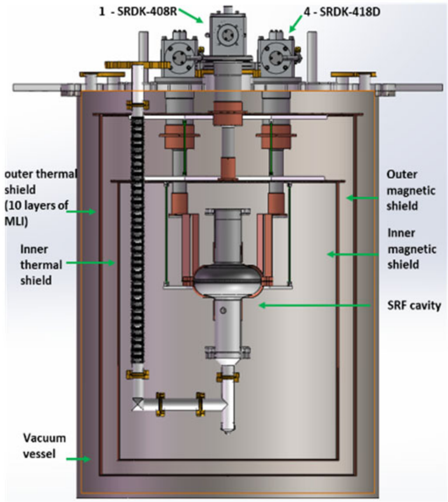
$Q_0 \sim 1.1 \times 10^{10}$ @4.2K @ low field, max. $E_{acc} \sim 17.3$MV/m

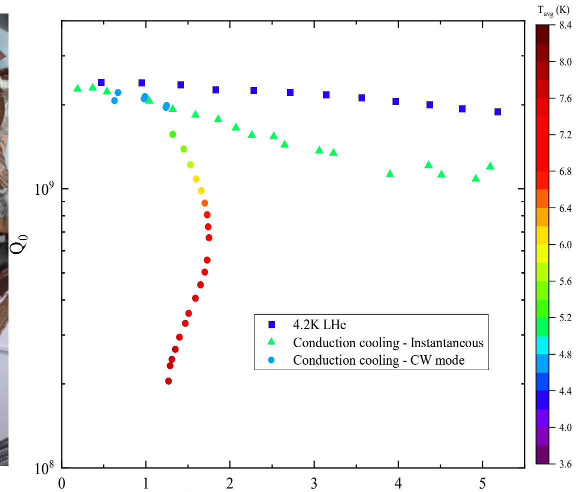


Vertical Tests (2023)	T grad., cooling rate	Q_0 @ ~1.0 MV/m
NS03(1st,Oct. 17)	15.7 K/m, ~6 min/K	3.3E9
NS06(1st,Oct. 17)	15.7 K/m	3.0E9
NS03(2nd,Oct. 18)	110	1.1E9
NS03(3rd,Oct. 23)	2.7 K/m, ~10 min/K	4.9E9
NS06(3rd,Oct. 23)	2.7	4.7E9

Vertical tests at different cooling rate

Conduction cooling of Nb_3Sn cavity





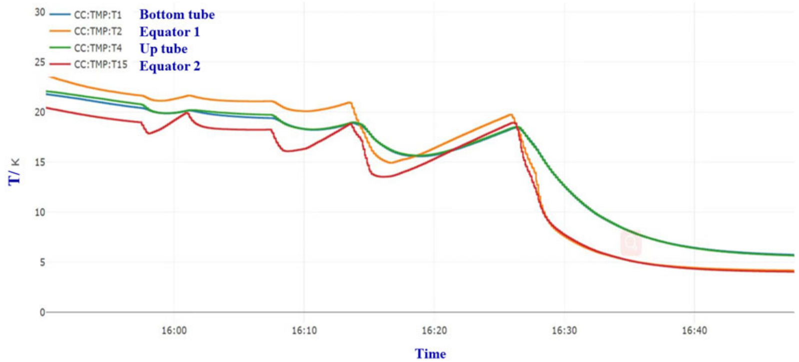
Nb_3Sn cavity

Conduction cooling

$Q_0 \sim$ 7E8

@ E_{acc} = 1.75 MV/m

P_c = 0.57 W

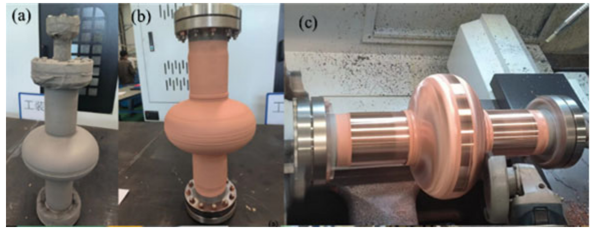


Cryocooler on and off, 17-18 K, ΔT < 2 K

T<16 K, cryocooler on, cooling down to 4 K

Next step

- Choose the best Nb_3Sn cavity NS04
- Cold spray with copper
- Slower cooling controlled with heater



(a) sandblasted (b) cold sprayed (c) mechanical polished

Question/Discussion

- What's the best cooling rate for vertical test and conduction cooling?

3bc

Nb_3Sn on Nb: Challenges

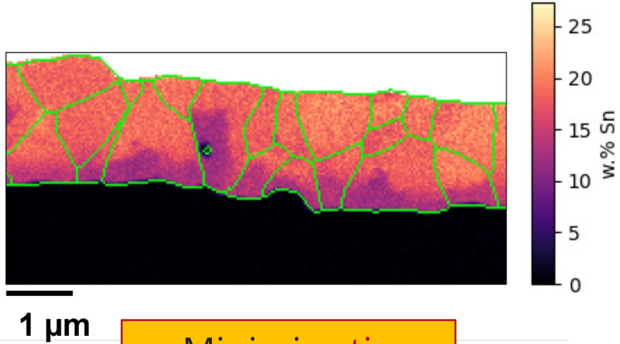
CLASSE
Cornell Laboratory for Accelerator-based ScienceS & Education

Goal for conduction-cooled SRF cavity technology: Reach higher Q_0 at 4.2K

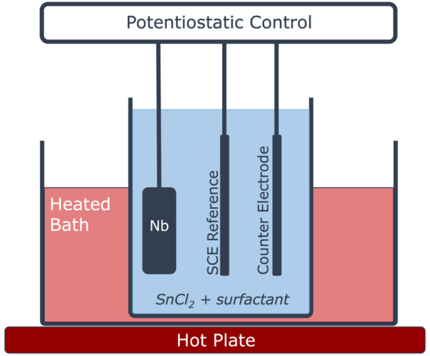
Main challenge: achieve a smooth Nb_3Sn film with uniform thickness and stoichiometry

→ Improving vapor diffusion:

sample studies have shown that pre-nucleation chemical treatments affect tin coverage on Nb substrate

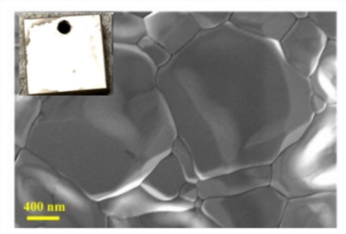


→ Alternative growth method: electrochemical synthesis



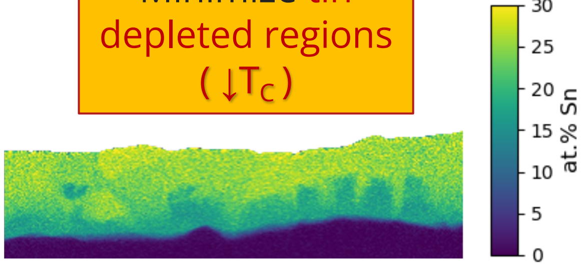
Electrochemical deposition

Anneal > 900℃ to thermally convert to stoichiometric, smooth Nb_3Sn



Lower surface roughness

Minimize tin depleted regions (↓T_C)

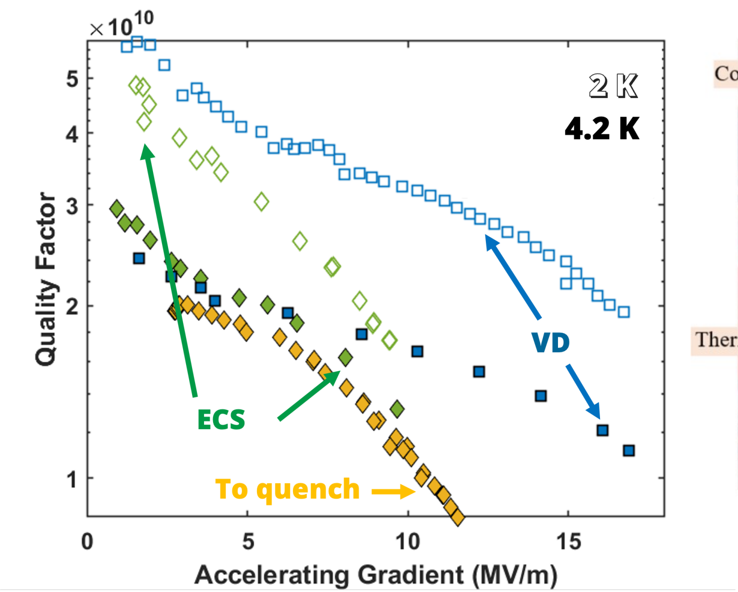


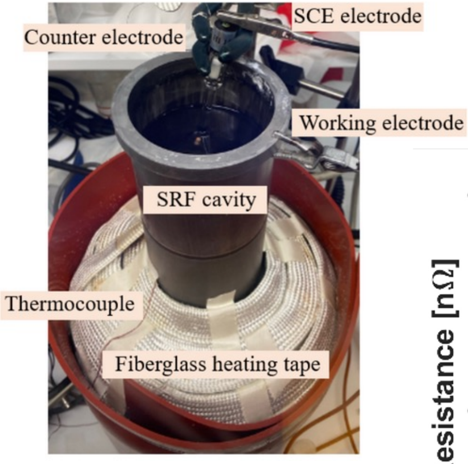
Z. Sun *et al* 2023 *Supercond. Sci. Technol.* **36** 115003
DOI 10.1088/1361-6668/acf5ab

Proof of Principle: Electrochemical Synthesis

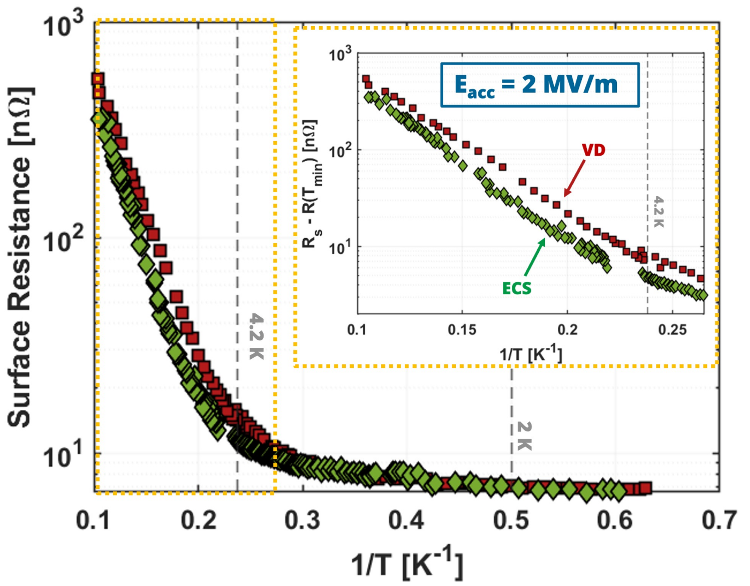
This alternative growth method provides uniform tin nucleation and sufficient Sn supply in critical times

⟹ **smoother** Nb_3Sn films with **little variation in Sn concentration with depth**.





→ Very low BCS low resistance



→ First ever alternative growth method to vapor diffusion to achieve **quality factors >10^{10}** at **4.2K**