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Performance of vapor-diffused Nb_3Sn grown on Nb

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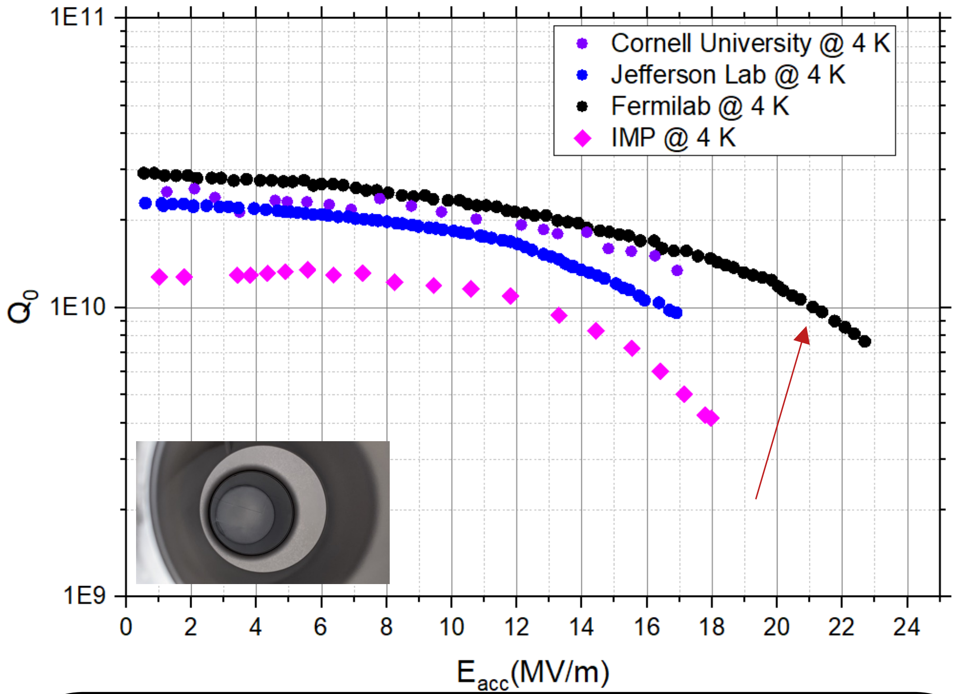
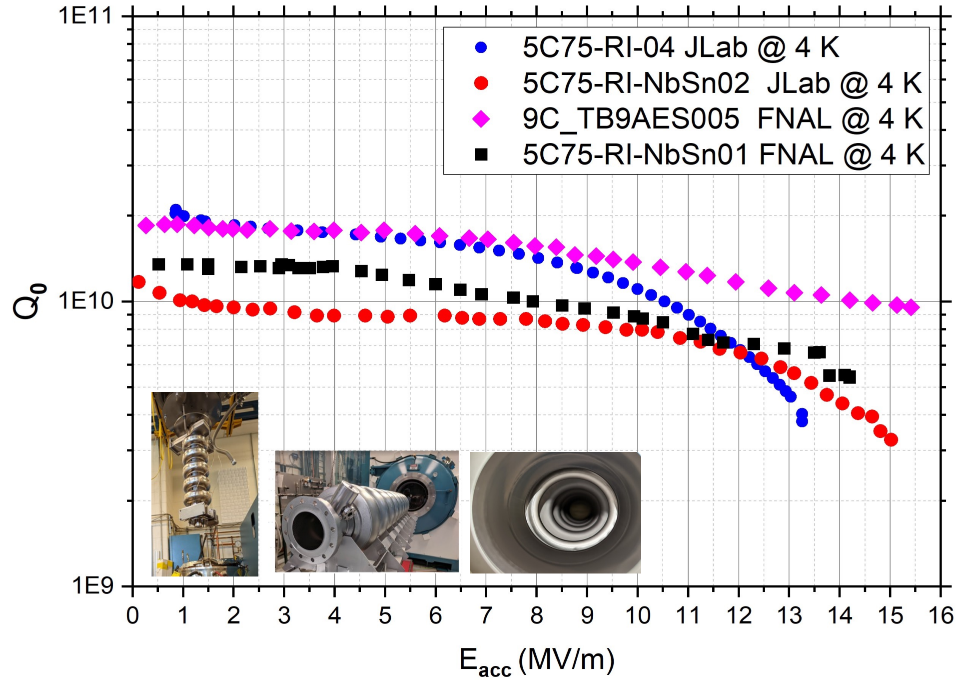
R&D 1.3/1.5 GHz single-cell cavity performance



Multi-cell cavity performance



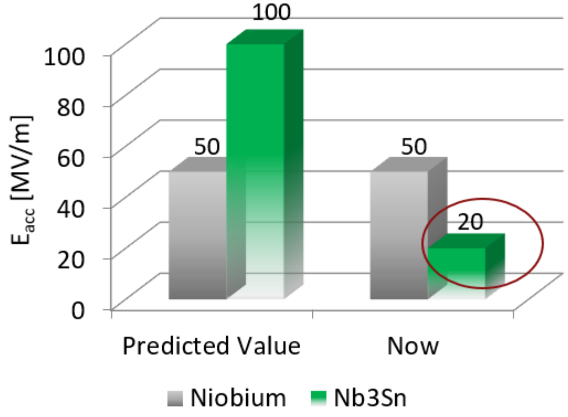
- 1.3/1.5 GHz single-cell cavities attains accelerating gradient in excess of 20 MV/m with Q ~10^{10}.
- Cavities of various frequencies (650 MHz, 952 MHz, 2.6 GHz, 3.6 GHz) coated at different facilities show comparable performance.
- 952 MHz and 650 MHz cavities successfully operated with cryocoolers.

- 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.

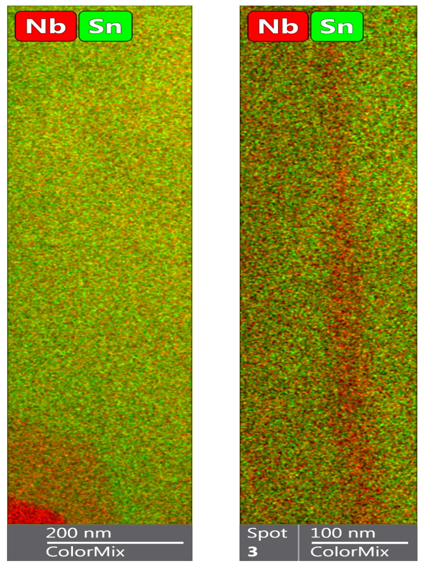
U. Pudasaini et al. "Managing Sn-Supply to Tune Surface Characteristics of Vapor-Diffusion Coating of Nb_3Sn", presented at the SRF'21, East Lansing, MI, USA, Jun.-Jul. 2021, doi:10.18429/JACoW-SRF2021-TUPTEV013.
S. Posen et al. "Advances in Nb_3Sn superconducting radiofrequency cavities towards first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

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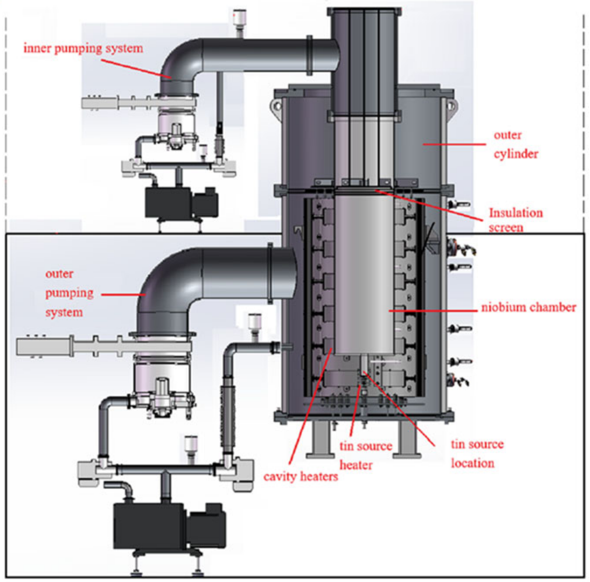
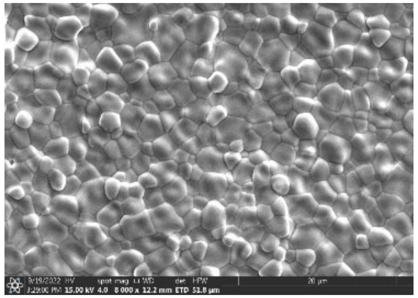
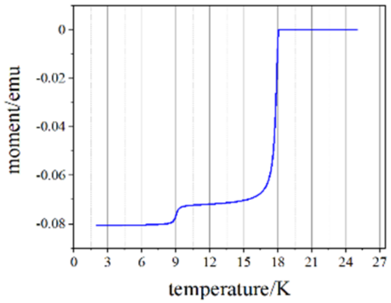
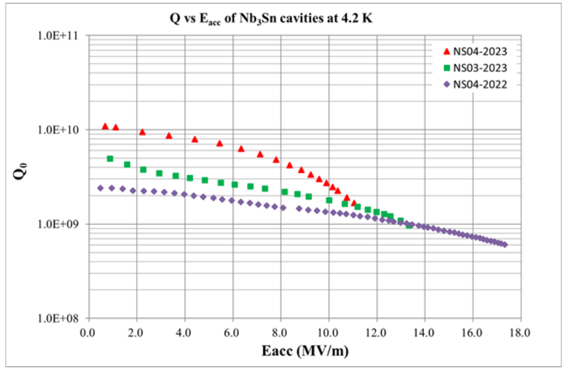
Nb_3Sn Cavities Coated by Tin Vapor Diffusion (Jiankui Hao, PKU)



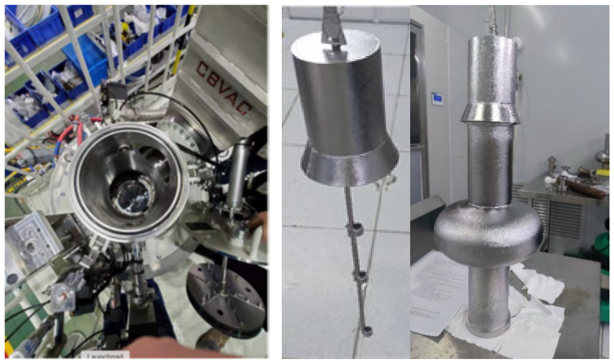




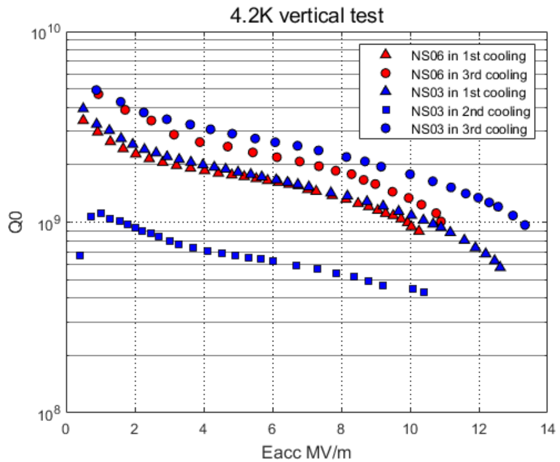


Coating: 1250°C, 120 min, Annealing: 1150 °C, 60 min

$Q_0 \sim 1.1\times10^{10}$ @4.2K @ low field, max. $E_{acc} \sim 17.3$MV/m



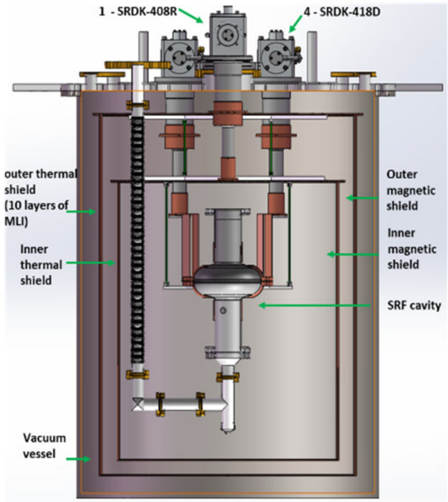
3 tin sources

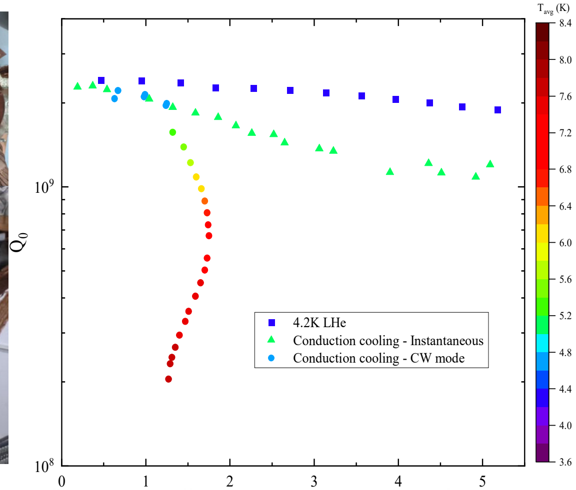


Vertical Tests (2023)	T grad., cooling rate	Q_0 @ ~1.0 MV/m
NS03(1st,Oct. 17)	15.7 K/m, ~6 min/K	3.3E9
NS06(1st,Oct. 17)	15.7 K/m	3.0E9
NS03(2nd,Oct. 18)	110	1.1E9
NS03(3rd,Oct. 23)	2.7 K/m, ~10 min/K	4.9E9
NS06(3rd,Oct. 23)	2.7	4.7E9

Vertical tests at different cooling rate

Conduction cooling of Nb_3Sn cavity





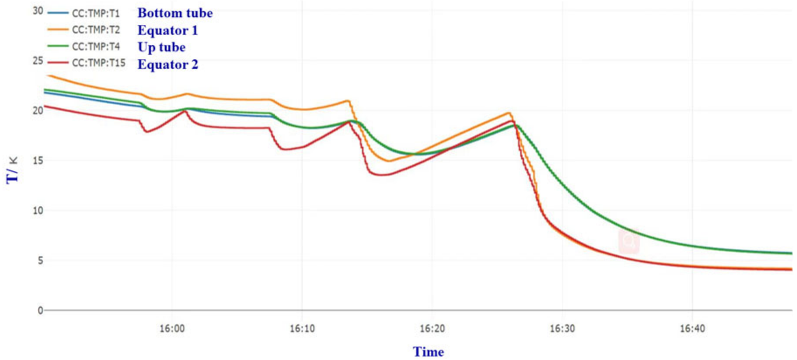
Nb_3Sn cavity

Conduction cooling

$Q_0 \sim$ 7E8

@ E_{acc} = 1.75 MV/m

P_c = 0.57 W

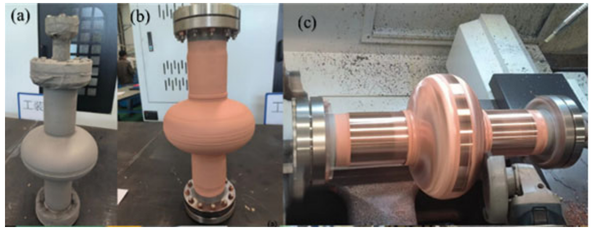


Cryocooler on and off, 17-18 K, ΔT < 2 K

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?

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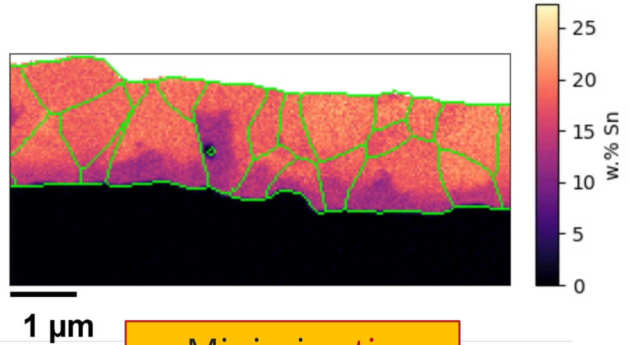
Nb_3Sn on Nb: Challenges

CLASSE
Cornell Laboratory for Accelerator-based ScienceS & Education

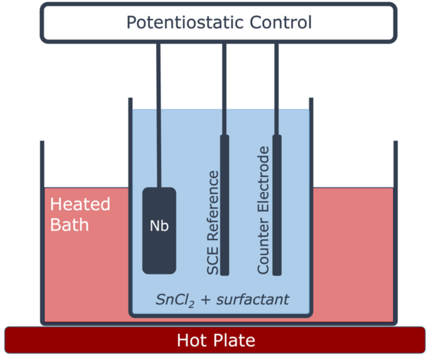
Goal for conduction-cooled SRF cavity technology: Reach higher Q_0 at 4.2K

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

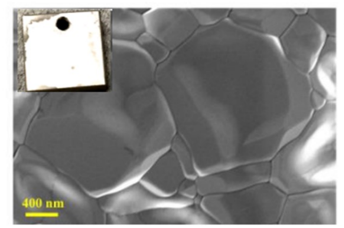


→ Alternative growth method: electrochemical synthesis



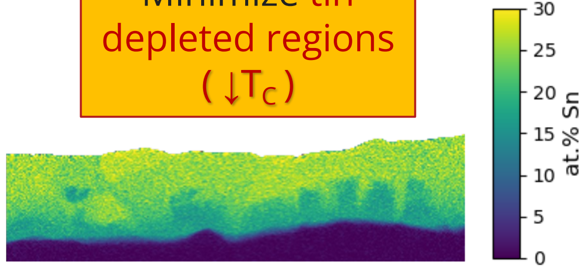
Electrochemical deposition

Anneal > 900°C to thermally convert to stoichiometric, smooth Nb_3Sn



Lower surface roughness

Minimize tin depleted regions (↓T_C)

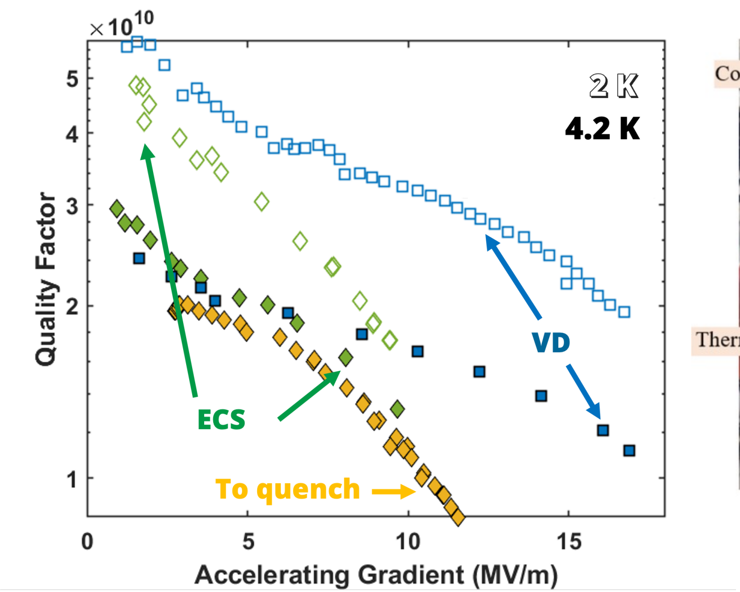


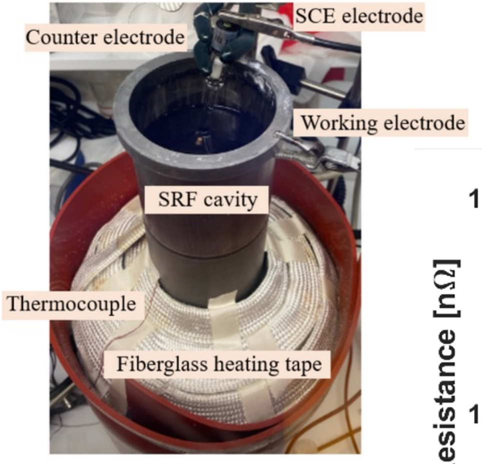
Z. Sun *et al* 2023 *Supercond. Sci. Technol.* **36** 115003
DOI 10.1088/1361-6668/acf5ab

Proof of Principle: Electrochemical Synthesis

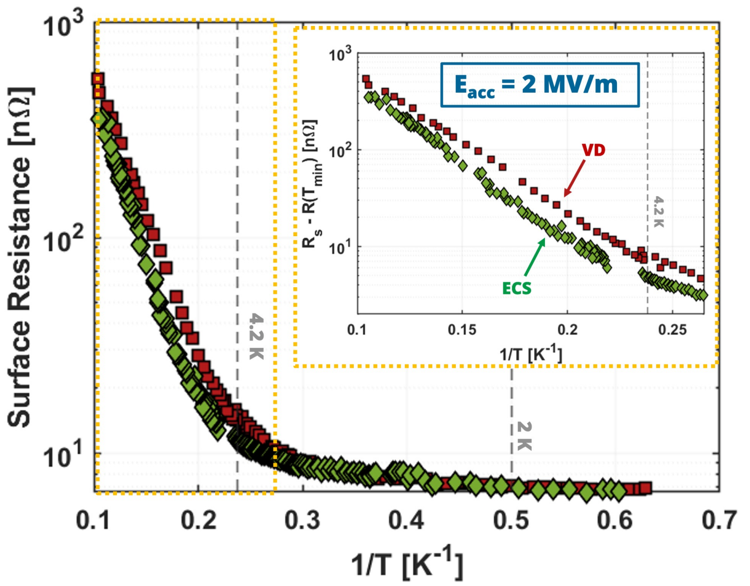
This alternative growth method provides uniform tin nucleation and sufficient Sn supply in critical times

⟹ **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**