Center for BRIGHT BEAMS

CLASSE

Cornell Laboratory for Accelerator-based ScienceS &Education

Functionalizing Advanced Materials and Surfaces in Superconducting RF

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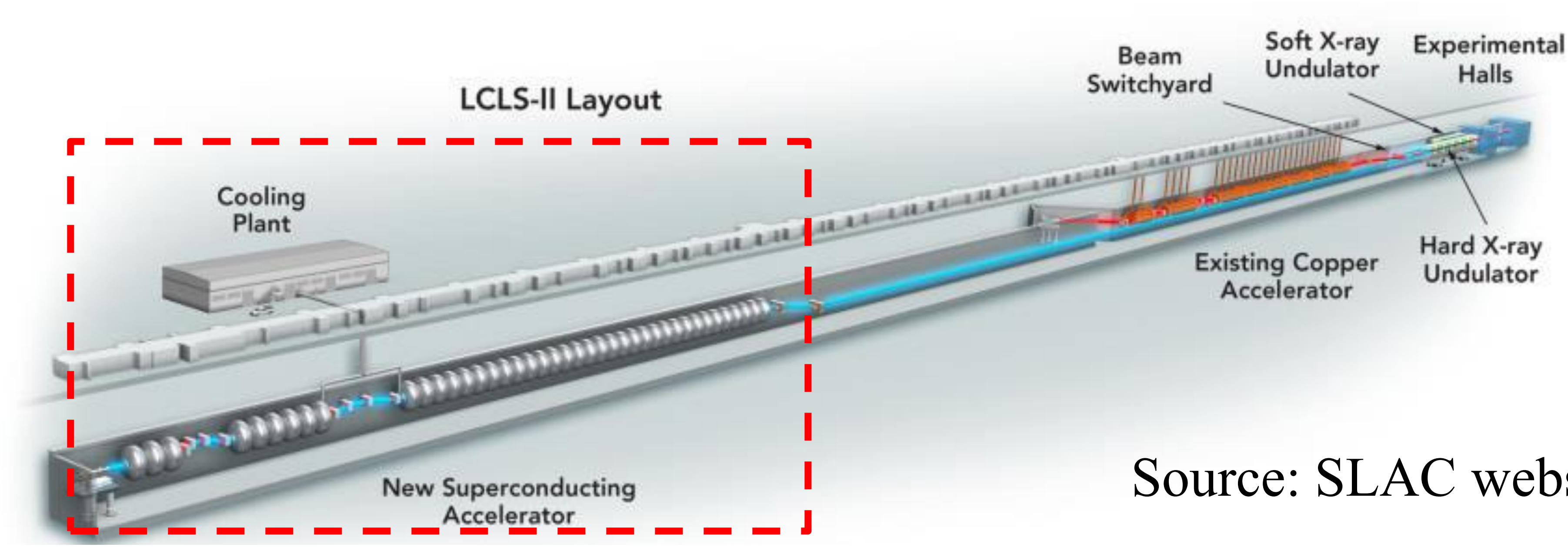
Before we start

- **Motivation**
  - Introduce several demonstrated projects, hoping for their continuity on a cavity scale
    - Cavity studies are costly and time/effort-consuming
    - Fundamental materials studies are the same

- **Acknowledgement**
  - NSF grant PHY-1549132
  - DOE grant DE-SC0008431
  - RF test data was from Matthias Liepe's group
  - STEM data was from David Muller's group

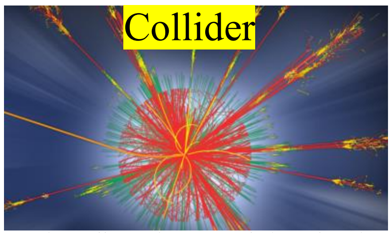
Particle accelerator and SRF cavity



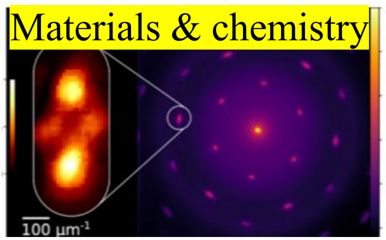
Source: SLAC website

- **Applications:** high-energy charged particles (electrons) and X-rays

https://en.wikipedia.org/wiki/Free-electron_laser

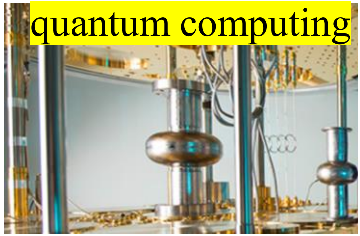


https://www.home.cern/science/accelerators/large-hadron-collider



https://cbb.cornell.edu/research/ultrafast-electron-diffraction-kev-beamline

https://frib.msu.edu/about/index.html

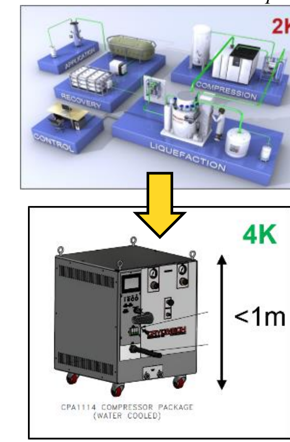


https://www.fnal.gov/pub/science/particle-detectors-computing/quantum.html

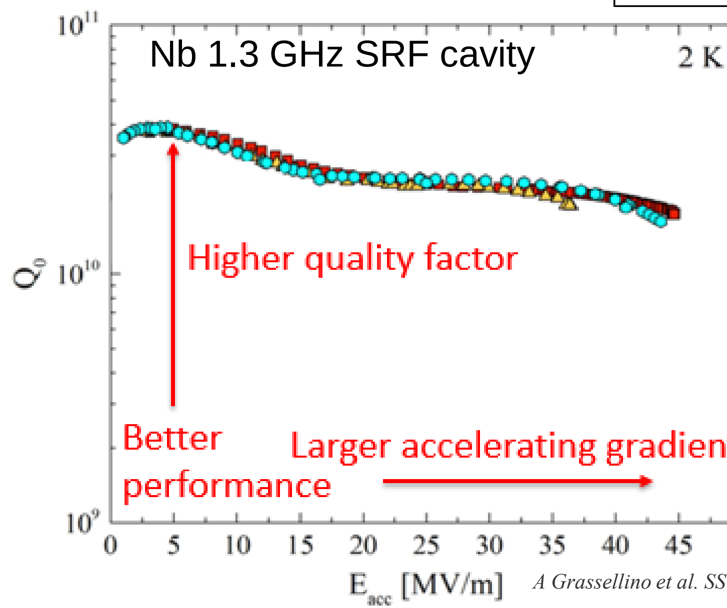
State-of-the-art: Nb SRF performance

N. Stilin et al., Eng. Res. Express, 2023

- **Performance metrics**
  - High beam energy
  - High accelerating gradient
  - Low cost
  - Reduced size



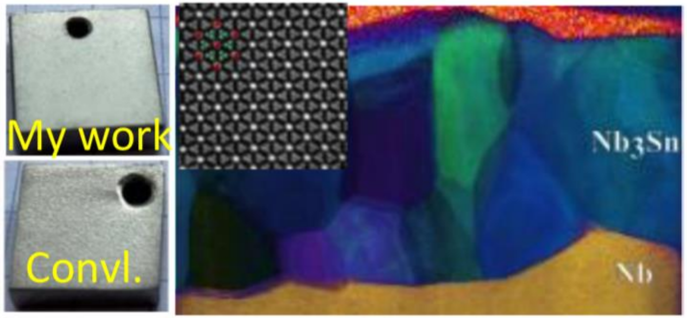
- **Nb cavities approach the theoretical limit**
  - Quality factor (Q_0)
  - Surface resistance ($1/Q_0$)
  - Accelerating gradient (E_{acc})
  - Operation temperature



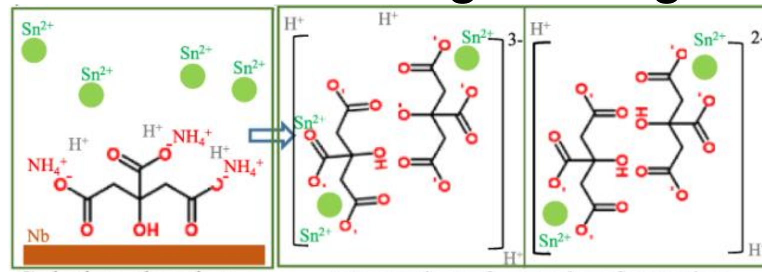
A Grassellino et al. SST 2017

Materials Science

Z. Sun et al. SST, 115003, 2023



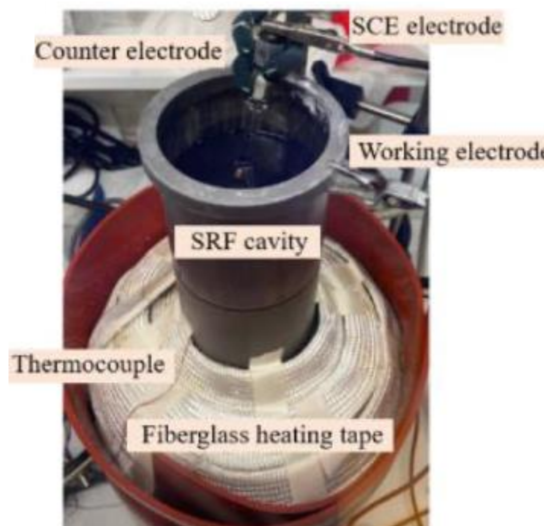
Chemical Engineering



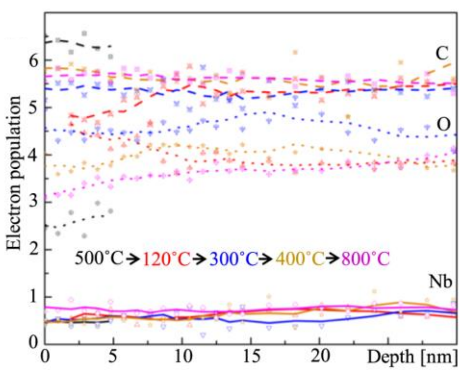
Electrochemical synthesis

Advanced materials-driven SRF-based particle accelerator

SRF

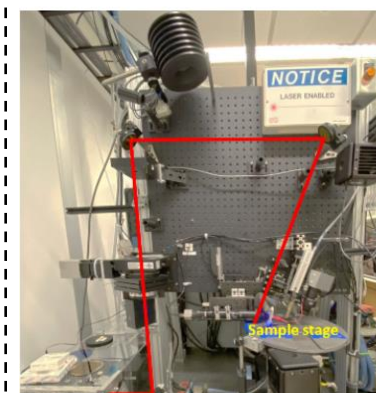


Surface chemistry



Z. Sun et al. SST, 115030, 2023

Laser-materials interaction



Z. Sun et al. Small, 2023

Project 1: Nb_3Sn

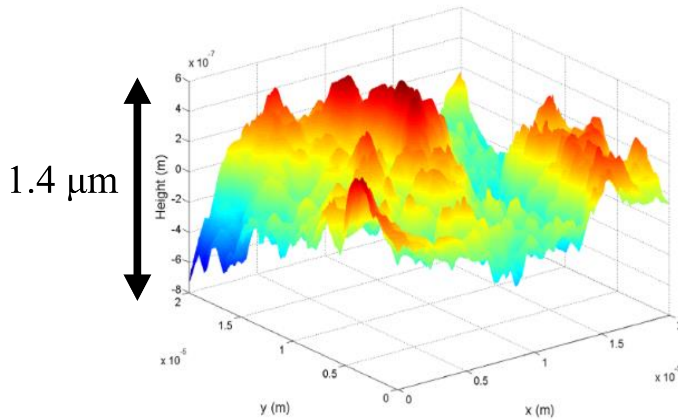
- **Performance potential**

	Nb	**Nb_3Sn**
Tc	9 K	18 K
Q_0 at 4.2K	6×10^8	6×10^{10}
Superheating field	~200 mT	~400 mT
Max. E_{acc}	~50 MV/m	~100 MV/m

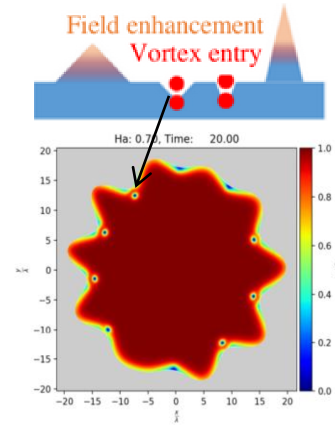
- Enabling cryocooler operating at 4.2 K
  - ✓ Low cryogenic cost and complexity
- Increased Q_0
- Theoretically high E_{acc}

Issues in vapor diffusion

- **Surface roughness**

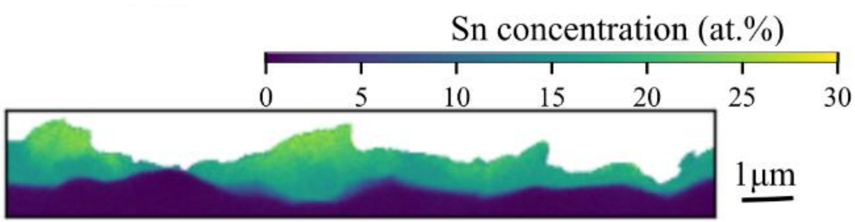


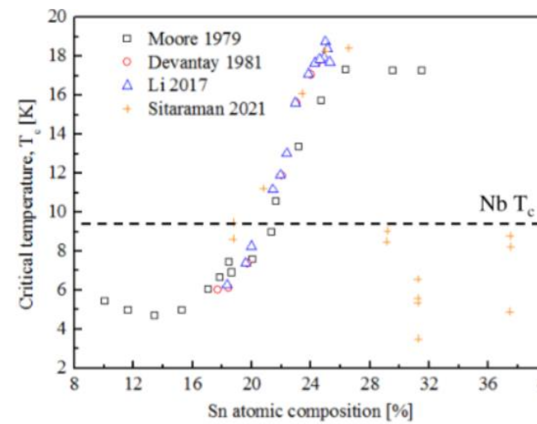
Porter et al., SRF17



Pack et al., PRB, 2020

- **Sn depleted region**

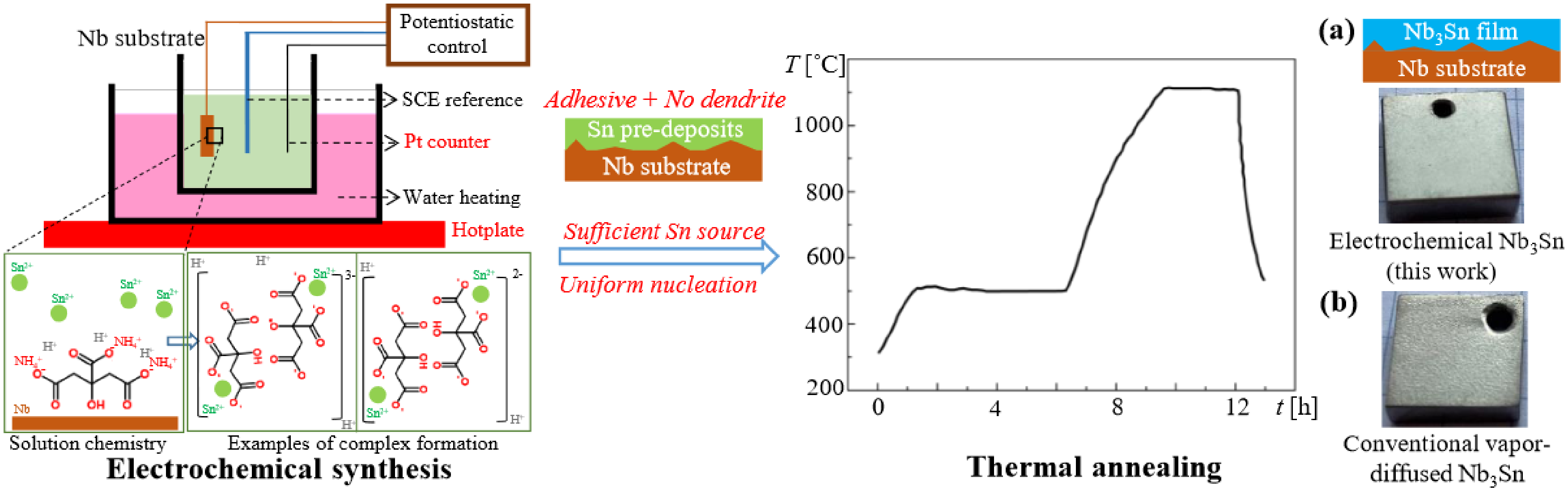




Seed-free electrochemical synthesis

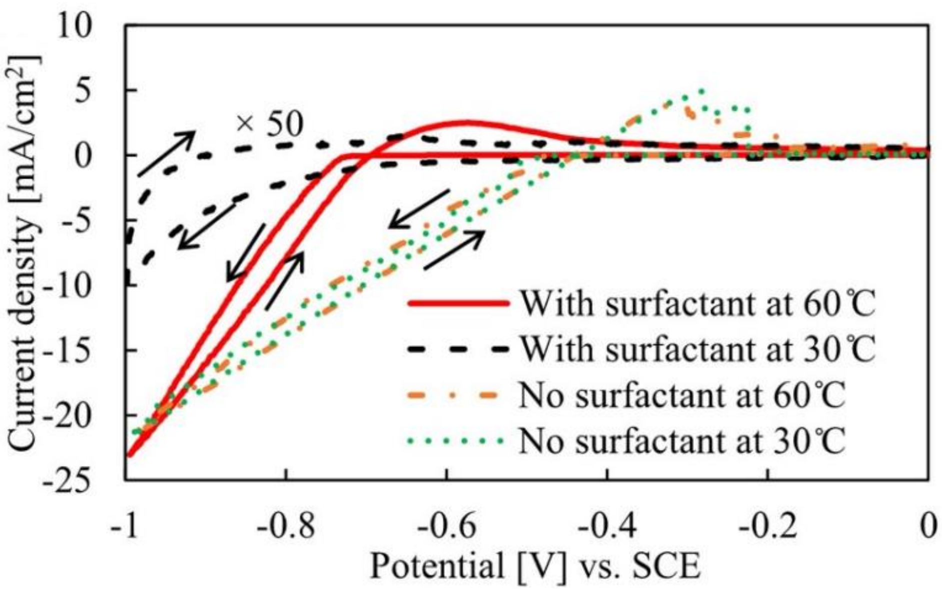
Z. Sun et al. SST, 115003, 2023
Z. Sun et al. APL Mater, 2023

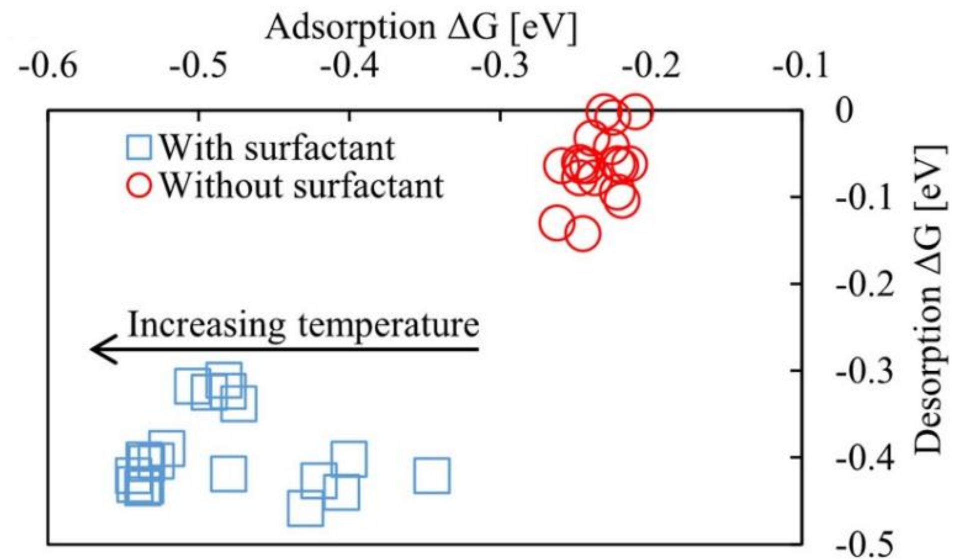
- **Kinetic solution using electrochemical Sn**
  - Should later consider oxygen-involved thermodynamic routes



Electrochemical mechanism

Z. Sun et al. SST, 115003, 2023



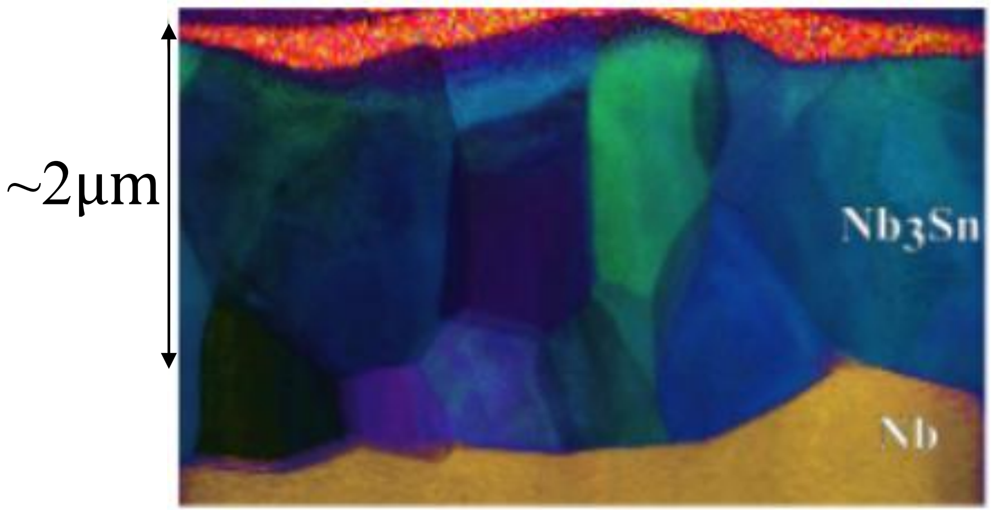


- Surfactant assisted
- A particular type of Sn-surfactant complex activated
- Manipulation of proton through ph, T, and redox potential

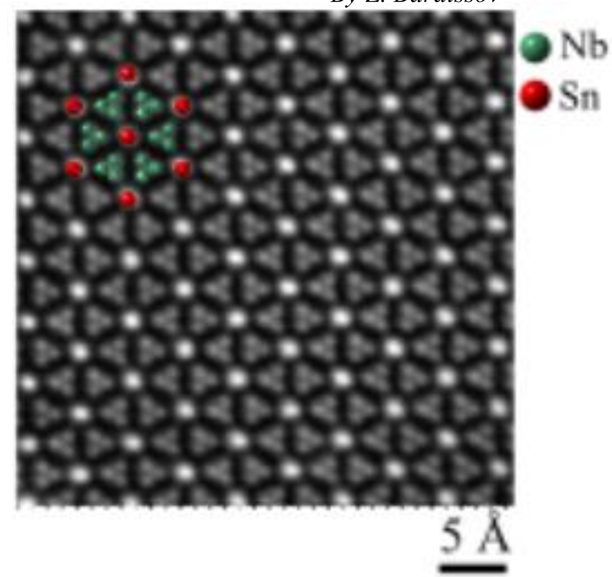
Z. Sun et al. SST, 115003, 2023

Electrochemical Nb_3Sn

- **Cross-sectional STEM**
  - Likely switch from heterogenous to homogenous nucleation

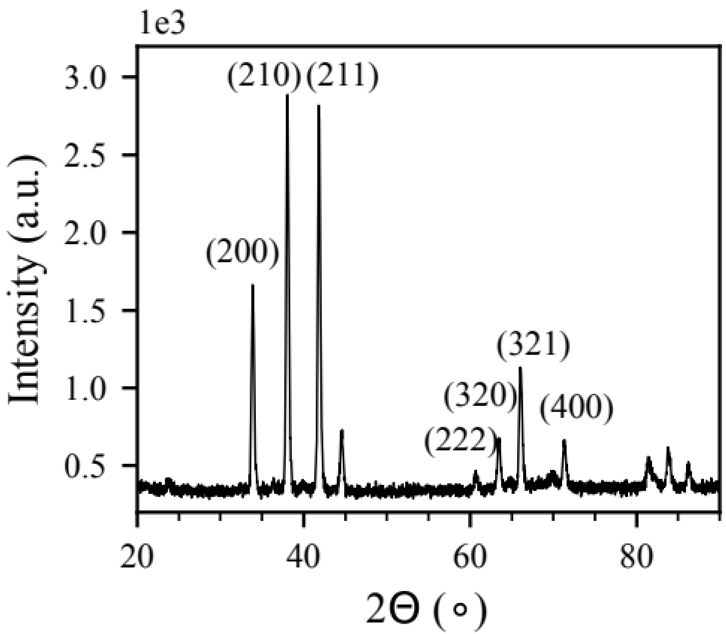


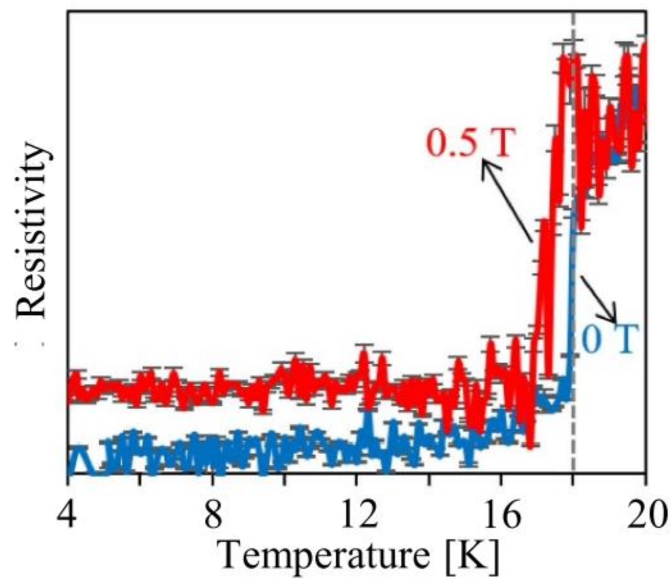
By Z. Baraissov



Electrochemical Nb_3Sn

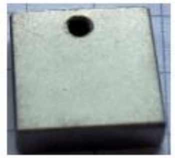
- **Structure & Tc**





Three benefits: smoothness

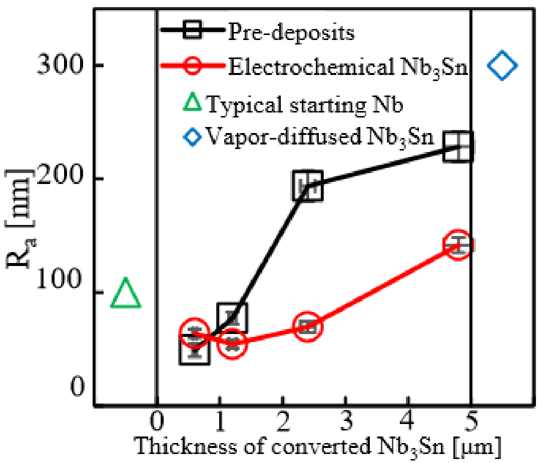
Z. Sun et al. SST, 115003, 2023



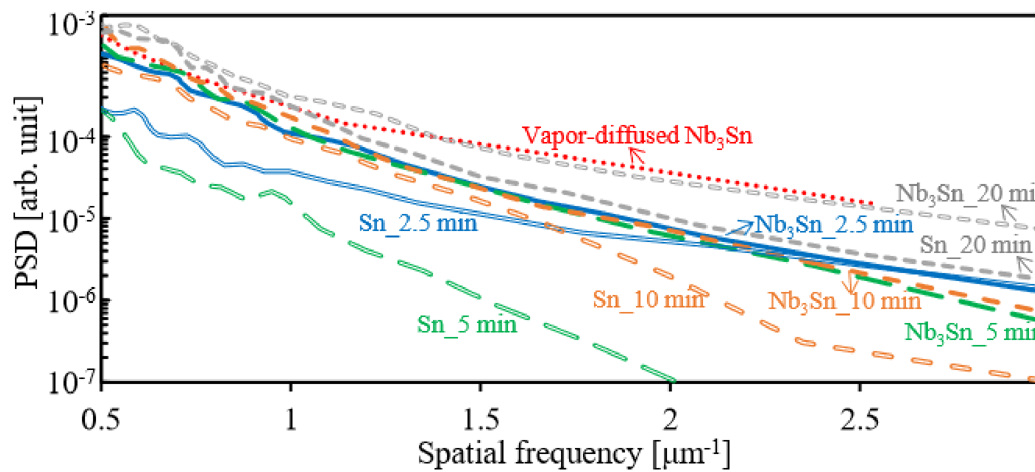
Electrochemical Nb_3Sn (this work)

Conventional vapor-diffused Nb_3Sn

- **Average surface roughness**



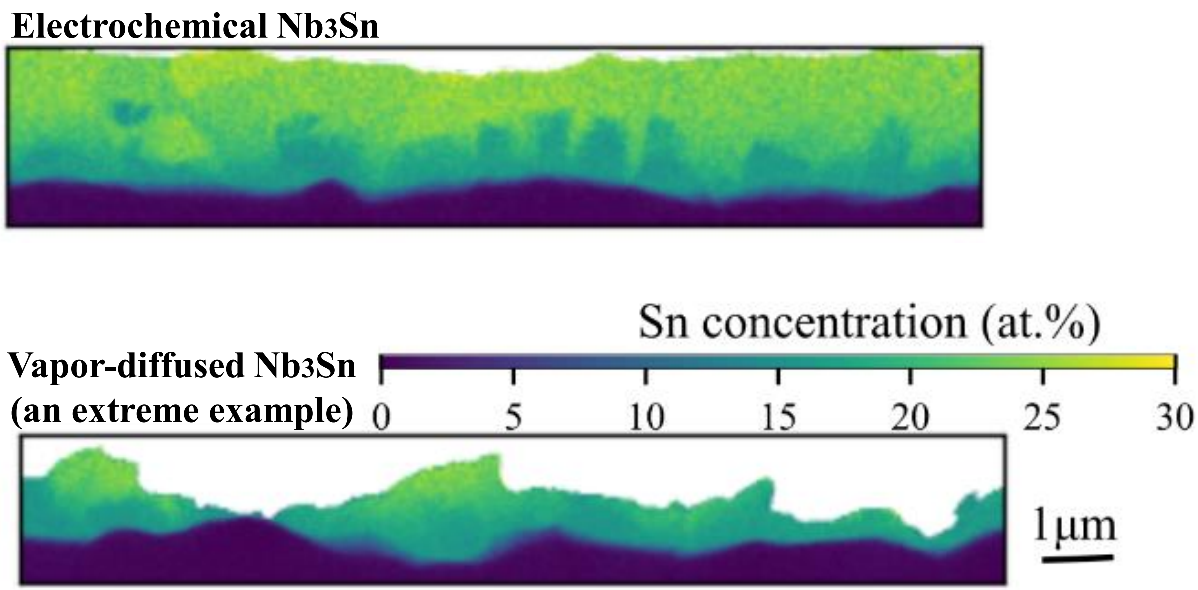
- **Fast Fourier transformation**



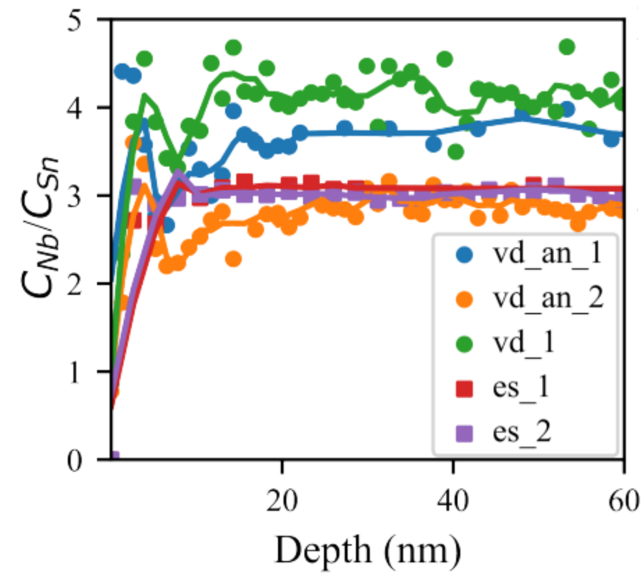
Three benefits: stoichiometric

Z. Sun et al. SST, 115003, 2023

- Cross-sectional Sn map



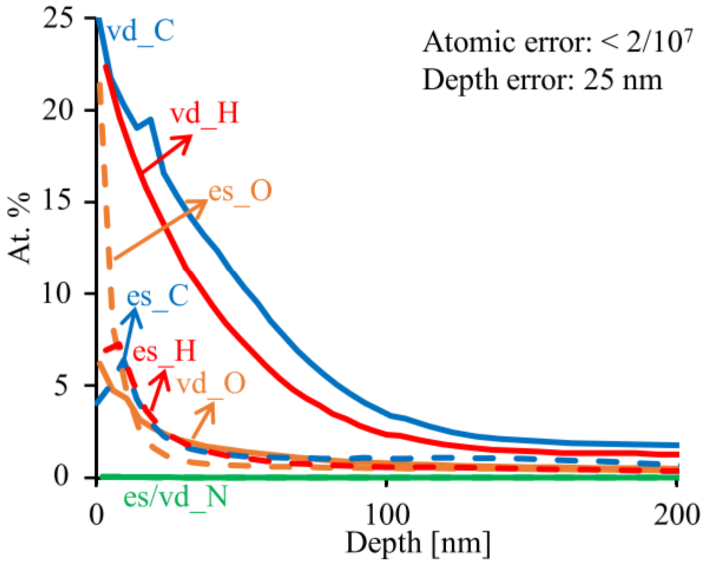
- Nb/Sn ratio vs. depth



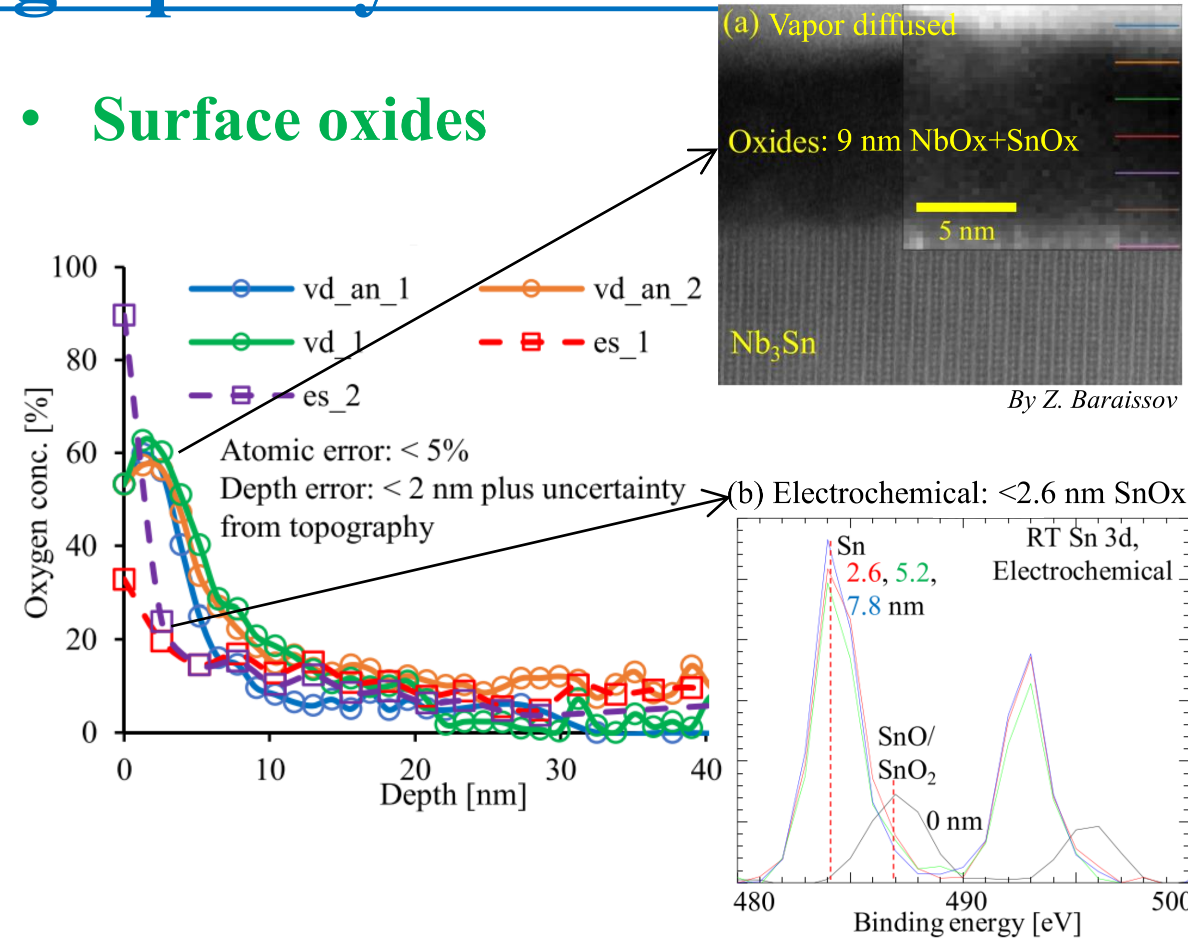
Three benefits: high-purity+thin oxide

Z. Sun et al. SST, 115003, 2023
Z. Sun et al. SST, 115030, 2023

- **SIMS depth profiling**

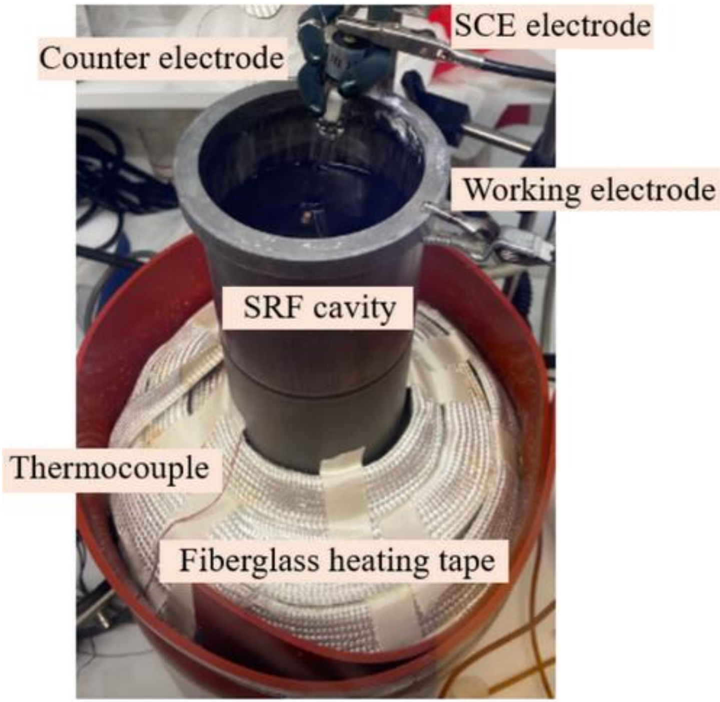


- **Surface oxides**

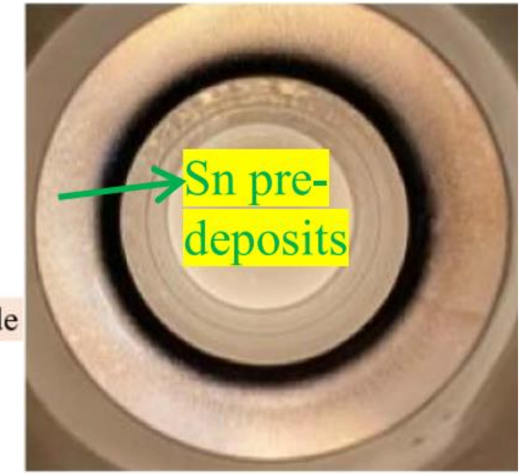


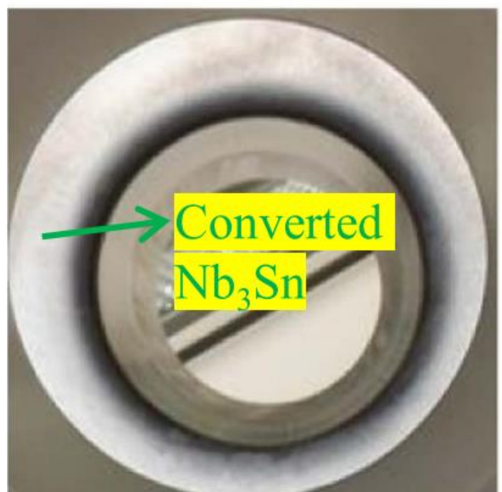
Custom process scale-up

Z. Sun et al. SST, 115003, 2023
Z. Sun et al. SRF'23

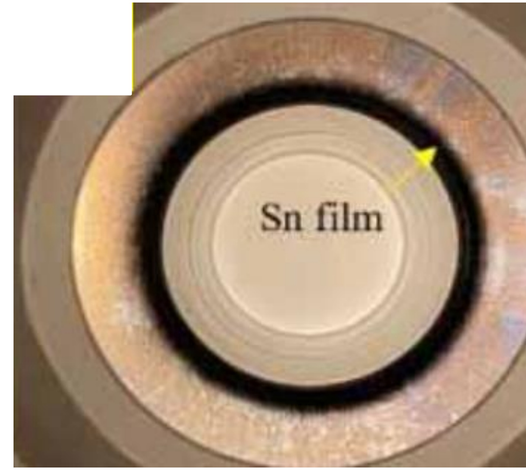


Top side





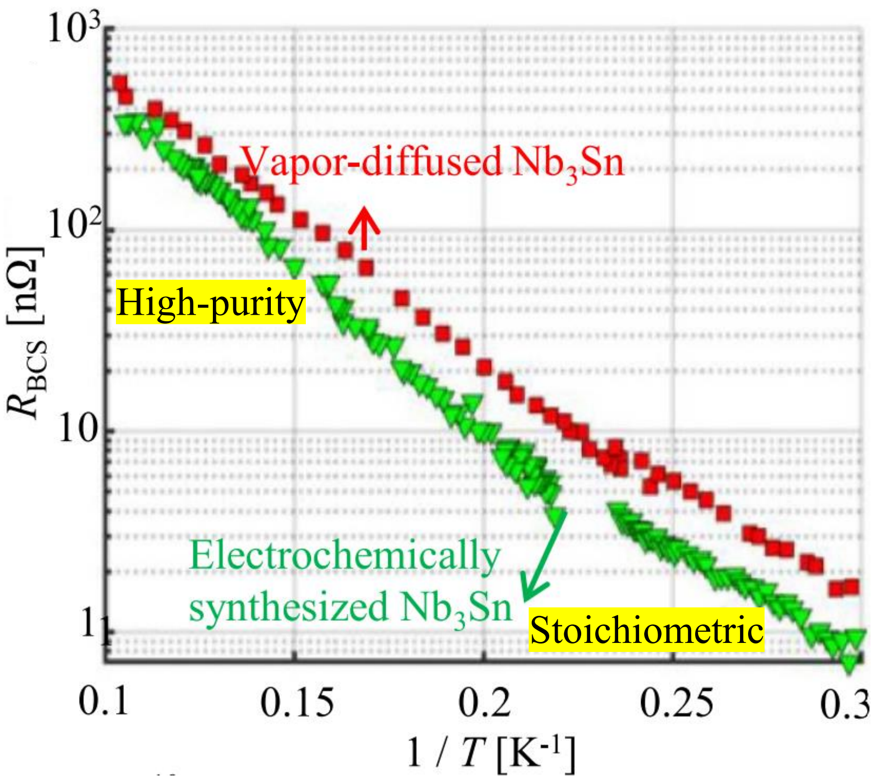
Bottom side

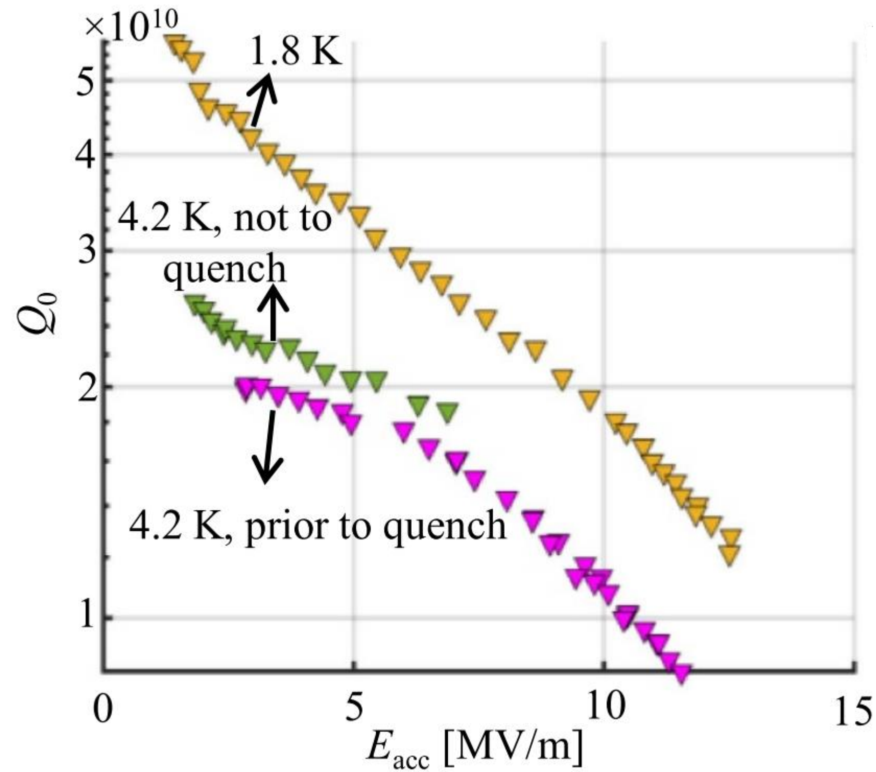


SRF performance

Z. Sun et al. SST, 115003, 2023

- **Record-low BCS resistance (<1 nΩ, below testing limit)**
- **Quench field at 13 MV/m**

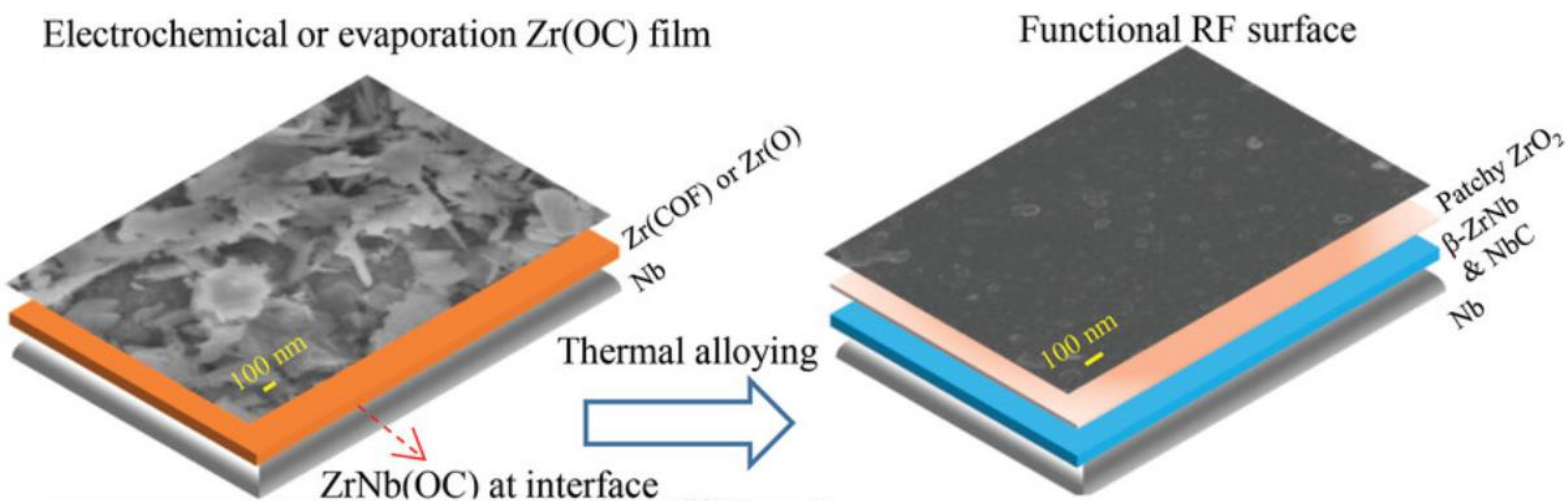




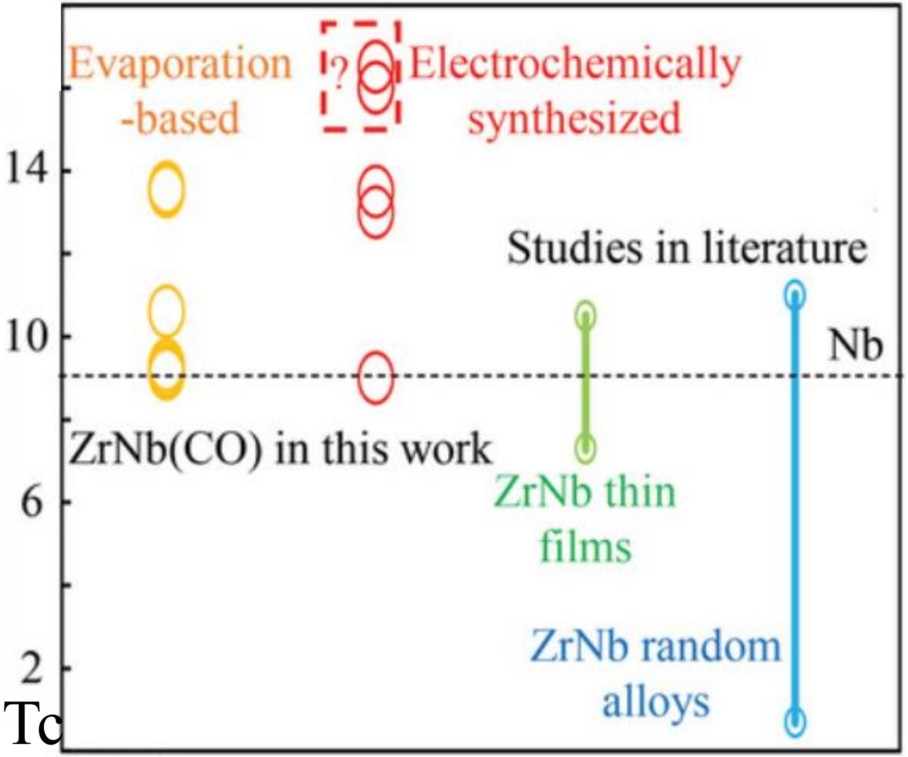
Project 2: ZrNb(CO), new candidate

Z. Sun et al., Adv. Electron. Mater., 2023
N. Sitaraman et al., Phys. Rev. Appl., 2023

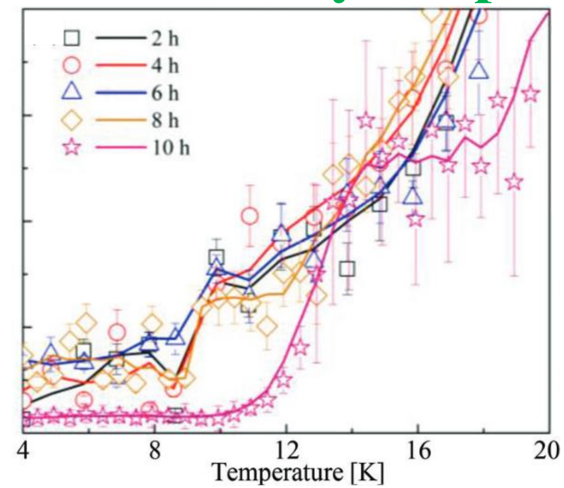
- Suitably high T_c: improves coherence length and lowers sensitivity to material defects
- Observed ZrO_2: wide-bandgap capping
- Increased B_{sh} with Zr doping (by CBB theorists)



Record T_c : 13 – 16 K

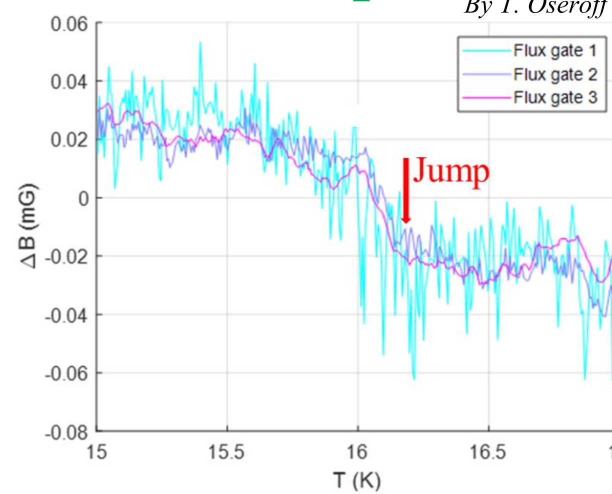


- **Resistivity drop**



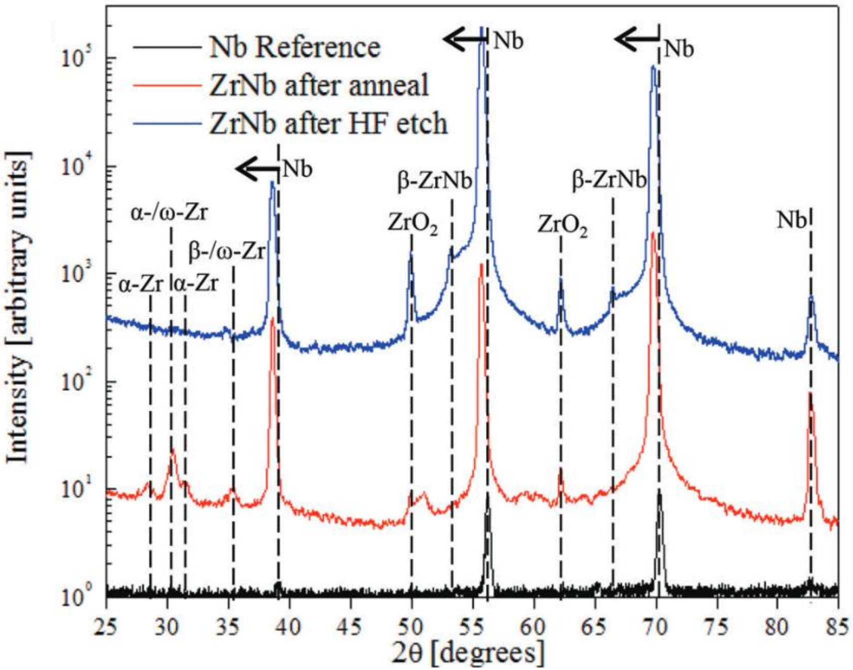
- **Flux expulsion**

By T. Oseroff



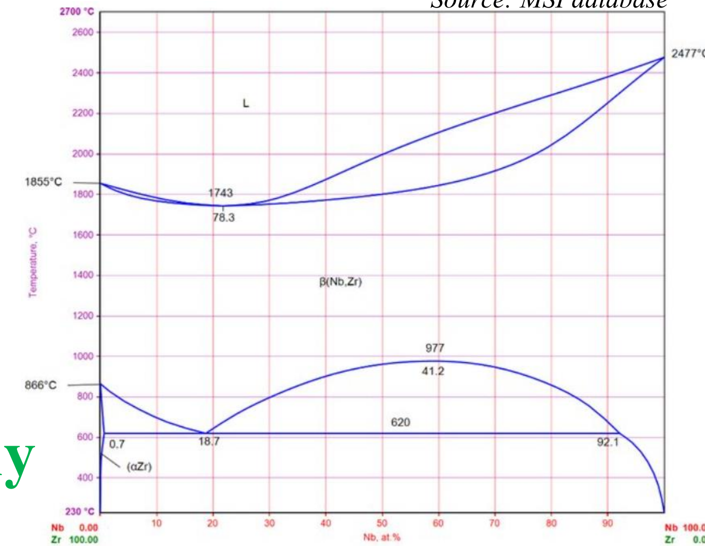
Mechanism: locking ordered bcc phase

Z. Sun et al., Adv. Electron. Mater., 2023
N. Sitaraman et al., Phys. Rev. Appl., 2023



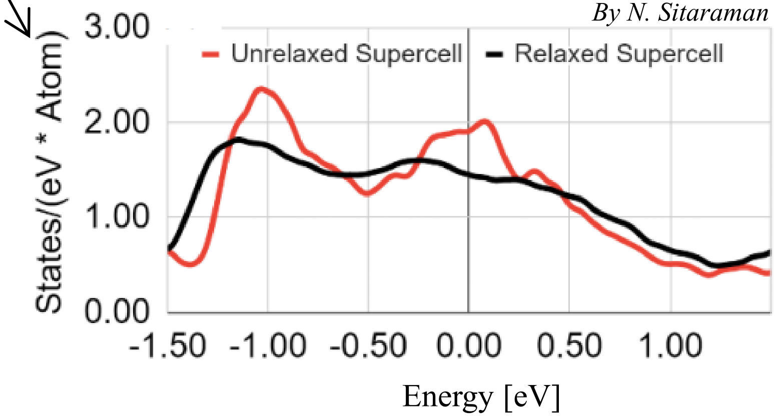
How

Source: MSI database



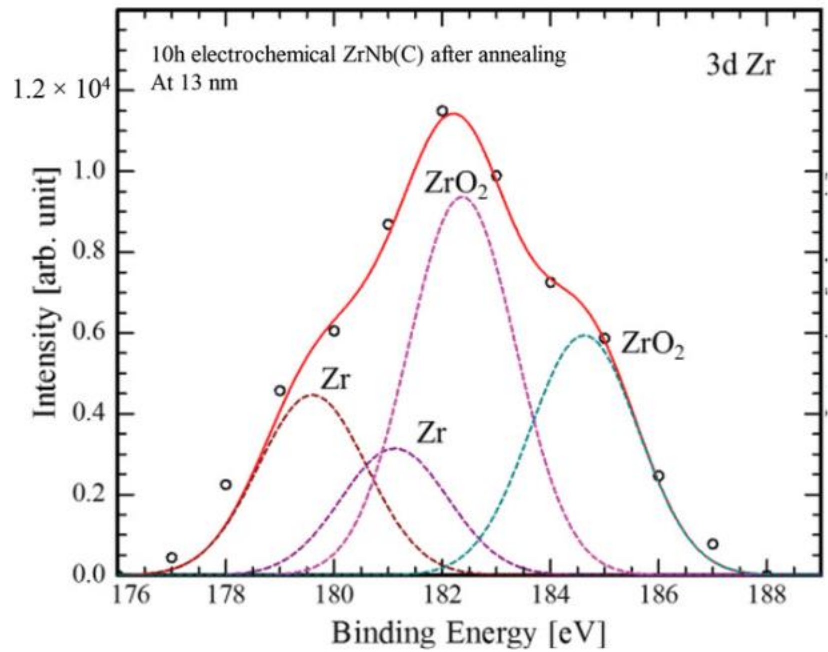
Why

By N. Sitaraman



Surface ZrO_2

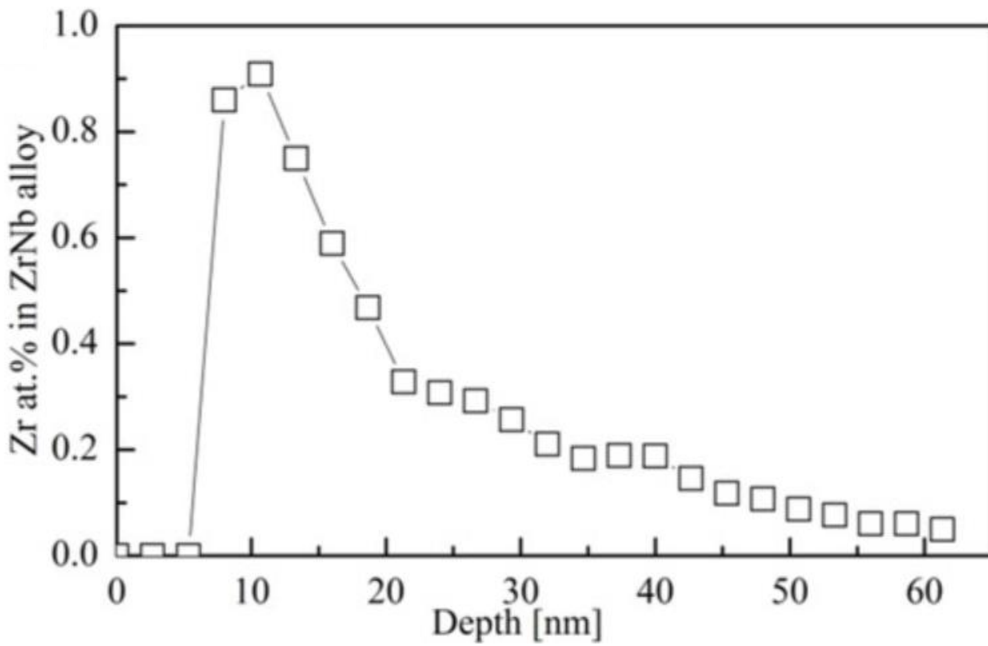
- **Stable and insulating**
- **Zr gettering and only ZrO_2 observed**



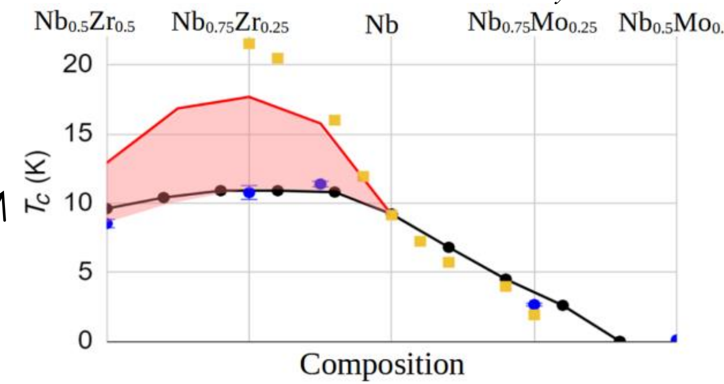
Zr doping profile

- **Further optimization needed**

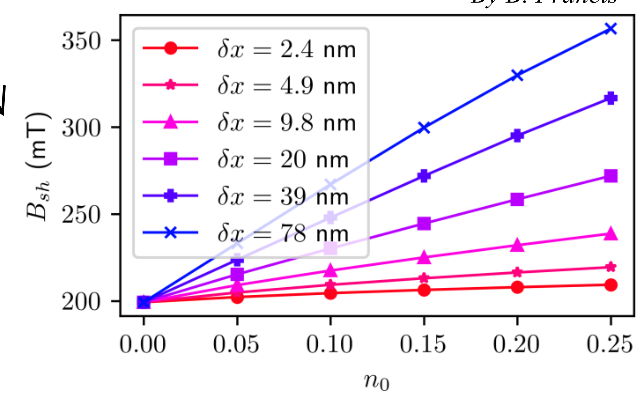
Z. Sun et al., Adv. Electron. Mater., 2023
N. Sitaraman et al., Phys. Rev. Appl., 2023



By N. Sitaraman

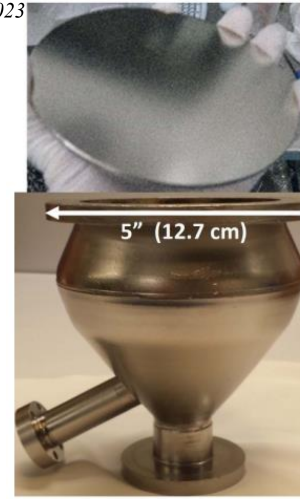


By B. Francis



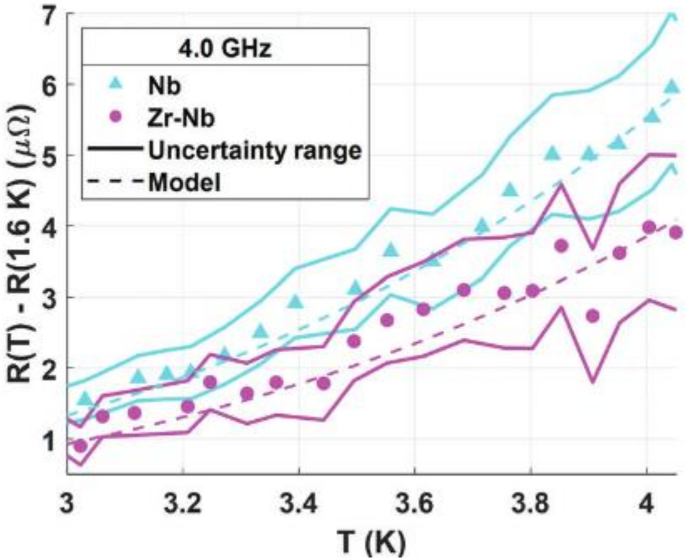
SRF performance

Z. Sun et al., Adv. Electron. Mater., 2023
T. Oseroff et al., SST, 2023

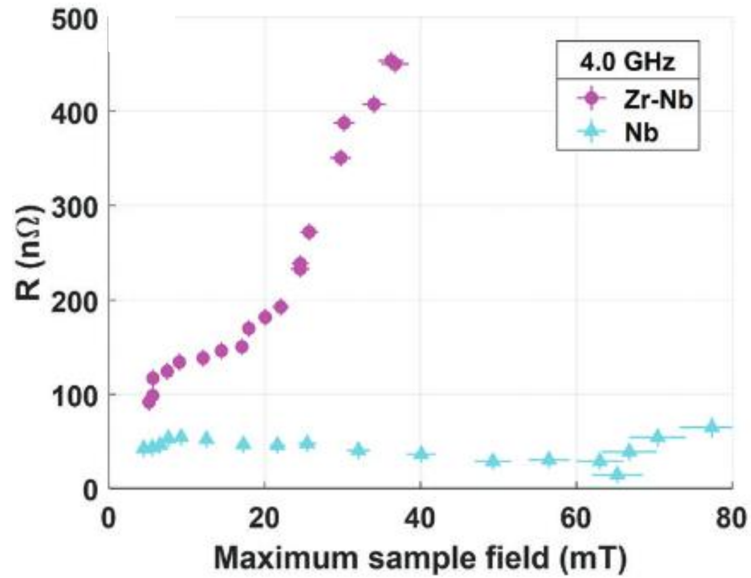


By T. Oseroff

- **BCS resistance**



- **Surface resistance**



Project 3: surface design

- A "handbook" of surface oxide profiles after UHV baking (oxygen processing) or N2 processing

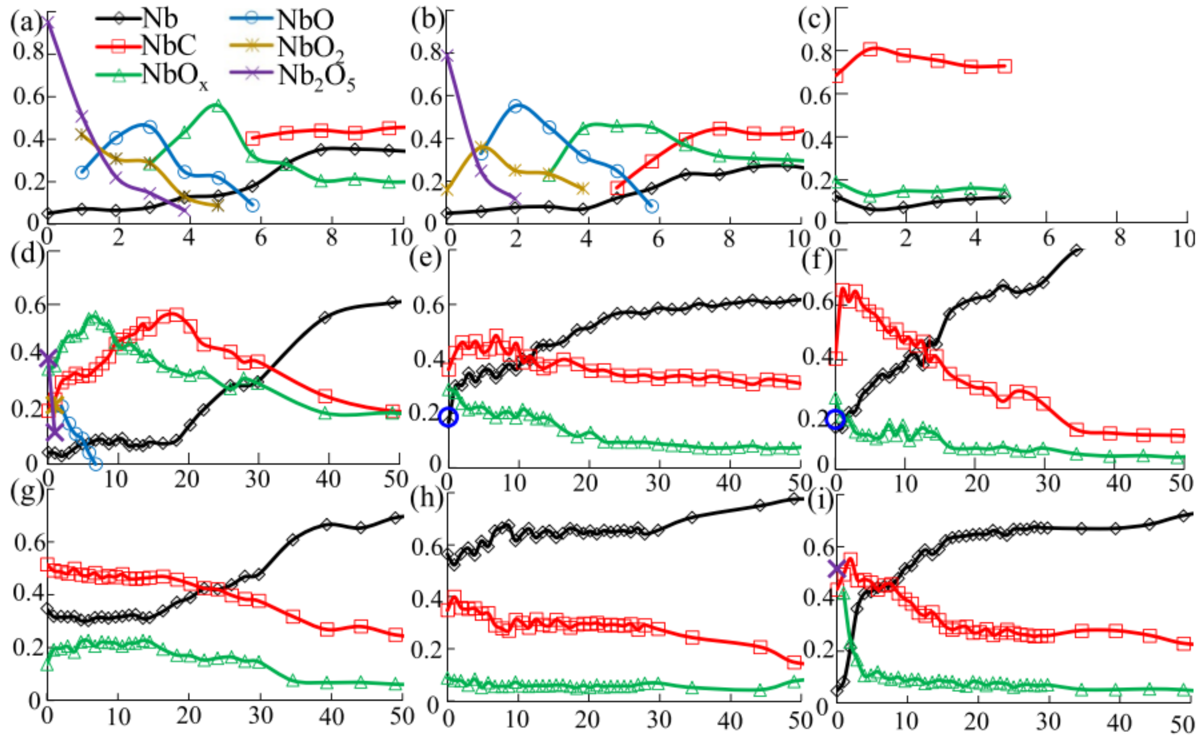
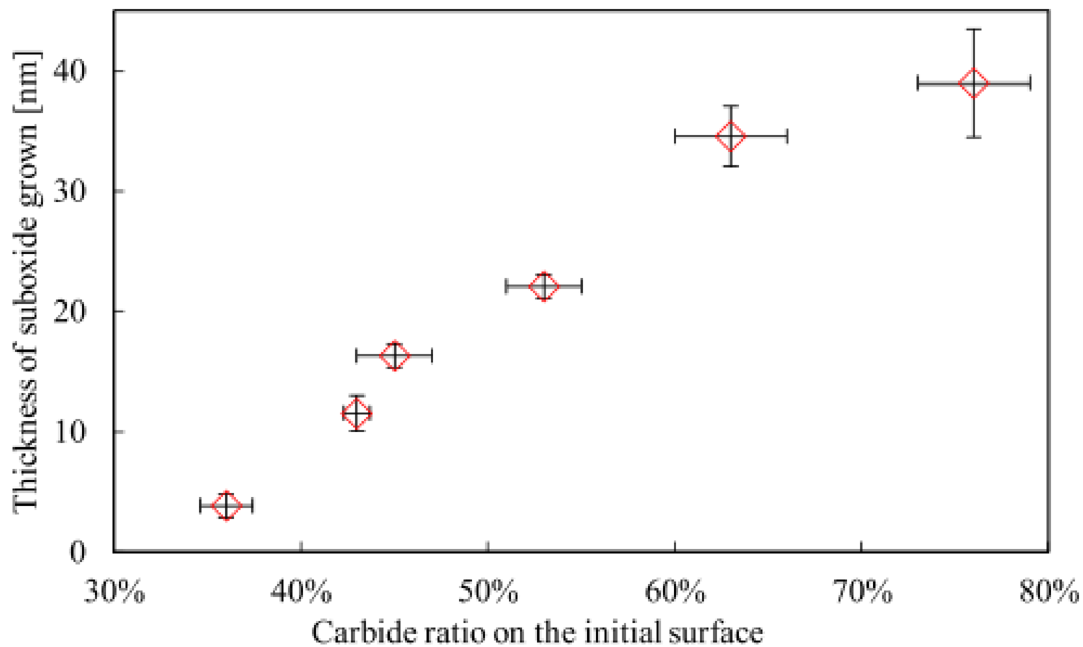


Figure 3. Structural profiles of UHV-baked Nb: comparative proportion of different Nb motifs resolved by XPS peak fitting of Nb 3d spectra, plotted as a function of depth in nm. The spectra were taken *in situ* at (a) RT, (b) 200 °C, (c) 500 °C, (d) 120 °C, (e) 300 °C, (f) 400 °C, and (g) 800 °C, in the indicated sequence, with air exposure between measurements. A reference sample was (h) baked directly at 800 °C and then (i) exposed to air. The expected fitting residue is between 5%–10%.

Project 3: surface design

- Subsurface impurity effects

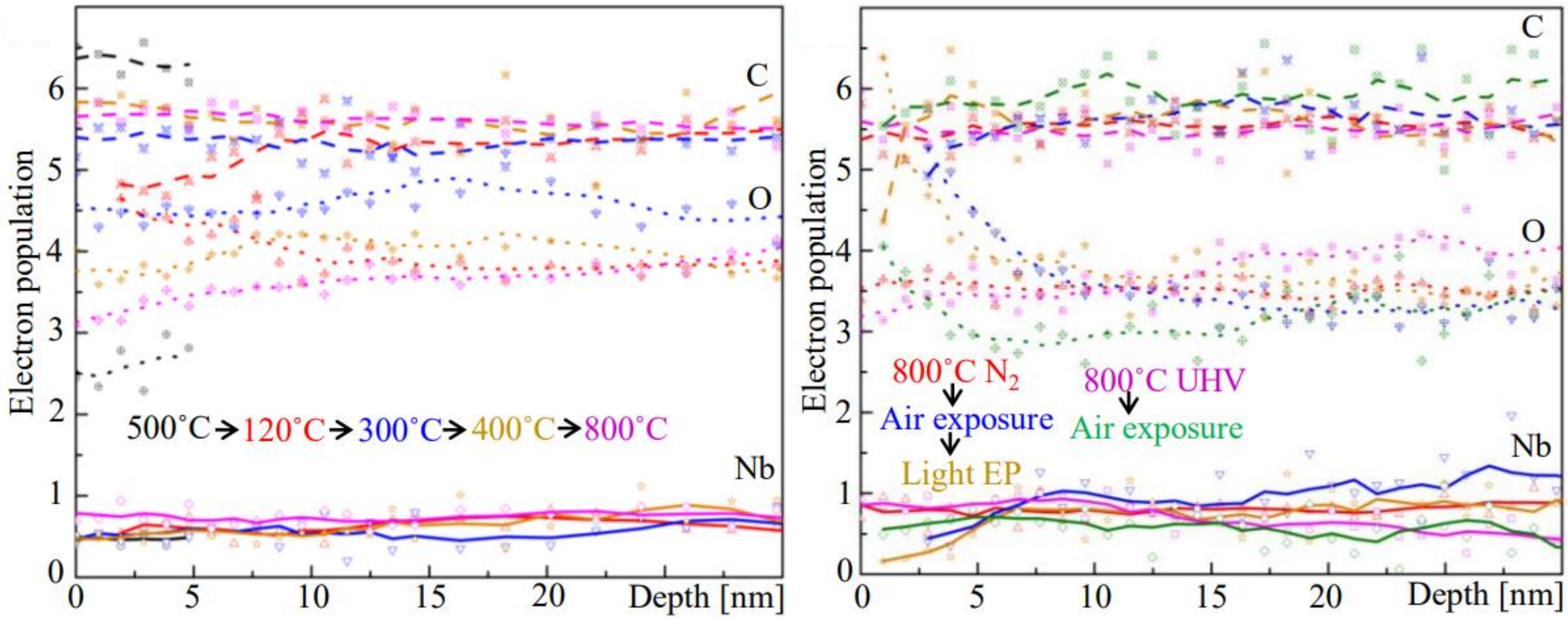


- ○ Initial carbide formation controls the subsequent suboxide growth

Z. Sun et al.,SST, 115030, 2023

Project 3: surface design

- Subsurface impurity effects

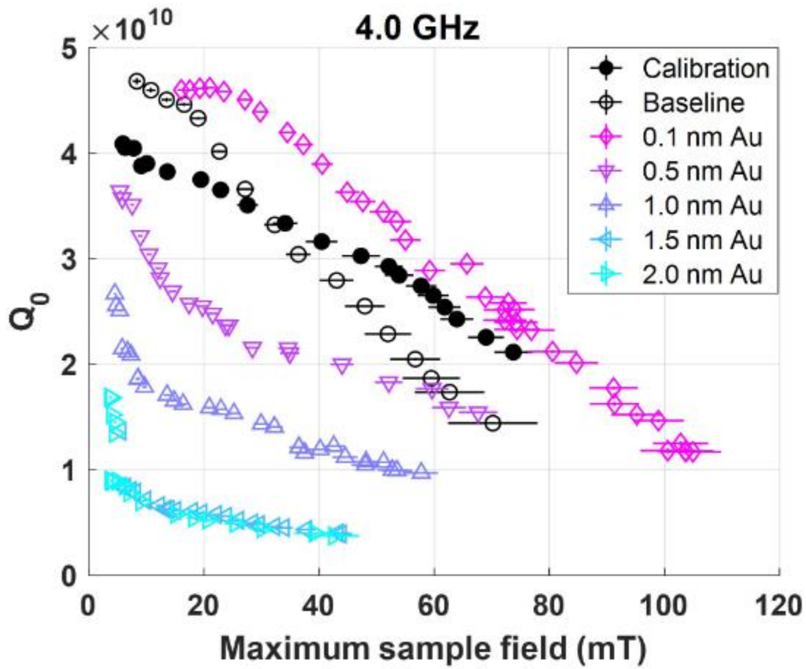


  - These second phases further control the valence electron distributions

One relevant demonstration

T. Oseroff et al., SST, 2023

- Au/Nb bi-layers (T. Oseroff led)



Outlook

- Showcase three projects driven by materials science strategies to develop next generation SRF resonant cavities.

- Expect collective efforts worldwide on more cavity results to further demonstrate these strategies.

Thank you for listening!