Development and characterization of Nb_3Sn/Al_2O_3 superconducting multilayers for high-performance radio-frequency applications

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TFSRF

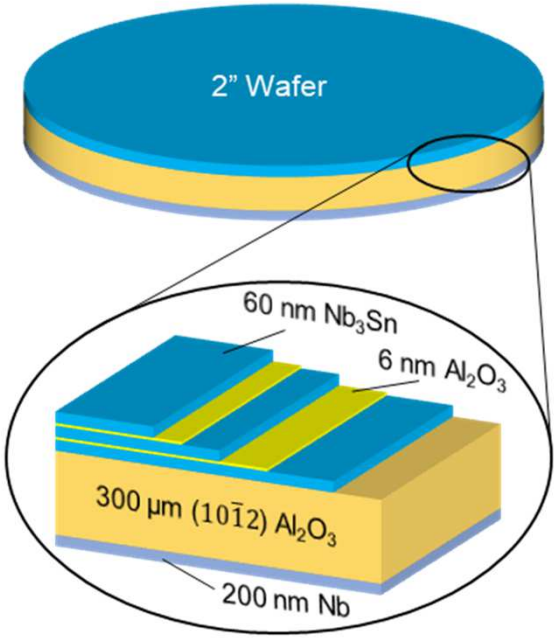
3/17/21

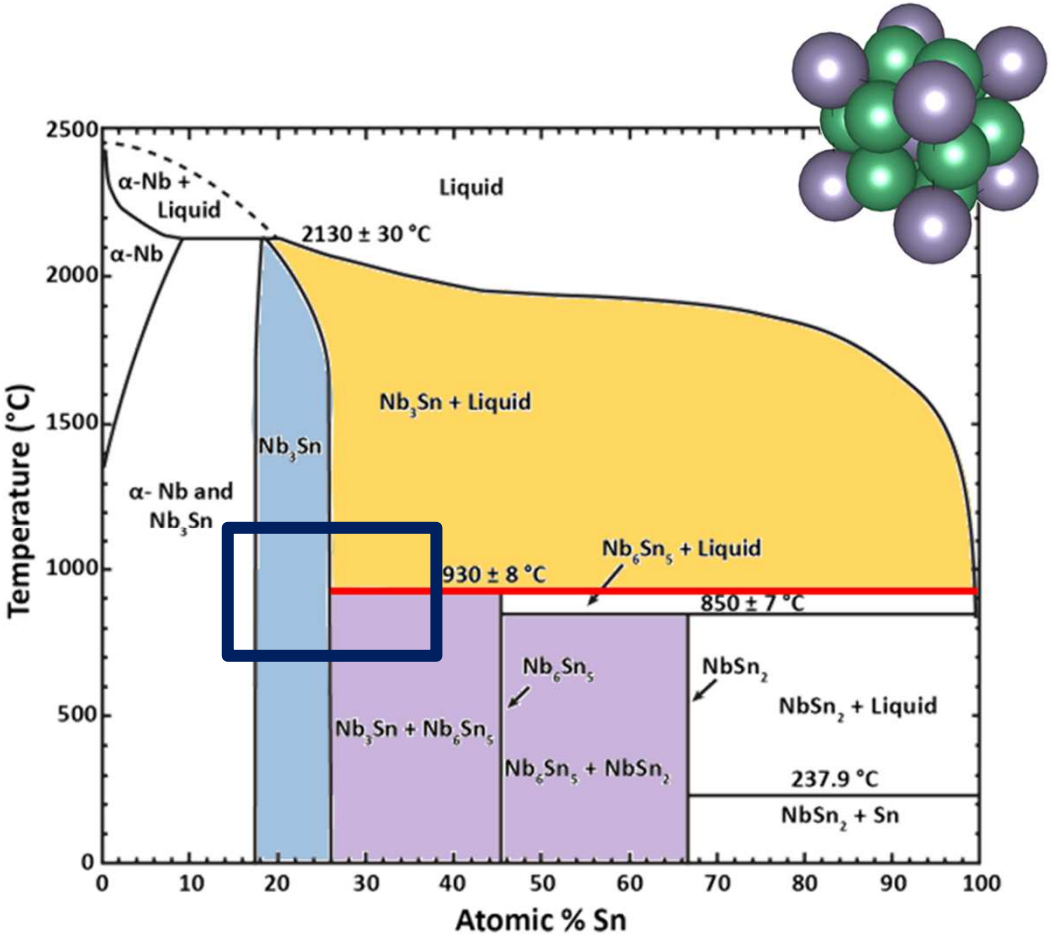
Outline

- Nb_3Sn Film Growth
- SIS structural characterization
- RF Measurements

Nb_3Sn – film growth background

The goal:



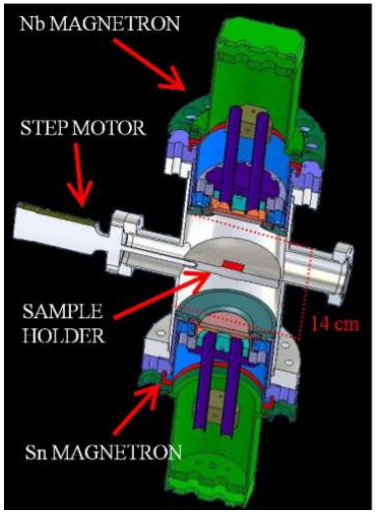


Nb_3Sn thin films can be difficult.

Nb_3Sn – film growth background

There are numerous methods for growing Nb_3Sn films

- Sn vapor diffusion
- Single-target sputtering
- E-beam co-evaporation
- Multilayer deposition + annealing
- The important thing is to be able to tune the Sn content.



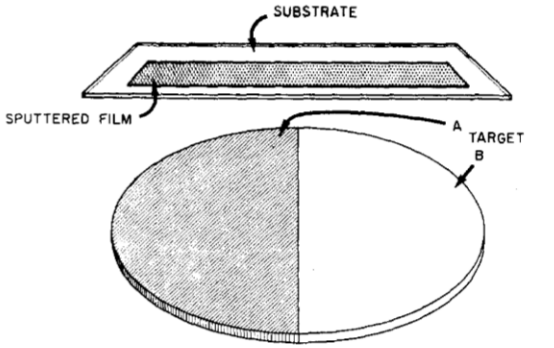


FIG. 1. The relative positions of the sputtering target and substrate.

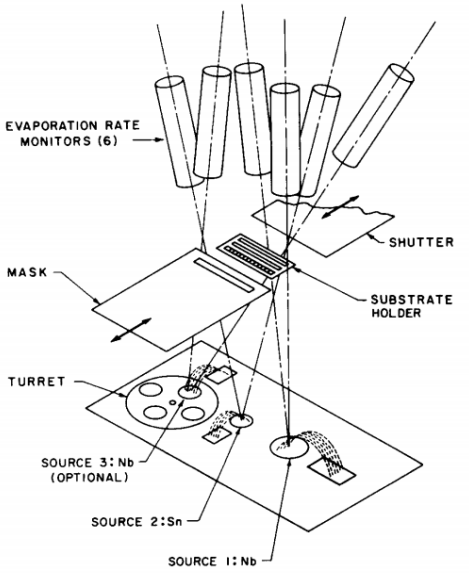
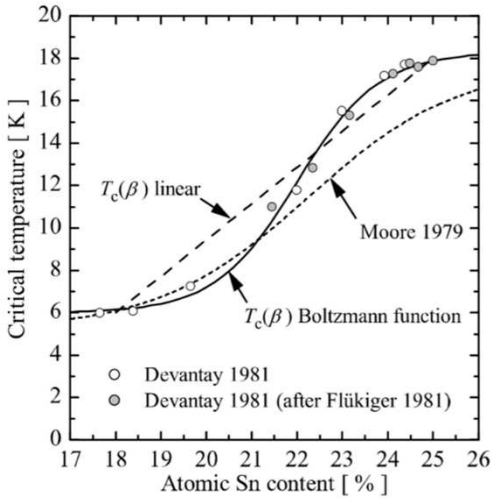


FIG. 1. Schematic of electron-beam deposition system showing linear source arrangement.



J.J. Hanak, 1970, *Journal of Applied Physics*

D.A. Rudman, 1984, *Journal of Applied Physics*

A.A. Rossi, SRF2009

A. Godeke, 2006, *Superconduct. Sci. Tech.*

Growing Nb_3Sn – Controlling Sn

IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-21, NO. 2, MARCH 1985

RF SURFACE RESISTANCE IN Nb_3Sn THIN FILMS

L. H. Allen, W. J. Anklam, M. R. Beasley, R. H. Hammond, and J. P. Turneaure
W. W. Hansen Laboratory of Physics
Stanford University
Stanford, CA 94305

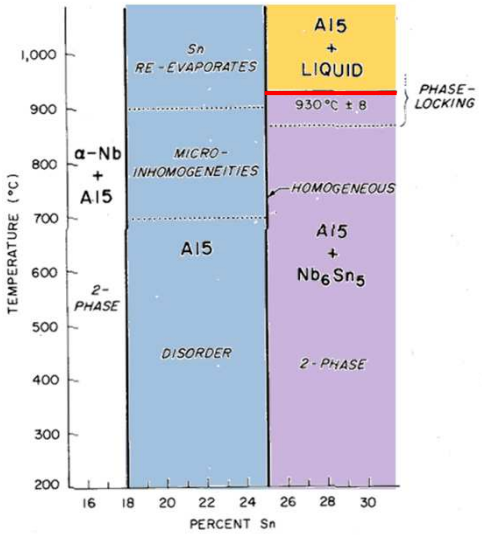


Fig. 2. A portion of the Nb-Sn phase diagram. The phase fields are labeled in large type and bounded by solid lines. The diagram is further divieded into regions which are labeled in italics with a description of the main characteristic of thin films which are prepared there.

IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-23, NO. 2, MARCH 1987

RF SURFACE RESISTANCE OF Nb_3Sn, NbZr, and NbN Thin Films

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Stanford, CA 94305

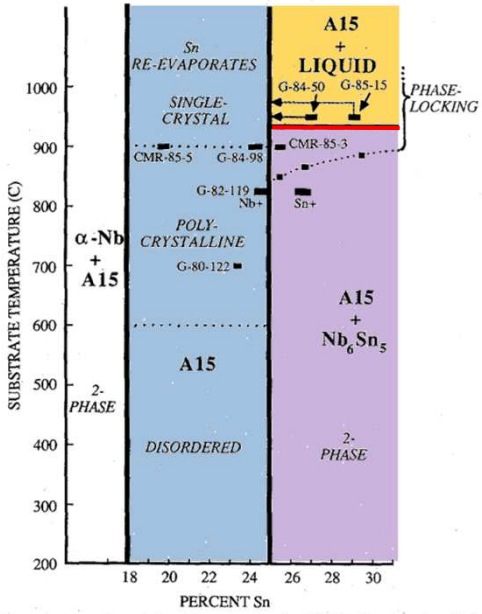
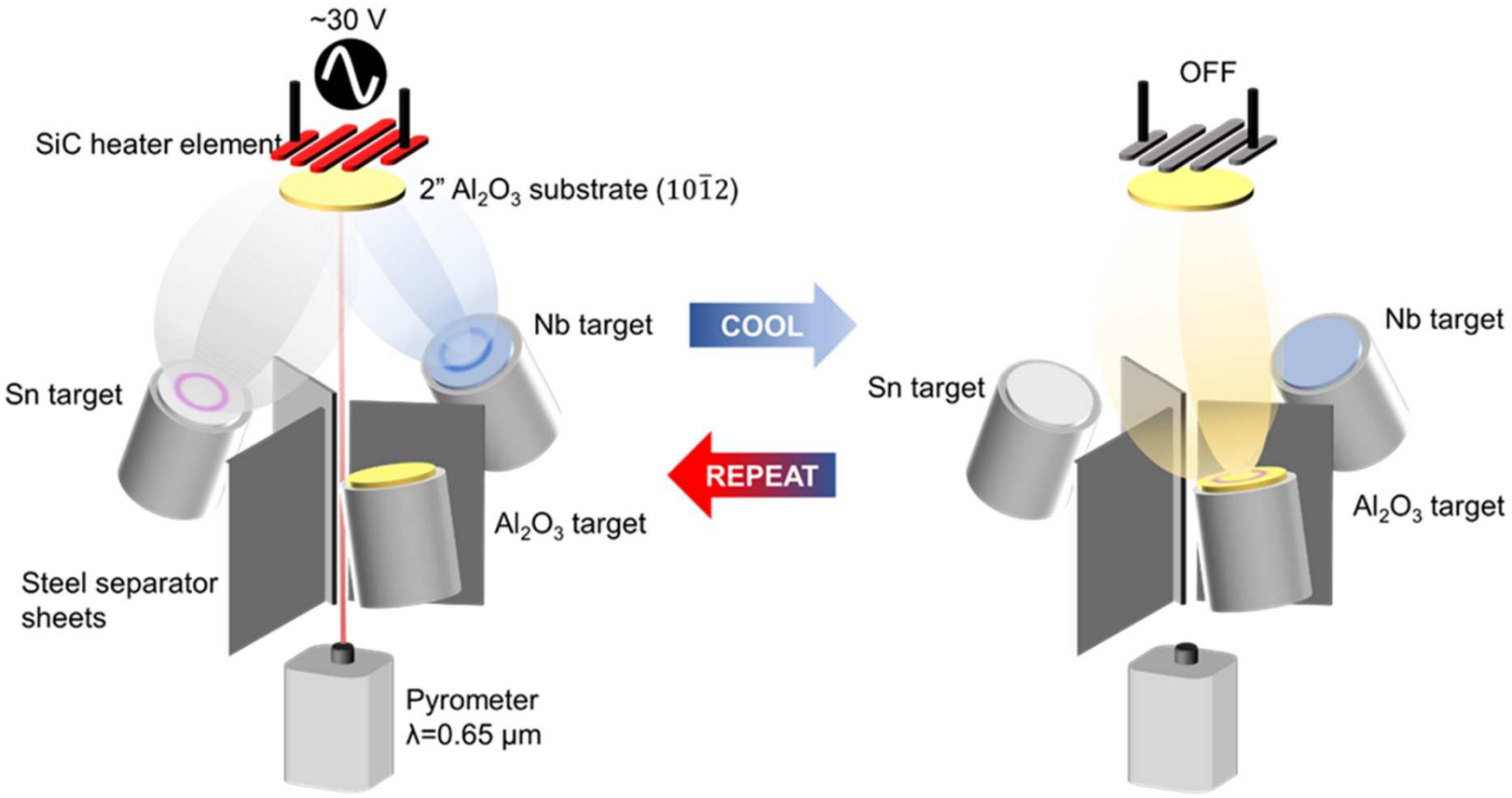
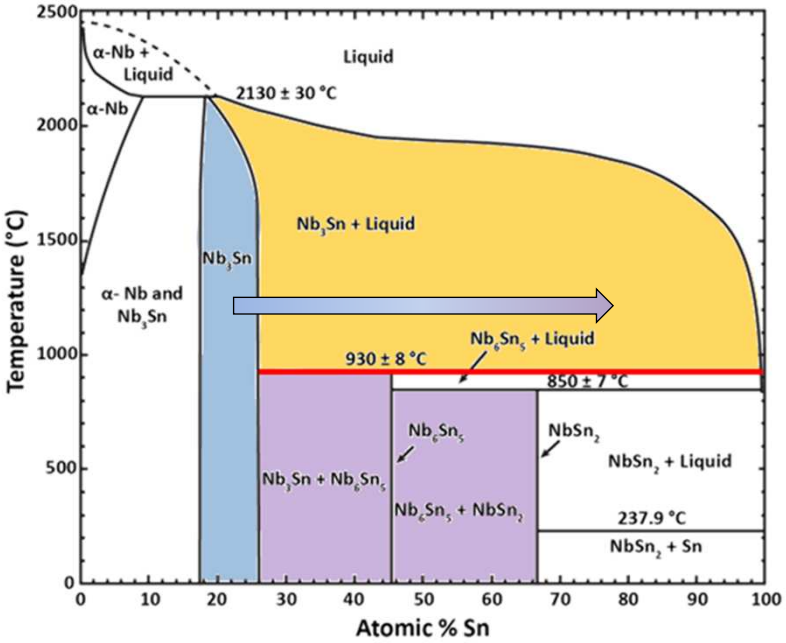


Fig. 1. A portion of the phase diagram for Nb-Sn showing the A15 phase field and adjacent regions. Italicized comments refer to the properties of films prepared in those regions, and the location of the dotted lines separating the regions are approximate. Samples discussed in this paper are marked at their deposition temperature and composition.

Nb_3Sn Growth Setup

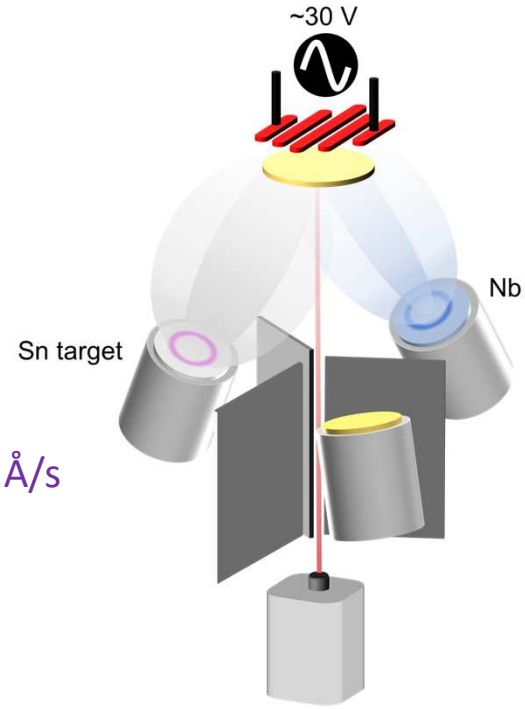


Nb_3Sn Films - Stoichiometry



Sn rate (Å/s)	Nominal % Sn
0.4	22
0.8	46
1.0	59
1.5	68
2.0	74
2.5	78

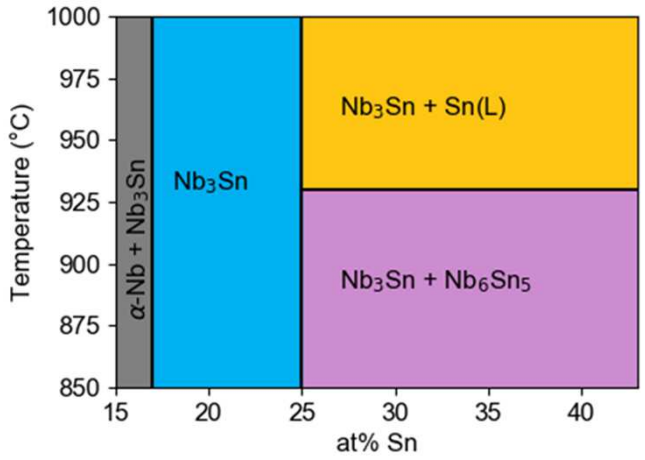
Sn flux
0.4 – 2.5 Å/s

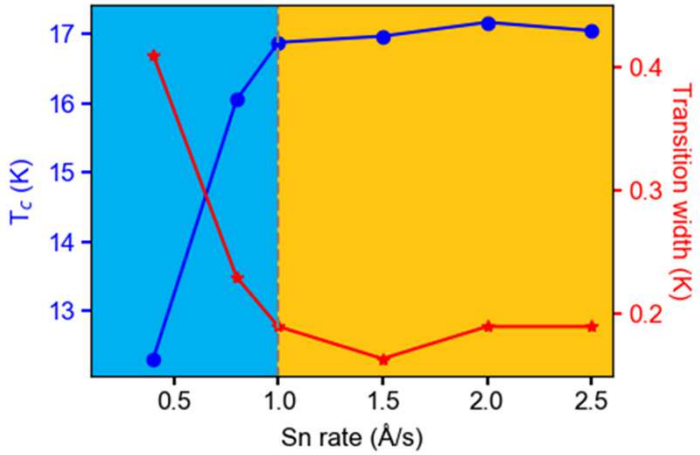


Nb flux – fixed
(0.7 Å/s)

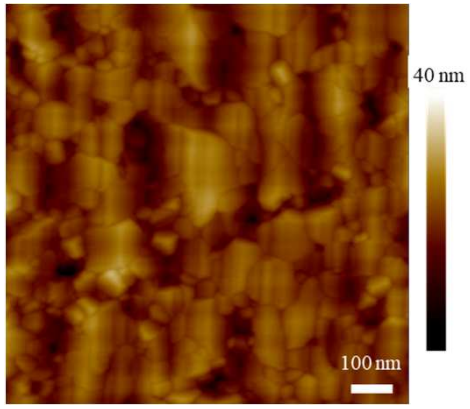
Nb_3Sn Films - Stoichiometry

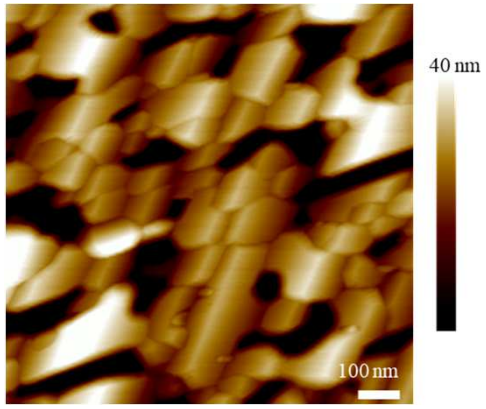
Sn flux adjustment series





Roughness is also affected.





0.8 Å/s Sn

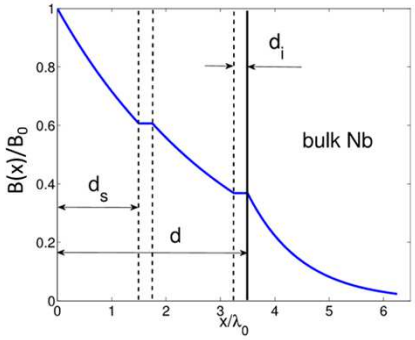
1.5 Å/s Sn

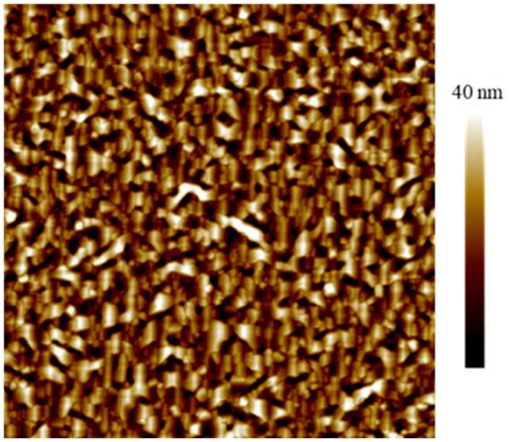
Picked 1.5 Å/s for the rest of samples.

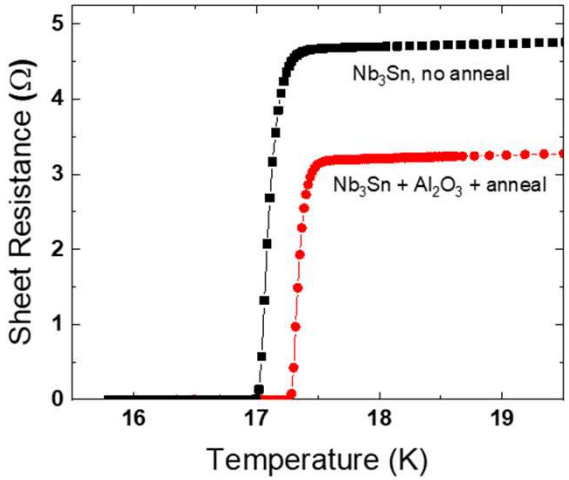
Multilayers – Al_2O_3

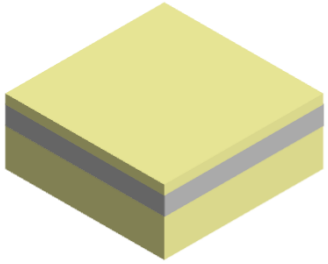
Requirements:

1. Don't degrade Nb_3Sn with Al_2O_3
2. Don't destroy Al_2O_3 layer with upper Nb_3Sn film growths









SC properties improve with cap + anneal

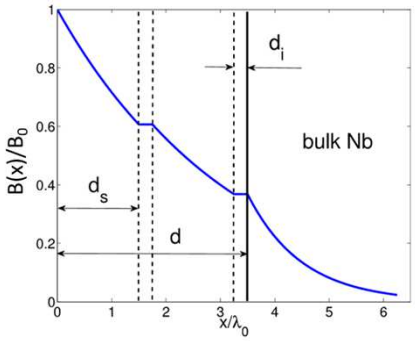
→ Disorder in Nb_3Sn?

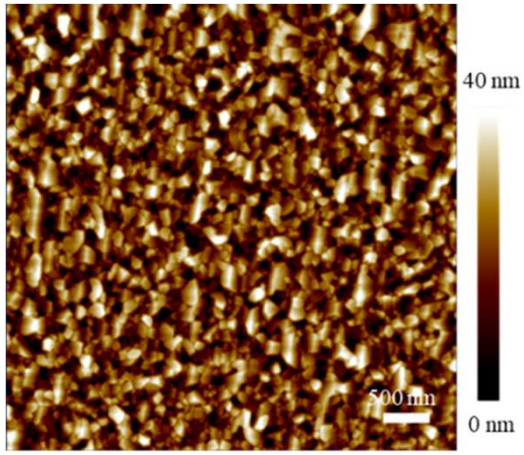
→ Composition gradient?

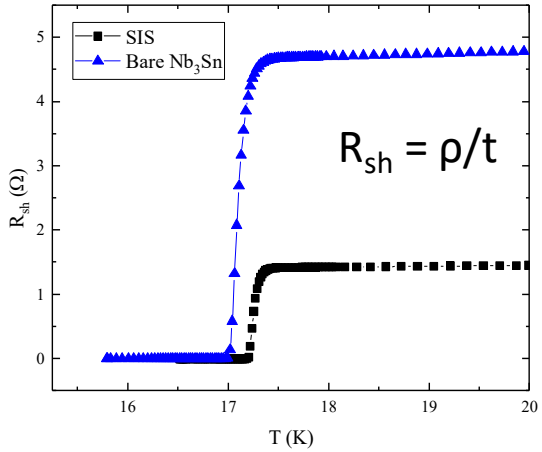
Multilayers – Al_2O_3

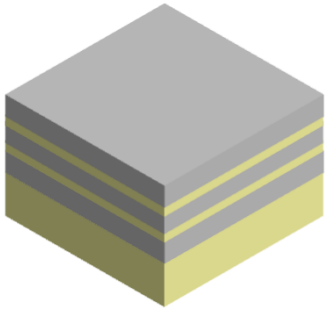
Requirements:

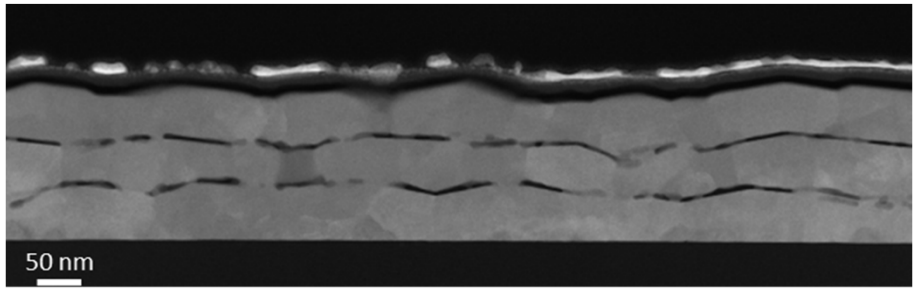
1. Don't degrade Nb_3Sn with Al_2O_3
2. Don't destroy Al_2O_3 layer with upper Nb_3Sn film growths



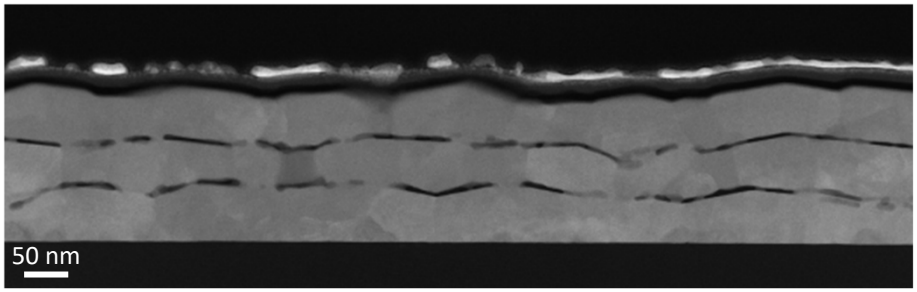




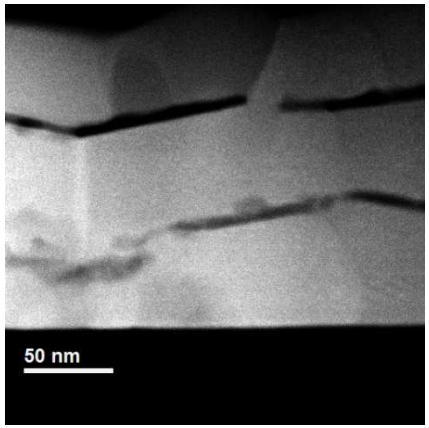


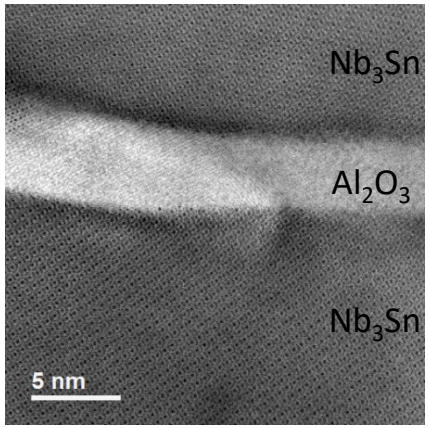


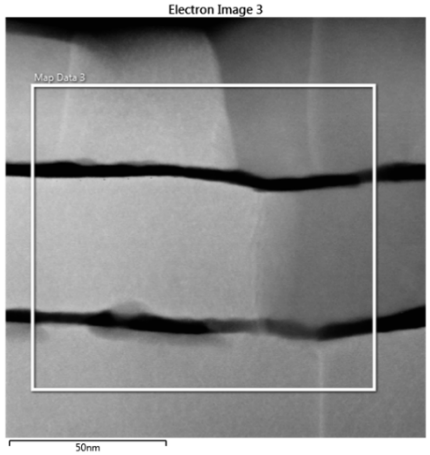
TEM Composition Mapping



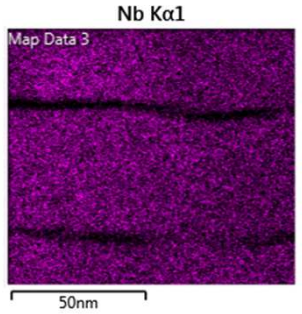
Al_2O_3 present, but incomplete

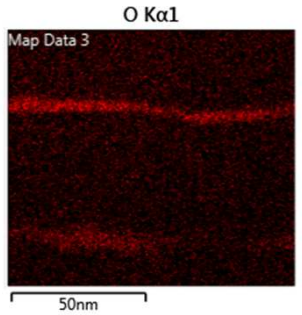


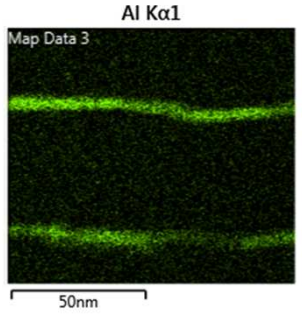




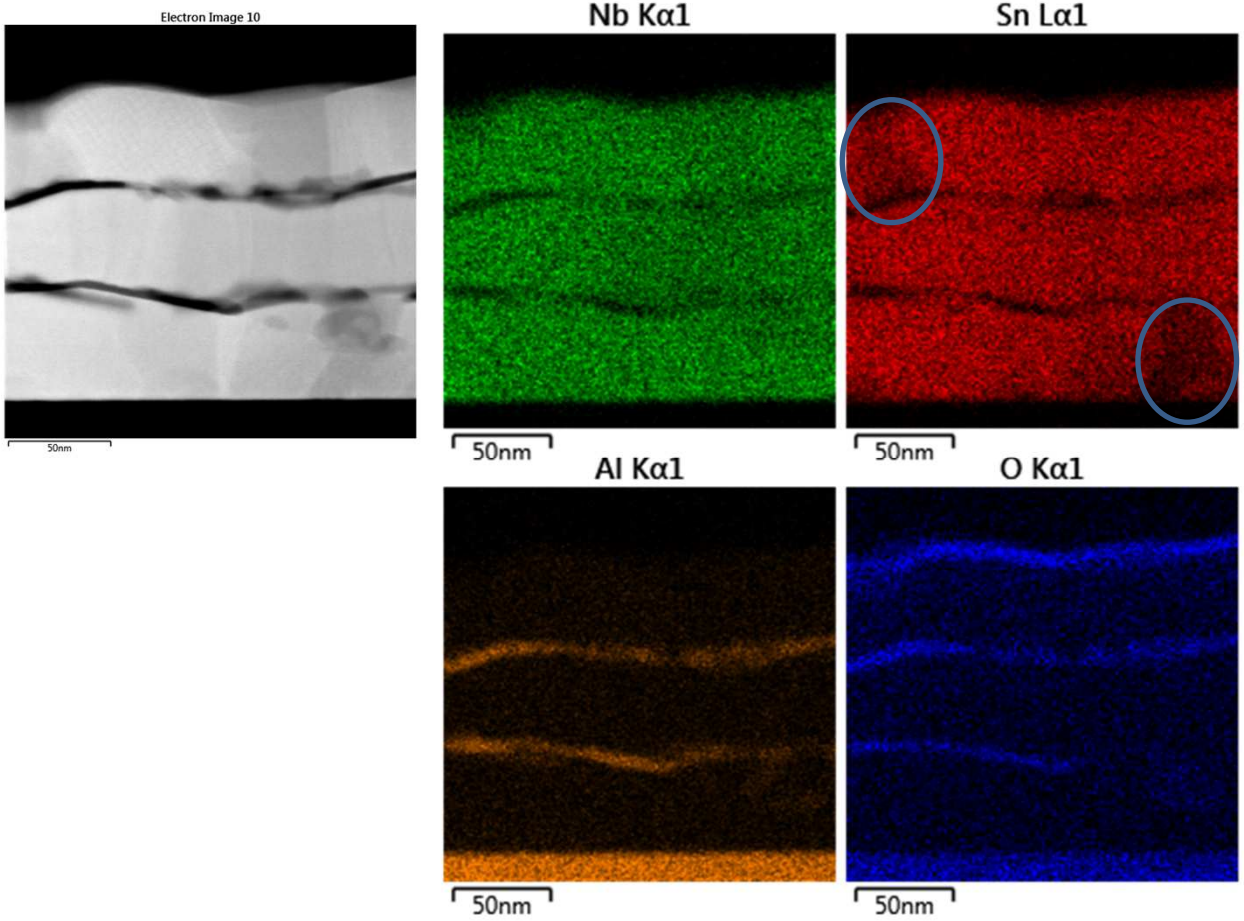
Al_2O_3 layer well-confined

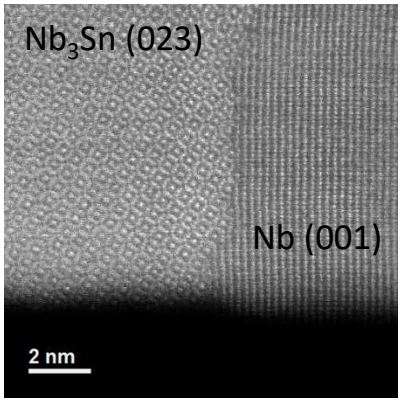






Multilayers – SIS



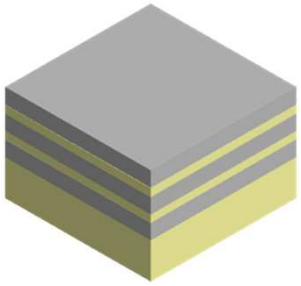


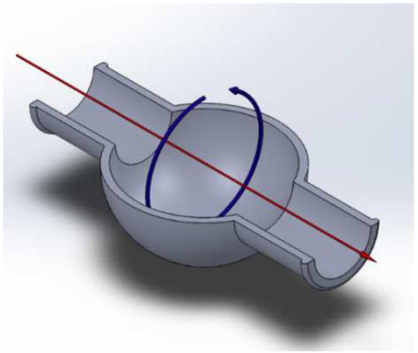
Regions of Sn deficiency
Pure Nb grains

- Oxide layer
- Nb grains
- Discontinuous Al_2O_3

How do these affect RF properties?

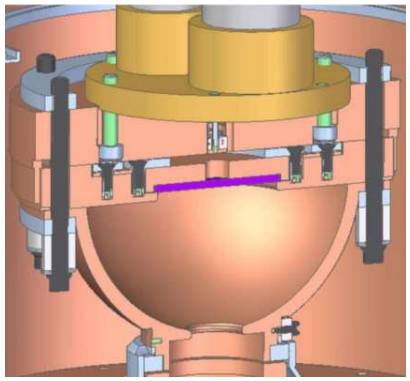
Measuring RF Properties





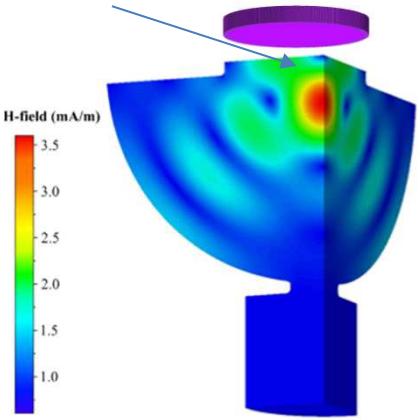
Parallel B
RF field (GHz)

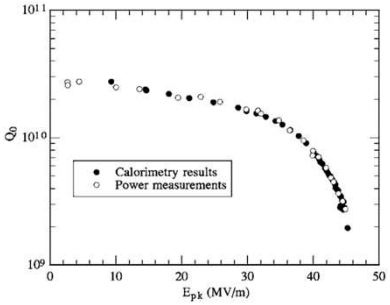
Option 2: Grow 2” wafers



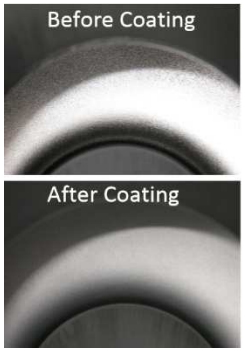
Test system @ SLAC, 11.4 GHz

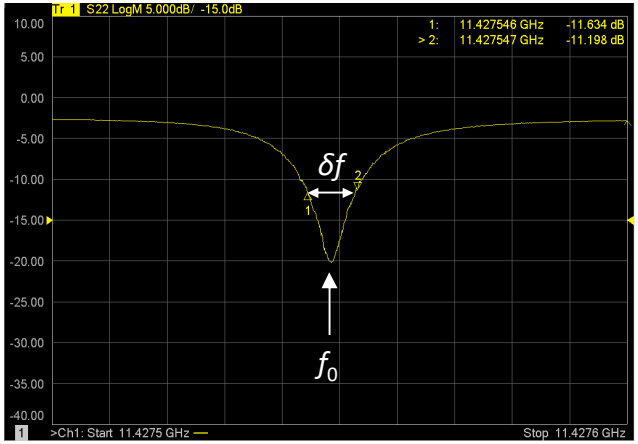
30% of dissipation





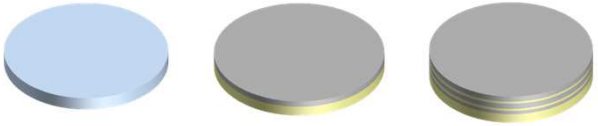
Option 1: Coat a cavity





Posen, S. *Phys. Rev. ST Accel. Beams* 17, 112001 (2014)
Welander, PB. *Proceedings of SRF2015*, 735-738

RF Wafer Measurements

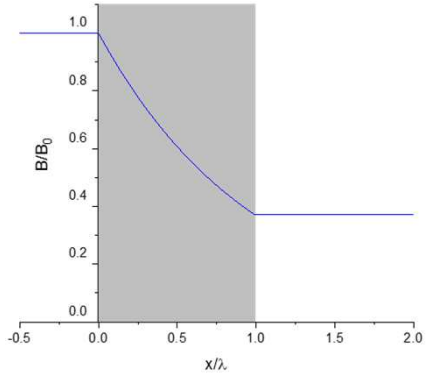


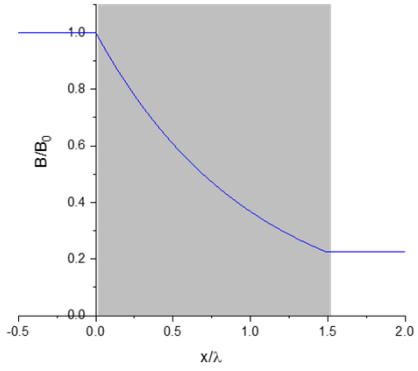
Bulk Nb 120 nm Nb_3Sn SIS

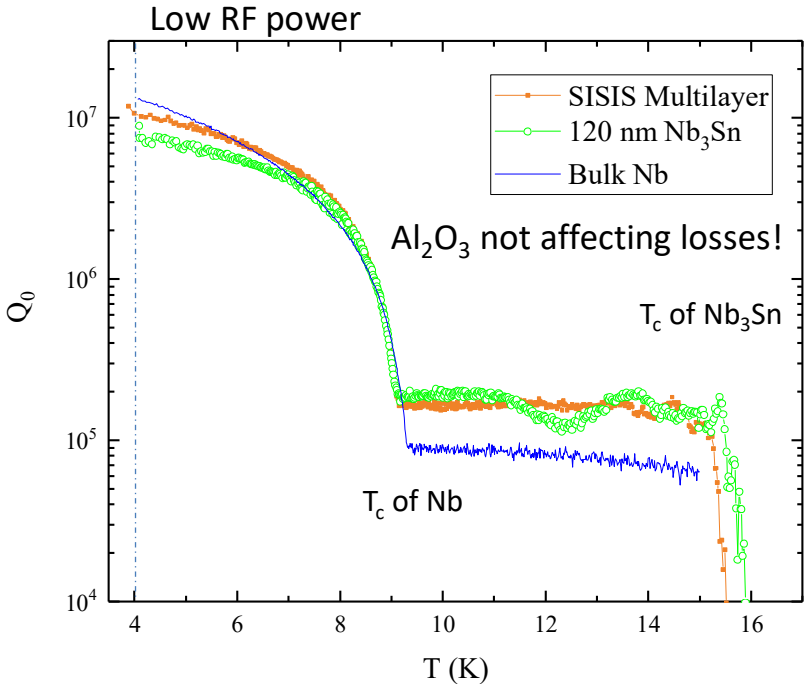
60 nm Nb_3Sn
6 nm Al_2O_3 } 3x

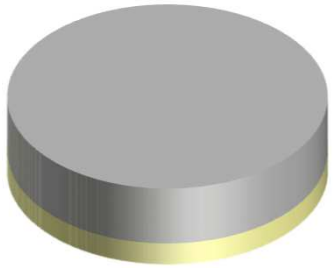
$$R_s = \frac{A\omega^2}{T}\exp\left(-\frac{\Delta(T)}{k_B T}\right) + R_i$$

t_{film} 120 nm ~ λ_{Nb3Sn}
Losses in the substrate



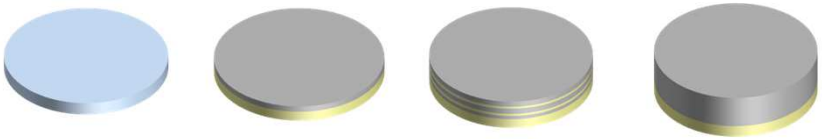






500 nm Nb_3Sn
~4λ_{Nb3Sn}

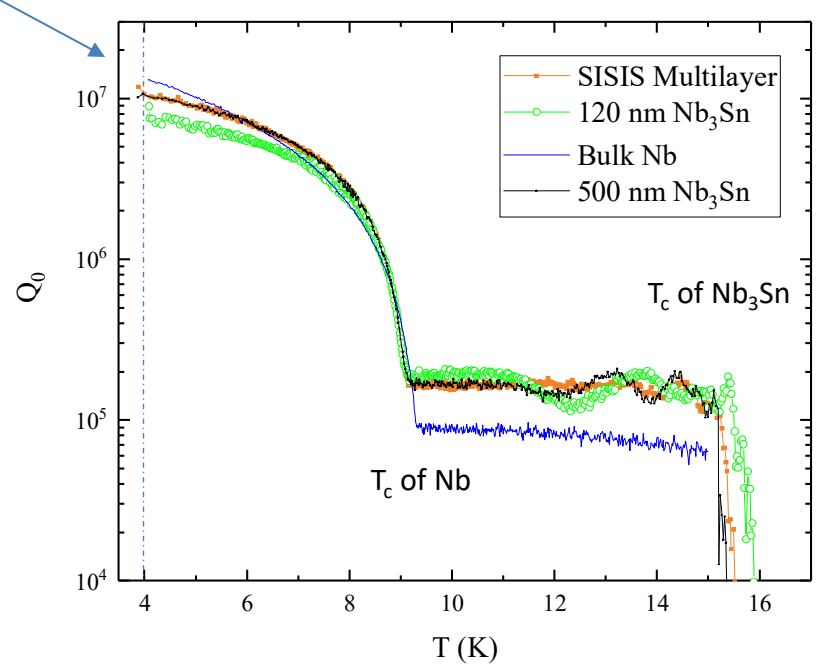
RF Wafer Measurements



Bulk Nb

120 nm Nb_3Sn

SIS
60 nm Nb_3Sn
6 nm Al_2O_3
} 3x

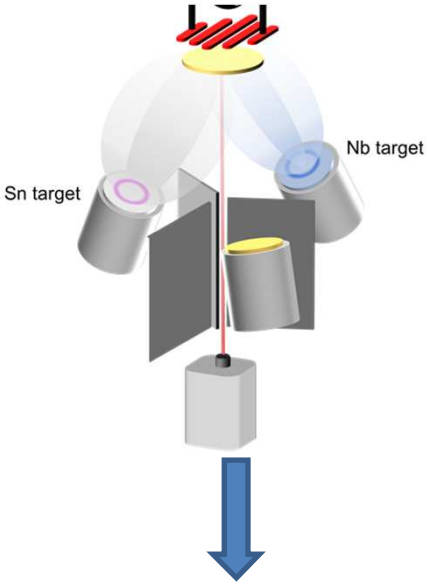


Q_0 has a ceiling with the current growth method

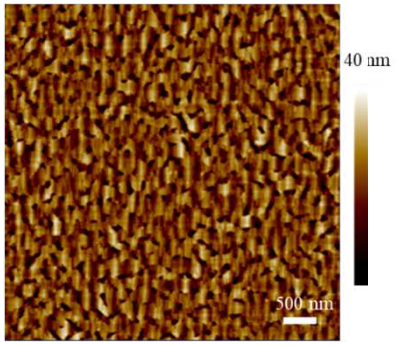
- Oxide layer?
- Disorder in Nb_3Sn?
- Nb precipitates?

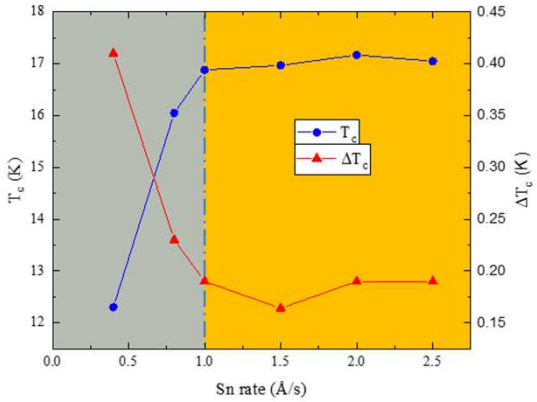
Summary

High-T growth method



Thin films, composition control

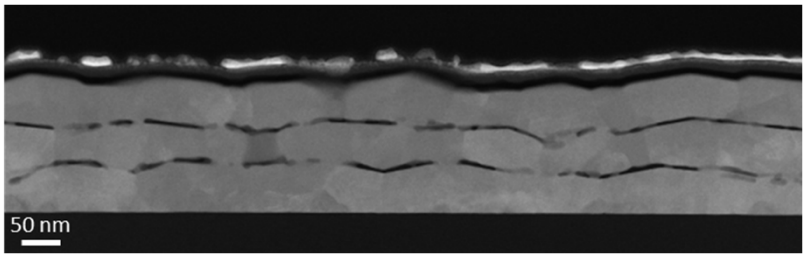


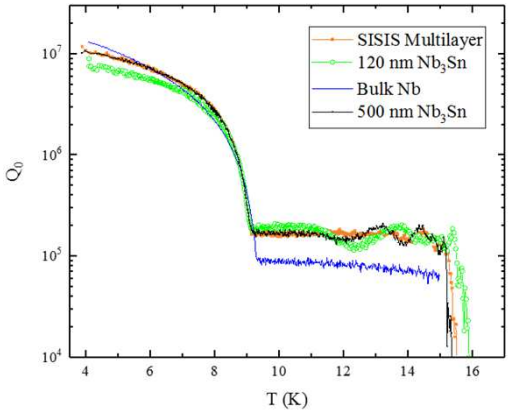


1st iteration
SIS physics exploration

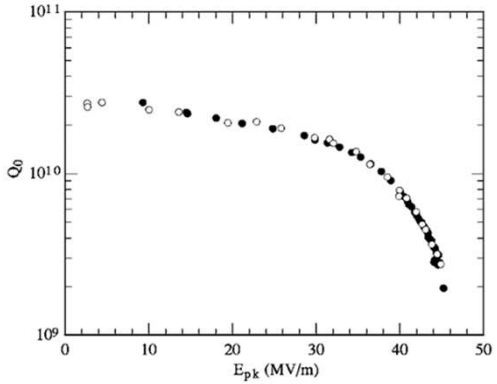
RF characterization tool

SIS multilayers

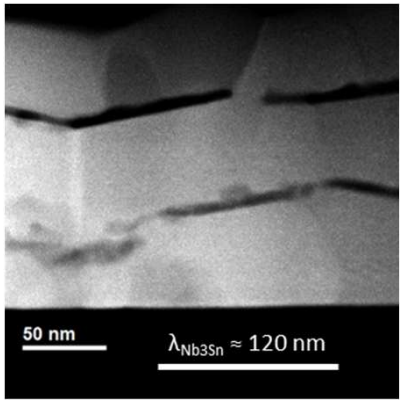




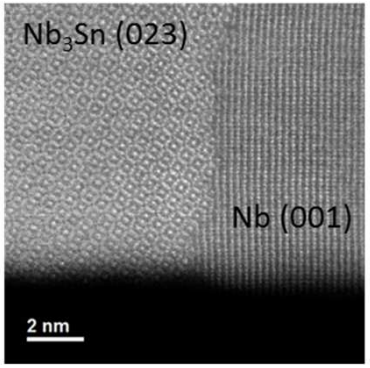
Summary – Next Questions



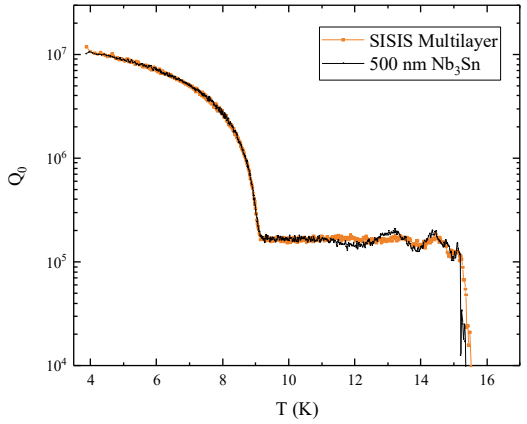
High-field performance



Al_2O_3 morphology effects



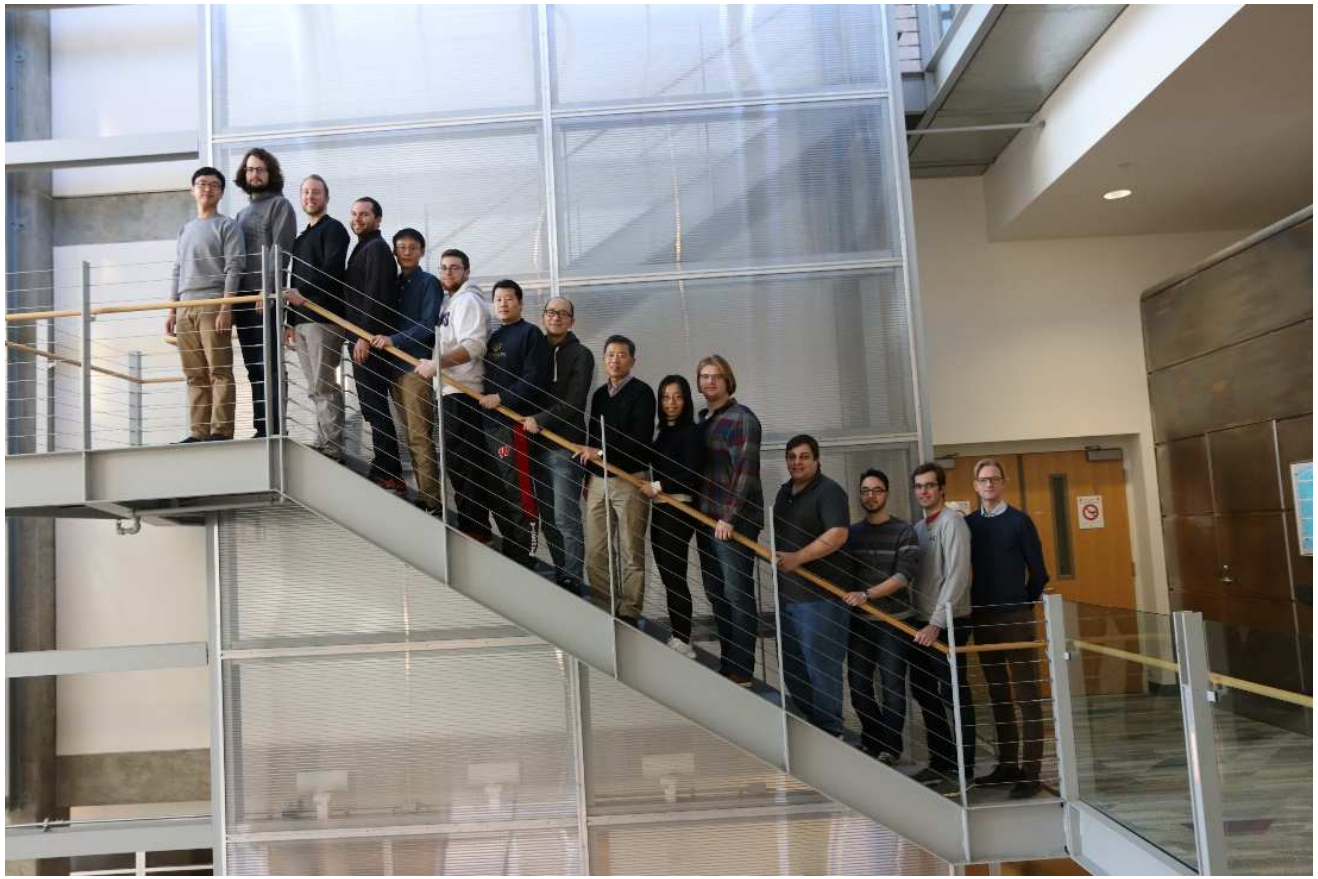
How to eliminate Nb?



What limits Q_0?

Posen, S. Phys. Rev. Applied 4, 044019 (2015)

Acknowledgments



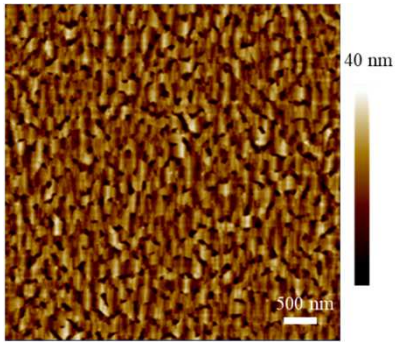
Collaborators:
Paul Welander – SLAC
Lin Xie – SUST
Tak Kametani – FSU
Lian Li – WVU
Jigang Wang – ISU

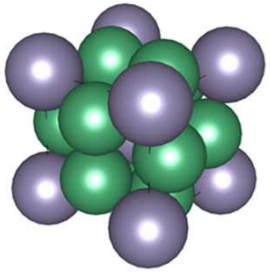
Oxide Lab Members

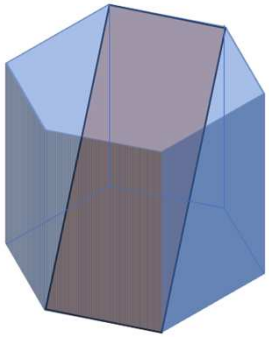
Questions?

Extra Slides

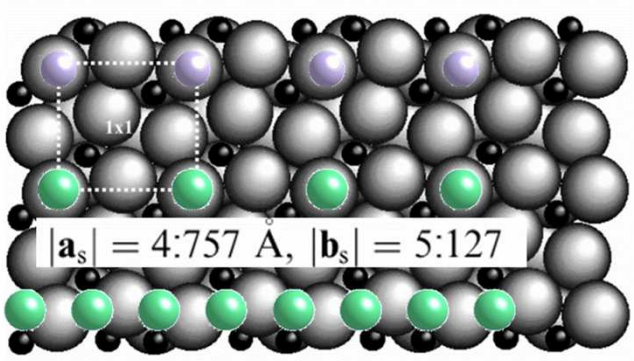
Nb_3Sn Films - Structure

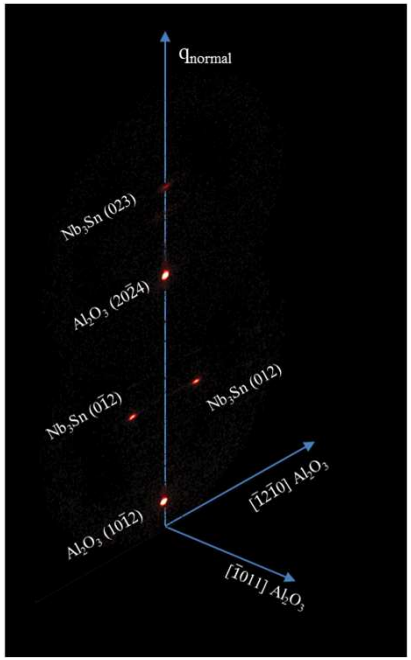


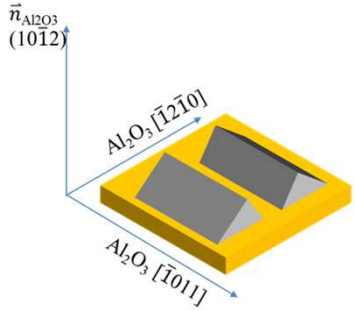


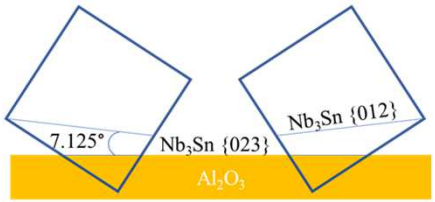


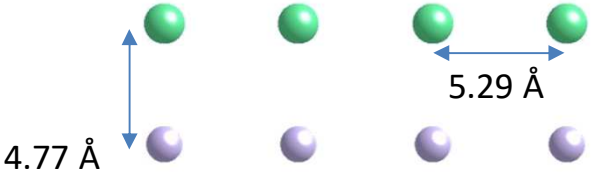
R-Al_2O_3 ($10\bar{1}2$)

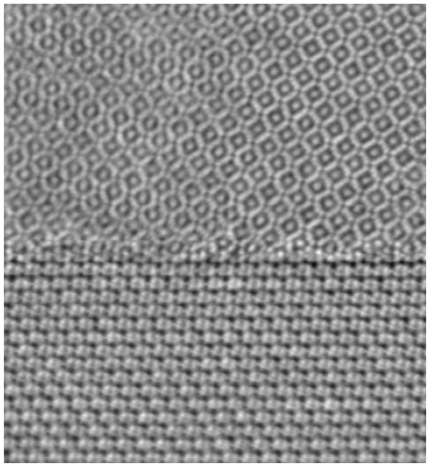




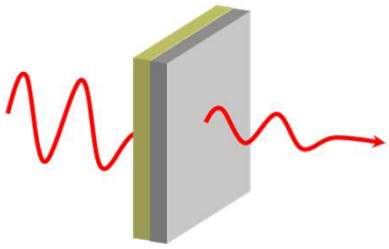


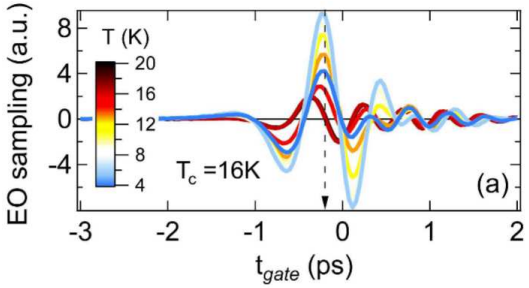


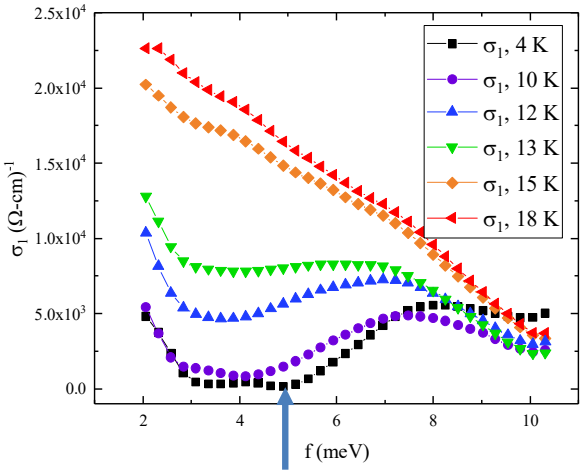




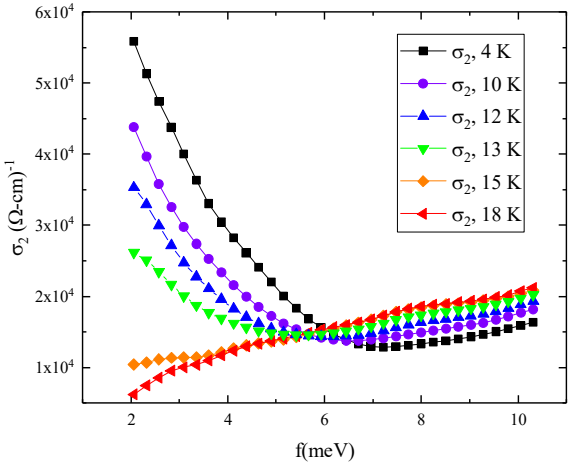
THz spectroscopy

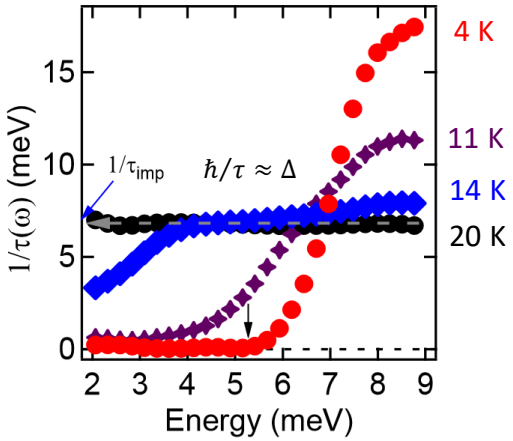






$2\Delta \sim 5$ meV





$$\xi_0 = \hbar v_F / \pi\Delta$$

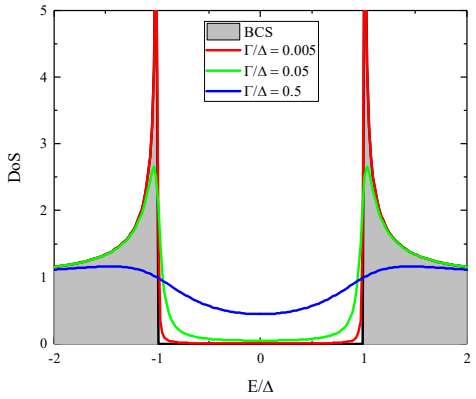
$$v_F \tau = l_{mfp}$$

$$\xi_0 = v_F \tau / \pi = l_{mfp} / \pi$$

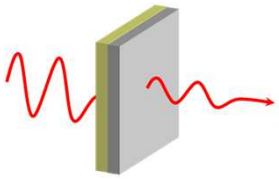
$$\xi_0 \approx l_{mfp}$$

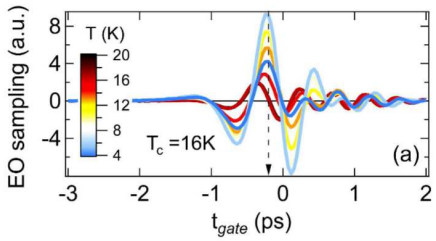
Expect low scattering

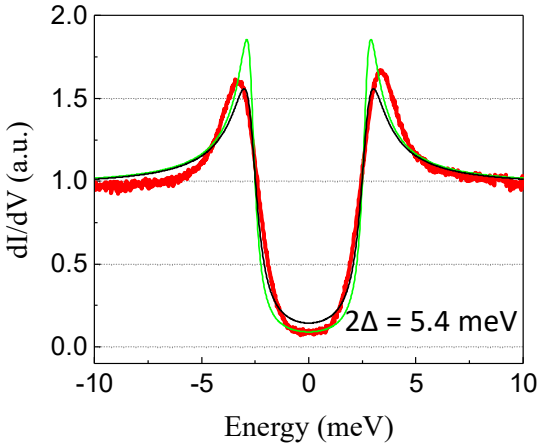
STM and THz measurements

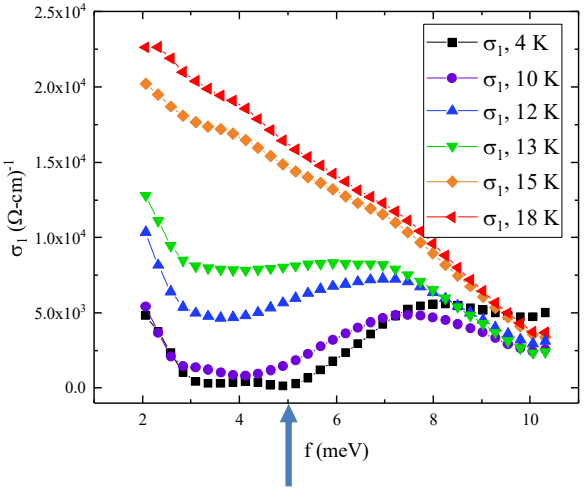


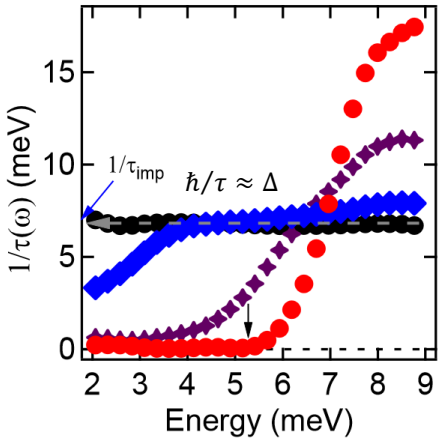
$$R_s = \frac{A\omega^2}{T}\exp\left(-\frac{\Delta(T)}{k_B T}\right) + R_i$$











$R_i(\Gamma = 0.46) = 8.6\ \mathrm{n\Omega}$
$R_i(\Gamma = 0.3) = 3.7\ \mathrm{n\Omega}$

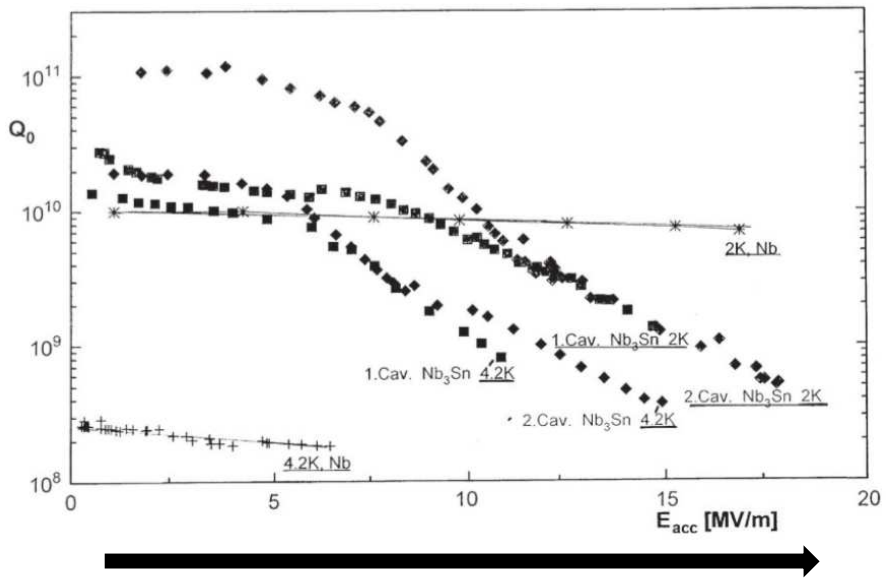
$R_{i_{\mathrm{Nb}}} \approx 10\ \mathrm{n\Omega}$

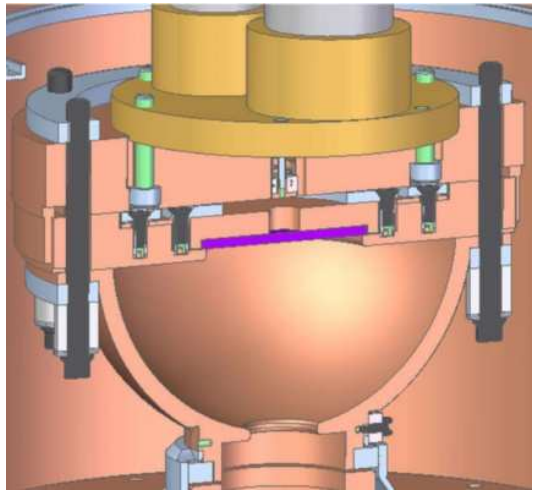
2Δ ~ 5 meV

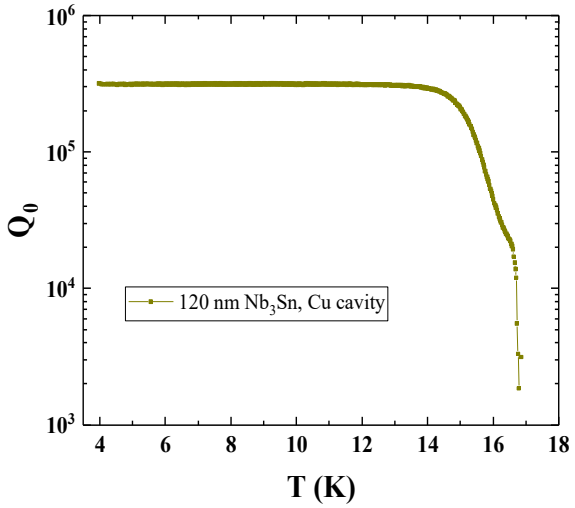
$\xi_0 \approx l_{mfp}$

Expect low scattering

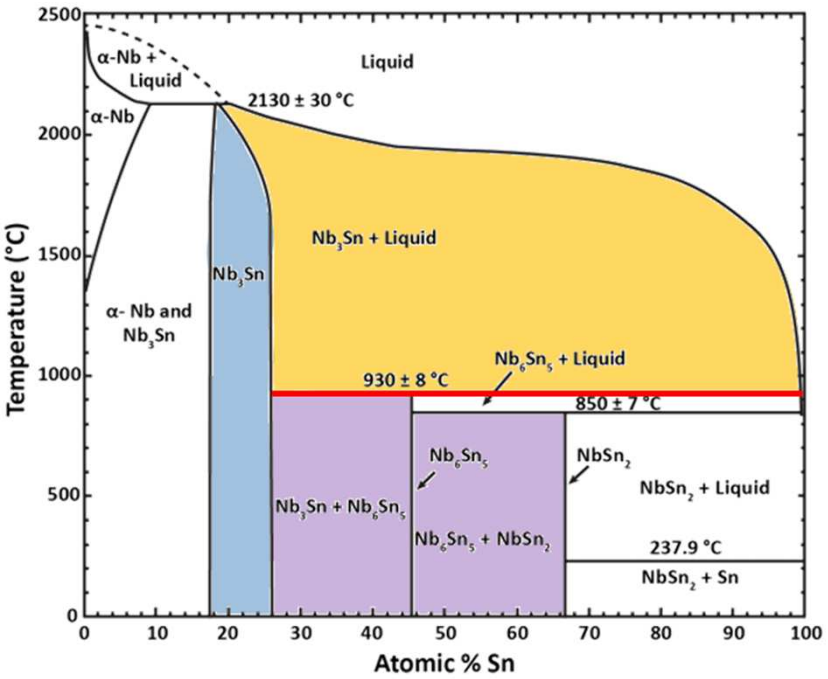
High-Field Measurements

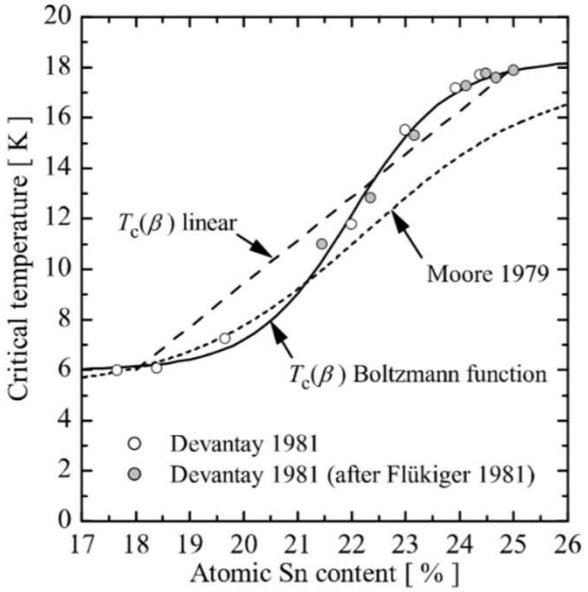






Growing Nb_3Sn





Below 930 °C: Nb_6Sn_5, $NbSn_2$ are stable

Single-phase Nb_3Sn region: 17-25%

Above 930 °C: Nb_3Sn + Sn(L)