Nb_3Sn SRF Cavity Development at Fermilab

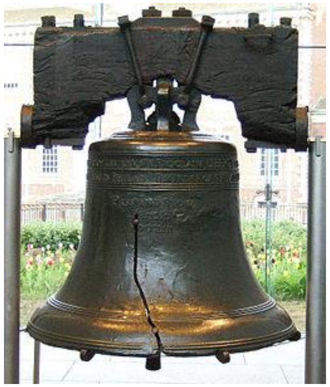
Sam Posen

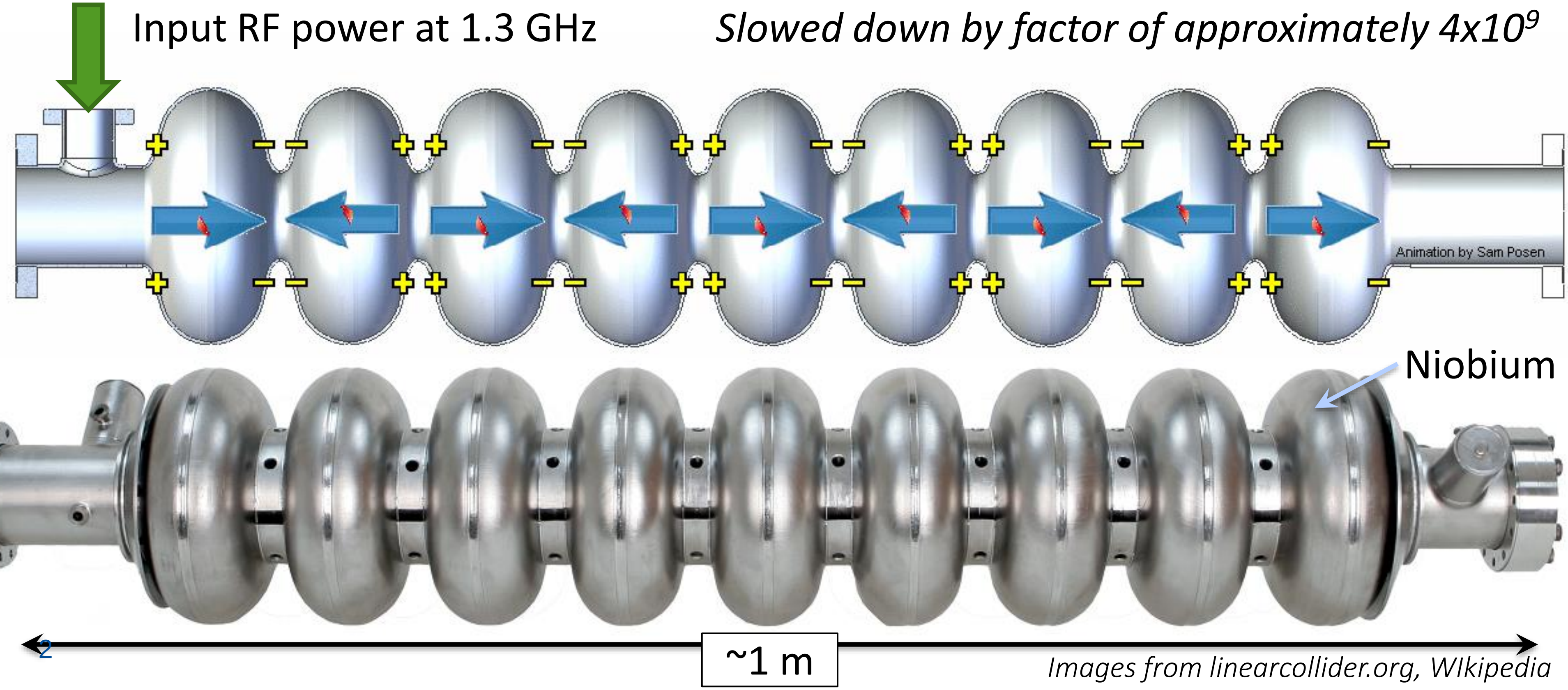
NSCL Nuclear Science Seminar

September 12, 2018

Particle Acceleration via SRF Cavities

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Over billions of cycles, large electric field generated
- Particle beam gains energy as it passes through





Images from linearcollider.org, WIkipedia

Particle Acceleration via SRF Cavities

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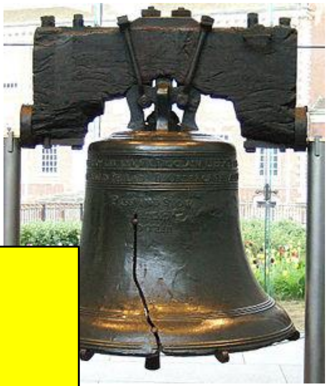
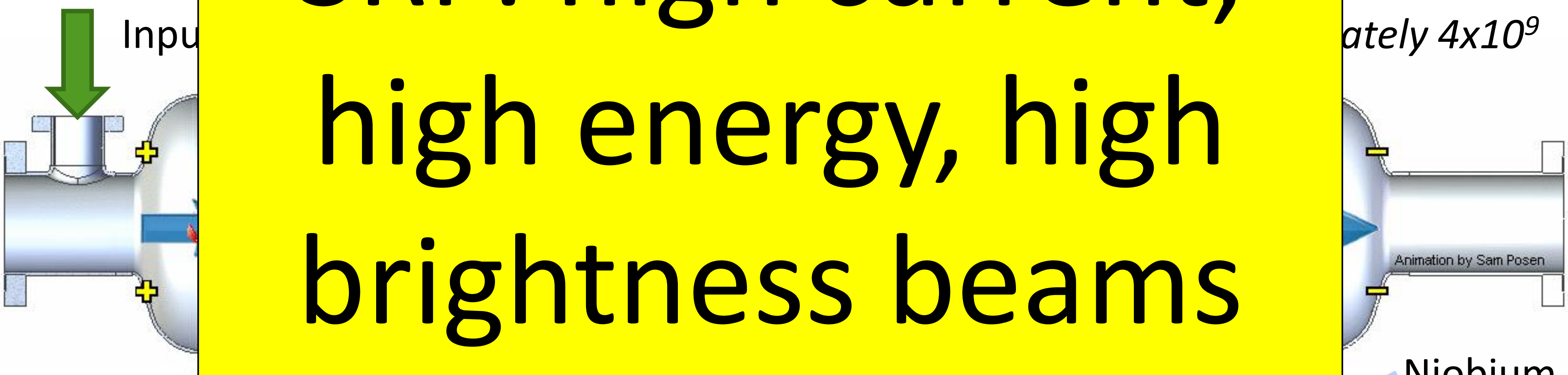
- Over billions of cycles, large electric field generated
- Par

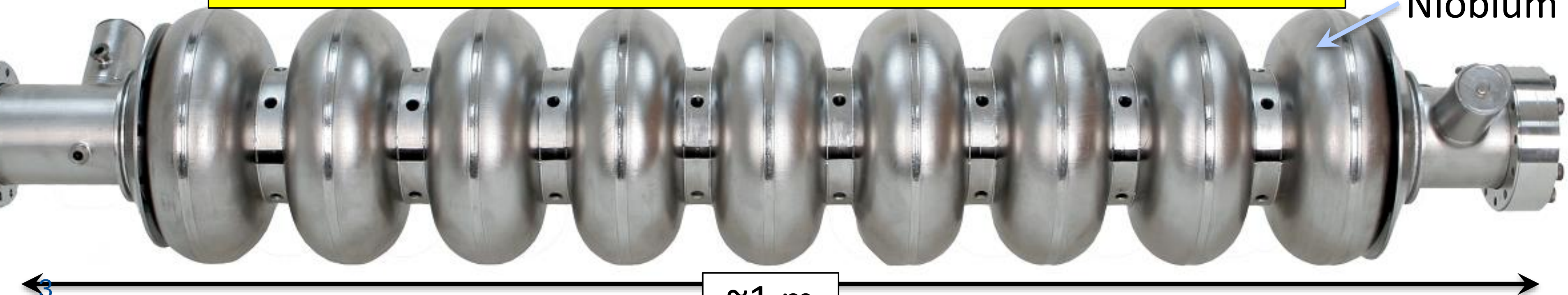


SRF: high current, high energy, high brightness beams

Inpu

ately $4x10^9$



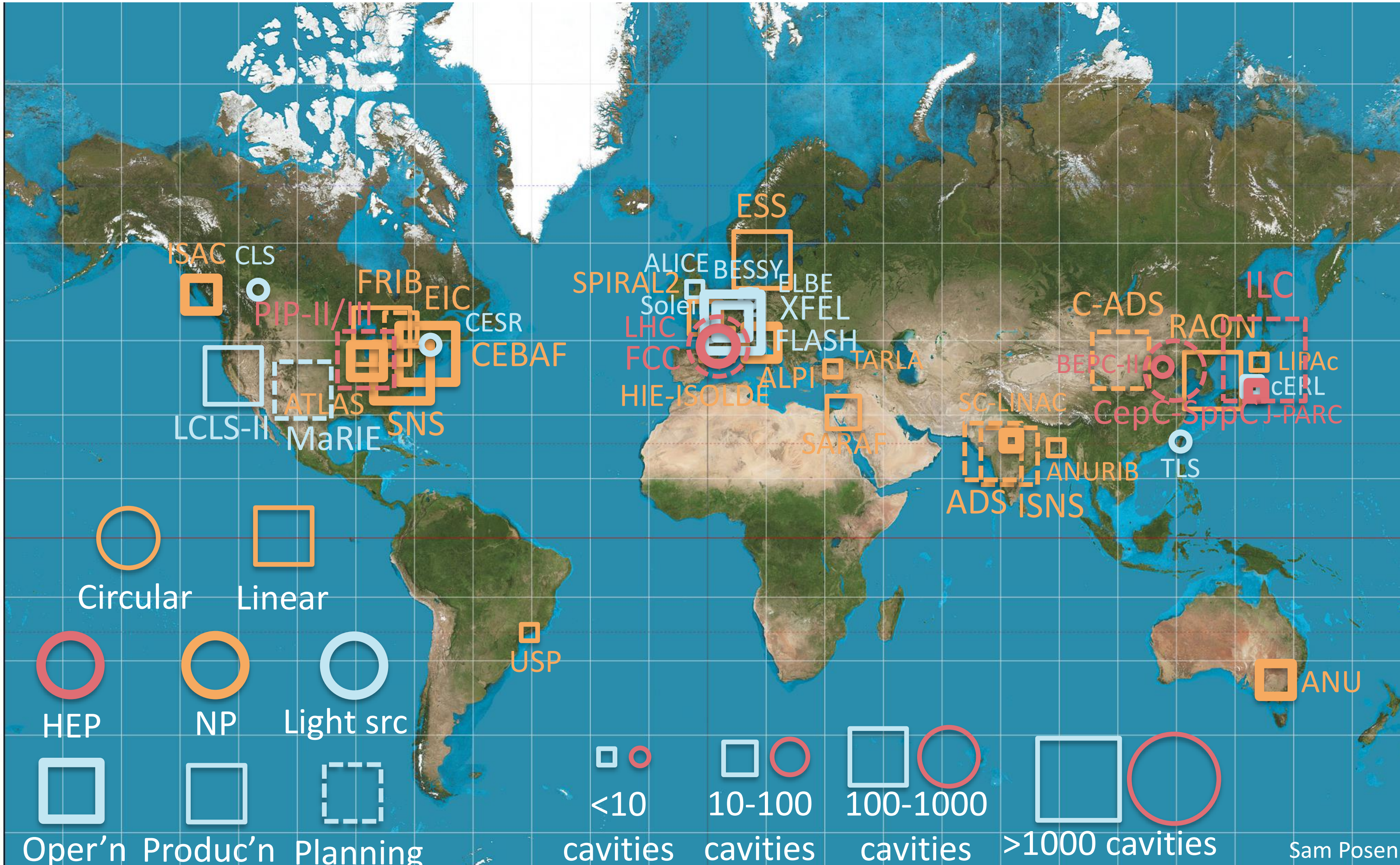


Images from linearcollider.org, WIkipedia

Impact of SRF on Accelerators for Science

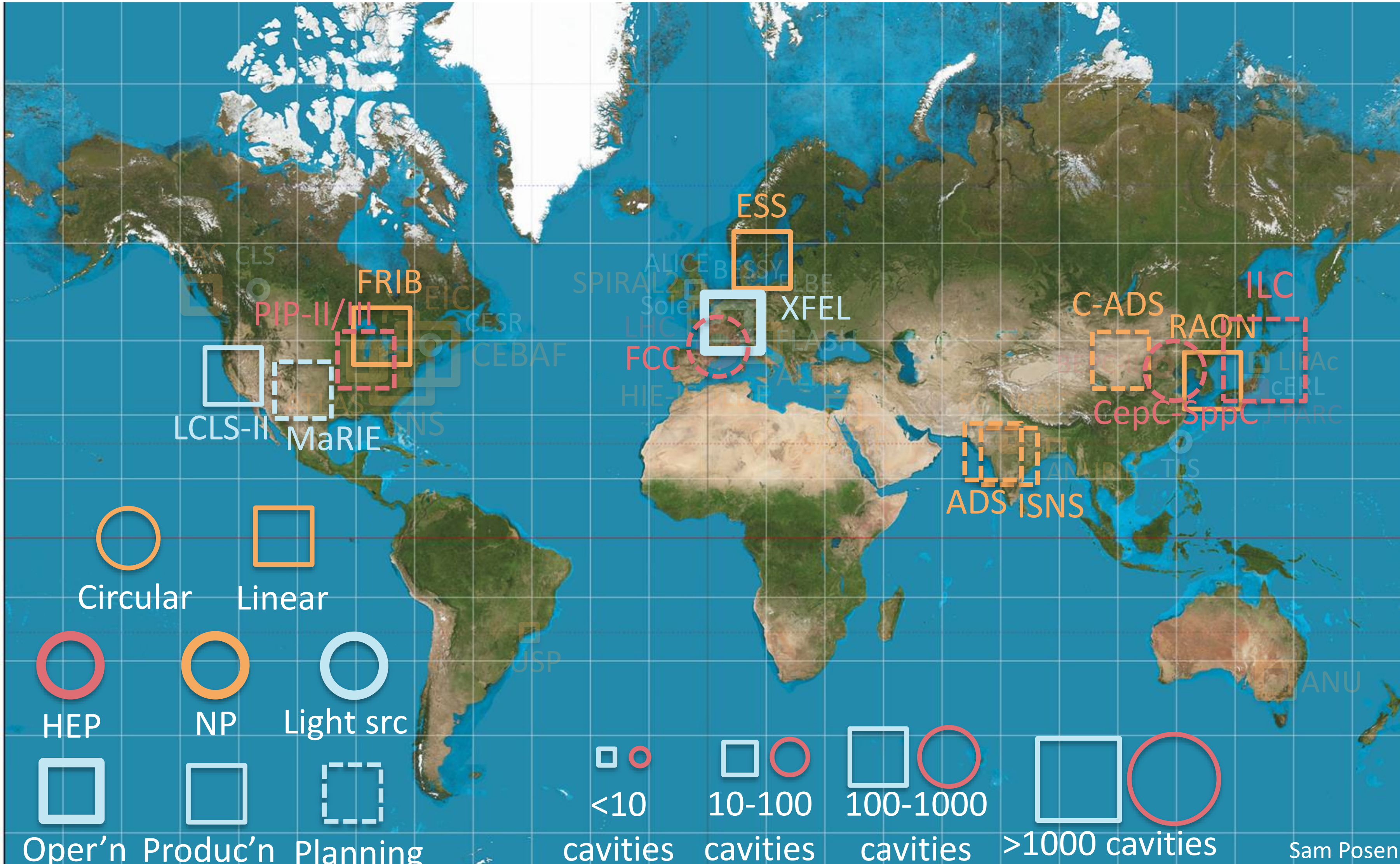
- Low energy nuclear physics, for nuclear shape, spin, vibration
  - Heavy ion linacs
- Medium energy nuclear physics, structure of nucleus, quark-gluon physics
  - Recirculating linac
- Nuclear astrophysics, for understanding the creation of elements
  - Facility for rare isotope beams (FRIB)
- X-Ray Light Sources for life science, materials science & engineering
  - Storage rings, free electron lasers, energy recovery linacs
- Spallation neutron source for materials science and engineering, life science, biotechnology, condensed matter physics, chemistry
  - High intensity proton linac
- Future High Intensity Proton Sources for
  - Nuclear waste transmutation, energy amplifier, power generation from Thorium
- High energy physics for
  - Electron-positron storage ring colliders, linear collider, proton linacs for neutrinos

SRF Accelerators Around the World



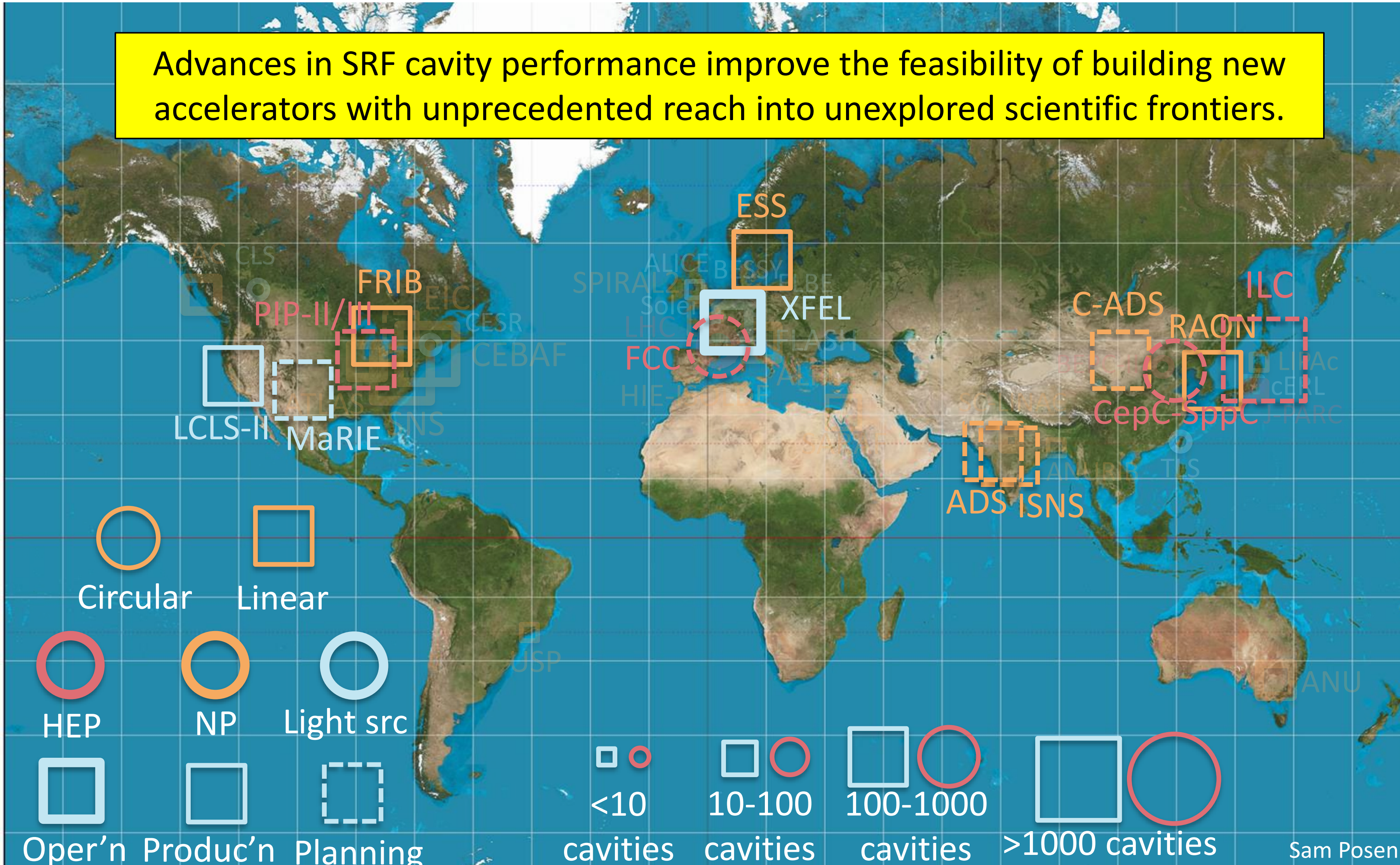
Map from Wikipedia. Non-exhaustive facility list.

SRF Accelerators Around the World



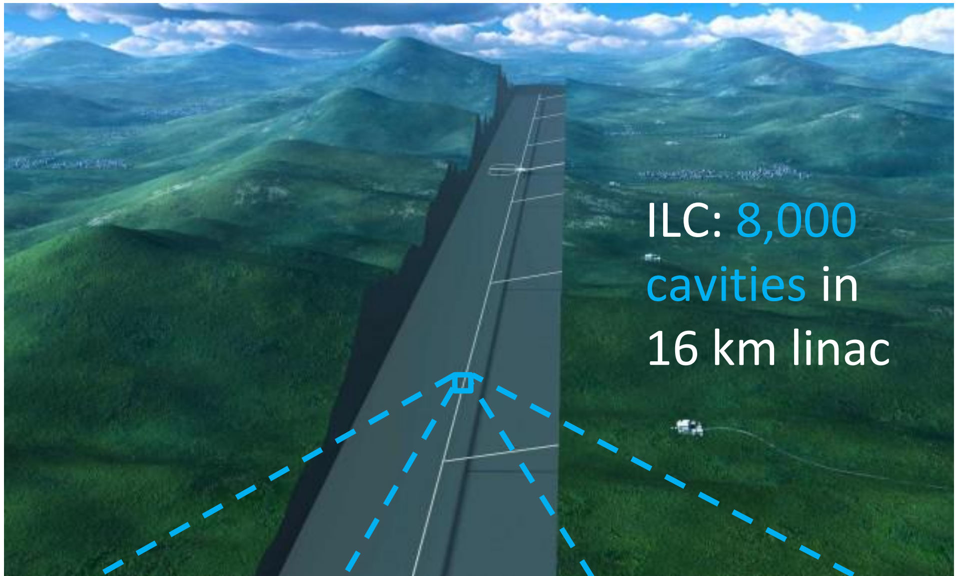
Map from Wikipedia. Non-exhaustive facility list.

SRF Accelerators Around the World



Map from Wikipedia. Non-exhaustive facility list.

Gradient -> Length for Linear Accelerator



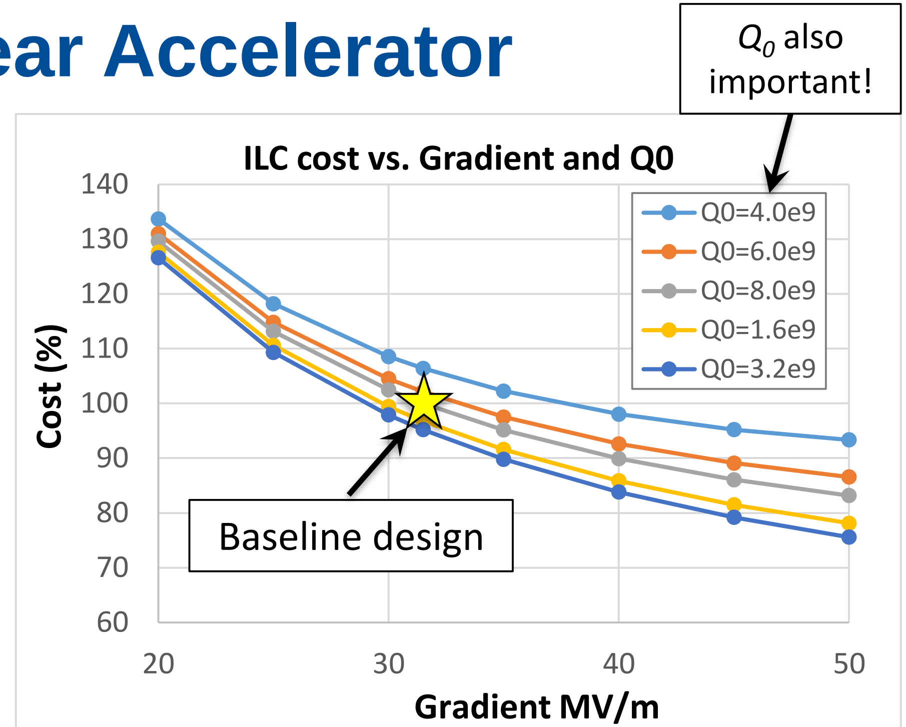


Image from linearcollider.org. Tunnelflug video by European XFEL. Cost analysis by N. Solyak

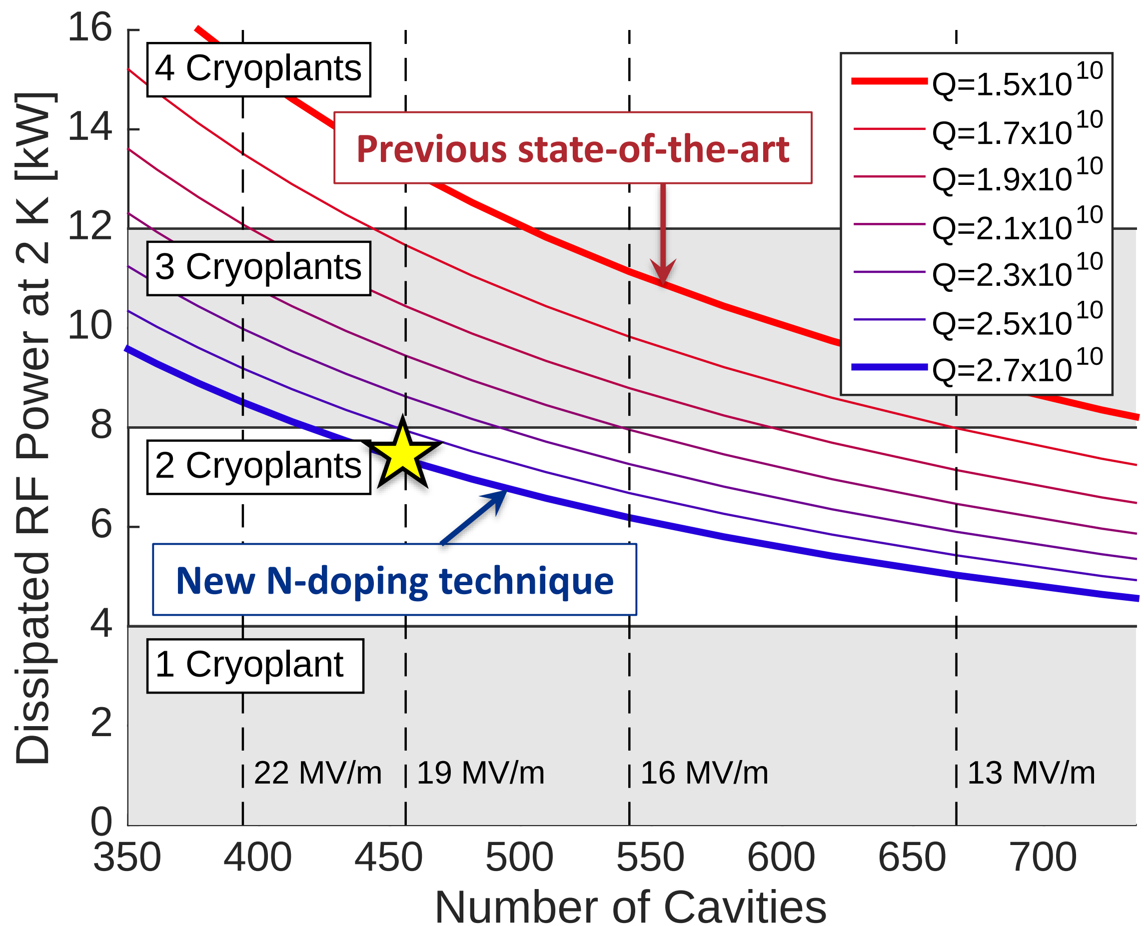
Q_0 -> Cryogenic Infrastructure, Operating Cost

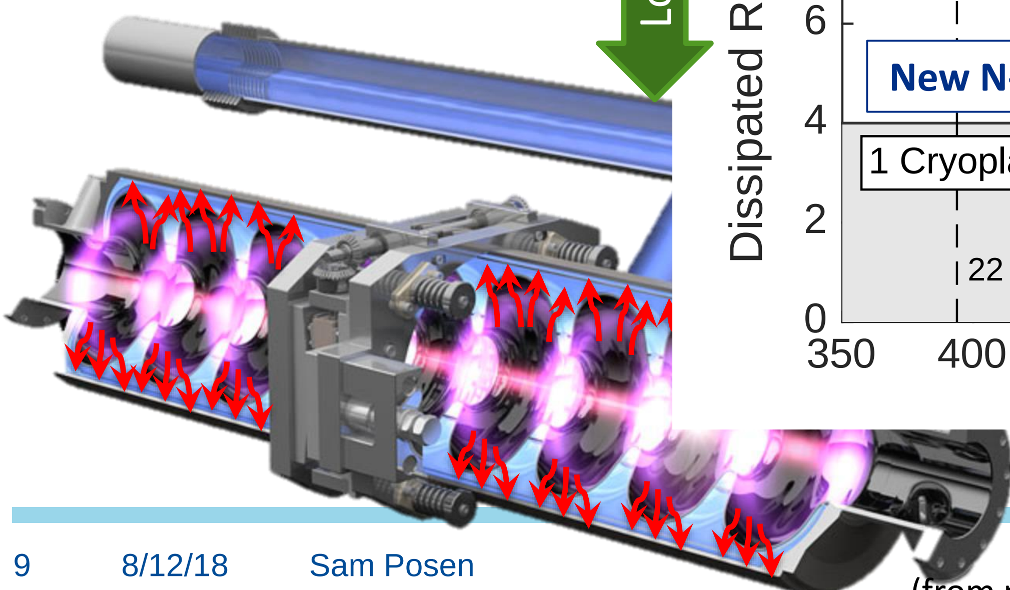
$$P_{diss} \sim E_{acc}/Q_0$$

(for fixed E_{max})

Lower cost

8 GeV CW SRF Linac

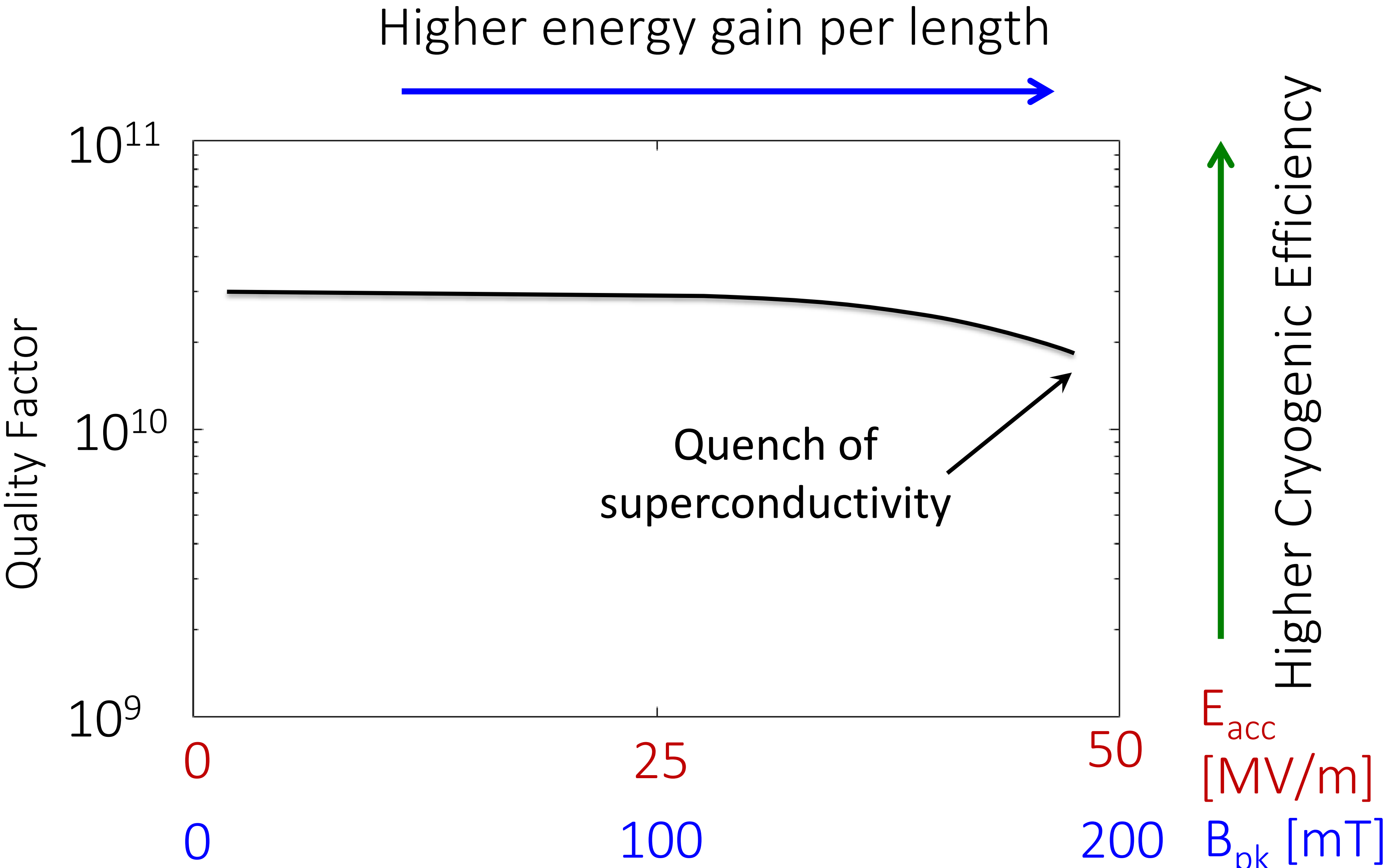




Lower cost

Above is a rough calculation for LCLS-II upgrade
(from me, not to be considered official numbers from project)

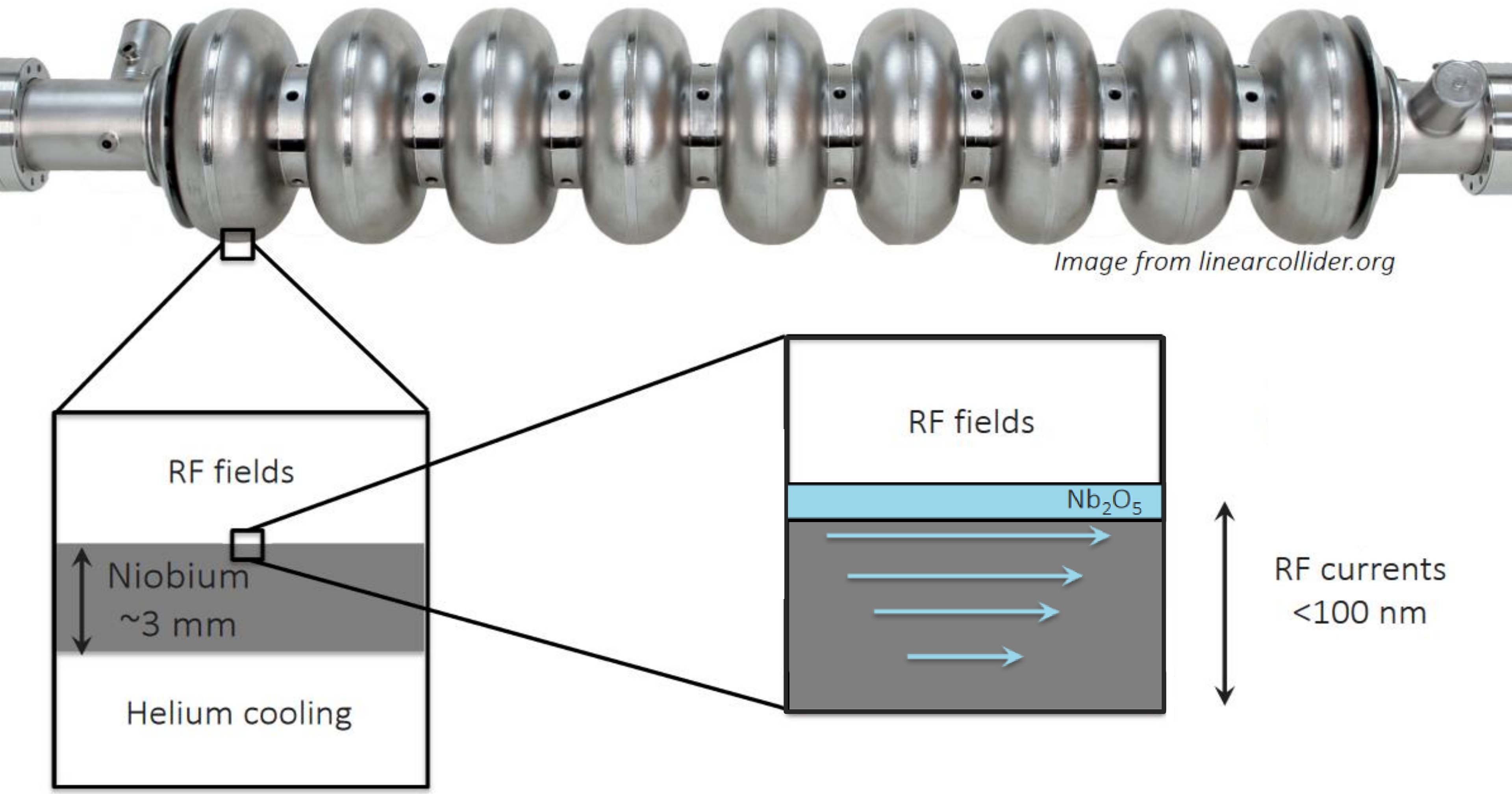
SRF Figures of Merit: Q vs E Curve



Slide adapted from M. Liepe

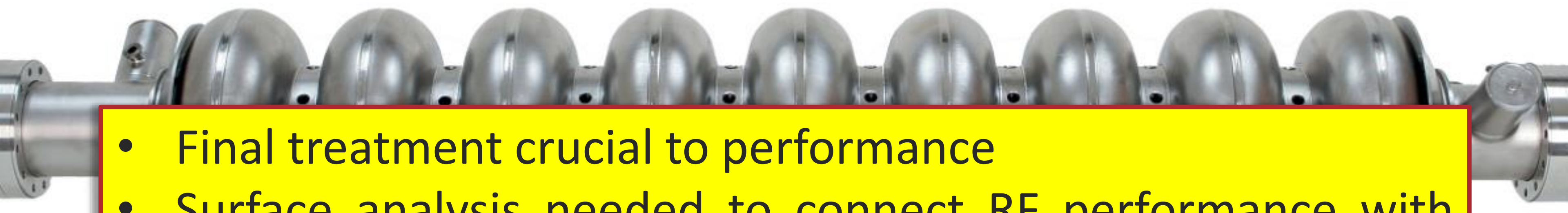
Cavity performance depends on nm properties of inner surface

- RF currents concentrated in the first ~100 nm of the **inner surface**

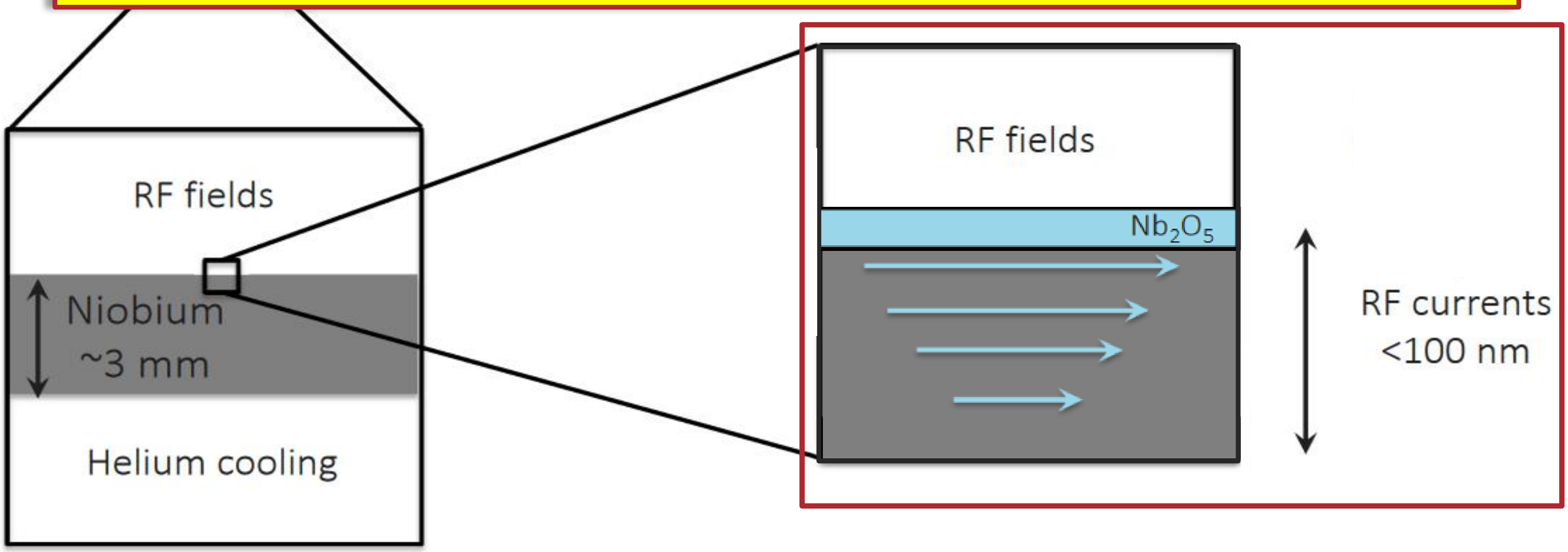


Cavity performance depends on nm properties of inner surface

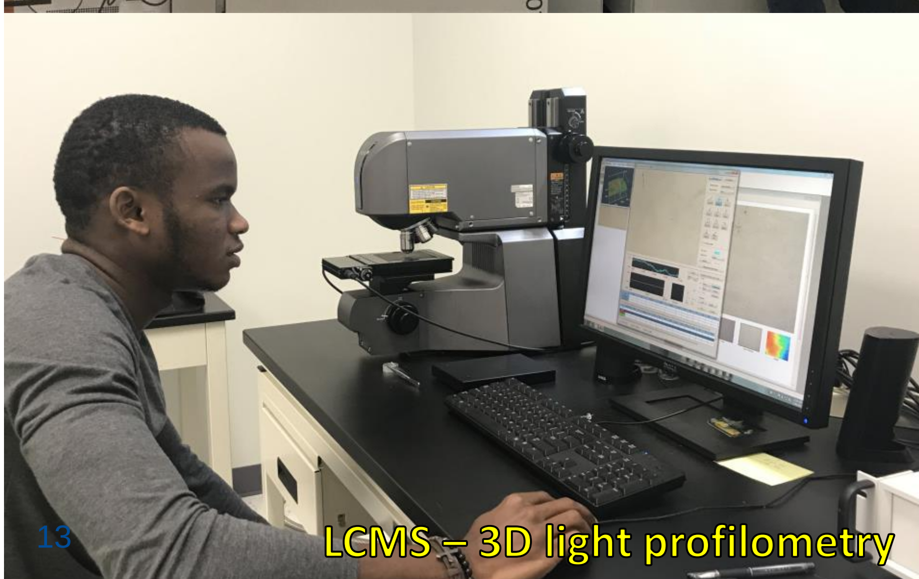
- RF losses concentrated in the first ~100 nm of the **inner surface**



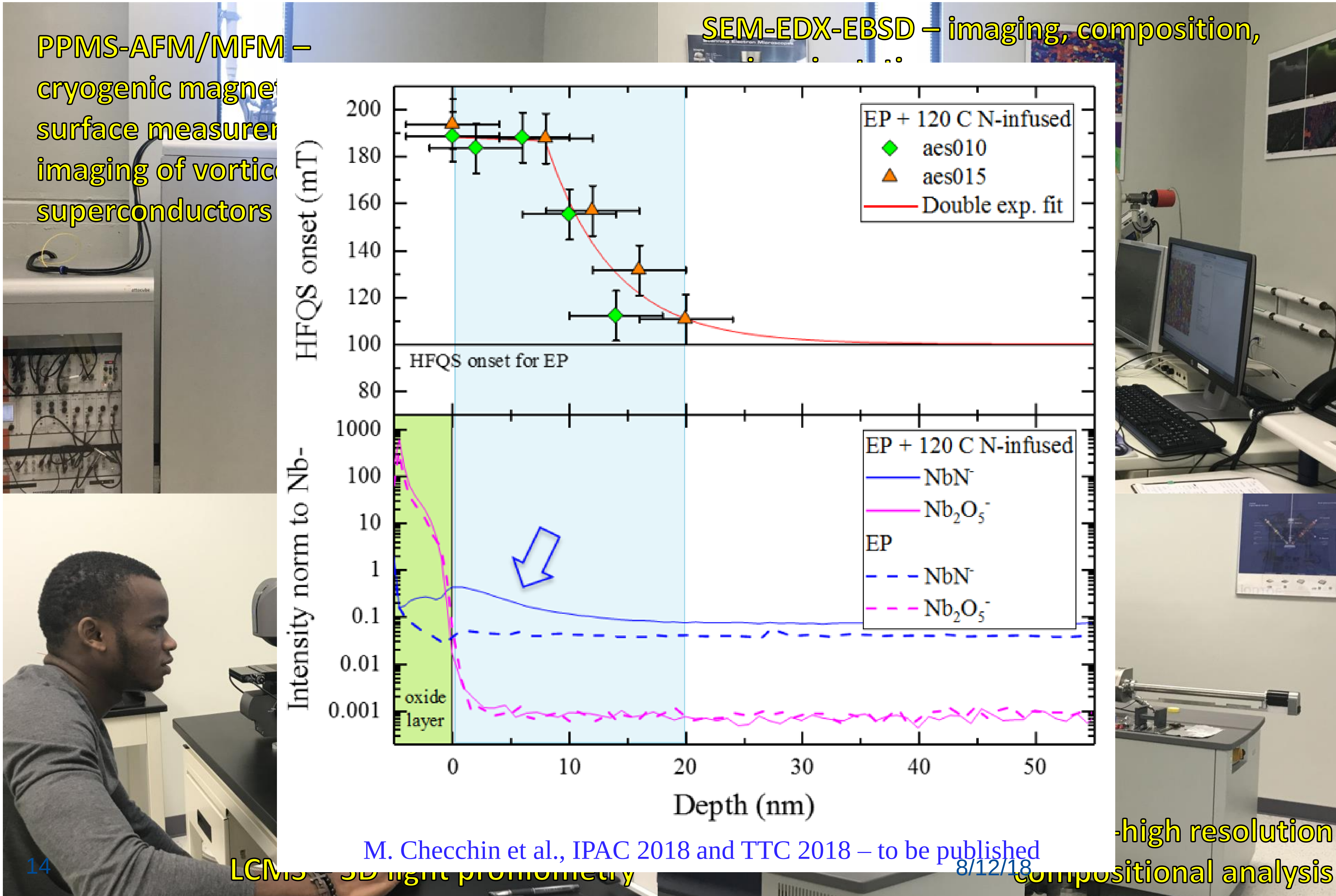
- Final treatment crucial to performance
- Surface analysis needed to connect RF performance with material properties



Fermilab Materials Science Laboratory – Understanding how to push performance through investigation of microstructure



Fermilab Materials Science Laboratory – Understanding how to push performance through investigation of microstructure

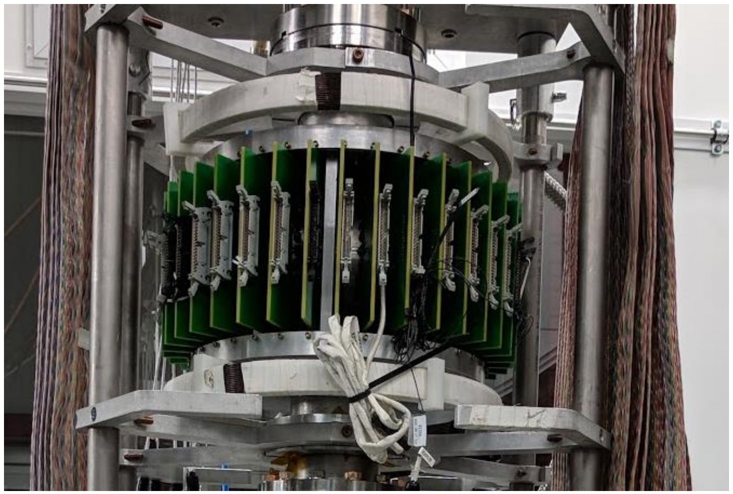


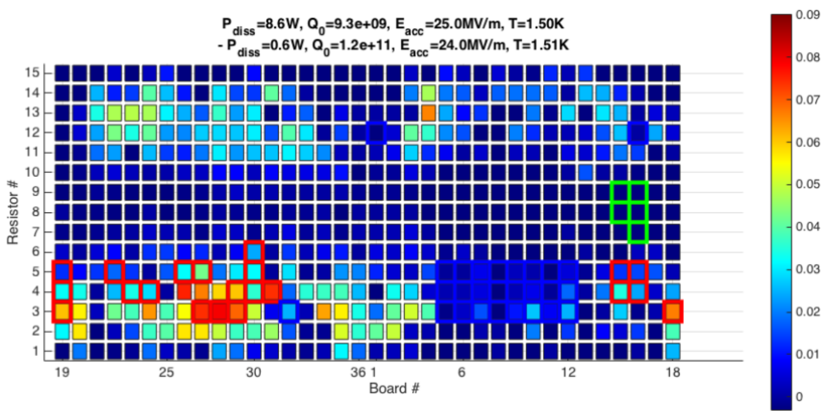
M. Checchin et al., IPAC 2018 and TTC 2018 – to be published

Material characterization of inner cavity surface

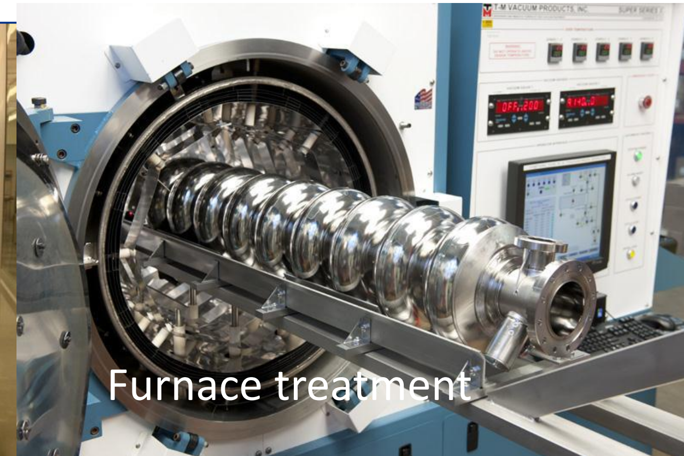
RF characterization + T-map highlight areas with different dissipative behavior

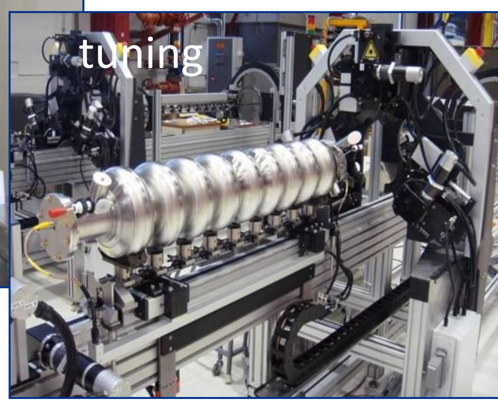
Generation of cavity cut-outs leads to the most representative samples that can be analyzed





Major Cavity Processing/Treatment Facilities





Cryomodule Assembly

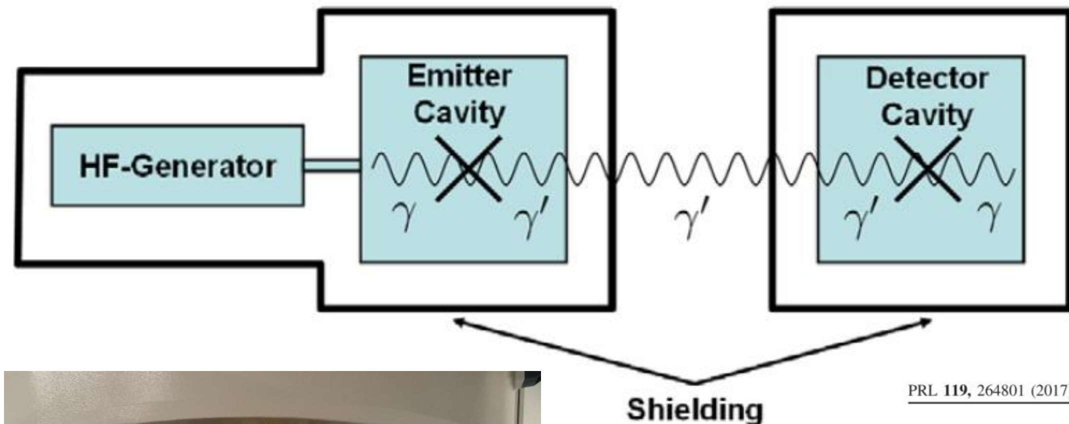
- Facilities used for: clean assembly of cryomodules, from individual cavities to accelerator-ready module
- Projects/Programs served: LCLS-II, PIP-II, future SRF accelerator projects, opportunity for assembly of high gradient R&D cryomodule to push state-of-the-art
- Uniqueness of facility: one of two major cryomodule assembly facilities in the US, ~4 of this scale in the world

Example: LCLS-II Cryomodule Assembly

Non-accelerator SRF applications: quantum computing and dark sector searches

S. R. Parker *et al*, Phys. Rev. D 88, 112004 (2013)
J. Hartnett *et al*, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Looking for hidden paraphotons



Q_{DET}, Q_{EM} < 10^5 so far used

$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar \omega_\gamma}\right)^8 |G|^2$$

Q_{DET}, Q_{EM} > 10^{10} **SRF can offer >10 orders of magnitude improvement in sensitivity to χ**

FNAL new large dilution refrigerator capable of (>50) **3D-SRF qubits**
(New Ultra low T SRF Facility)

PRL 119, 264801 (2017) PHYSICAL REVIEW LETTERS week ending 29 DECEMBER 2017

Understanding Quality Factor Degradation in Superconducting Niobium Cavities at Low Microwave Field Amplitudes

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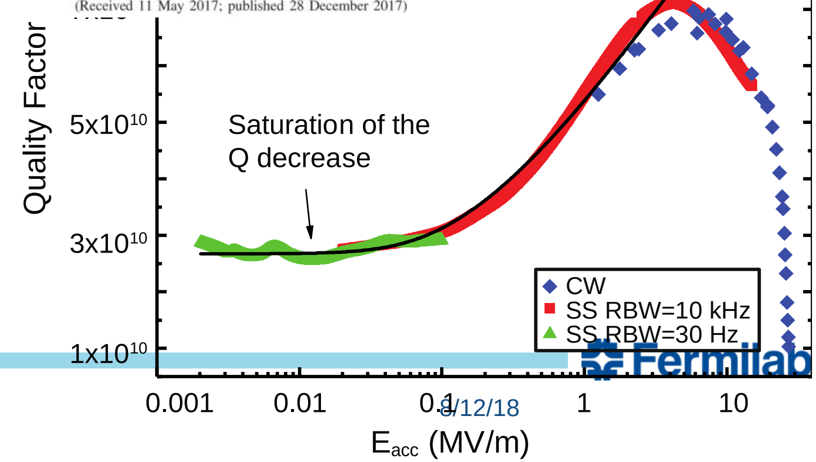
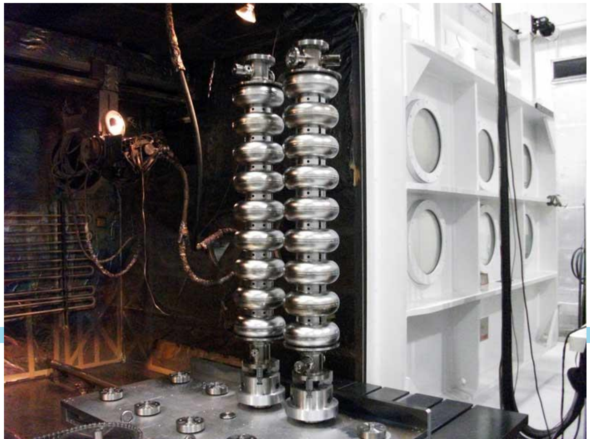


Nb_3Sn SRF Coating at Fermilab

Why is Niobium the Traditional SRF Material?

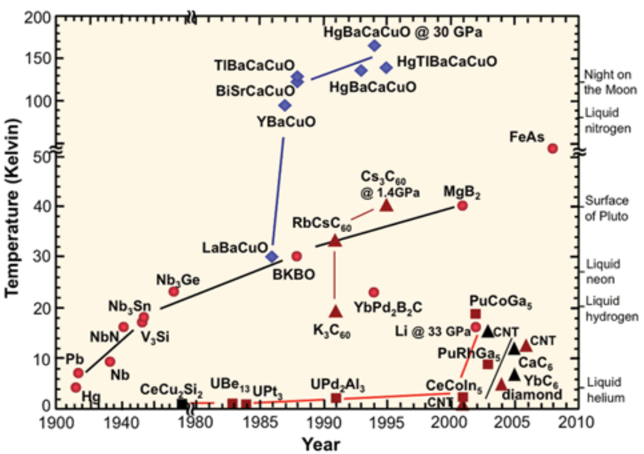
- Niobium has been the material of choice for SRF cavities for the last ~50 years
- Niobium has some of the best superconducting properties of all elements including highest critical temperature $T_c \sim 9.2$ K
- Easy to work with – purify, make sheets, form, weld, treat
  - Not a compound! Don't need to achieve precise stoichiometry
- Other important features: good structural and thermal properties in bulk form, long coherence length (relatively low defect sensitivity), doesn't react with water

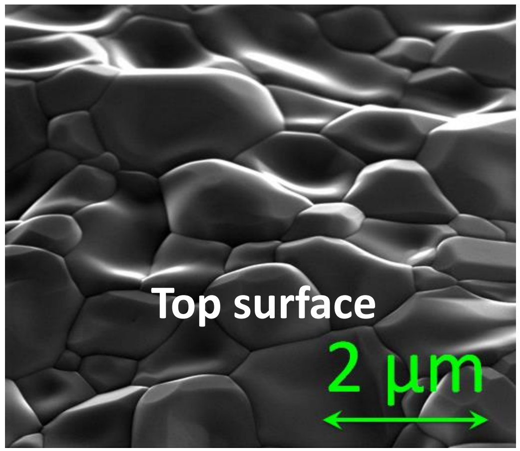
Images from Roark, G. Orly, ESS, SRF 2015, and Fermilab

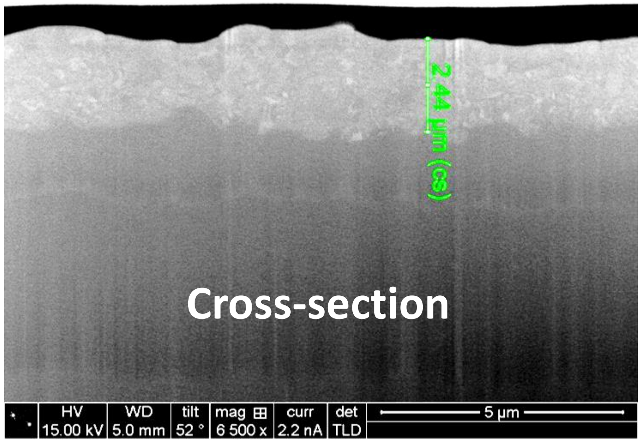


Why Consider Nb_3Sn?

- Larger T_c, larger predicted ultimate field (see next slides)
- Niobium compound: can convert existing cavities
- Only two elements – next step in stoichiometric complexity
- Coherence length smaller than niobium but still several nm
- Brittle and low thermal conductivity, but can be used as a film with thickness large compared to the RF penetration depth



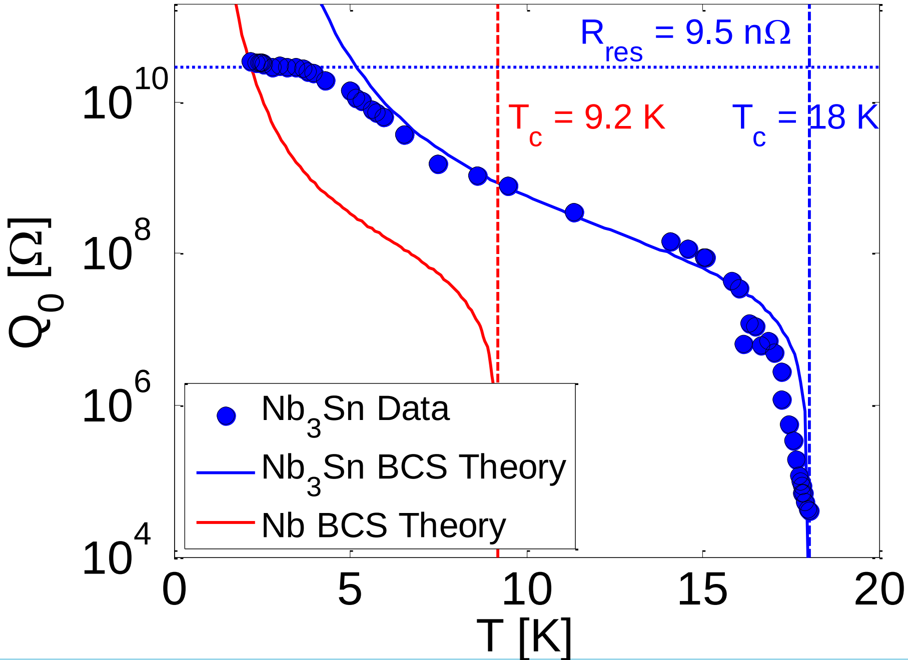


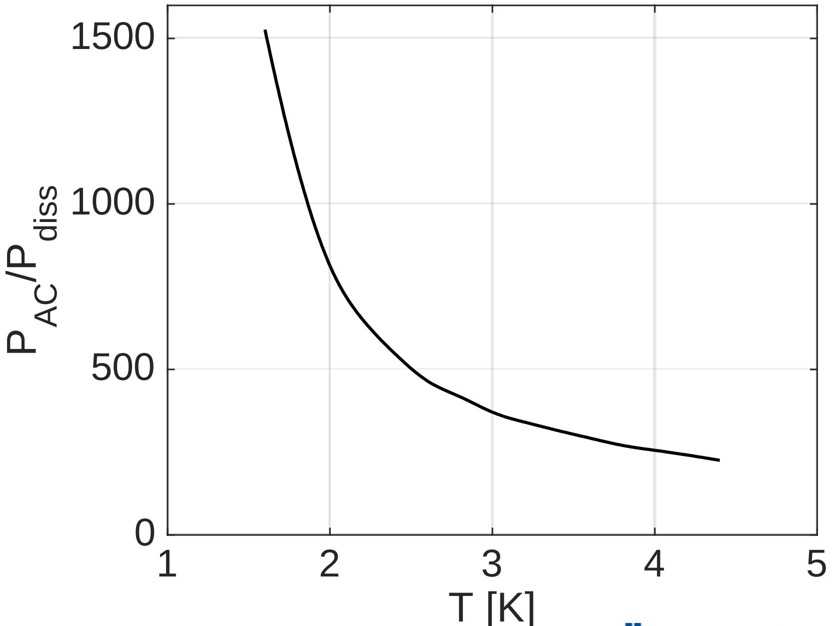


High $Q_0(T)$ via Nb_3Sn

- Large T_c ~ 18 K for Nb_3Sn
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76T_c/T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

CERN cryogenic plant

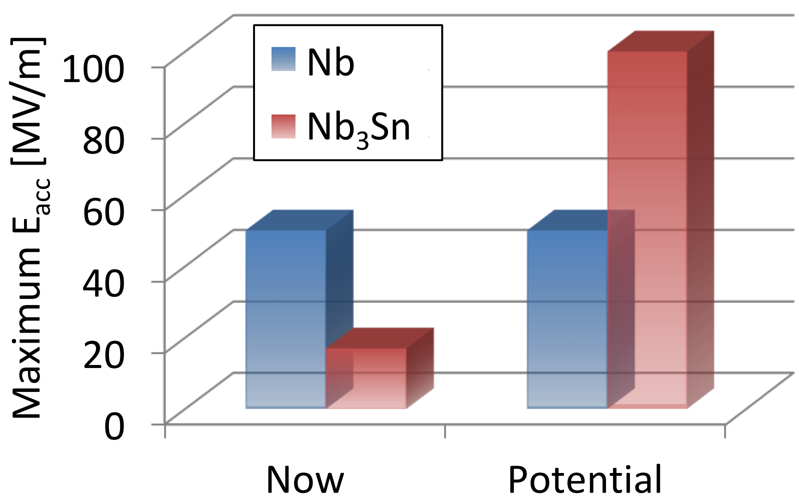


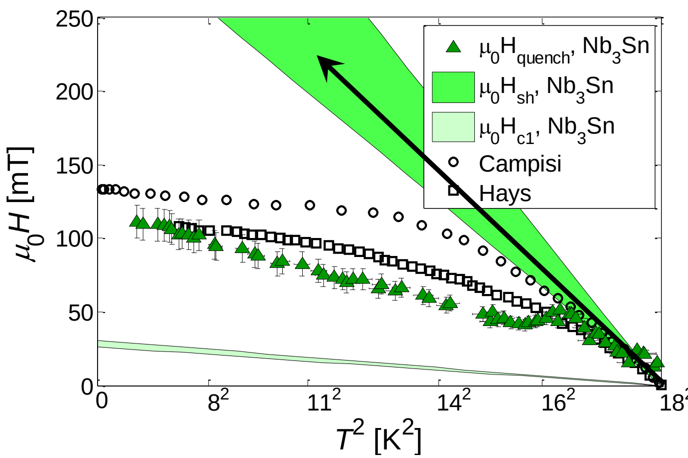


Fermilab

Maximum Accelerating Field

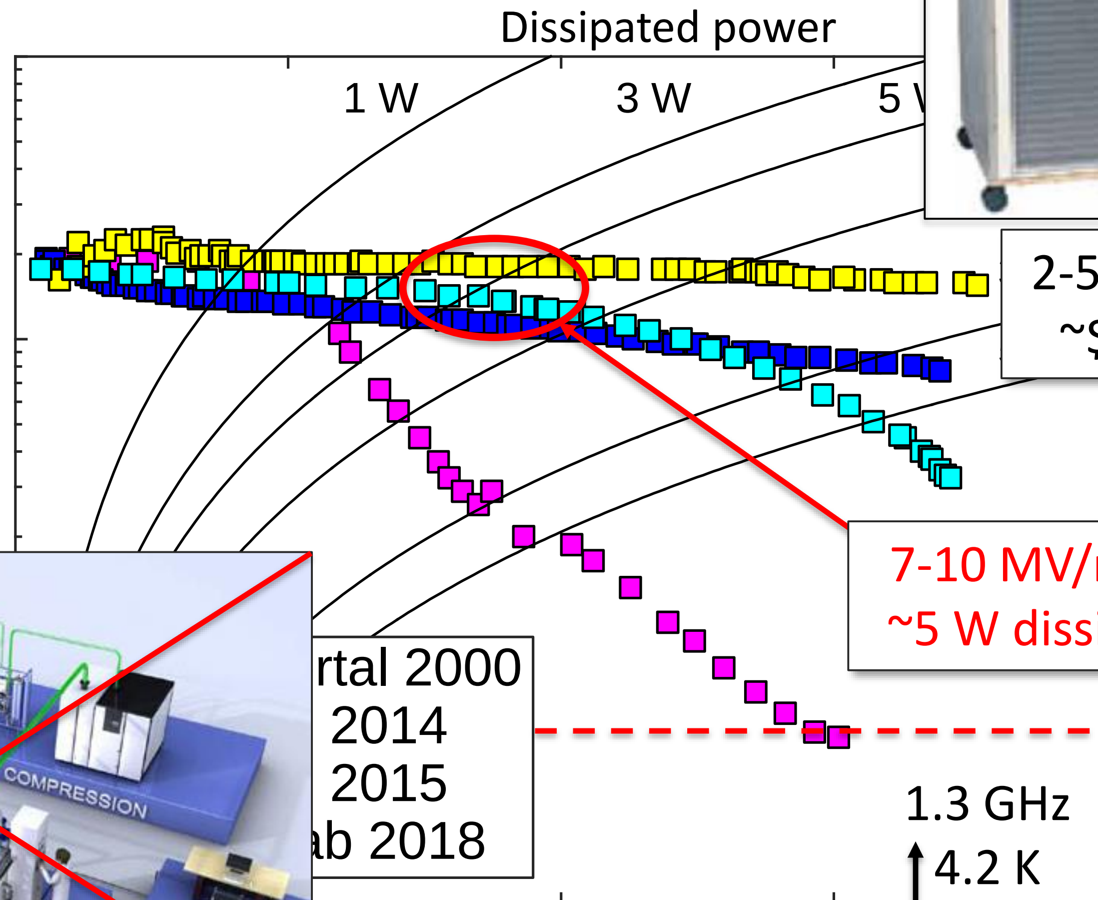
- For high gradient applications, the superheating field of Nb_3Sn is predicted to be twice that of niobium, potentially providing twice as large acceleration per unit length
- This is significantly beyond current performance levels
- R&D to avoid microstructural inhomogeneities may improve maximum fields

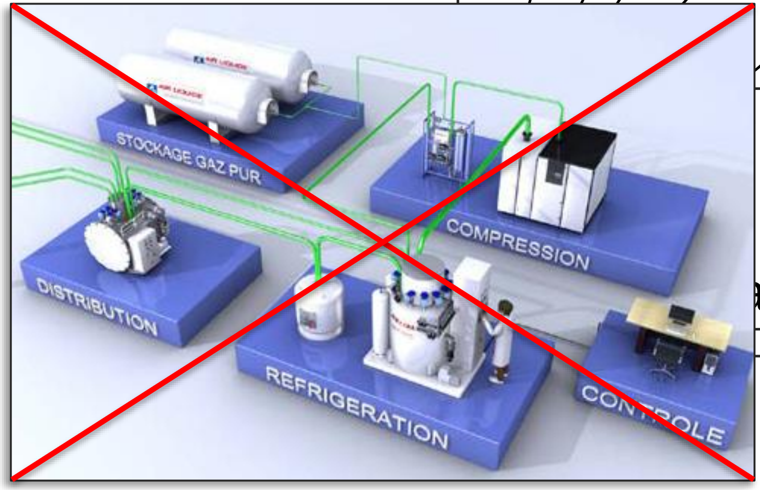




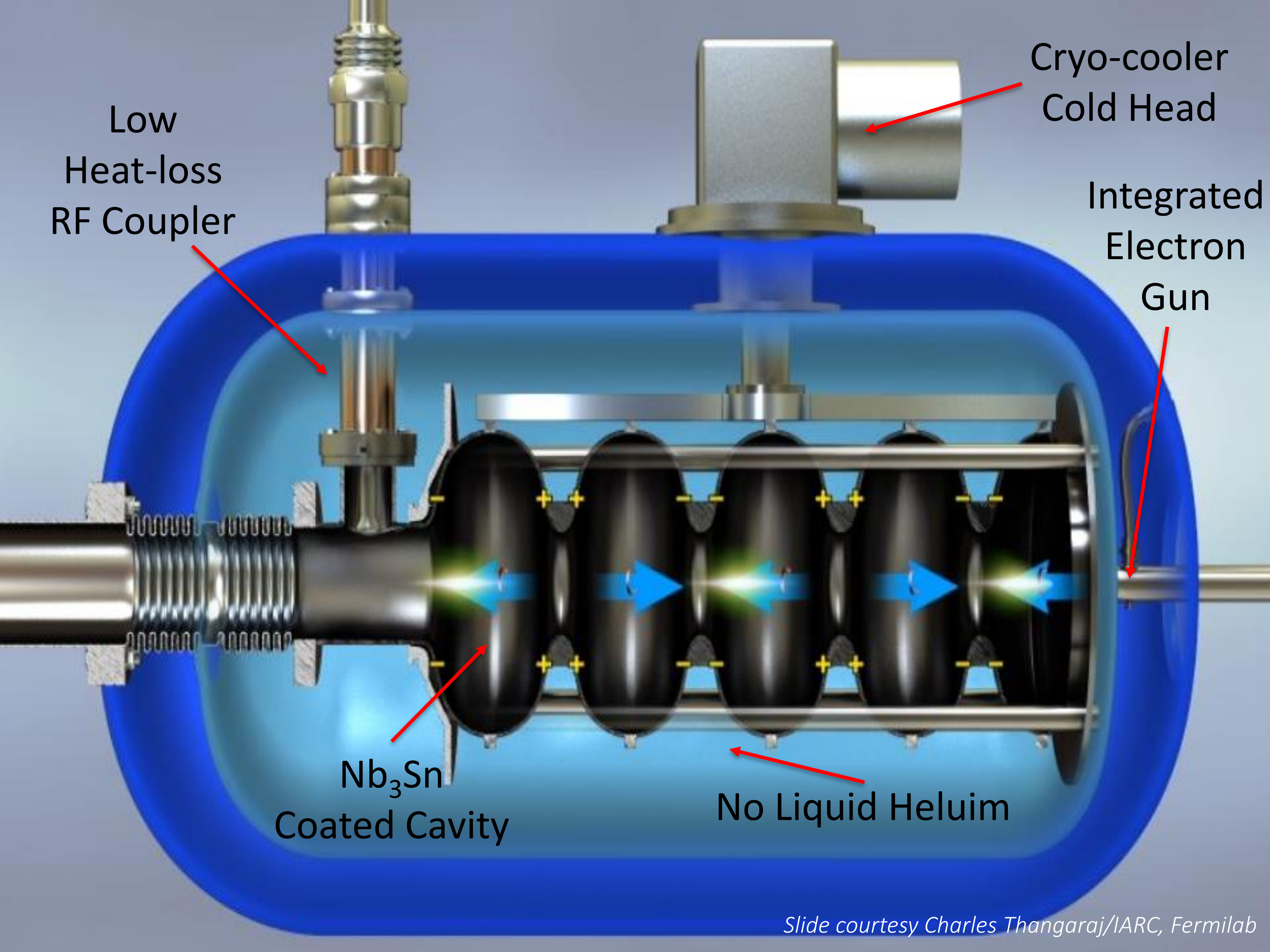
S. Posen, N. Valles, and M. Liepe, *Phys. Rev. Lett.*, 115, 047001 (2015).

Possibility for Cryocooler





Small-Scale Accelerators



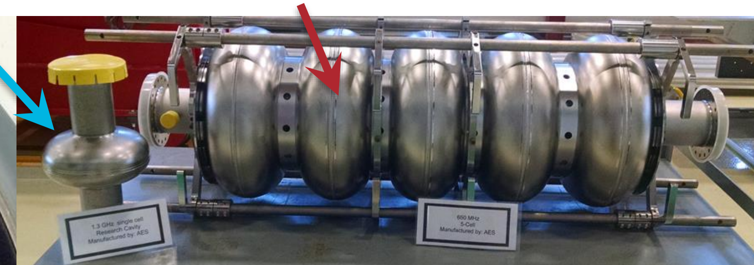
Slide courtesy Charles Thangaraj/IARC, Fermilab

Nb_3Sn SRF Experimental Program at Fermilab

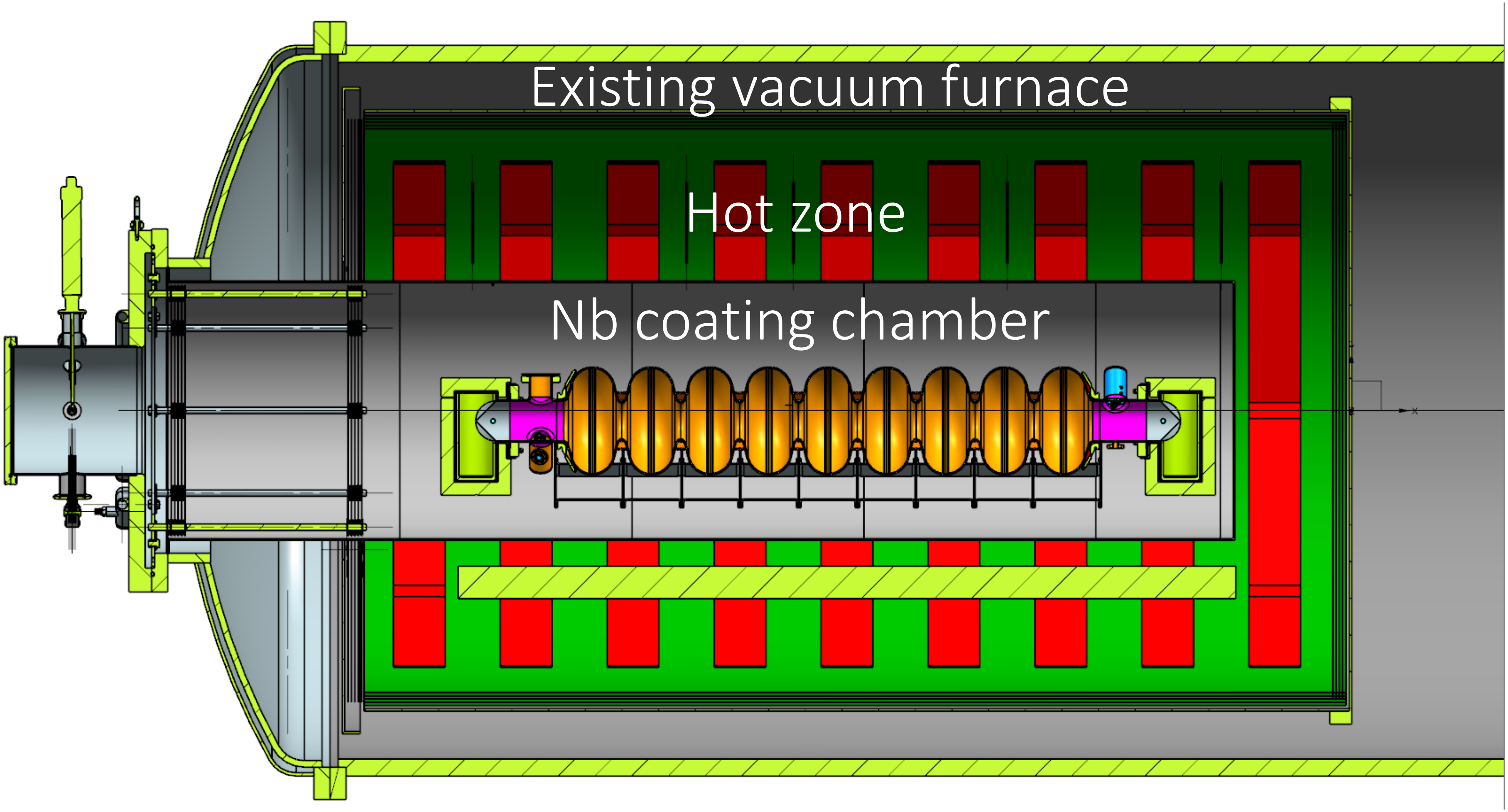
- Program initiated in 2015, first coatings in early 2017
- Nb_3Sn SRF program goals:
  1. Process development to push performance: Q_0 and E_{acc}
  2. Scale up to production-style cavities and study in cryomodule-like environment

1.3 GHz 1-cell (current state of Nb_3Sn R&D)

650 MHz 5-cell (future)



Fermilab Nb_3Sn Coating System

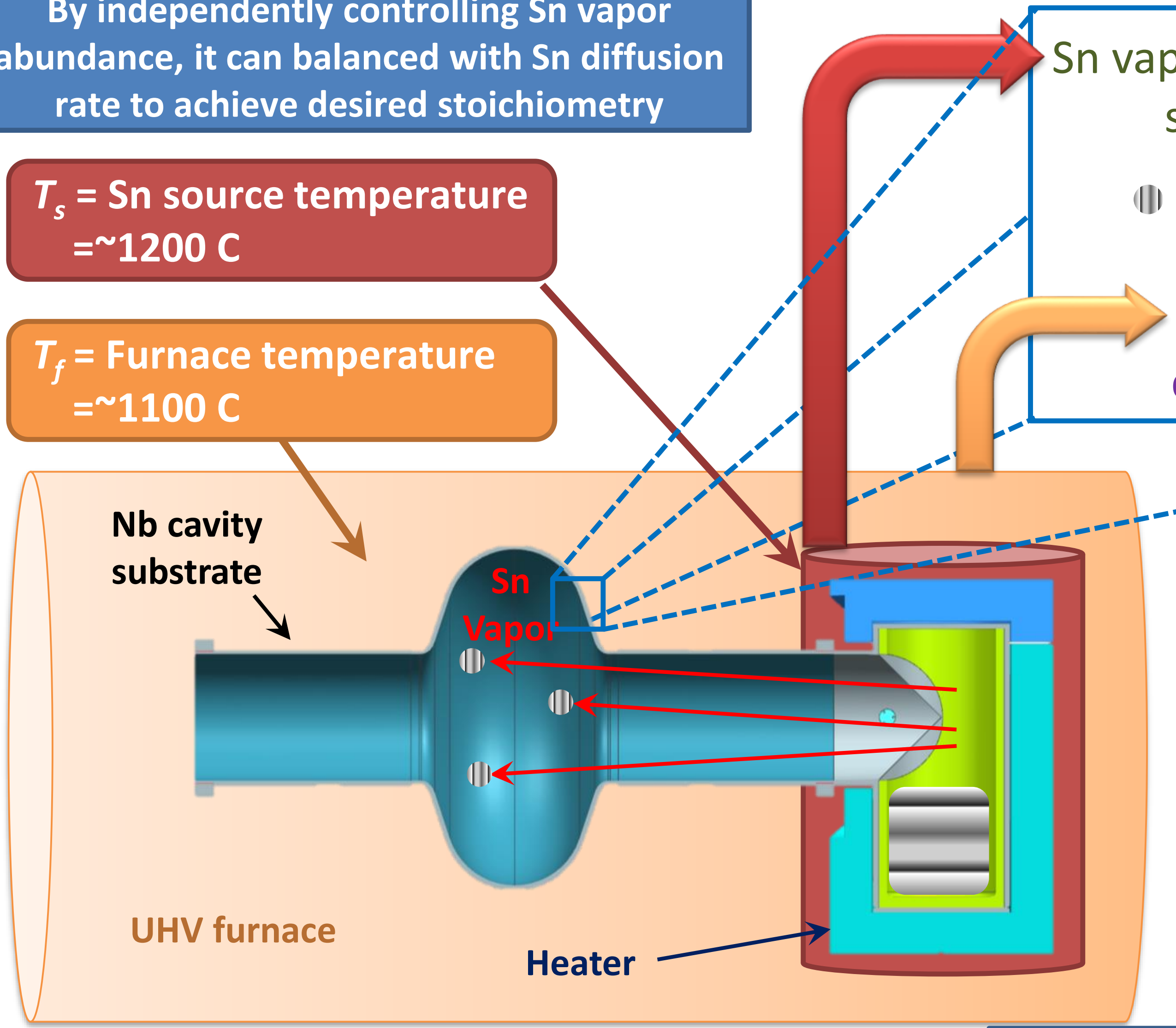


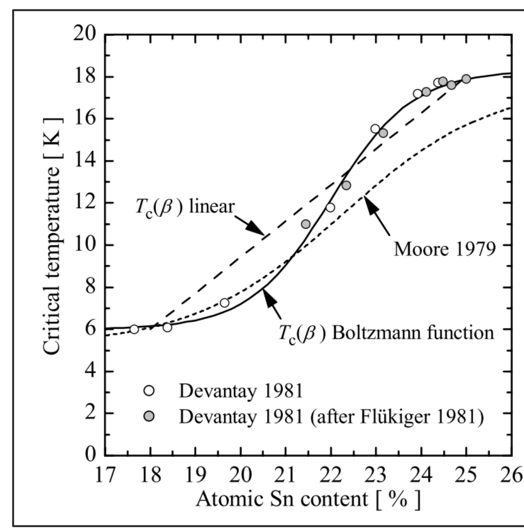
First and only Nb_3Sn coating chamber capable of coating 1.3 GHz 9-cell cavities or 5-cell 650 MHz cavities

Coating Parameter Optimization

Coating Mechanism: Vapor Diffusion

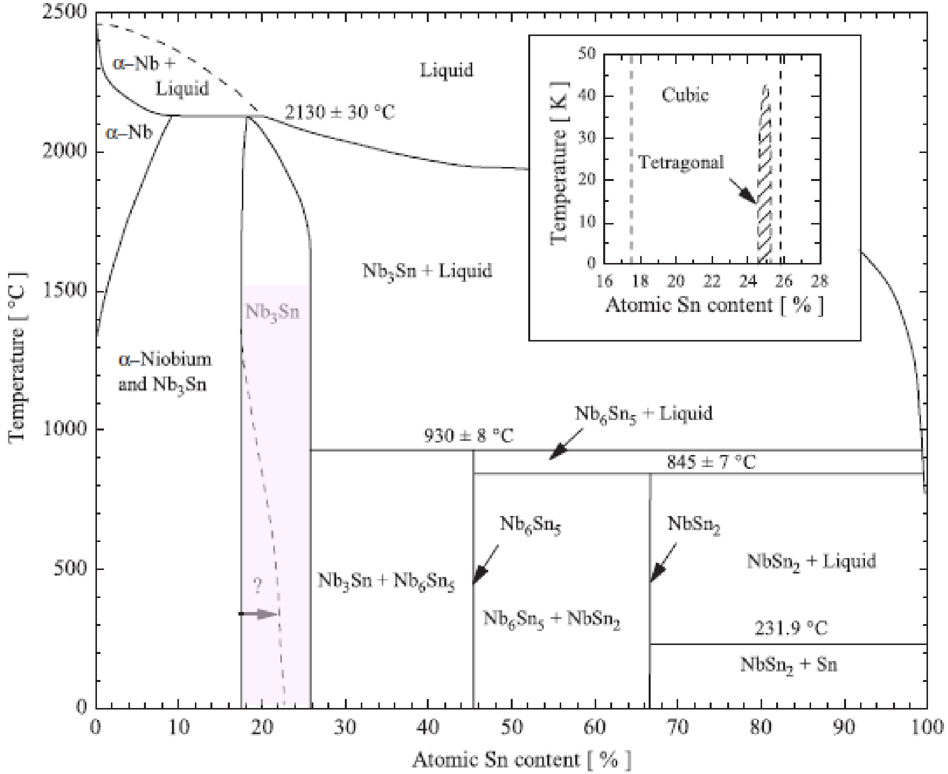
By independently controlling Sn vapor abundance, it can balanced with Sn diffusion rate to achieve desired stoichiometry

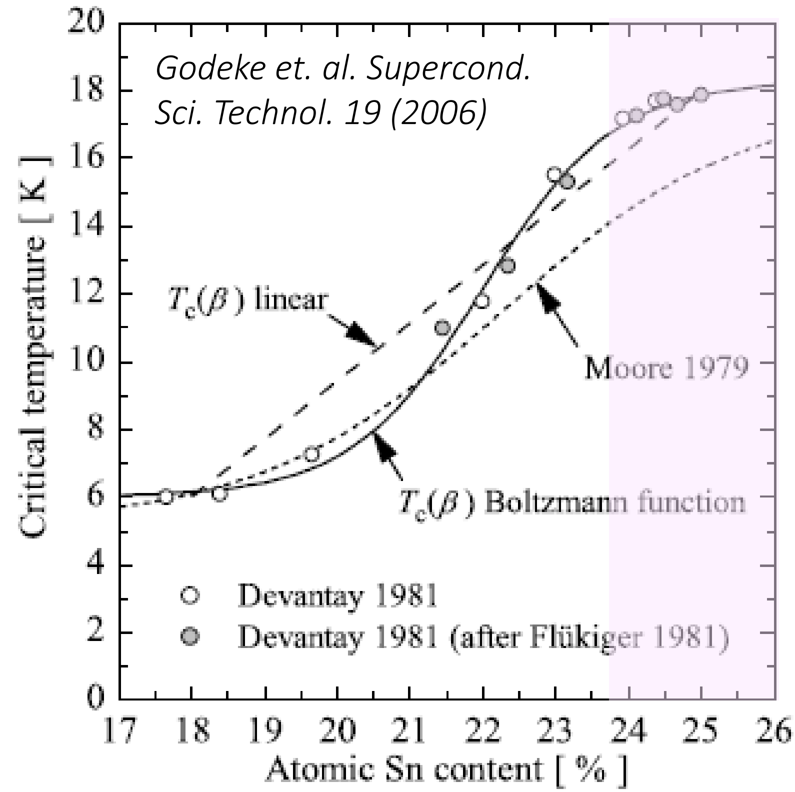




Technique development: Saur and Wurm, Die Naturwissenchaften 1962, Hillenbrand et al. IEEE Transactions on Magnetics 1977, Peiniger et al, SRF'88.

“Phase Locking” to Achieve Desired Composition





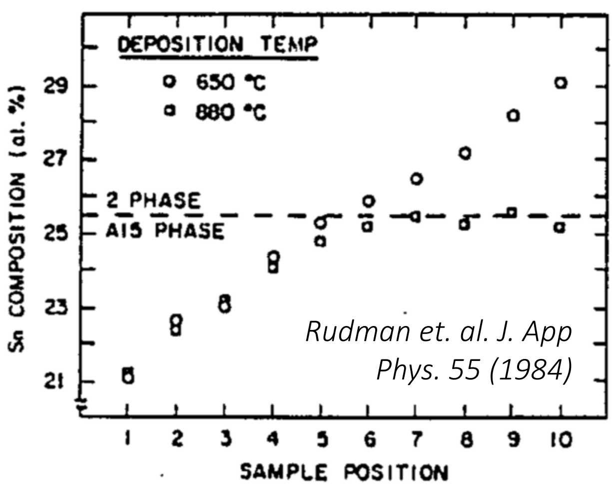
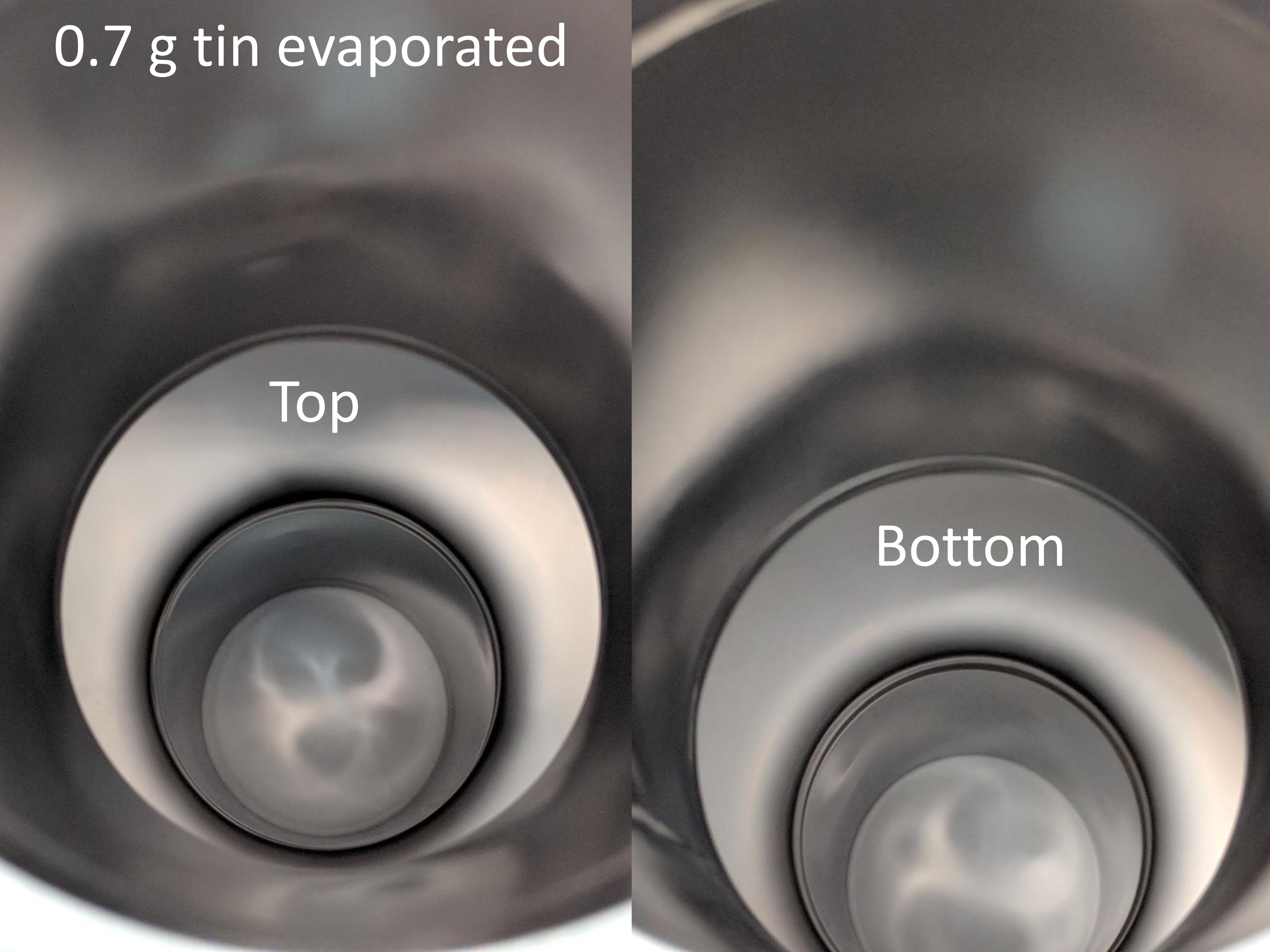
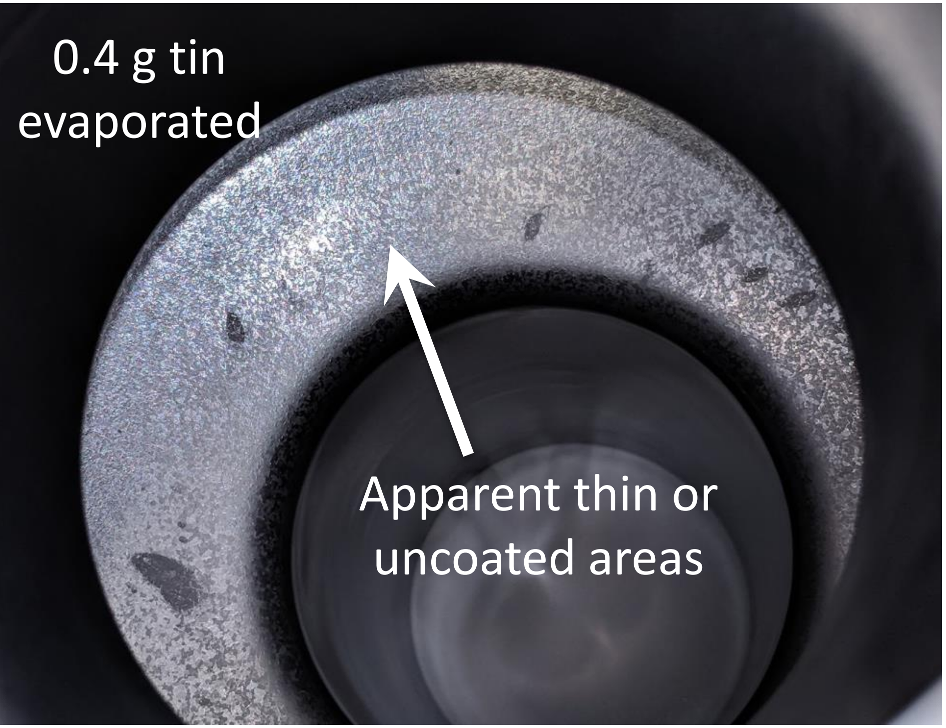


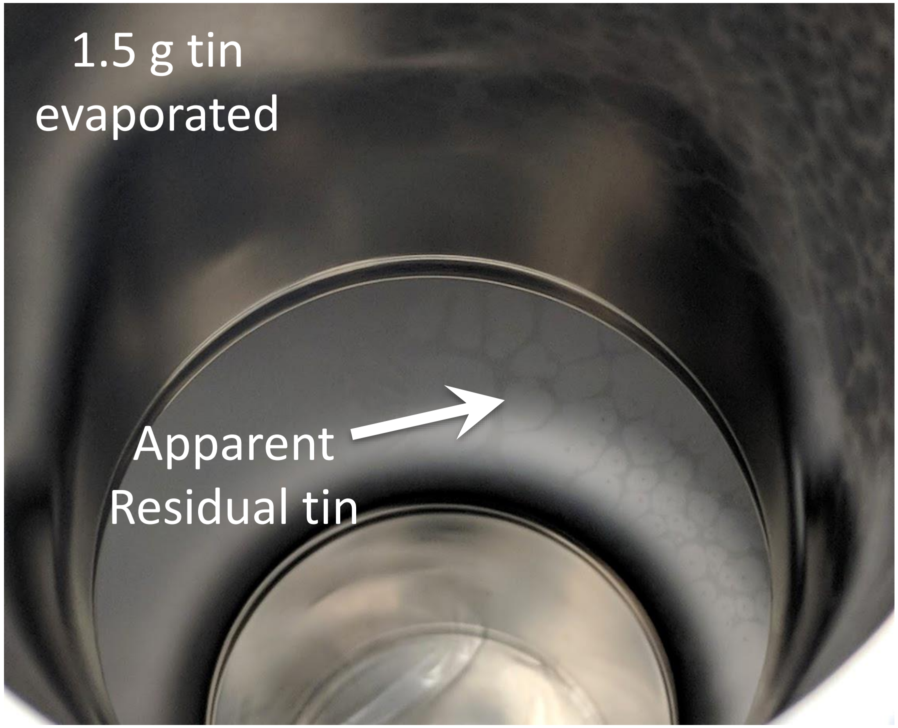
FIG. 7. The variation of sample composition with substrate position for two depositions in the compositional gradient configuration using different substrate temperatures. For sufficiently high substrate temperatures sample composition "locks" at phase boundary.

1. Stoichiometric A15 Nb_3Sn: ~18-26 at.% of Sn
2. Nb_3Sn with 24-26 at.% of Sn to get Tc~18K


0.7 g tin evaporated
Top
Bottom

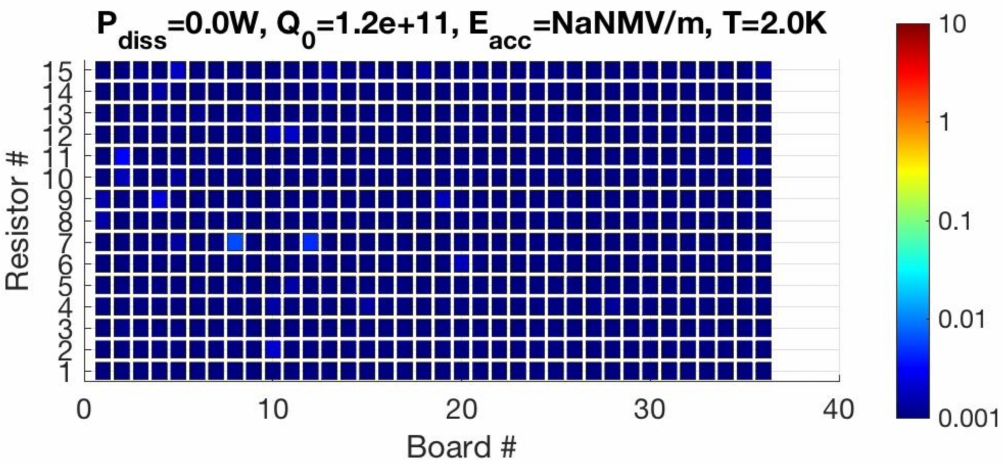
Coating Parameter Optimization

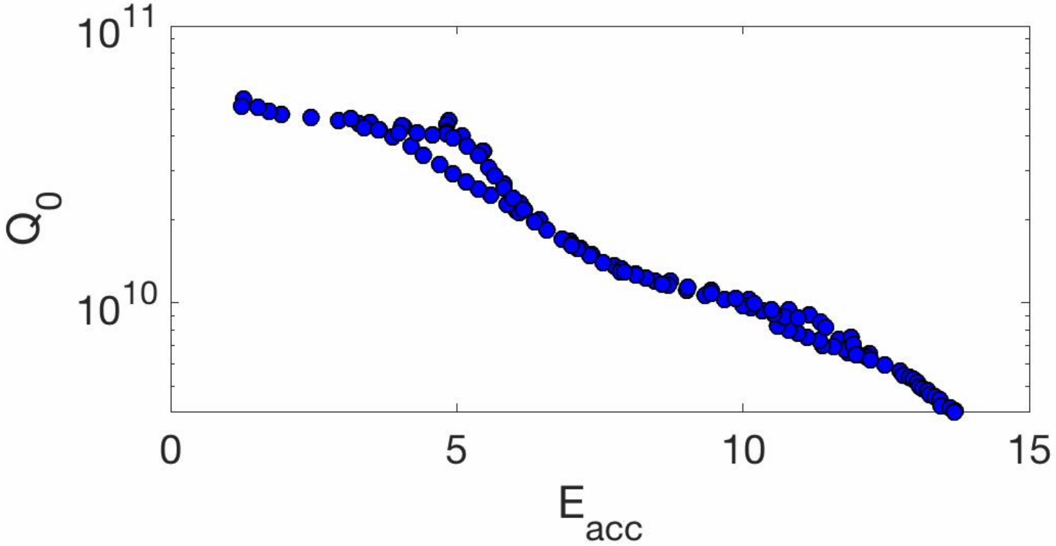




- Parameter optimization to avoid over-/under-coating
- Several parameters found to be important:
  - Crucible diameter
  - Heater power
  - Coating time
  - Annealing time

Extremely Important Tool – T-map





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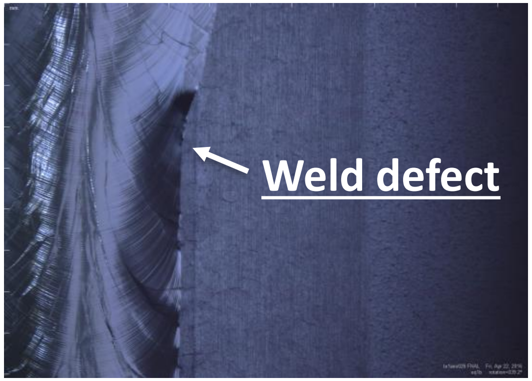
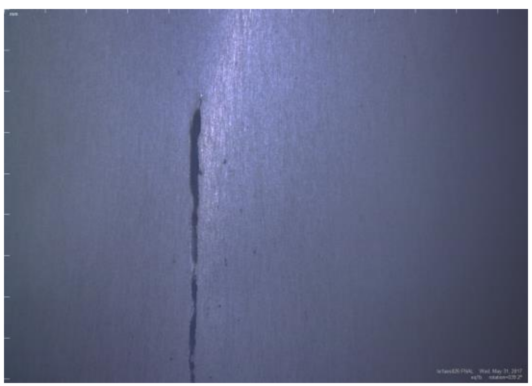
Spot #1 – Board 33, resistor #8, 37.4 degrees



As Received

Coating #1

Coating #1 + anodized



Post CBP #1

Post CBP #2

Coating #2

Coating Parameter Optimization

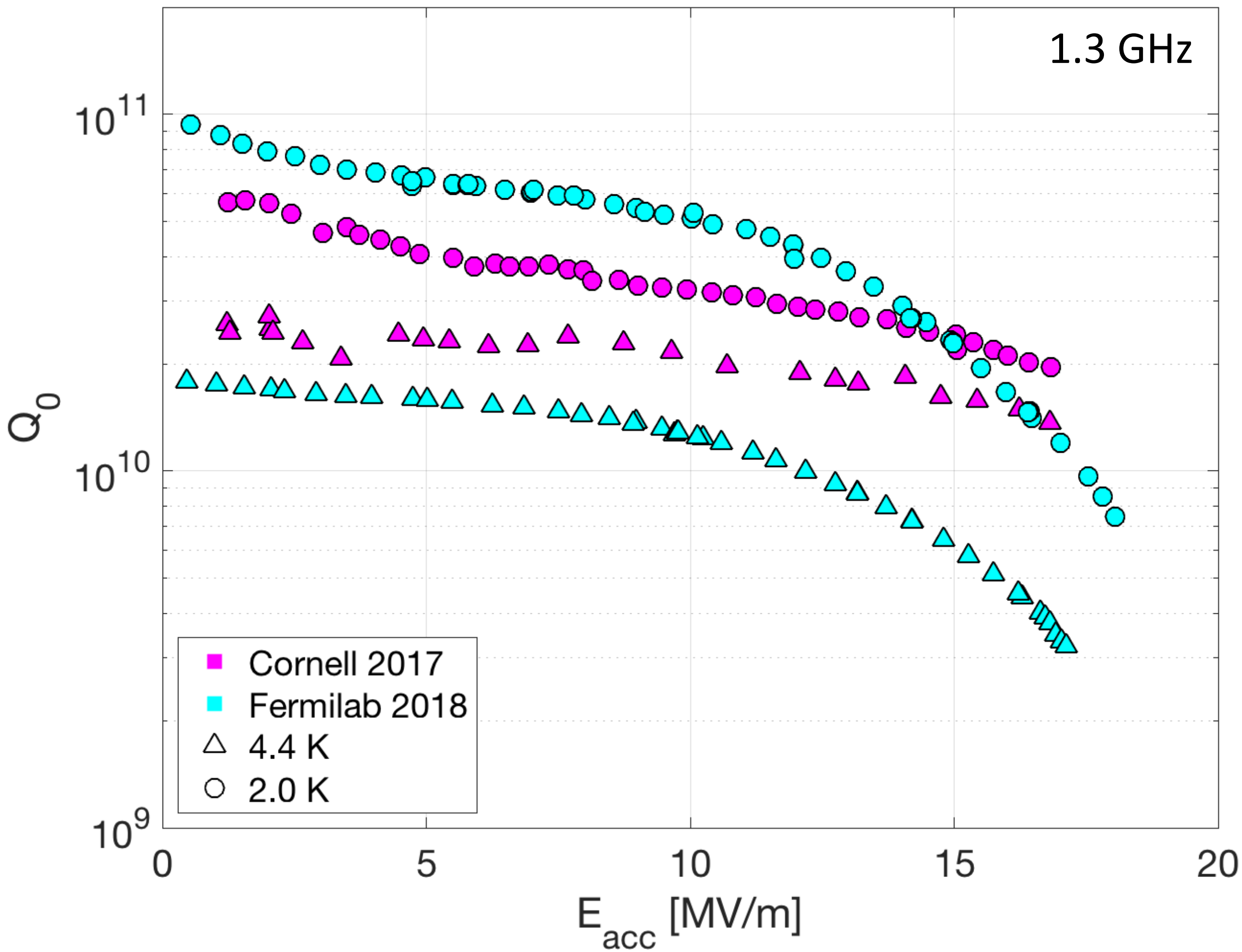
- To date, best appearance and performance at Fermilab achieved with:
  - Smallest diameter crucible tested
  - Heater at maximum power (crucible ~1200 C)
  - Cavity anodized to 30 V prior to coating

S. Posen, TTC Meeting 2018, Tokyo, Japan

Q vs E

- Very high Q_0 at 2.0 K ~5e10 at useful fields ~10 MV/m
- Excellent low and mid-field Q_0 at 4.4 K >1e10
- Still some Q-slope but nice quench field
- Sharp 18 K transitions

S. Posen, TTC Meeting 2018, Tokyo, Japan

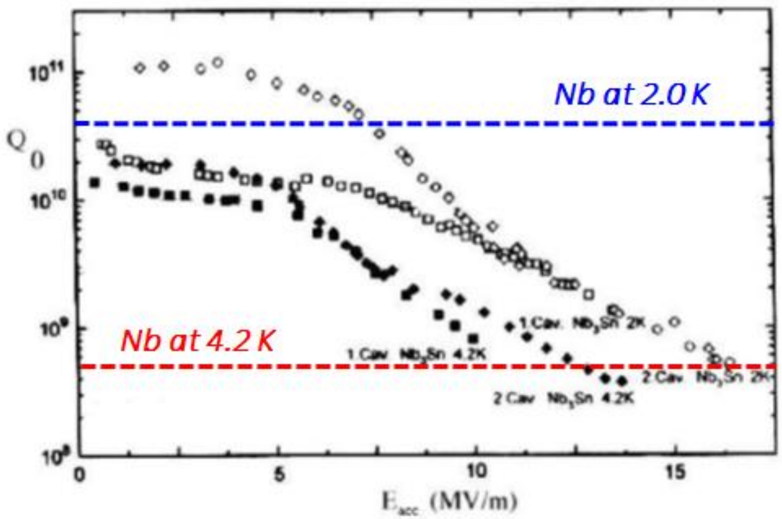


Nb at 2.0 K, 10 MV/m: ~1×10^{10} - 3×10^{10}
Nb at 4.4 K, 10 MV/m: ~3×10^{8} - 5×10^{8}

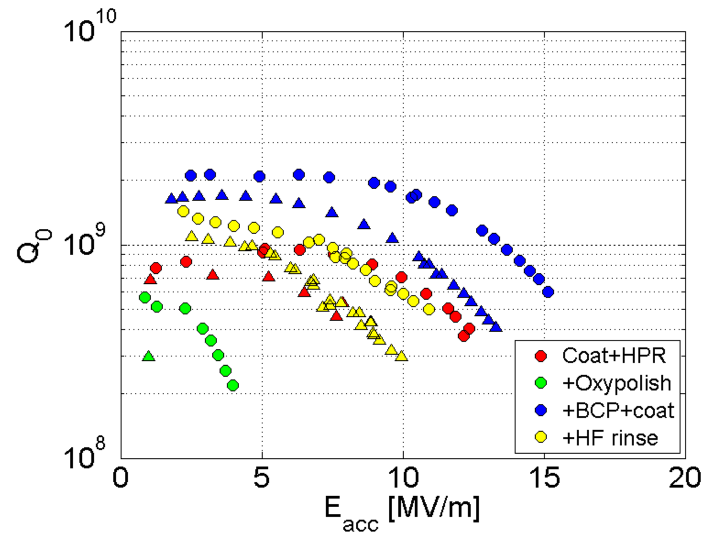
Surface Studies and Q-Slope

Hints for Improvements: What causes Q-Slope?

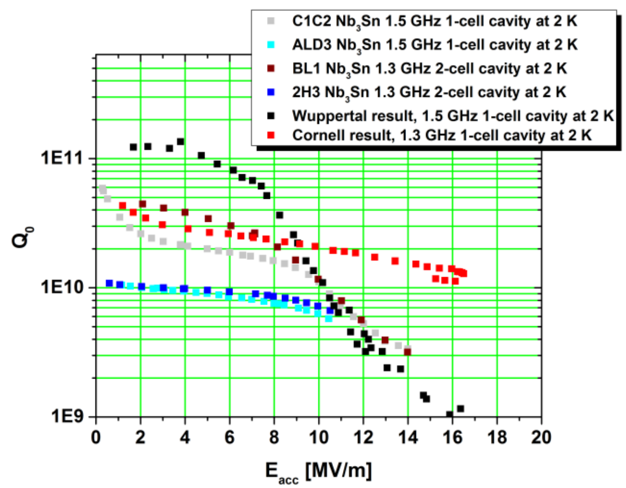
Wuppertal



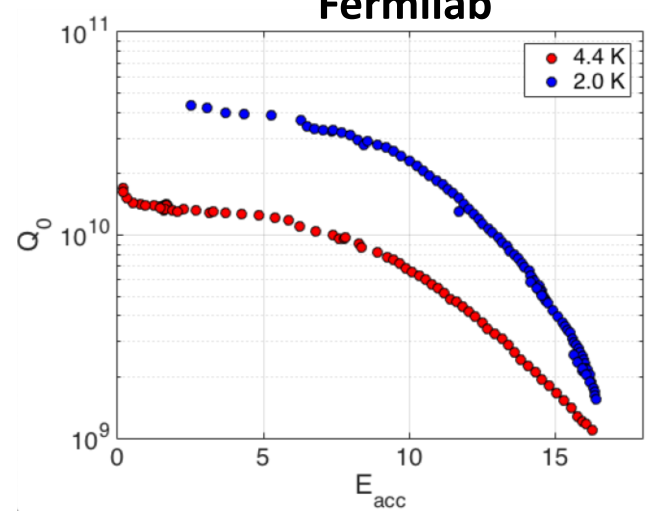
Cornell



Jefferson Lab

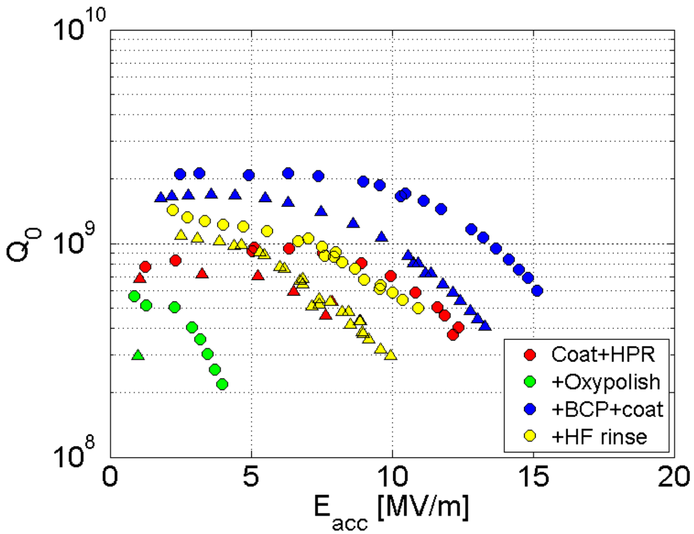


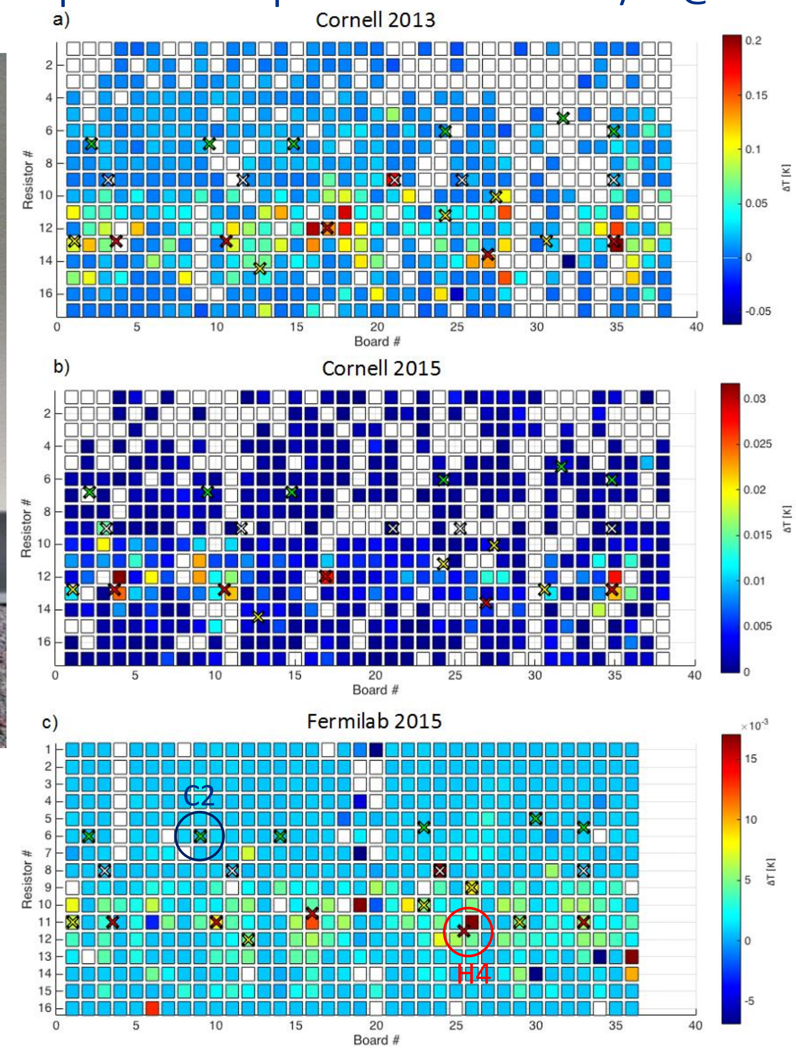
Fermilab



Nb_3Sn-Coated Nb Cavity (ERL1-5) and Cutout Samples

Temperature map was taken at 9 MV/m @ 4.2K



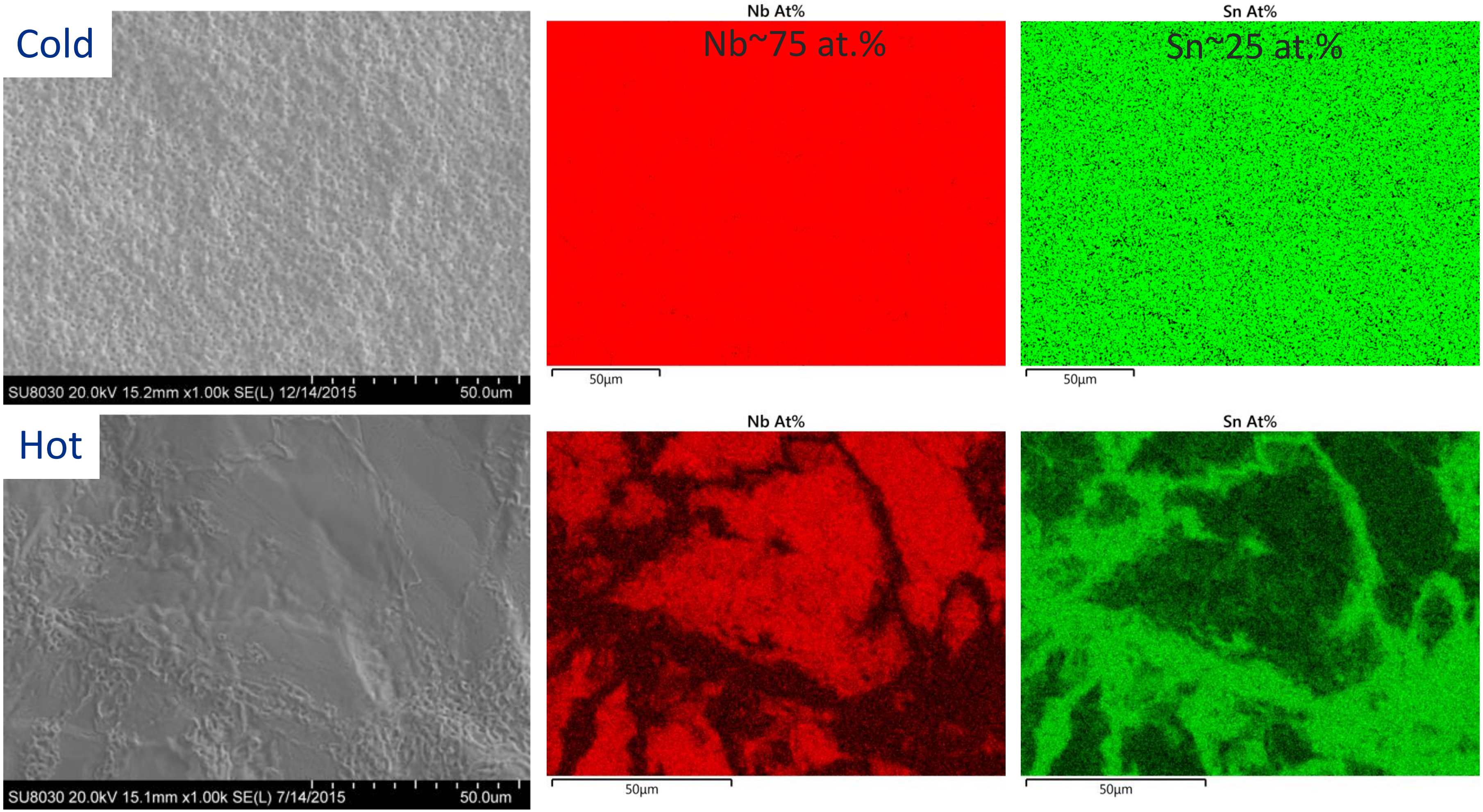


Red – hot spot
Green – cold spot
Yellow – medium spot
White – Equator

Q of 10^9 @ low fields; significant Q-slope starting from 5 MV/m

Y. Trenikhina, S. Posen, A. Romanenko, M. Sardela, J.-M. Zuo, D. L. Hall and M. Liepe, Supercond. Sci. Technol., 31 015004 (2017).

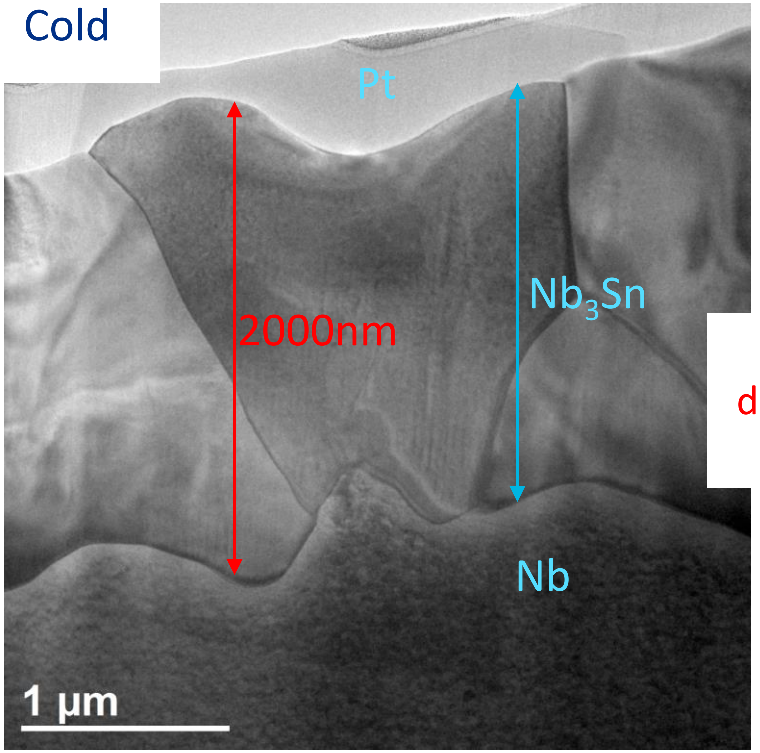
Cold vs. Hot cutout: SEM/EDS at 20 kV



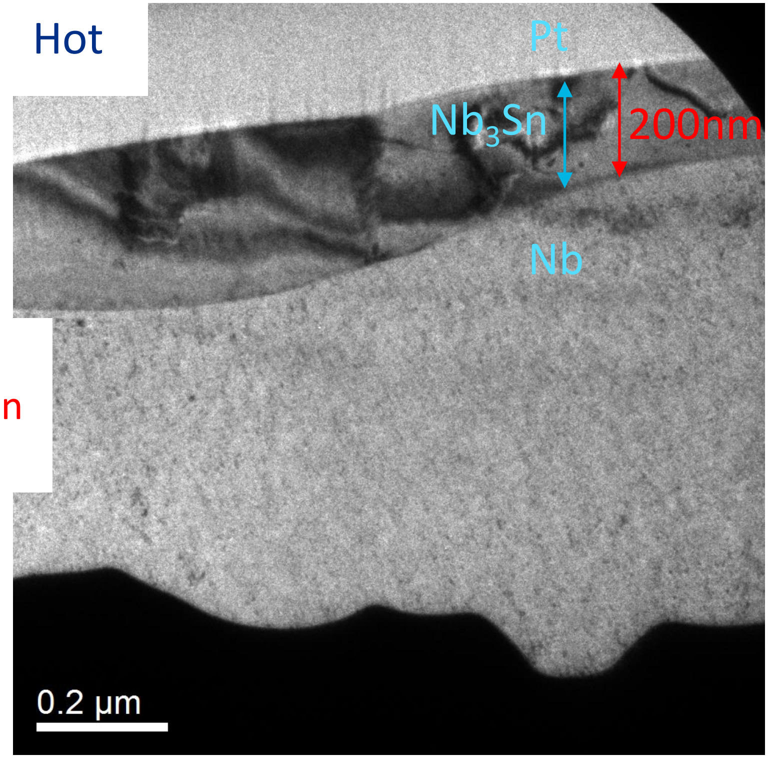
Hot cutout: what are the “patchy” regions?

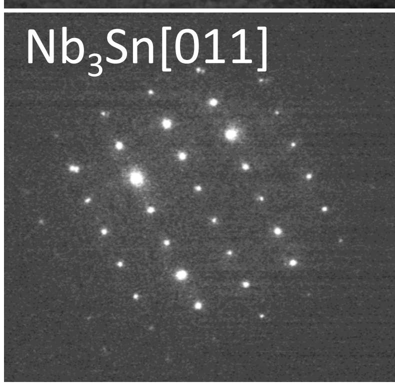
Y. Trenikhina, S. Posen, A. Romanenko, M. Sardela, J.-M. Zuo, D. L. Hall and M. Liepe, Supercond. Sci. Technol., 31 015004 (2017).

Cold vs. Hot: TEM on cross-sectional samples



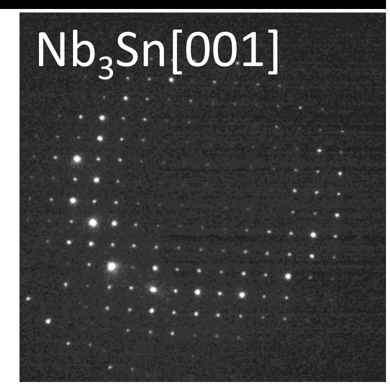
~10 times difference in thickness





Both cutouts have Nb_3Sn A15 structure

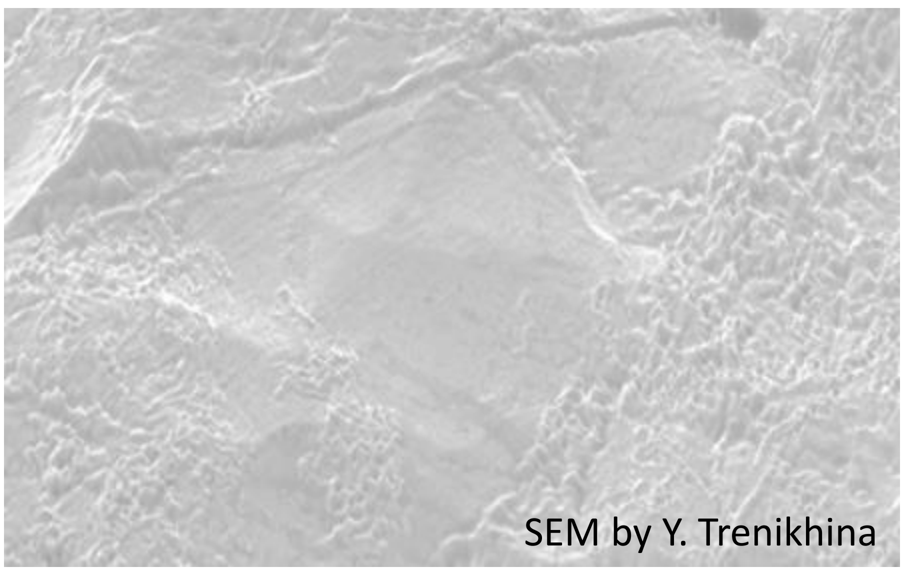
Hot cutout shows extremely thin regions, only ~1 RF penetration depth



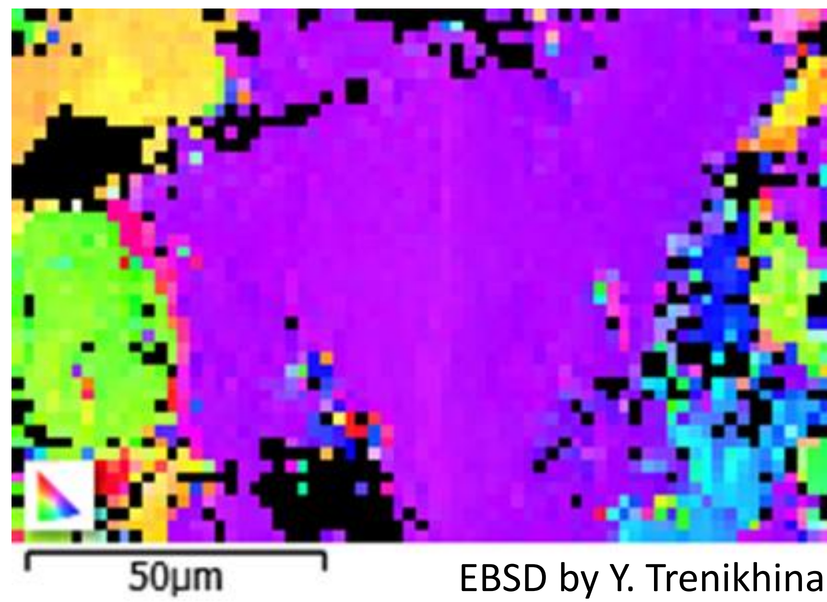
Y. Trenikhina, S. Posen, A. Romanenko, M. Sardela, J.-M. Zuo, D. L. Hall and M. Liepe, *Supercond. Sci. Technol.*, 31 015004 (2017).

Thin Regions are Unusually Large Grains

- EBSD analysis of grain orientation reveals that the thin regions in the hot spots are in fact large grains, with diameter ~100 microns vs ~1 micron for standard Nb_3Sn grains



SEM by Y. Trenikhina

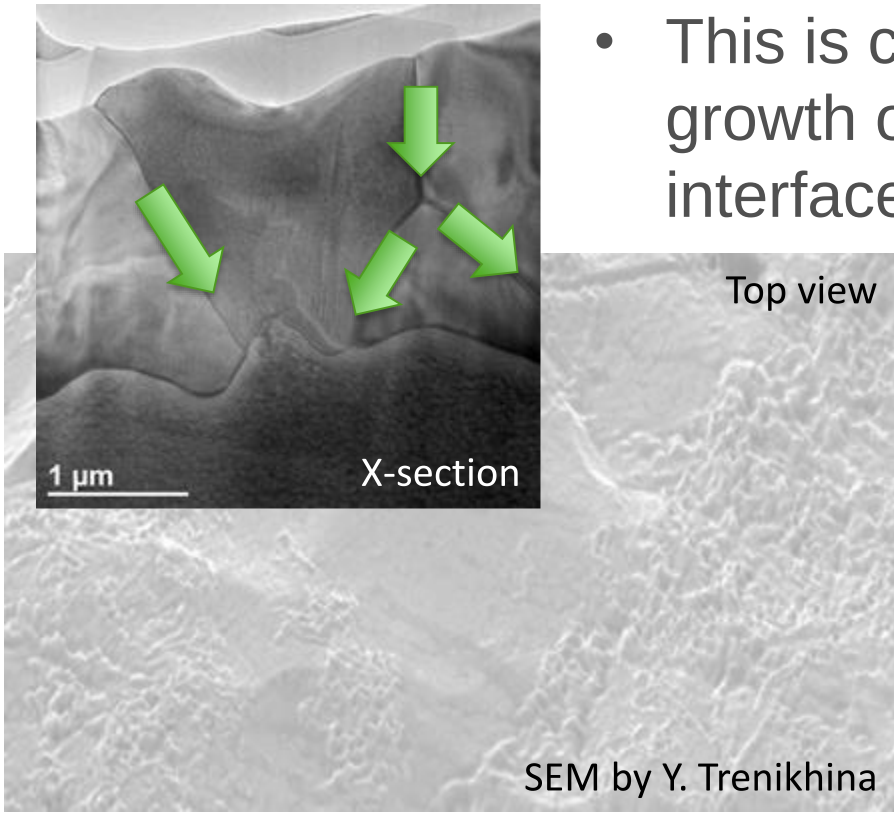


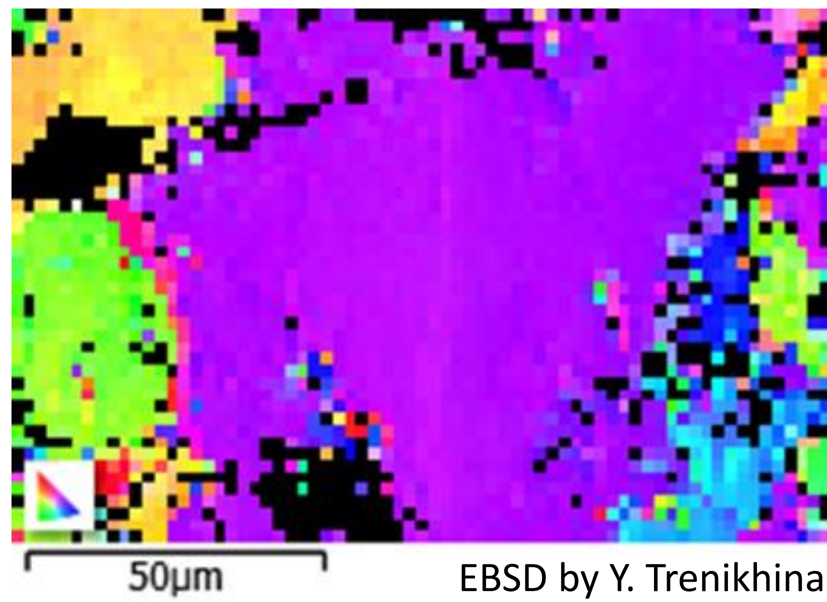
EBSD by Y. Trenikhina

Y. Trenikhina, S. Posen, A. Romanenko, M. Sardela, J.-M. Zuo, D. L. Hall and M. Liepe, Supercond. Sci. Technol., 31 015004 (2017).

Thin Regions are Unusually Large Grains

- EBSD analysis of grain orientation reveals that the thin regions in the hot spots are in fact large grains, with diameter ~100 microns vs ~1 micron for standard Nb_3Sn grains
    - This is consistent with mechanism for growth of grains: diffusion of tin to interface via grain boundaries



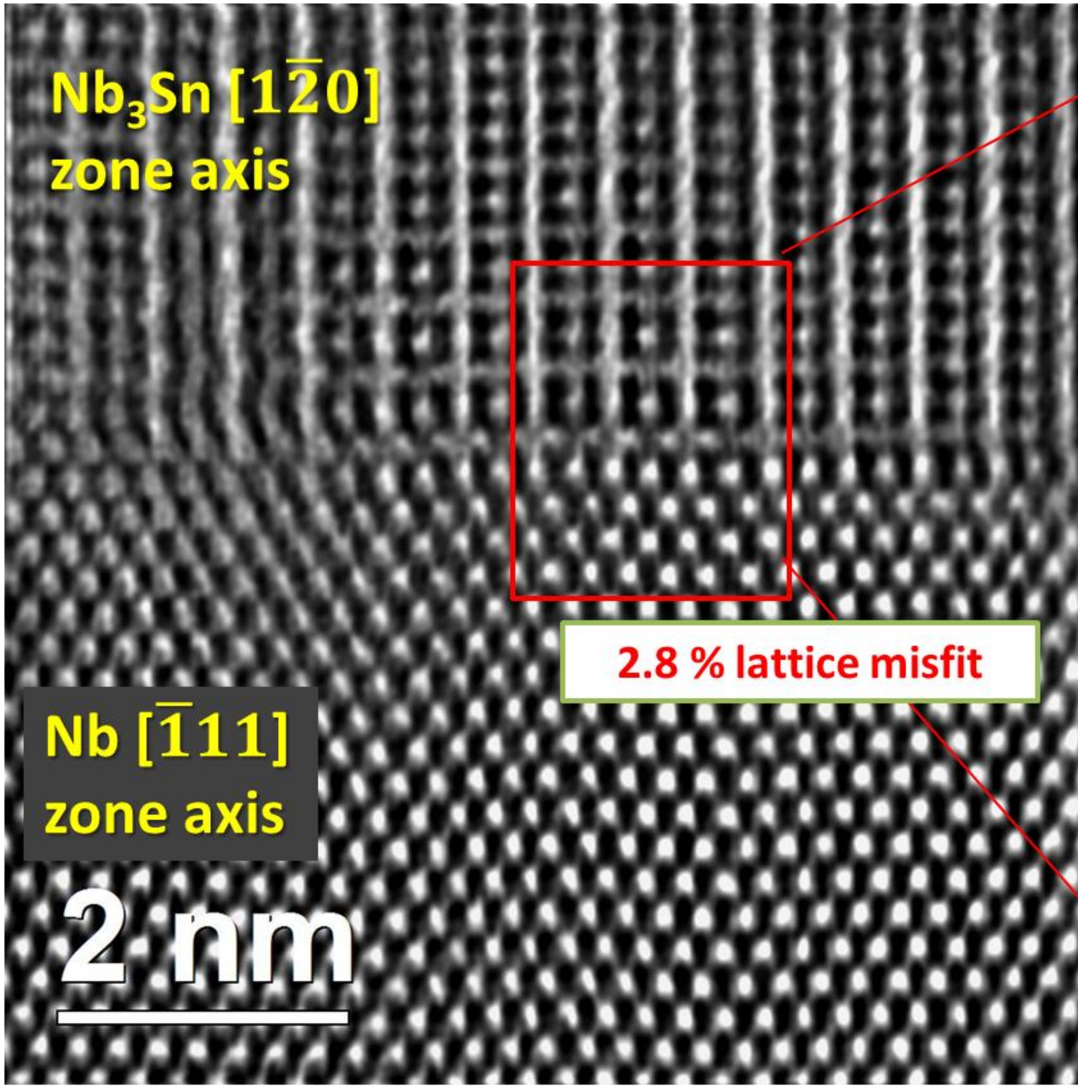


EBSD by Y. Trenikhina

Y. Trenikhina, S. Posen, A. Romanenko, M. Sardela, J.-M. Zuo, D. L. Hall and M. Liepe, Supercond. Sci. Technol., 31 015004 (2017).

Epitaxial orientation relationships at Nb/Nb_3Sn

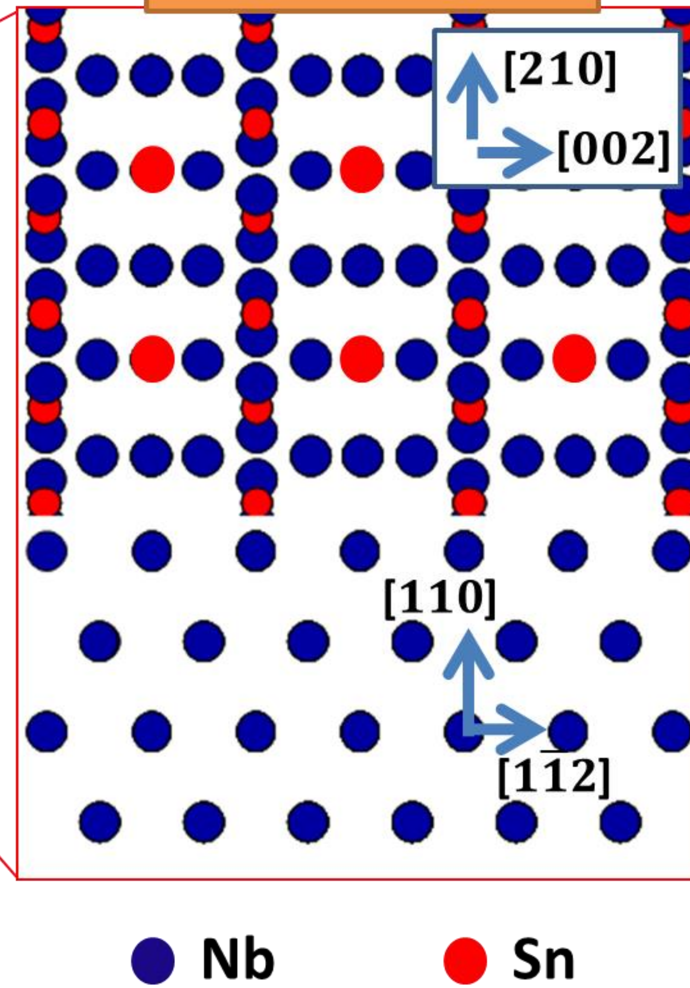
Normal Grain Thickness



Orientation A

Nb_3Sn $(1\bar{2}0)$//Nb $(\bar{1}11)$

Nb_3Sn (002)//Nb $(1\bar{1}2)$

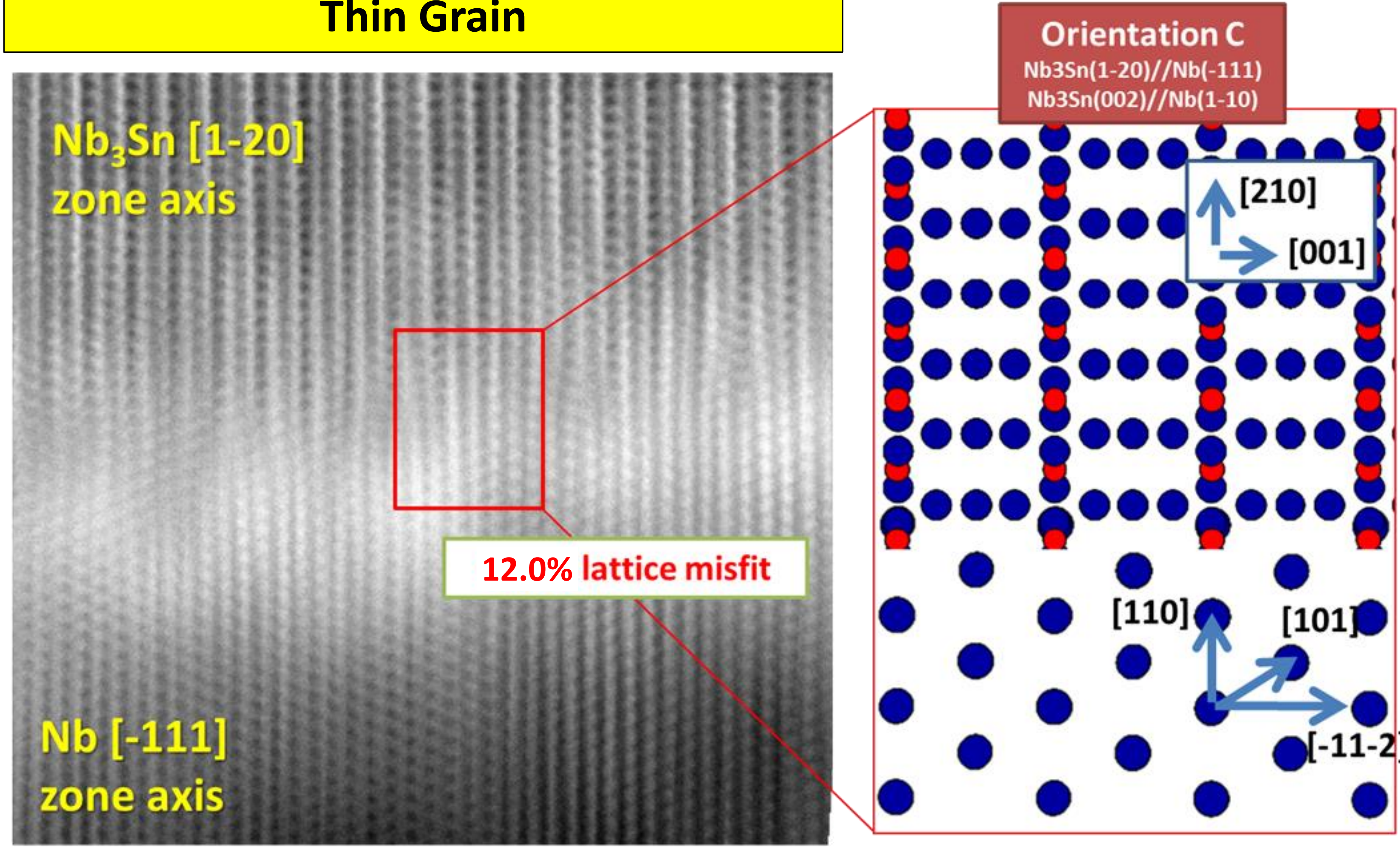


Jae-Yel Lee, Northwestern University / Fermilab

https://arxiv.org/abs/1807.03898

Epitaxial orientation relationships at Nb/Nb_3Sn

Thin Grain



Jae-Yel Lee, Northwestern University / Fermilab

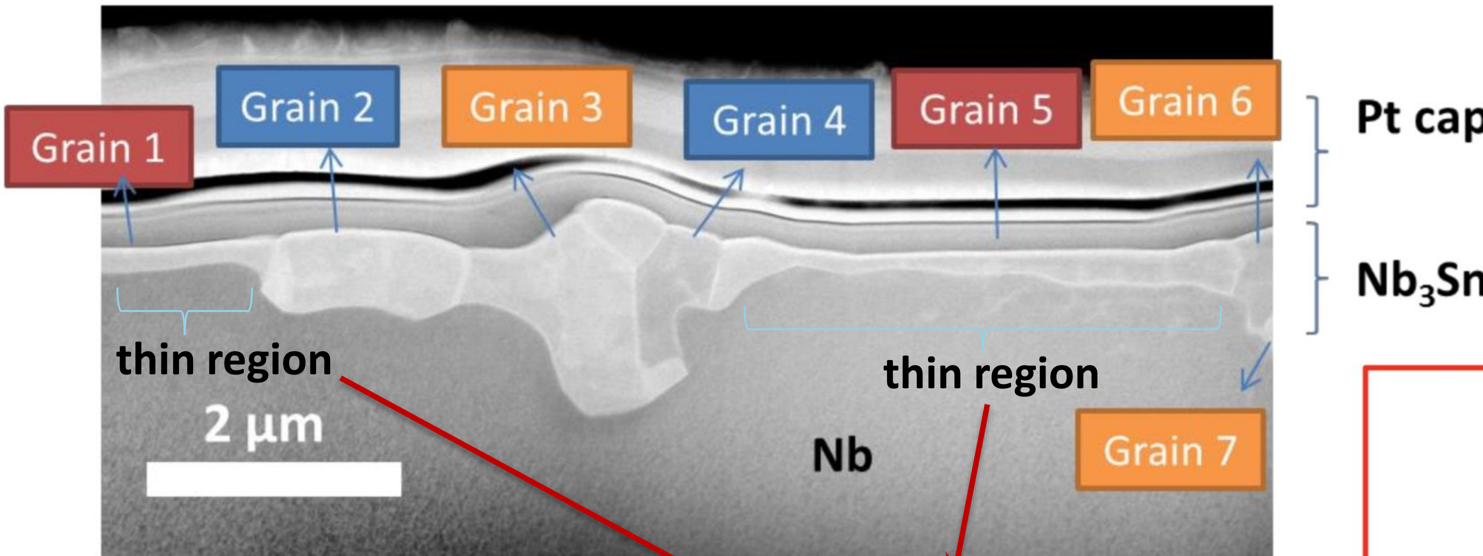
https://arxiv.org/abs/1807.03898

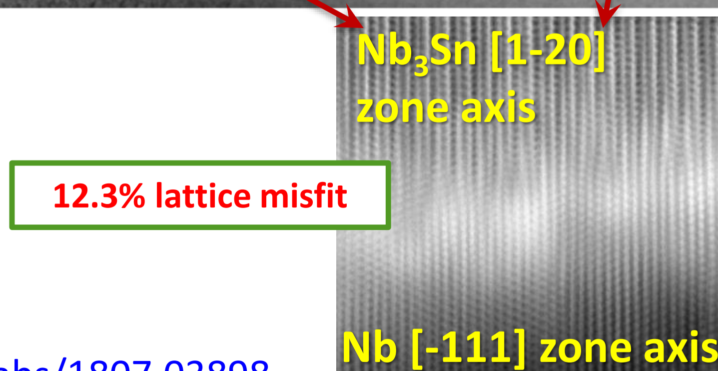
Orientation relationship vs mistfits, Sn-deficient regions, GBs

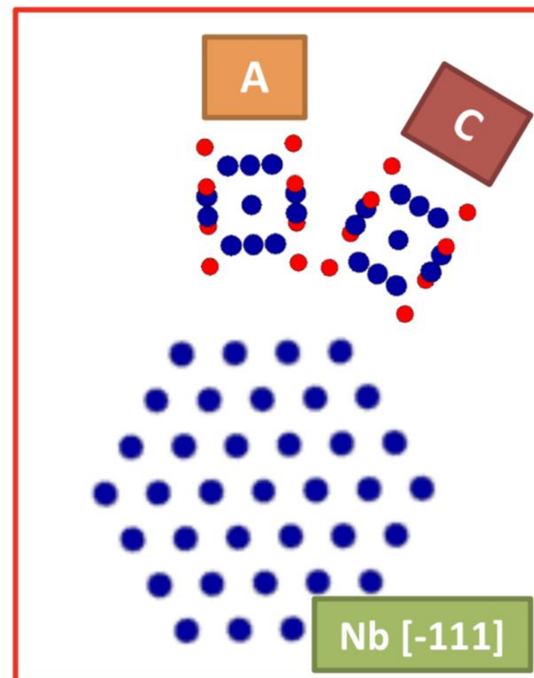
Orientation A
$Nb_3Sn\ (1\bar{2}0)//Nb\ (\bar{1}11)$
$Nb_3Sn\ (002)//Nb\ (1\bar{1}2)$

Orientation B
$Nb_3Sn\ (1\bar{2}0)//Nb\ (\bar{1}11)$
$Nb_3Sn\ (002)//Nb\ (23\bar{1})$

Orientation C
$Nb_3Sn\ (1\bar{2}0)//Nb\ (\bar{1}11)$
$Nb_3Sn\ (002)//Nb\ (0\bar{1}1)$







https://arxiv.org/abs/1807.03898

Jae-Yel Lee, Northwestern University / Fermilab

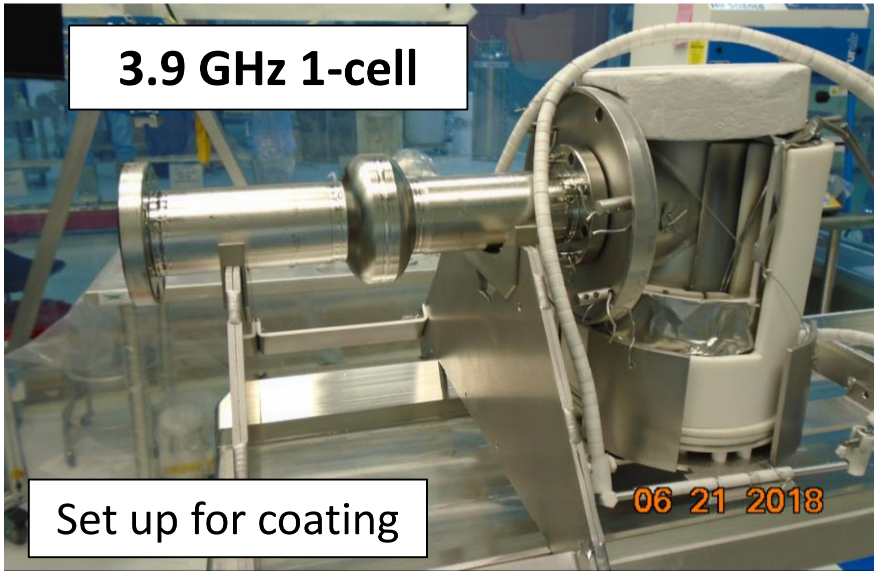
Thin Region Summary and Outlook

- For cavity with poor performance, worst regions show:
  - Thin coating
  - Composed of large, single grains
  - With specific orientation relative to Nb substrate
- Now need to extend lessons learned to prevent the formation of these regions
- Improved understanding particularly key for multicell cavities, where first attempts have shown substantial presence of “patchy” regions

On the Horizon

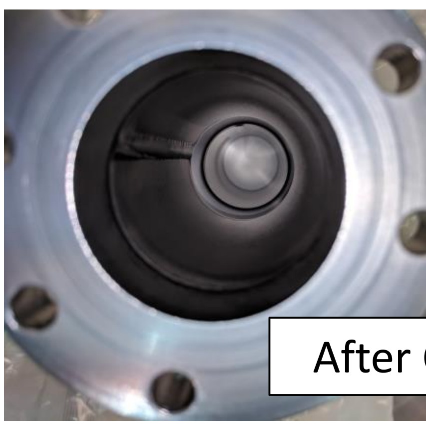
Nb_3Sn Coatings of 3.9 GHz and 650 MHz Cavities

How do properties scale with frequency? Residual and BCS resistance, Q-slope, quench field…

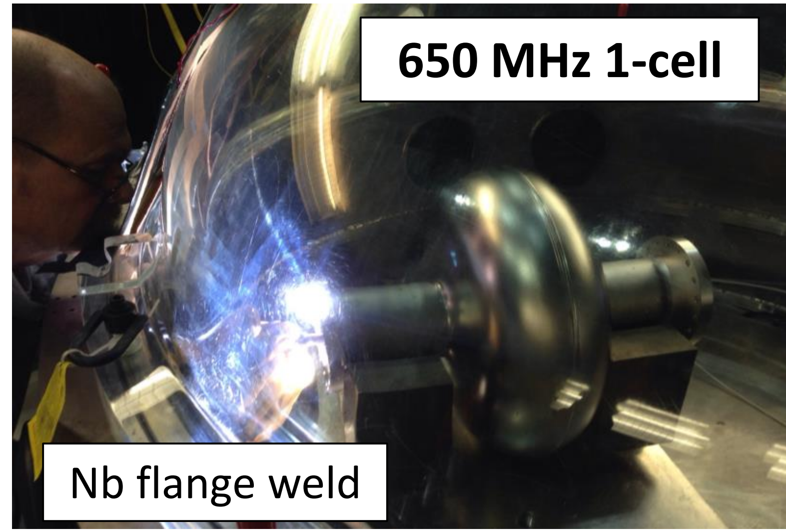


3.9 GHz 1-cell

Set up for coating

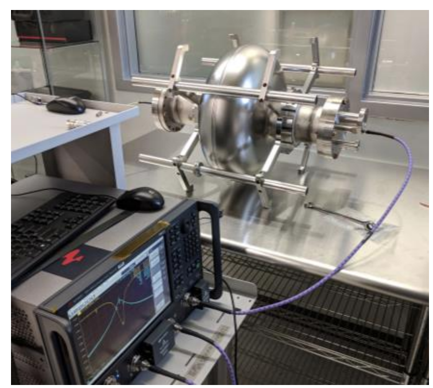


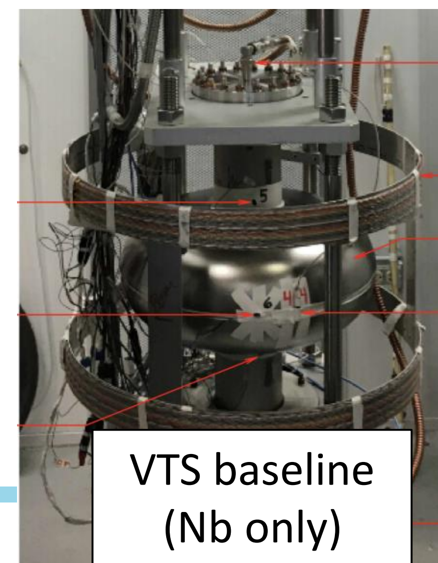
After Coating



650 MHz 1-cell

Nb flange weld

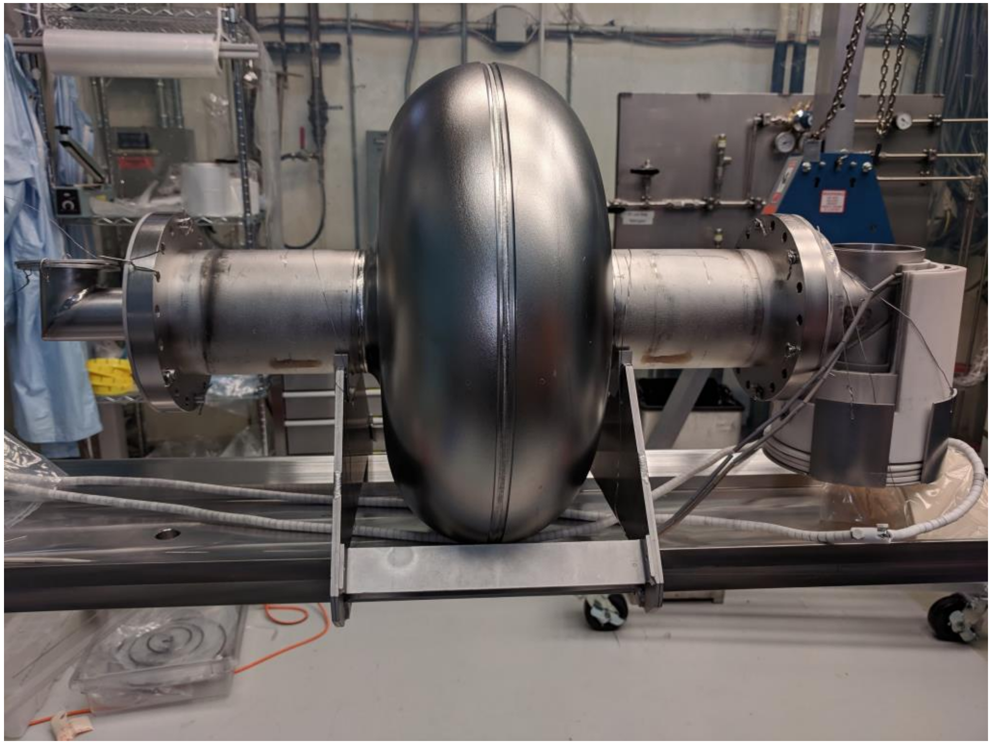


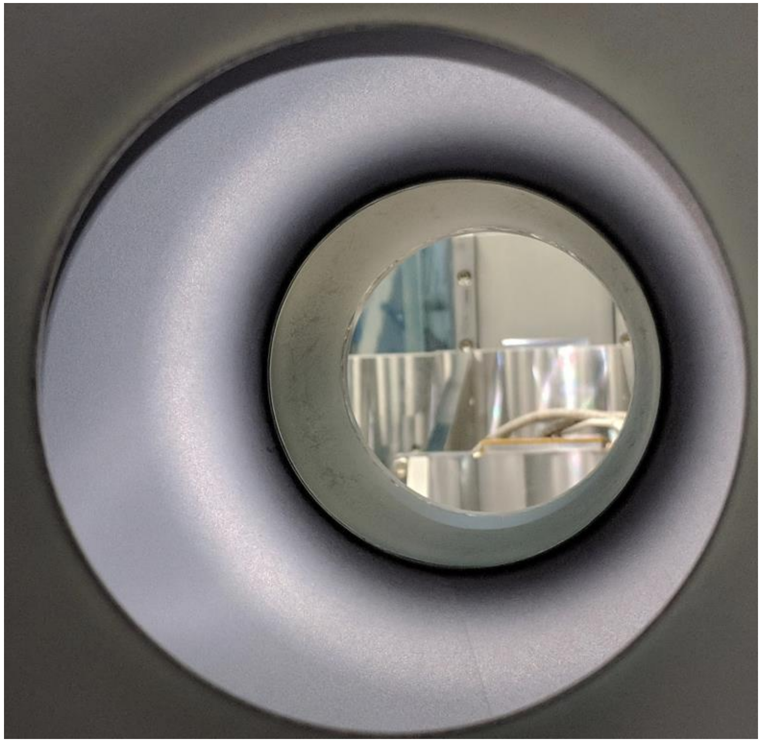


VTS baseline
(Nb only)

650 MHz 1-cell Coated with Nb_3Sn

- Very first coating on 9/4 (1 week ago)
- Vertical test in ~2 weeks

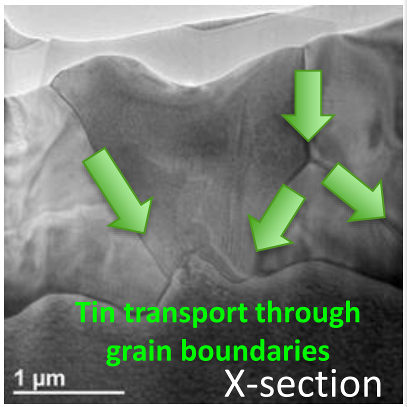


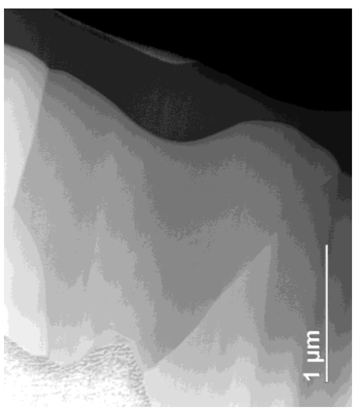


Increasing E_{acc} in Nb_3Sn Cavities

- Several promising paths forward for continued progress including:

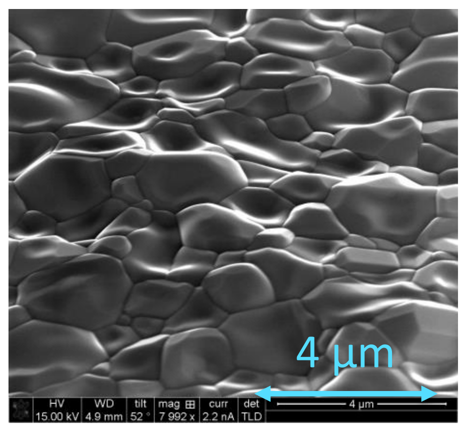
Reducing low tin content regions



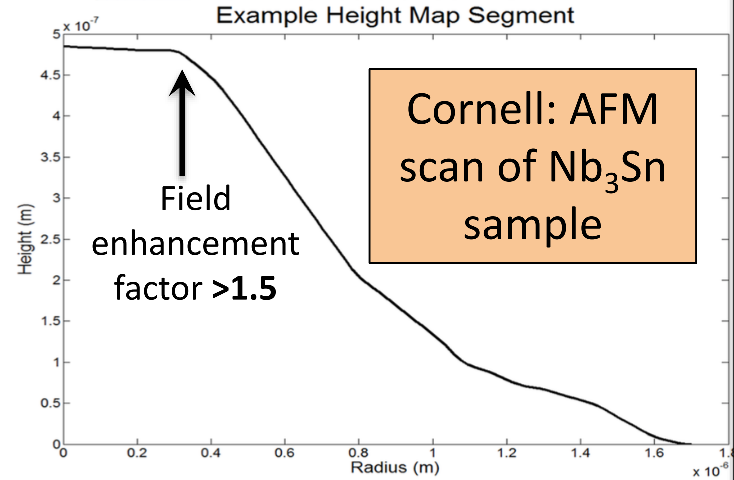


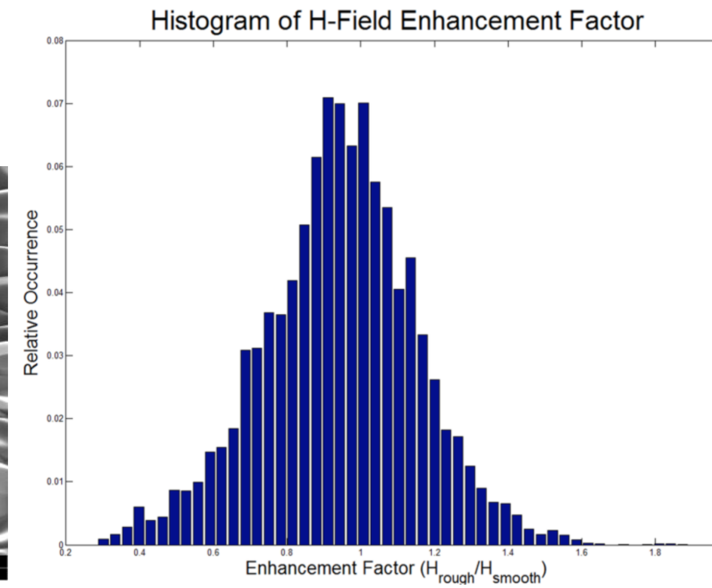
Y. Trenikhina, S. Posen, D. Hall, and M. Liepe, Proc. SRF Conference 2015, TUPB056, 2015

Smoothing sharp-edged surfaces



S. Posen, Ph.D. Thesis, Cornell University (2015).





R. Porter, D. L. Hall, M. Liepe, J. T. Maniscalco, Proc. Linac Conference 2016, MOPRC027 (2016).

Summary and Outlook

- **Superconducting radiofrequency cavities** accelerate particle beams at large facilities in a diverse range of scientific applications, with more being added every year
- **Nb_3Sn** offers a path to **operation at higher temperatures**, where cooling is substantially more efficient, potentially opening new applications
- Nb_3Sn **focus for near future**:
  - Reproducibility on single cells
  - Push to remove Q-slope and increase maximum gradient
  - Move into other frequencies and into multicells