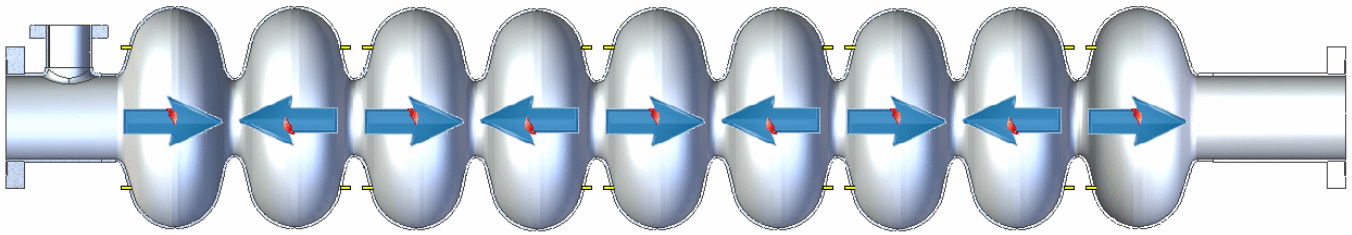
Next-Generation Nb_3Sn Superconducting RF Cavities



Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Presented by Nicole Verboncoeur*, Cornell University, NY, USA

Co-contributors:

Zeming Sun, Gabriel Gaitan, Liana Shpani, Sophia Arnold, Carly Allen, Cornell University, NY, USA

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Kensei Umemori and Hayato Ito, KEK, Japan

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Outline

Background

Upcoming Facilities

R&D

Applications

Outline

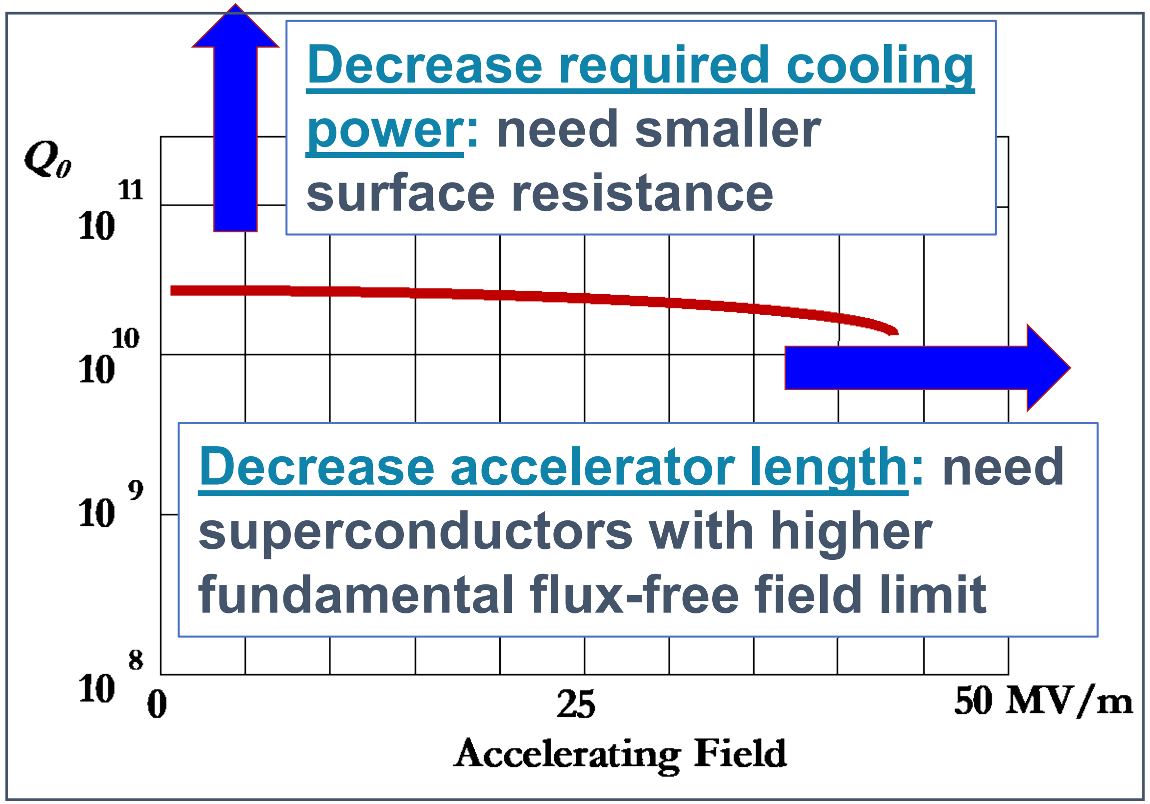
Background

> Why Do We Love Nb_3Sn?

> How Do We Make Nb_3Sn Cavities?

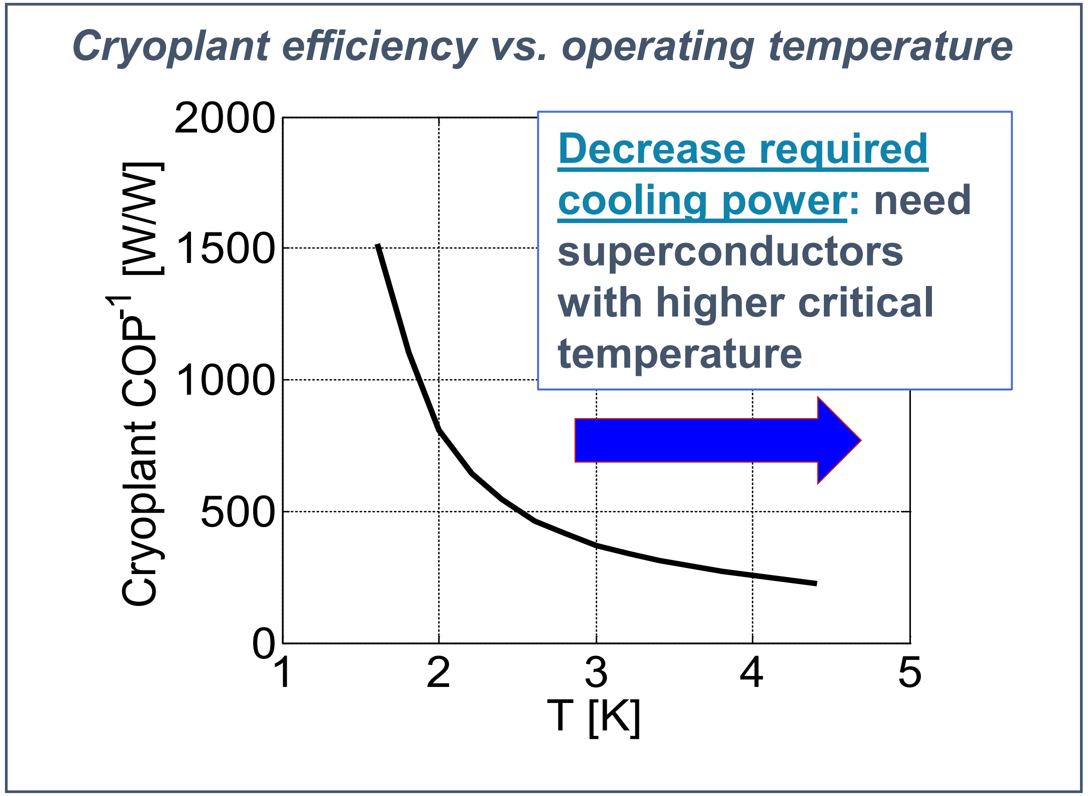
Why Do We Love Nb_3Sn?

Nb is Good But We Need to Do Better



Decrease required cooling power: need smaller surface resistance

Decrease accelerator length: need superconductors with higher fundamental flux-free field limit

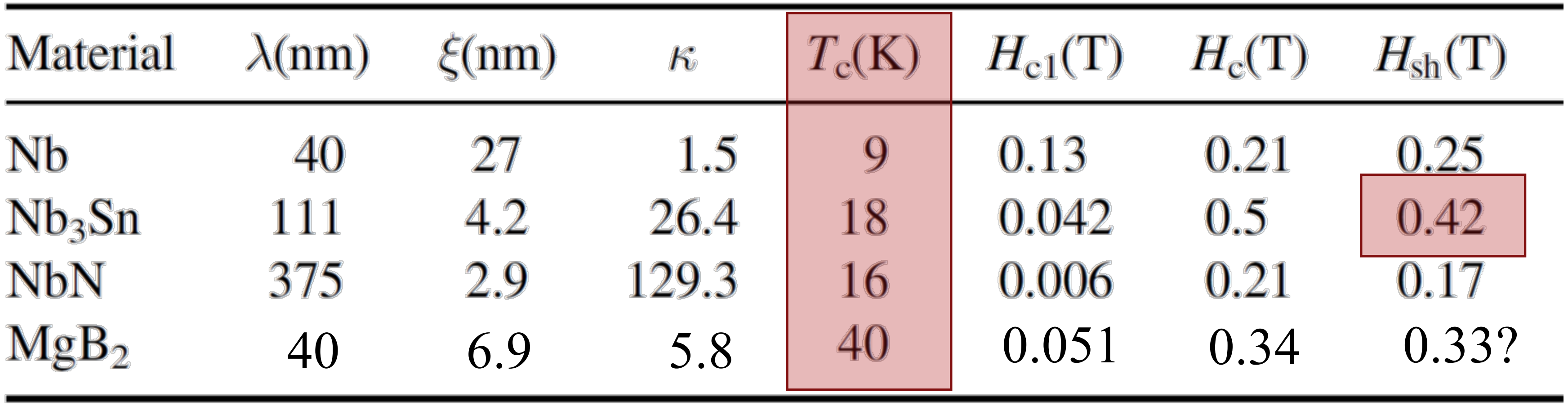


Decrease required cooling power: need superconductors with higher critical temperature

$$Q_0 = \frac{f}{bandwidth} \propto \frac{1}{R_S}$$

$$P_{AC,cooling} \propto \frac{\mathrm{COP}^{-1}(T)}{Q_0}$$

Nb_3Sn is a Promising Material



Material	λ(nm)	ξ(nm)	κ	T_c(K)	H_{c1}(T)	H_c(T)	H_{sh}(T)
Nb	40	27	1.5	9	0.13	0.21	0.25
Nb_3Sn	111	4.2	26.4	18	0.042	0.5	0.42
NbN	375	2.9	129.3	16	0.006	0.21	0.17
MgB_2	40	6.9	5.8	40	0.051	0.34	0.33?

$$R_{BCS} \propto f^2 e^{(-const*T_C/T)}$$

Higher critical temperature = lower losses and/or higher operating temperature

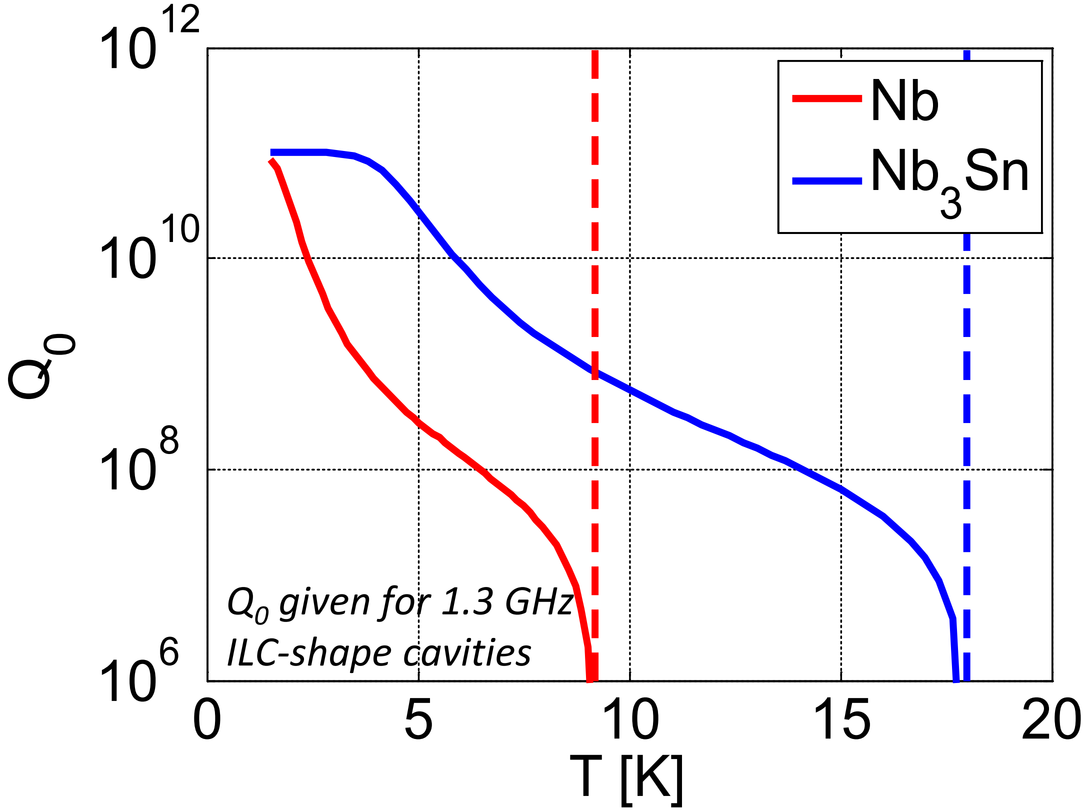
$$E_{acc,max} \propto H_{sh}$$

Higher superheating field H_{sh} = higher accelerating fields

Nb_3Sn is a Promising Material

Increased Accelerating Field

	Niobium	Nb_3Sn
Superheating field	240 mT	420 mT
Max. E_{acc} (theoretical limit)	55 MV/m	**100 MV/m**



Q_0 given for 1.3 GHz ILC-shape cavities

Lower Cooling Cost and Complexity

	Niobium	Nb_3Sn
Critical Temperature T_c	9 K	18 K
Q_0 at **4.2 K**	6×10^8	**6×10^{10}**
Q_0 at 2.0 K	3×10^{10}	$>10^{11}$

Q_0 given for 1.3 GHz ILC-shape cavities

$$\boxed{Q_0} = \frac{f}{bandwidth} \propto \frac{1}{R_S}$$

Higher Q_0

$$\boxed{P_{AC,cooling}} \propto \frac{COP^{-1}(T)}{Q_0}$$

7 kW → 1 kW

$$R_{BCS} \propto \boxed{f^2} e^{(-const*T_C/T)}$$

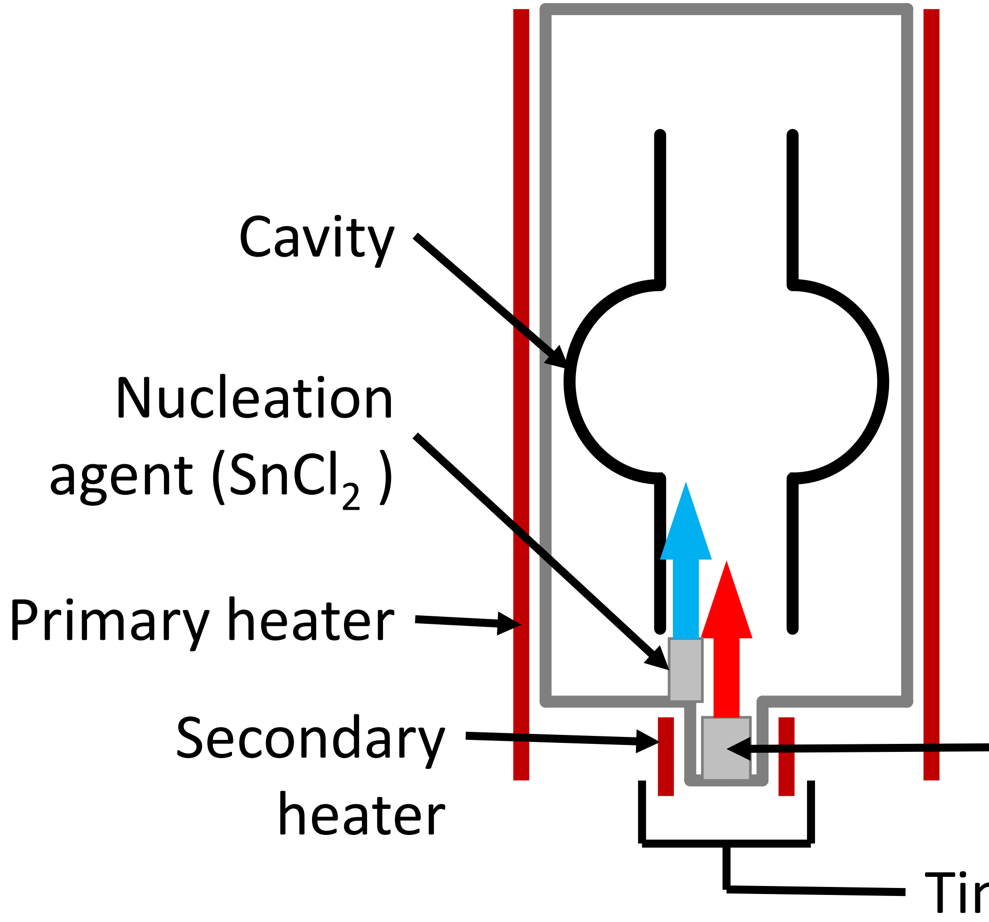
Higher operation frequency

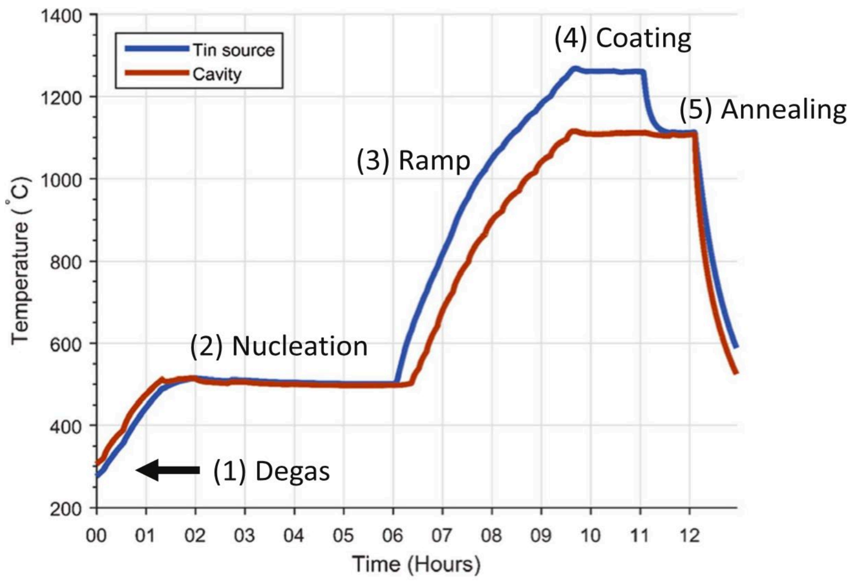
$$\boxed{E_{acc,max}} \propto H_{sh}$$

Higher accelerating gradient

How Do We Make Nb_3Sn Cavities?

Thermal Vapor Diffusion Furnace





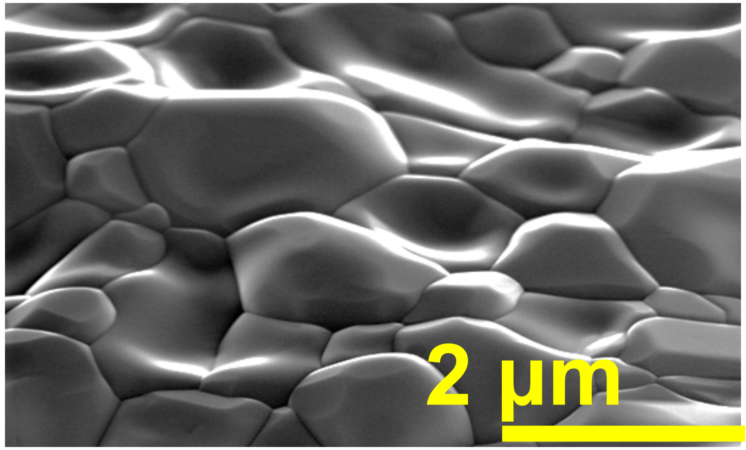
“Wuppertal” configuration, i.e., with secondary heater for the tin source

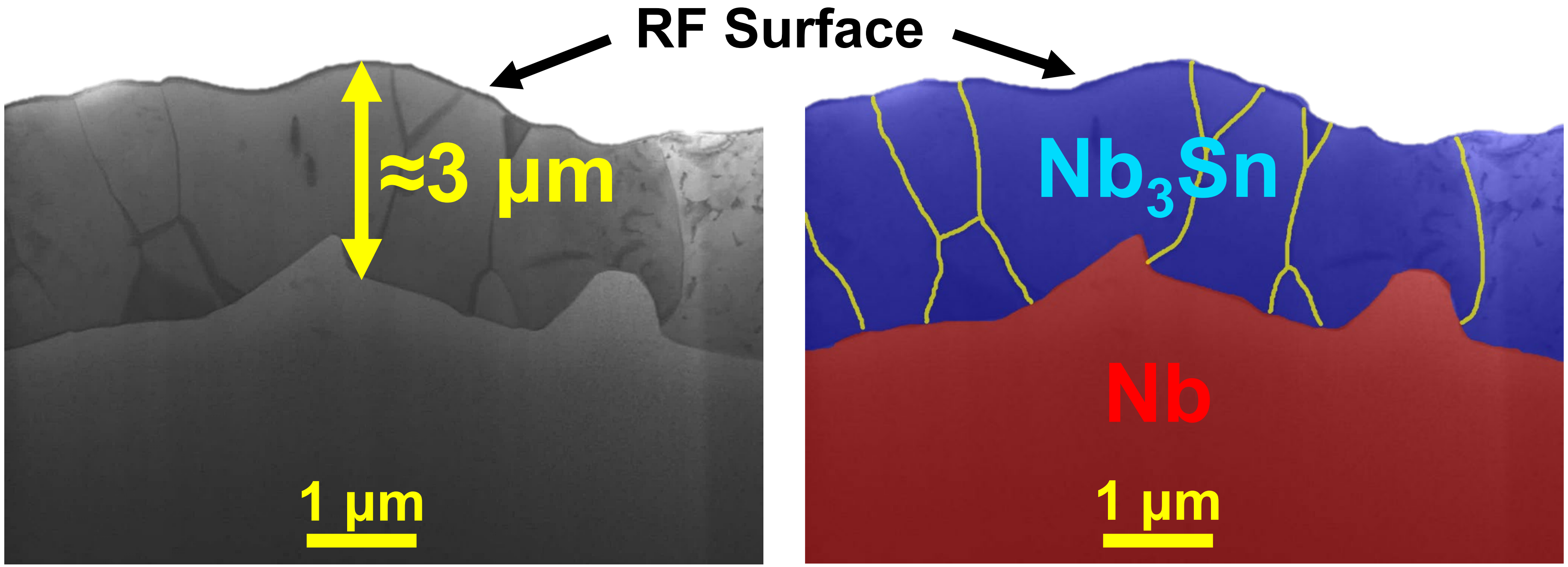
Optimized nucleation and temperature profile

S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 (2014).

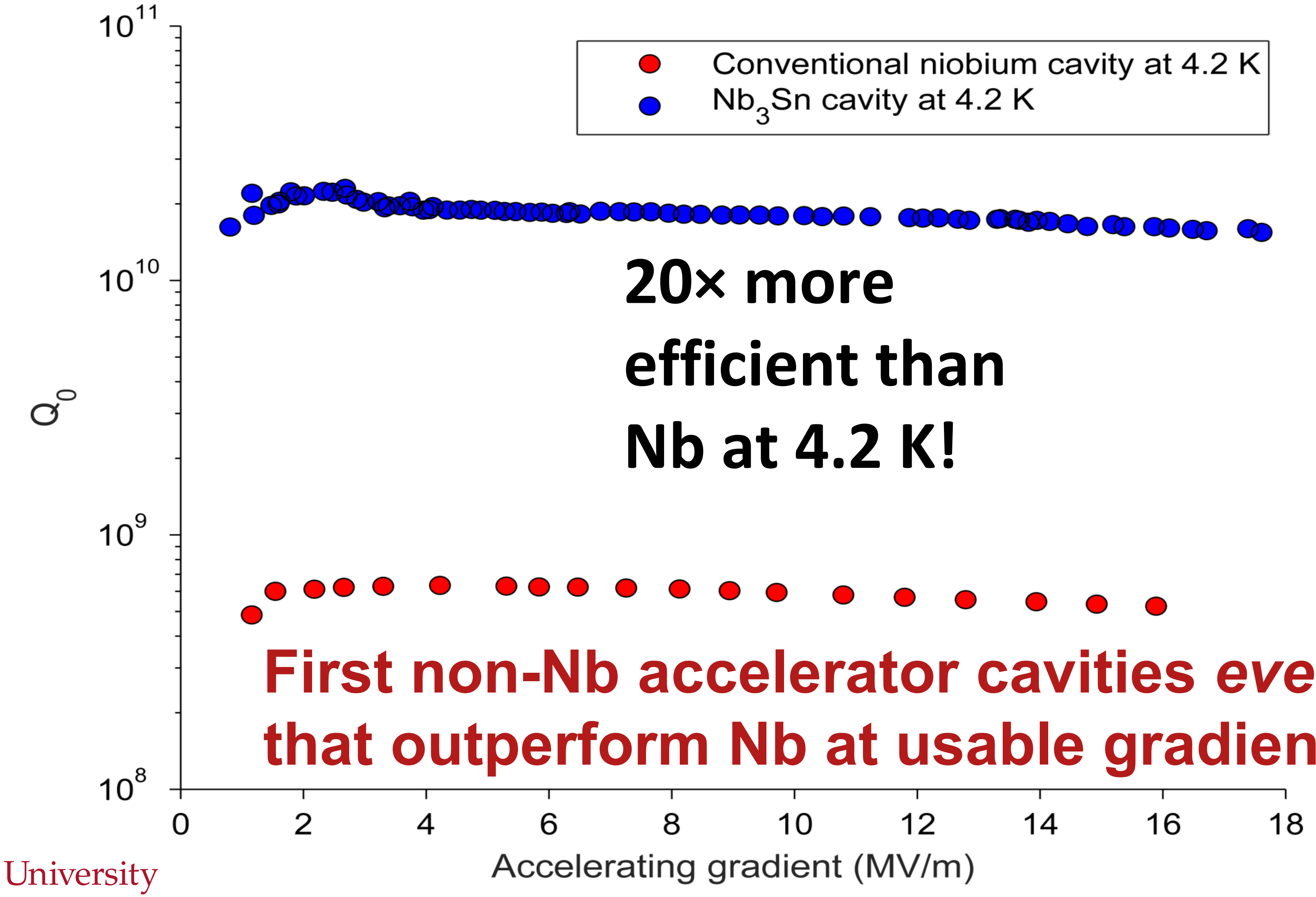
Thin Films

Nb_3Sn forms a polycrystalline layer on the surface of the niobium





Cornell Resurrects Nb_3Sn as an SRF Material



20× more efficient than Nb at 4.2 K!

First non-Nb accelerator cavities *ever* that outperform Nb at usable gradients!

S. Posen et al., Applied Physics Letters 106, Issue 8 (2015).

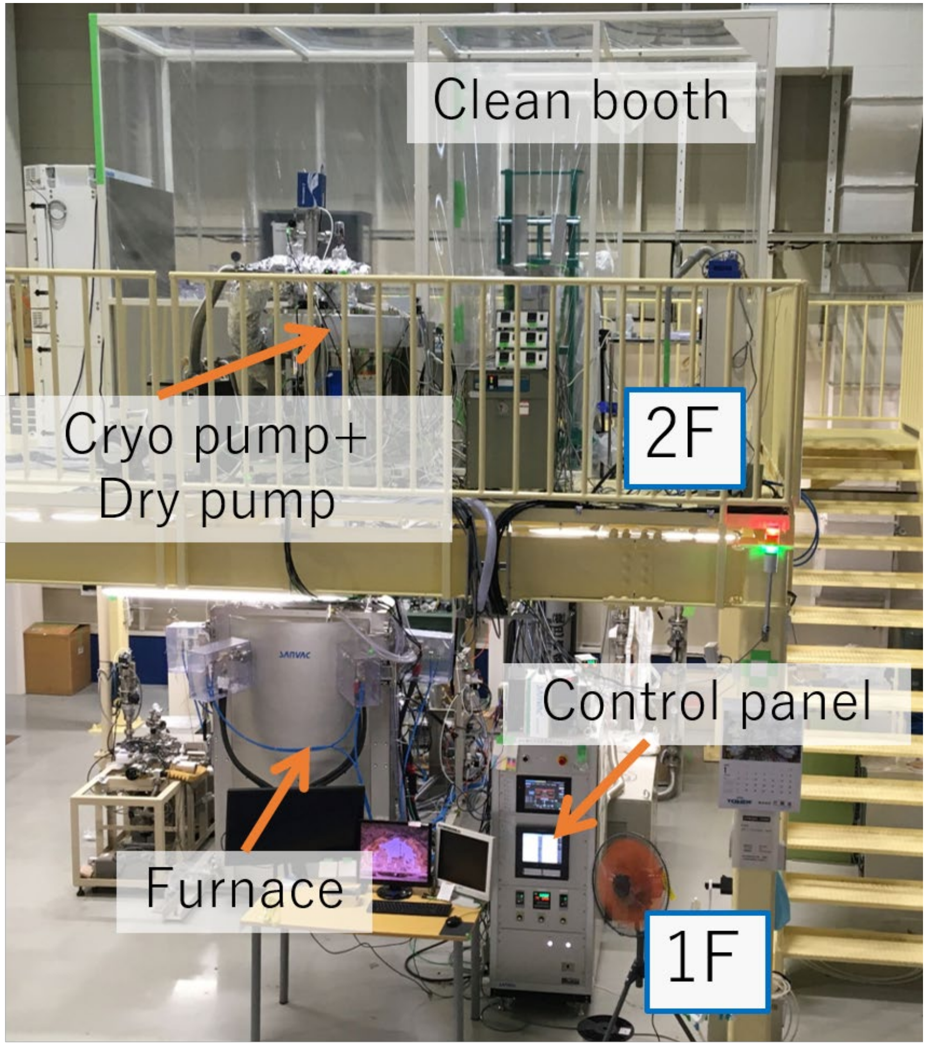
U.S. DOE award DE-SC0008431

Upcoming Facilities

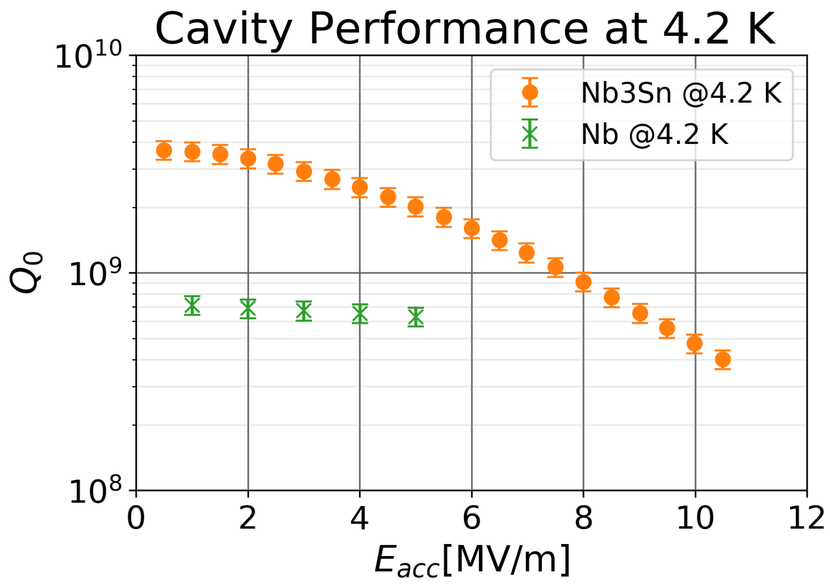
Nb_3Sn: Worldwide Effort

And many more!

Nb_3Sn activity at KEK



Slide courtesy of Kensei Umemori and Hayato Ito, KEK



- After construction of Nb_3Sn coating system, first Nb_3Sn results were obtained at FY2021. Q is not ideal.
- Clean environment were prepared, to eliminate contamination.
- Coating parameters are under investigation using coupon cavity.

R&D

> Better Films

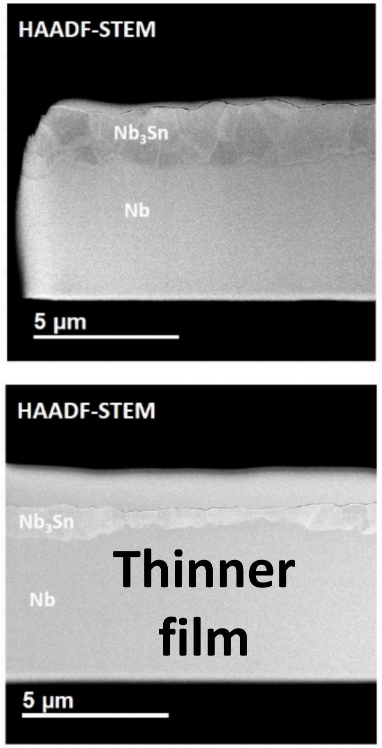
> Alternative growth methods

Better Films

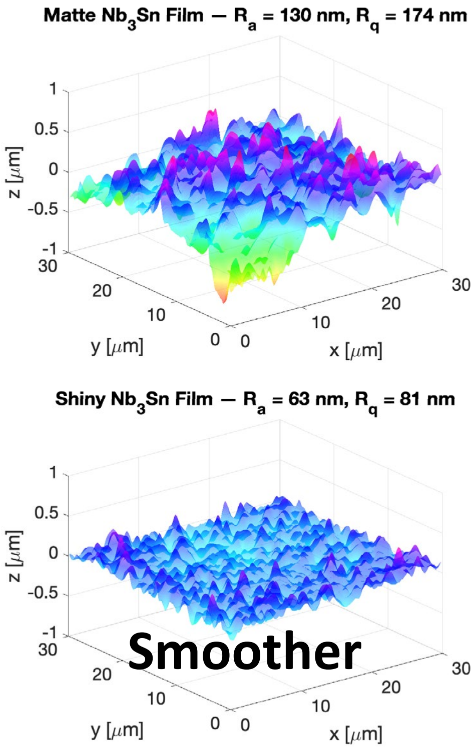
Fermilab – Demonstration of >20 MV/m in 1-Cell Nb_3Sn Cavities

- Demonstration of gradients >20 MV/m (highest was 24 MV/m) on single cell Nb_3Sn cavities
- Expected cause for increase is modified coating process that gives thinner films with lower surface roughness

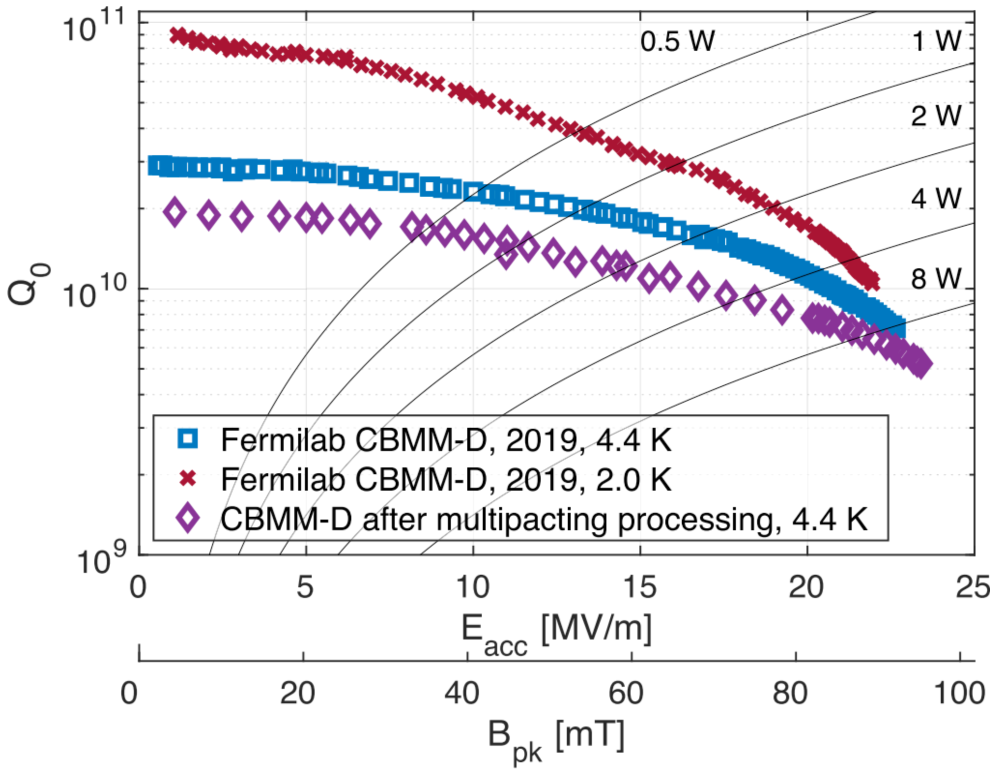
Reproducibility is still tricky – not yet reliable to achieve >20 MV/m, but continued efforts are underway to refine process for uniform, thin, smooth films



Thinner film



Smoother

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Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S Posen[1], J Lee[1,2], D N Seidman[2,3], A Romanenko[1], B Tennis[1], O S Melnychuk[1] and D A Sergatskov[1]

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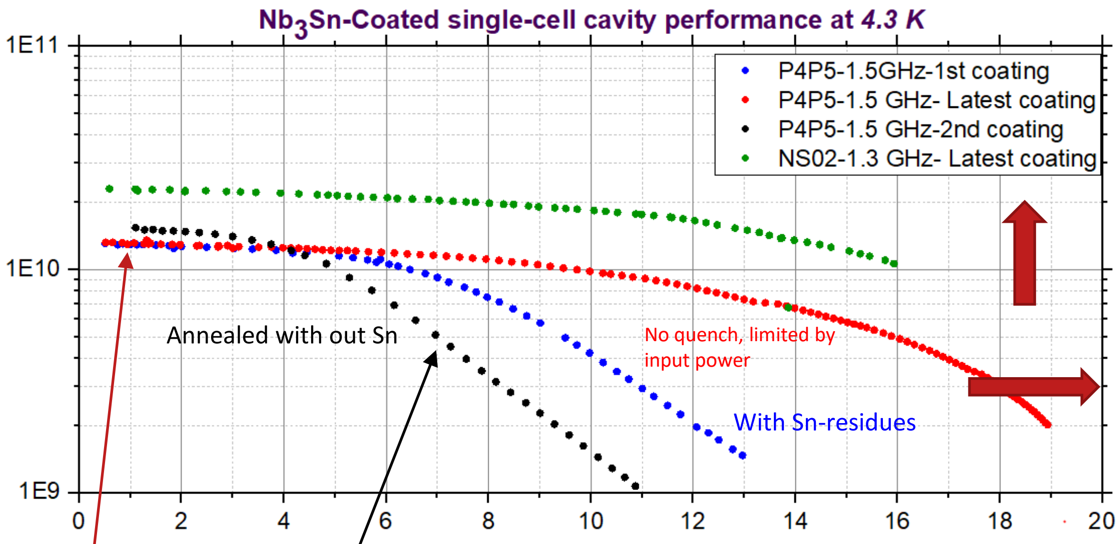
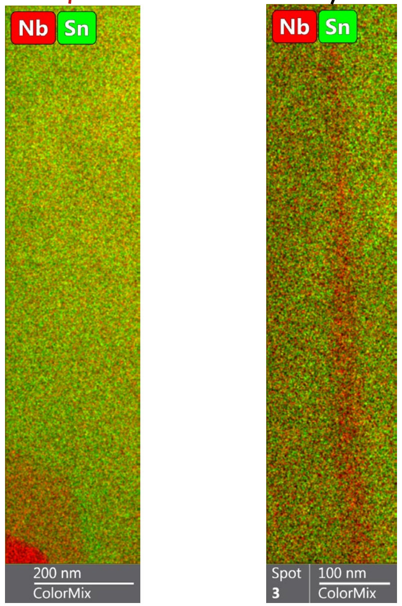
Citation S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

Development of Nb_3Sn-coated cavities at JLab

Slide Courtesy of U. Pudasaini



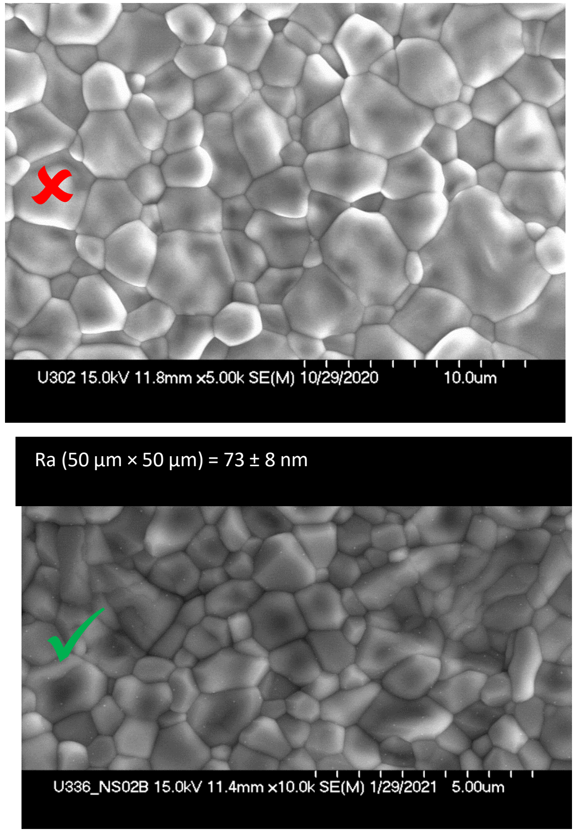


TEM analysis of grain boundaries with and without Q-slope

Coating with small grain sizes, smoother surfaces, and thinner (~ 1 µm) thinner coating with no Sn segregation or deficient grain boundary correlates with better performing cavities.
Further optimization of the coating process to enhance cavity performance is in progress.

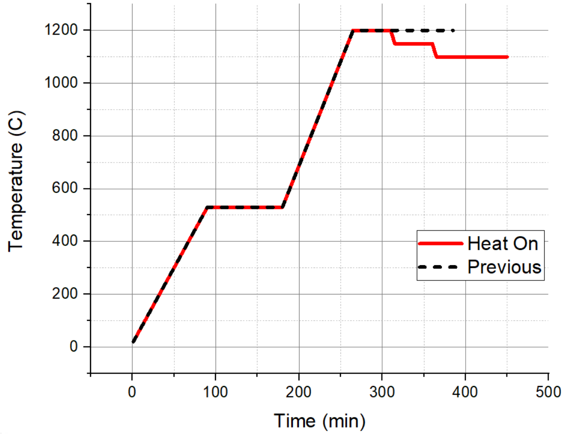
Witness sample analysis correlating RF performance and coating parameters

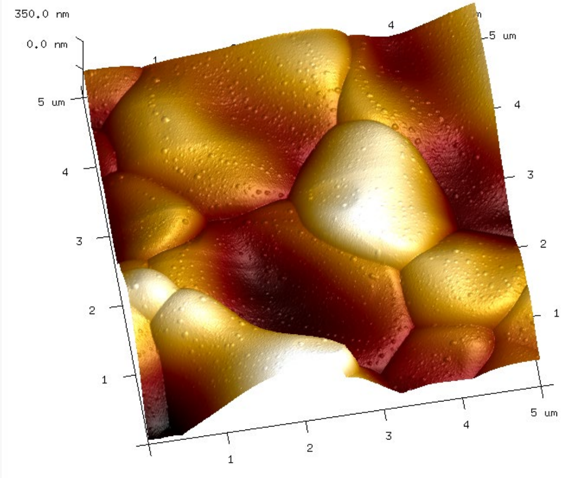
Ra (50 µm × 50 µm) = 202 ± 54 nm



Ra (50 µm × 50 µm) = 73 ± 8 nm

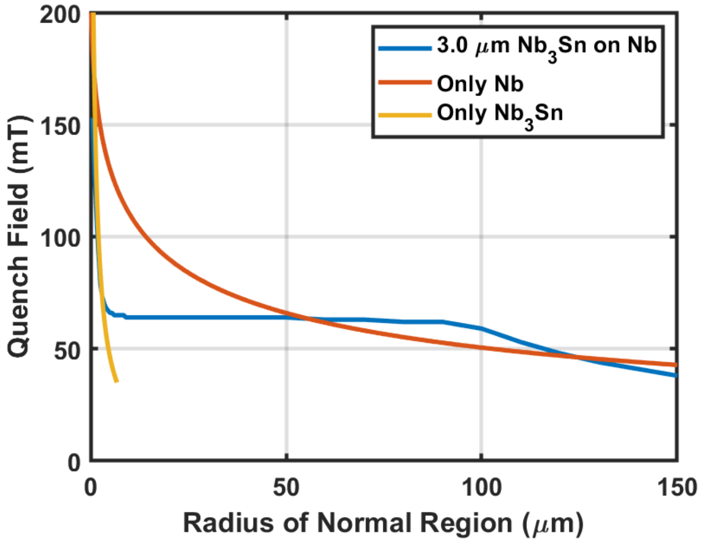
Grain size and roughness

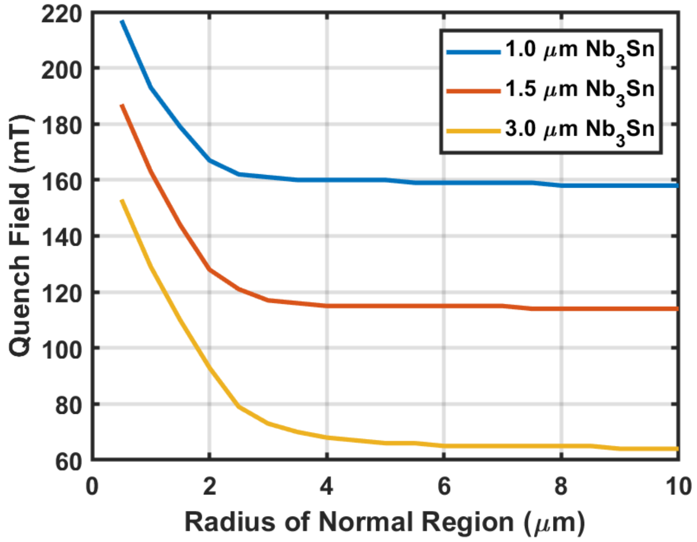




Recurrent Sn residues contributing to residual resistance

Cornell Thin Film Cavity





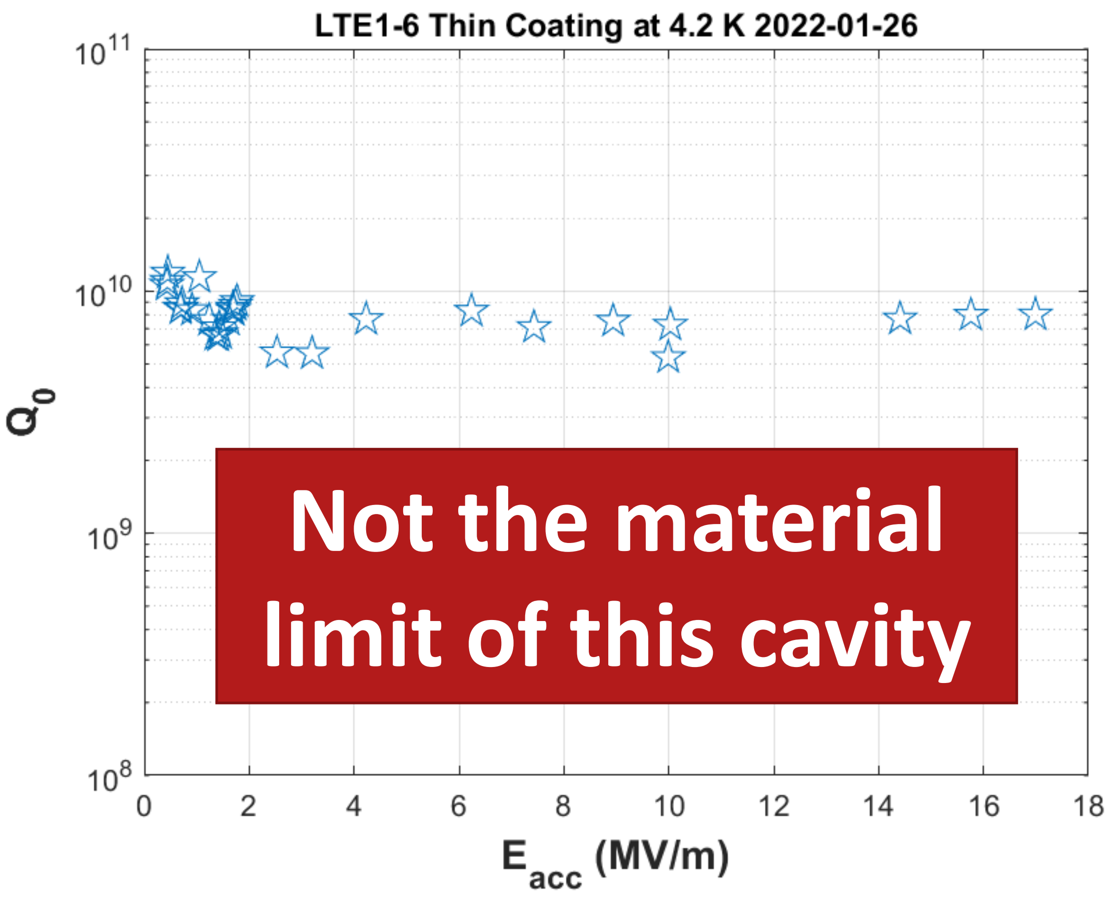
Nb substrate thermally stabilizes Nb_3Sn film

Higher quench fields possible

Thin Film Cavity

Typical Nb_3Sn Cavity

Thin Film Cavity

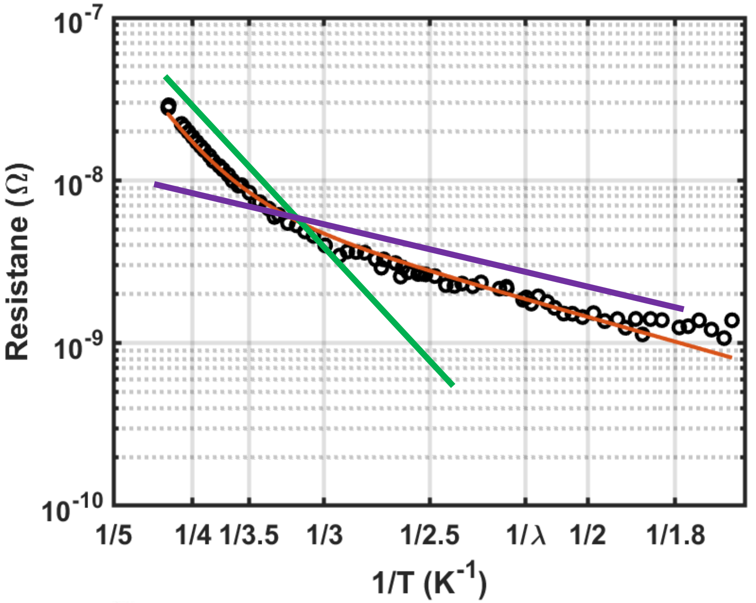


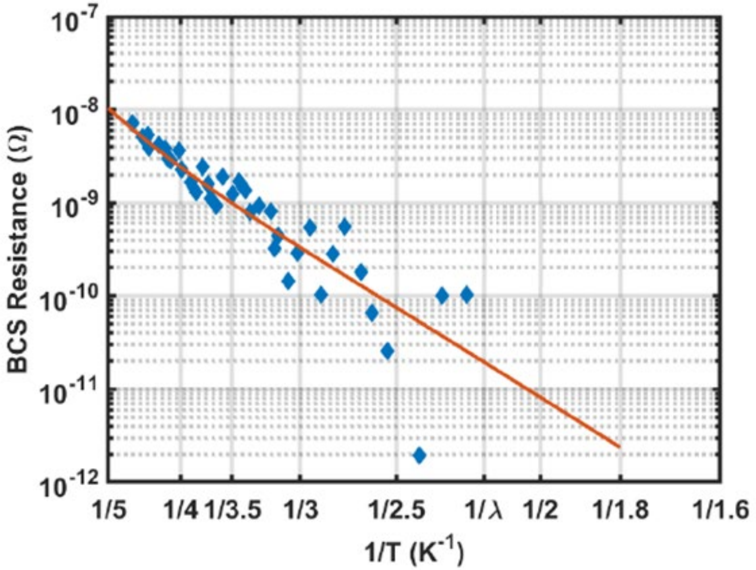
Not the material limit of this cavity

Quench at ~17 MV/m due to field emission

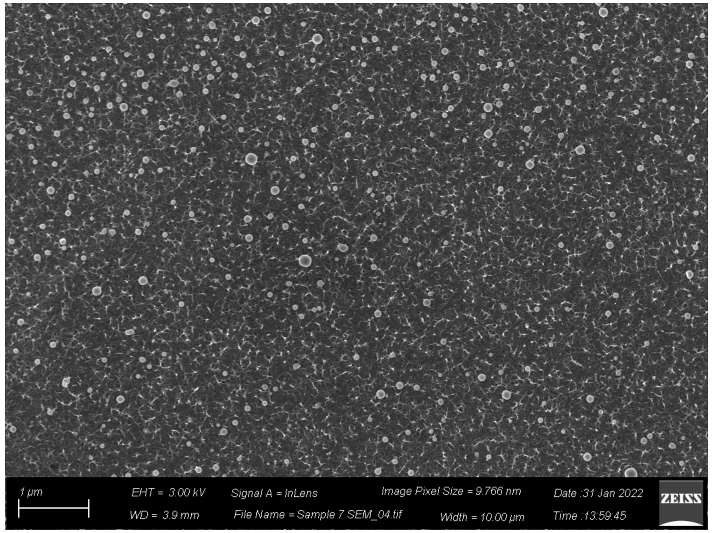
Higher Sn availability during nucleation phase

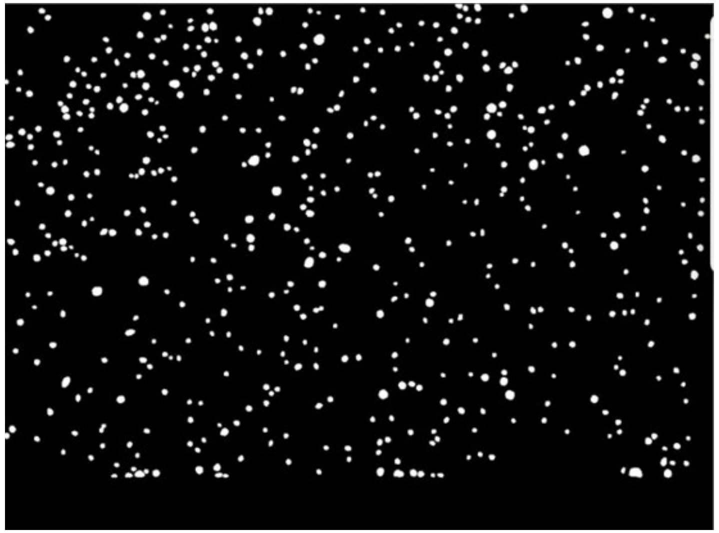
Purer Nb_3Sn, Lower R_{BCS}





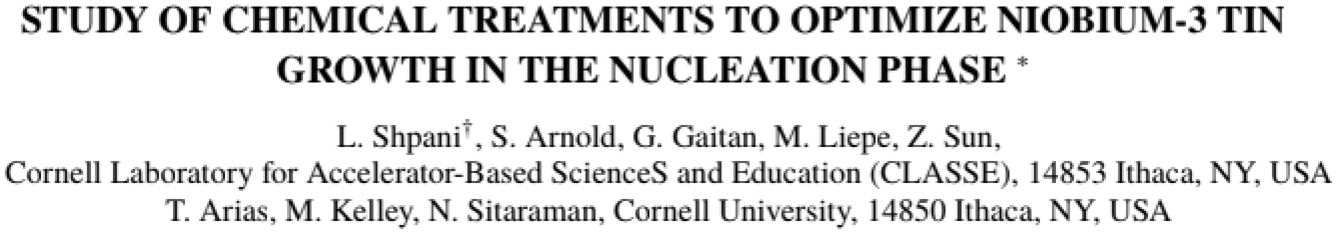
Surface Treatments for Improved Nucleation





Testing the effects of various chemical treatments of various pH on Nb_3Sn nucleation

- Bake in Cornell Tin furnace stopping at nucleation stage
- Quantifying uniformity of nucleation site distribution through average nearest neighbor distance and density analysis using ImageJ for image processing
- Early results favor low pH solutions



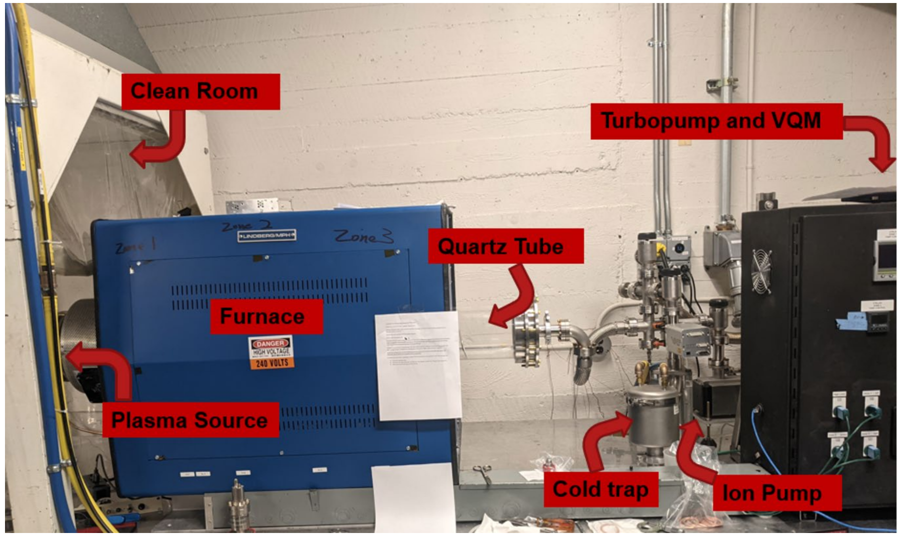
STUDY OF CHEMICAL TREATMENTS TO OPTIMIZE NIOBIUM-3 TIN GROWTH IN THE NUCLEATION PHASE *

L. Shpani†, S. Arnold, G. Gaitan, M. Liepe, Z. Sun,
Cornell Laboratory for Accelerator-Based ScienceS and Education (CLASSE), 14853 Ithaca, NY, USA
T. Arias, M. Kelley, N. Sitaraman, Cornell University, 14850 Ithaca, NY, USA

See IPAC 2022 proceedings (above) and Liana Shpani at poster THPOGE015

Alternative Coating Methods

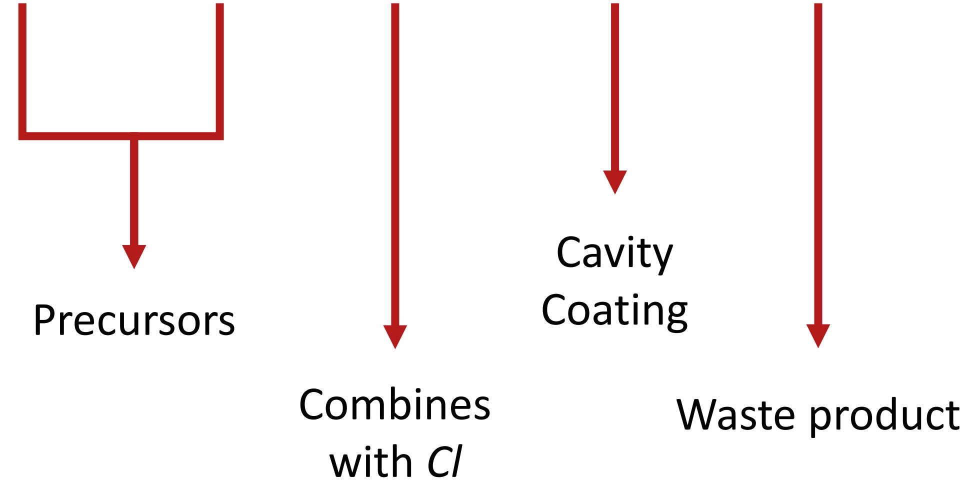
CVD for Nb_3Sn

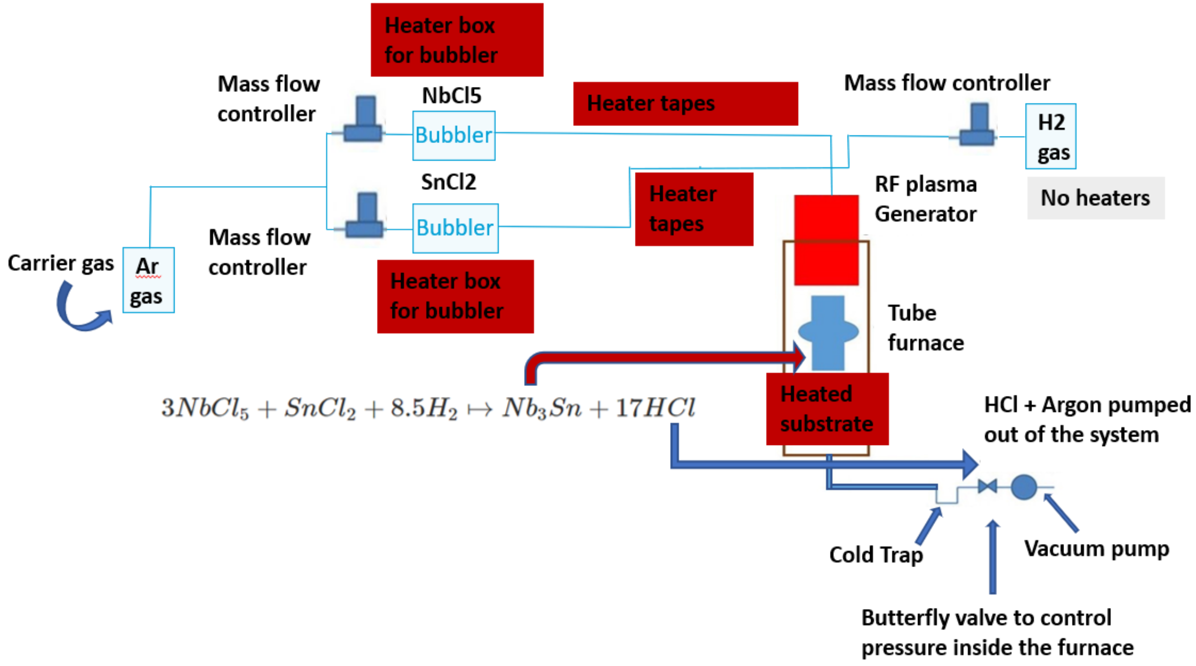


Significant progress on Chemical Vapor deposition furnace

- Main aspects of design have been finalized and parts ordered
- GUI has been designed
- Hoping to test this coming fall

$$3NbCl_5 + SnCl_2 + 8.5H_2 \rightarrow Nb_3Sn + 17\ HCl$$





Gabriel Gaitan and Zeming Sun

Towards Applications

> Multicell Designs

> Cryomodule Designs

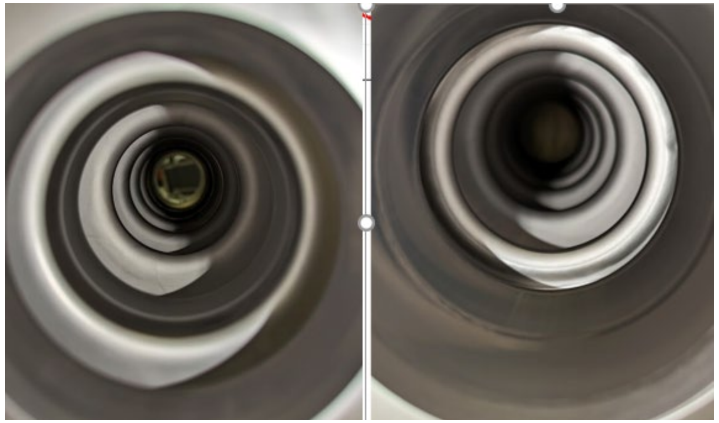
Multicell Designs

Development of Nb_3Sn-coated cavities at JLab

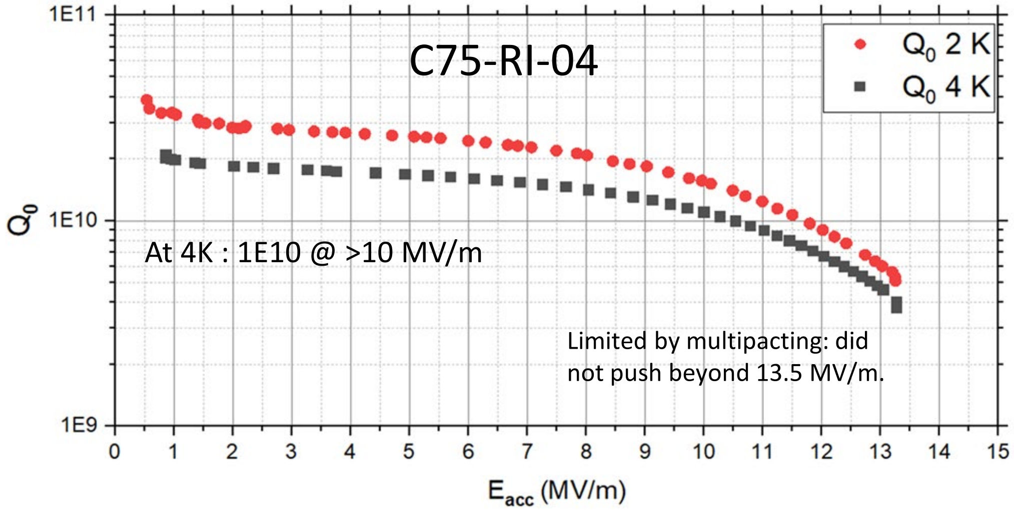
Slide Courtesy of U. Pudasaini

C75 cavity made from large grain Nb.

Nicole Verboncoeur | LINAC 2022

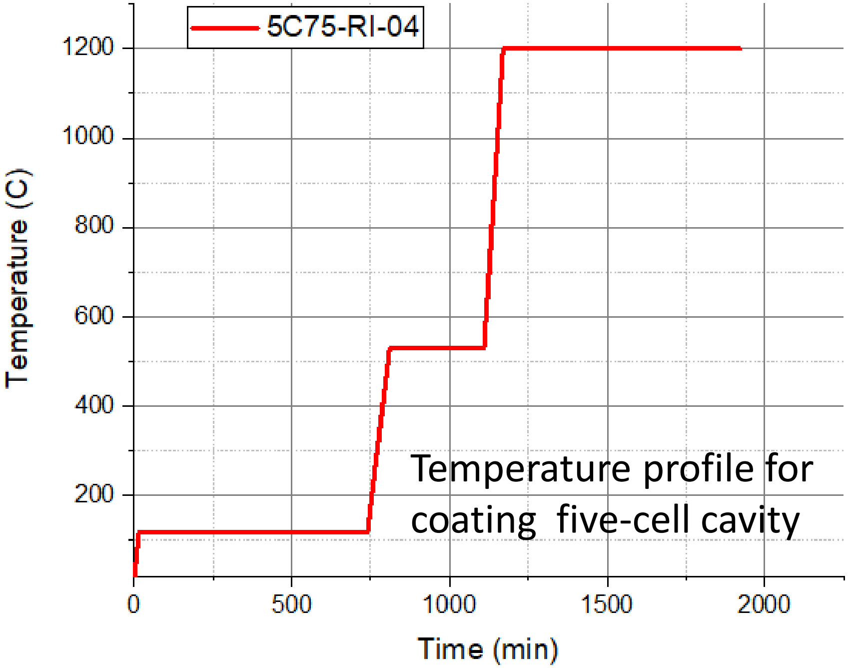


Uniform coating.



At 4K : 1E10 @ >10 MV/m

Limited by multipacting: did not push beyond 13.5 MV/m.



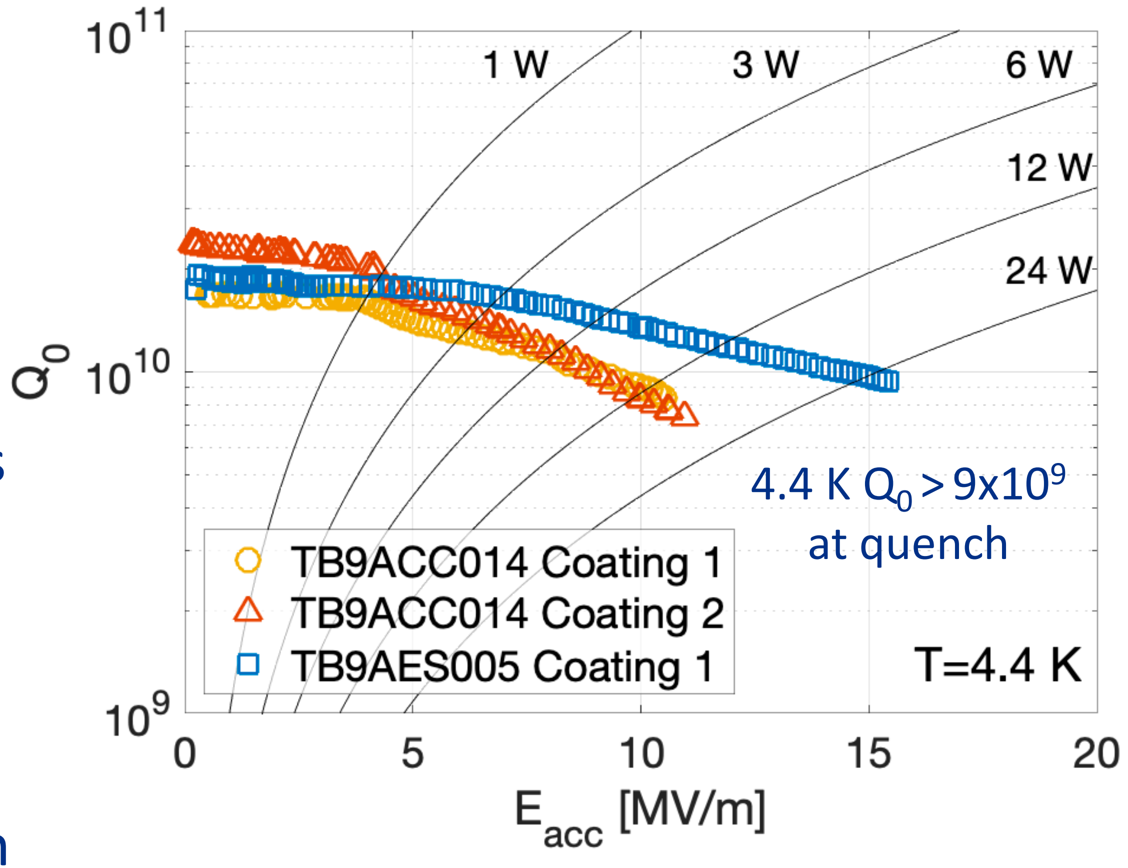
Temperature profile for coating five-cell cavity

Nb_3Sn cavities are qualified to build a pair to install in a quarter cryomodule (G. Eremeev's ECA).

The goal is to install the CM and install in JLab UITF next year.

Fermilab – First 9-cell Nb_3Sn Cavities

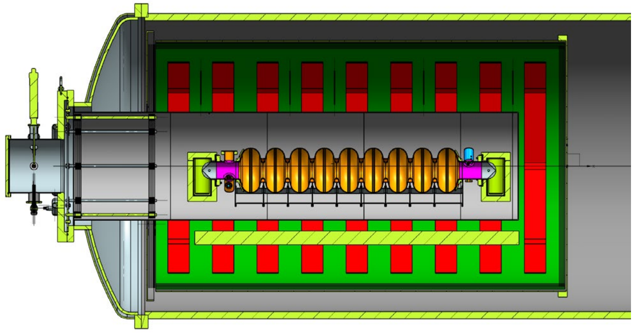
- Coated full ILC-style 9-cell cavities, including complex geometry HOM cans, standard NbTi flanges
- Promising performance in vertical test, as high as ~15 MV/m with Q~9x10^9 at 4.4 K
- Performance in practical accelerator structure shows potential of Nb_3Sn for first industrial accelerator applications

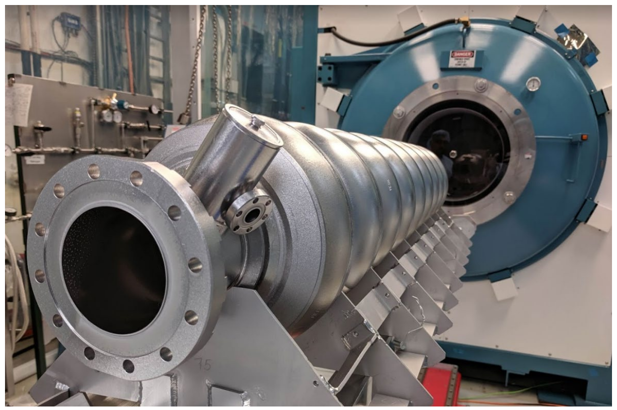


4.4 K $Q_0 > 9x10^9$ at quench

Nb_3Sn-coated 9-cell cavities TB9ACC014 and TB9AES005

Includes correction for stainless steel flanges 2x0.8 nΩ





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Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S Posen[1], J Lee[1,2], D N Seidman[2,3], A Romanenko[1], B Tennis[1], O S Melnychuk[1] and D A Sergatskov[1]

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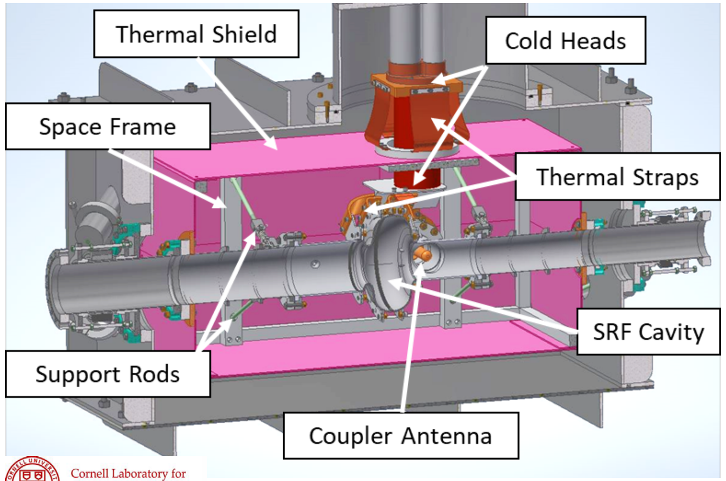
Superconductor Science and Technology, Volume 34, Number 2

Citation S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

Turn-Key Compact Cryomodules

Cryostats and Industry Applications



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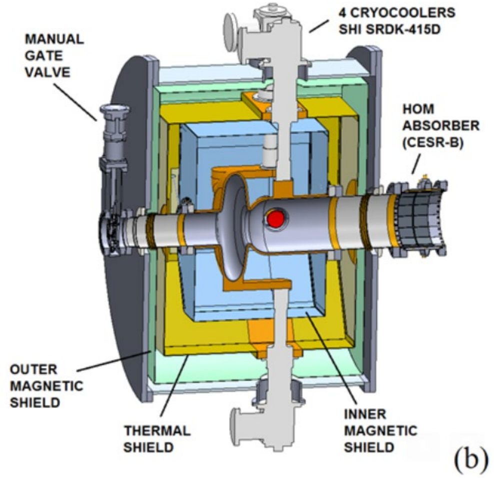
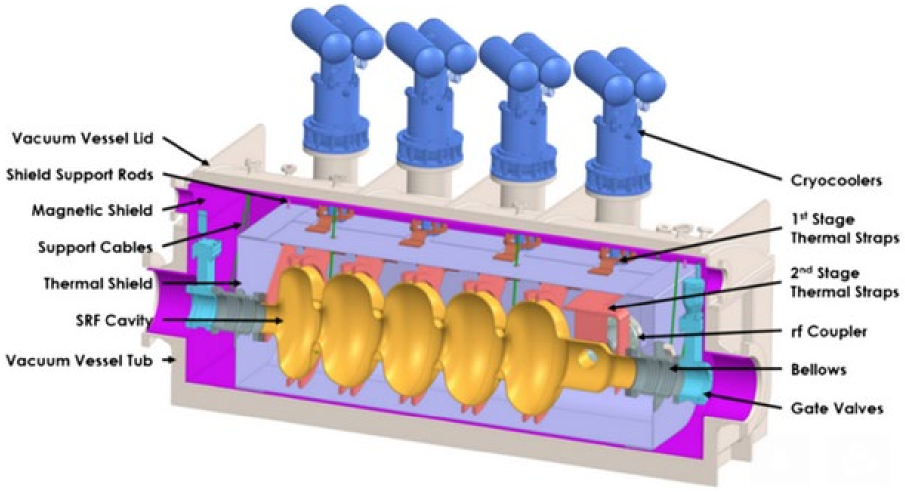
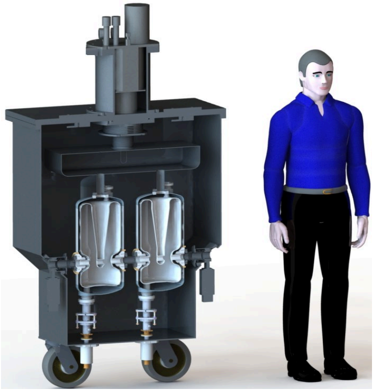


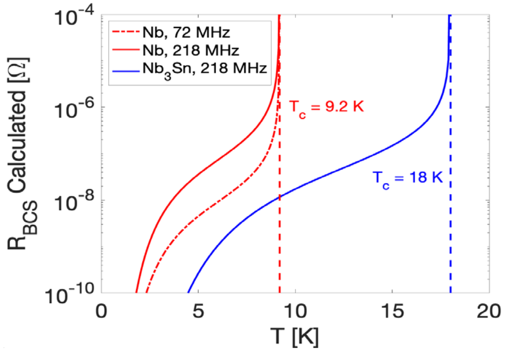
Jefferson Lab



Fermilab

Nb$_3$Sn for Nuclear Physics (Collaboration ANL/FNAL/Radiabeam)





Fermilab

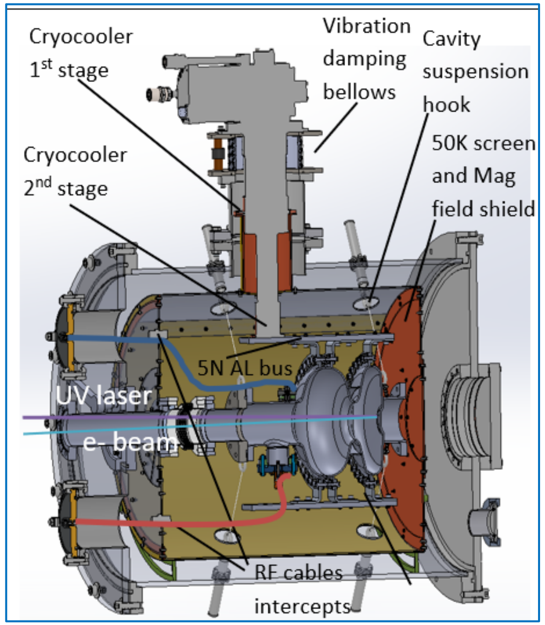
FNAL Lead: Sam Posen

Argonne NATIONAL LABORATORY

Lead lab; PI: Mike Kelly

RadiaBeam

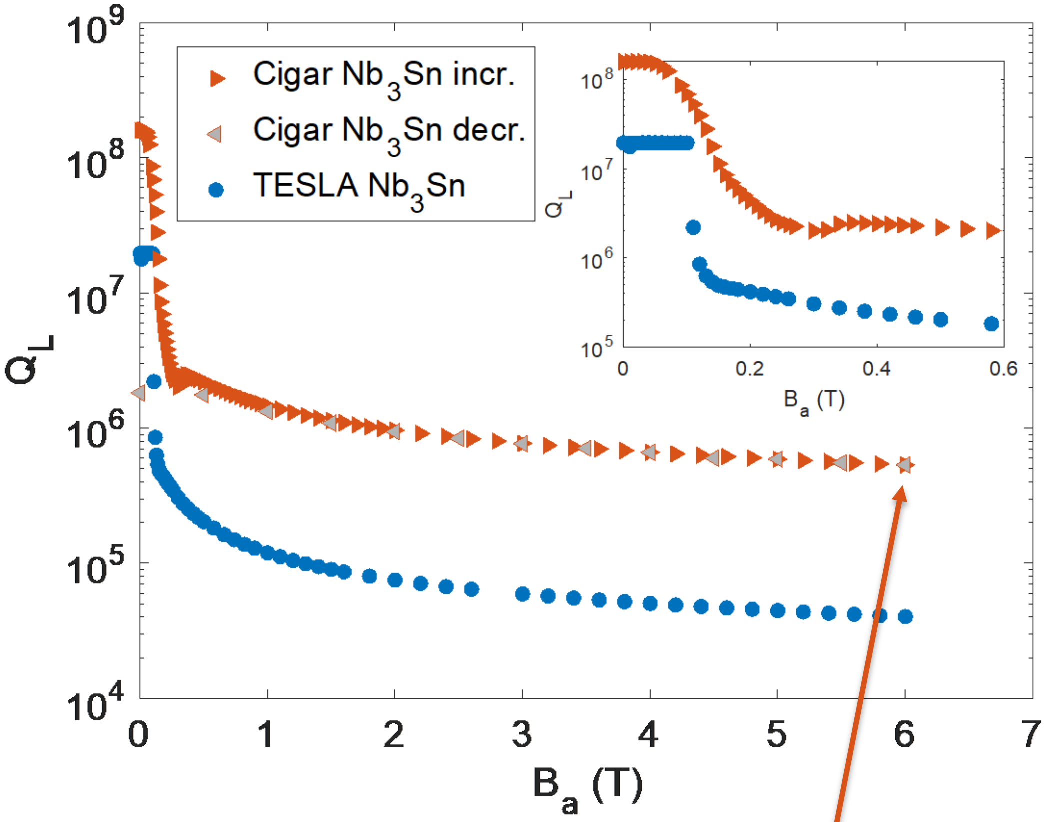
RB Lead: Sergey Kutsaev



Nb$_3$Sn for Industrial Accelerators (Collab. Euclid/FNAL/BNL)

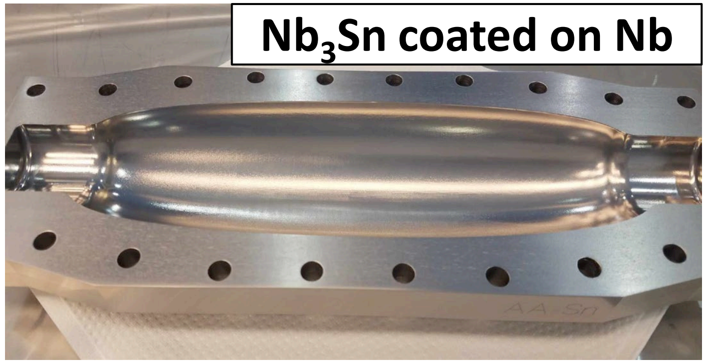
Fermilab – Nb_3Sn Cavity for Axion Dark Matter Search

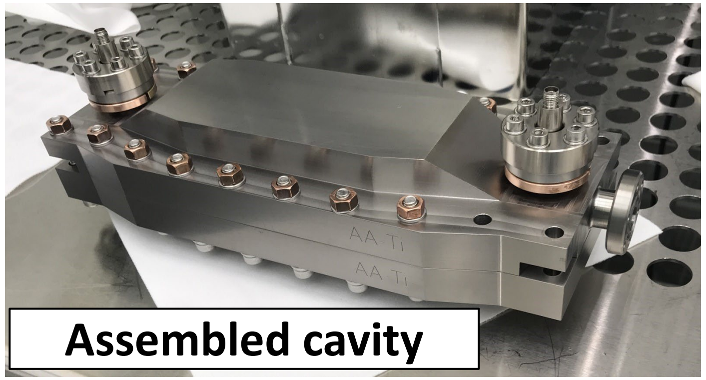
- For dark matter axion search based on haloscopes, sensitivity depends on cavity Q0 in multi-tesla applied field
- Very different regime than SRF accelerators! Need high B_{c2} material and special geometry
- Achieved Q_0 of $5x10^5$, significantly higher than typical material (copper)
- Now working on tunable version that could be used in an experiment



Q_0 of $5x10^5$ at 6 T, 4.2 K, 3.9 GHz

Posen et al., “Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches” arxiv:2201.10733, 2002


Nb_3Sn coated on Nb


Assembled cavity

Conclusion

Progress on Nb_3Sn Marches Forward

> More and more Nb_3Sn coating facilities can be found all around the world

> R&D pushes to further improve Nb_3Sn performance

> Practical applications are in early stages at facilities

Acknowledgements

Co-contributors:
Zeming Sun, Gabriel Gaitan, Liana Shpani, Sophia Arnold, Carly Allen, *Cornell University*
Sam Posen and Grigory Eremeev, *Fermi National Laboratory*
Kensei Umemori and Hayato Ito, *KEK*
Uttar Pudasaini, *Thomas Jefferson National Laboratory*

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James Sears
Greg Kulina
Terri Gruber-Hine
Holly Conklin

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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Fermilab

Jefferson Lab

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