Overview of Nb_3Sn Cavity Progress (for CW machines)

Grant No. DE-SC0008431

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Special Thanks to:
Sam Posen and Grigory Eremeev, FNAL
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Gabriel Gaitan, Matthias Liepe, Ryan Porter, Neil Stilin, Nicole Verbonceour, Cornell University
for their significant contributions!

Outline

1. Why Nb_3Sn?
2. How do we grow it?
3. State-of-the-art performance
4. Case Study: LCLS-II
5. Remaining Challenges

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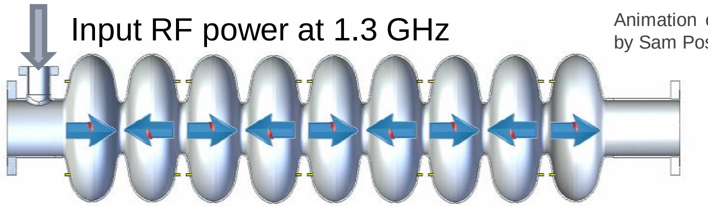
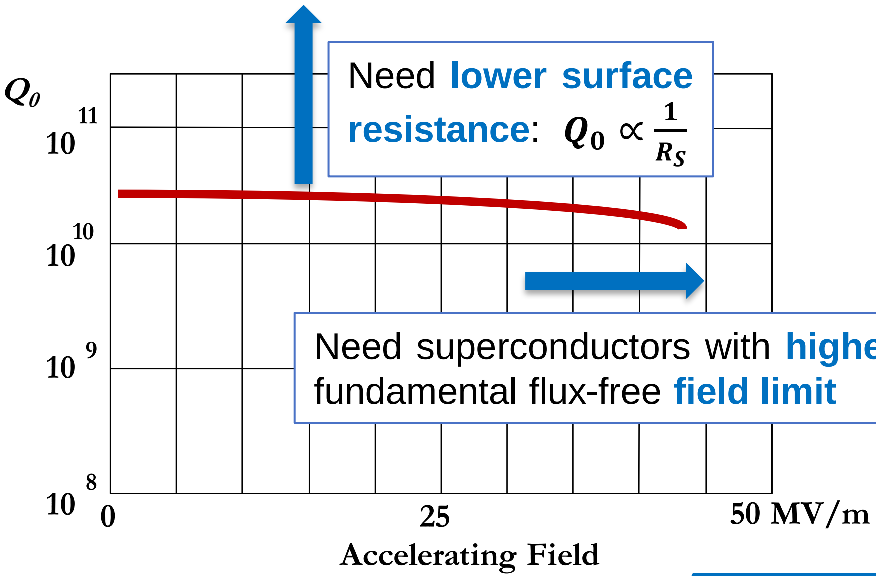
Goals:

1. Decrease accelerator length
   → **Higher accelerating gradients**
2. **Decrease cooling power**

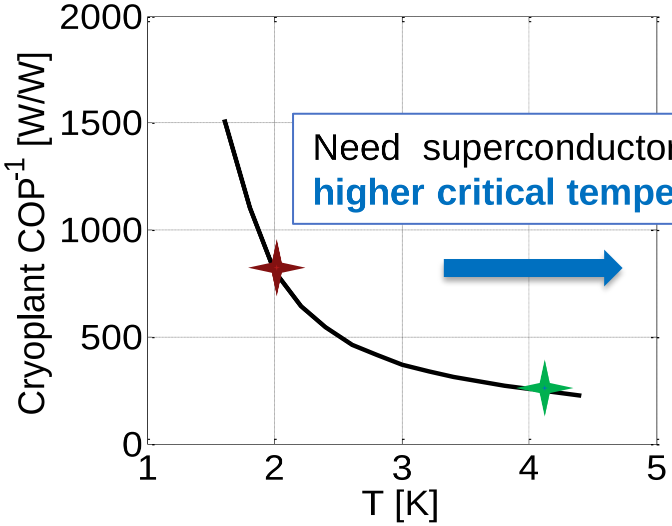


Slowed down by factor of approximately 4x10^9



Need **lower surface resistance**: $Q_0 \propto \frac{1}{R_S}$

Need superconductors with **higher** fundamental flux-free **field limit**



Need superconductors with **higher critical temperature**

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

Nb_3Sn: A Very Promising Material

Material	λ(nm)	ξ(nm)	κ	T_c(K)	B_{C1}(T)	B_{C1}(T)	B_{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?

Higher critical temperature T_c:

- → **lower losses**
- → **higher operating temperature**
- → can operate at **higher frequency**

$$R_{BCS} \propto f^2 e^{-const.\times T_C/T}$$

Higher superheating field B_{sh}= **higher accelerating gradients**: $E_{acc,max} \propto B_{sh}$

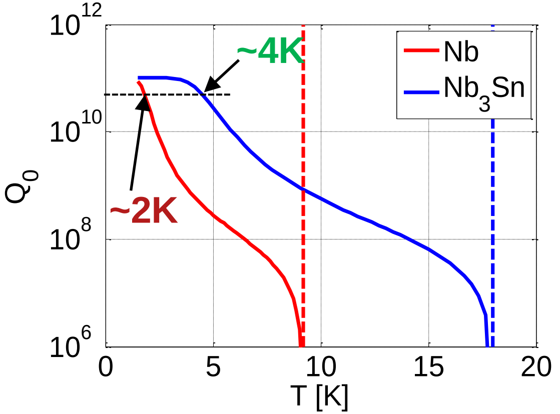
Nb_3Sn Potential

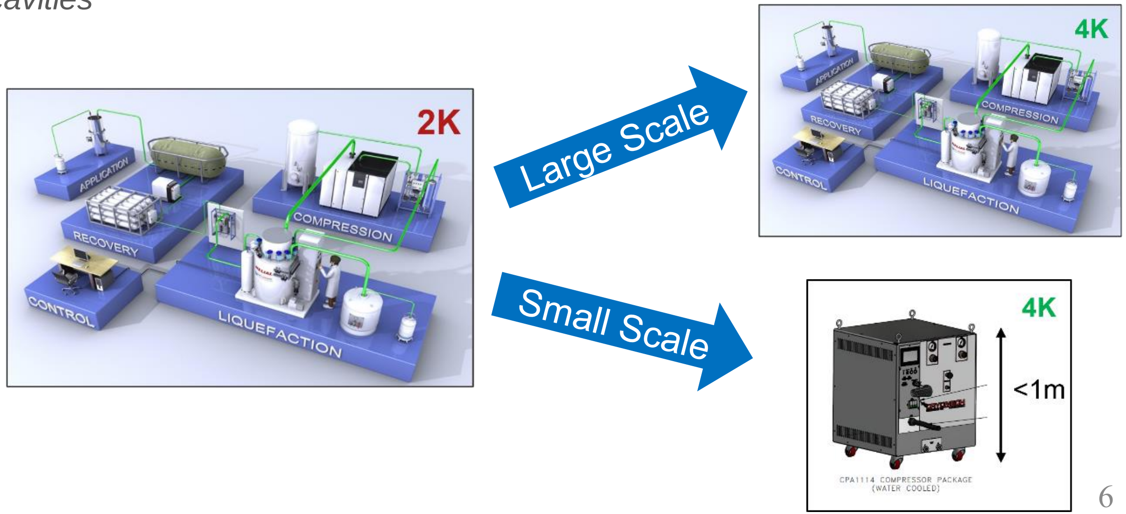
	Nb	Nb_3Sn
Superheating Field (B_{sh})	240 mT	420 mT
Max. E_{acc}	55 MV/m	100 MV/m
Critical Temperature (T_C)	9 K	18 K
Q_0 at 4.2K	6×10^8	6×10^{10}
Q_0 at 2K	3×10^{10}	$>10^{11}$

→ **Higher energy gain**
- → **Shorter** accelerators

→ **Lower cooling cost and complexity**
- → **4.2K operation** with **high cryo-efficiency** (!!)
- → No superfluid helium

*Q_0 given for 1.3 GHz **single-cell** ILC-shape cavities*





Outline

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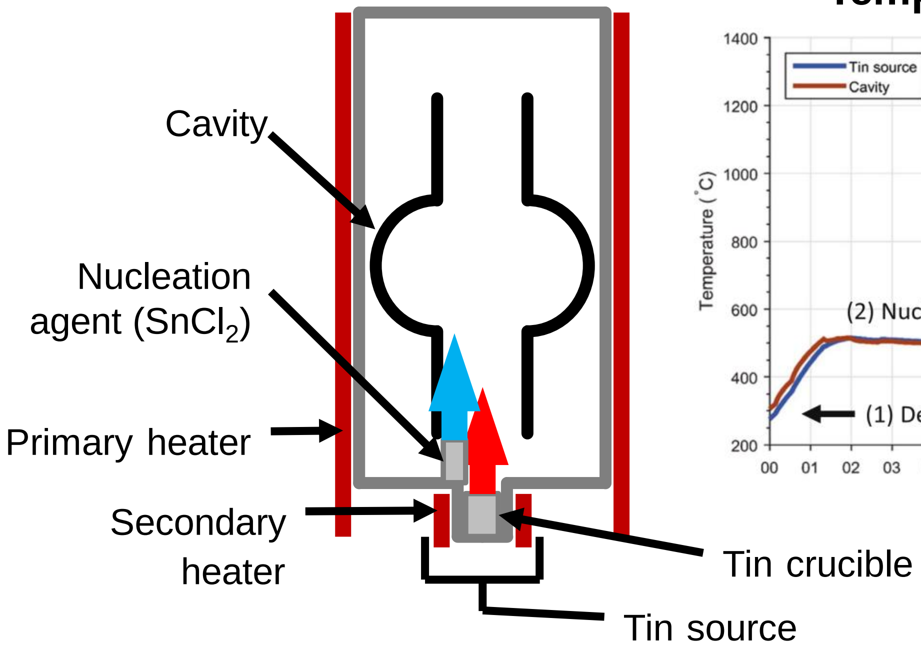
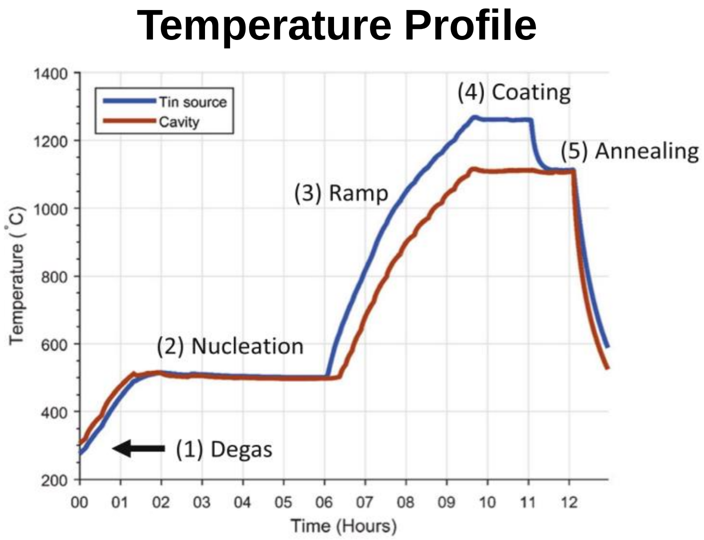
Thermal Vapor Diffusion





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

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

Nb_3Sn Coatings

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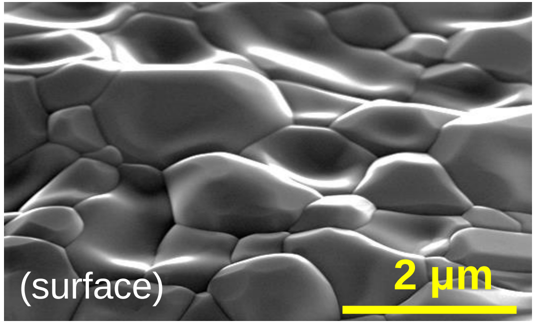
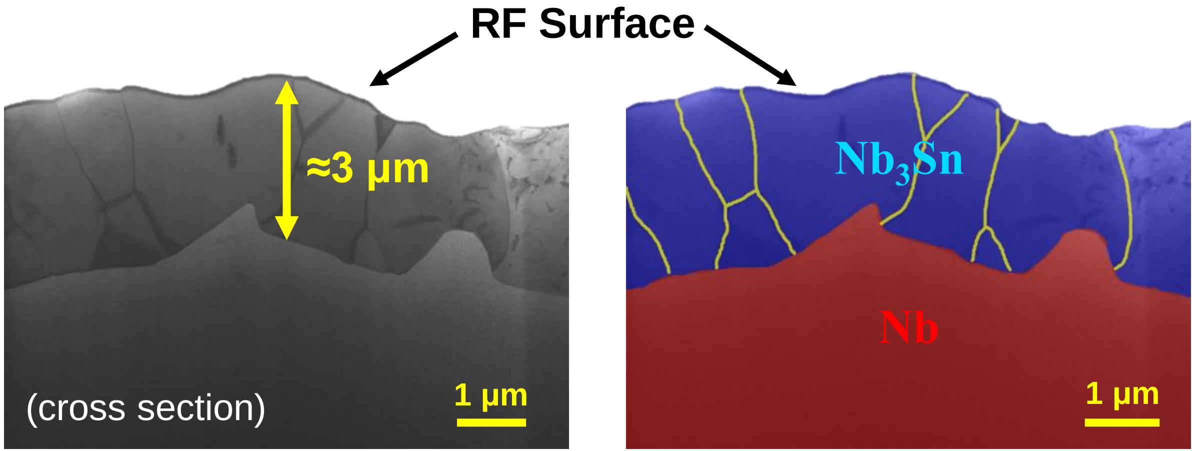
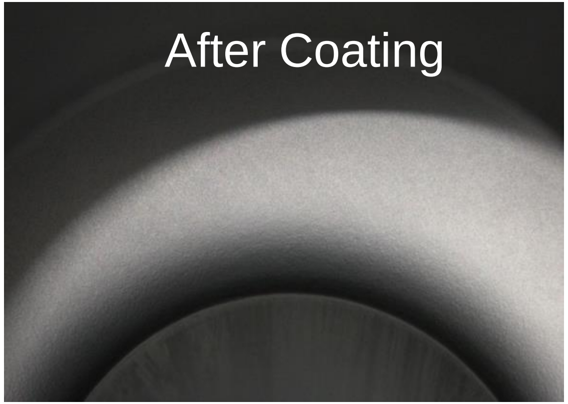
Nb_3Sn forms a polycrystalline layer on the surface of the niobium

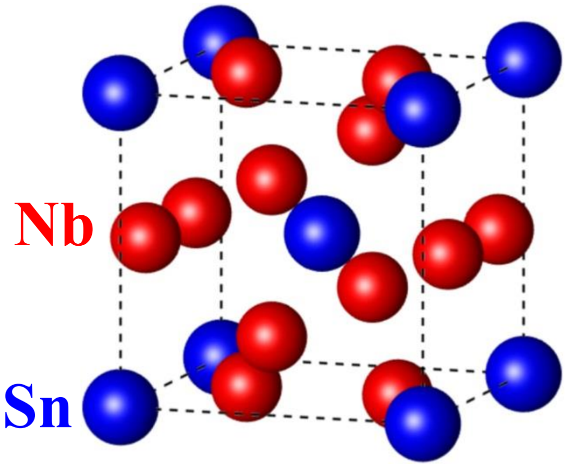






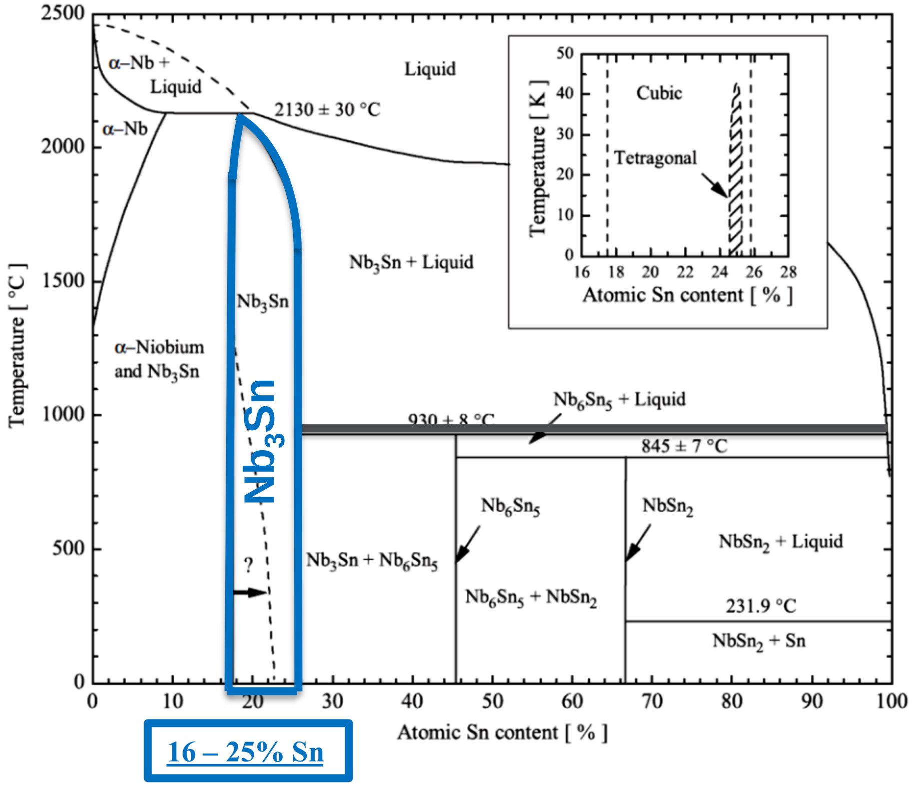
Stoichiometry and T_C

Nb_3Sn Structure



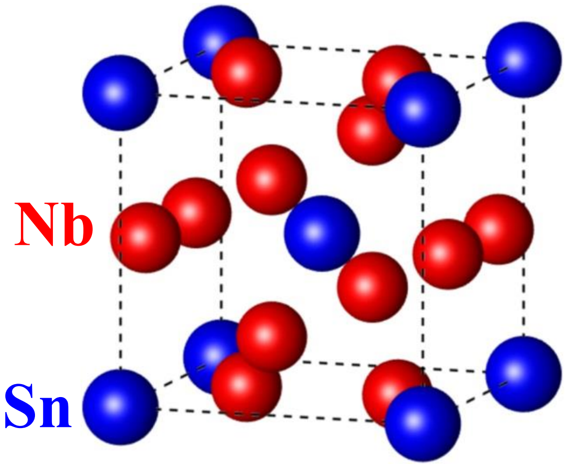
- Must maintain stoichiometry
- Tin-depleted Nb_3Sn has a low T_C

Nb_3Sn Phase Diagram



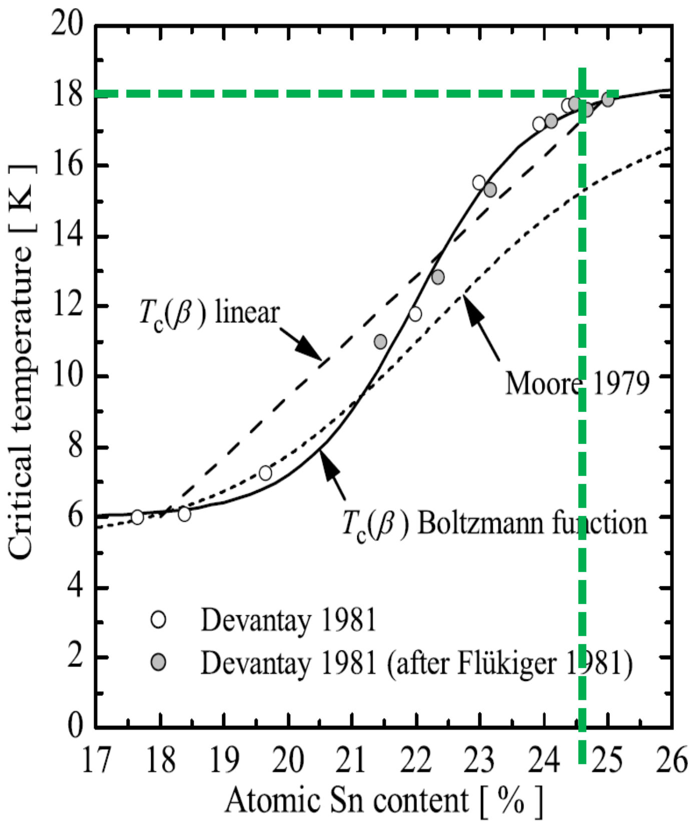
Stoichiometry and T_C

Nb_3Sn Structure



24 to 25% target

T_c vs. Tin Content



- Must maintain stoichiometry
- Tin-depleted Nb_3Sn has a low T_C

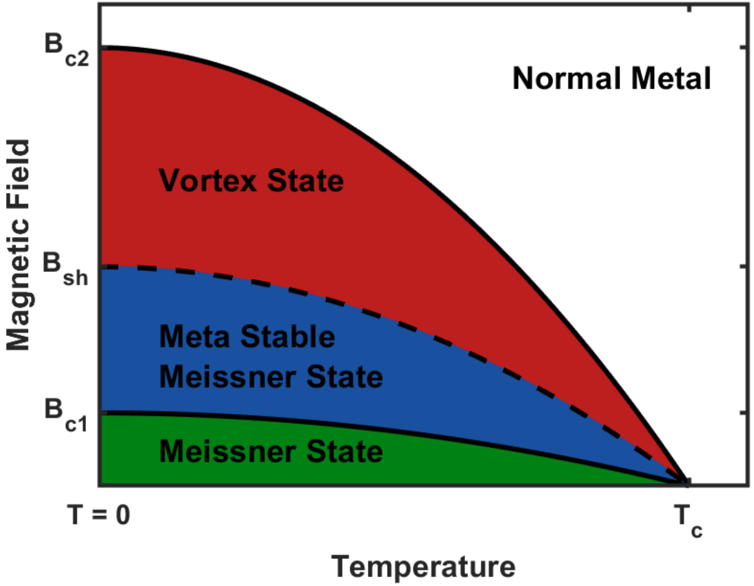
A. Godeke, Supercond. Sci. Tech, 2006

Material Challenges

- Material is brittle
- Low thermal conductivity

} ***Thin films help***

- Small coherence length $\xi \sim$ 3-4 nm
  → Sensitive to small defects
  → Small first critical field B_{c1}
    → Need to operate in the flux free metastable Meissner state



⇒ Need high quality Nb_3Sn films!

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Cornell Nb_3Sn Breakthrough Performance

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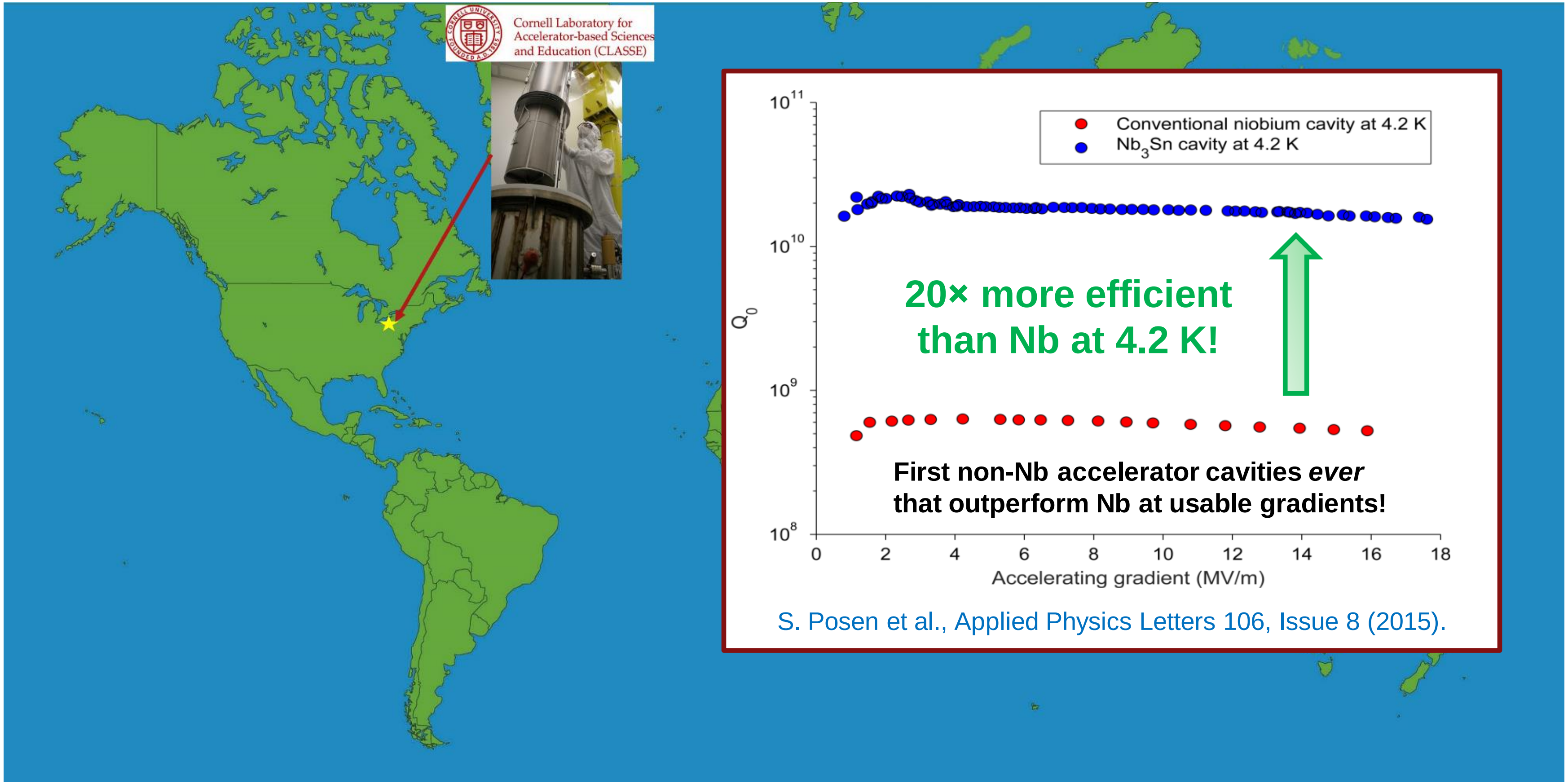
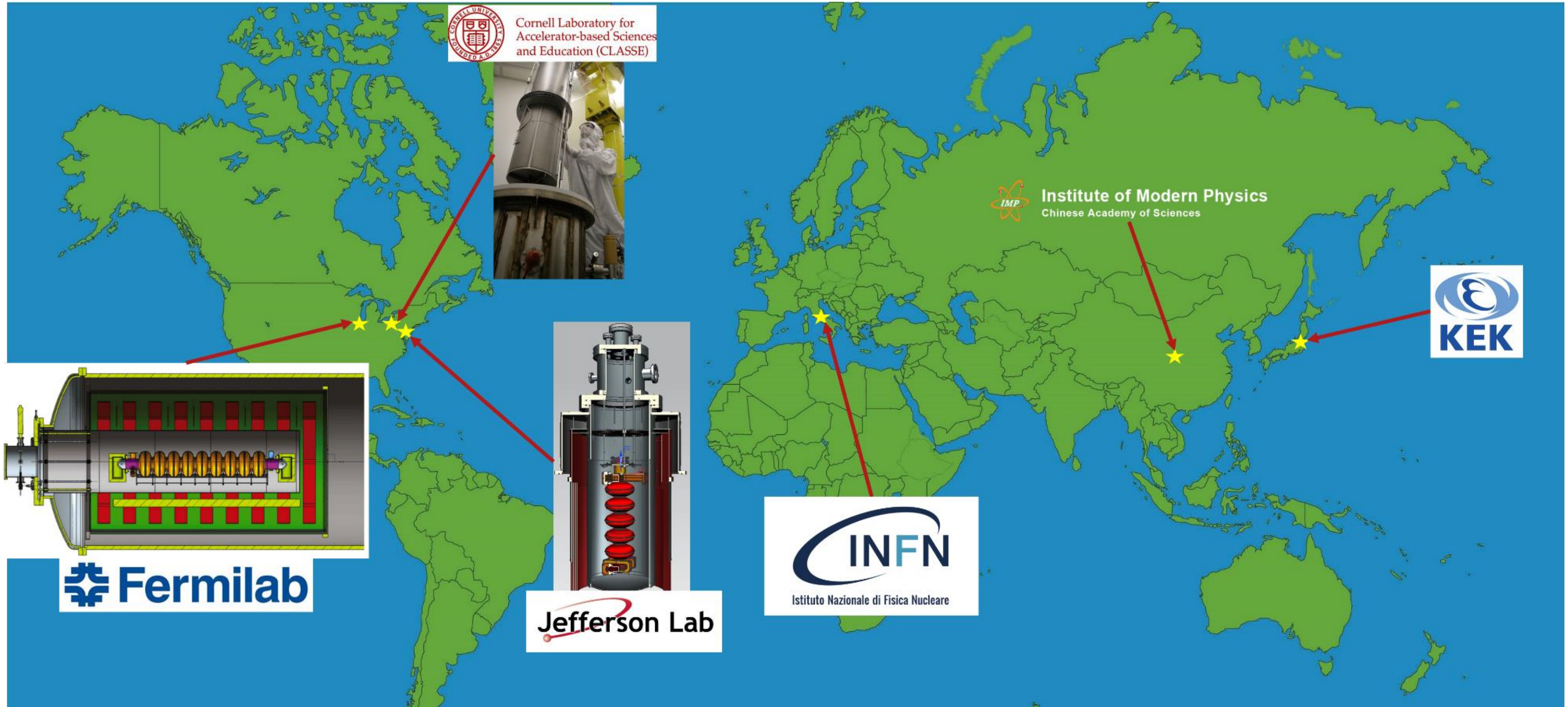


S. Posen et al., Applied Physics Letters 106, Issue 8 (2015).

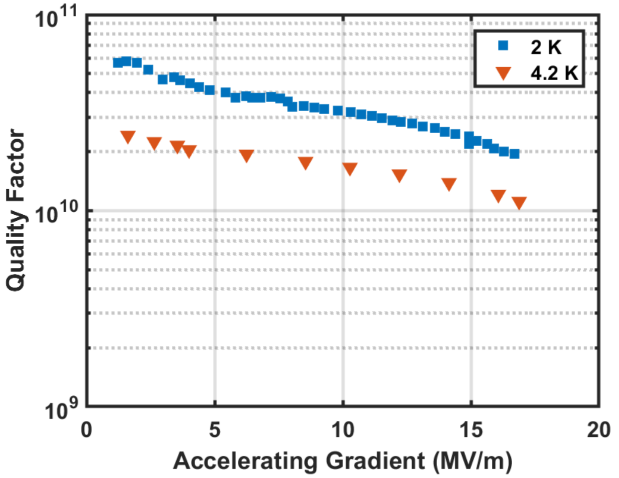
Nb_3Sn Around the World



And many more!

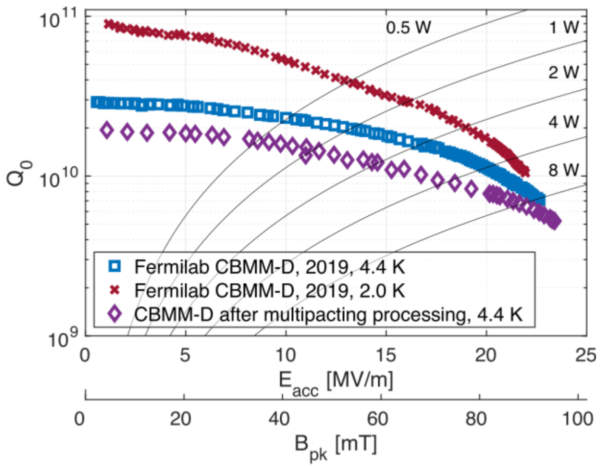
State-of-the-Art

Cornell University



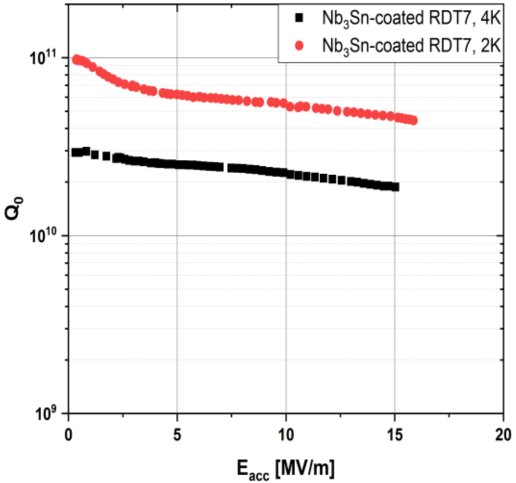
Fermilab

S. Posen, https://doi.org/10.1088/1361-6668/abc7f7



Jefferson Lab

U. Pudasaini, SRF'19



- **~4 K operation** with $Q_0 > 10^{10}$ at typical CW operating fields achieved at all 3 labs
- Current quench fields: **16-22 MV/m** (FNAL holds world record)
- **Reproducible** performance!

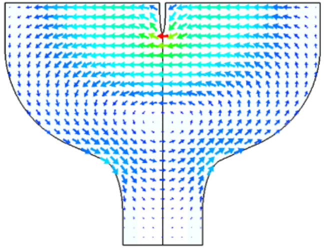
*(Note: Plots are for **single cell** cavities)*

Ongoing R&D at Cornell

- Thin Film Cavity

N. Verboncoeur et al., in Proc. 2022 International Particle Accelerator Conference (IPAC 2022)

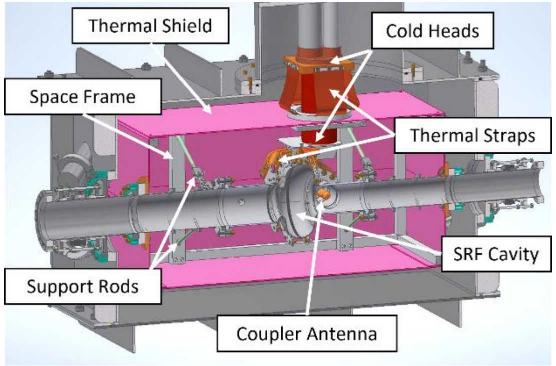
- A high field sample host cavity



- Sample studies to **improve nucleation** step of vapor diffusion

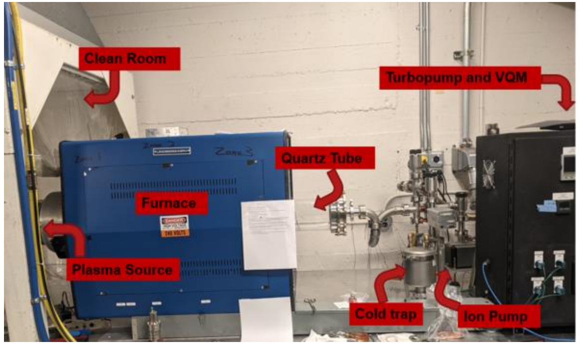
L. Shpani et al., in Proc. 2022 International Particle Accelerator Conference (IPAC 2022)

- Nb_3Sn Cryomodule R&D



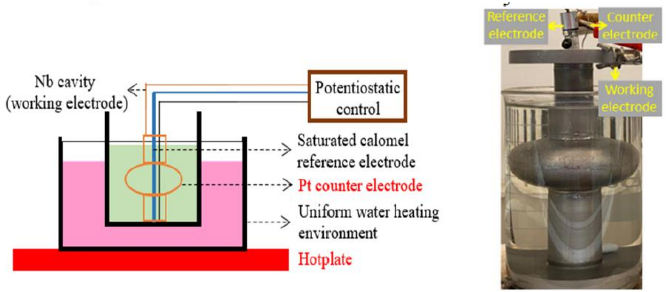
N. Stilin et al., in Proc. 2022 International Particle Accelerator Conference (IPAC 2022)

- Chemical Vapor Deposition **(CVD)**



G. Gaitan et al., in Proc. 2022 North American Particle Accelerator Conference (NAPAC 2022)

- Electrochemical deposition

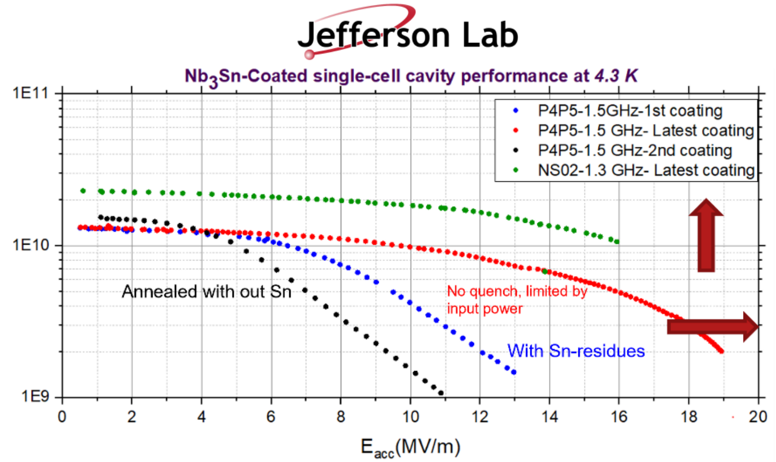


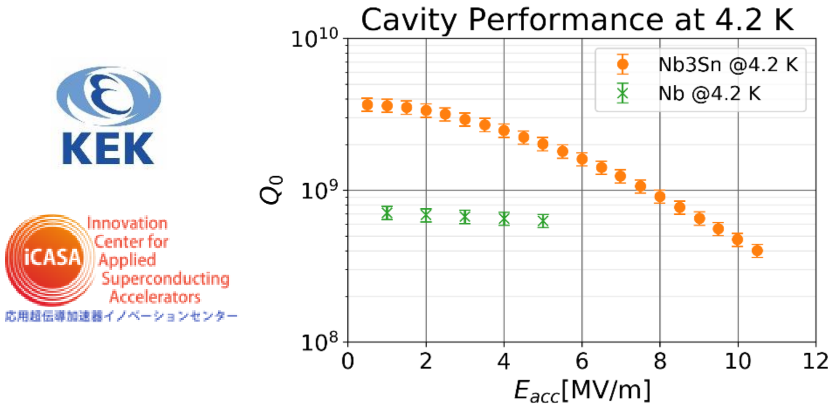
Z. Sun et al., in Proc. 2021 International Conference on RF Superconductivity (SRF'21)

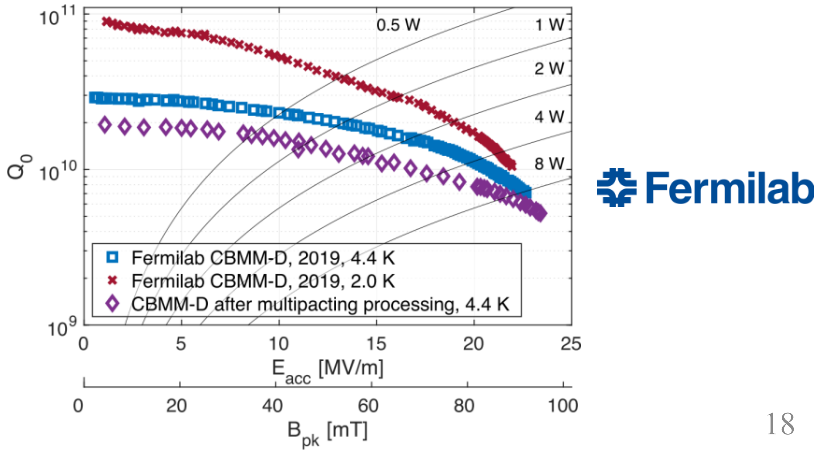
Ongoing R&D outside of Cornell (Examples)

- FNAL and JLab are working on **optimizing the coating process** to **reduce surface roughness** and achieve **thinner coatings.**

- KEK constructed a **Nb_3Sn coating system**, **first results** obtained in 2021.







Outline

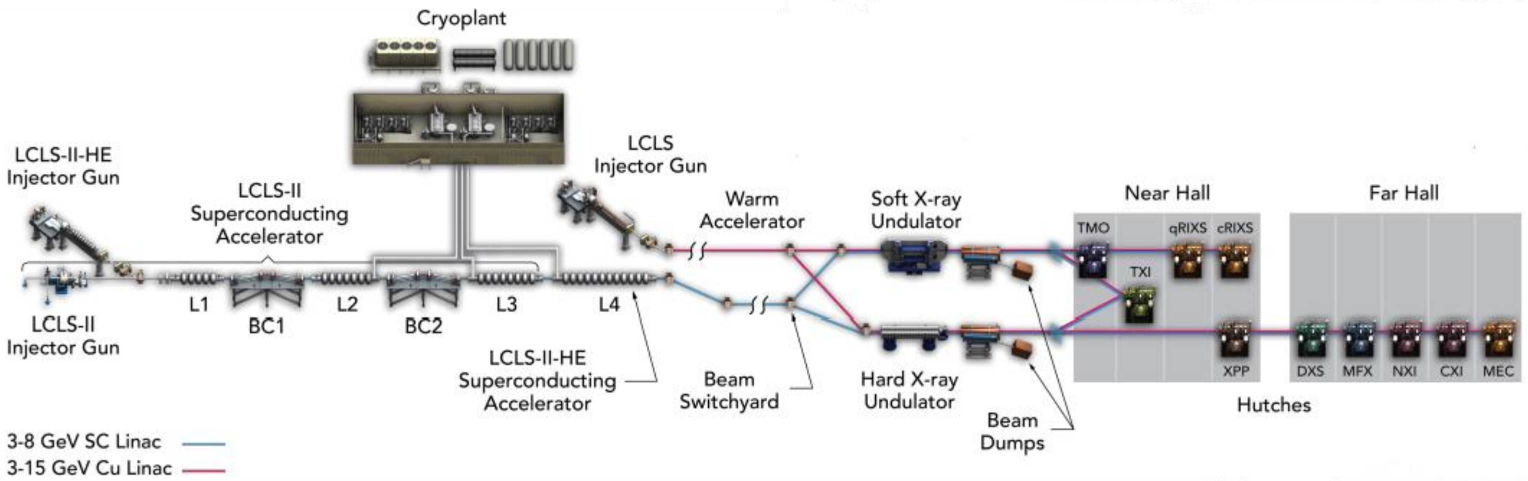
Case Study: LCLS-II

LCLS-II will be the **first XFEL based on** 4GeV **continuous wave superconducting RF** (CW-SRF) **accelerator technology.**

→ **280** 1.3 GHz cavities with E_{acc} of 16 MV/m

→ Nitrogen-doped niobium SRF cavities can reach **high** $\boldsymbol{Q_0} = 2.7 \times 10^{10}$

→ Operates at **2K**



What if we used Nb_3Sn instead?

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N-doped Nb at 2K

$$P_{dis} = N_{cavities} \times \frac{E_{acc}^2}{\frac{R_a}{Q_0} Q_0} \times L_{cell}^2$$

$$= 2.65\ kW$$

1 W takes 800 W of wall power to cool

$$\therefore \boldsymbol{P_{used} \approx 2\ MW}$$

Using **2K superfluid** helium cryoplant.

Nb_3Sn at 4.2K

$$P_{dis} = \begin{cases} 3.58\ kW \text{ for } Q_0 = 2 \times 10^{10} \\ 1.19\ kW \text{ for } Q_0 = 6 \times 10^{10} \end{cases}$$

1 W takes 200 W of wall power to cool

$$\therefore \boldsymbol{P_{used}} \approx \begin{cases} \boldsymbol{0.7\ MW \text{ for } Q_0 = 2 \times 10^{10}} \\ 0.2\ MW \text{ for } Q_0 = 6 \times 10^{10} \end{cases}$$

Using **4K atmospheric** cryoplant.

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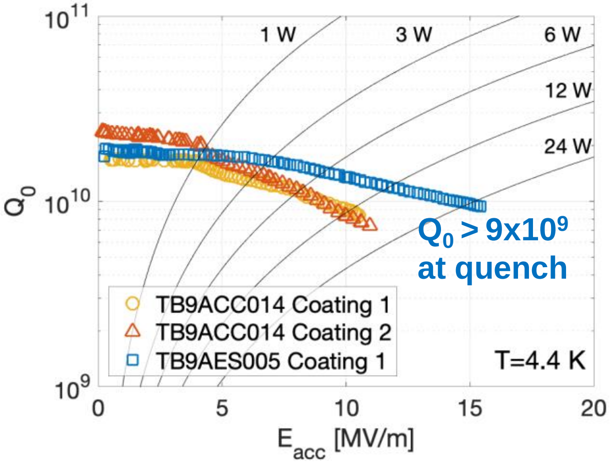
Fermilab

- 9-cell 1.3GHz cavities coated and RF tested.



PAPER • OPEN ACCESS

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]

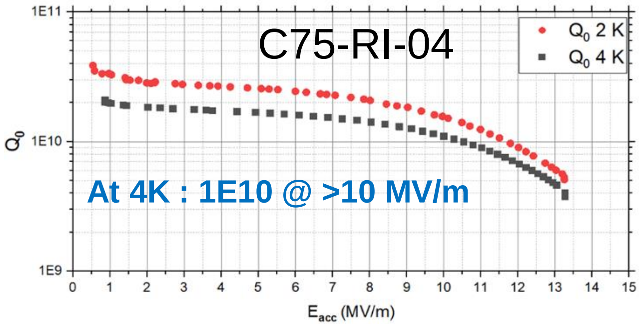
Published 11 January 2021 • © 2021 The Author(s). Published by IOP Publishing Ltd

Superconductor Science and Technology, Volume 34, Number 2

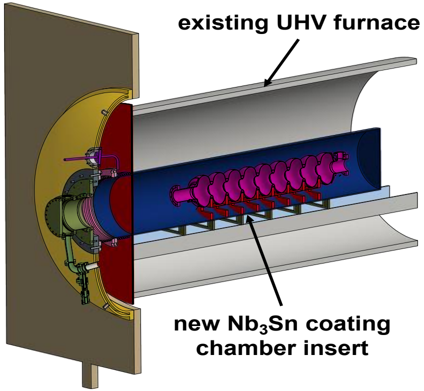
Citation S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

Jefferson Lab

- 5-cell 1.5GHz cavity coated and RF tested.



C75 cavity made from large grain Nb



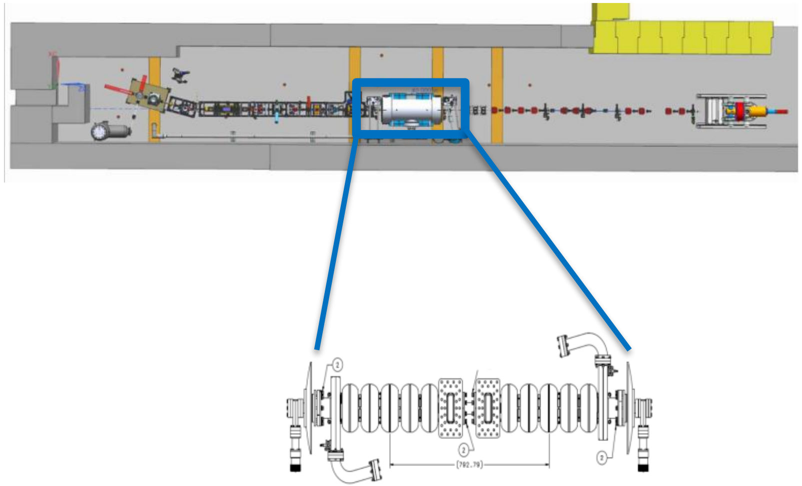
Cornell: Multicell coating facility under development.

Helium Based Cryomodules

A further challenge is **implementing multi-cell cavities in accelerator cryomodules**.

- Material is **brittle** – sensitive to deforming
- Slow cooldown – need small temperature gradient across cavity
- 4K operation challenges
  → **Microphonics**

Nb_3Sn cavities for Upgraded Injector Test Facility (UITF) at JLab



G. Eremeev et al., Proceedings LINAC 2016 (MOPLR024)
S. Pokharel et al., Proceedings IPAC 2022 (MOPOTK051)

Conduction Cooled Cryomodules

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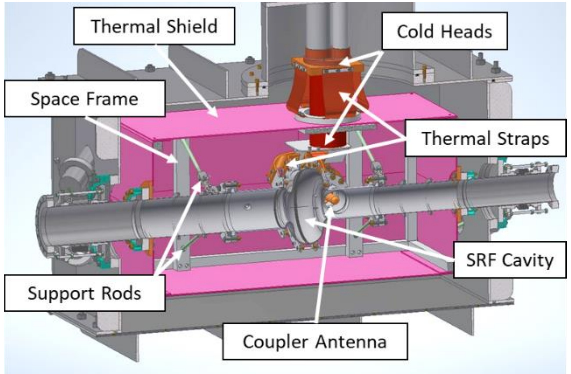
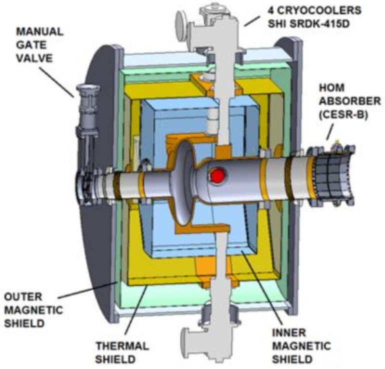


Jefferson Lab

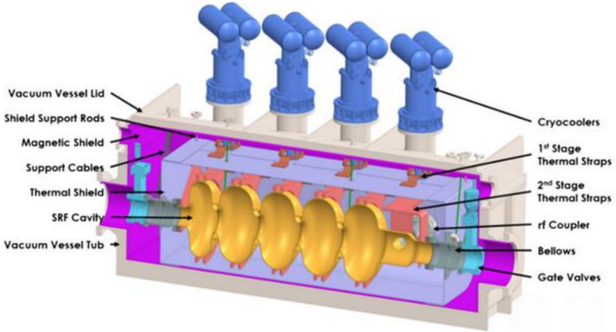


Nb_3Sn for Nuclear Physics (Collaboration ANL/FNAL/Radiabeam)

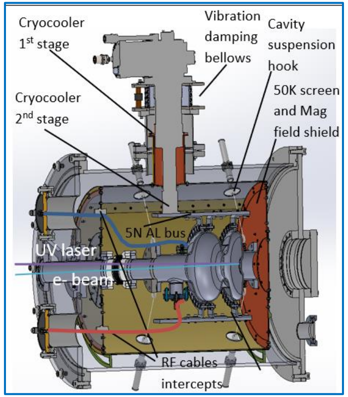
Argonne NATIONAL LABORATORY

Lead lab
PI: Mike Kelly

Wastewater Treatment →



Fermilab



Fermilab

FNAL Lead: Sam Posen

Nb_3Sn for Industrial Accelerators (Collab. Euclid/FNAL/BNL)

Key Takeaways

- Nb_3Sn is a **high-potential material** for next-generation SRF cavities
  → **Higher energy gain**
  → **Lower cooling cost and complexity**

- Nb_3Sn **coating facilities are established** around the World (Cornell, FNAL, JLab, KEK, etc.)

- Ongoing R&D will **improve Nb_3Sn performance** of Nb_3Sn films
  → **Thinner films**
  → **Reduced surface roughness**

- **Applications** are at **early stages**
  → Multicell Nb_3Sn cavities
  → Prototype cryomodule testing
  → Turn-key compact cryomodules

Stay tuned !