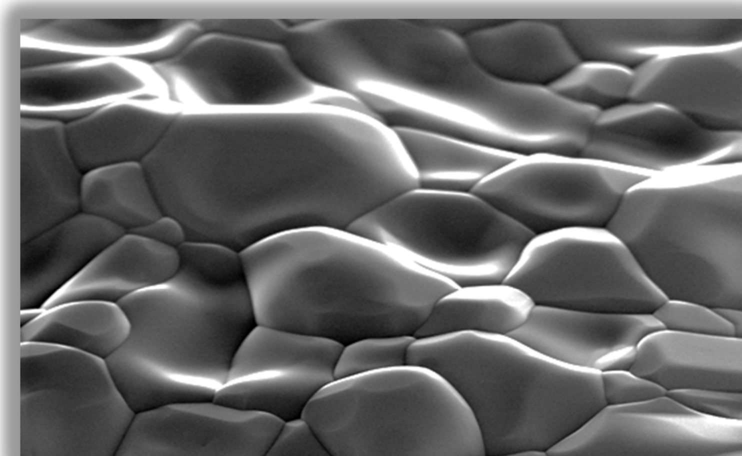
Superconducting RF for the Future: Is Nb_3Sn ready for next-generation accelerators?

Matthias Liepe

Professor of Physics; Head Cornell SRF Group

Cornell University



NSF

The Center for BRIGHTBEAMS

Department of Energy United States of America

The Life Story of Nb_3Sn SRF (as of now)

I. Promise: Why Nb_3Sn for SRF?
II. Early Years and Disappointments
III. Rebirth: Let's try again…
IV. Growing Up: The quest for higher performance
V. Maturity: Nb_3Sn SRF accelerator applications

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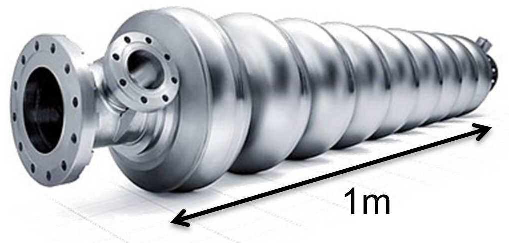
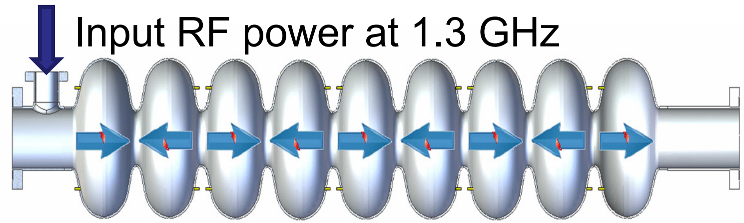
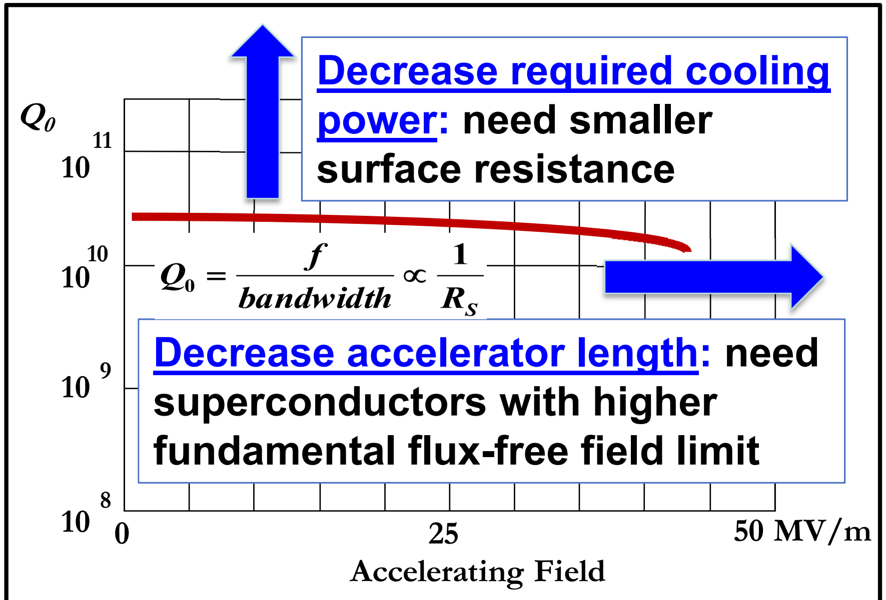
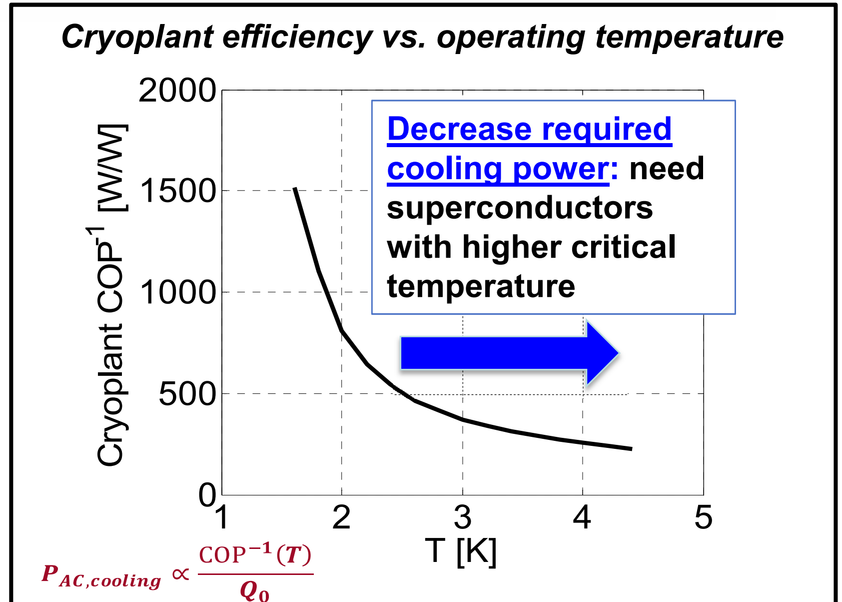
SRF 101





Slowed down by factor of approximately 4×10^9





Beyond Niobium

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	0.24
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

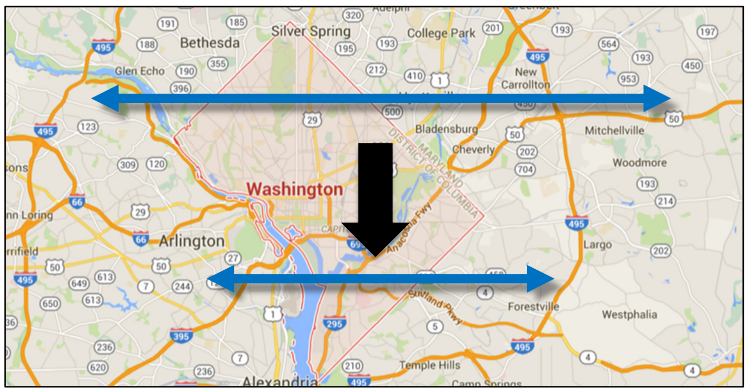
Potential of Nb_3Sn Cavities

Increased Accelerating Field

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

⇒ Shorter accelerators

⇒ Higher energy gain

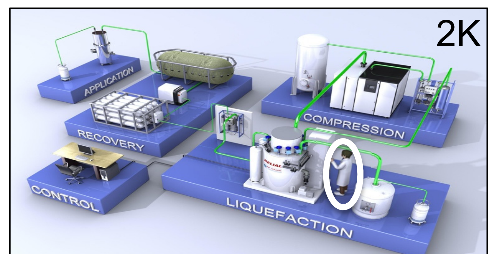


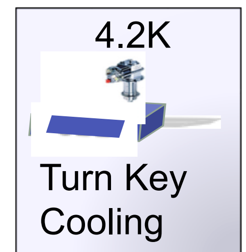
Map shown for scale only.

Lower Cooling Cost and Complexity

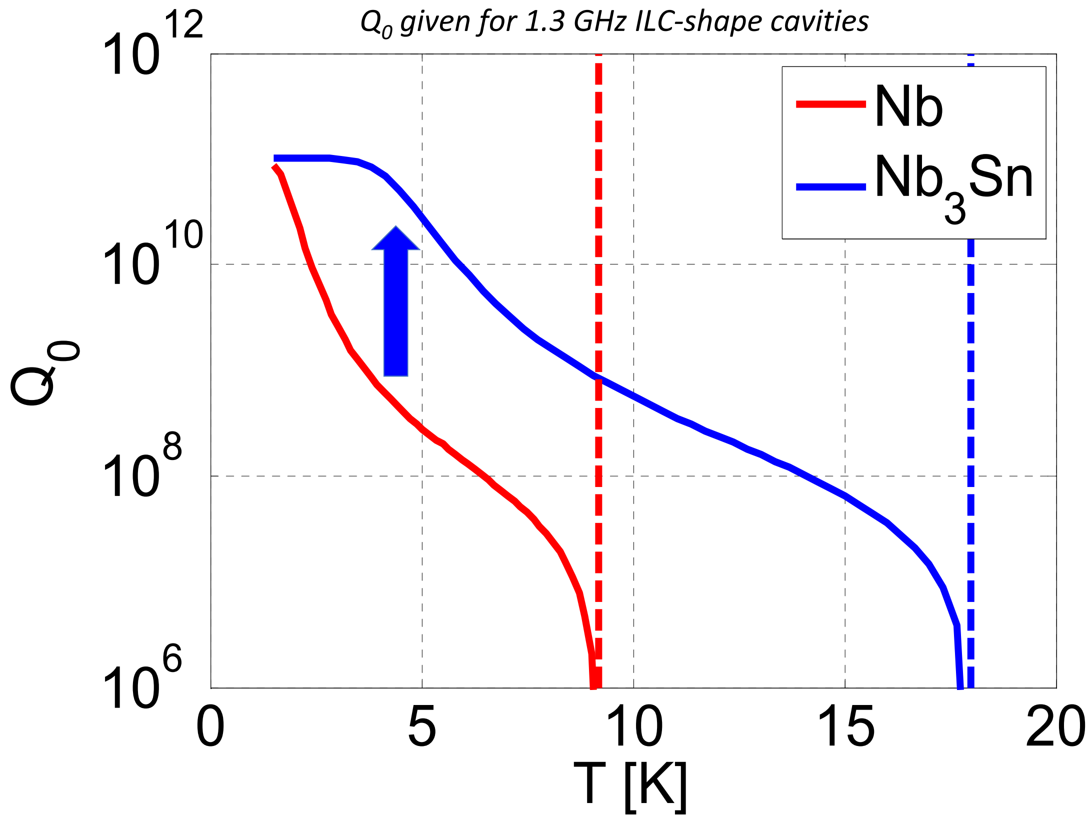
	Niobium	Nb_3Sn
Critical Temperature T_c	9 K	18 K
Q_0 at **4.2 K**	6×10^8	**6×10^{10}**
Q_0 at 2.0 K	3×10^{10}	$>10^{11}$

Q_0 given for 1.3 GHz ILC-shape cavities

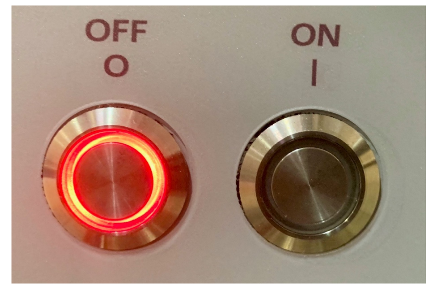




Nb_3Sn: High Temperature (4.2K) Operation



- ⇒ **4.2K operation with high cryo-efficiency (<u>game changer</u>!)**
- ⇒ **No superfluid helium**
- ⇒ **No need to use large, low frequency cavities to run at 4.2K**
- ⇒ **Simpler, smaller, cheaper helium refrigerators**
- ⇒ **Use of turn-key cryocoolers (for smaller applications)**

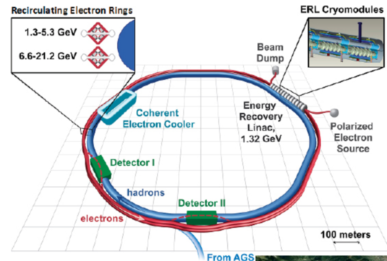


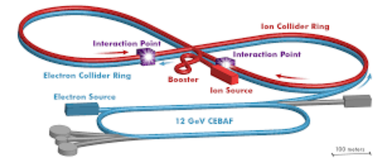
Potential Future Nb_3Sn SRF Applications

Large-scale SRF driven accelerators operating in continuous mode:

Key: reduced cryogenic cooling power

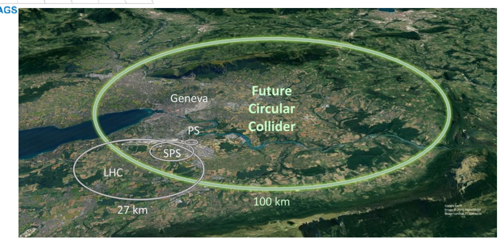
- **Future FELs**
- **Electron-Ion collider**
- **Future circular collider (FCC) …**





SRF driven, pulsed accelerators:

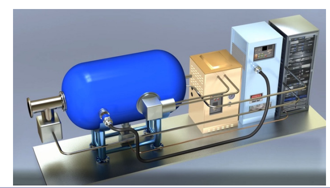
Key: increased energy



Small SRF driven accelerators:

Key: reduced cryogenic cooling power and simplified cryo-systems

- **Small-scale science accelerators**
- **Industrial and medial applications**



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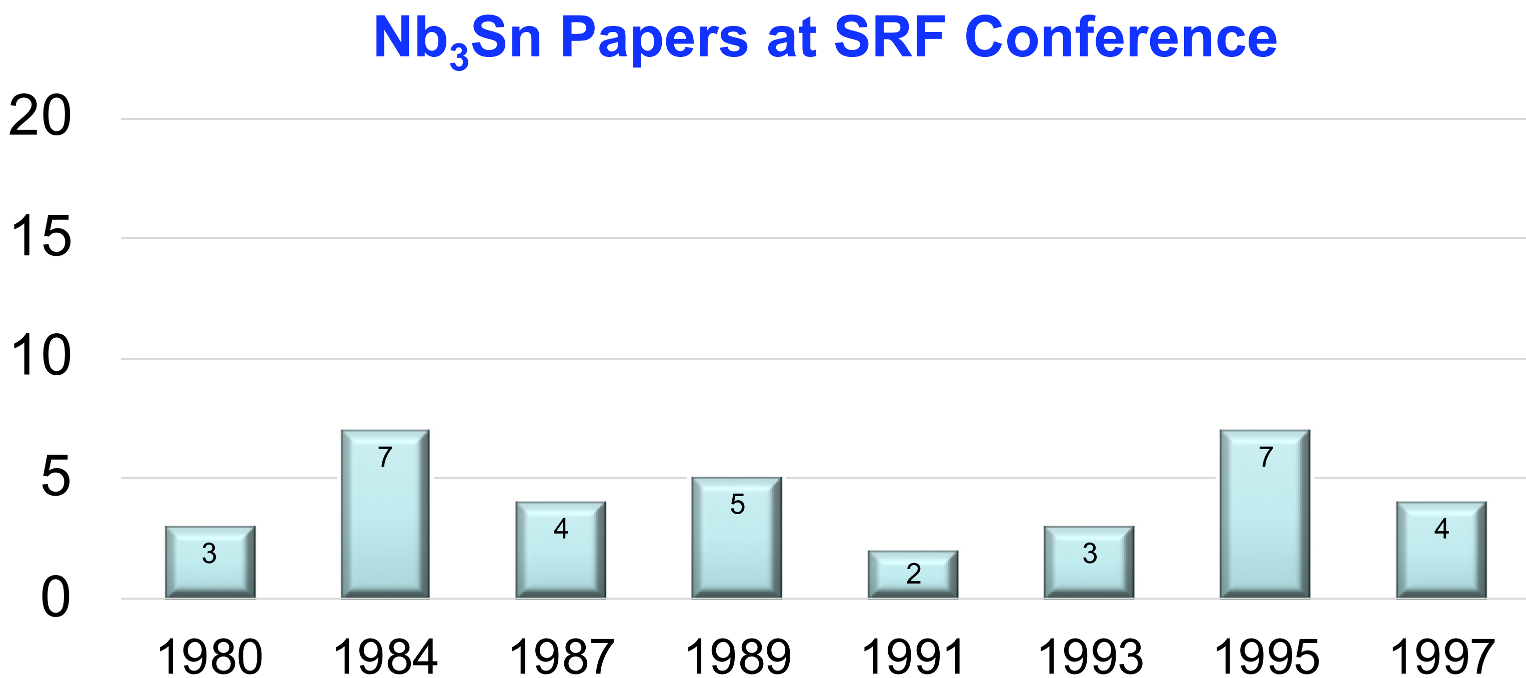
And so Nb_3Sn SRF R&D began 40 Years ago…



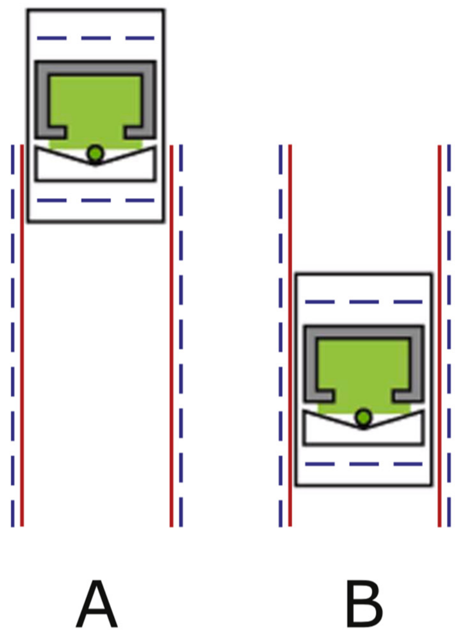
Siemens AG, K.F Karlsruhe (Cornell)

U. of Wuppertal

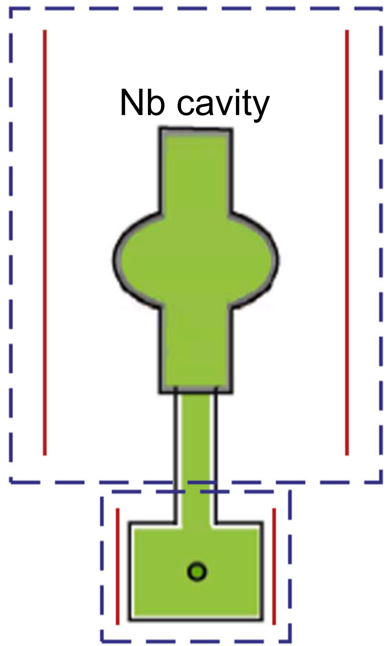
RF testing at JLAB, Cornell, SLAC, CERN…

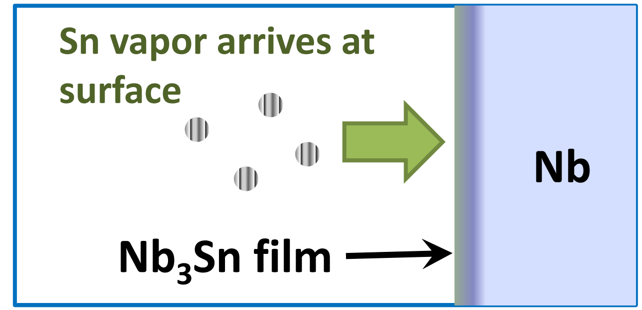
Tin Vapor Diffusion Process (Simplified)

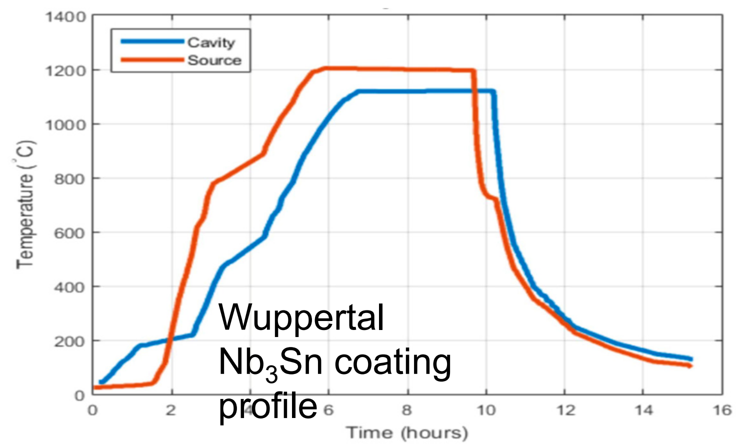
Siemens



Wuppertal





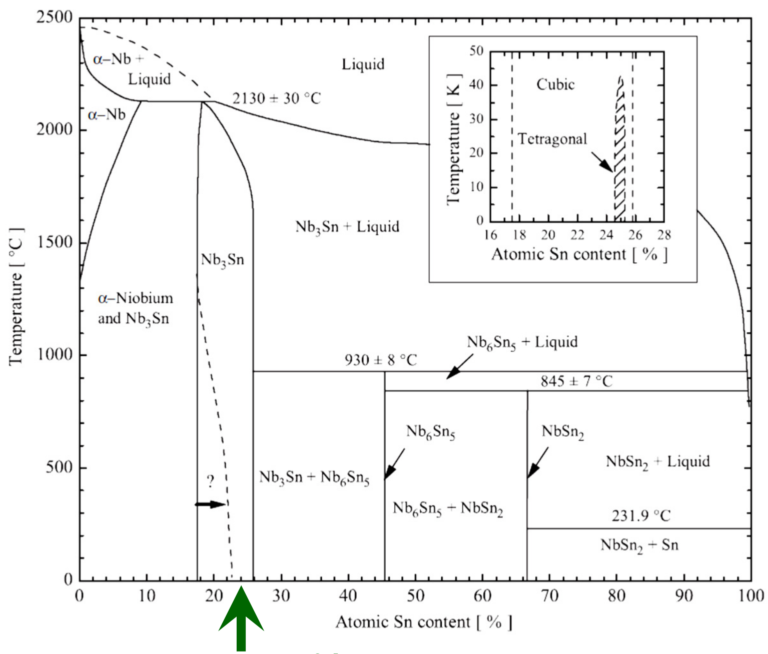


Tin source — Heating element — Area exposed to tin gas

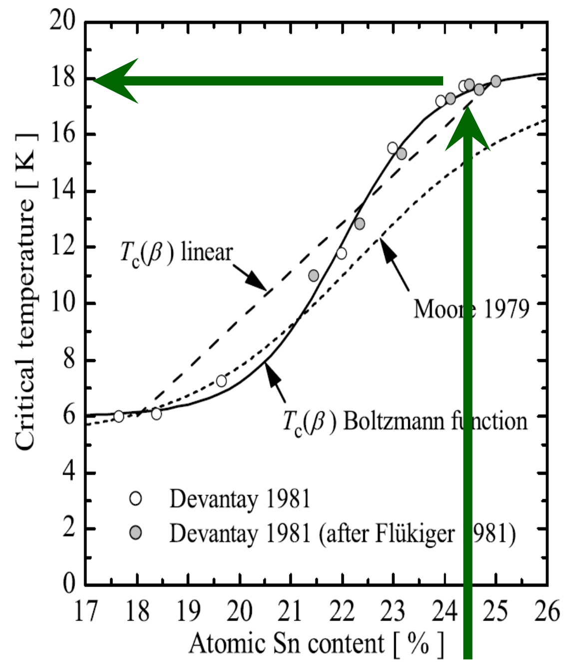
Figures from Supercond. Sci. Technol. 30 (2017) 033004

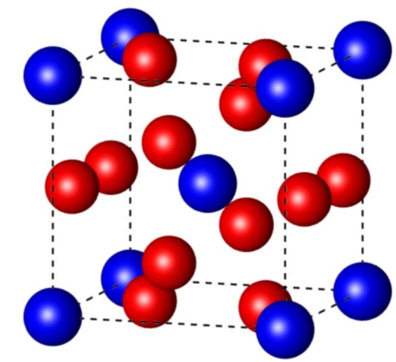
Nb_3Sn Challenge: Stoichiometry and T_c

Nb_3Sn Phase Diagram



T_c vs. Tin Content





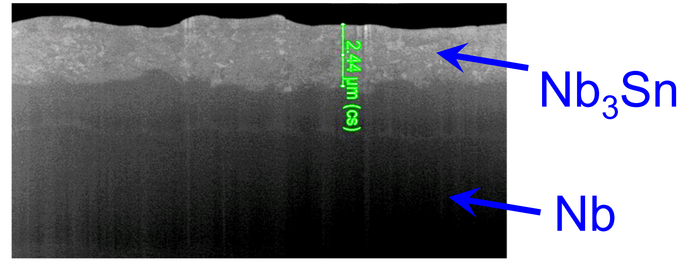
Blue: tin
Red: niobium

A. Godeke, Supercond. Sci. Tech, 2006

More Nb_3Sn Challenges

- Material is brittle
- Low thermal conductivity

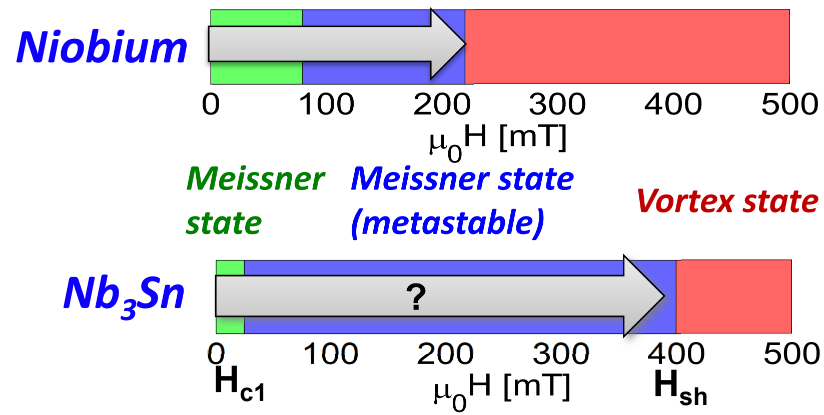
Thin films avoid/reduce these



- **Small coherence length ξ ~ 3 - 4 nm**
  - **Sensitive to small defects**
  - **Small first critical field H_{c1}**

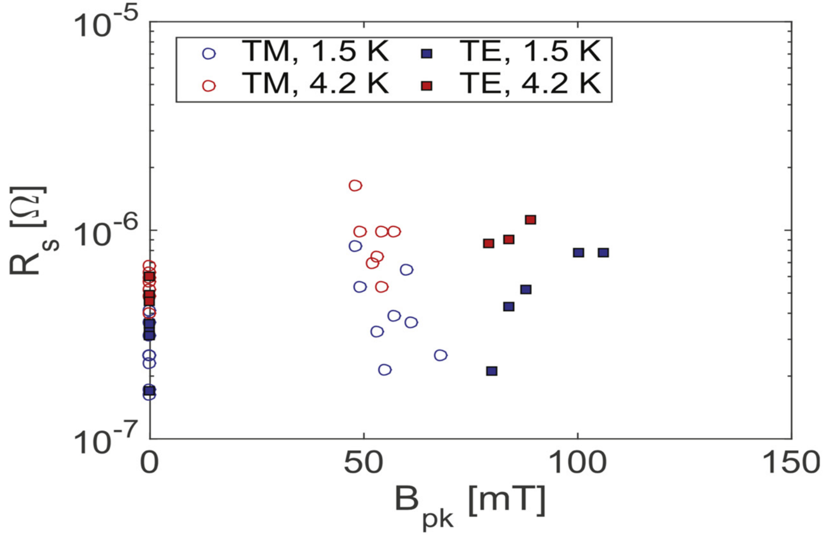
    ⇒ Need to operate in the flux free metastable Meissner state

⇒ Need high quality Nb_3Sn films!

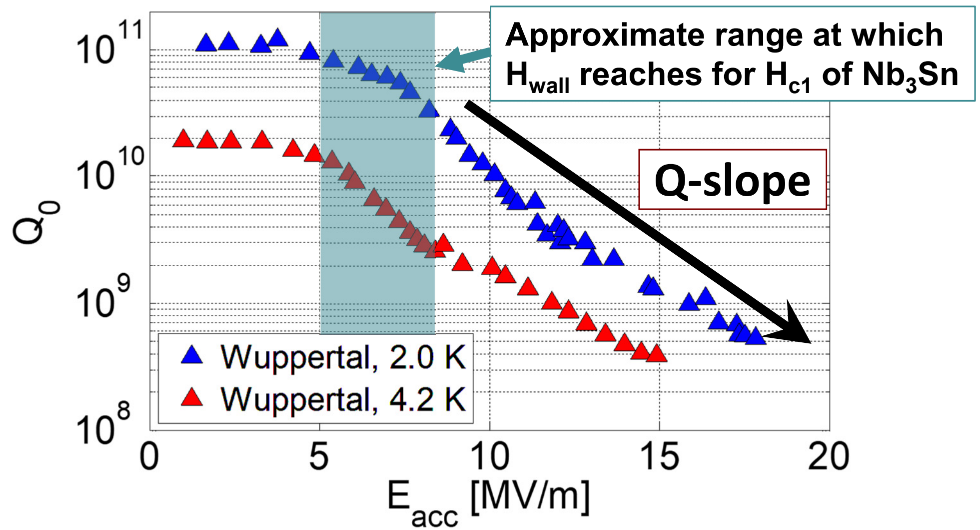


First Nb_3Sn Cavities: Reality around 2000

10 GHz Nb_3Sn TM and TE cavities Siemens



1.5 GHz elliptical Nb_3Sn cavities U. Wuppertal

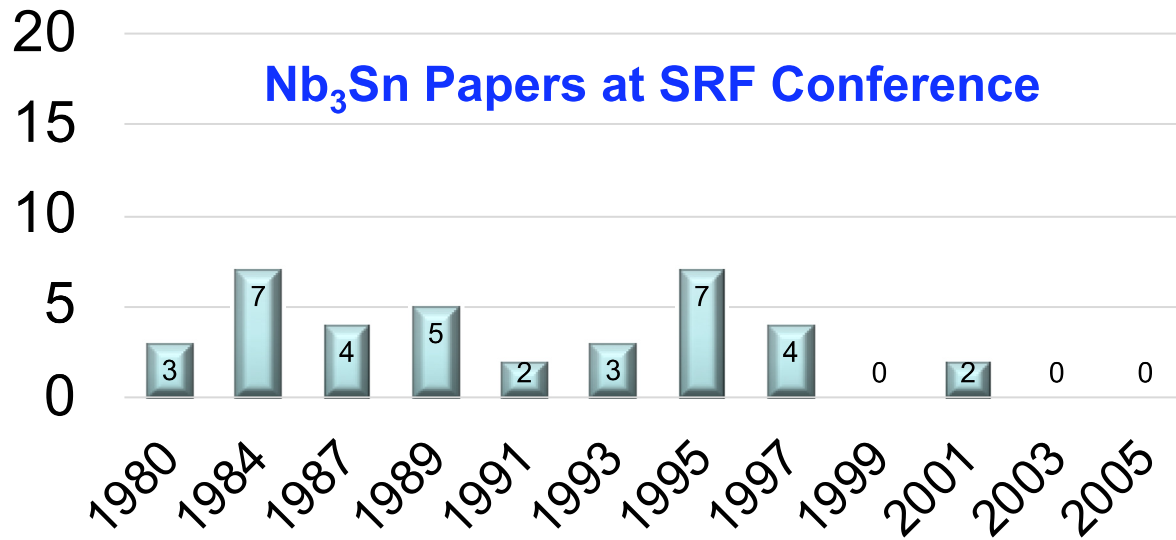


- **Usable field gradients**, **but strong Q-slop** (at least at lower frequency)
  ⇒ Practical or fundamental limits due to vortex entry above H_{c1}?

The End?

Disappointing results.

Interest in Nb_3Sn faded away….



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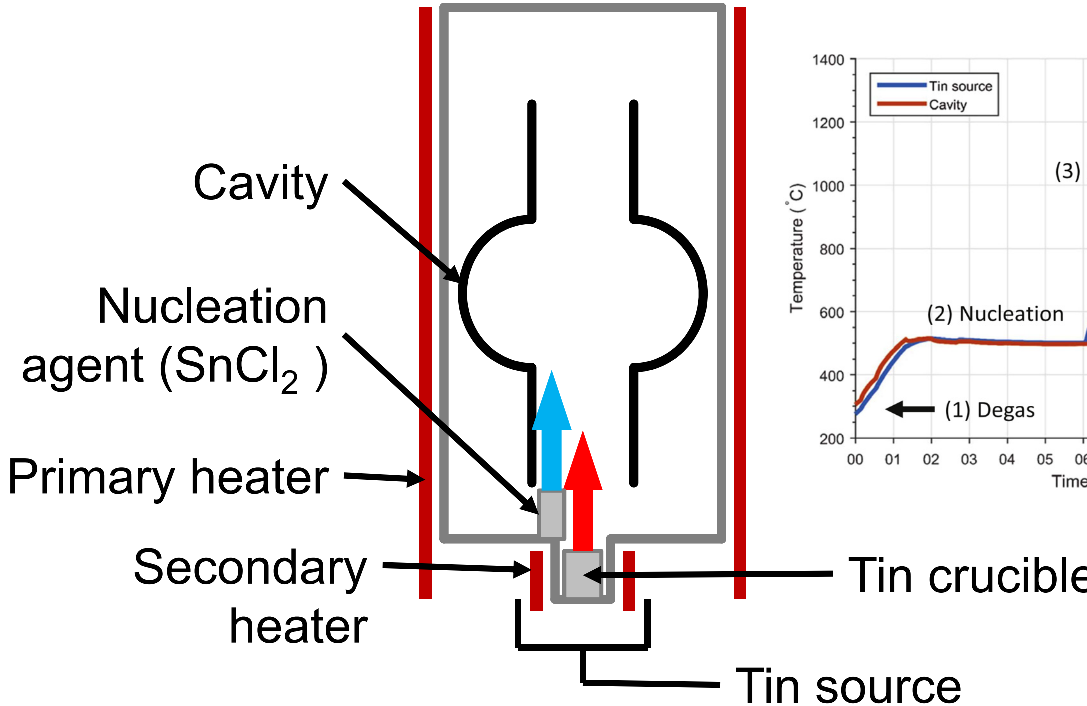
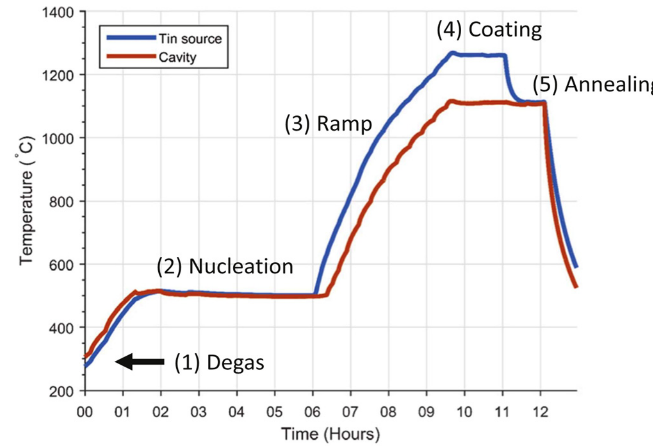
The Rebirth of the Phoenix: Nb_3Sn SRF Mark II

A phoenix depicted in a book of legendary creatures
by FJ Bertuch (1747–1822)

Rebirth of Nb_3Sn SRF

Cornell Nb_3Sn Vapor Diffusion Furnace





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

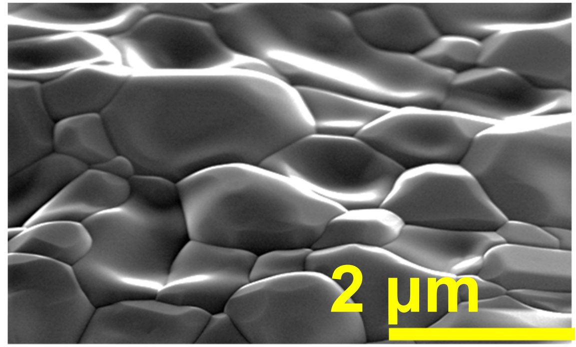
Optimized nucleation and temperature profile

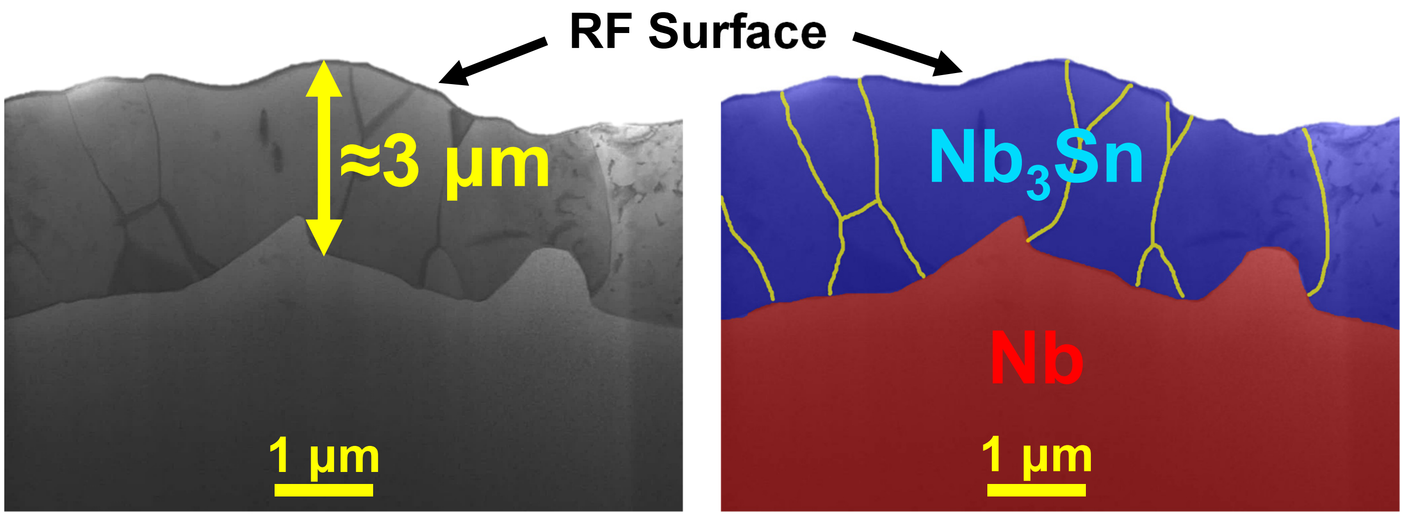
S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 (2014).

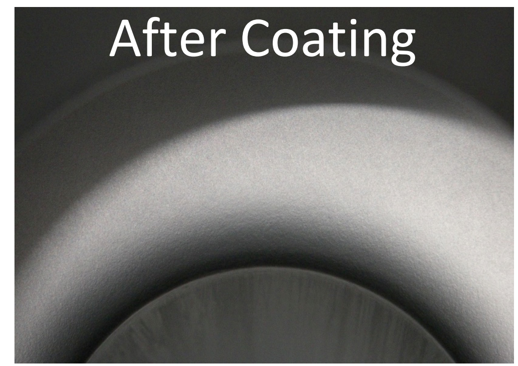
U.S. DOE award DE-SC0008431

Nb_3Sn Coatings

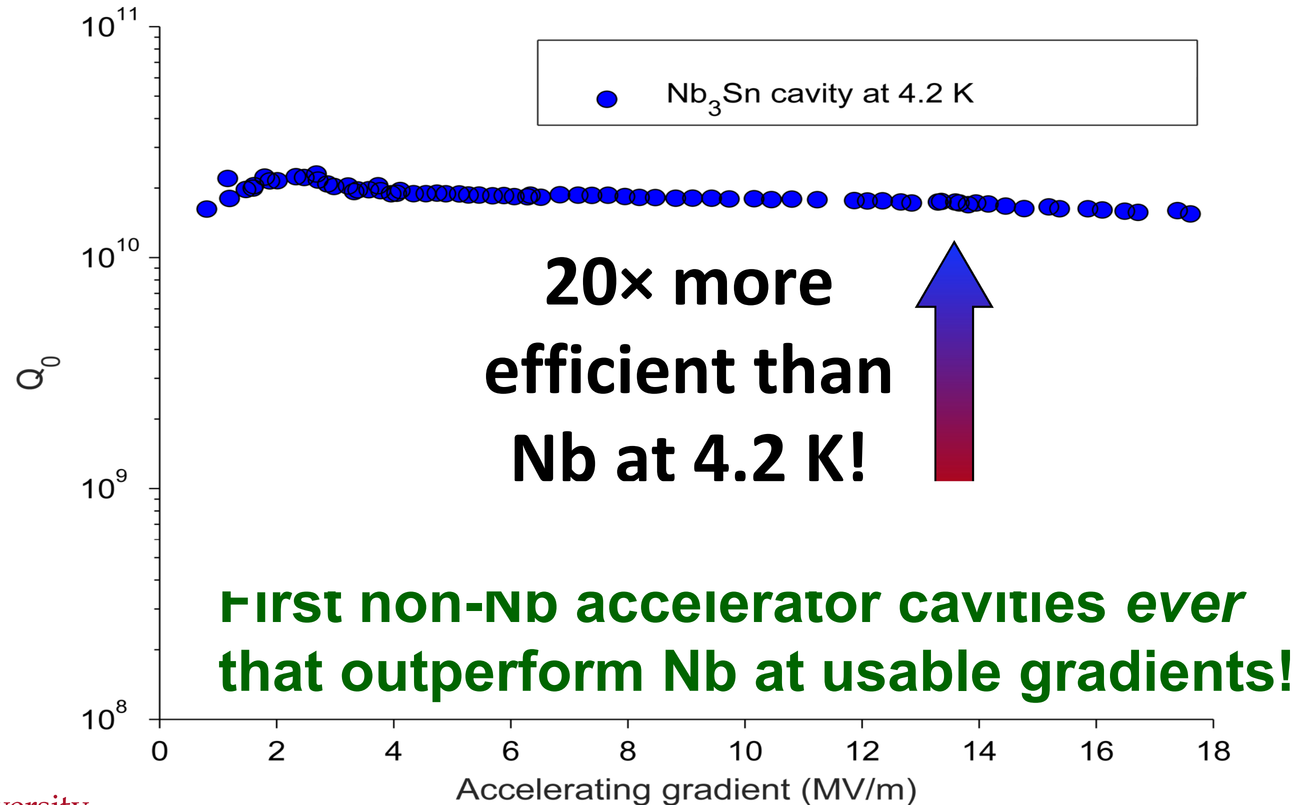
Nb_3Sn forms a polycrystalline layer on the surface of the niobium







Cornell 1.3 GHz Nb_3Sn Cavity Breakthrough 4.2K Performance

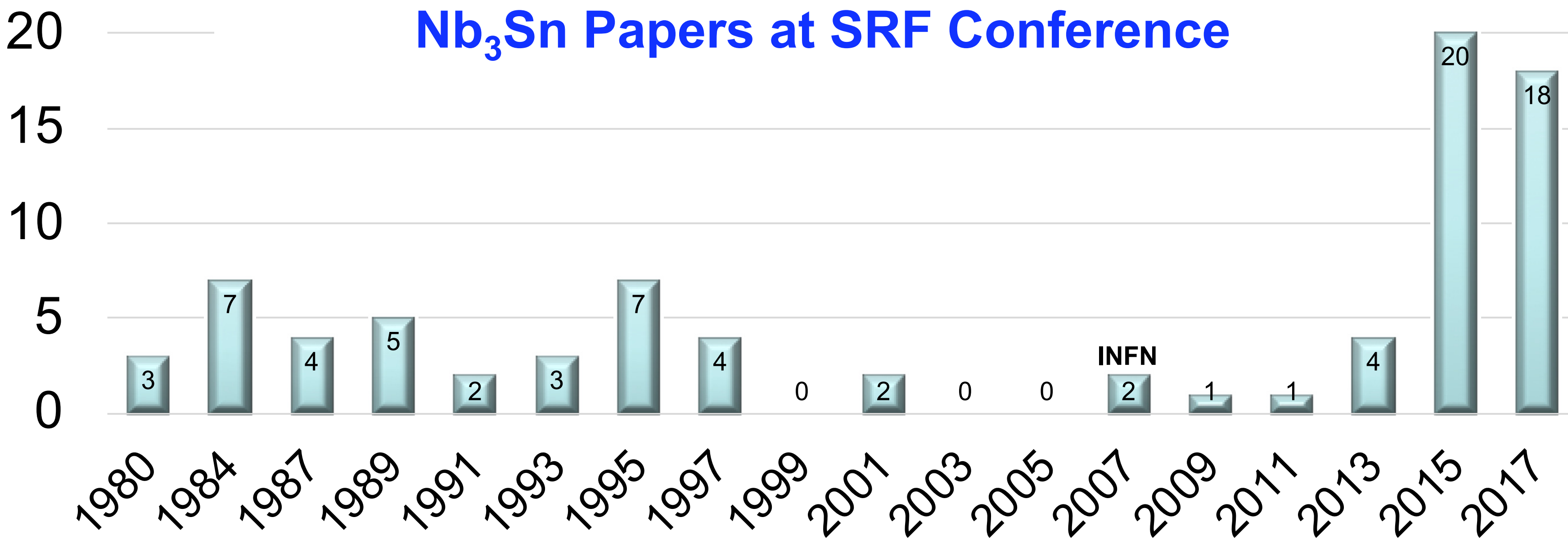


Cornell University

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

U.S. DOE award DE-SC0008431

The Rebirth of Nb_3Sn SRF R&D



Siemens AG, K.F Karlsruhe (Cornell)

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RF testing at JLAB, Cornell, SLAC, CERN…

Cornell

JLAB

FNAL

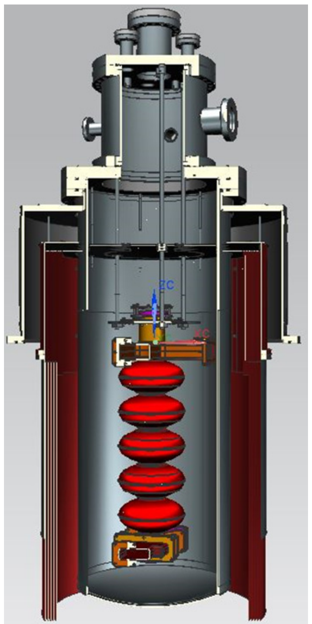
CERN

PKU, IMP, KEK…

JLAB and Fermilab Nb_3Sn Vapor Diffusion Furnaces

JLAB Nb_3Sn Coating System

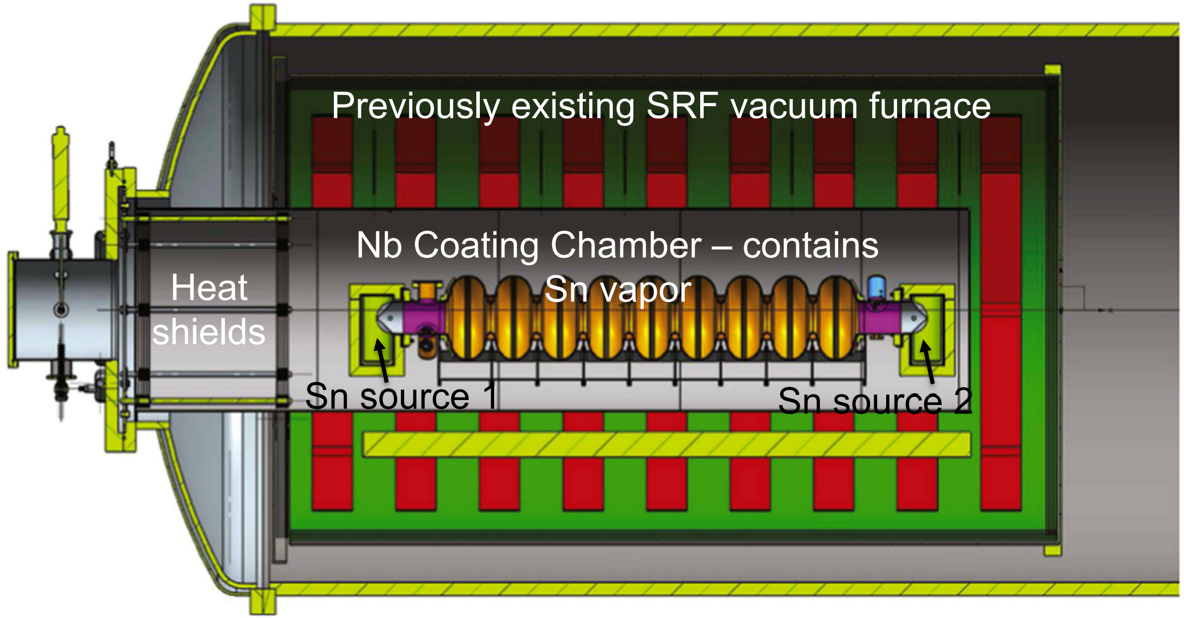
Jefferson Lab **Grigory Eremeev**



"Siemens" configuration, i.e., no secondary heater for the tin source

Fermilab Nb_3Sn Coating System

Sam Posen Fermilab



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

1.3 GHz Nb_3Sn Cavity Performance: State-of the Art

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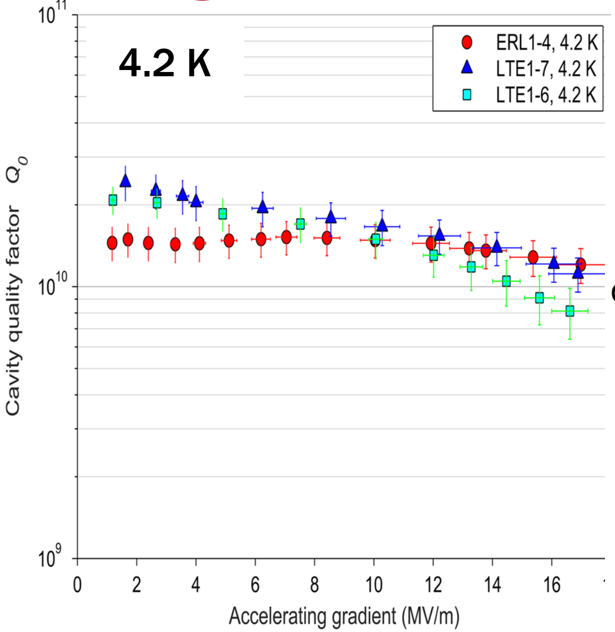
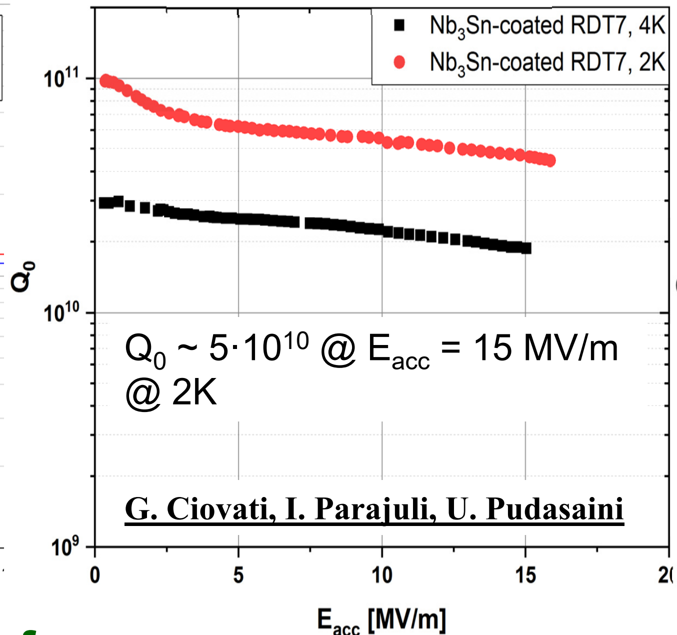
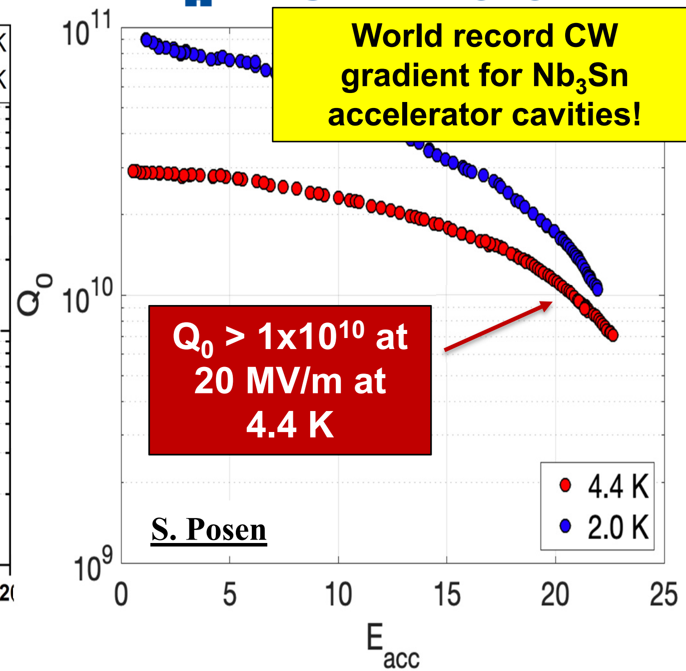


Jefferson Lab

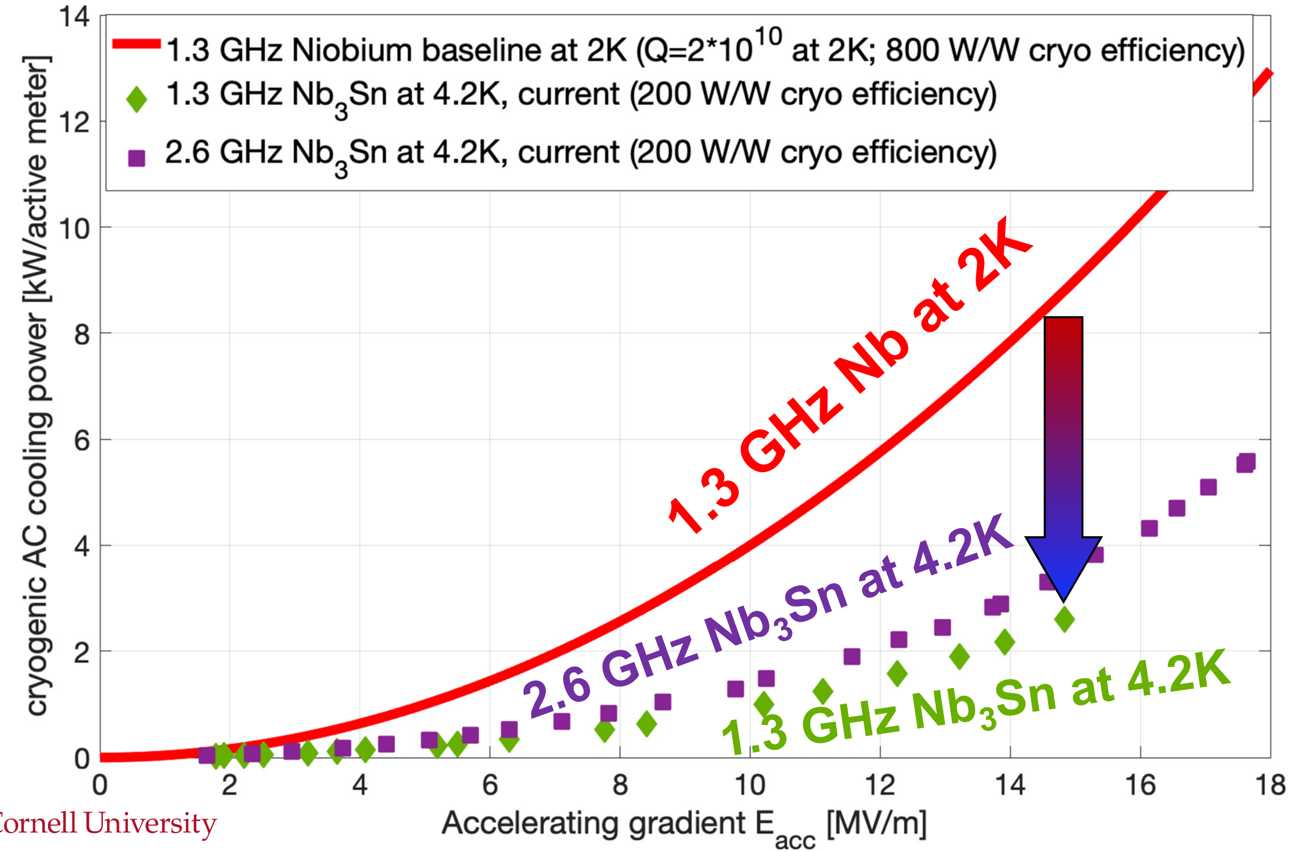


Fermilab



- **Very reproducible performance**
- **~4K operation with unprecedented Q $>10^{10}$ at typical CW operating fields**
- **Current quench fields: 16 – 22 MV/m (FNAL world record)**

Drastic Reduction in Cryogenic Losses



- **>60% reduction in AC cooling power**
- **Simplified cryo system (4.2K vs 2K operation)**

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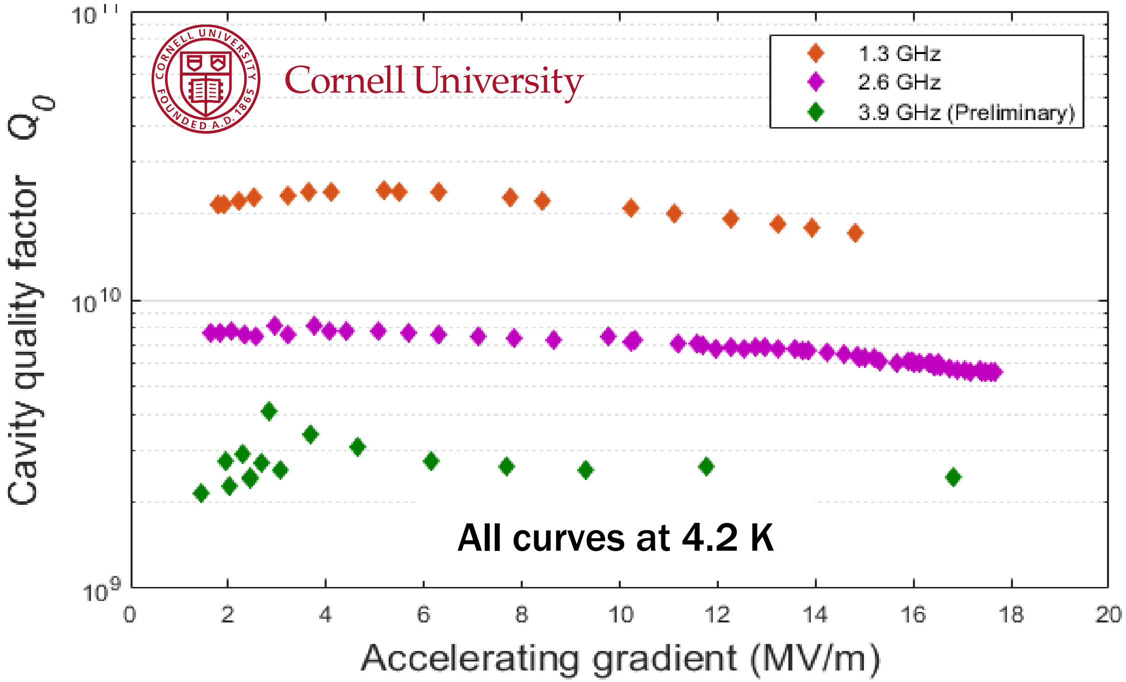
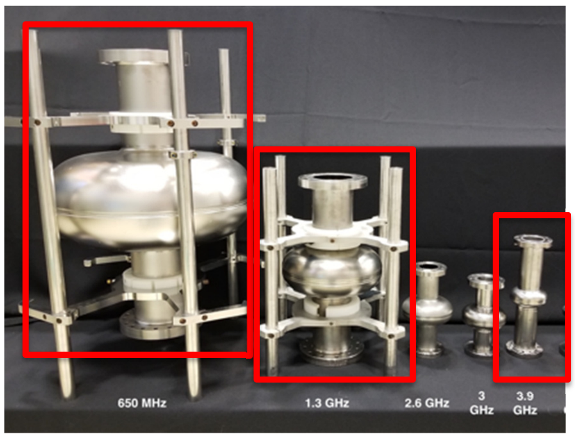
Quest 1: Higher (multi-GHz) RF Frequencies



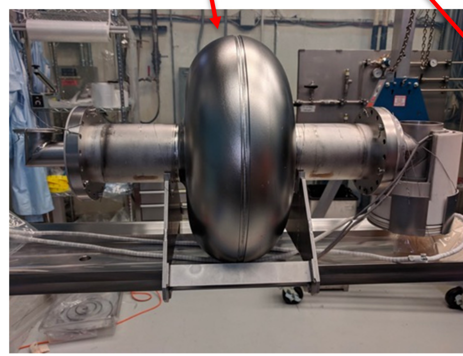
- **First high-performance Nb_3Sn elliptical TM010 cavities**
- **Example: 50x more efficient than Nb at 2.6 GHz and 4.2 K**
- **1.3 GHz and 2.6 GHz cavities have ~ same cryo loss / active length**

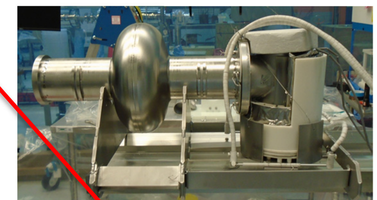
Fermilab Frequency Dependence Study

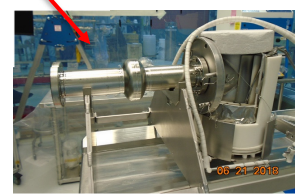
- Frequency dependence of R_{BCS}, R_{res}, quench, trapped flux sensitivity
- 650 MHz is an interesting step between scaling up form a 1-cell 1.3 GHz to a 9-cell 1.3 GHz cavity
- Better understand how vapor diffusion process scales with different sized substrates



Fermilab Nb_3Sn SRF program: a number of 1.3 GHz cavities already coated and tested; these are the first 650 MHz and 3.9 GHz cavities

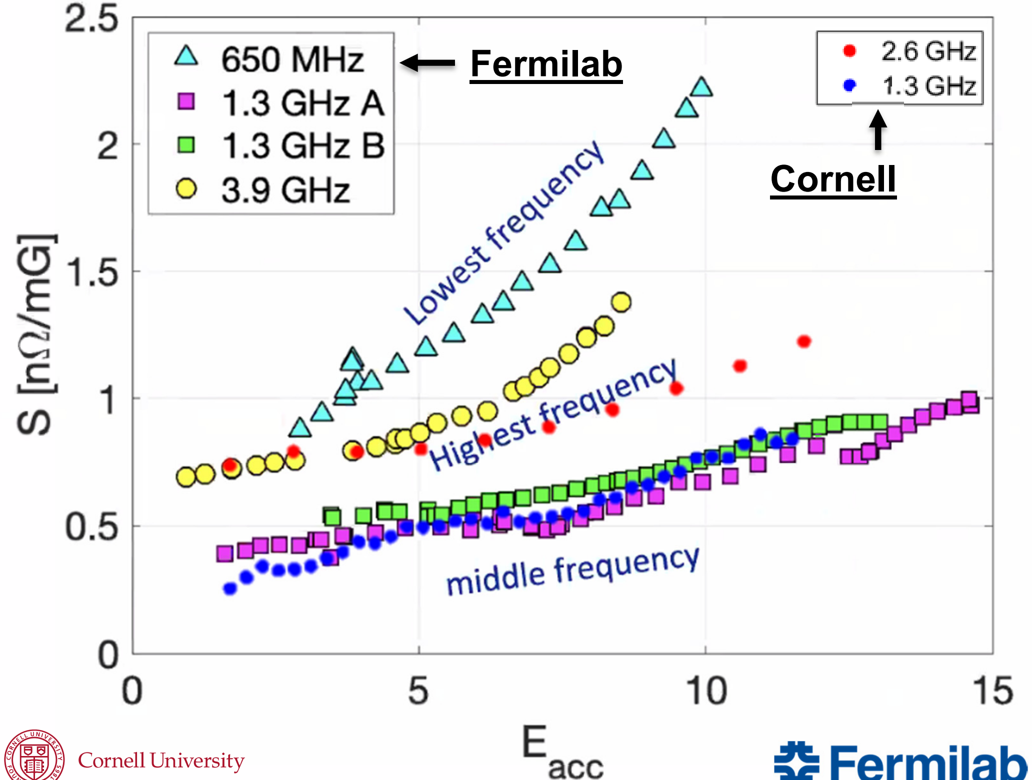






Nb_3Sn: Frequency Scaling of Trapped Flux Losses

Sensitivity = $\Delta R/B_{trapped}$



- Initial results show unexpected, **slow scaling with frequency** above ~1 GHz:
  - ~ $\sqrt{f}$ dependence
  - Good news for high frequency Nb_3Sn
- Non monotonic frequency dependence <1 GHz?

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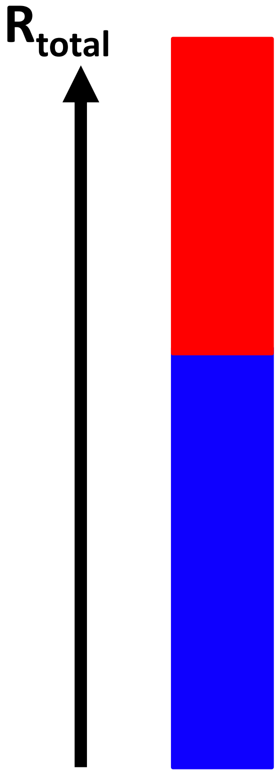
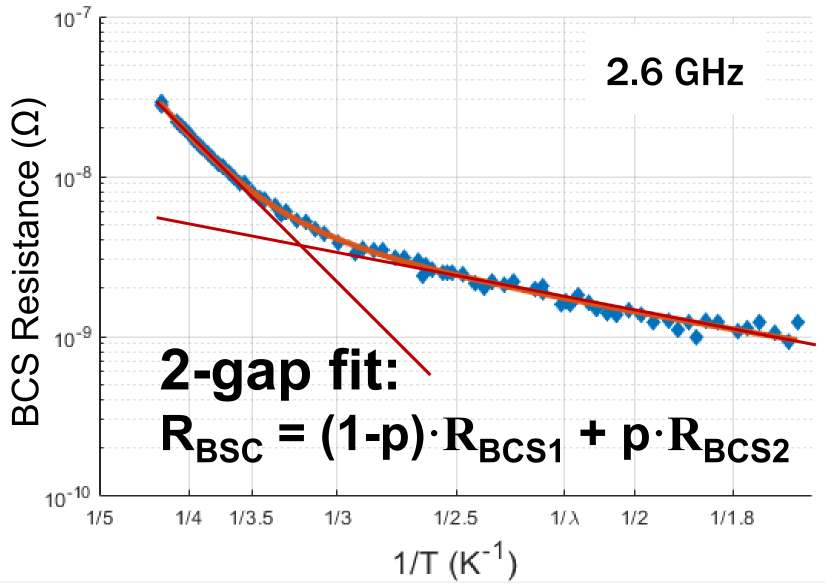
Fermilab

Quest 2: Even Higher Q_0



Two important contributions to surface resistance at 4.2K:

- R_{res} from trapped flux
  => Improve magnetic shielding and cool down uniformity
- R_{BCS} (T)

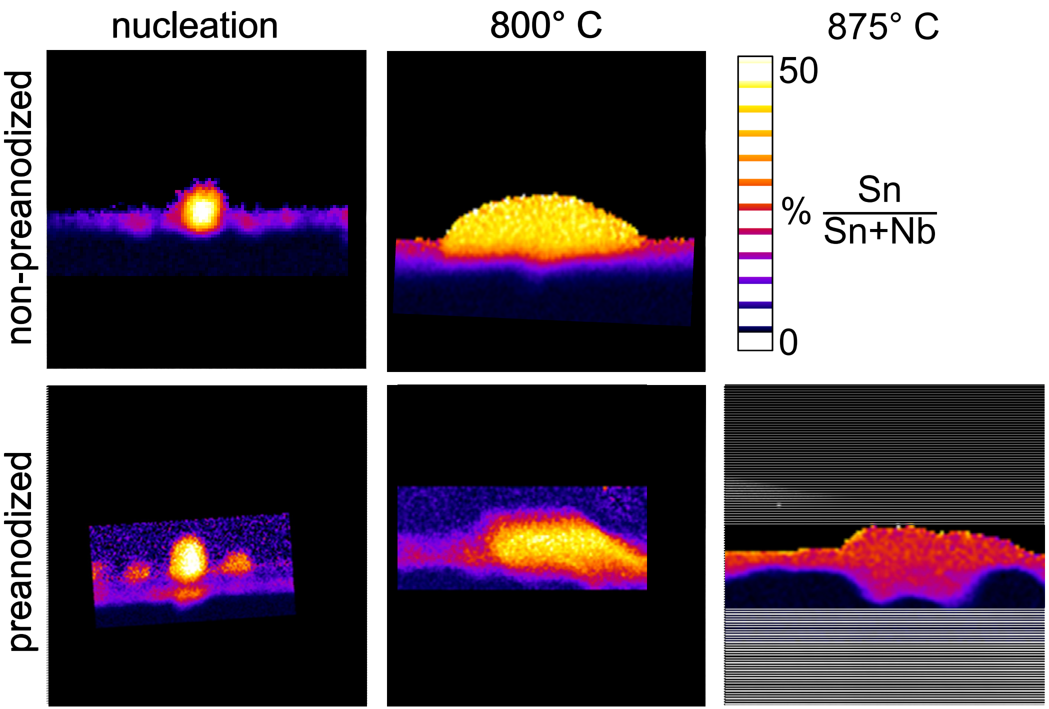


- At higher temperatures (≳4K): "normal" Nb_3Sn gap dominates losses
- At lower temperatures (≲3K): second, small gap dominates losses
- Ratio p ~ 10^{-5}

Nb_3Sn Vapor Diffusion Growth

The Center for BRIGHTBEAMS

TEM/EDX of Nb_3Sn Throughout Growth

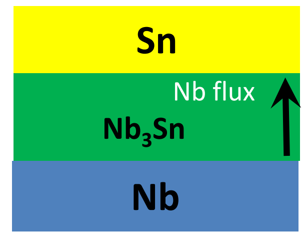


D. Muller, P. Cueva

Simulation of Diffusion and Growth

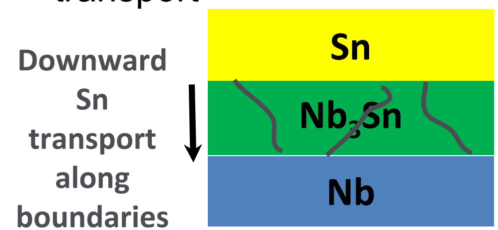
Initial growth:

- Nb diffusion

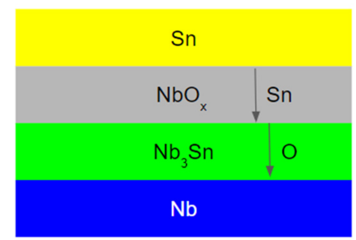


Grain-bound. assist. growth:

- Fast downward Sn transport



Nb3Sn Growth on Niobium Oxide

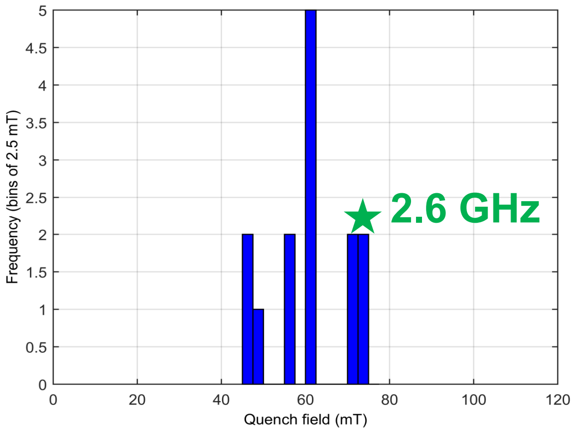


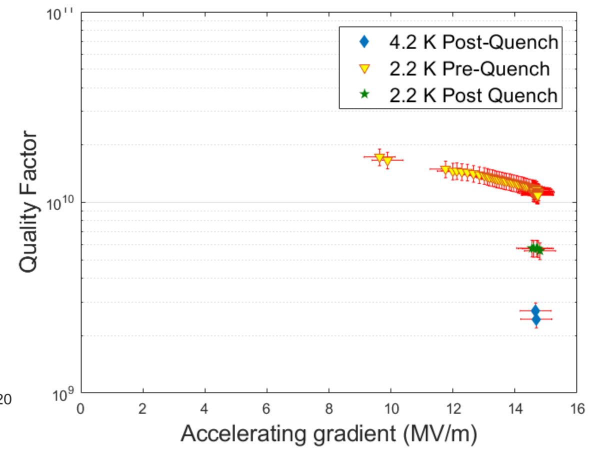
N. Sitaraman, T. Arias

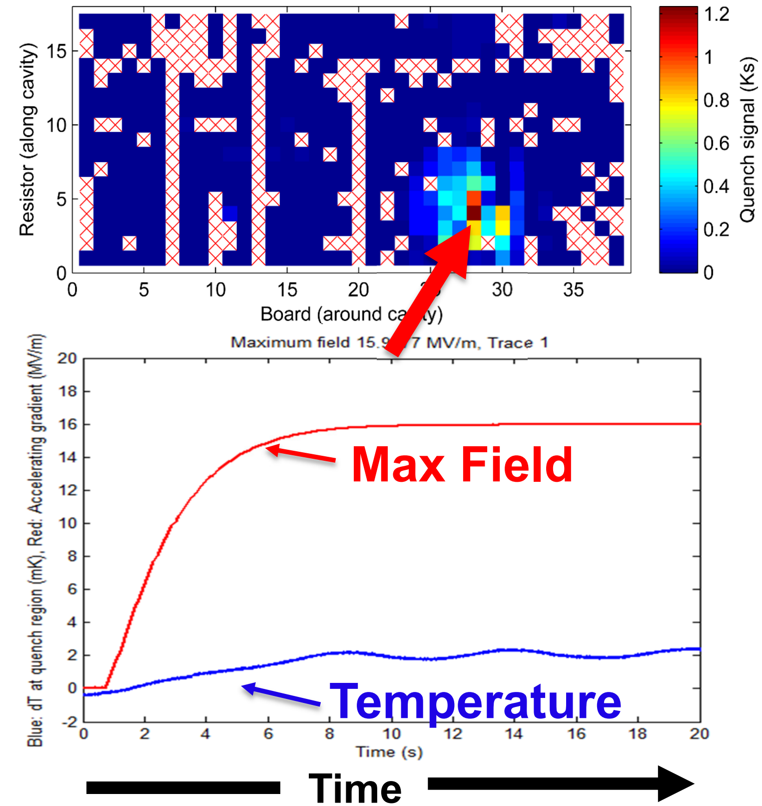
New insights => Higher-performing Nb_3Sn cavities

Quest 3: Higher Quench Fields

Signature of Quench in Nb_3Sn





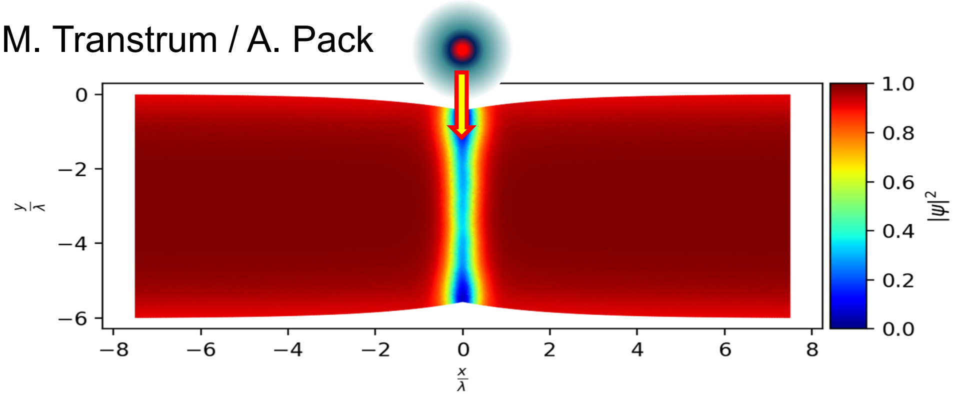


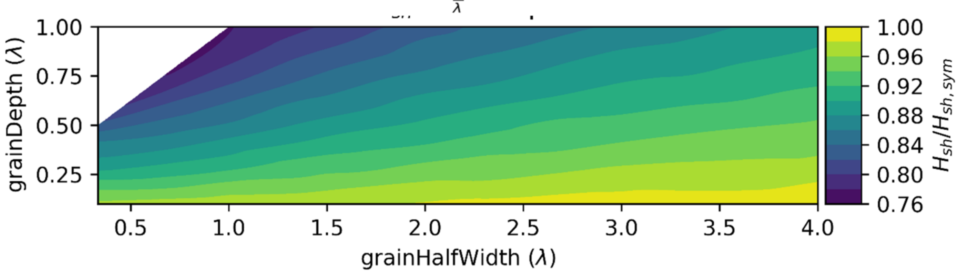
- **Weak dependence on RF frequency**
- **So significant change vs T** (1.7K to 4.2K)
- **Nb_3Sn cavity field limited by localized defects**
- **Just below quench: Quantized jumps in losses**
  - **Vortex entry?**

Candidate Defect: Grain Boundaries?

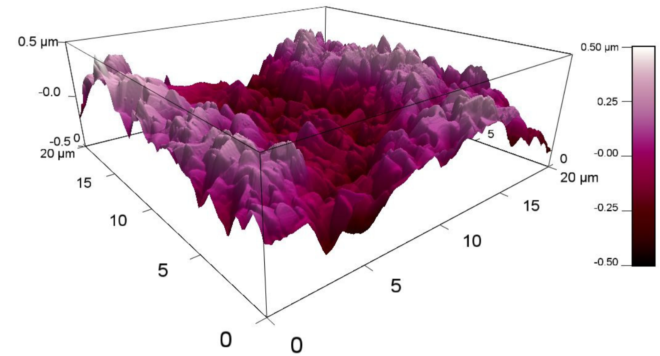
Ginzburg-Landau Simulation of Vortex Nucleation In Grain Boundaries

M. Transtrum / A. Pack

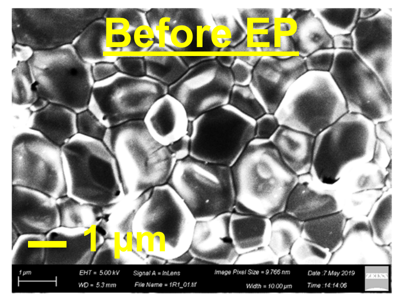


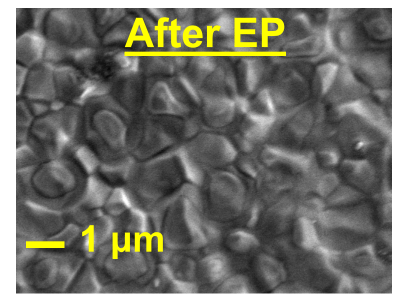


- Geometry of grain boundaries lowers vortex entry field (for ξ << λ Nb3Sn!)



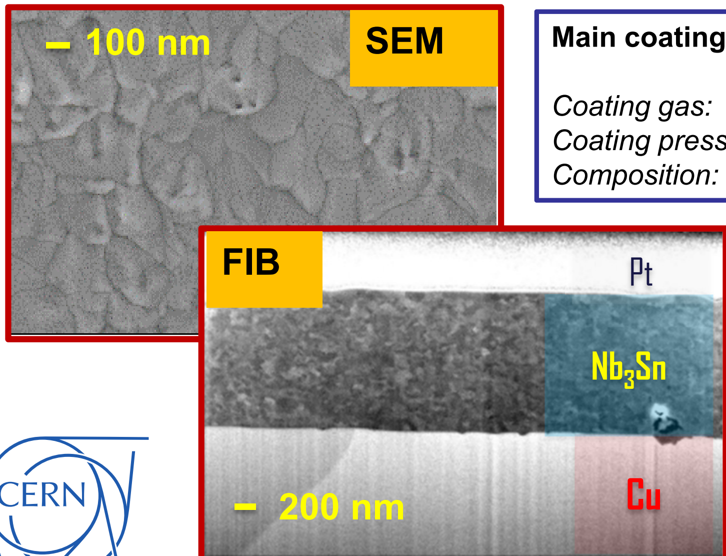
- Surface roughness enhances local surface fields
- Short EP can ~half roughness





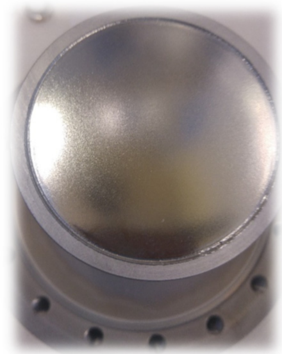
Quest 4: Lower Cost via Coating on Bulk Copper

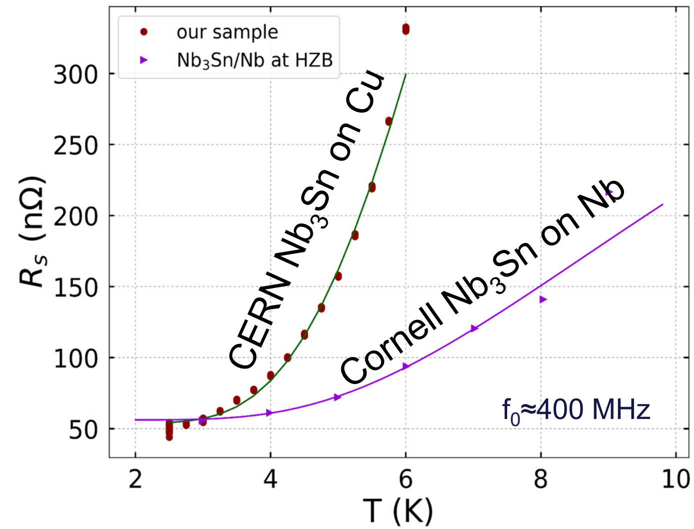
- **Electrochemical plating** studies at FNAL and Cornell
- **Magnetron sputtering** at CERN:



Main coating parameters:

Coating gas: *Ar* or *Kr*
Coating pressures: $7 \cdot 10^{-4}$ *mbar* … $5 \cdot 10^{-2}$ *mbar*
Composition: *Sn* 20 At% to 27 At%





First RF results are encouraging, but more work needed to improve Sn concentration (Tc) and likely grain size

For more details see: E. A. Ilyina, *et al. Supercond. Sci. Technol.*, **32** *(2019)*

The Life Story of Nb_3Sn SRF (as of now)

I. Promise: Why Nb_3Sn for SRF?
II. Early Years and Disappointments
III. Rebirth: Let's try again…
IV. Growing Up: The quest for higher performance
V. Maturity: Nb_3Sn SRF accelerator applications

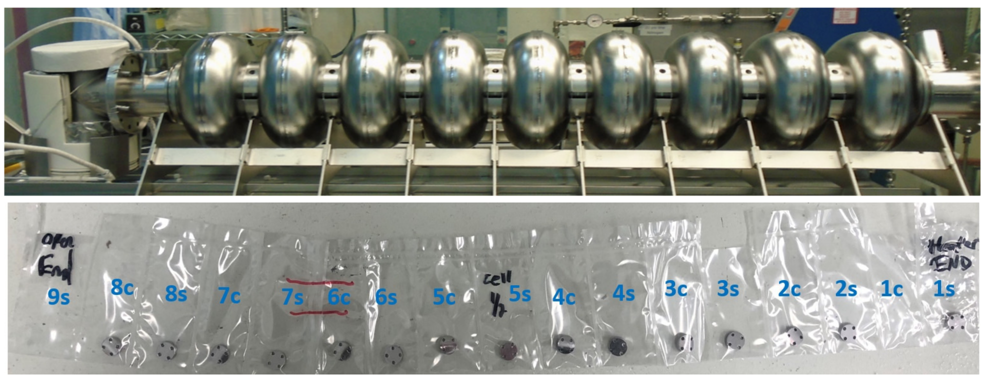
Nb_3Sn Multi-cell Cavities for Accelerator Applications

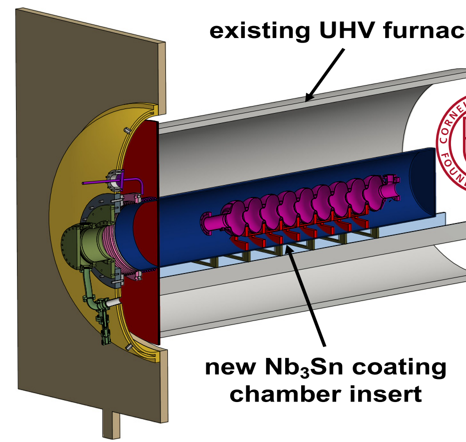
- **JLAB:** **5-cell 1.5 GHz** cavity coated and RF testing started
- **Fermilab:** Coating successful with **1.3 GHz 9-cell** sample host cavity – **very good uniformity**. Full coating and RF testing of 9-cell coming this summer
- **Cornell:** Multicell coating facility under development

Jefferson Lab

IA320 after coating

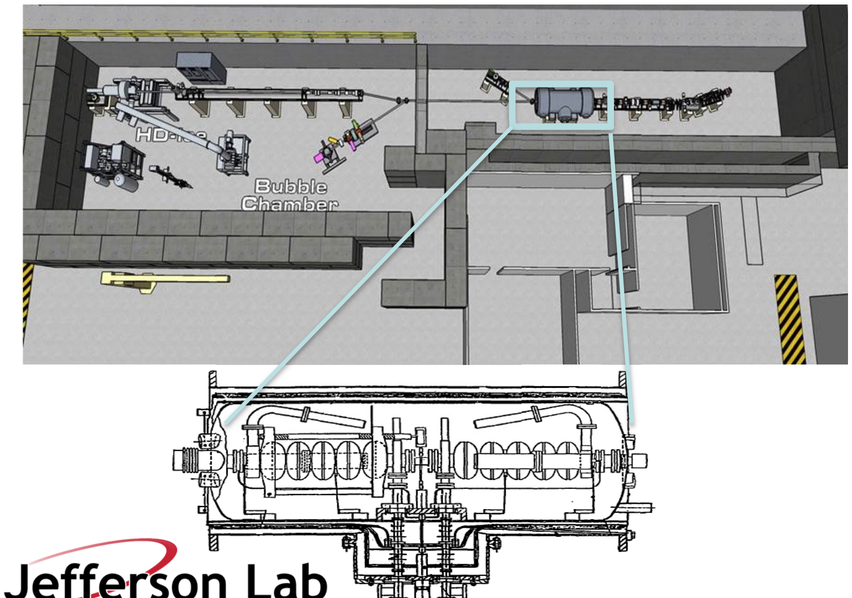
Fermilab





(Potential) Nb_3Sn Accelerator Applications

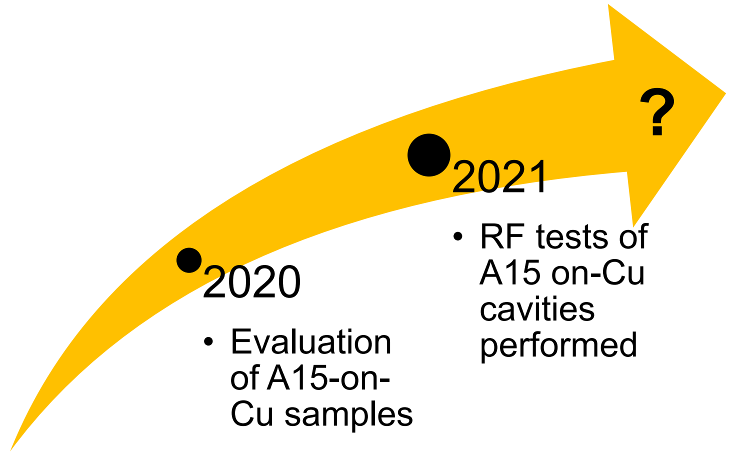
Nb_3Sn cavities for Upgraded Injector Test Facility (UITF) @ Jlab



Jefferson Lab

D. Abbott et al. , Phys. Rev. Lett. 116, 214801
B. DiGiovine et al., Proc. AIP Conf. 1563, 239 (2013)
http://wiki.jlab.org/ciswiki/index.php/Main_Page

Nb_3Sn on Copper Studies at CERN for FCC

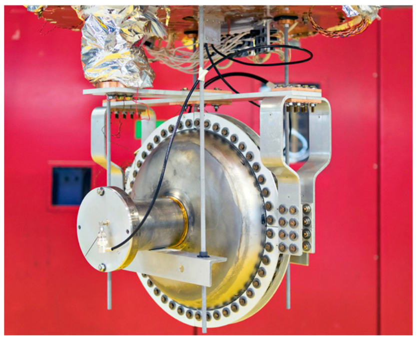


"The A15 compounds have the potential to outperform niobium…"

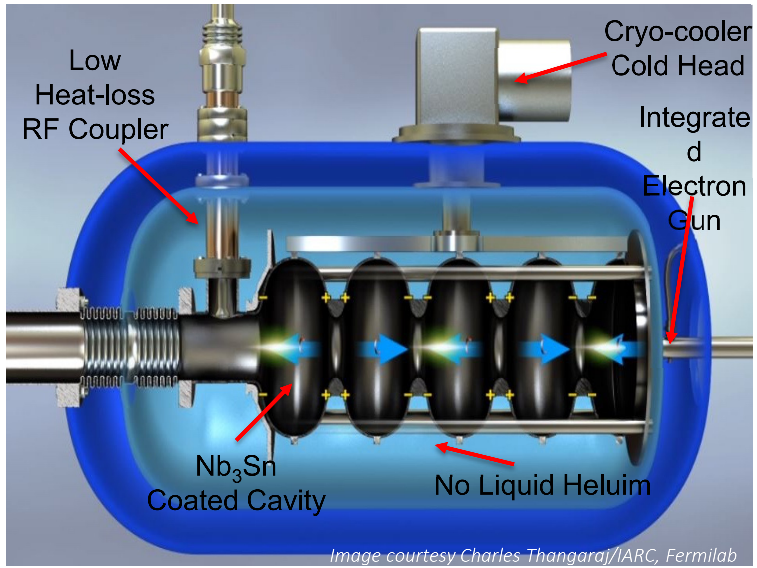
See FCC conceptual design report @ fcc.web.cern.ch

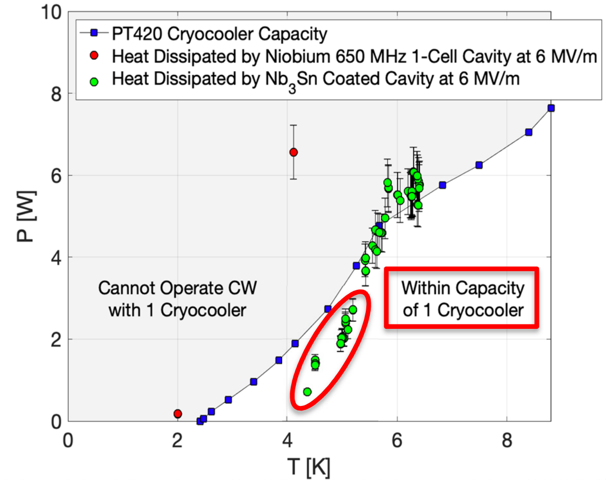
Fermilab Nb$_3$Sn for Compact SRF Accelerator at Fermilab

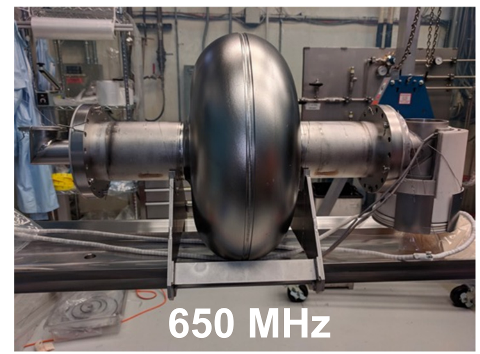
- Development underway for compact Nb$_3$Sn SRF cavity based accelerator at Fermilab, with cooling by **cryocooler**
  - Industry, medicine, security, science
- R&D on **conduction cooling** shows feasible method to remove heat without cryogens



R.C. Dhuley et al. "Thermal Link Design for Conduction Cooling of SRF Cavities Using Cryocoolers," *IEEE Transactions on Applied Superconductivity* Vol. 29-5 (2019)



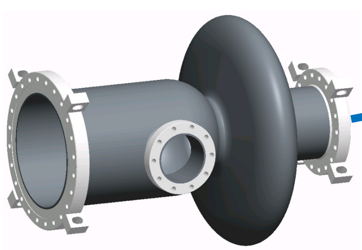


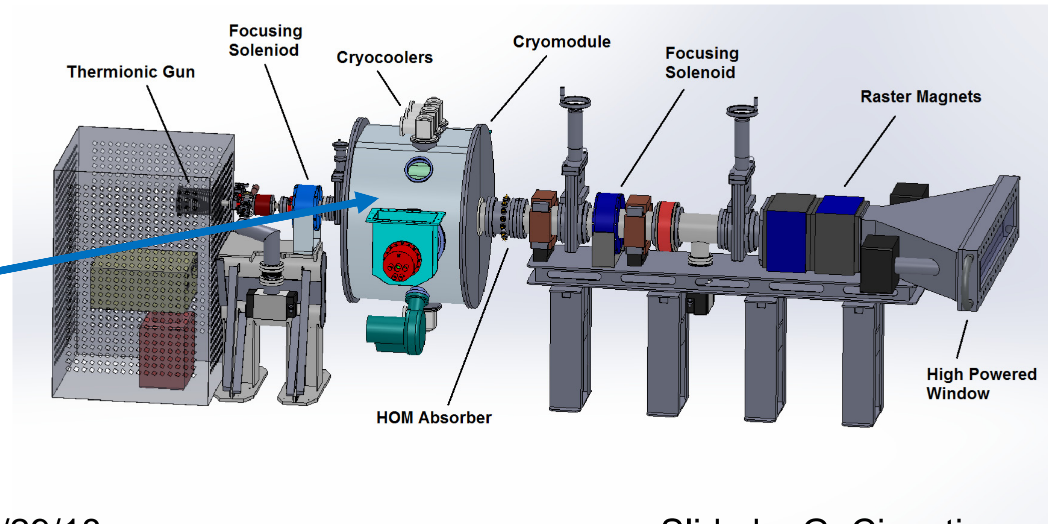


Compact High-Power CW SRF for Industrial Application

- 1-year design collaboration among JLAB, AES, General Atomics
- Funded by DOE-HEP (Accelerator Stewardship)
- Use in **wastewater and flue-gas treatment**
- **1 MeV, 1 A** electron beam

Nb_3Sn/Nb/Cu β=0.5 single-cell cavity, **conduction cooled with four 1.5 W cryocoolers**

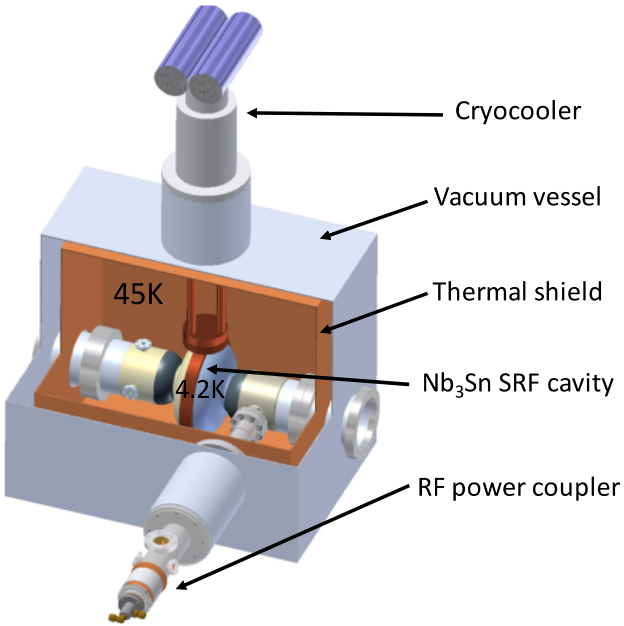


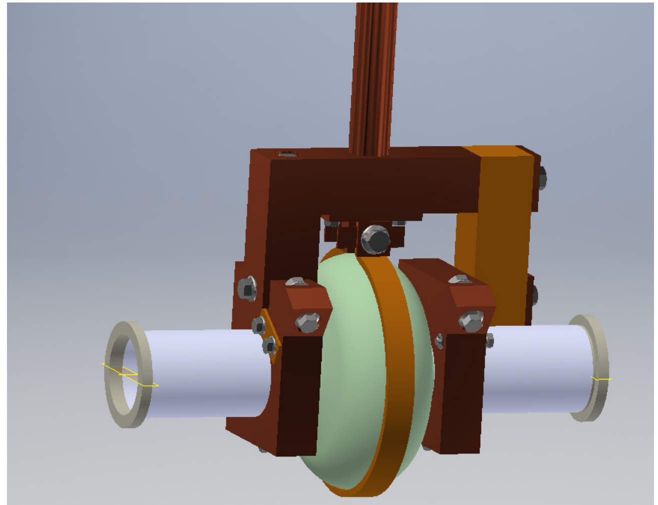


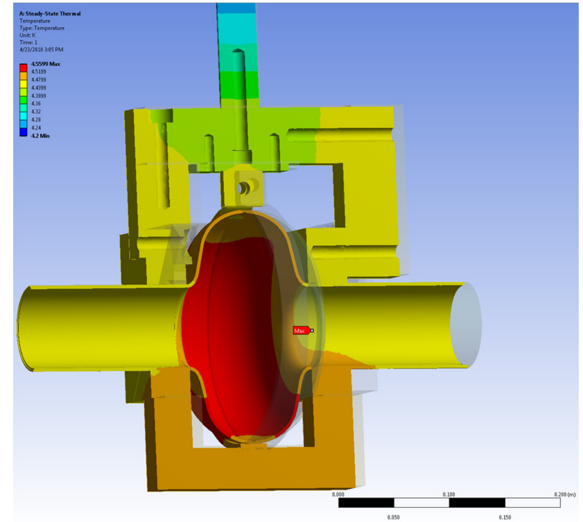
Patent on Cryomodule design filed on 01/29/18

Slide by G. Ciovati

Compact Nb_3Sn Cryomodule Development at Cornell







- **Design study of conduction cooling of Nb_3Sn cavity from cryocooler indicates feasibility**

Is Nb_3Sn ready for next-generation accelerators?

✓ **Nb_3Sn coating facilities established (650 MHz – multi-GHz)**

- Cornell, JLAB, FNAL … more coming

✓ **Nb_3Sn 1-cell vapor diffusion coatings at Cornell, JLAB, FNAL demonstrate performance needed for applications**

- ~4K operation with unprecedented Q >10^{10} at 1.3 GHz
- Drastic reduction in cooling power and complexity
- 16 – 22 MV/m quench fields (similar to LCLS-II cavities)
- Robust and reproducible process
- Robust cavities (no issues with HPR, long term stability…)
- Demonstration of multi-GHz Nb_3Sn cavities opens path to compact SRF

Is Nb_3Sn ready for next-generation accelerators?

✓ **First multicell Nb_3Sn cavities underway**

- Good uniformity of coating already achieved

✓ **Cryomodule and technical R&D started**

- ✓ Compact cryomodules
- ✓ Cryocooler with conduction cooling

✓ **Future R&D (addressing technological challenges):**

- Nb_3Sn cavity frequency tuning (Nb_3Sn films are brittle)
- Microphonics control at ~4K
- …

⇒ **First applications within 5 years realistic goal**

⇒ **Ongoing R&D will lead to even higher performance and further cost reduction (e.g. Nb_3Sn on copper)…stay tuned**

Thank you for your attention!

Special thanks to

Sam Posen, FNAL
Grigory Eremeev, TJNAF
Marco Arzeo, CERN
Nathan Sitaraman, **Paul Cueva**, **Alden Pack**, **Ryan Porter**, CBB

for providing some of the material for this talk!

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."

Sir Winston Churchill, Speech in November 1942