Nb_3Sn for Axion Searches

Sam Posen

Quantum Technologies for Fundamental Physics Workshop
3 September 2023

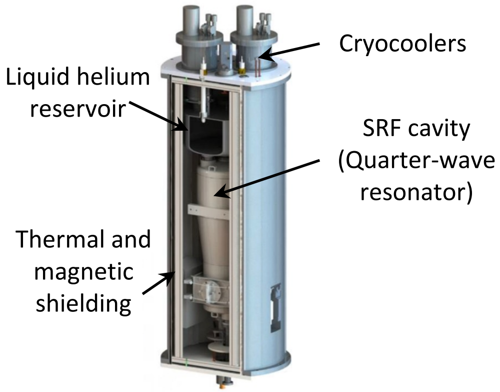
1. **Nb_3Sn SRF cavities**
2. First Nb_3Sn SRF studies in Tesla-scale field
3. Future outlook and Summary

Nb_3Sn Cavities for Particle Accelerators

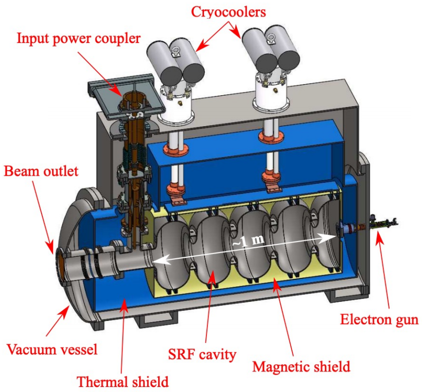
- Nb has long been the material of choice for SRF accelerators
- Nb_3Sn is under development, and we have shown that it can achieve high Q ~10^{10} even at 4 K
- Immediate promise for 'compact accelerators'
- With continued R&D, Nb_3Sn is predicted to exceed Nb maximum field

Potential Near-Term Applications of Nb_3Sn Cavities

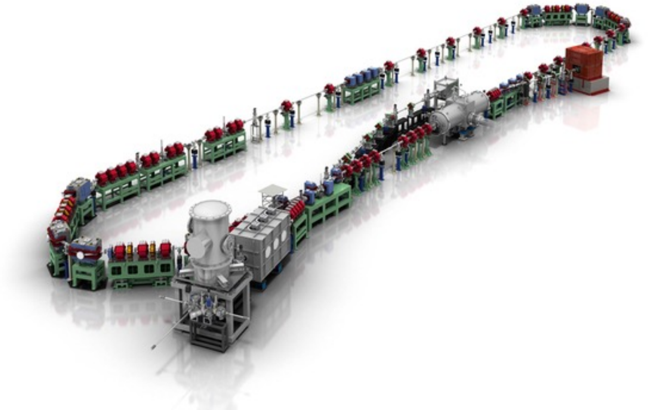
- Nb_3Sn is a potentially enabling technology for CW accelerator applications that could be realized in the near future:
  - Stand-alone cryomodules (e.g. isotope separator, harmonic cavities)
  - Compact high power accelerators (e.g. water treatment)
  - Turnkey/high MTBF energy recovery linacs (e.g. isotope production, EUV sources)



S. Kutsaev et al, *IEEE Trans. App. Superc.* 30, 8, 2020

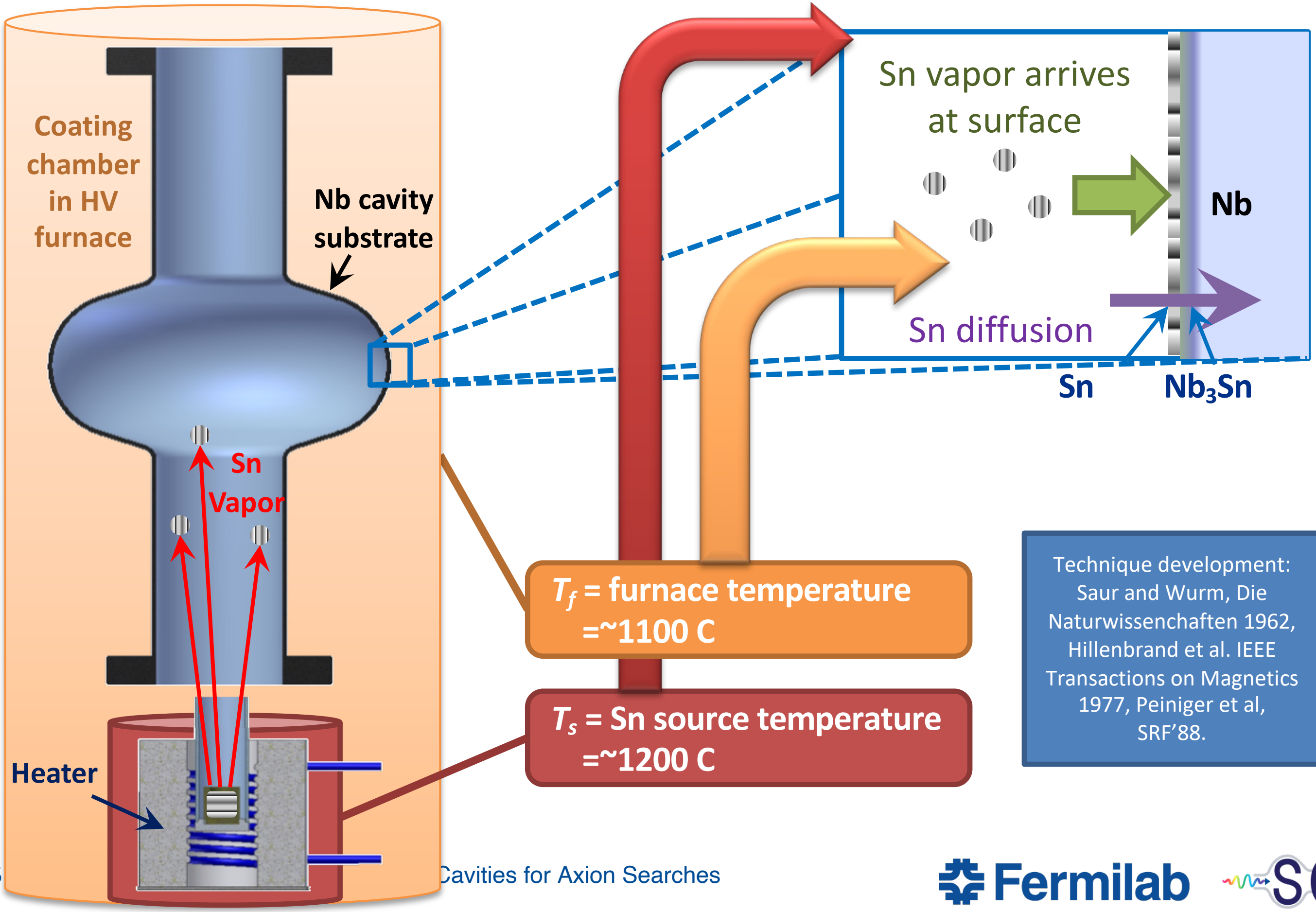


R.C. Dhuley et al, *Phys. Rev. Accel. Beams.* 25, 041601 (2022).

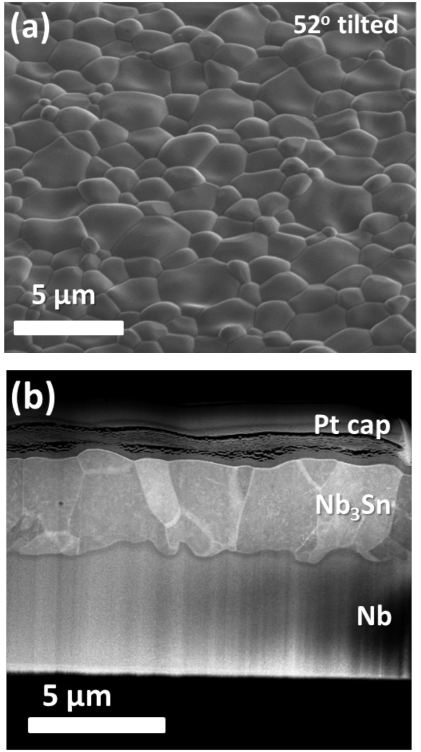


Y. Morikawa et al, New industrial application beamline for the cERL in KEK, IPAC'19, THPMP012

Coating Mechanism: Vapor Diffusion

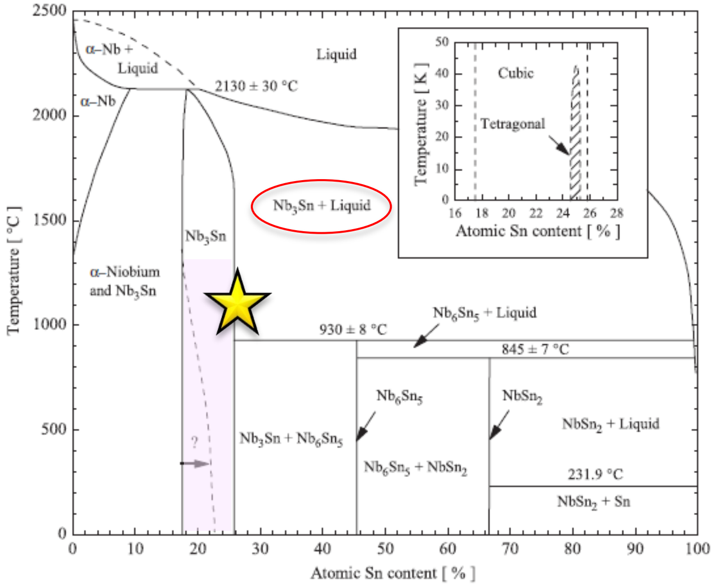


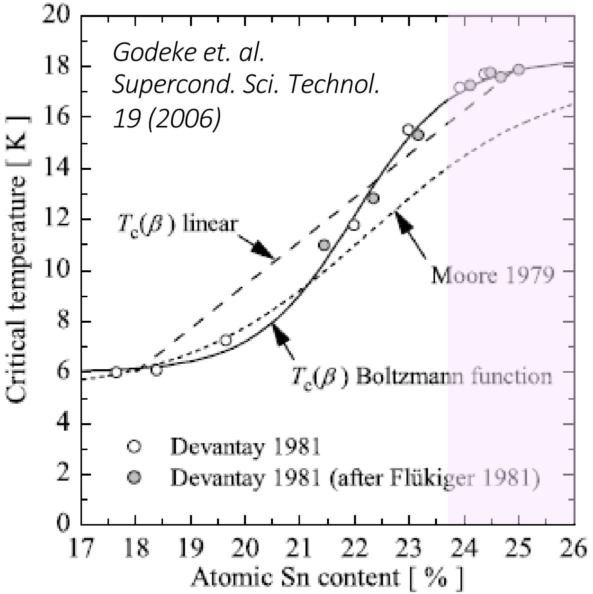
Technique development: Saur and Wurm, Die Naturwissenchaften 1962, Hillenbrand et al. IEEE Transactions on Magnetics 1977, Peiniger et al, SRF'88.



SEM images of Nb_3Sn film coated on Nb: a) surface, b) cross-section

“Phase Locking” as Control for Desired Composition





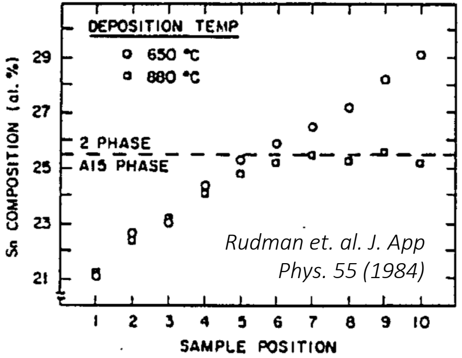
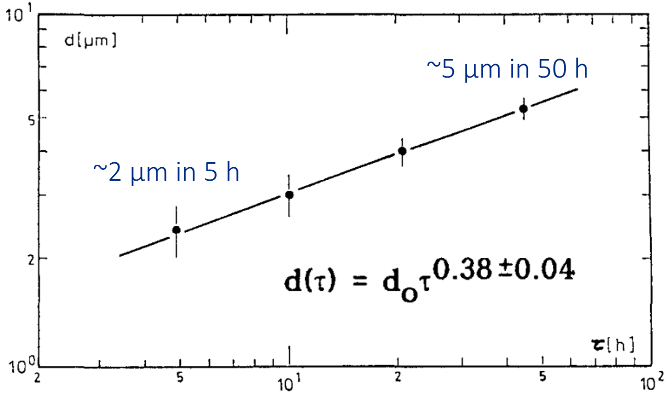
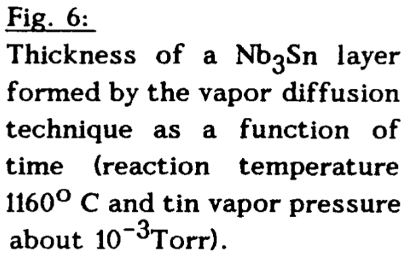


FIG. 7. The variation of sample composition with substrate position for two depositions in the compositional gradient configuration using different substrate temperatures. For sufficiently high substrate temperatures sample composition "locks" at phase boundary.

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

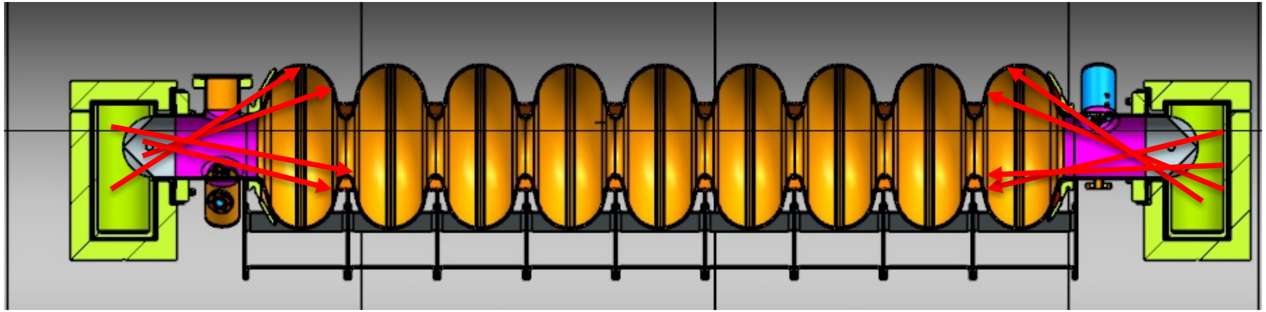
Diffusion Limited Growth as Control for Uniform Thickness





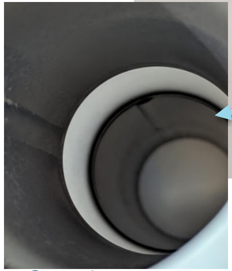
M. Peiniger et al., "Work on Nb_3Sn cavities at Wuppertal" Proceedings of The Third Workshop on RF Superconductivity (1988)

- Coating mechanism is diffusion limited – as film becomes thicker locally, less tin is consumed, more re-evaporates and moves to other areas
- Another "self regulating" feedback mechanism to help with uniformity

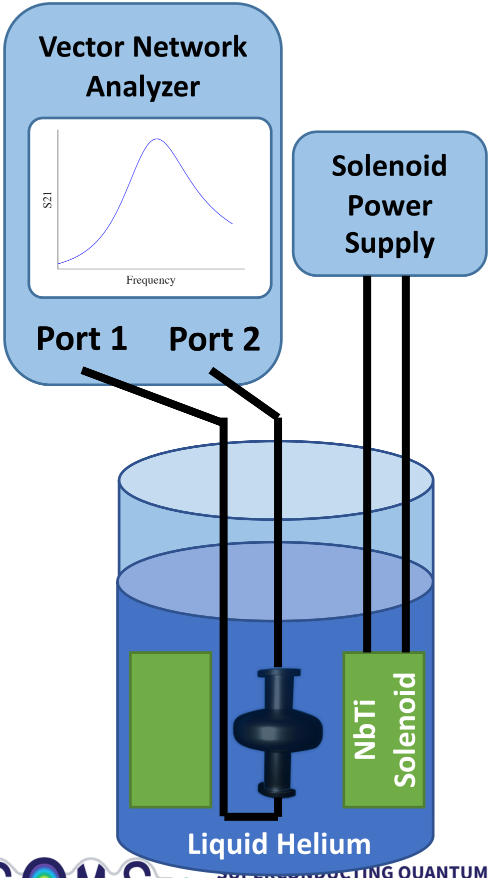


1. Nb_3Sn SRF cavities
2. **First Nb_3Sn SRF studies in Tesla-scale field**
3. Future outlook and Summary

First Test – Put Existing Cavity into 6 T Field and Measure Q_0

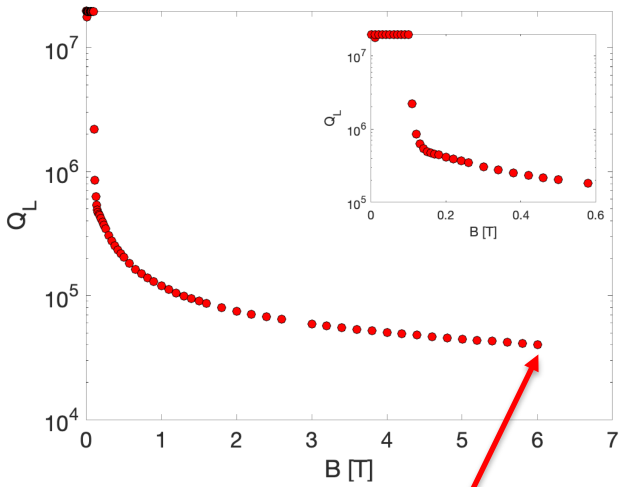


Nb$_3$Sn-coated 3.9 GHz elliptical shape cavity



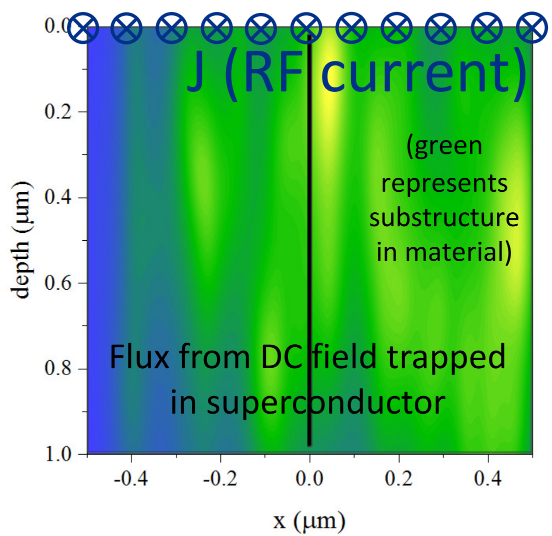
Results from First Cavity (Accelerator Type Cavity)

- Q_0 ~$4x10^4$ at 6 T
- Q_0 lowered due to flux dissipation – Lorentz force $\mathbf{F} \sim \mathbf{J} \times \mathbf{B}$
- Not expecting best possible results from first test due to geometry – cavity walls highly perpendicular to applied field



Q_0 of $4x10^4$ at 6 T, 4.2 K, 3.9 GHz

F (Lorentz force)



B (DC magnetic field)

M. Checchin and A. Grassellino, "Vortex Dynamics and Dissipation under High-Amplitude Microwave Drive," Phys. Rev. Applied *14, 044018 (2020)*

M. Checchin et al. "Frequency dependence of trapped flux sensitivity in SRF cavities," Appl. Phys. Lett. *112, 072601 (2018)*

Flux motion analysis by Mattia Checchin
Details in arXiv:2201.10733 (2022)

Figure of Merit

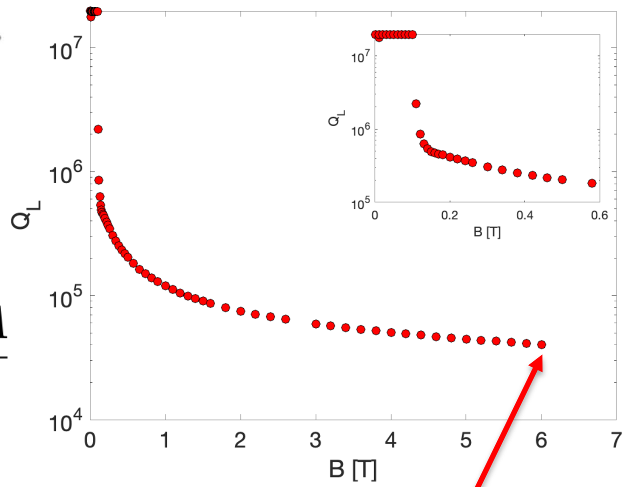
$$P_c = \frac{1}{2\mu_0^2}\int R_{\rm fl} B_s^2\, dA.$$

$$Q_0 = \frac{\omega W}{P_c},$$

$$\mathrm{FoM} = \frac{\int \mathbf{B}\cdot\hat{\mathbf{n}}\ |\mathbf{B}_{\rm RF}|^2\, dA}{B_0\ \int |\mathbf{B}_{\rm RF}|^2\, dV}$$

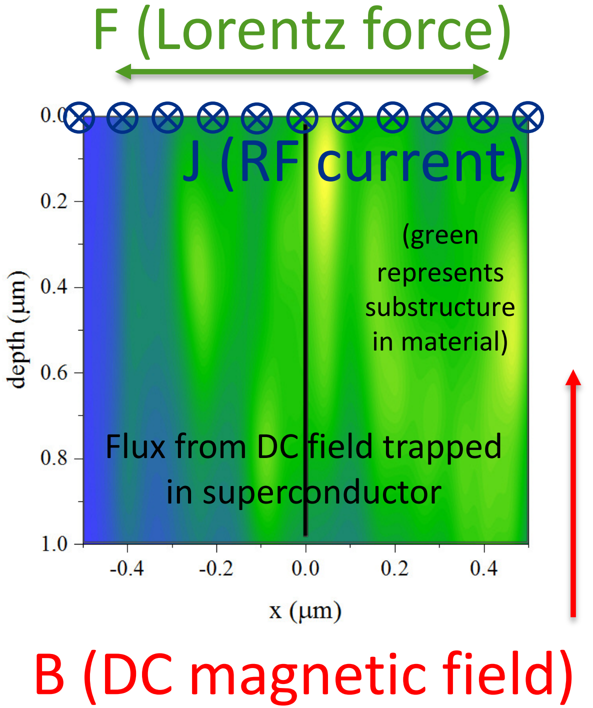
Different behavior than copper cavities – specialized superconducting cavity geometry will be different

Details in S. Posen et al., Phys Rev Applied (2023) (accepted)



Q_0 of 4x10^4 at 6 T, 4.2 K, 3.9 GHz

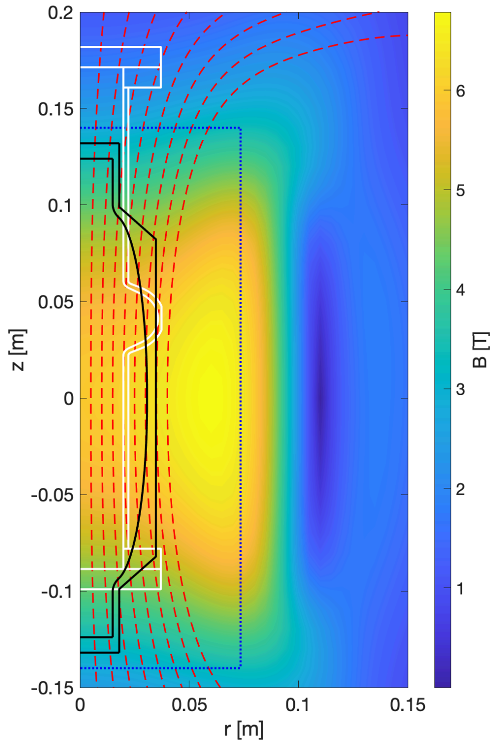
M. Checchin et al. "Frequency dependence of trapped flux sensitivity in SRF cavities," Appl. Phys. Lett. *112, 072601 (2018)*



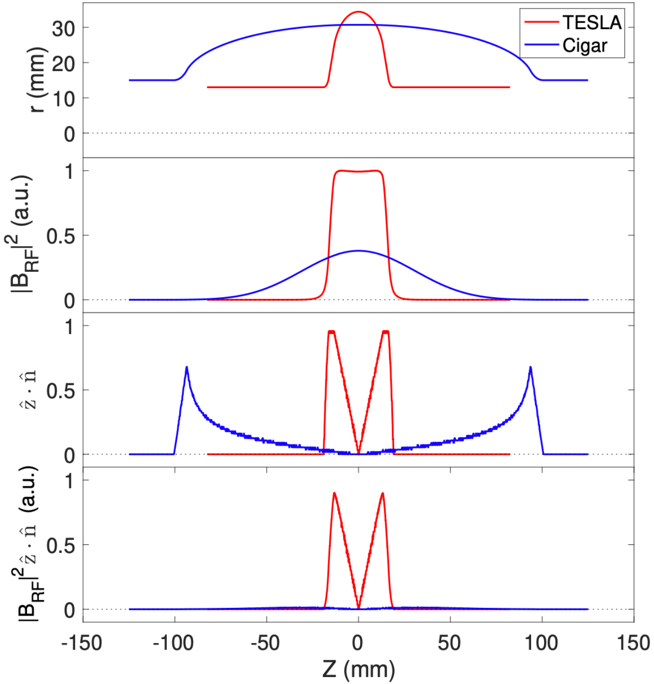
Flux motion analysis by Mattia Checchin

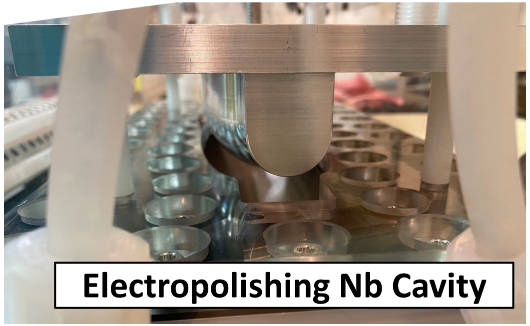
Details in arXiv:2201.10733 (2022)

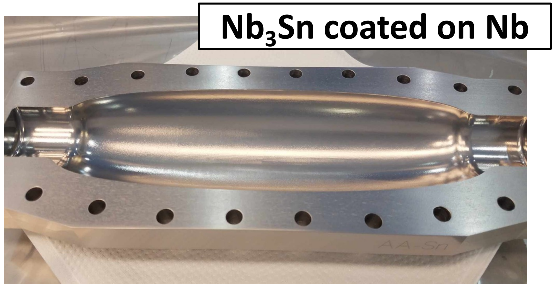
Second Cavity – Specialized Geometry

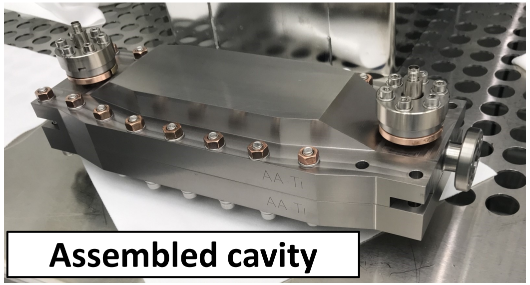


- Second cavity designed to minimize $\hat{\mathbf{z}} \cdot \hat{\mathbf{n}} |\mathbf{B}_{\mathrm{RF}}|^2$

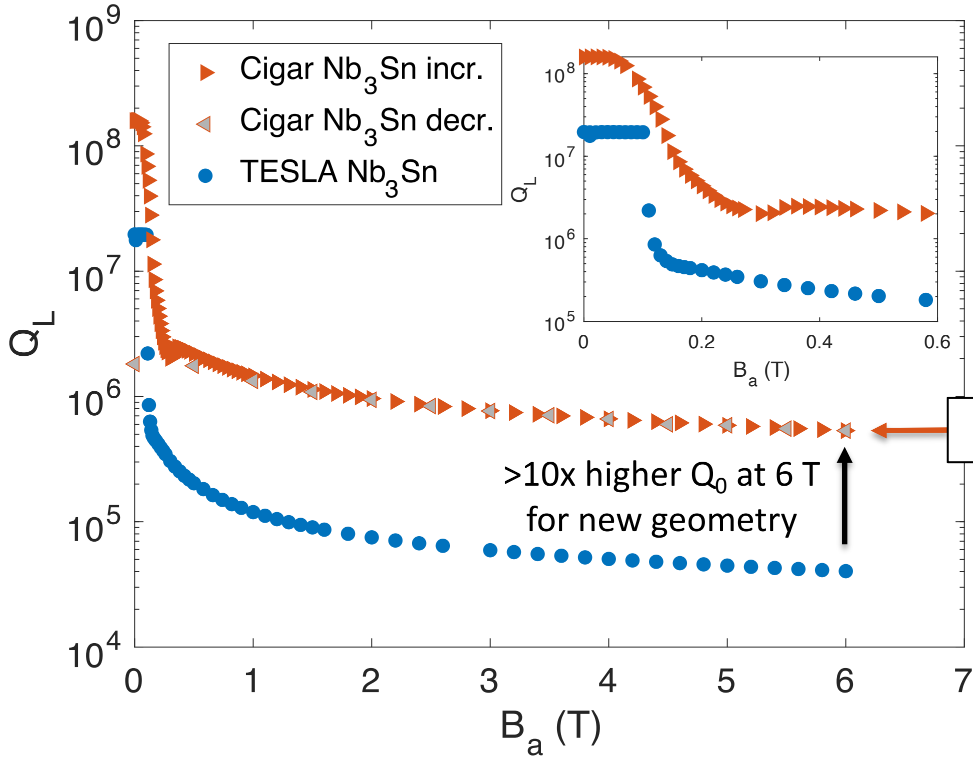








Results of Second Cavity



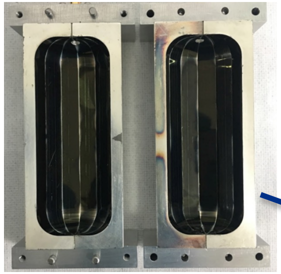
Q_0 of 5x10^5 at 6 T, 4.2 K, 3.9 GHz

Details in 'Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches'

S. Posen et al., Phys Rev Applied (2023) (accepted)

Comparison to Previous Results

- Challenging to compare to other cavities due to different frequencies and fields, but clearly much better than copper, and among the highest Q_0 measured in multi-tesla fields
- Superconducting cavities from other groups (table) also show promising results – SRF cavities have potential for axion searches



Source	Material	f (GHz)	B_a (T)	T (K)	Q_0
This work	Nb_3Sn	3.9	6.0	4.2	$(5.3\pm0.3)\times10^5$
[1]	NbTi/Cu	9.08	5	4.2	2.95×10^5
[2]	Nb_3Sn	9	8	4.2	6×10^3
[2]	REBCO	9	11.6	4.2	7×10^4
[3]	YBCO	6.93	8.0	4.2	3.2×10^5

[1] D. Alesini *et al.*, "Galactic axions search with a superconducting resonant cavity," *Phys. Rev. D*, vol. 99, no. 10, 101101, (2019).
[2] J. Golm *et al.*, "Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter," 3–7, (2021).
[3] D. Ahn *et al.*, "Superconducting cavity in a high magnetic field," *arxiv:2002.08769*, (2020).

Recently reported Q_0 of 1e7 with HTS tapes, fixed frequency – not yet published to my knowledge

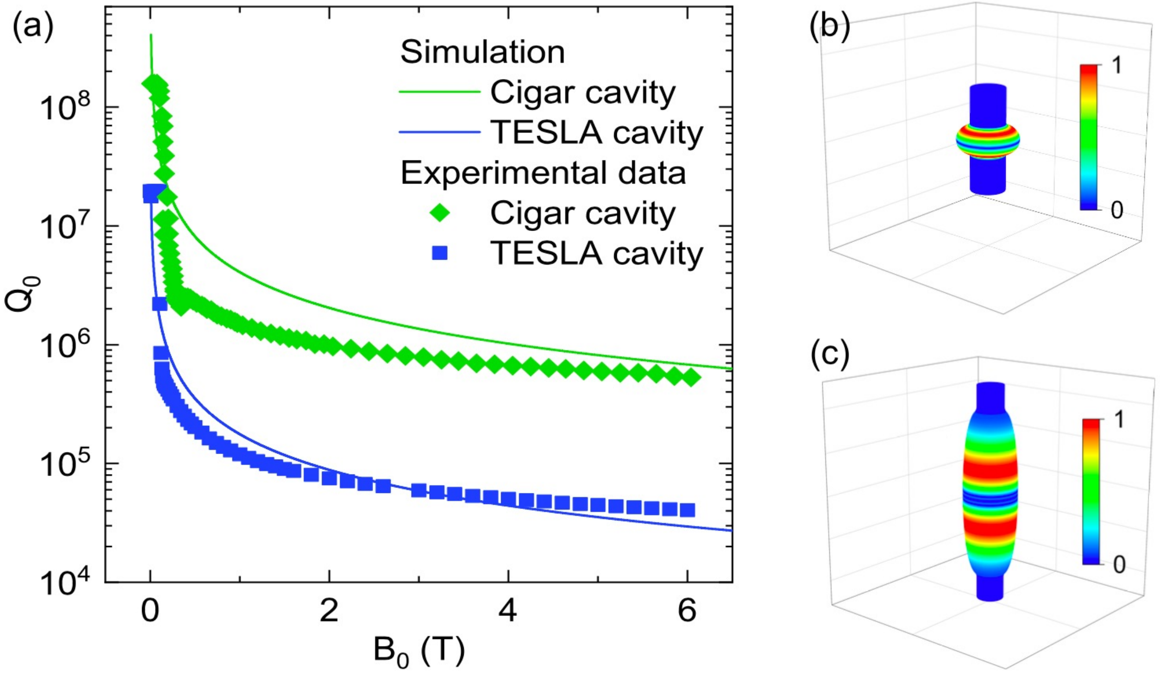
Comparison to Theoretical Model

$$P_c = \frac{1}{2\mu_0^2} \int R_{\mathrm{fl}} B_s^2 \, dA.$$

$$Q_0 = \frac{\omega W}{P_c},$$

$$\mathrm{FoM} = \frac{\int \mathbf{B} \cdot \hat{\mathbf{n}} \, |\mathbf{B}_{\mathrm{RF}}|^2 \, dA}{B_0 \int |\mathbf{B}_{\mathrm{RF}}|^2 \, dV}$$

Different behavior than copper cavities – specialized superconducting cavity geometry looks different



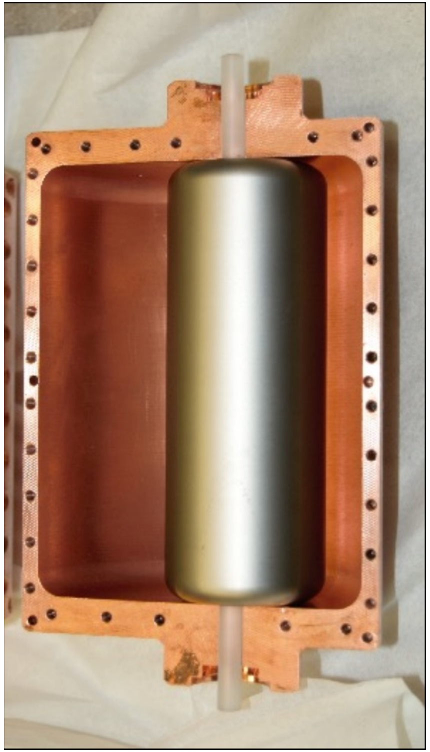
Details in 'Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches'
S. Posen et al., arXiv:2201.10733 (2022)

1. Nb_3Sn SRF cavities
2. First Nb_3Sn SRF studies in Tesla-scale field
3. **Future outlook and Summary**

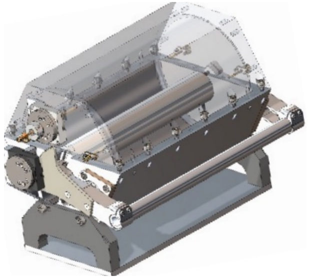
Taking a look out at the horizon…

First Exploration of SQMS/ADMX Team-up

- We have been working with Gp Carosi, Andrew Sonnenschein, and their team to design and fabricate a Nb_3Sn tuning rod for ADMX Sidecar
- To my knowledge, this would be the first hybrid (NC-SC) tuneable superconducting cavity in multi-tesla magnetic field
- If we improve Q_0, could be an excellent stepping off point for continued joint ADMX/SQMS efforts towards superconducting cavities for axion haloscopes

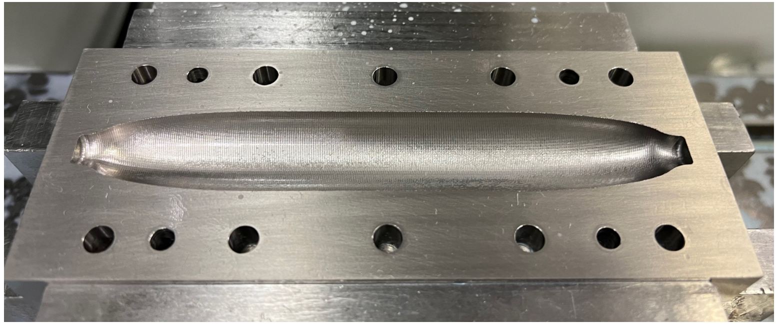


From Gp's talk



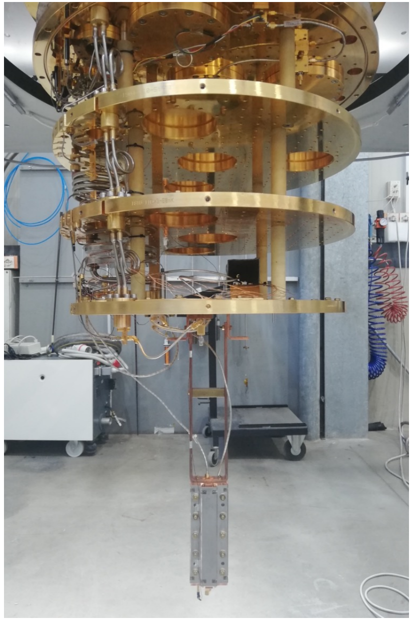
Future?

9 GHz Nb_3Sn Cavity Made at FNAL for INFN Frascati



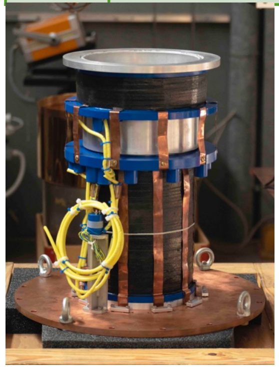
Characterization of Q_0 vs B of the Nb_3Sn cavity at LNF

Go see the poster by A. Rettaroli



T cavity	**130 mK**
T noise	**5 K**

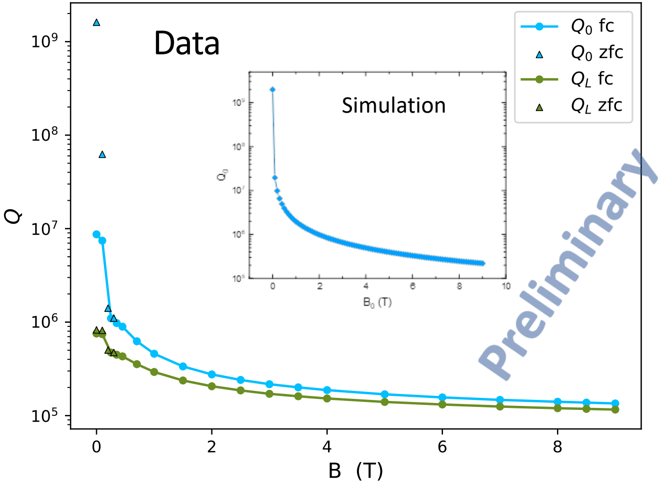
B_{av}	8.447 T
V_{cav}	0.068 L
C_{010}	0.69
β	0.08
Q_0	135000
freq	8.99554 GHz



Picture of the setup: the Nb_3Sn cavity fabricated at FNAL is attached to the coldest temperature stage of the LNF dilution refrigerator.

When the DR is closed, the cavity is in a high magnetic field of up to 9T, thanks to the SC magnet on the right.

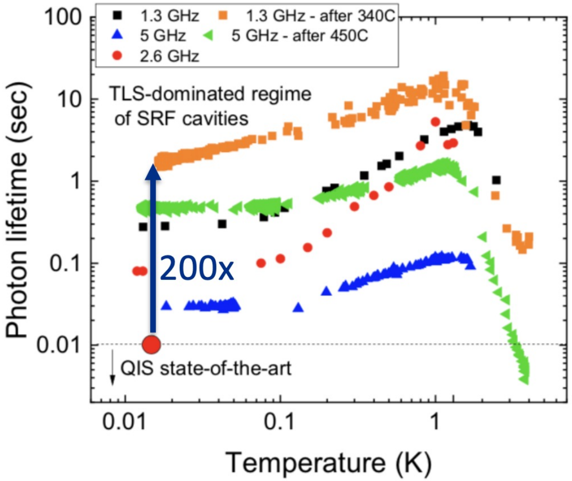
Extracted unloaded quality factor in magnetic field. At 0 T, the Q_0 value reaches $1.6{\times}10^9$. The coupling has beeen estimated at zero field at resonance and then rescaled properly at higher fields.



Q_0(9T) measured	135,000
Q_0(9T) simulation	250,000
Q_0(Cu)	90,000

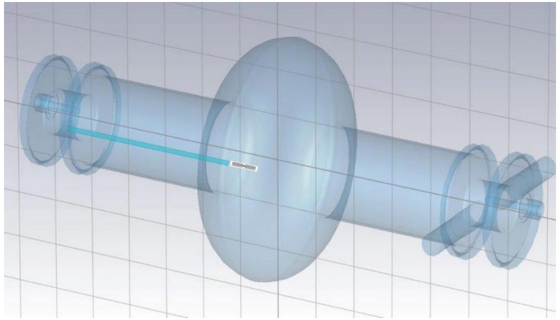
Some Future Directions

Materials

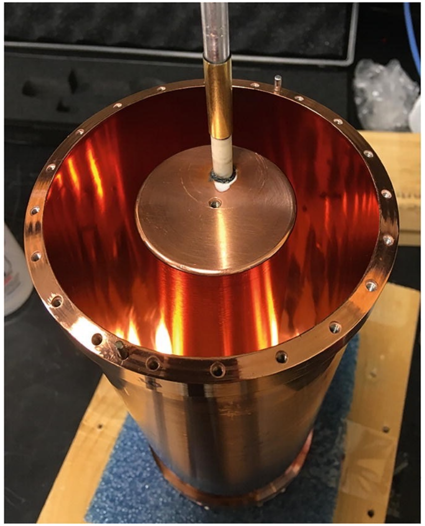


A. Romanenko *et al*, Phys. Rev. Applied 13, 034032 (2020)

Sensing



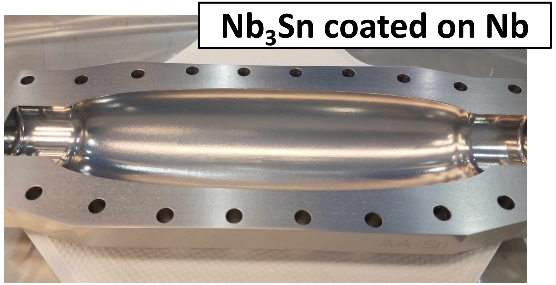
Sensing

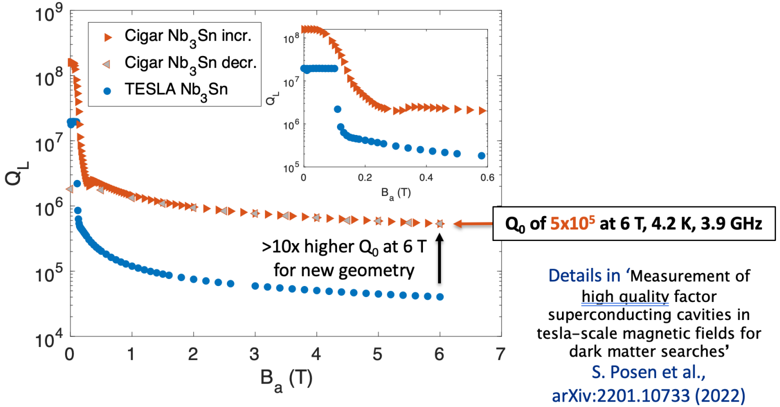


From ADMX

Summary

- Nb_3Sn superconducting radiofrequency cavities are a promising technology for particle accelerators – high Q_0 at 4 K, potential for very high accelerating field
- For completely different reasons than our interest for accelerators (i.e. due to its high H_{c2}), Nb_3Sn cavities are also promising for axion haloscopes
- First studies show Q_0 of $5x10^5$ in a 6 T field at 4 K
- A number of promising future directions!





Details in 'Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches'
S. Posen et al., arXiv:2201.10733 (2022)

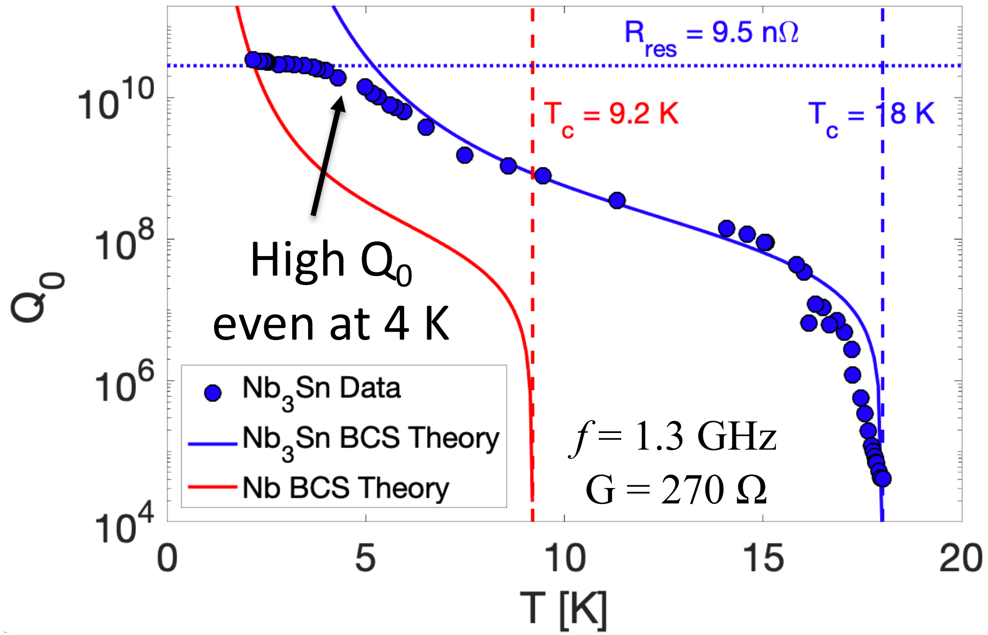
Fermilab SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- BACKUP

Advantages of Nb_3Sn Cavities: Higher Q_0 at High Temperature

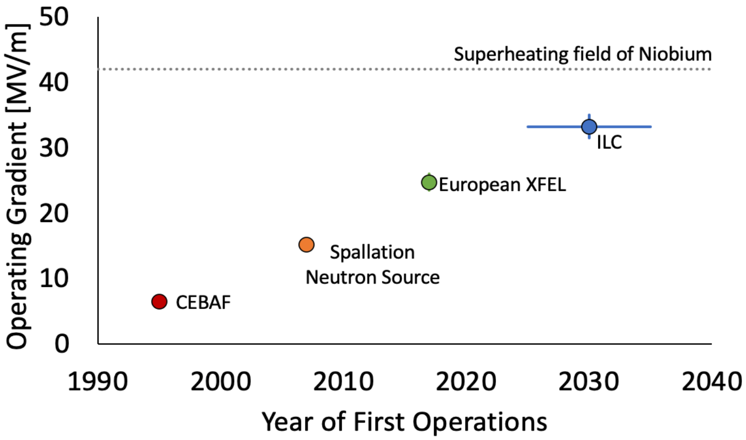
- Nb_3Sn has substantially higher T_c than Nb (18 K vs 9 K)

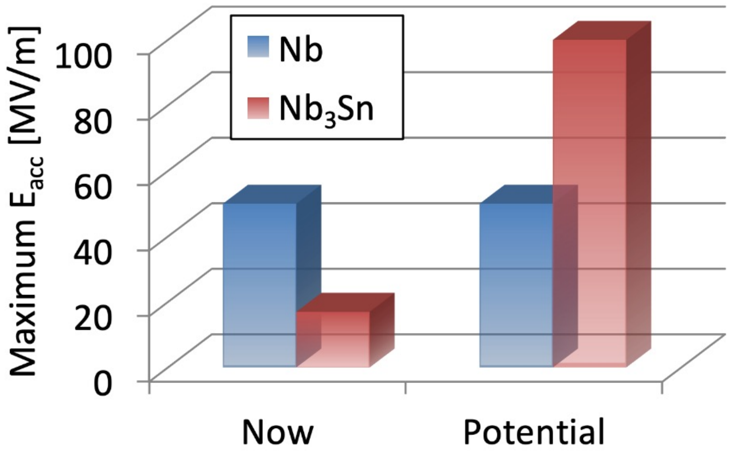
- High Q_0 at relatively high temperatures
  - Potential for high $Q_0 > 10^{10}$ in ~4.5 K operation in liquid helium
  - Potential for replacing cryoplant with cryocoolers
  - Even eliminating liquid helium via conduction cooling
- Impacts for high duty factor applications, especially small and medium-scale



Advantages of Nb_3Sn Cavities: Higher Superheating Field

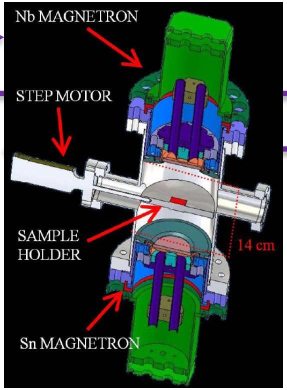
- Decades of R&D have made it possible to operate Nb cavities at higher and higher accelerating gradients, enabling new accelerator-based science over the years
- Developed mitigation methods for many limitation mechanisms
- State-of-the-art Nb cavities are limited very close to the superheating field H_{sh} of Nb
- *Predicted* H_{sh} of Nb_3Sn ~2x that of niobium
- Reaching H_{sh} would correspond to ~100 MV/m – currently far from this, but substantial progress

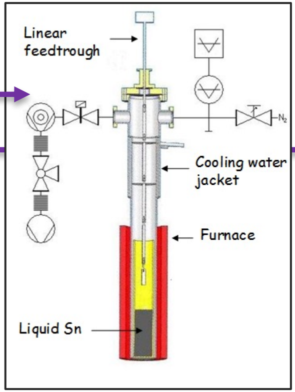


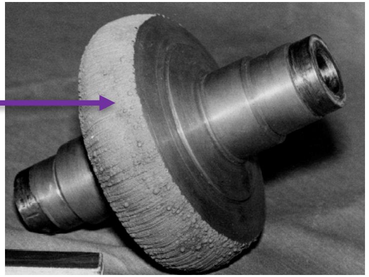


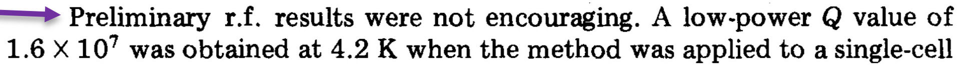
Methods for Fabricating Nb_3Sn Coatings

- Many different manufacturing methods attempted for Nb_3Sn SRF cavities, including:
  - Multilayer sputtering
  - Liquid tin dipping
  - Molten salts electrodeposition
  - Mechanical plating
  - Metal-organic CVD
  - E-beam co-evaporation
  - Bronze Process
  - Cold evaporation



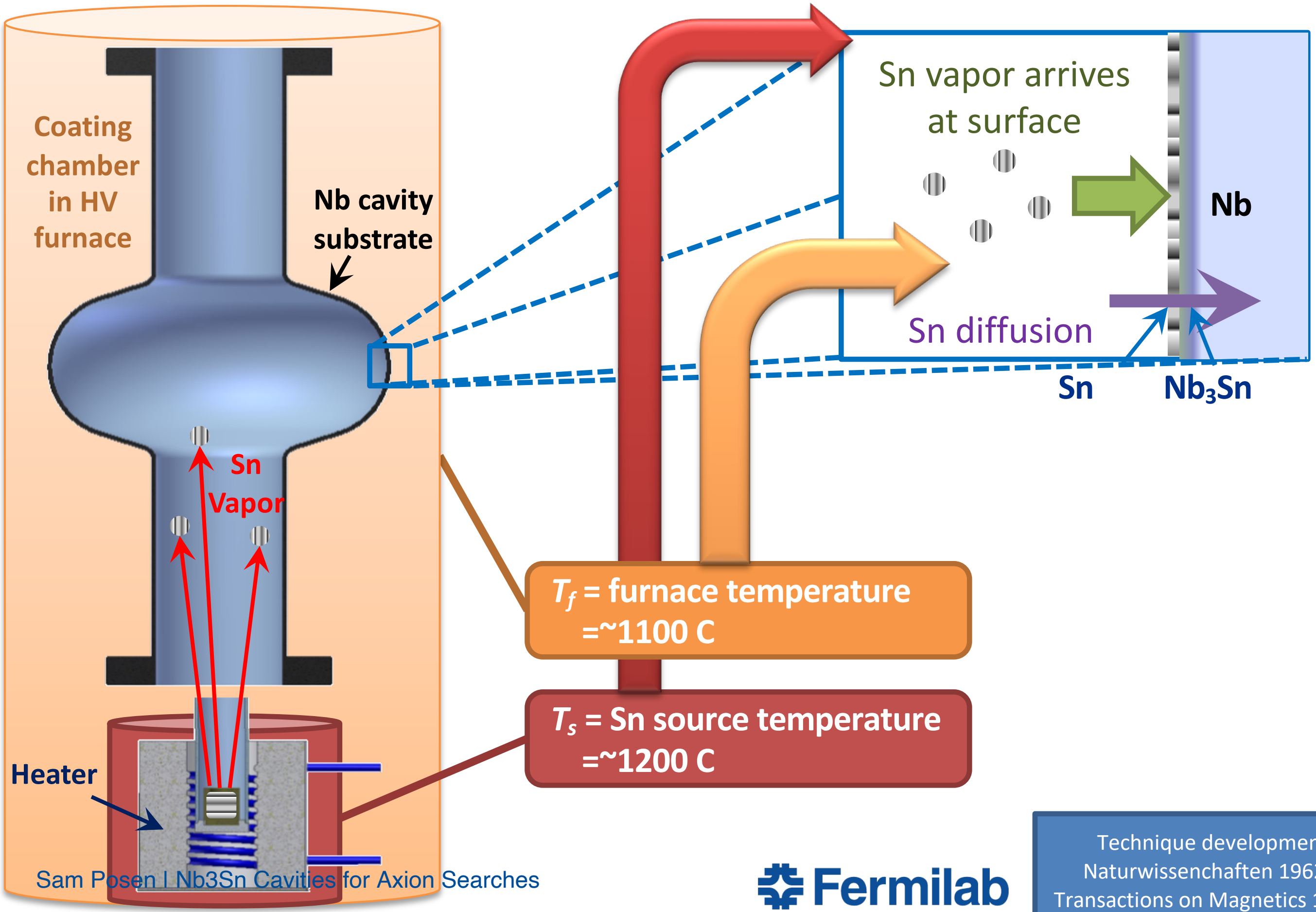






- Work continues on these, but so far no good RF results
- The **only** method to have produced promising RF results so far is Vapor Diffusion

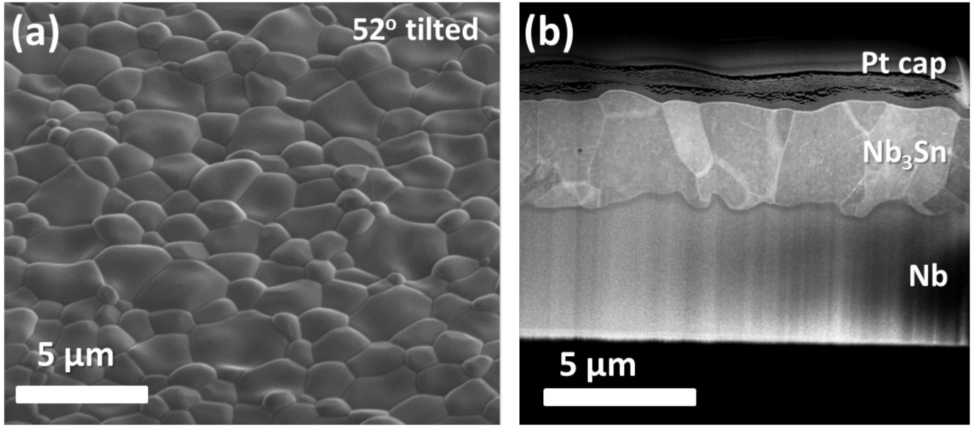
Coating Mechanism: Vapor Diffusion



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

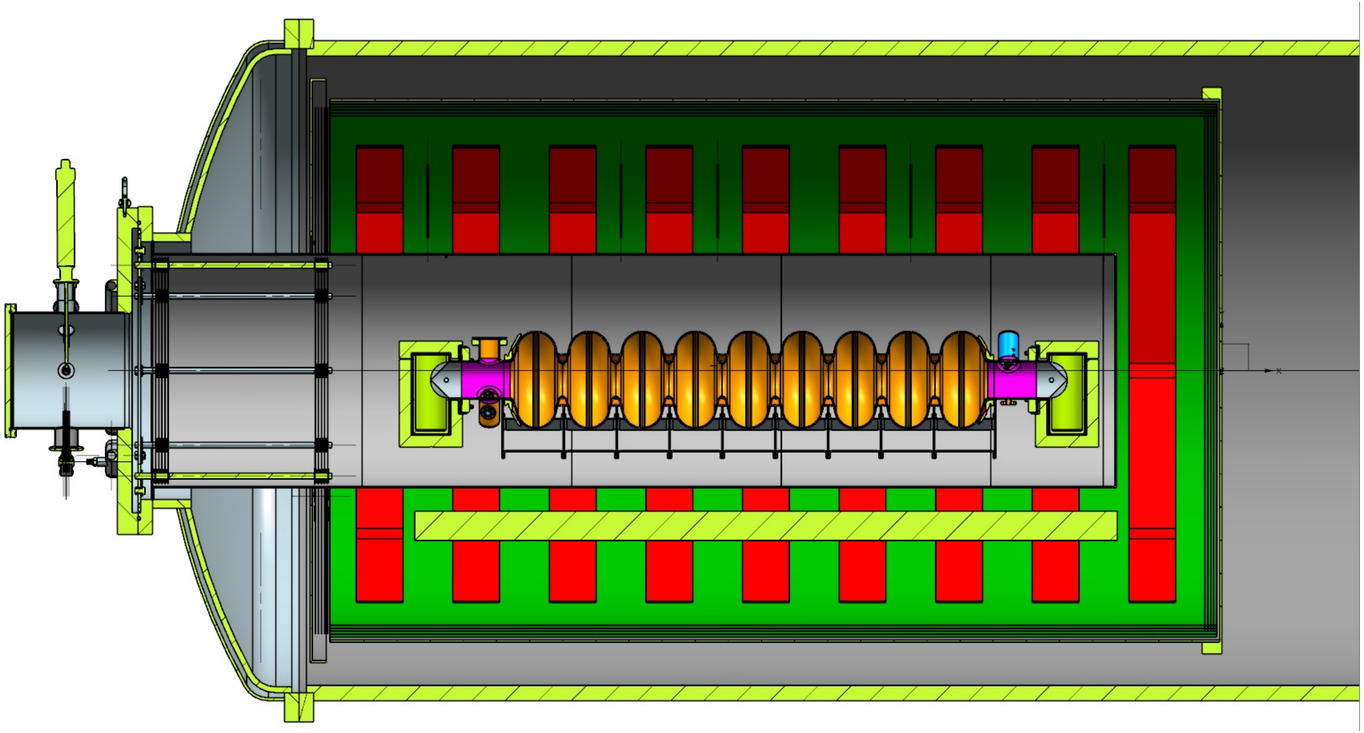
Vapor Diffusion Nb_3Sn Microstructure

- Some similarities to Nb_3Sn in magnet wires, but different fabrication process has some key features for SRF:
  - Strict control of impurities – **no copper** (NC: small levels can degrade $Q\sim10^{10}$)
  - Can achieve very clean grain boundaries
  - Relatively smooth surface to avoid field enhancement
- Requires high temperatures – uses niobium substrate, but niobium material cost typically is relatively small fraction overall

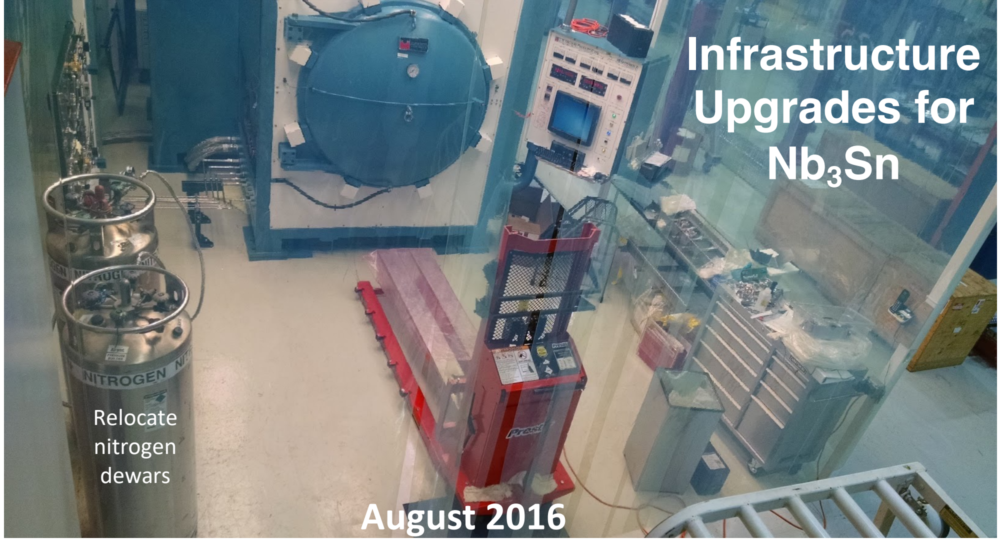


SEM images of Nb_3Sn film coated on Nb: a) surface, b) cross section

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

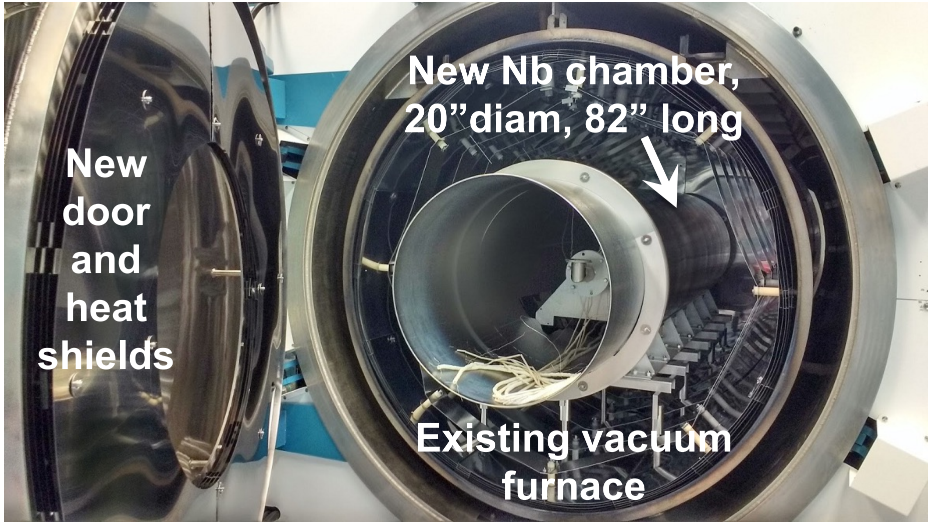


SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Nb Coating Chamber (protects furnace from Sn)

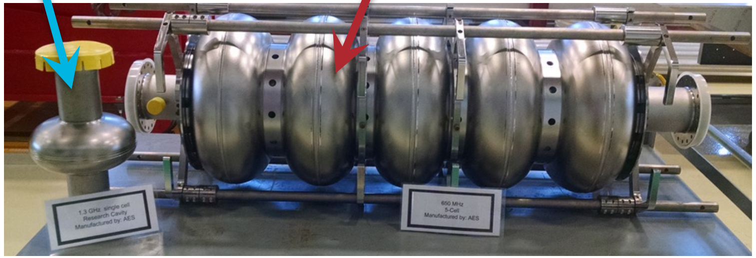
Installation of New Door

Fermilab Nb_3Sn Coating Furnace

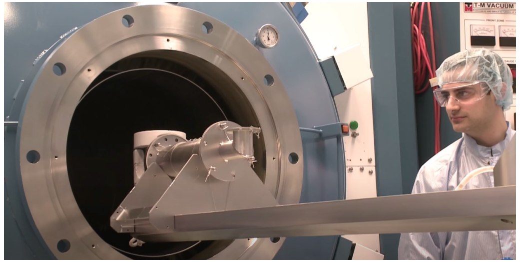


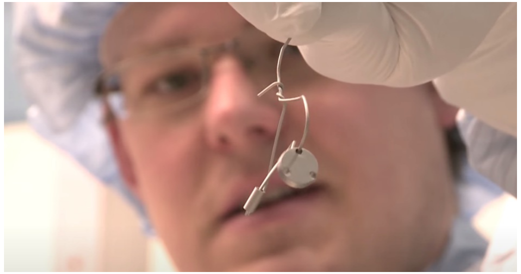
1.3 GHz 1-cell (previous state of Nb_3Sn R&D)

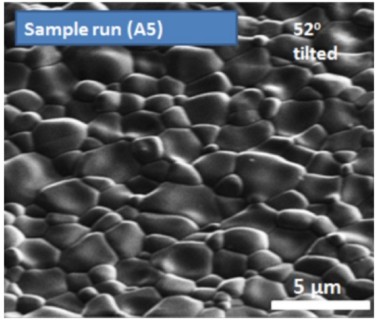
650 MHz 5-cell (new furnace size)

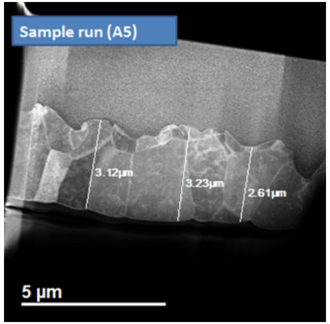


Start with Evaluation of Nb_3Sn in Samples

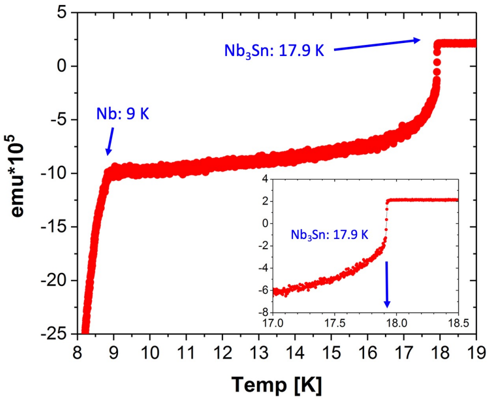




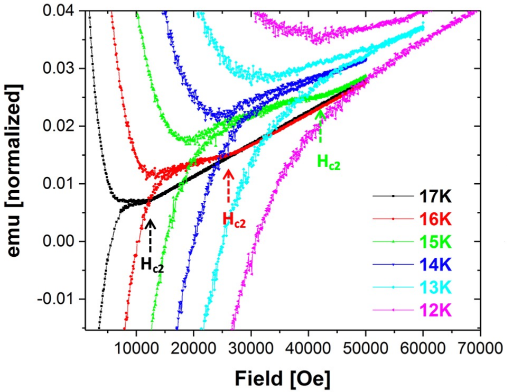


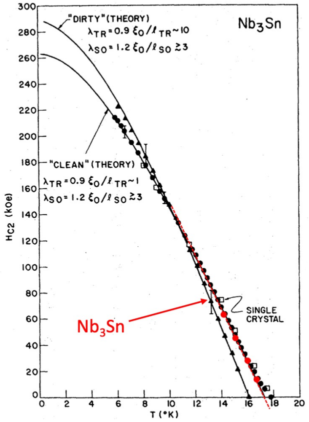


Microstructure Evaluation



Critical Temperature 18 K





Coherence Length via H_{c2} vs T ~3.5 nm (Performed at NHMFL)

Coherence Length

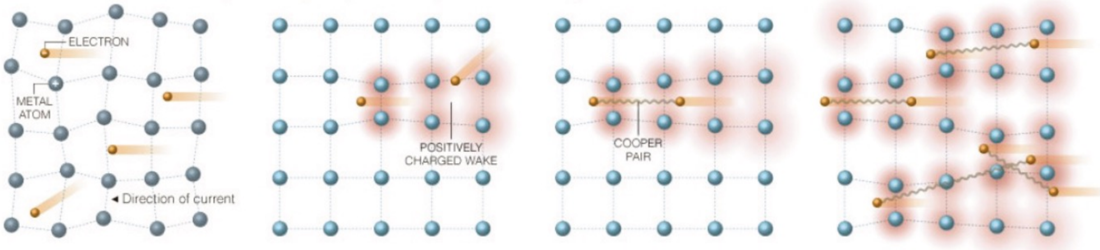
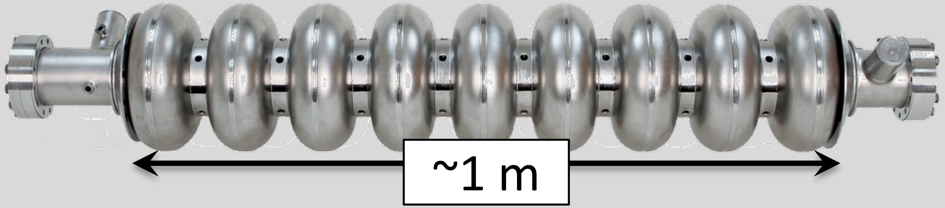


Image from The New York Times

- Superconductor's coherence length ξ: length scale for wavefunction of cooper pairs
- Disorder with size > ξ can cause interruption of superconductivity
  - Nb ξ ~ 30 nm
  - Nb_3Sn ξ ~ 3 nm
  - HTS ξ can be <nm!
- Expect Nb_3Sn is less "forgiving" than Nb for surface defects
- For current state-of-the-art Nb_3Sn, expect this to be gradient limit – working on reducing defects

Especially helpful to have "self-regulating" coating mechanism considering length scales. ξ ~3 nm but cavity size is ~1 m. Self-regulation helps to reduce likelihood of defects that can degrade performance.



References – Nb_3Sn SRF Manufacturing Methods

- **CVD**: V. Cernusko. “Preparation and critical currents of vapour-deposited Nb_3Sn compound,” *Czech J. Phys. B*. Vol. 26, pp. 1156-1160, 1976.
- **CVD**: L. Hand, “CVD superconducting RF cavities: past, present, and future,” Cornell Physics Department, n.d.
- **Review**: R. Sharma. “A Review on A-15 Superconductors for RF Cavity Applications,” *International SRF Thin Films Workshop*, INFN, 2006.
- **Dipping**: S. Deambrosis et al. “A15 superconductors by thermal diffusion in 6 GHz cavities,” *Proc. SRF14*, Berlin, Germany, pp. 155-158, 2009.
- **Sputtering**: A. Rossi, “Nb_3Sn films by multilayer sputtering,” *Proc. SRF14*, Berlin, Germany, pp. 149-154, 2009.
- **Mechanical**: S. Deambrosis et al. “The progress of Nb_3Sn and V_3Si,” *Proc. SRF14*, Berlin, Germany, pp. 392-399, 2009.
- **MOCVD**: G. Carta et al. “Attempts to deposit Nb_3Sn by MOCVD,” *International SRF Thin Films Workshop*, INFN, 2006.
- **E-Beam**: L. Allen et al. “RF surface resistance of high-Tc superconducting A15 thin films.” *IEEEE Transactions on Magnetics*,” vol. MAG19, no. 3, 1983.
- **Bronzing**: M. Hakimi. “Bronze-processed Nb_3Sn for RF applications,” *Journal of Less-Common Metals*, vol. 139, pp. 159-165, 1988.
- **Sn Layers**: J. Hasse et al. “On the microwave absorption of superconducting Nb_3Sn,” *Z. Physik*, vol. 271, pp. 265-268, 1974.
- **Molten Salts**: V.N. Kolosov. “Evaluation of high-frequency superconductivity of Nb_3Sn coatings obtained by joint electrochemical deposition,” *Refractory Metals in Molten Salts*, pp. 239-244, 1998.