Superconducting RF for the Future: Is Nb$_3$Sn ready for next-generation accelerators?

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Cornell University
I. Promise: Why Nb$_3$Sn for SRF?
II. Early Years and Disappointments
III. Rebirth: Let’s try again…
IV. Growing Up: The quest for higher performance
V. Maturity: Nb$_3$Sn SRF accelerator applications
The Life Story of Nb$_3$Sn SRF (as of now)

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Decrease required cooling power: need smaller surface resistance

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

\[ Q_0 \propto \frac{f_{\text{bandwidth}}}{R_s} \]

Cryoplant efficiency vs. operating temperature

Decrease required cooling power: need superconductors with higher critical temperature

\[ P_{\text{AC,cooling}} \propto \frac{\text{COP}^{-1}(T)}{Q_0} \]
Beyond Niobium

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$(nm)</th>
<th>$\xi$(nm)</th>
<th>$\kappa$</th>
<th>$T_c$(K)</th>
<th>$H_{c1}$(T)</th>
<th>$H_c$(T)</th>
<th>$H_{sh}$(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>40</td>
<td>27</td>
<td>1.5</td>
<td>9</td>
<td>0.13</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>111</td>
<td>4.2</td>
<td>26.4</td>
<td>18</td>
<td>0.042</td>
<td>0.5</td>
<td>0.42</td>
</tr>
<tr>
<td>NbN</td>
<td>375</td>
<td>2.9</td>
<td>129.3</td>
<td>16</td>
<td>0.006</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>40</td>
<td>6.9</td>
<td>5.8</td>
<td>40</td>
<td>0.051</td>
<td>0.34</td>
<td>0.33?</td>
</tr>
</tbody>
</table>

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

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 Nb₃Sn Cavities

### Increased Accelerating Field

<table>
<thead>
<tr>
<th>Niobium</th>
<th>Nb₃Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superheating field</td>
<td>240 mT</td>
</tr>
<tr>
<td>Max. $E_{acc}$ (theoretical limit)</td>
<td>55 MV/m</td>
</tr>
</tbody>
</table>

⇒ **Shorter accelerators**  
⇒ **Higher energy gain**

### Lower Cooling Cost and Complexity

<table>
<thead>
<tr>
<th>Niobium</th>
<th>Nb₃Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Temperature $T_c$</td>
<td>9 K</td>
</tr>
<tr>
<td>$Q_0$ at <strong>4.2 K</strong></td>
<td>$6 \times 10^8$</td>
</tr>
<tr>
<td>$Q_0$ at 2.0 K</td>
<td>$3 \times 10^{10}$</td>
</tr>
</tbody>
</table>

*Q₀ given for 1.3 GHz ILC-shape cavities*

- Lower Cooling Cost and Complexity
- **Turn Key** Cooling

Map shown for scale only.
Nb$_3$Sn: High Temperature (4.2K) Operation

- 4.2K operation with high cryo-efficiency (game changer!)
- 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)

\[ Q_0 \text{ given for 1.3 GHz ILC-shape cavities} \]

\[ Q_0 \begin{cases} \approx 10^{12} & \text{at } T = 0 \text{ K} \\ \approx 10^{10} & \text{at } T = 5 \text{ K} \\ \approx 10^{8} & \text{at } T = 10 \text{ K} \\ \approx 10^{6} & \text{at } T = 15 \text{ K} \\ \approx 10^{4} & \text{at } T = 20 \text{ K} \end{cases} \]
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 medical applications
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And so Nb\textsubscript{3}Sn SRF R&D began 40 Years ago…

**Nb\textsubscript{3}Sn Papers at SRF Conference**

<table>
<thead>
<tr>
<th>Year</th>
<th>Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>3</td>
</tr>
<tr>
<td>1984</td>
<td>7</td>
</tr>
<tr>
<td>1987</td>
<td>4</td>
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<tr>
<td>1989</td>
<td>5</td>
</tr>
<tr>
<td>1991</td>
<td>2</td>
</tr>
<tr>
<td>1993</td>
<td>3</td>
</tr>
<tr>
<td>1995</td>
<td>7</td>
</tr>
<tr>
<td>1997</td>
<td>4</td>
</tr>
</tbody>
</table>

Siemens AG, K.F Karlsruhe (Cornell)  
U. of Wuppertal  
RF testing at JLAB, Cornell, SLAC, CERN…
Tin Vapor Diffusion Process (Simplified)

Siemens

Wuppertal

Sn vapor arrives at surface

Nb

Nb$_3$Sn film

Wuppertal Nb$_3$Sn coating profile

A  Tin source  B  Heating element

Area exposed to tin gas

Nb$_3$Sn Challenge: Stoichiometry and $T_c$

**Nb$_3$Sn Phase Diagram**

- Temperature vs. Atomic Sn content
- Diagram showing phases: α-Nb, Nb$_3$Sn, Nb$_5$Sn$_3$, NbSn, Liquid
- Target stoichiometry: 24 to 25%

**T$_c$ vs. Tin Content**

- Critical temperature vs. Atomic Sn content
- Blue: tin
- Red: niobium
- Target: 24 to 25%

More Nb$_3$Sn Challenges

- Material is brittle
- Low thermal conductivity

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

$\Rightarrow$ Need high quality Nb$_3$Sn films!
First Nb$_3$Sn Cavities: Reality around 2000

10 GHz Nb$_3$Sn TM and TE cavities
Siemens

1.5 GHz elliptical Nb$_3$Sn 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$_3$Sn faded away….

Nb$_3$Sn Papers at SRF Conference

RIP
Nb$_3$Sn SRF
1979 – 2001?
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The Rebirth of the Phoenix: Nb$_3$Sn SRF Mark II

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

Rebirth of Nb$_3$Sn SRF
Cornell Nb$_3$Sn Vapor Diffusion Furnace

"Wuppertal" configuration, i.e., with secondary heater for the tin source
Optimized nucleation and temperature profile


U.S. DOE award DE-SC0008431
Nb$_3$Sn forms a polycrystalline layer on the surface of the niobium.

Before Coating

After Coating
Cornell 1.3 GHz $\text{Nb}_3\text{Sn}$ Cavity Breakthrough 4.2K Performance

$20 \times$ more efficient than $\text{Nb}$ at 4.2 K!

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


U.S. DOE award DE-SC0008431
JLAB and Fermilab Nb$_3$Sn Vapor Diffusion Furnaces

**JLAB Nb$_3$Sn Coating System**

- “Siemens” configuration, i.e., no secondary heater for the tin source

**Fermilab Nb$_3$Sn Coating System**

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

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Previously existing SRF vacuum furnace

- Nb Coating Chamber – contains Sn vapor
- Sn source 1
- Sn source 2
1.3 GHz Nb$_3$Sn Cavity Performance: State-of the Art

- 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)

World record CW gradient for Nb$_3$Sn accelerator cavities!
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$_3$Sn 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
• Frequency dependence of $R_{\text{BCS}}$, $R_{\text{res}}$, 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$_3$Sn SRF program: a number of 1.3 GHz cavities already coated and tested; these are the first 650 MHz and 3.9 GHz cavities
Initial results show unexpected, slow scaling with frequency above ~1 GHz:

- $\sqrt{f}$ dependence
- Good news for high frequency Nb$_3$Sn
- Non monotonic frequency dependence <1 GHz?
Two important contributions to surface resistance at 4.2K:

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

At higher temperatures ($\gtrsim 4K$): "normal" Nb$_3$Sn gap dominates losses

At lower temperatures ($\lesssim 3K$): second, small gap dominates losses

Ratio $p \sim 10^{-5}$
Nb₃Sn Vapor Diffusion Growth

TEM/EDX of Nb₃Sn Throughout Growth

- Nucleation
- 800°C
- 875°C

Simulation of Diffusion and Growth

Initial growth:
- Nb diffusion

Grain-bound. assist. growth:
- Fast downward Sn transport

 Nb₃Sn Growth on Niobium Oxide

New insights => Higher-performing Nb₃Sn cavities
Signature of Quench in Nb₃Sn

- Weak dependence on RF frequency
- So significant change vs T (1.7K to 4.2K)
- Nb₃Sn 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 $\xi << \lambda_{\text{Nb3Sn}}$)

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

Before EP

After EP

M. Liepe, Cornell University
IPAC 2019
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.

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• **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
(Potential) $\text{Nb}_3\text{Sn}$ Accelerator Applications

$\text{Nb}_3\text{Sn}$ cavities for Upgraded Injector Test Facility (UITF) @ Jlab

$\text{Nb}_3\text{Sn}$ on Copper Studies at CERN for FCC

2020
- Evaluation of A15 on-Cu samples

2021
- RF tests of A15 on-Cu cavities performed

“The A15 compounds have the potential to outperform niobium…”

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

http://wiki.jlab.org/ciswiki/index.php/Main_Page
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

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• 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

$\text{Nb}_3\text{Sn/Nb/Cu } \beta = 0.5$ single-cell cavity, conduction cooled with four 1.5 W cryocoolers

Patent on Cryomodule design filed on 01/29/18
Design study of conduction cooling of Nb$_3$Sn cavity from cryocooler indicates feasibility
Is Nb$_3$Sn ready for next-generation accelerators?

✓ Nb$_3$Sn coating facilities established (650 MHz – multi-GHz)
  • Cornell, JLAB, FNAL … more coming

✓ Nb$_3$Sn 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$_3$Sn cavities opens path to compact SRF
Is Nb$_3$Sn ready for next-generation accelerators?

- First multicell Nb$_3$Sn 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$_3$Sn cavity frequency tuning (Nb$_3$Sn 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$_3$Sn on copper)…stay tuned
Special thanks to

**Sam Posen**, FNAL
**Grigory Eremeev**, TJNAF
**Marco Arzeo**, CERN

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