Nb$_3$Sn – Present Status and Potential as an Alternative SRF Material

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**Limits of Modern SRF Technology**

### Low DF, high energy
- Energy gradient in state of the art Nb cavities limited by $B_{sh}$ (ultimate limit)
- **Limit: $B_{sh}$**

### High DF / CW
- Large dynamic load
- Cost optimum gradient relatively low: $P_{diss} \sim E_{acc}^2/Q_0$
- **Limit: $Q_0$**

- **ILC:** 16,000 cavities in 31 km linac
- Cryoplants for large linacs cost \$100 million and require MW of power

*Image from Rei Hori, linearcollider.org
Image from D. Delikaris, Cryogenics at CERN, 2010*
## Potential of Nb$_3$Sn

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Potential of Nb₃Sn

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$\eta_{4.2\,K} / \eta_{2.0\,K} \approx 3.6$, simpler cryoplant

Increase in $Q_0$ via N-doping

Approximate $E_{acc}$ and $Q_0$ given for 1.3 GHz TeSLA or 1.5 GHz CEBAF cavities with $R_{res}$ small

Halve # of cavities to reach energy?
• For lower-energy **industrial applications**, it may not be cost-effective to have a supply of 2 K LHe

• Higher $T_c$ of Nb$_3$Sn allows low-loss operation with atmospheric 4.2 K LHe, or even gas/supercritical He

• Flue gas, waste water treatment, isotope production, security
**Nb$_3$Sn Challenges**

Flux lattice in a Type II Superconductor


**Nb$_3$Sn Phase Diagram**

*A. Godeke, Supercond. Sci. Tech, 2006*
Cornell Coating Chamber

- Cavity at 1100 C
- Tin Container at 1200 C
- Flange to UHV furnace
- Copper transition weld from stainless to Nb
- Heat Shields
- Nb Witness Samples
- Nucleation Agent: SnCl$_2$
- Sn, High Purity
Coating Procedure

- Degas: ~1 day
- Nucleation: 5 hours
- Coating: 3 hours
- Surface diffusion: 0.5 hours

4 C-type thermocouples: 2 for cavity temperature, 2 for tin source temperature
Coated Cavity

Before Coating

After Coating

Standard Nb cavity

Nb$_3$Sn-Coated

Nb$_3$Sn layer $\sim$2-3 $\mu$m
• Pioneering work at Siemens AG, U. Wuppertal, K.F. Karlsruhe, SLAC, Cornell U., Jefferson Lab, and CERN

• U. Wuppertal:
  – Very small $R_s$ values in Nb$_3$Sn cavities
  – Strong Q-slope, cause uncertain

• Losses in material between crystal grains
• Performance similar in appearance to Nb/Cu
• Systematic study on small samples: strong effect from grain size
• Preliminary annealing attempts on cavities gave poor results

Images adapted from T. Proslier et al., NuFact09 and M. Hein et al., IEEE Trans. Supercond., 2001
• First cavity: Wuppertal recipe
• Strong Q-slope observed similar to Wuppertal

1.3 GHz single cell Cornell ERL shape
• Found could grow grains by factor of ~2 while maintaining desired stoichiometry by modifying Wupperatal recipe
  
  — Extra annealing step: Furnace at 1100 C, but tin heater off

No annealing step, average grain size ~1 µm
Anneal 6 hours, average grain size ~2 µm
• 6 hour annealing during coating process
• No strong Q-slope observed
4.2 K Comparison Curves

1.3-1.5 GHz single cell elliptical cavities

- **Q₀** vs. **E_{acc} [MV/m]**
- **Nb₃Sn, Cornell, 6 h anneal, 4.2 K**
- **Nb₃Sn, U. Wuppertal, 4.2 K**
- **Nb, 4.2 K**
2.0 K Comparison Curves

Cornell Nb$_3$Sn data multiplied by cryoplant efficiency at 4.2 K vs 2 K (ratio ~ 3.6)

$Q_0$, Adjusted for Cryoplant Efficiency Relative to 2.0 K

$E_{acc}$ [MV/m] 1.3-1.5 GHz single cell elliptical cavities
Resetting the Surface

• BCP 10 minutes inside and outside to clean entire surface before putting cavity into clean room furnace
• 10 micron BCP inside to reset RF surface
1.3 GHz single cell Cornell ERL shape

Repeatability

- Coat+HPR, 2.0 K
- Coat+HPR, 4.2 K
- +Etch+Coat+HPR, 2.0 K
- +Etch+Coat+HPR, 4.2 K

$Q_0$, $10^9$, $10^10$, $E_{acc}$ [MV/m]
Temperature maps show excess heating in small area in high magnetic field region – possible defect?

After quench, $T = 2 \text{ K}$, $E_{\text{acc}} = 13 \text{ MV/m}$, $Q_0 = 2 \times 10^9$
• Try to prevent/remove defects via:
  – HF rinse (layer is thin, so need very light removal)
  – Centrifugal barrel polishing (first use on Nb₃Sn)
  – EP substrates (first use on Nb₃Sn)
Material Removal

$1.3 \, \text{GHz single cell Cornell ERL shape}$

- Coat+6h Anneal, 2.0 K
- Coat+6h Anneal, 4.2 K
- +HF Rinse, 2.0 K
- +HF Rinse, 4.2 K
- +Etch+Coat+6h Anneal, 2.0 K
- +Etch+Coat+6h Anneal, 4.2 K
- +Barrel Polish, 2.0 K
- +Barrel Polish, 4.2 K
- +8 h at 120 K, 4.2 K
- +Etch+Coat+15h Anneal, 2.0 K
- +Etch+Coat+15h Anneal, 4.2 K
Material Removal

1.3 GHz single cell Cornell ERL shape

- BCP+Coat+HPR, 2.0 K
- BCP+Coat+HPR, 4.2 K
- EP+Coat+HPR, 2.0 K
- EP+Coat+HPR, 4.2 K

Graph showing the relationship between $Q_0$ and $E_{acc}$ [MV/m] for different materials and temperatures.
Developing New Understanding

Just After Coating

After HF Rinse
Pulsed Quench Field

Forward Power from Klystron [MW]

- $P_f$
- $B_{pk}$

Time to Quench $[\mu s]$

- $B_{quench}$

$T_c = 18.0 \pm 0.1 \text{ K}, B_{sh}(0) = 0.39 \pm 0.05 \text{ T}, B_{c1}(0) = 27 \pm 5 \text{ mT}$

Data

$B_{sh}(0)[1-(T/T_c)^2]$  
$B_{c1}(0)[1-(T/T_c)^2]$
• The R&D furnace for Nb₃Sn development has been delivered and commissioned empty in November 2013.

• The Nb₃Sn insert has been converted from horizontal to vertical orientation, loaded with a CEBAF-shape 1-cell cavity (C3C4), Sn, and SnCl₂, and installed into the new furnace. The commissioning run was done in “Siemens” configuration at temperatures of interest in March 2013.

• The coating system is planned to be commissioned with separate heating and cooling of Tin crucible, “Wuppertal” configuration.
The single cell (C3C4) was found to have complete coating without any droplets on the RF surface.

The cavity went through the standard preparation procedure for RF testing, i.e., degreasing, HPR, etc., evacuated, and tested at 4 and 2 K.

The cavity had the transition temperature of about 18 K. The low field $Q_0$ was $7 \times 10^9$ at 4 K and $9 \times 10^9$ at 2 K. The cavity exhibited strong Q-slope dropping to about $1 \times 10^9$ at 8 MV/m at both temperatures.
• Alternative materials can benefit future SRF linacs
  – Nb easy to work with, but reaching fundamental limits
  – Nb$_3$Sn very promising – order of magnitude more efficient, twice energy gain per length

• New research: significant Nb$_3$Sn performance improvement
  – Strong Q-slope suppressed after extra annealing step
  – High Q$_0$ at useful fields, T = 4.2 K
  – First cavity to outperform niobium

• With continued R&D can surpass limitations
  – Fundamental studies for better understanding
  – Modern cavity treatments never used on Nb$_3$Sn
Acknowledgements

• My advisor Matthias Liepe
• Fellow Cornell graduate students
• Collaborators