Developing the Next Generation of SRF Cavities with Nb$_3$Sn

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Superconducting RF Cavities

Input RF power at 1.3 GHz

(RSlowed down by factor of approximately 4x10^9)

RF fields

Helium cooling

Niobium ~3 mm

RF currents ~1 μm

(RStandard SRF material)
Nb$_3$Sn Coating on Niobium Cavity


RF currents $\sim 1 \mu$m

RF fields

0.5 $\mu$m
**Nb$_3$Sn $Q_0(T)$**

- Large $T_c \sim 18$ K
- Very small $R_{BCS}(T) - R_{BCS}(T) \sim e^{-1.76T_c/T}$
- High $Q_0$ even at relatively high $T$
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

Big effect! Cryoplants for large installations cost $\sim$100 million and require MW of power.
Higher $Q_0(T)$ with Nb$_3$Sn

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- Very small $R_{BCS}(T) \sim R_{BCS}(T) \sim e^{-1.76T_c/T}$
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Possibility of cryocooler operation!

Industrial accelerators for treatment of wastewater & flue gas, border security...
Increased Metastable Limit in Nb$_3$Sn

- Superconductors can remain flux-free even above $H_{c1}$
- Ultimate metastable limit is “superheating field” $H_{sh}$
- $H_{sh}$ of Nb: ~200 mT (~50 MV/m)
- Predicted $H_{sh}$ of Nb$_3$Sn: ~400 mT
- Achieving $H_{sh}$ would have huge impact on high energy colliders

ILC: 16,000 cavities in 31 km linac

Energy cost from core ($\xi$) first; Energy gain from field ($\lambda$) later

Slide adapted from J. P. Sethna
Pioneering Nb$_3$Sn Cavity Research

a lower $\Delta / 1/$. These potential advantages are

1. a higher working temperature (for $R_{\text{res}}(\text{Nb}) \approx R_{\text{res}}(\text{Nb}_3\text{Sn})$
2. a better thermal stability
3. a higher superconducting limit ($B_c \sim T_c$)
4. a lower surface resistance $R_S$ (if $R_{\text{res}}(\text{Nb}_3\text{Sn})$ can be reduced)

At the moment niobium – the element with the highest $T_c$ (9.2 K) – is nearly always used in superconducting HF-applications. Any

Because of its high critical temperature ($T_c = 18.3$ K) Nb$_3$Sn has to be considered as an alternative material. This choice is supported by the high thermodynamic critical field ($B_c = 0.535$ T) of this alloy. It has to be shown, however, that rf structures of complex shape, like disc loaded waveguides for accelerator application can be coated with a Nb$_3$Sn layer of good quality and that high accelerating fields can be reached. It also must be shown, that the reduced energy gap $\Delta / kT_c$ is comparable to the one measured for niobium. $A$ has to be determined and it

G. Arnolds and D. Proch, Wuppertal, 1977

B. Hillenbrand, Siemens (1980)

G. Müller et al., U. Wuppertal (2000)
Superconductor Coherence Length

- Coherence length $\xi \sim$ Cooper pair interaction distance
- Gives size of disorder that superconductor is sensitive to
- Nb: $\xi \sim 20$ nm – Nb$_3$Sn: $\xi \sim 3$-4 nm
- Can small-$\xi$ superconductors remain in a metastable flux-free state in RF magnetic fields?

G. Müller et al., U. Wuppertal (2000)

Flux-free state (metastable)  Flux penetration

Fundamental?  Q-slope

Approximate $H_{c1}$ (onset of metastability)  4.2 K
Superconductor Coherence Length

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- Gives size of disorder that superconductor is sensitive to

Critical question:
Is $\xi$ of Nb$_3$Sn so small that $H_{c1}$ is the limit?

G. Müller et al., U. Wuppertal (2000)
Cornell R&D
Coating Mechanism: Vapor Diffusion

By independently controlling Sn vapor abundance, it can be balanced with Sn diffusion rate to achieve desired stoichiometry.

- $T_f = \text{furnace temperature} = \sim 1100 \text{ C}$
- $T_s = \text{Sn source temperature} = \sim 1200 \text{ C}$
Cornell Nb$_3$Sn Coating Chamber

- Water Cooling
- Flange for Connection to UHV Furnace
- Mo Rods for Heater Power
- Outer Heat Shields
- Thermocouple Holder
- Tin Source Heater
- Feedthroughs
- Stainless-Cu-Nb Transition
- Coating Chamber
- UHV Furnace
- Hot Zone
Cornell Nb$_3$Sn Coating Chamber

Water Cooling

Flange for Connection to UHV Furnace

Mo Rods for Heater Power

Tungsten feet

Tin Source Heater

Thermocouple Holder

Inner heat shields

Tin crucible

Witness samples

Inn heater heater

Hot Zone

Stainless-Cu-Nb Transition

Feedthroughs

Coating Chamber

UHV Furnace
Sample Studies

- Composition 25% tin as desired
- Near ideal $T_c$ 18 K, sharp transition
- 2-3 $\mu$m thickness to screen RF

![Graph showing composition depth profile and FIB images of Nb$_3$Sn sample with 20 $\mu$m thickness.](image)
Cavity Coating

Before Coating

After Coating
Early Coatings

- There were some difficulties early on.
Lesson learned: temperature gradient between tin source and substrate strongly affects grain size.
Later Coatings

Very high $Q_0$ at low fields, similar to Wuppertal cavities

Factor of 10 improvement in $Q_0$ at medium fields compared to Wuppertal

$Q_0$

$E_{\text{acc}}$ [MV/m]

Wuppertal
Cornell Coating 'A'
Cornell Coating 'B'

4.2 K
Later Coatings

Very high $Q_0$ at low fields, similar to Wuppertal cavities

First accelerator cavity made with an alternative superconductor that outperforms Nb at usable gradients!

- Wuppertal
- Cornell Coating 'A'
- Cornell Coating 'B'

$Q_0$ vs. $E_{acc}$ [MV/m]

4.2 K
Later Coatings

Very high $Q_0$ at low fields, similar to Wuppertal cavities

Factor of 10 improvement in $Q_0$ at medium fields compared to Wuppertal

Accelerating gradient reaches 17 MV/m

$Q_0$ vs. $E_{\text{acc}}$ [MV/m]

- Wuppertal
- Cornell Coating 'A'
- Cornell Coating 'B'
- Cornell Coating 'C'

4.2 K
Improved Cooldown

- Same cavity, but with improved cooldown procedure by Daniel Hall, Cornell (slide courtesy Daniel)

![Graph showing quality factor $Q_0$ vs. accelerating gradient (MV/m)]

- Small thermal gradients give better performance
- This cavity exceeds LCLS-II spec by a factor of 2
Cryogenic Power Requirements, 1 cell at 1.3 GHz

Required Wall Power for Cooling [W] vs. Temperature [K]

- **Red line**: Nb, N-doped
- **Blue line**: Nb₃Sn, 2015
- **Dashed blue line**: Nb₃Sn, Goal
- **Star**: LCLS II Spec

Key Parameters:
- $E_{\text{acc}} = 16 \text{ MV/m}$
- $R_{\text{res}} = 3 \text{ n} \Omega$
- $R_{\text{res}} = 10 \text{ n} \Omega$
- $R_{\text{res}} = 3 \text{ n} \Omega$

Current performance: outperforms Nb!!

With Continued R&D

Fermilab
Can small-\(\xi\) superconductors remain in a metastable flux-free state above \(H_{c1}\)?

- Yes! \(H_{c1}\) is NOT a fundamental limit
Pulsed Quench Field

- Used high power RF (MW) from klystron with short pulses
- Pulse length ~100 μs to try to outpace thermal effects
- Measure quench field as a function of temperature
- Compare to predicted limit of metastable state
High Gradients – Klystron Measurements

![Graph showing data and trend lines](image)

Data
Metastable Limit Prediction

With Continued R&D

Heating at defect/or second phase behavior takes over

E_{acc} at Quench [MV/m]

0 0.2 0.4 0.6 0.8 1

0 10 20 30

(T/T_c)^2

Data
Metastable Limit Prediction

Low Tin Content \( \text{Nb}_3\text{Sn} \)

Transition? 

\[ Q_0 \]

\[ 10^{11} \]
\[ 10^{10} \]
\[ 10^9 \]
\[ 10^8 \]

\[ T \text{ [K]} \]

2 4 6 8 10 12 14 16

\[ \text{Coating 1} \]
\[ \text{Material Removal 1} \]
\[ \text{Coating 2} \]
\[ \text{Material Removal 2} \]

\[ \text{BCS Theory} \]


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Devantay 1981

Devantay 1981 (after Flükiger 1981)

Moore 1979

\[ T_c(\beta) \text{ linear} \]

\[ T_c(\beta) \text{ Boltzmann function} \]

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Fermilab

5/12/2016  Sam Posen  Nb3Sn SRF Cavities
Low Tin Content Nb$_3$Sn

- XRD by Argonne collaborators at Advanced Photon Source
- Reveals 2 strong peaks corresponding to 24-25% tin and 19-20% tin

XRD studies courtesy T. Proslier, Argonne National Lab

Low Tin Content Nb$_3$Sn?

Outlook
**Nb$_3$Sn Outlook**

- Proof-of-principle established on small cavities at Cornell
  - Outperforms Nb at useful temperatures and gradients
- R&D initiatives at Fermilab, Cornell, JLab, and CERN for continued progress
- Significant interest:
Exciting topic: 2 DOE Early Career research grants this year on Nb$_3$Sn SRF cavities!

Posen, Sam, Fermi National Accelerator Laboratory, Batavia, IL, "Developing the Next Generation of Superconducting RF Cavities with Nb$_3$Sn," selected by the Office of High Energy Physics.

Nb$_3$Sn SRF R&D at Fermilab

- Increase accelerating gradients $E_{\text{acc}}$
  - Eliminate low tin content regions, study fundamental field limits with high power RF, study influence of disorder

- Increase quality factors $Q_0$
  - Study origins of residual surface resistance, reduce influence of thermocurrents, retain high $Q_0$ to high fields

- Scale process up to production-style cavities
  - 9-cell 1.3 GHz, 5-cell 650 MHz: show ready for applications

Parameters for new recipe → Coat samples then measure SEM/EDX, PPMS → Coat 1-cell cavities, RF test w/ T-map → Coat multi-cell cavities, RF test

Feedback for coating parameters: $T_c$, microstructure, composition, uniformity, $R_s$, quench field...
Fermilab Furnace
1.3 GHz 9-cell

- Inner heat shields
- Coating chamber (Nb)
- Modified door
- Chamber support
- Cavity support (Nb)
- Tin Source
650 MHz 5-cell
Fermilab Outlook

• Activities towards Nb$_3$Sn coating capability:
  – Upgrade of Fermilab large UHV furnace and chilled water system for high temperature operation (1300 C)
  – Design and production of niobium coating chamber for furnace to contain tin vapor
  – Modifications of UHV furnace to accommodate chamber
  – New lifting capabilities in UHV furnace area
  – …

• First coatings on samples anticipated in fall 2016

• Single cell cavities to be coated after satisfactory samples are obtained
Final Thought

e-beam accelerator

Future Nb₃Sn coating chamber

e-beam welding
Special Thanks

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