Nb$_3$Sn Cavities: Material Characterisation and Coating Process Optimisation

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The promise of Nb$_3$Sn

- An intermetallic alloy of niobium and tin with a $T_c$ of 18 K
- BCS resistance at 4.2 K is low enough to operate at cavity without pumping on the cryostat
- Superheating field of 400 mT corresponds to a peak theoretical field of 90 MV/m in ILC cavities
This time two years ago

Data from “Understanding and Overcoming Limitation Mechanisms in Nb3Sn superconducting Cavities”, Sam Posen, Cornell University, 2015
Talk outline

• Altering the coating procedure
  – What happens to the RF performance?

• Characterising Cornell’s Nb$_3$Sn
  – What kind of properties does it have?

• Practical use of Nb$_3$Sn
  – What performance can be expected for state-of-the-art Nb$_3$Sn cavities in a cryomodule?
Altering the coating process

What changes?
Cornell’s Nb$_3$Sn vapour diffusion

Coating chamber in UHV furnace at 1100 C

Nb cavity substrate

Sn Vapor

Auxilliary Heater for Sn container at 1200 C
The coating process

1. Nucleation
2. Ramp with $\Delta T$
3. Coating stage
4. Annealing stage

Source thermocouple reading
Chamber thermocouple reading

Thermocouple reading (°C)

Time

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Simulating tin usage

Time elapsed since coating began (hours)

Tin remaining in crucible (grams)

- Standard coating
- Extended coating time
- Extended annealing time
- Short annealing time
- Elevated coating temperature
- Elevated annealing temperature
- Measured tin post-coating
What was changed?

1. No change
2. Longer coating
3. Hotter coating
4. Hotter anneal
Changes in residual resistance

Initial results:
- Get tin to the surface faster
- Tin gas must have a short mean free path
- You can overdo the amount of tin you put on the surface
Changes in BCS performance

Initial results:

- An annealing period is necessary to produce a good BCS superconductor
Spectral gap dependence on field

Initial results:

• No closing of the energy gap – yet?

Where to next with the coating?

- We have begun exploring the coating parameter space

- The goal is to now lower the total surface resistance as much as possible
Material characterisation

What have we made?
Material characterisation

• What material characteristics are responsible for the RF performance – both $Q_0$ and quench field?

• Surface analysis: TEM/EDX, SEM, AFM, XRD
Presence of tin depleted phases

\[
\text{Nb}_3\text{Sn layer}
\]

\[
\text{Nb substrate}
\]

Image courtesy of Thomas Proslier, ANL
Presence of tin depleted phases

Niobium

Image courtesy of Thomas Proslier, ANL
Presence of tin depleted phases

Image courtesy of Thomas Proslier, ANL
Presence of tin depleted phases

Image courtesy of Thomas Proslier, ANL
Surface uniformity

- Stoichiometric defects are on the order of 1 µm or less

- Have we seen any that are bigger than that?
Regions of poor tin coverage

- Yes!
- But it’s rare – only one example
Regions of poor tin coverage

Green – good coverage

Red – poor coverage

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Regions of poor tin coverage
Regions of poor tin coverage

See poster this afternoon – TUPB049
Why is tin-depletion bad?

Image courtesy of Thomas Proslier, ANL

Measuring the flux-entry field

Pulsed test data shows evidence of two or more phases in play

Ultimate flux entry field is only 150 mT?
Surface roughness

Surface is rough – it will cause field enhancement

Image courtesy of James Maniscalco, Cornell University

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How do we avoid bad phases?

![Graph showing the ratio of stoichiometric Nb₃Sn to all phases for different conditions.](image)

- No nucl. agent or ∆T
- No ∆T
- Standard recipe
- Extended coating
- Extended anneal
Nb₃Sn as a practical application

- Would cryomodule designs have to be modified to accommodate Nb₃Sn cavities?

- Is Nb₃Sn approaching a state where we would consider using it in an accelerator?
Sensitivity to trapped flux

\[ \text{Nb}_3\text{Sn} : 0.68 \pm 0.15 \text{ n\Omega/mG} \]

120°C baked Nb : 0.82 \pm 0.068 n\Omega/mG

N-doped Nb : 3.4 \pm 0.57 n\Omega/mG

\text{Nb}_3\text{Sn} \text{ cavities have to be cooled slowly}

No more sensitive to trapped flux than 120 °C baked niobium
Trapped flux and Q-slope

![Graph showing trapped flux and Q-slope](image-url)
Impact of the cooldown procedure

Small thermal gradients give better performance

This cavity exceeds LCLS-II spec by a factor of 2

LCLS-II spec adjusted for operation at 4.2 K

Quality factor $Q_0$

Accelerating gradient (MV/m)

ERL1-4, 4.2 K, test February 2015
ERL1-4, 4.2 K, test September 2014

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Summary and conclusions

• The current limitations of Nb₃Sn are due to its fabrication and are not fundamental to the material itself
  – Current limitation: stoichiometry, tin-depletion

• We are optimising the coating process
  – Looks promising!

• Nb₃Sn cavities are not sensitive to losses from trapped flux

• The state of the art has exceeded the LCLS-II specifications by a factor of 2
The world’s first Nb$_3$Sn accelerator?

Stay tuned
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Nb₃Sn is growing!
Fermilab Nb$_3$Sn Program

- **Fermilab**: Nb$_3$Sn R&D program funded by LDRD
- Will build a coating chamber large enough for TeSLA 9-cell cavities or 650 MHz 5-cells
- Continue R&D to push performance and begin proof of concept for practical applications
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Thank you for your attention