Nb$_3$Sn for SRF applications

High efficiency cavities for future accelerators

Grigory Eremeev

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Acknowledgements

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- Matthias Liepe, Ryan Porter, Sam Posen, et al.
- JLab technical staff
Outline

- Motivation
- Background
- Current status
- Path forward
Niobium and its limitations

Niobium – best superconducting properties among all pure metals:
- $T_c \sim 9.25 \text{ K}$;
- $H_c \sim 2000 \text{ Oe}$;
- $R_{\text{bcs}} \sim 0.0001 \text{ m}\Omega$ at 2 K

$\text{Nb: } R_s \sim 0.0001 \text{ m}\Omega$
$\text{Cu: } R_s \sim 10 \text{ m}\Omega$

$Q^{\text{nb}} \sim 10^{11}$ up to $E_{\text{acc}} = 50 \cdot 10^6 \text{ Volts per meter}$
Niobium and its limitations

Limitation: High-purity Nb, sheet inspection, CBP, etc
Solution: Improved cavity shape

Limitation: Electron field emission
Solution: High-pressure rinsing, cleanroom procedures

Limitation: Electropolishing, low temperature baking, ...
Solution: Further improved cavity shapes

“Borrowed” from M. Liepe
Core Competencies

- Accelerator Science and Technology
- Large Scale User Facilities/Advanced Instrumentation
- Nuclear Physics

Mission Unique Facilities

- Continuous Electron Beam Accelerator Facility
CEBAF SRF cavities

C20/C50

C100

C75

1.5 GHz @ 2K
JLab SRF is a part of global efforts to improve SRF technology.

\[ R_{BCS} \approx \frac{R_n}{\sqrt{2}} \left( \frac{\hbar \omega}{\pi \Delta} \right)^{\frac{3}{2}} \frac{\sigma_1}{\sigma_n} \approx A \sqrt{\rho_n} e^{-\frac{\Delta}{k_B T}} \]

\[ \Delta = 1.45 \text{ meV} \implies R_s \geq 5 \text{ n}\Omega \text{ @ } 2K \text{ @ } \sim 1 \text{ GHz} \]

H_{c} \sim 200 \text{ mT} \implies H_{sh} \sim 240 \text{ mT} \implies E_{\text{acc}} \sim 50 \text{ MV/m}

Nb\_3Sn
Ideas for the future

I suggest another key mechanism is at play
- In addition to surface barrier (superheating) there is a “time barrier”
  - There should be enough time for vortices to nucleate/dissipate
- Vortex nucleation is governed by the characteristic time scale of order parameter changes, so-called $\tau_\phi$
  - If flux penetration/dissipation is happening or not depends on the relation between $\tau_\phi$ and RF period $T_\text{RF}$
    - $\tau_\phi > T_\text{RF}$ => vortex-induced dissipation is delayed beyond Hsh
    - $\tau_\phi < T_\text{RF}$ => Hc1 and superheating become more relevant – more DC-like
    - $\tau_\phi > T_\text{RF}$ => vortices don’t matter as they never form
- $\tau_\phi \ll 1$ ns is only relevant for gapless superconductors (which Nb is not) was understood by e.g. Tinkham and Bezuglii in late 1980s
- For gapped superconductors at low $T$: $\tau_\phi \ll \tau_\text{RF} \ll 1$ ns for Nb

So, what caused the improvement?

800°C BCP on hot spot cut-out 120°C baked cavity cut-out
What are the better SRF Materials?

<table>
<thead>
<tr>
<th>Material</th>
<th>Nb</th>
<th>Nb&lt;sub&gt;3&lt;/sub&gt;Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_c) [K]</td>
<td>9.25</td>
<td>18.3</td>
</tr>
<tr>
<td>(\rho_n) [(\mu\Omega\text{cm})]</td>
<td>0.1</td>
<td>~ 5</td>
</tr>
<tr>
<td>(H_{\text{sh}}(0)) [T]</td>
<td>0.24</td>
<td>~ 0.45</td>
</tr>
<tr>
<td>(\Delta) [meV]</td>
<td>1.45</td>
<td>~ 3.1</td>
</tr>
<tr>
<td>(Q^{\text{BCS}} \text{ @ 2K})</td>
<td>~ 5 (\cdot) (10^{10})</td>
<td>~ 5 (\cdot) (10^{14})</td>
</tr>
<tr>
<td>(Q^{\text{BCS}} \text{ @ 4K})</td>
<td>~ 5 (\cdot) (10^8)</td>
<td>~ 5 (\cdot) (10^{10})</td>
</tr>
<tr>
<td>(E_{\text{acc}}) [MV/m]</td>
<td>~ 50</td>
<td>~ 100</td>
</tr>
</tbody>
</table>

- s-wave superconductor
- large energy gap
- high \(H_{\text{sh}}\)
- low normal-conducting resistivity
**Nb3Sn properties and perspectives**

\[
R_{BCS} \approx \frac{R_n}{\sqrt{2}} \left( \frac{\hbar \omega}{\pi \Delta} \right)^{3/2} \frac{\sigma_1}{\sigma_n} \approx A \sqrt{\rho_n} \left( e^{-\frac{\Delta}{k_B T}} \right)
\]

\[\Delta \sim 3.1 \text{ meV} \Rightarrow R_s \geq 5 \text{ n}\Omega \ @ \ 4.3 \text{K} @ \sim 1 \text{ GHz}\]

\[H_c \sim 540 \text{ mT} \Rightarrow H_{sh} = 0.84 \cdot H_c \sim 450 \text{ mT} \Rightarrow E_{acc} \sim 100 \text{ MV/m}\]
**Nb₃Sn**: past and present

**Nb₃Sn for SRF!! ... not exactly new**

- 1953, discovered by B. Matthias et al.
- 1962, Saur and Wurm
- 1973, Siemens AG
- 1974, Karlsruhe
- 1974, Cornell University
- 1975, University of Wuppertal
- 1986, CERN
- ...
- ...
- ...
- ...
- 2009, Cornell University
- 2012, Jefferson Lab
- 2015, Fermilab

**“Siemens” configuration**


**“Wuppertal” configuration**


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High Tc?
Nb$_3$Sn: Cornell, Jlab, and Fermilab

Water Cooling

Flange for Connection to UHV Furnace

Mo Rods for Heater Power

Outer Heat Shields

Thermocouple Holder

Tin Source Heater

Coating Chamber

UHV Furnace

Stainless-Cu-Nb Transition

Feedthroughs

Cornell

Jlab

Fermilab

Modified door

Chamber support

Cavity support (Nb)

Inner heat shields

Coating chamber (Nb)

Tin Source

Nb$_3$Sn
Nb$_3$Sn cavities cooled by cryocoolers

Cryocooler-cooled cryomodules?!
**Nb$_3$Sn cavities for compact light sources**

- **Injector Gain**: 4 MeV
- **Accelerator Cryomodule Gain**: 20-25 MeV
- **Number of Cryomodules**: 1
- **Number of Cavities**: 2-4
- **Frequency**: 352 MHz
- **Operating Temperature**: 4.5 K
- **RF Amplitude Stability**: 0.1%
- **RF Phase Stability**: 50 fs
- **Cavity Type**: Spoke or Elliptical

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**Diagram**

- Laser
- SRF Photoinjector
- SRF Linac
- Bunch compressor
- Inverse Compton scattering
- 30 kW beam dump
- X-ray beamline
- Laser coherent enhancement cavity
- ~kW cryo-cooled Yb laser

**Flowchart**

- Coherent Light Source Cavity R&D Plans
  - Develop Novel Cavity Designs Optimized for 4K Operation
  - Develop Cavity Performance Specifications
  - Develop and Optimize Cavity Designs: Beam Dynamics, Electromagnetic
  - Complete Cavity Engineering Design
  - Prototype and Qualify Designs at 4K

- Evaluate Methods for Reducing Cryogenic Heat Loads
  - Develop Plasma Processing
  - Evaluate Nb3Sn

- Test Methods for Reducing Cryogenic Heat Loads


http://wiki.jlab.org/ciswiki/index.php/Main_Page
## 4K vs 2K beam quality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>March 23, 2016</th>
<th>June 17, 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHL Condition</td>
<td>K</td>
<td></td>
<td>0L02-7,8</td>
</tr>
<tr>
<td>Cavities</td>
<td>#</td>
<td>0L02-7,8</td>
<td>0L02-7,8</td>
</tr>
<tr>
<td>Gradient</td>
<td>MV/m</td>
<td>5.00, 5.32</td>
<td>5.00, 5.32</td>
</tr>
<tr>
<td>PSET (Crest)</td>
<td>deg</td>
<td>164.8, 83.2</td>
<td>-168.4, 123.6</td>
</tr>
<tr>
<td>Momentum</td>
<td>MeV/c</td>
<td>6.34</td>
<td>6.47</td>
</tr>
<tr>
<td>Laser Used</td>
<td>Hall</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Max Intensity (IBC0L02)</td>
<td>µA</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Horizontal Normalized Emittance (MQJ0L02)</td>
<td>mm-mrad</td>
<td>0.38 ± 0.01</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>Horizontal Beta (MQJ0L02)</td>
<td>m</td>
<td>5.21 ± 0.08</td>
<td>9.55 ± 0.12</td>
</tr>
<tr>
<td>Horizontal Alpha (MQJ0L02)</td>
<td>rad</td>
<td>-1.01 ± 0.01</td>
<td>-3.03 ± 0.04</td>
</tr>
<tr>
<td>Vertical Normalized Emittance (MQJ0L02)</td>
<td>mm-mrad</td>
<td>0.34 ± 0.01</td>
<td>0.54 ± 0.01</td>
</tr>
<tr>
<td>Vertical Beta (MQJ0L02)</td>
<td>m</td>
<td>2.53 ± 0.06</td>
<td>15.8 ± 0.1</td>
</tr>
<tr>
<td>Vertical Alpha (MQJ0L02)</td>
<td>rad</td>
<td>-0.42 ± 0.01</td>
<td>-4.39 ± 0.02</td>
</tr>
<tr>
<td>Horizontal Profile Scan (IHA2D00)</td>
<td>mm</td>
<td>2.35 ± 0.02</td>
<td>1.46 ± 0.02</td>
</tr>
<tr>
<td>Momentum Spread (dp/p)</td>
<td>%</td>
<td>0.22%</td>
<td>0.14%</td>
</tr>
<tr>
<td>Energy Spread (dE/E)</td>
<td>keV</td>
<td>14</td>
<td>9</td>
</tr>
</tbody>
</table>
Jlab Nb$_3$Sn development timeline

2012 2013 2014 2015 2016 2017 2018

SCNBSN
ARDNB3
ECA
FY

2.0 K fit parameters
$R_s^1 = R_s^5 = (14 + 0.1 \frac{E_{acc,local}}{(MV/m)})^2 \Omega$
$R_s^2 = R_s^4 = (14 + 4 \frac{E_{acc,local}}{(MV/m)})^2 \Omega$
$R_s^3 = (25 + 4 \frac{E_{acc,local}}{(MV/m)})^2 \Omega$

Q$_0$ expectation @ 4.3 K w/o end-cap losses (28 n$\Omega$ in the end cells)

CE5IA007 test results
Baseline test @ 2K, 28apr2016

007 test results
FY test @ 2K, 28apr2016

It [———] in $\pi$ mode @ 2.0 K
It [———] in $\pi$ mode @ 4.3 K
It [———] in 4$\pi$/5 mode @ 4.3 K
It [———] in 3$\pi$/5 mode @ 4.3 K
It [———] in 2$\pi$/5 mode @ 4.3 K

$E_{acc}$ [MV/m]
0 2 4 6 8 10 12
109
1010
Present single-cell work

Wuppertal data:

Cornell data:

JLab data:

DOE’s Office of Science Selects 49 Scientists to Receive Early Career Research Program Funding

Zum anderen wurde zur Reduktion des Sauerstoffpartialdrucks im Ofeninneren der Resonator außen mit einer 0.5 mm dicken Titanfolie ummantelt. Dies führte während der Nb₃Sn-Beschichtung zu einer Titanbeschichtung der Resonatoraußenfläche. Eine geringe Verunreinigung der innen aufwachsenden Nb₃Sn-Schicht durch hineindiffundierendes Titan wird man praktisch kaum vermeiden können (siehe Kap. II.3). Dieser Effekt wird aber als unkritisch angesehen, da nach Ref. 71 Titananteile von 5% nur zu einer $T_c$-Reduktion von weniger als 0.2 K führen. Zur Vermeidung von Keimbildungsproblemen
Titanium hypothesis

Recent data after the coating system upgrade

- Following system upgrade, Q-slope free $\text{Nb}_3\text{Sn}$-coated cavity were observed
  - $Q_0$ improved at all fields
  - At low fields, $Q_0$ reached $10^{11}$
  - $Q_0 \sim 5 \cdot 10^{10} @ E_{\text{acc}} = 15 \text{ MV/m}$
  - Cavities are still coated in “Siemens” configuration, i.e., no secondary heater for the tin source
- The cavity had NbTi flanges replaced with Nb flanges

$G. \text{ Ciovati, I. Parajuli, U. Pudasaini}$
Current data

- Q-slope free Nb$_3$Sn-coated cavity was reproduced on another cavity
- Consistent Q$_0$ between Q-slope free cavities
- Q-slope limited performance for some coatings was linked to variation in Sn source; studies are ongoing
- RDT7, RDT10 & TE1G001 had NbTi flanges replaced with Nb flanges

U. Pudasaini
“patches” : single crystal thin Nb$_3$Sn layers

Voids/pits

Sn nanoresidue
Concentration gradients

Sn concentration in films is very similar for different processing.

Thickest Nb$_3$Sn films produced to date

Small concentration gradient ~ 0.1 %/μm
Concentration gradients, stoichiometry, and sputtering

The goal: precise control of Sn content in Nb$_3$Sn films

Surface resistance is comparable to vapor diffused samples

Step is due to uncoated region

Needs to reduce/eliminate voids, e.g., by adjust heat treatment
Application to 5-cell cavities

Upgrade commissioning

The new coating chamber

IA320 after coating

System upgrade design

\( \text{Nb}_3\text{Sn} \)

8/9/2019
CEBAF 5-cell cavities

Tested by C. Reece!

\[ \text{Nb}_3\text{Sn} \]
The first CEBAF cavity coated in the upgraded system

The cavity limited at $E_{\text{acc}} = 11 \text{ MV/m}$ in the baseline test before coating

Results are shown for the coating #8 done in Nov. 17

Coated cavity had high $Q_0(\sim 10^{11})$, but a strong $Q$-slope

Re-tests after December 2017 to see if there is any degradation

Clear degradation in August test...why?
5-cell cavity coating results

Uniform coating, no obvious asymmetry!

U. Pudasaini
Pair work and results

Previous practical Nb₃Sn accelerating structure record is 80 keV!

Cavity was tuned several times

Lapping media after flange polish
Pair work and results

Quality factor and quench degraded after the cavity was tuned by about 200 kHz down. Tuning added field-dependent surface resistance, which increase by about 30 nΩ at low fields.
Strain sensitivity

Degradation of critical current as a function of strain for some materials

Dependence of the critical temperature on strain in Nb$_3$Sn

A. Godeke, Ph.D. dissertation
M. Mentink, Ph.D. dissertation
The goal was to simulate compression and extension of the center cell. The cavity needs to be squeezed/stretched beyond the desired frequency change in order to achieve the desired plastic deformation.

1 mm change in the cavity length corresponds to ~300 kHz of the frequency change.

Simulation by W. Crahen
Tuning simulation

Equivalent Total Strain: 0.71 mm jaw compression yields 0.25 mm deformation

Equivalent Total Strain: -1.445 jaw compression yields 1 mm deformation
Tuning simulation

Expected degradation due to $T_c$ reduction is not consistent with the measurement.
Weak points?

Surface imperfection are likely high stress points, where strain exceeds the average levels and significantly degrades surface resistance → smoothen the surface by centrifugal barrel polish.

**Void in Nb$_3$Sn coating, C3C4 cutout**

**Pit from nanopolishing media overcoated with Nb$_3$Sn**
The quality of the substrate could be important...
Baseline test of the new C75 cavities for Nb$_3$Sn project

- 5C75-RI-NbSn1, 4 June 2019
- 5C75-RI-NbSn2, 19 July 2019
- IA110, 25 June 1992
C75 cavity coating

Uniform coating, no obvious asymmetry... in the second cavity!
Nb$_3$Sn-coated C75 cavity test results

Talk Title Here
## Installation of Nb$_3$Sn-coated C75 into UITF

<table>
<thead>
<tr>
<th>Application</th>
<th>Beam Energy</th>
<th>Beam Current</th>
<th>Experiment Duration</th>
<th>Notes</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commission QCM for CEBAF</td>
<td>6 MeV, but prefer up to 10 MeV</td>
<td>up to 100 uA</td>
<td>three or four 1-week long tests</td>
<td>tests complete before long shutdown of 2020, when QCM to be installed at CEBAF</td>
<td>R. Kazimi</td>
</tr>
<tr>
<td>Commission H1Ice for CEBAF</td>
<td>~8 MeV</td>
<td>up to 100 nA for tuning, 0.25 to 5 nA for production</td>
<td>four or five run periods, one-month long each</td>
<td>target provides transverse polarization required for 3 A-rated Hall B experiments</td>
<td>A. Sandorfi</td>
</tr>
<tr>
<td>Manufacturing polarized targets for CEBAF via DNP</td>
<td>1 - 10 MeV</td>
<td>1 to 10 uA</td>
<td>hours, days</td>
<td>likely some R&amp;D to determine optimum polarizing conditions</td>
<td>C. Keith</td>
</tr>
<tr>
<td>Bubble Chamber astrophysics</td>
<td>4 - 10 MeV</td>
<td>0.01 to 100 uA</td>
<td>3 weeks, as often as possible</td>
<td>UITF better location than CEBAF injector, when CEBAF shutdowns are short</td>
<td>R. Suleiman</td>
</tr>
<tr>
<td>MeV parity violation experiment</td>
<td>10 MeV</td>
<td>milliamperes preferred, will reduce experiment duration</td>
<td>months to years</td>
<td>requires polarized electron beam, transmission geometry offers advantages</td>
<td>R. Carlini</td>
</tr>
<tr>
<td>Testing Nb3Sn-coated cavities</td>
<td>determining the beam energy of test cavity is point of test</td>
<td>up to 100 uA</td>
<td>as many tests as possible</td>
<td>Nb3Sn cavities require only 4K Helium</td>
<td>G. Eremerov</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>2 - 10 MeV</td>
<td>100 uA</td>
<td>imagine week-long test durations over three years</td>
<td>together with local partners</td>
<td>G. Ciovati</td>
</tr>
<tr>
<td>Polarized positron source</td>
<td>5 - 10 MeV</td>
<td>up to 100 uA</td>
<td>staged tests, likely many required, 1-week long duration</td>
<td>requires polarized electron beam</td>
<td>J. Grames</td>
</tr>
<tr>
<td>EIC fast kicker tests</td>
<td>5 - 10 MeV</td>
<td>up to 100 uA</td>
<td>two 1-week long tests</td>
<td>together with sbir-partner</td>
<td>H. Wang</td>
</tr>
<tr>
<td>EIC testing high bunch charge</td>
<td>5 - 10 MeV</td>
<td>up to 100 uA</td>
<td>two 1-week long tests</td>
<td>requires polarized electron beam</td>
<td>J. Grames and J. Guo</td>
</tr>
</tbody>
</table>
Strain sensitivity is not necessarily an issue for new designs

Compact high-power CW SRF accelerator for industrial application

- 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

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

- Patent on Cryomodule design filed on 01/29/18
Nb$_3$Sn-coated 952 MHz cavity

$952$ MHz EIC cavity @ 4.3K, 26 June 2019

$\sigma_0$

$10^{10}$

$10^9$

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

multipacting
The goal is to optimize the coating process towards $Q_0$ of $10^{11}$ at $E_{acc} = 20$ MV/m at 2 K.

- Cavities w/o Q-slope were produced in “Siemens” configuration
- $Q_0$ of $10^{11}$ are measured at low fields
- Current focus is on low-field and medium field Q-slopes
- Temperature-controlled Sn source is being built
- It may be challenging to consistently reach $E_{acc} = 20$ MV/m w/o cleanroom around the coating system.

U. Pudasaini
The goal is to study coating degradation by accelerating electron beams in a cryomodule with $Q_0$ of $10^{10}$ at $E_{acc} = 10$ MV/m at 4 K.

- Substrate issues were resolved with the two new C75 cavities
- Discovered significant degradation after tuning likely related to surface features
- Possible mitigations are smooth surface and minimized tuning
- The best solution may involve redesign of a quarter cryomodule
**Summary #3: optimum Nb₃Sn layers**

- **Magnet holder rod**
- **Water in** & **Water out**
- **Welded bellow 1**: This bellow will expand and compress according to the movement of bellow 2 to keep the magnet holder rod in stationary position.
- **Ceramic**: Used to electrically isolate the cathode from cavity.
- **Welded bellow 2**: This bellow will expand and compress bring the desired target near to cavity surface.
- **Nb target**
- **Sn target**

The goal: precise control Sn content in Nb₃Sn films.

Md. N. Sayeed
Thank you for your attention!