SRF Cavities Beyond Niobium: Potential and Challenges

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Outline

• Motivation – Why Look Beyond Niobium?
• Properties to look for in alternative SRF materials
• 3 materials with large amounts of recent development: 1) \( \text{Nb}_3\text{Sn} \), 2) \( \text{MgB}_2 \), 3) \( \text{NbN} \)
• SIS multilayer films
• Other materials, briefly
• Summary
Why Look at Alternative SRF Materials?
Why Look Beyond Niobium?

- Two figures of merit: $E_{\text{acc}}$ and $Q_0$ ($\sim R_s^{-1}$)
- After years of development, Nb cavities are starting to reach fundamental limits of the material

Sam Posen - SRF Cavities Beyond Niobium - NAPAC13
Why Look Beyond Niobium?

• CW SRF linacs – Cost driver: cryogenics
  – Cost optimum for Nb: operate ~2 K, where $R_s$ is small
  – Alternative materials can have much smaller $R_s$ at ~2 K: smaller cryo plant and less grid power
  – Materials with higher $T_c$ may allow operation at higher T: LHe at atmospheric pressure or even cold gas

• High energy SRF linacs – Cost driver: number of cavities
  – RF critical field fundamentally limits $E_{acc}$, and therefore sets minimum number of cavities required to reach a given energy
  – Alternative material with higher critical magnetic field: fewer cavities required to reach same energy

Need long term R&D to realize full potential of new materials, but already a Cornell Nb$_3$Sn cavity is superior to Nb cavities for some applications. Fast growth over the next years can be expected with continuous R&D.
What Properties to Look for in Alternative Materials?
- RF limit is superheating field $B_{sh}$, NOT $B_{irr}$
  - EXCLUDE vortices, not pin them inside superconductor!
    Normal conducting vortex cores = huge RF dissipation

- Surface defects with size $\sim \xi$ can reduce barrier to vortex penetration—need "large enough" $\xi$
  - Nb has $\xi \sim 20$ nm and it gets very close to $B_{sh}$
  - New results on Nb$_3$Sn with $\xi \sim 3$ nm show barrier intact

Larger Max Field $\Rightarrow$ Fewer Cavities Needed
Properties to Look for in Materials: What Gives Small Surface Resistance?

- Temperature dependent surface resistance from BCS theory: $R_{BCS}$
  - Need large $T_c$, small normal resistivity $\rho_n$

- Temp. independent “residual resistance”: $R_s(T) = R_{BCS}(T) + R_{res}$ – not well understood
  - Strong connections between grains: it is known that weak links can contribute to $R_{res}$

Smaller $R_s$ ➔ Smaller Cryogenic Costs

Vaglio, (1998)

LHC & SNS cryo equipment. Images from USPAS lectures by Tom Peterson and John Weisend
Properties to Look for in Materials: Requirements for Cavity Operation

- Ability to conform to complex geometry over large area
- Decent thermal conductivity for cooling to avoid breakdown
- Minimal surface roughness—avoid field enhancement
- Cleanliness: Potential field emitting dust? Is there a method to clean surface contaminants?
### Experimental Properties of Promising Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda(0)$ [nm]</th>
<th>$\xi(0)$ [nm]</th>
<th>$B_{sh}$ [mT]</th>
<th>$T_c$ [K]</th>
<th>$\rho_n(0)$ [µΩcm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>50</td>
<td>22</td>
<td>210</td>
<td>9.2</td>
<td>2</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>111</td>
<td>4.2</td>
<td>410</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>185</td>
<td>4.9</td>
<td>210</td>
<td>40</td>
<td>0.1</td>
</tr>
<tr>
<td>NbN</td>
<td>375</td>
<td>2.9</td>
<td>160</td>
<td>16</td>
<td>144</td>
</tr>
</tbody>
</table>

Parameters for: Nb from [1] assuming RRR = 10; Nb$_3$Sn from [2]; NbN from [3]; MgB$_2$ from [4] and [5]. $B_{sh}$ for Nb found from equation in [6] and for others calculated from [7]. $B_c$ used to calculated $B_{sh}$ found from [8] eq. 4.20.


**Material parameters vary with fabrication.** References were chosen to try to display realistic properties for polycrystalline films.
$\text{Nb}_3\text{Sn}$
**Potential**

- Small $R_s$ – Small $\rho_n$, high $T_c \sim 18$ K (twice Nb)
- Large $B_{sh} \sim 400$ mT (twice Nb)
- Decent $\xi \sim 3$-4 nm
- Can alloy existing Nb cavities
- Non-reactive

**Challenges**

- Material is brittle
- Low thermal conductivity

Images from Cornell

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Challenges With Films (Any Material)

- Film/substrate interface can trap flux from thermocurrents if cooled quickly or non-uniformly
  - Require new cooldown after quench to regain small $R_s$
- Coating only a few µm thick: to clean surface, only light chemistry available
- Large structures: welding coated pieces together difficult, coating entire structure also difficult
Preparation Methods

Liquid Tin Dipping – INFN

Problems with tin droplets on surface and spurious tin-rich phases

*S. Deambrosis et al. (2009)*

Cathodic Arc Deposition – Alameda Applied Sciences

- More energetic ions than sputtering
- Low $T_c$ measured

*M. Krishnan et al. (2012)*

Multilayer Sputtering – INFN

- Alternate coatings of Nb and Sn, then anneal
- No encouraging RF results so far

*A. Rossi et al. (2009)*
Preparation Methods

Pulsed Laser Deposition - KEK

- Studies have started
- Also use PLD for MgB₂

Vapor Diffusion – Cornell and Jefferson Lab

- Pioneering studies 80s-90s at Siemens AG and U. Wuppertal
- In UHV furnace, tin vapor alloys with Nb cavity
- Very promising RF results

S. Mitsunobu et al.

Coating chamber in UHV furnace at 1100 C

Nb cavity substrate

Sn Vapor

Auxilliary Heater for Sn container at 1200 C
Preliminary studies with samples have been done. RF measurements on a sample indicated the transition temperature of 17.9 K and RF surface resistance of about 30 \( \mu \Omega \) at 9 K and 7.4 GHz.

The horizontal insert has been built and inserted in the furnace. The first furnace run has been done at 1200 \(^\circ\)C for 2 hours.

R&D furnace for \( \text{Nb}_3\text{Sn} \) development was ordered in October 2012, delivered in August 2013, and is being commissioned.
• Achieved fields ~12 MV/m at 4.2 K with $Q_0 \times 10^{10}$, 20 times higher than niobium

• Breakthrough performance: the first alternative material accelerator cavity with significantly smaller $R_s$ than niobium at useful gradients and temperatures

• Performance level already useful for some applications
• Proves that even with small ξ of Nb₃Sn (making it more vulnerable to surface defects), energy barrier prevents vortex penetration

• Shows the potential of alternative SRF materials

See details in talk tomorrow! (9:15 in Aud. A)
Current Status of Nb$_3$Sn

- Cavity fabrication is established – Nb$_3$Sn ready for first applications
- Far smaller $R_s$ than Nb achieved down to 2 K
- Surface mag. fields up to $\sim$55 mT with small $R_s$
  - Achieved $E_{\text{acc}}$ is useful, but far below ultimate limit of material, superheating field
  - Nb: 200 mT, Nb$_3$Sn $\sim$400 mT
MgB$_2$
**MgB$_2$**

### Potential
- Small $R_s$ – small $\rho_n$, very high $T_c \sim 40$ K (smaller gap dominates $R_s$, but still good)
- B$_{sh}$ not clear yet, but possible range ~200-600 mT. Need more development of SRF quality MgB$_2$ films
- Very high $T_c$ raises possibility of operation at high T
- Decent $\xi \sim 5$ nm

### Challenges
- Mg highly reactive with oxygen: must have very small background during coating
- $R_s$ increase with field predicted for two gap materials, but might be possible to reduce it
- Reacts with water – “capping” layer may be required

_T. Tajima, Los Alamos_  
_X. Xi, Temple U._
Hybrid Physical-Chemical Vapor Deposition

- **Schematic View**
  - **get rid of oxygen prevent oxidation**
  - **pure source of B**
  - **generate high Mg pressure: required by thermodynamics**
  - **high enough T for epitaxy**
  - **HPCVD Process gives excellent $T_c$**
  - **Working towards cavity coating capability**

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• $R_s$ lower than Nb at 10 GHz for $T > \sim 4$ K
• Little increase in $R_s$ with B up to 12 mT

*MgB$_2$* films produced at STI (Superconducting Technologies Inc. – B. Moeckly et al) by reactive co-evaporation
Low-Power $R_s(T)$: MgB$_2$ and Nb

$R_s$ extrapolated to 2.2 GHz by $f^2$ for the dielectric-resonator data

MgB$_2$ films produced by B. Moeckly at STI (Superconducting Technologies Inc.) by reactive co-evaporation
Current Status of MgB$_2$

- Several sample studies; cavity fabrication is coming soon
- Smaller $R_s$ than Nb achieved at high temperature and frequency
  - Need to show small $R_{res}$ is possible
- Only relatively small gradients measured so far, as no cavities built yet
  - Need to see if two-gap nature increases $R_s$ at high gradients
NbN
Potential
• Small $R_s$ – high $T_c$ $\sim$ 15 -17 K
• $B_{sh}$ okay $\sim$ 150-200 mT
• Decent $\xi$ $\sim$ 3 nm
• Might be possible to treat large Nb cavities with N$_2$ in furnace

Challenges
• Complex phase diagram – very difficult to achieve correct phase for furnace treatment
• Tests show large $R_{res}$
• Recently $R_s$ reduction in Nb measured after N$_2$ furnace treatment—speculated cause was superconducting NbN growth, but sample $T_c$ revealed that another mechanism must have been responsible

Sputtered NbN, C. Anoine et al. (2013)
APL 102603
Multilayers
Multilayers

• A. Gurevich proposal: don’t use bulk films—use alternating layers of thin superconductor and insulator on top of bulk superconductor, “SIS multilayers”

• Enhancement of $B_{c1}$ (onset of metastable state) in thin films avoids problem of vortex penetration at small defects

A. Gurevich, APL 012511 (2006)
CVD of NbN (AlN) layers

High Temperature CVD using Nb (Al) Chloride and NH₃

\[ \text{Nb}_{(s)} \text{ (or Al)} + x \text{Cl}_2 \]
\[ \downarrow \]
\[ \text{NH}_3 + \text{H}_2 \]
\[ \downarrow \]
\[ \text{NH}_3 + \text{H}_2 \]
\[ \downarrow \]
\[ \text{NbCl}_x + x/2 \text{H}_2 \]
\[ \text{NbN} \]

substrate

susceptor

\[ T = 900-1800 \, ^\circ \text{C} \]

F. Weiss et al., Grenoble IPT

- CVD, HPCVD, ALD, sputtering, HiPIMS
- S: NbN, NbTiN, MgB₂
- I: MgO, AlN, Al₂O₃

C. Antoine, CEA
• Addition of Ti can increase NbN resistivity, thermodynamic stability
• JLab starting to use this material for multilayers: $T_c$ and $R_s$ measured
New Theory from Cornell

- Investigated multilayers proposal fundamentally
- Used only well established theoretical tools (free energy) applied to SIS structure
- Find that $B_{c1} = 0$ and only small possible gain in maximum metastable field

Free energy lower here than outside for penetrating fluxoid

$B_{\text{ext}} > B_{\text{sh}}$

$B_{\text{ext}} = B_{\text{sh}}$

$B_{\text{ext}} > B_{c1}$

$B_{\text{ext}} = B_{c1} = 0$

Gibbs Free Energy of a Vortex [J]

Distance into Structure [nm]
Other Possible Materials

- **YBCO** ($T_c \sim 95$ K) – nonlinear increase in $R_s$ with field, Large $R_{res}$
- **Oxypnictides** ($T_c \sim 20$-60 K) – difficult structure, but exciting possibility: more research needed
- **$V_3Si$, $Mo_3Re$, $Nb_3GaAl$** ($T_c \sim 10$-20 K) – further investigation needed

Summary

• Alternative SRF materials offer lower $R_s$, higher $T_c$, higher $B_{sh}$ than niobium → more efficient cavities (factor of 10-100?), higher gradients (factor of 2?)

• Breakthrough $\text{Nb}_3\text{Sn}$ cavity: at 4.2 K and usable gradients, $Q_0$ is 20 times higher than Nb (details tomorrow morning)

• $\text{MgB}_2$ looks very promising—first cavities soon!
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