Next-Generation Superconducting RF Technology based on Advanced Thin Film Technologies and Innovative Materials for Accelerator Enhanced Performance & Energy Reach

Snowmass 2021
AF7: Accelerator Technology R&D

LOI - 205

Background

Superconducting RF Technology has been the building block for many high-energy physics accelerators, essentially based on bulk niobium (Nb). Over the past decades, the RF performance of bulk Nb cavities has continuously improved with material and surface developments (nitrogen surface doping, infusion...).

Long-term solutions for superconducting radio-frequency (SRF) surfaces further efficiency enhancement?
Methods and materials deliberately producing the sub-micron-thick critical surface layer in a controlled way.

- Other forms of Nb and other superconducting materials to improve SRF cavity performance beyond the Nb sheet material intrinsic limits.
- Higher efficiency & quality control
- Fully engineered and truly application-tailored SRF surface strategies

...dramatically reduce capital and operating costs for future accelerators lower the cost-of-entry of SRF technology for large scale facilities and compact accelerators.
Next Generation Nb/Cu SRF Cavities Based on Advanced Coating Technology for CW Accelerators

Increased temperature stability due to Cu substrate higher thermal conductivity
- Operation at 4.5 K, generating capital and operational cost savings
- Material cost saving, particularly for low frequency structures
- Easily machinable and castable structures

Perspectives for significant cryomodule simplification.

Novel deposition techniques exploiting species energetics offer opportunities to improve and manipulate film structure and performance

Explore alternative materials with higher critical temperature and critical fields

Alternate Materials and Advanced Structures for Higher Gradients and High Q

Alternative materials with higher critical temperature and critical field are the prime candidates to disrupt the established bulk Nb technology.

### Materials Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ [K]</th>
<th>$\Delta S$ [mJ/mol]</th>
<th>$H_c(0)$ [T]</th>
<th>$H_{tr} (T)$</th>
<th>$H_{tr} (B)$</th>
<th>$\frac{\Delta B}{\Delta B}$</th>
<th>$\Delta B$ [mV]</th>
<th>$A$ [meV]</th>
<th>$\xi$ [nm]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>0.23</td>
<td>2</td>
<td>200</td>
<td>0.17</td>
<td>0.28</td>
<td>0.219</td>
<td>40</td>
<td>1.5</td>
<td>26</td>
<td>II</td>
</tr>
<tr>
<td>Pb</td>
<td>7.2</td>
<td>80</td>
<td>N/A</td>
<td>N/A</td>
<td>48</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>NbTiN</td>
<td>15.6</td>
<td>70</td>
<td>239</td>
<td>0.03</td>
<td>15</td>
<td>0.274</td>
<td>200-350</td>
<td>2.6</td>
<td>&gt;5</td>
<td>II, I comp</td>
</tr>
<tr>
<td>NbSn</td>
<td>16.2</td>
<td>70</td>
<td>239</td>
<td>0.03</td>
<td>15</td>
<td>0.274</td>
<td>200-350</td>
<td>2.6</td>
<td>&gt;5</td>
<td>II, I comp</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>35.5</td>
<td>100</td>
<td>580</td>
<td>0.03</td>
<td>15</td>
<td>0.274</td>
<td>200-350</td>
<td>2.6</td>
<td>&gt;5</td>
<td>II, I comp</td>
</tr>
<tr>
<td>Mg$_2$Ge$_2$</td>
<td>45.5</td>
<td>100</td>
<td>580</td>
<td>0.03</td>
<td>15</td>
<td>0.274</td>
<td>200-350</td>
<td>2.6</td>
<td>&gt;5</td>
<td>II, I comp</td>
</tr>
<tr>
<td>2H-NbSe$_2$</td>
<td>71.5</td>
<td>120</td>
<td>120</td>
<td>0.03</td>
<td>15</td>
<td>0.274</td>
<td>200-350</td>
<td>2.6</td>
<td>&gt;5</td>
<td>II, I comp</td>
</tr>
<tr>
<td>Pr nietides</td>
<td>30.5</td>
<td>550</td>
<td>500-600</td>
<td>0.03</td>
<td>&gt;100</td>
<td>0.756</td>
<td>200</td>
<td>10.20</td>
<td>2</td>
<td>SC-SC</td>
</tr>
</tbody>
</table>

![Image of multifilamentary Nb coil with SIS structure](image)

*Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)*
*Alex Gurevich, AIP ADVANCES 5, 017112 (2015)*
Compact SRF Accelerators for Societal Applications

The emergence of reliable, energy efficient high Q systems, based on highly performing film-based SRF cavities along with transformative development with cryocoolers would impact societal applications ranging from medicine to industry.

Cost effective compact superconducting accelerators will reduce the footprint and capital investment of

- Medical machines - cancer therapy, medical radioisotope production
- environmental remediation
- accelerator-driven systems (ADS) - nuclear waste transmutation, power generation
- high-intensity proton accelerators for homeland security (nuclear weapons detection).

Most critical area of development

**Energy efficiency**

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**Compact cavity cooled by cryocoolers for environmental applications**


R C Dhuley et al 2020 Supercond. Sci. Technol. 33 06LT01
Advances in Thin Film Nb on Cu Technology

Energetic condensation

Substrate Fabrication & Processing

Full control over final SRF performance with strict process protocols

Further tailoring opportunities:
N doping on films
Advances in Thin Film Nb on Cu Technology

Developments across shapes & frequencies

Next-Generation SRF Thin Film Technologies
Nb$_3$Sn Development

**Material studies to understand the fundamental growth mechanism linking with RF performance**

- Potential factors contributing to recurrent Q-slopes in Nb$_3$Sn cavities.
  - Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in RF-affecting thin regions.

**Process Development**

- Modification of coating process based on learnings from correlated material and RF studies of Nb$_3$Sn samples resulted in the removal of recurrent Q-slopes.

**Multi-cell cavity coating for accelerator application**

- Despite early cavities suffered non-uniformity, enhanced substrate quality and continuously updated coating process resulted in notable improvement.

**Multi-metallic conduction cooled Nb3Sn-coated cavity**

- These cavities progress to quarter cryomodule for the first-ever beam test.

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- Materials such as Nb$_3$Sn offer order of magnitude improvements in operating efficiency, and a theoretical pathway to 100 MV/m gradient.

- Recent R&D efforts have demonstrated that the persistent Q-slope and gradient limitation observed in the past are not fundamental but process induced and therefore amenable to improvement.

- Alternative deposition approaches such as sputtering, energetic condensation and atomic layer deposition (ALD) should be fully explored for enhanced properties and conformality.

- Early results with sequential and stoichiometric deposition both on Nb and on Cu are promising and could prove to push the Nb$_3$Sn technology further.
Alternative Materials to Nb & Multilayered Structures

- Develop alternative materials such as NbTiN, NbN, Nb₃Sn Va₃Si, ... with advanced coating techniques.

Especially for low melting temperature substrates (Cu, CuSn, Al...)

- Newly discovered high temperature superconducting (HTS) materials (pnictides ...) would be particularly interesting if any of them turns out to have favorable microwave properties

- Advanced coating techniques

Re-HiPIMS

ALD

High quality dense films
Improved conformality

Conformal, self-limiting
nm precision
Precursors difficult

Alternative Materials to Nb & Multilayered Structures

- The combination of such materials with adequate dielectric material in multi-layered structures have been conceived as a performance enhancer for bulk Nb and Nb/Cu film cavities. Theoretical models predict that appropriately fabricated nanometric superconductor-insulator-superconductor (SIS) multilayer films can delay vortex penetration in Nb surfaces allowing them to sustain higher surface fields than any pure material.

- Cap layers for surface passivation

- Meta-materials for functional surfaces

Next-Generation SRF Thin Film Technologies
Path Forward

Already well-established and fruitful international R&D collaborations
  JLab, SLAC, ODU, CORNELL, FNAL, FSU, W&M, ANL, Temple U. …  &
  CEA Saclay, CERN, DESY, HZB, INFN-LNL, KEK, STFC, TRIUMF and other institutions

should be fully supported and expanded in the following areas of R&D:

- **Theoretical and material studies** to gain in-depth understanding of the fundamental limitations of thin film superconductors under radio-frequency fields
- **Advanced coating technology** for Nb/Cu and alternative materials, Nb₃Sn, V₃Si, NbTiN …
  - Energetic condensation (electron cyclotron resonance (ECR), HiPIMS, kick positive pulse...)
  - Atomic Layer Deposition (ALD)
  - Hybrid deposition techniques
- **Cavity deposition techniques for development of superconductor-insulator-superconductor (SIS) nanometric layers** to further enhance the performance of bulk Nb and Nb/Cu
- **Improved cavity fabrication & preparation techniques**
  - electroforming, spinning, hydroforming, electro-hydro forming, 3D additive manufacturing
  - environmentally friendly electropolishing, diamond cutting, nano-polishing, plasma etching …
- **Cryomodule design** optimization
- Improvement of **accelerator ancillaries** with advanced deposition techniques
  - HiPIMS Cu coated bellows, power couplers...
What do we need?

Synergies between R&D programs, institutions along aligned path

Multiple RF test platforms (QPR, ...) for fundamental, detailed materials study
  --Doping, Nb$_3$Sn, peak fields, multi-layers, other A15, MgB$_2$...

Material research instruments

Expanded distribution of funding (GARD...) for National Labs & Universities

Continued investments are needed in R&D, production and test facilities.
  Labor
  Existing facility upgrade
  New facilities

Training of young Scientists and Engineers

Fostering industrial partners in US

Next-Generation SRF Thin Film Technologies
Summary

- SRF thin film technology based on advanced coating techniques offers many opportunities to fully engineer SRF surfaces:
  - Deliberate creation of the most favorable interface or functional interlayer
  - Tailoring of the most favorable film(s) structure
  - Properties enhancement with doping/infusion
  - Control over the final SRF surface with dry oxidation or cap layer protection.

- Bulk-like performance Nb films, alternative material films and SIS multilayer structures open the possibility of major system simplifications and enhanced performance.

- Such developments would be transformative not only for future high energy physics machines but will also bring forth the opportunity to upgrade existing machines to higher performance in achievable energies and cryogenic & power consumption, within the same footprint.

- Active community in the US and Internationally
Virtual International Workshop on Nb3Sn SRF Science, Technology, and Applications (Nb3SnSRF’20)
10-13 Nov 2020
https://indico.classe.cornell.edu/event/1806/

9th International Workshop on "Thin films applied to Superconducting RF: Pushing the limits of RF Superconductivity"
VIRTUAL EDITION
March 15-18, 2021
https://indico.jlab.org/e/TFSRF2021