Innovative $\text{Nb}_3\text{Sn}$ Thin Film Approaches and their Potential for Research and Applications

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An electro-chemical deposition technique, under US Patent Application, to produce Nb$_3$Sn coatings was developed in the last few years by FNAL in collaboration with Politecnico di Milano.

- The Nb$_3$Sn phase is obtained by electrodeposition from aqueous solutions of Sn layers and Cu intermediate layers onto Nb substrates followed by high temperature diffusion in inert atmosphere. Subsequent thermal treatments are realized at 700°C to obtain Nb$_3$Sn superconducting phase between 5.7 and 8.0 μm in thickness. All samples showed superconducting transport behavior, with a maximum obtained $T_c$ of 17.68 K and $B_{c20}$ ranging between 22.5 T and 23.8 T.

The Nb$_3$Sn phase is obtained by electrodeposition of Sn layers and Cu intermediate layers onto Nb substrates followed by high temperature diffusion in inert atmosphere. Electrodeposition was performed from aqueous solutions at current densities in the 20 to 50 mA/cm$^2$ range and at temperatures between 40 and 50°C. Subsequent thermal treatments were realized to obtain the Nb$_3$Sn superconductive phase.
The maximum obtained $T_c$ was 17.68 K and the $B_{c20}$ ranged between 22.5 T and 23.8 T.

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Electrodeposition of Cu seed layer onto a Nb substrate

- This electrodeposition step is made in a two electrodes cell, where the Anode is a pure Cu sheet and the Cathode a Nb foil.
- $T = 40\,^\circ C \ (104\,^\circ F)$
- $J = 30\, mA/cm^2$

The bath for this process is copper sulphate based:

- $\text{CuSO}_4 \quad 60\, g/l$
- $\text{H}_2\text{SO}_4 \quad 200\, g/l$
- $\text{HCl} \quad 40\, g/l$
Electrodeposition of Cu seed layer onto a Nb substrate
Electrodeposition of Cu seed layer onto a Nb substrate
Electrodeposition of Sn layer onto the Cu seed layer

- This electrodeposition step is made in a two electrodes cell, where the Anode is a pure Sn sheet and the Cathode is the Nb/Cu foil.
- \( T = 50^\circ C \) (122 F)
- \( J = 50 \text{ mA/cm}^2 \)

The bath for this process is:
Solderon MHS-W;
Solderon HS-300 Sn concentrate;
Solderon acid HC.
Electrodeposition of Cu barrier layer onto Sn

- This electrodeposition step is made in a two electrodes cell, where the Anode is a pure Cu sheet and the Cathode the Nb/Cu/Sn sample.
- $T = 50\, ^\circ C \ (122\, ^\circ F)$
- $J = 20\, mA/cm^2$

The bath for this process is pyrophosphate based:
- $Cu_2P_2O_7 \ 26\, g/l$
- $NaNO_3 \ 5\, g/l$
- $Na_4P_2O_7 \ 180\, g/l$
**Nb₃Sn Thin Films – Potential for SC Wire Research**

An inexpensive way to produce Nb₃Sn thin films on Nb can be used as a test bed to try different alloy materials for wires inexpensively and with fast turnaround to test their flux pinning properties. I see three possible ways to enhance the transverse component of pinning in Nb₃Sn:

1. Elongation of the grains along current direction – very difficult to achieve;
2. Introduction of axial ribbons to enhance transverse component of pinning – come up with ribbon materials that can be cold worked, do not dissolve at 700C and do not react with Sn. Potential candidates so far are Ta, Mo and V.
3. Introduction of materials that would deposit in the Nb₃Sn boundaries to stop the longitudinal flux motion.
Nb$_3$Sn Thin Films – Potential for SRF Research

1. High Q
2. High gradient
3. Low cost

Potential collaborations with:

- JLAB:
  - Anne Marie Valente
  - Rongli Geng
  - Charlie Reece, Grigory Eremeev

- KEK/NIMS: Hitoshi Hayano, Aki Kikuchi
Five ovens up to $1500 \degree C$ for heat treatment in Argon and in Oxygen.

**Back-up Slides**
Examples of DOE Reviews

Reviewer 1:
- The idea of electroplating Sn / Cu layers to form by post annealing Nb3Sn superconducting alloy for SRF cavity/magnet applications is quite innovative and must be pursued.
- The proposed approach would greatly reduce the cost and ease the large scale production of Nb3Sn cavities. Based on the work already accomplished, a breakthrough is clearly possible.
- The electroplating approach is a proven to be technologically inexpensive and highly scalable. The size of the market is on the order of 100th of millions of dollars.

Reviewer 2:
- These techniques, revived recently at Cornell and JLab have not offered major process innovation. One of their main disadvantages is that the cavities have to be heat treated in vacuum up to 800-900°C for the process. The proposed process takes place at lower temperatures in argon. The project builds on the significant results achieved by Dr. Barzi and collaborators in developing electrochemical and thermal syntheses of superconductive Nb3Sn films.
- Electrodeposition is an inexpensive, scalable, non-line-of-sight industrial manufacturing process.
- The technical challenge is significant but a successful implementation of the process on SRF cavities will be groundbreaking and could revolutionize the field of SRF cavities and particle accelerators with operation at 4K. This project could open the door to a new generation of particle accelerators for the medical and industrial fields.
- If successful, this project would lead to a process that could be applied to all future superconducting accelerators. The industrial and medical fields would also be interested to implement small accelerators based on this technology (significant reduction in cost and infrastructure). The market estimates for linear accelerators for medical applications is in the range of $6B and is expected to continue increasing.

Reviewer 3:
- Cornell's work has showed us the excellent properties of Nb3Sn film SRF cavity prepared with vapor diffusion approach. The Nb-rich region could be the reason that limits further improvement the properties. Electrochemical techniques, as adopted in this proposal, could eliminate or dramatically decrease the Nb-rich region area and further improve the properties toward real application of Nb3Sn film SRF cavity in turn.
- The techniques adopted are well developed and scalable, so if succeed, it is very possible to lead to a marketable process.

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A Model for $J_c$ in Granular Superconductors

Predictions of MDB model

$$J_c^\perp (B,T) \approx \frac{B_{c2}^2}{8\pi\mu_0\kappa^2 D} \left(1 - \frac{B}{B_{c2}}\right)$$

$$J_c^\parallel (B,T) \approx \frac{2\alpha d B_{c2}^2}{3\sqrt{3}\phi_0\mu_0\kappa^2 D} \left(\frac{\langle J_0 \rangle}{J_d}\right)^2 \frac{\left(1 - \frac{B}{B_{c2}}\right)^2}{\sqrt{B}}$$

Transverse Pinning

Longitudinal Pinning

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**Nb₃Sn Phase Diagram**

*Nb-Cu-Sn ternary phase diagram*

*Nb-Sn binary phase diagram*

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