Innovative Nb_3Sn Thin Film Approaches and their Potential for Research and Applications

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Premise

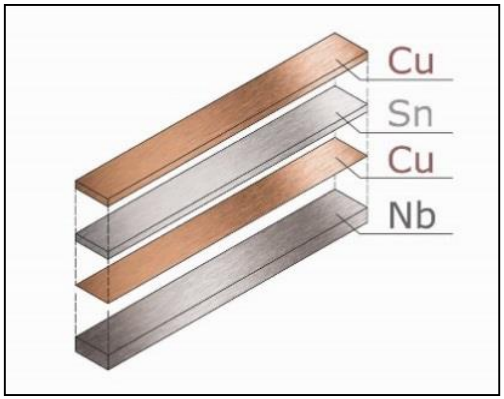
An electro-chemical deposition technique, under US Patent Application, to produce Nb_3Sn coatings was developed in the last few years by FNAL in collaboration with Politecnico di Milano.

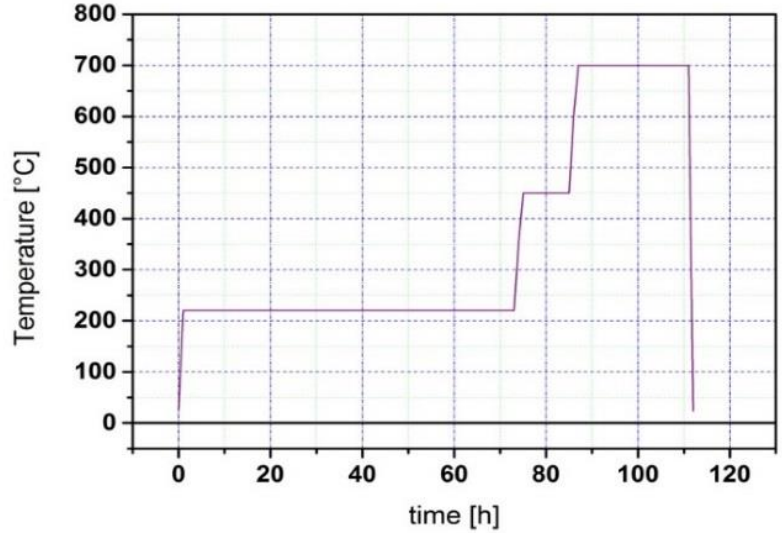
- **The Nb_3Sn phase is obtained by electrodeposition from aqueous solutions of Sn layers and Cu intermediate layers onto Nb substrates followed by high temperature diffusion in inert atmosphere. Subsequent thermal treatments are realized at 700°C to obtain Nb_3Sn superconducting phase between 5.7 and 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.**

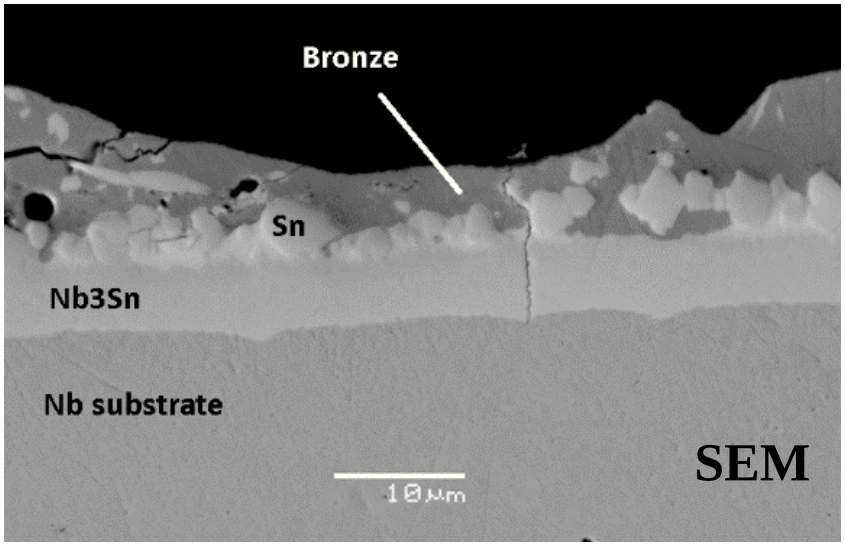
"Synthesis of Superconducting Nb_3Sn Coatings on Nb Substrates", E. Barzi, M. Bestetti, F. Reginato, D. Turrioni and S. Franz, Supercond. Sci. Technol. 29 015009.

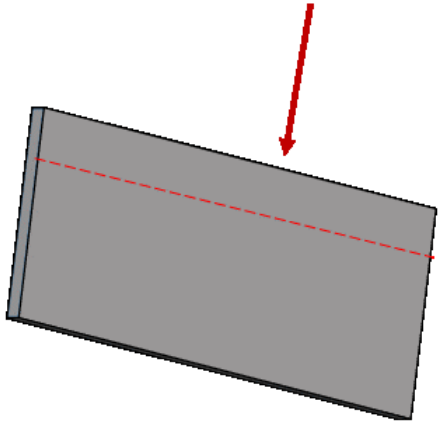
Nb_3Sn Thin Films on Nb

The Nb_3Sn 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/cm² range and at temperatures between 40 and 50°C. Subsequent thermal treatments were realized to obtain the Nb_3Sn superconductive phase.

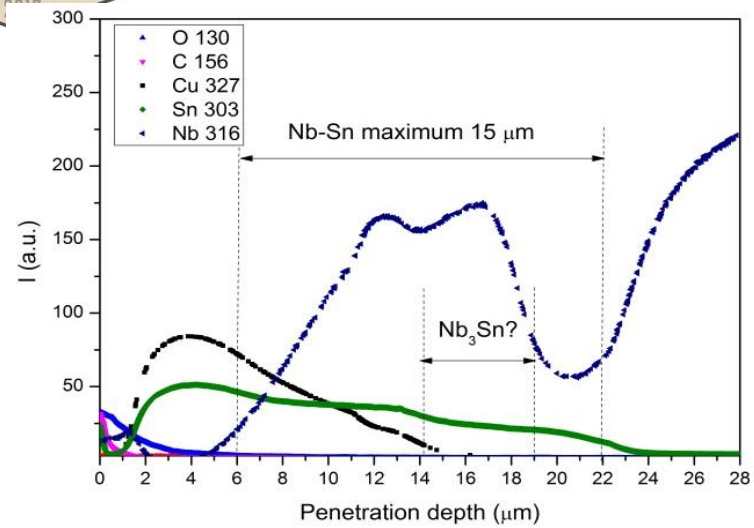




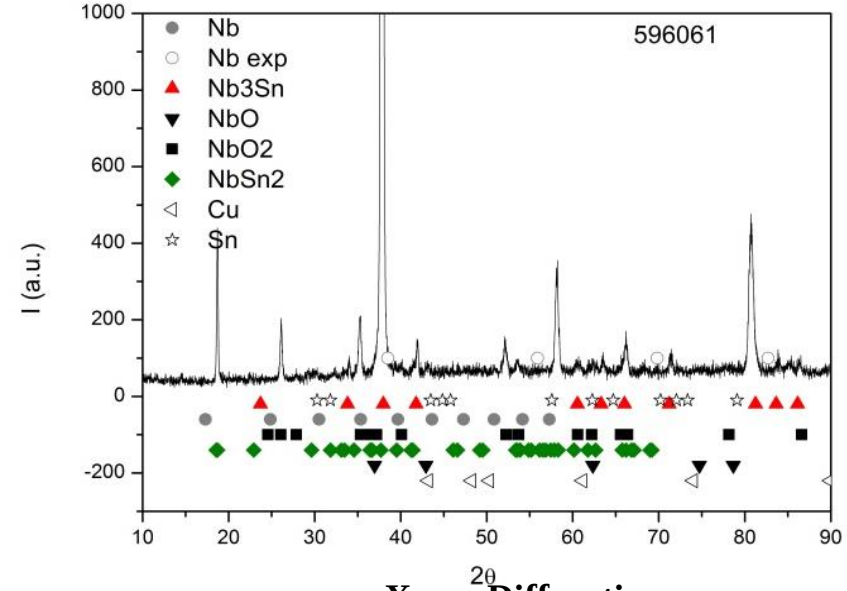




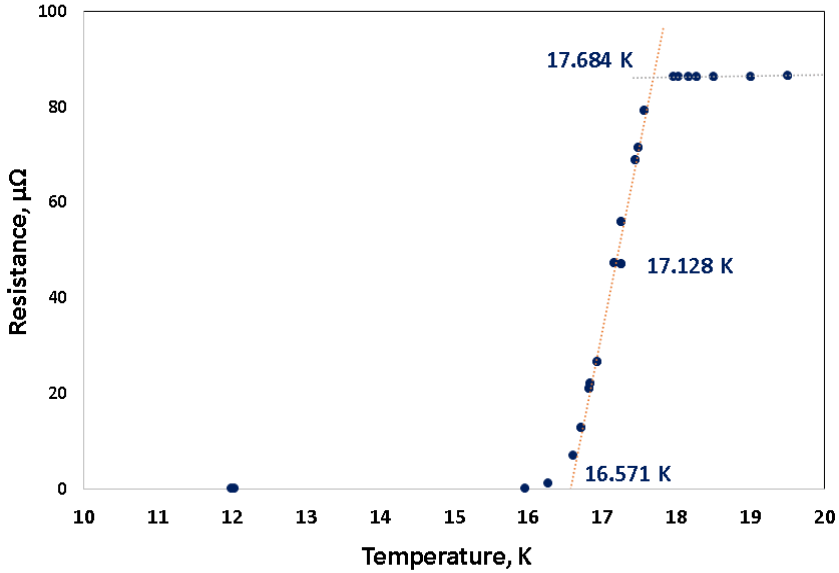
Nb_3Sn Thin Films on Nb - Results

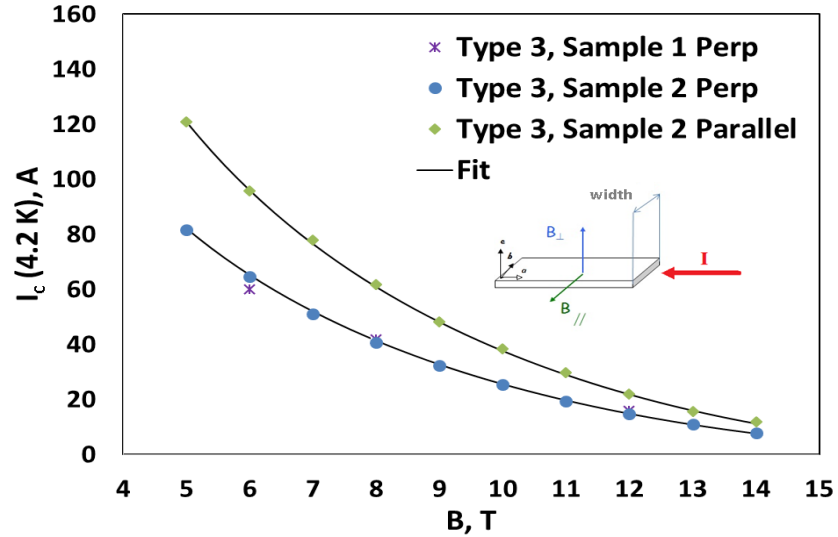


Glow Discharge Optical Emission Spectrometry



X-ray Diffraction





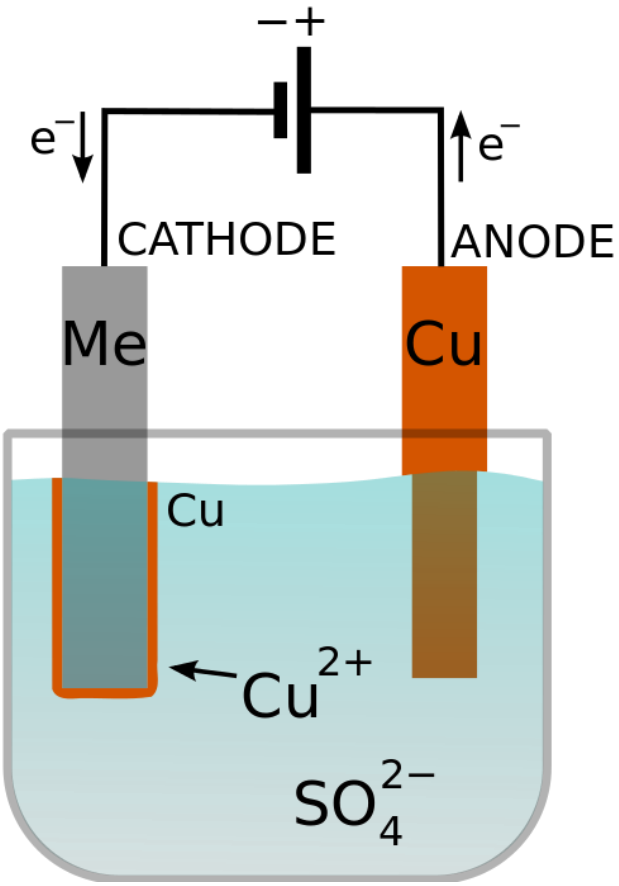
The maximum obtained T_c was 17.68 K and the B_{c20} ranged between 22.5 T and 23.8 T

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 = 40C (104 F)
- J = 30 mA/cm^2

The bath for this process is copper sulphate based:

$CuSO_4$	60 g/l
H_2SO_4	200 g/l
HCl	40 g/l



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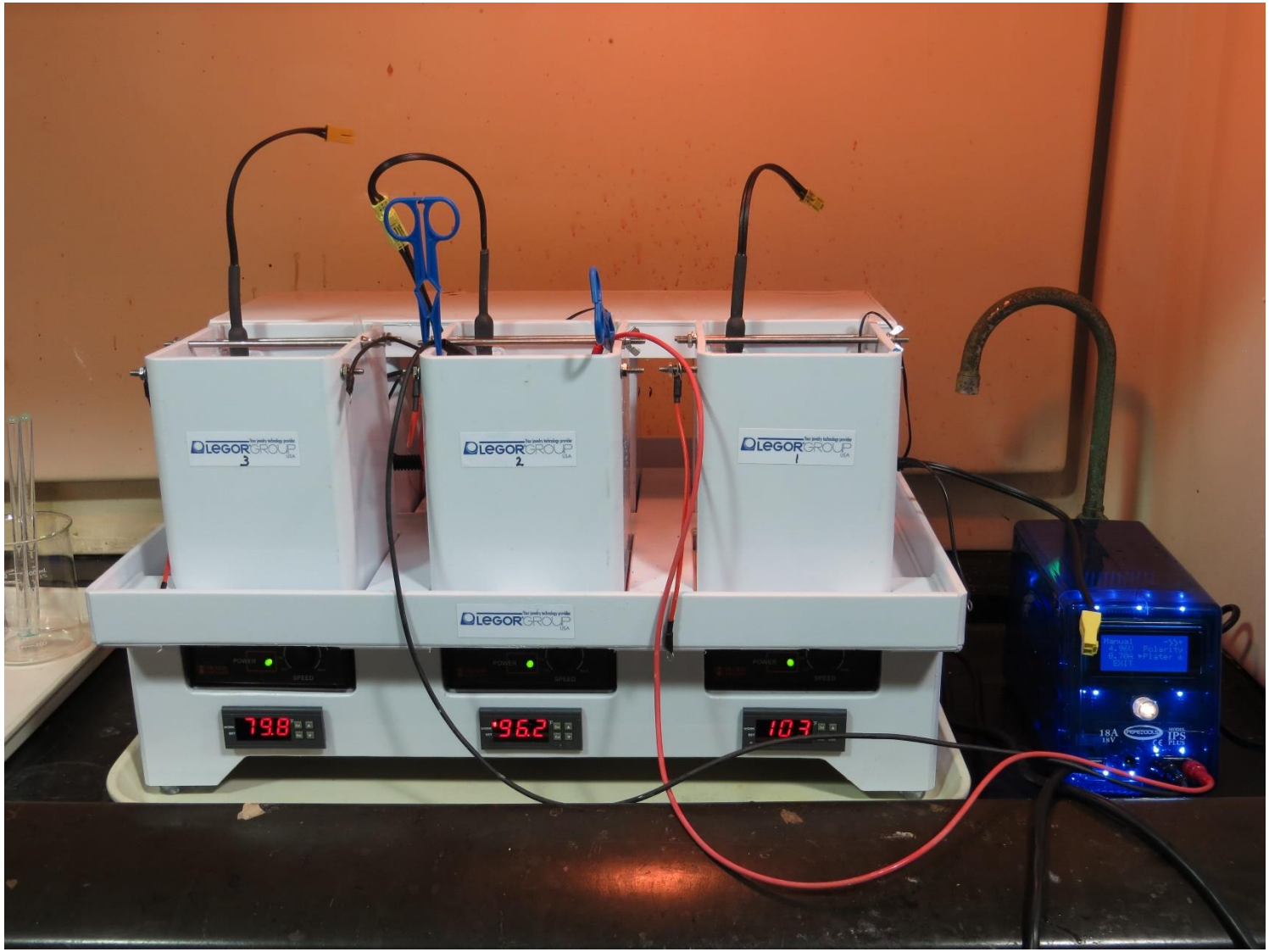
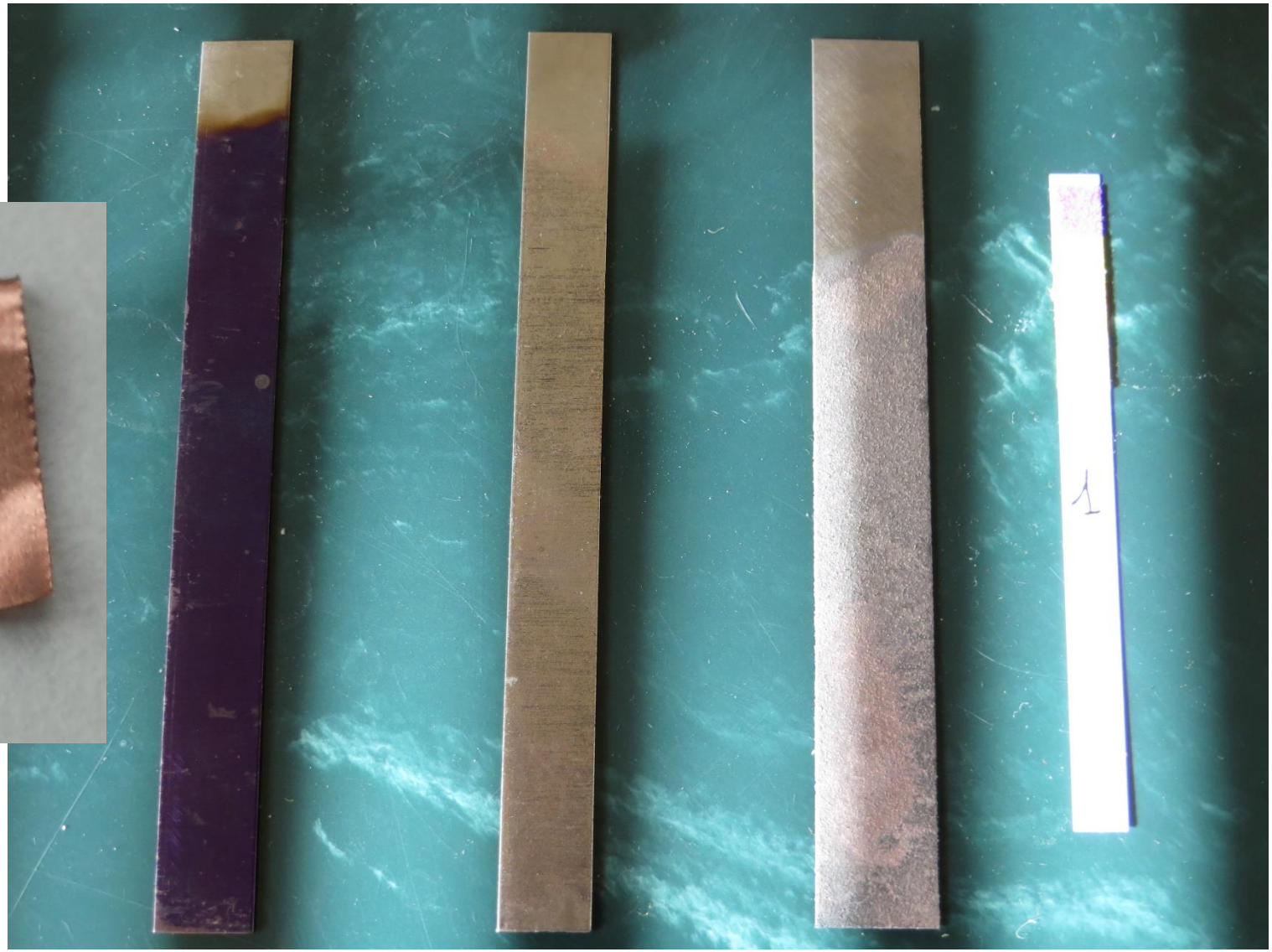


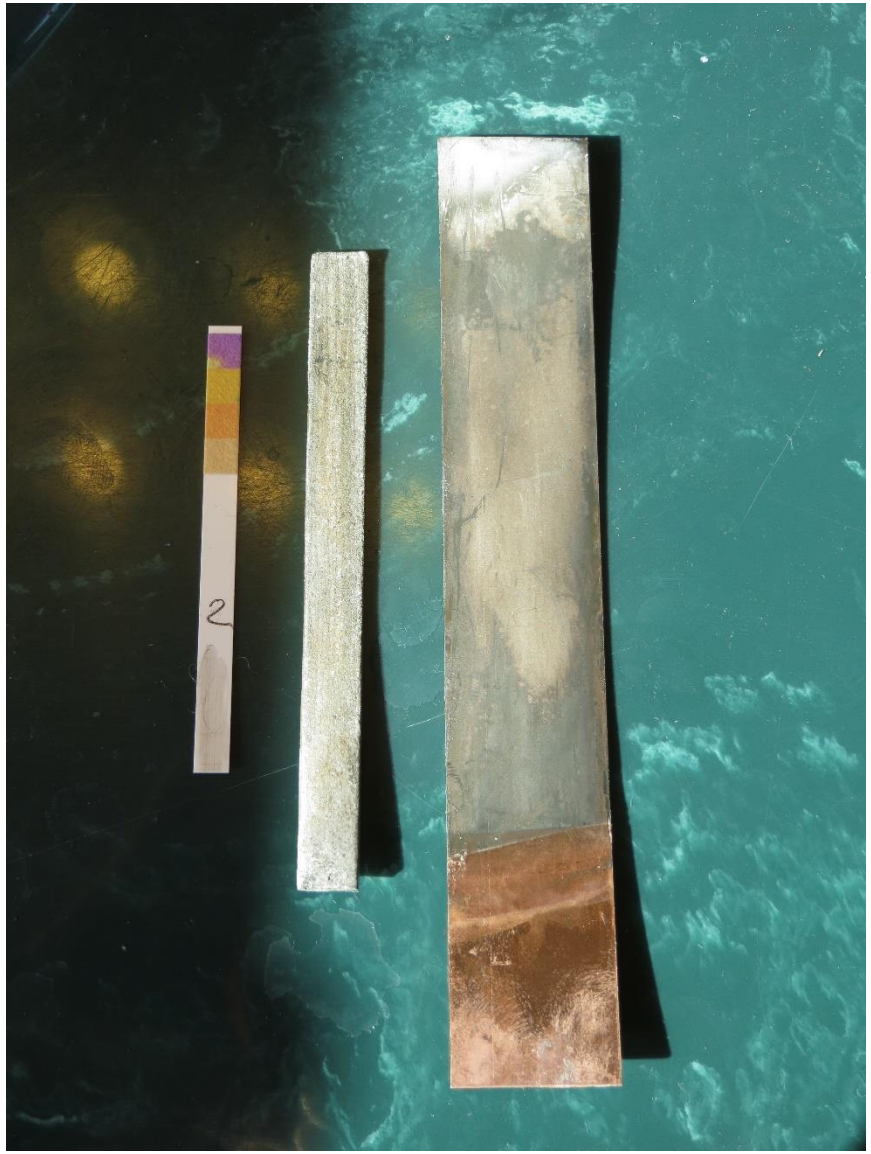
Electrodeposition of Cu seed layer onto a Nb substrate



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 = 50C (122 F)
- J = 50 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 = 50C (122 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

Nb_3Sn Thin Films – Potential for SC Wire Research

An inexpensive way to produce Nb_3Sn 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 Nb_3Sn:

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 Nb_3Sn boundaries to stop the longitudinal flux motion.**

Nb_3Sn 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**

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:

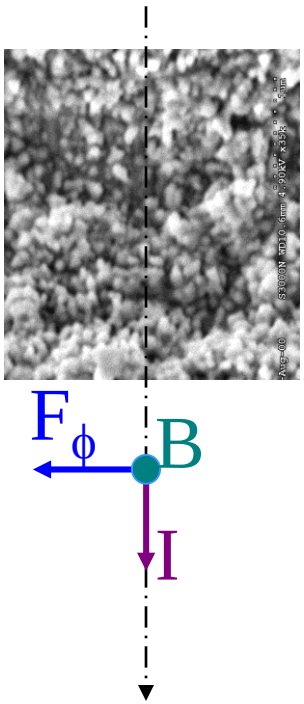
- **These techniques, revived recently at Cornell and JLab have not offered major process innovation. One of their main disadvantages is that the cavities have to be heat treated in vacuum up to 800-900°C for the process. The proposed process takes place at lower temperatures in argon. The project builds 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.**

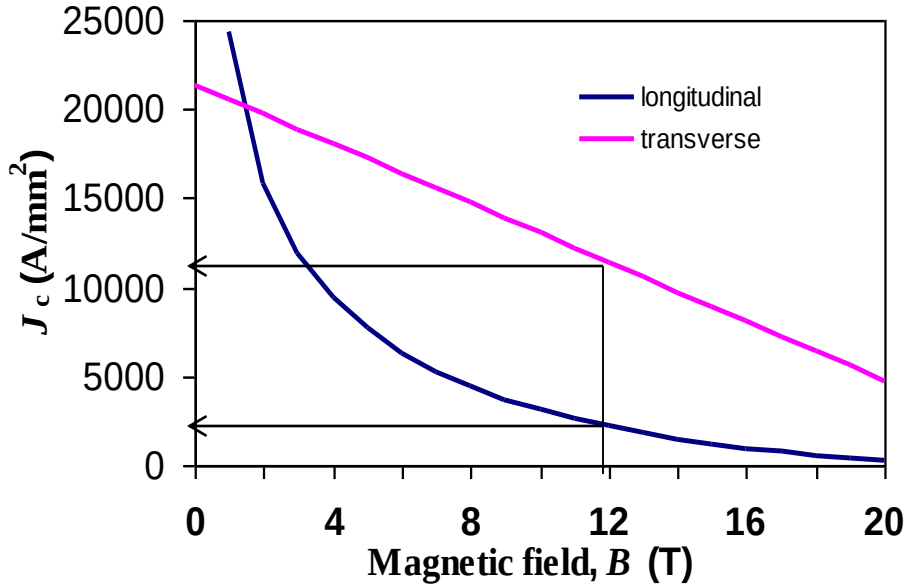
Reviewer 3:

- **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.**

A Model for J_c in Granular Superconductors

Predictions of MDB model





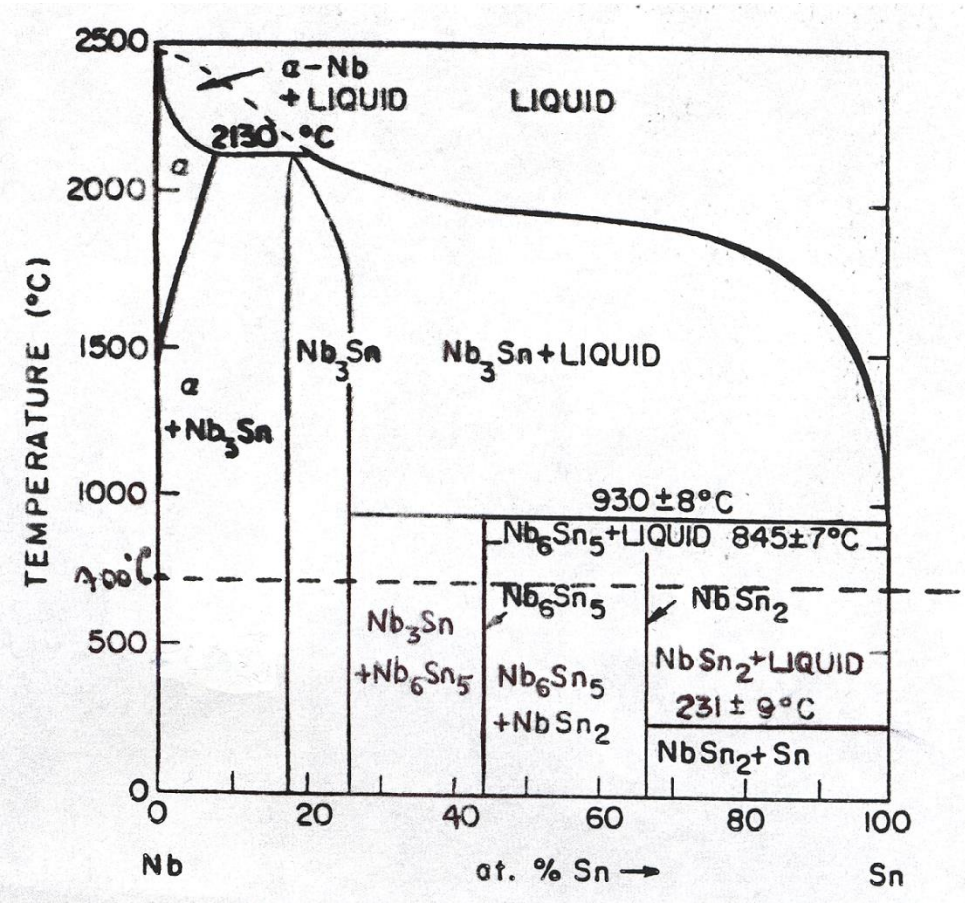
$$J_c^{\perp}(B,T) \approx \frac{B_{c2}}{8\pi\mu_0\kappa^2 D}\left(1-\frac{B}{B_{c2}}\right)$$

Transverse Pinning

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

Longitudinal Pinning

Nb_3Sn Phase Diagram



Nb-Sn binary phase diagram

Nb-Cu-Sn ternary phase diagram