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PVD Deposition Of Nb_3Sn From An Alloy Target On Copper

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on behalf of the team

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MOTIVATION

- Bulk niobium (Nb) has been for the past three decades: the material of choice for SRF applications:
  - It has the highest Tc (9.25K) for pure metal
  - It has highest lower magnetic field H_{c1}
  - Easy fabrication

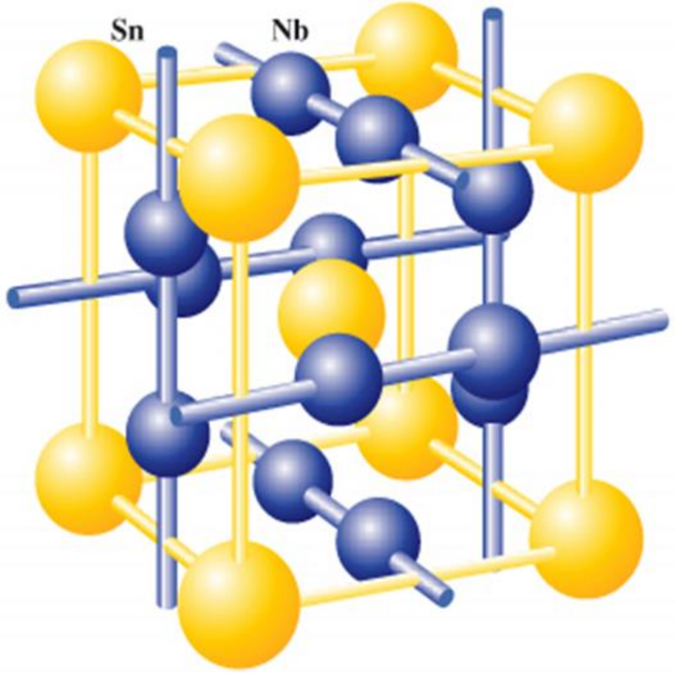
But it has achieved the magnetic field limitation so further improvement of cavity RF performance dictate to turn to other superconducting materials.

- Nb_3Sn alloy is type II superconductor with ideal Tc of 18 K and superheating field of 400 mT. Hence can offer improvement
  - Cryogenic efficiency
  - Higher accelerating field.
  - Recently there has been positive progress in producing Nb cavities with Nb_3Sn coating.

- The material can be deposited as thin film either in:
  - Single layer (Nb_3Sn on Cu or Nb)
  - Double layer (Nb /Nb_3Sn on Cu)
  - Multilayer (SIS): Nb /Insulator/ Nb_3Sn, on Cu

Nb_3Sn unit cell Structure

- The Sn atoms forms a bcc lattice and each cube face is bisected by orthogonal Nb chains.
- In bcc Nb the shortest distance between the atoms is 0.286 nm starting from a lattice parameters of a = 0.330 nm
- In Nb3SN the lattice parameters of about a = 0.529 nm for stoichiometric composition and the distance between the Nb atoms is 0.265 nm
- The reduction of distance between the Nb chains is responsible for the high Tc in comparison to bcc Nb.
- Sn deficiency may cause the Nb to occupy the site and effect the long range order

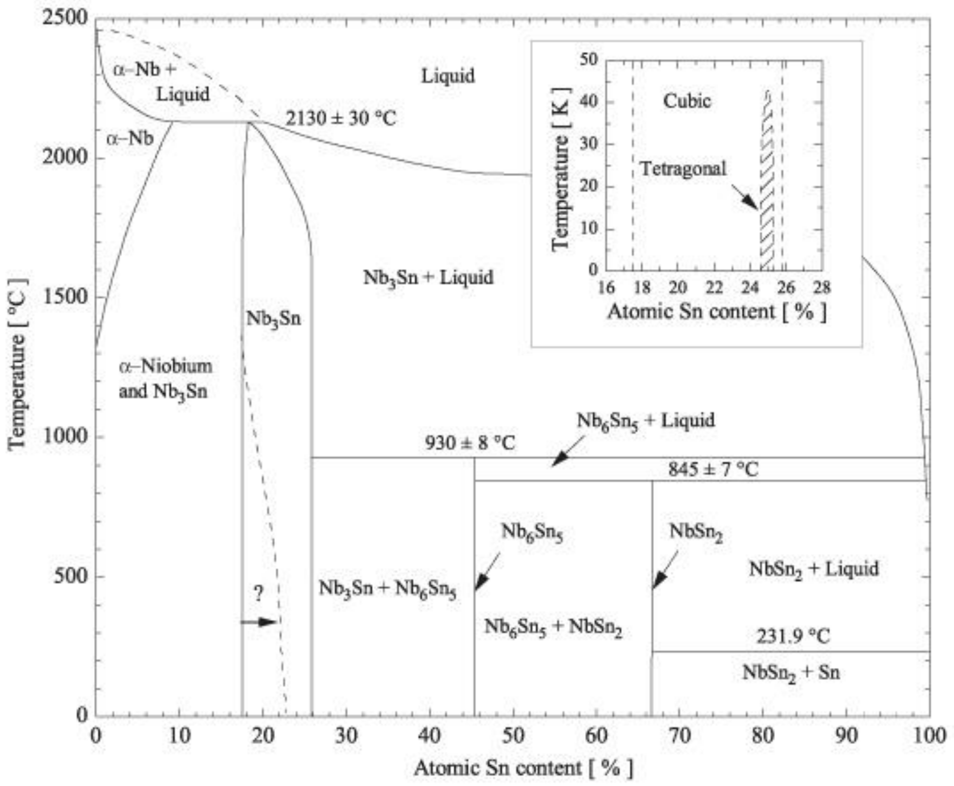


Nb_3Sn binary phase diagram

- Intermetallic niobium–tin is based on the superconductor Nb, which exists in a bcc Nb structure or a metastable Nb_3Nb A15 structure

- When alloyed with Sn and in thermodynamic equilibrium, it can form either Nb1−βSnβ (about 0.18≤β≤0.25) or the line compounds Nb6Sn5 and NbSn2.

- Both the line compounds at β = 0.45 and 0.67 are superconducting, with
  - Tc<2.8 K for Nb6Sn5
  - Tc<2.68 K for NbSn2



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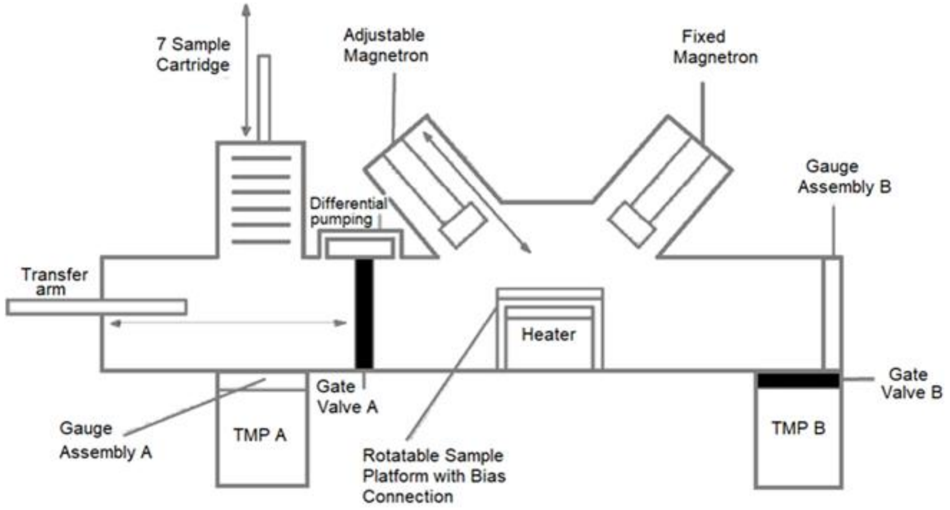
Nb_3Sn deposition system and parameters

- ❑ Magnetron sputtering from a RRR 300 Nb target
- ❑Substrate Temperature, Deposition Rate, Deposition Thickness, Substrate Bias, Concurrent Ion Bombardment can be varied independently.
- ❑Substrates are loaded into the load lock and system fully Baked.
- ❑Base pressure 2 x 10^{-9} mbar is routinely achieved

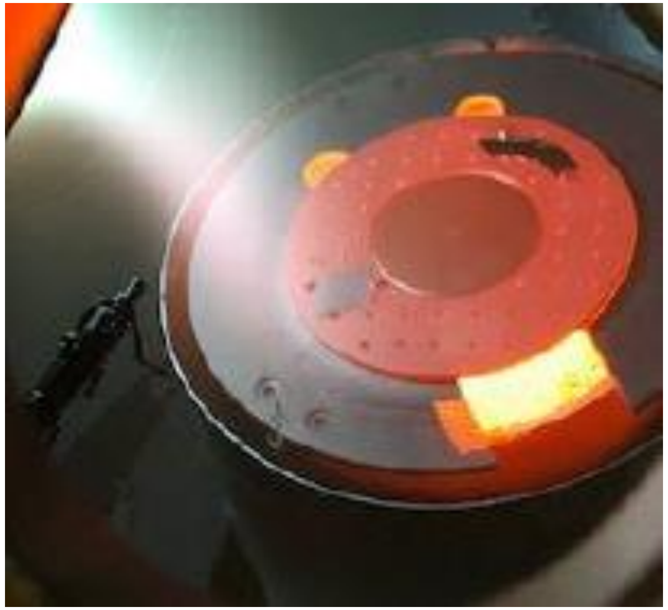


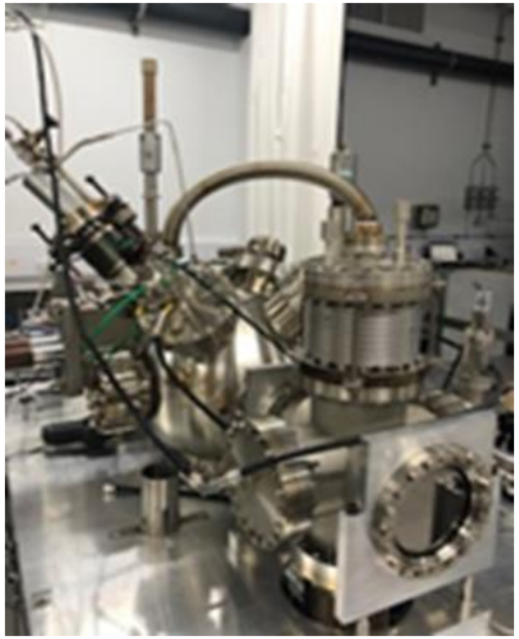
Nb deposition:

- 400 W, 470v, 0.85A
- 4 hours deposition
- DC sputtering

Nb3Sn deposition:

- 200 W, 489 V, 0.41 A
- 2 Hours deposition
- DC sputtering





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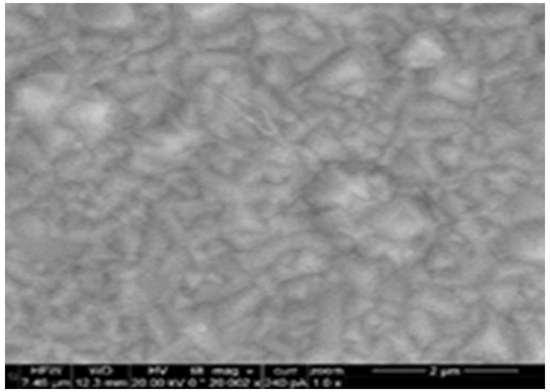
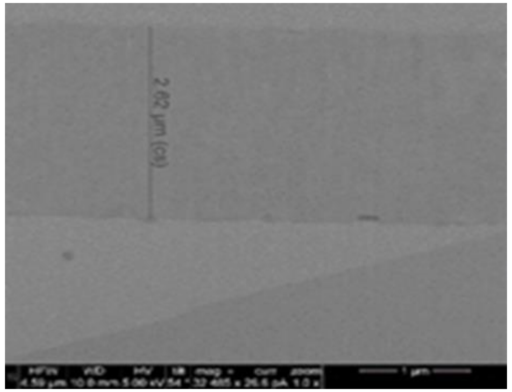
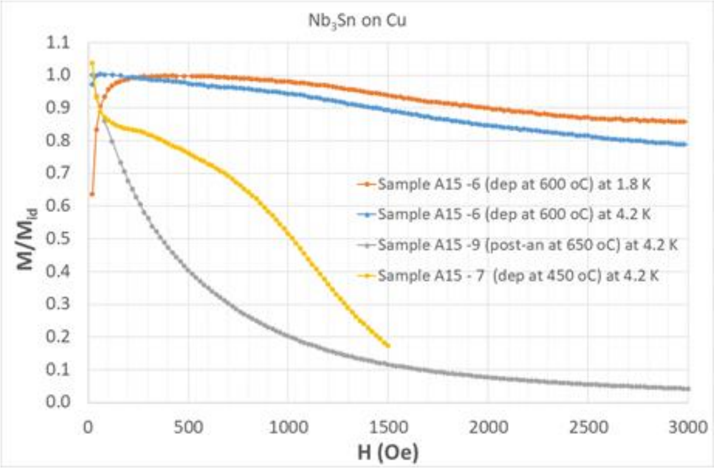
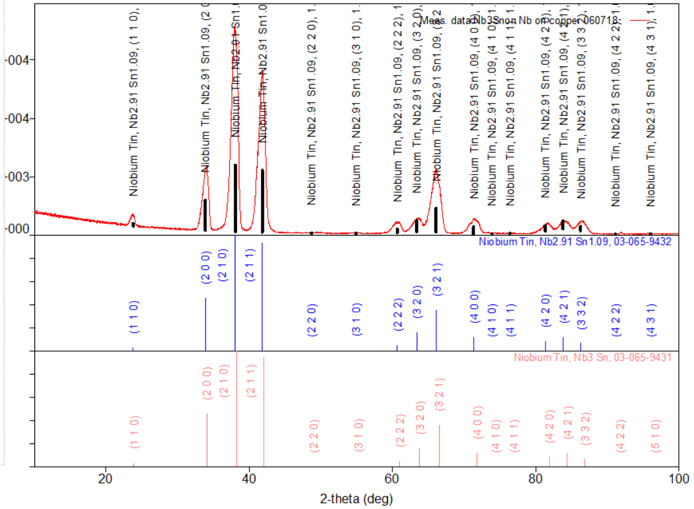
Cu/Nb_3Sn deposition (single layer) at various Temperature









- Nb$_3$Sn were deposited on copper with no prior chemical cleaning such (EP or SUBU5) at various Temperature of RT, 450°C and 600°C. The RT deposition showed no sign of superconductivity.
- Best performance in terms of superconducting properties is achieved by the film deposited at 600°C (A15-6) with a Tc of 15.7 K, a lattice parameters of 0.529 nm and grain size in order of 8 to10 nm.
- The film deposited at moderate temperature of 450°C was superconducting but its performance is much reduced with Tc of 14.6 K
- The film deposited at room temperature and then post annealed at 650°C (A15-9) has the worst performance since M/Mi drop sharply at very low field of about 10 mT.

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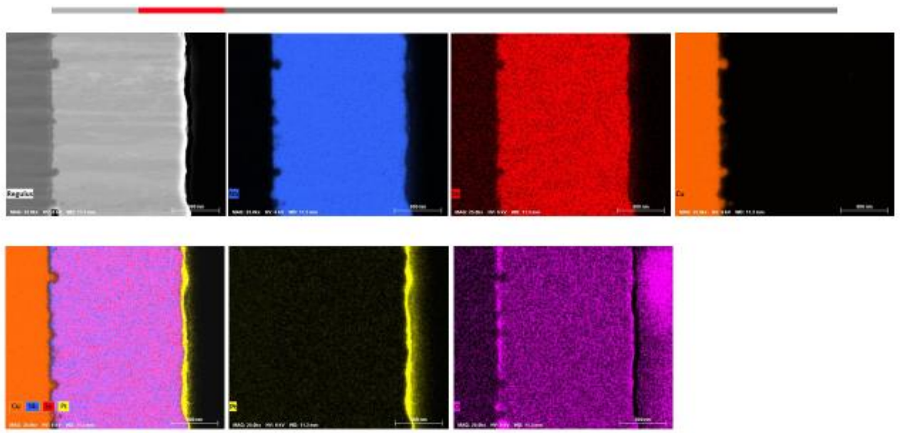
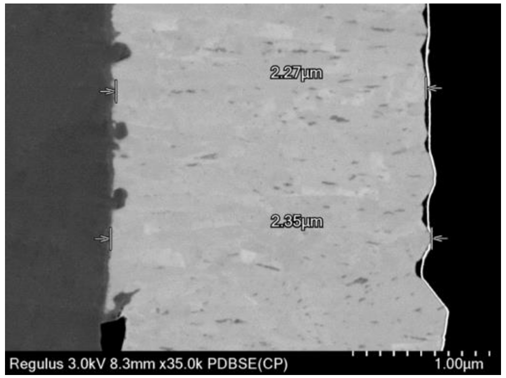
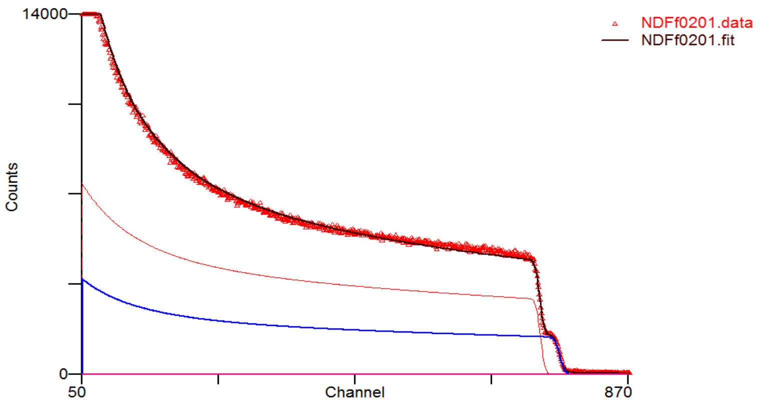
Cu (EP)LNL / Nb_3Sn (single layer)

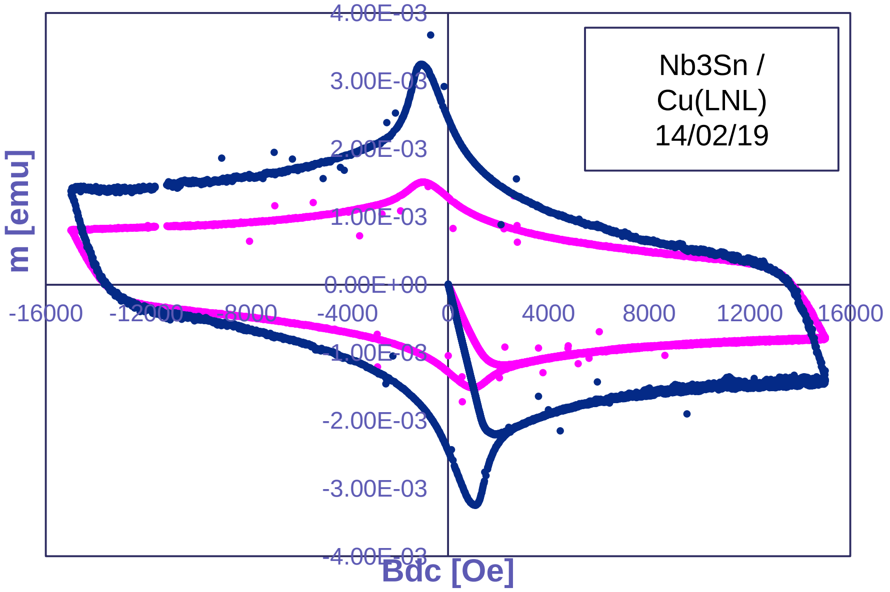
- There is some diffusion of copper at the interface
- There is a clear oxide layer at the interface despite high temperature treatment prior deposition (no prior chemical processing)
- There are area that it is Sn deficient.
- The Tc was determined to be between 17.75K (on sapphire) and 17.5 on copper
- First B_{en} estimated to be 50mT and 140mT deposited on Cu and Sapphire.

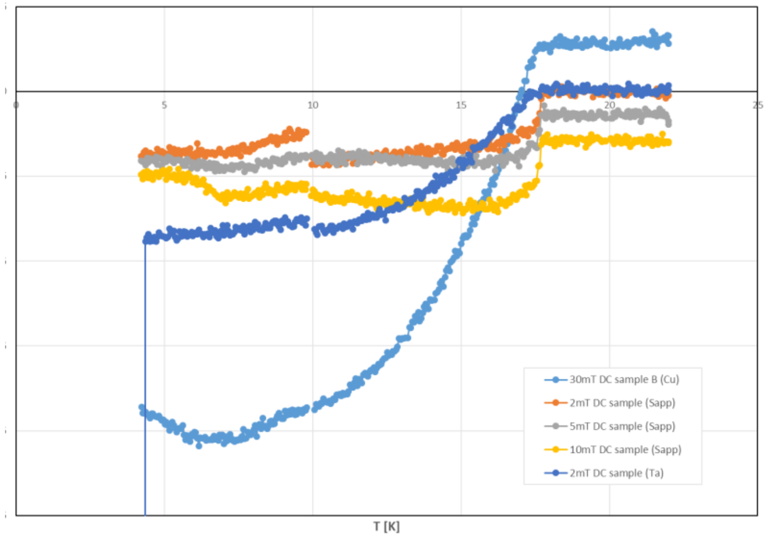




Layer	t (1e15at/cm2)	t (nm)	r(1e22at/cm3)	Nb	Sn	Al	O
1	7606.631	1489.817	5.106	75.0000	25.0000	0.0000	0.0000
2	821647.625	69631.156	11.800	0.0000	0.0000	40.0000	60.0000







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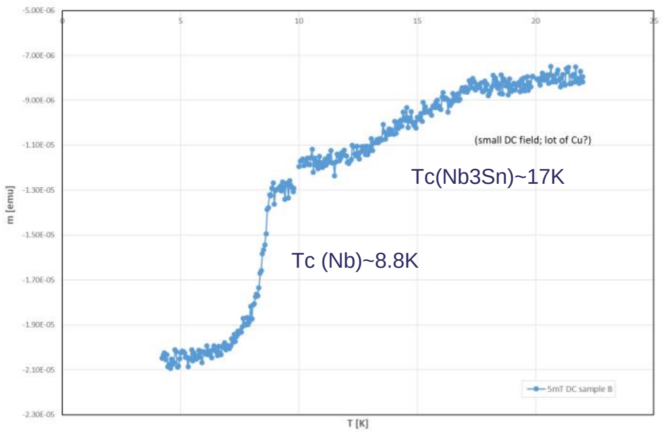
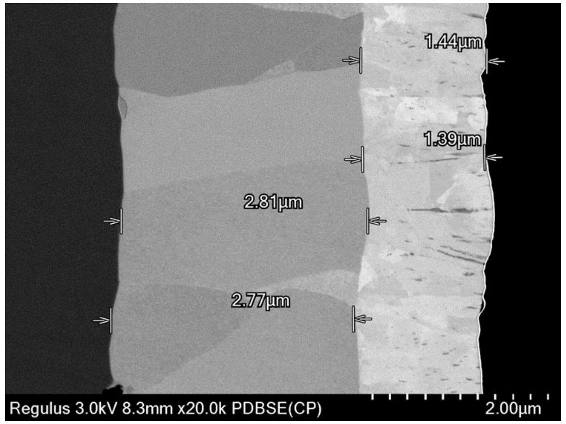
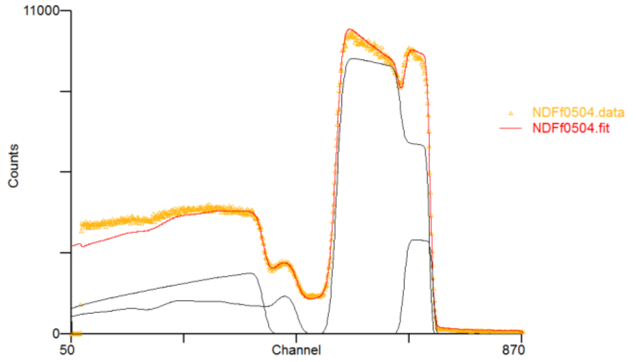
Cu /Nb/Nb_3Sn (double layer)

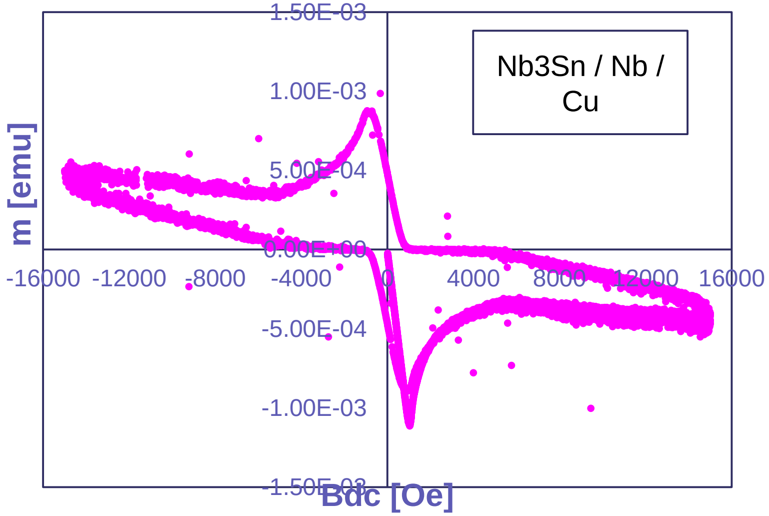
- The interfaces both at Cu/Nb and Nb/Nb3Sn is well define
- Nb layer is grown is large grain and in a perpendicular direction to the substrate surface
- No intermixing of elements is observed
- Some area of Sn deficiency and rich Sn in Nb3Sn layer can be observed
- First B_{en} is estimated at 95mT.

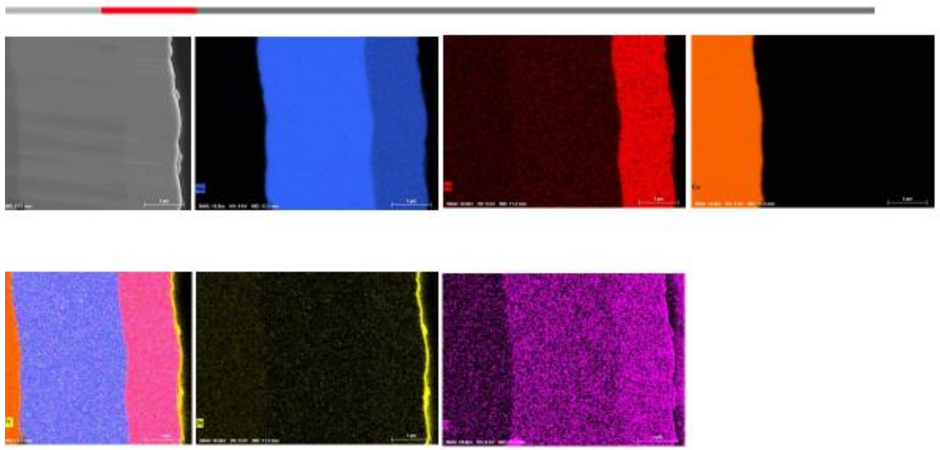




Layer	t (1e15at/cm2)	t (nm)	r(1e22at/cm3)	Nb	Sn	O	Al
1	7644.333	1497.201	5.106	75.0000	25.0000	0.0000	0.0000
2	15920.986	2855.270	5.576	100.0000	0.0000	0.0000	0.0000
3	898207.563	76119.281	11.800	0.0000	0.0000	60.0000	40.0000





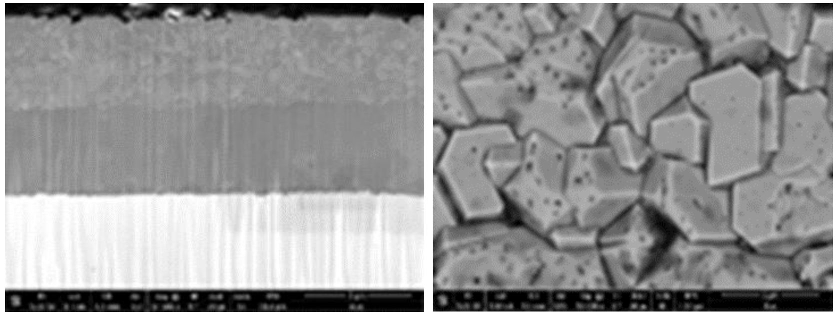


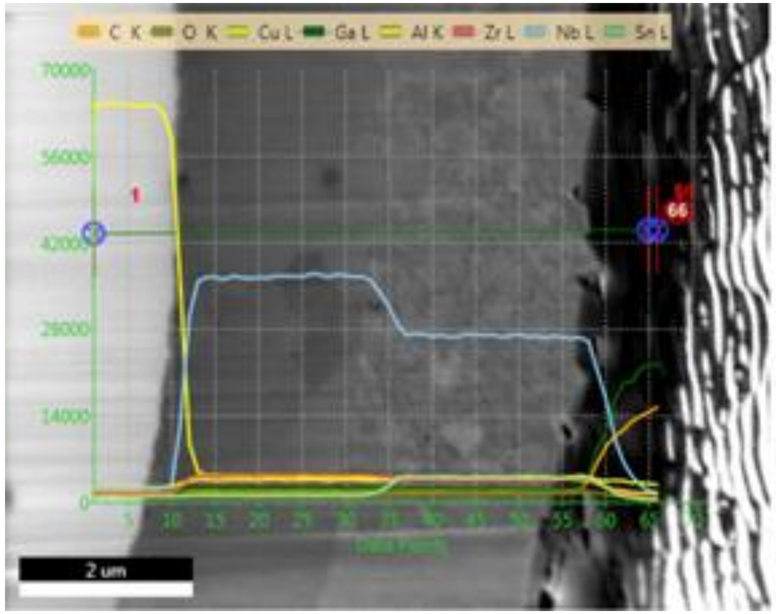
Cu/Nb/Nb_3Sn (double layer)

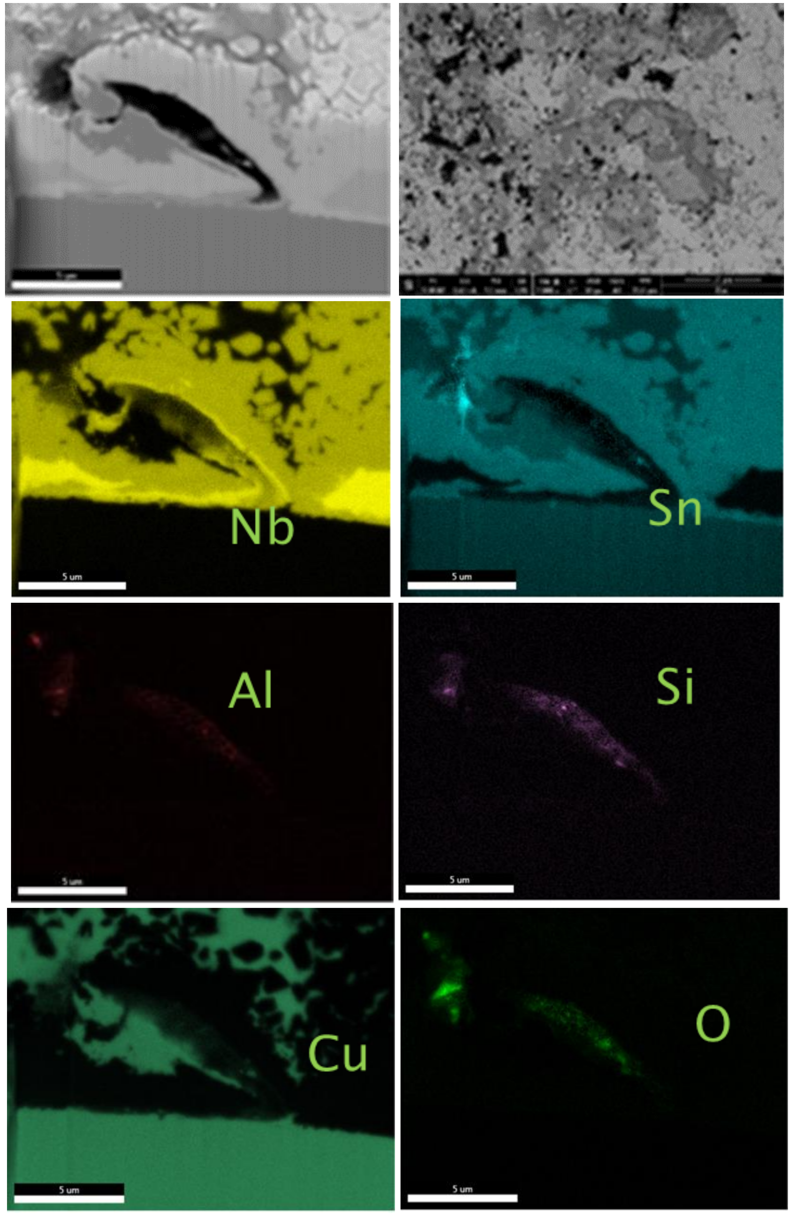
- Two distinct area can be observed:
  - Perfect area with sharp interface with correct stoichiometry for Nb3Sn layer
  - Copper diffusion from the interface to top surface.

- Nb and Nb_3Sn layers are completely intermixed and there is a substantial volume of copper substrate is present throughout the depth of the layer and at the surface

- Inside the cavity there are trace silicon and aluminium oxide.







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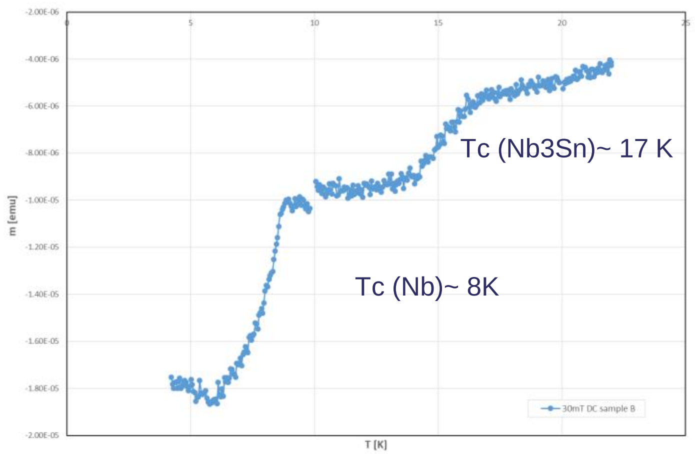
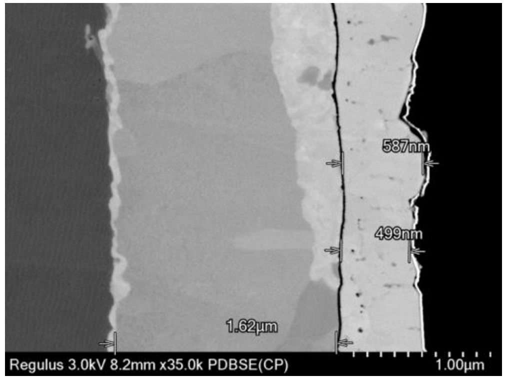
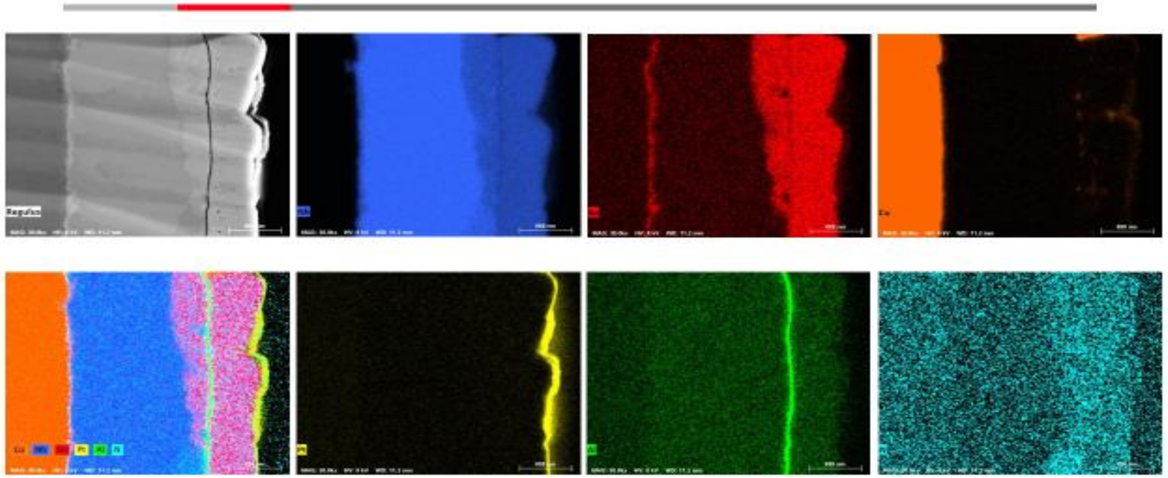
SIS Structure of thick Nb_3Sn/AlN/Nb multilayer on copper

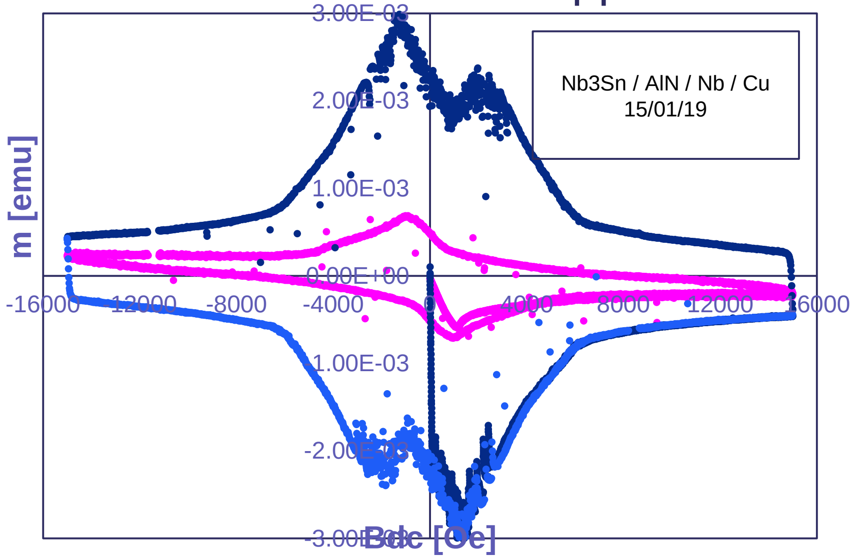
- Although the layers are well identified however there is again some degree of mixing can be observed.

1. Sn segregation at Cu/Nb interface
2. Nb_3Sn into Nb layer below the AlN layer at some places
3. Copper diffusion on to the surface
4. Some level of Nitrogen diffusion into all the layers.
5. The B_{en} in parallel external field is estimated to be 61mT and 4mT for Cu and Sapphire Substrate









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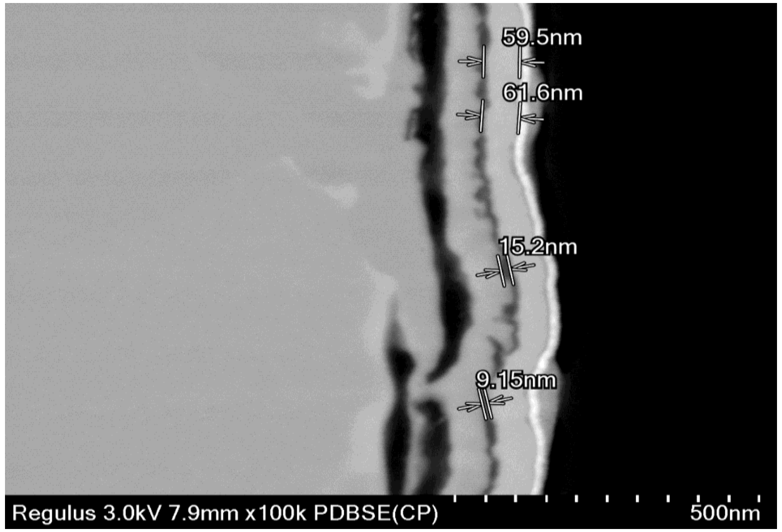
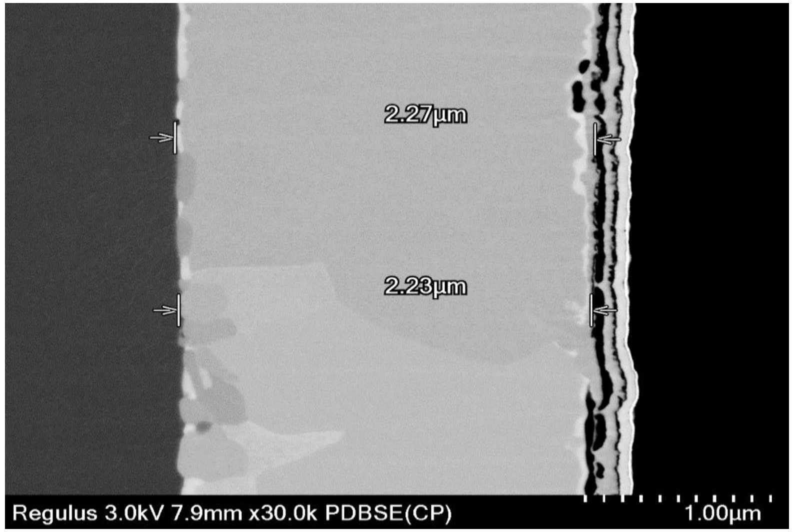
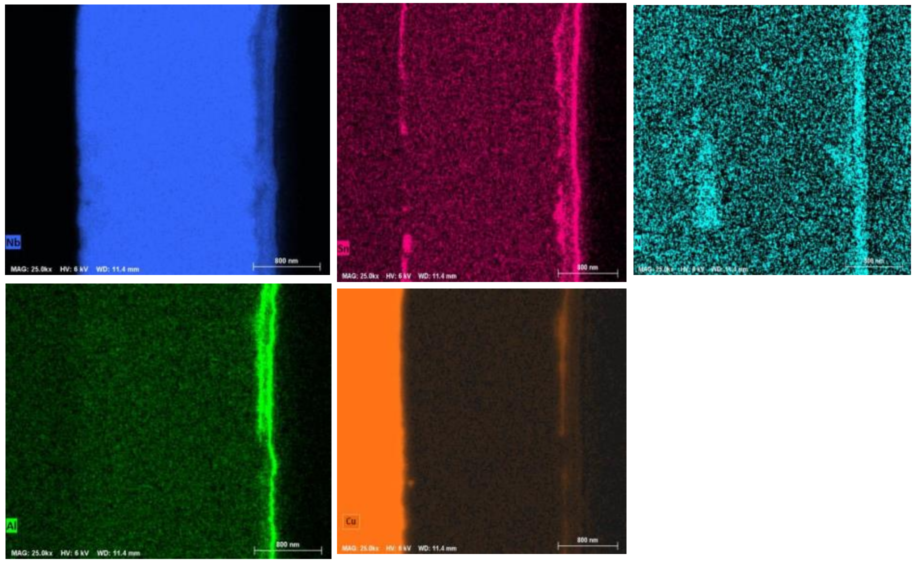
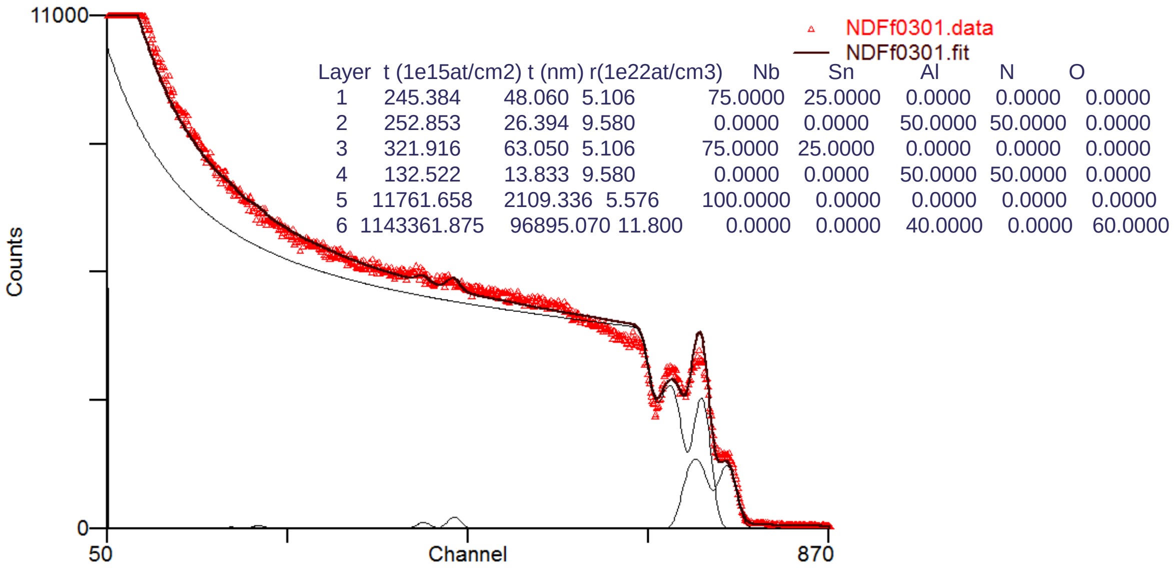
SIS Structure of thin layer $(Nb_3Sn/AlN)_2/Nb$ multilayer on Cu







- The observed distortion of the Nb_3Sn / AlN bilayer is most probably due to mechanical polishing prior to ion beam milling, since such distortion is not present in the RBS spectra
- The RBS analysis predicts stoichiometric layers with the second AlN layer almost being double the thickness of the first AlN layer. Similarly the first Nb_3Sn layer is 25% thicker than the second Nb_3Sn layer.



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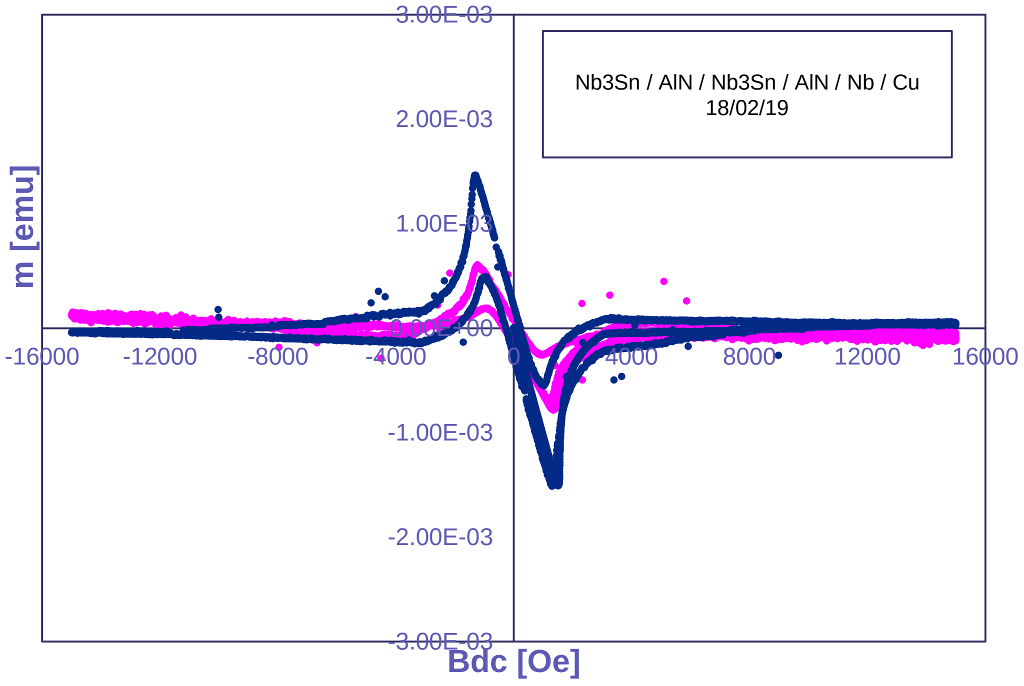
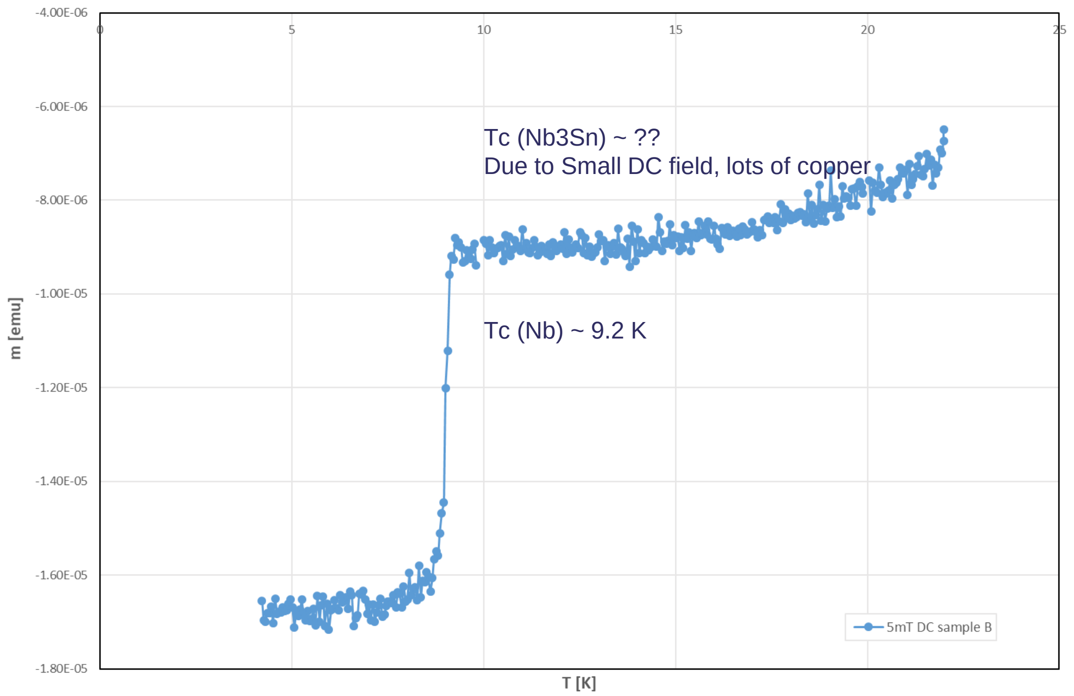
SIS Structure of thin layer $(Nb_3Sn/AlN)_2/Nb$ multilayer on Cu





- The B_{en} in parallel external field is estimated to be 108 mT and 130 mT for Cu and Sapphire Substrate
- There is nearly no hysteresis in the thin double SIS structure
- This can be due to the protective effect of multilayers which reduces the sensitivity to pinning effect.

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Summary

- Nb_3Sn can be successfully deposited from an alloy target with satisfactory SC properties when it is deposited at high temperature (around 600-650 °C).
- Final Smooth surfaces and sharp interface between layers can be achieved by suitable surface preparation method/process of substrate
- Impurities such as silicon oxide may cause complex defects to be formed when Nb3Sn is deposited in multilayer structure.
- Substrate preparation can influence the growth of the film and hence its SC properties
- Protective effect of multilayers to some extend is been shown:
  - Less sensitivity to pinning defects
    - Multilayer structure even without insulating layer reduced the hysteresis loop
    - Defects are still present in individual layers
    - Not detected anymore when SIS structure fully SC.
- Complementary non-destructive technique such as RBS proved to be a powerful technique to distinguish post sample preparation damage.

Special Thanks to all the team member

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Thank you

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