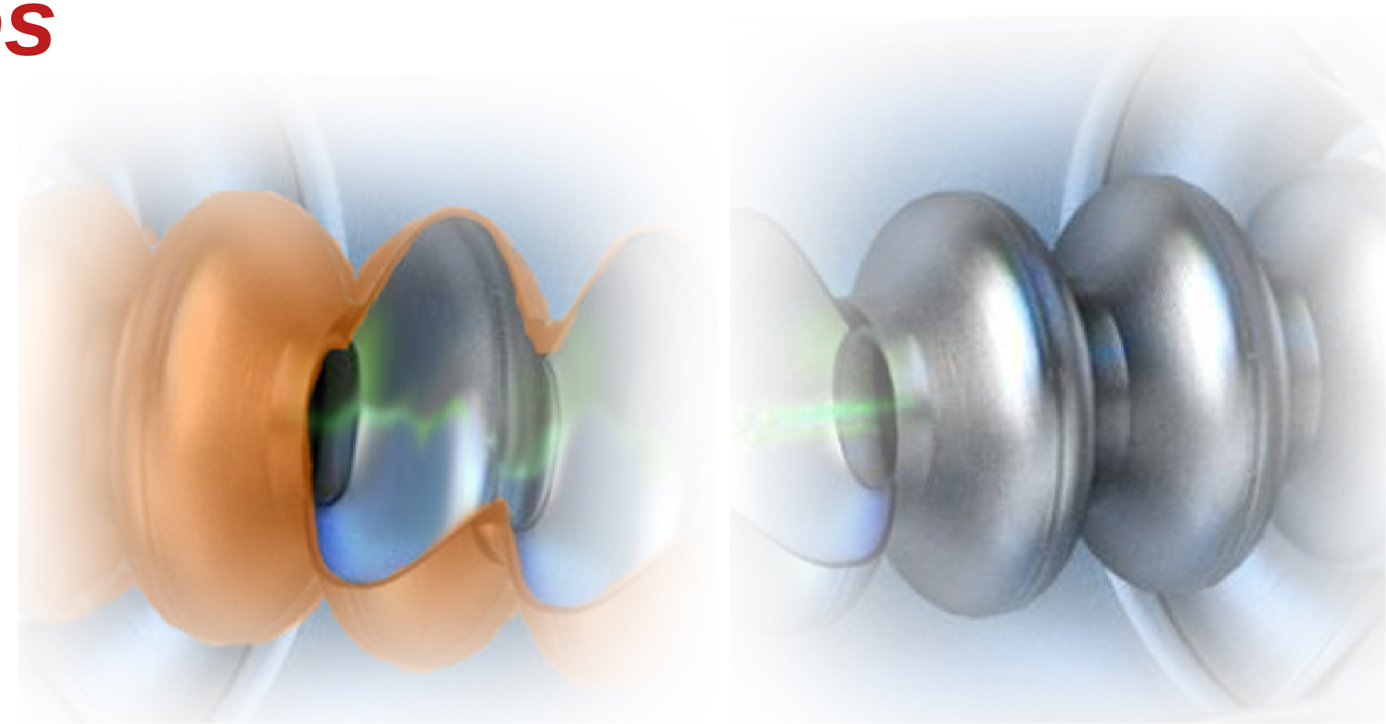
SRF Thin Film Activities @ JLab

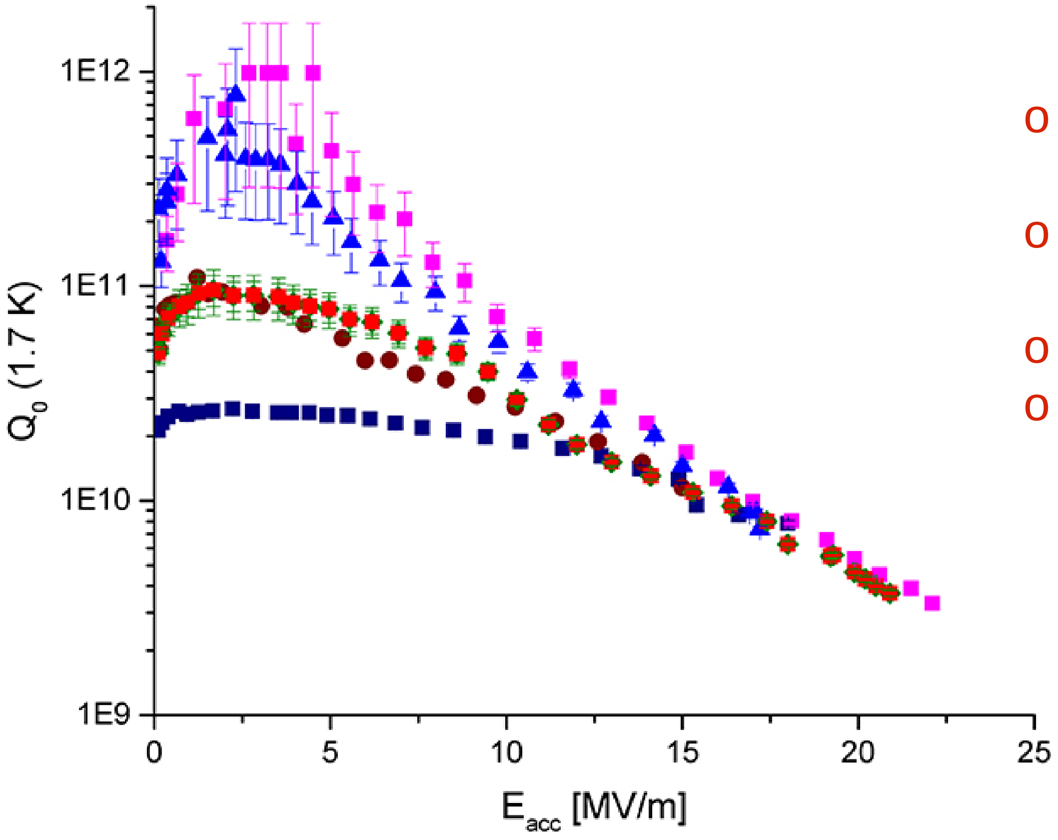


D.R. Beverstock, M.C. Burton, K. Macha, D. Manos, M. Kelley, A. Palczewski, U. Pudasaini, C.E. Reece, R.A. Rimmer, J.K. Spradlin, H. Tian, A.-M. Valente-Feliciano

Next Generation Nb/Cu SRF Cavities Based on Advanced Coating Technology for CW Accelerators

Nb/Cu Technology proof of principle with LEP2, LHC, ALPI machines

Great potential for cost savings and operational advantages for machines operating at lower frequency and relatively modest gradients



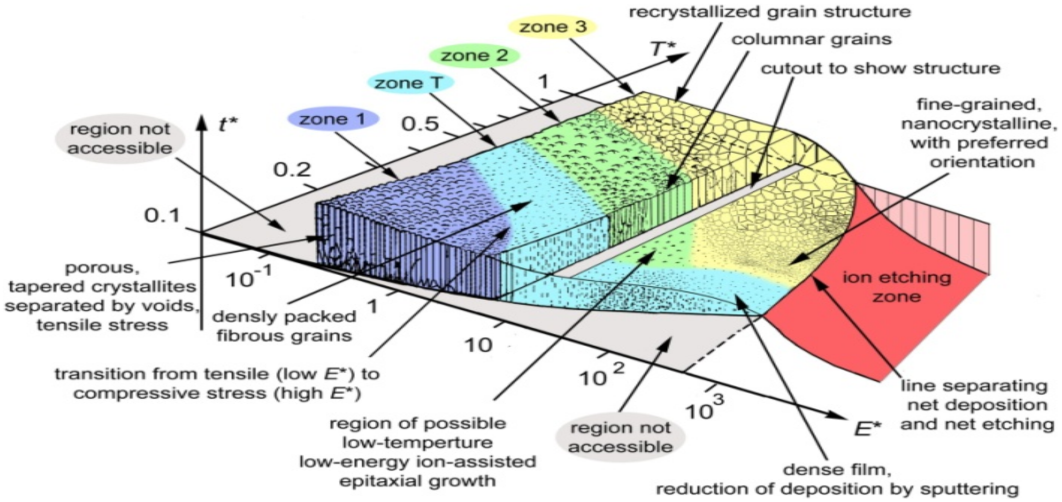
high current storage ring colliders : FCC, EIC and CEPC

- 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.

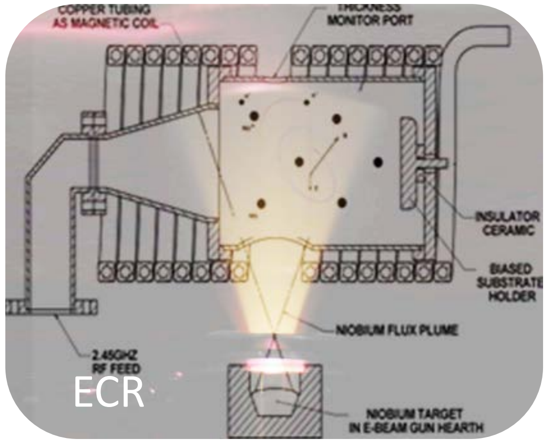
Energetic Condensation

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



Anders, André. "A structure zone diagram including plasma-based deposition and ion etching." *Thin Solid Films* 518.15 (2010): 4087-4090.

Electron Cyclotron Resonance (ECR)



No working gas

Singly charged ions (**64eV**)

produced in vacuum

Controllable

deposition energy

with Bias voltage

Excellent bonding

No macro particles

High Power Impulse Magnetron Sputtering (HiPIMS)

Requires working gas

Mulitply charged ions of Nb & Kr

Presence of neutrals

Controllable

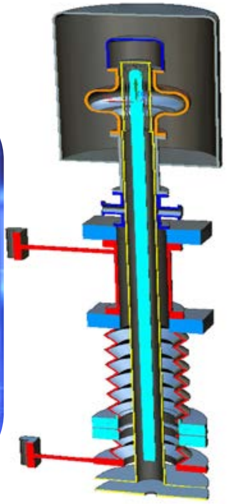
deposition energy

with Bias voltage

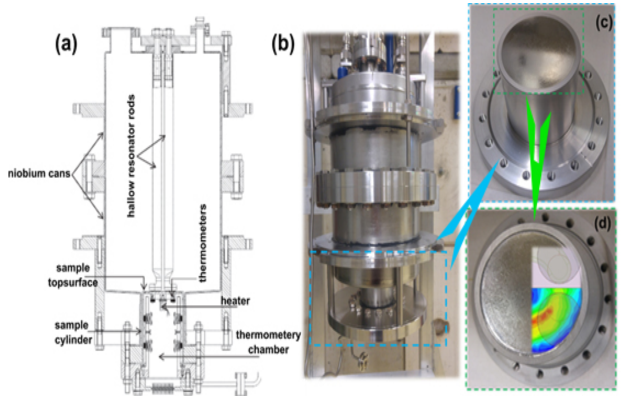
Excellent bonding

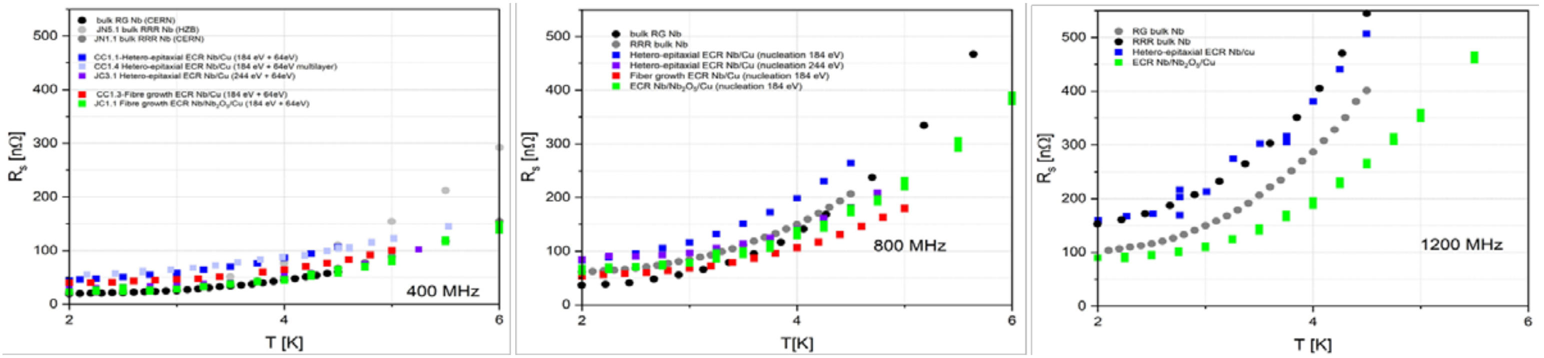
No macro particles

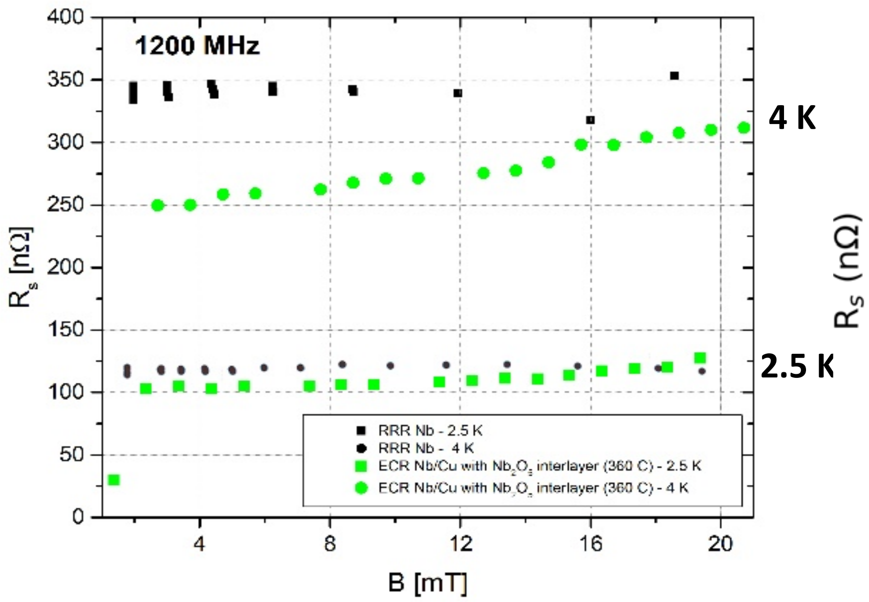
Ease of cavity configuration

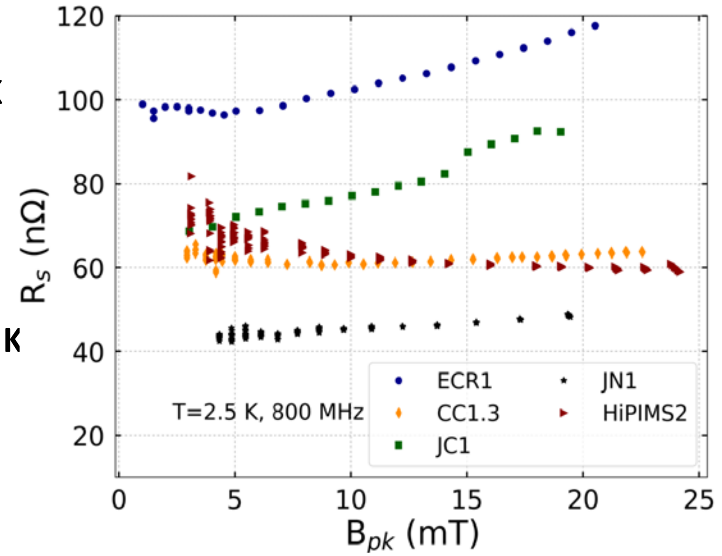


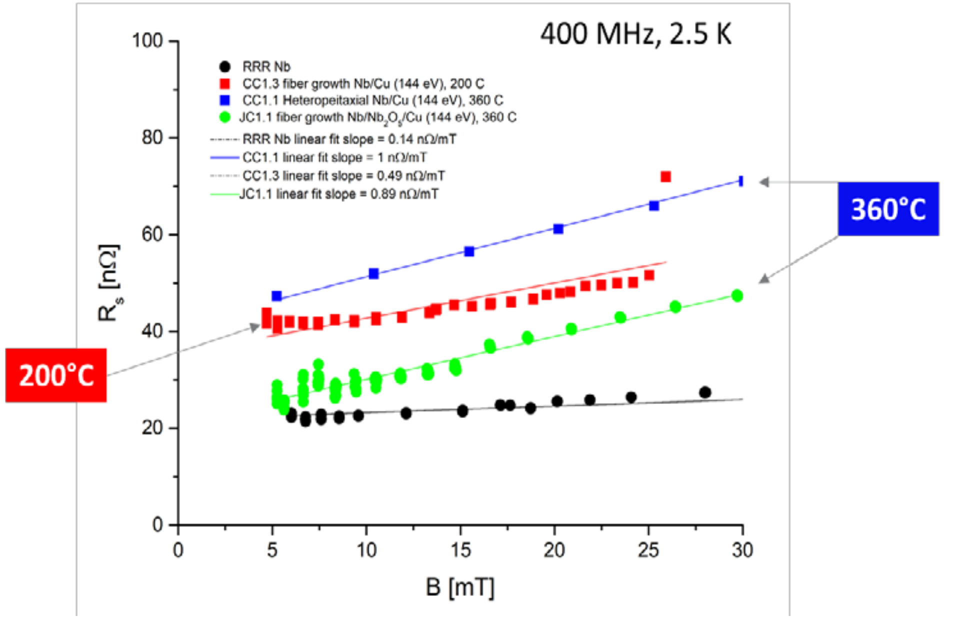
Nb/Cu via Energetic Condensation – ECR & HiPIMS





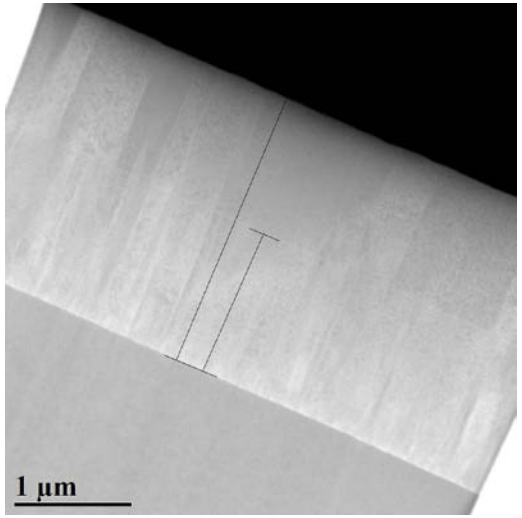


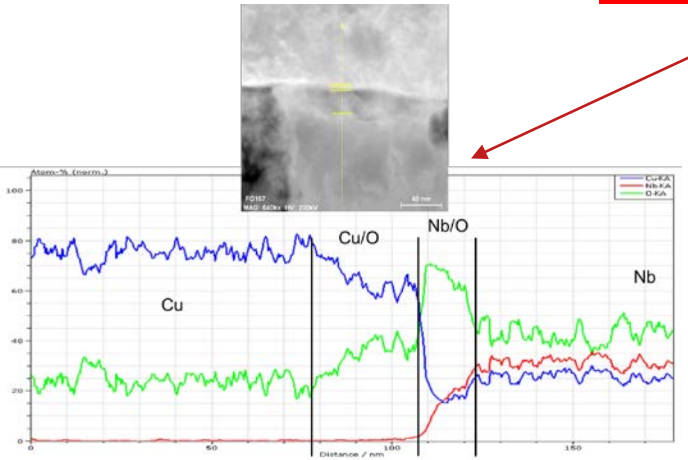


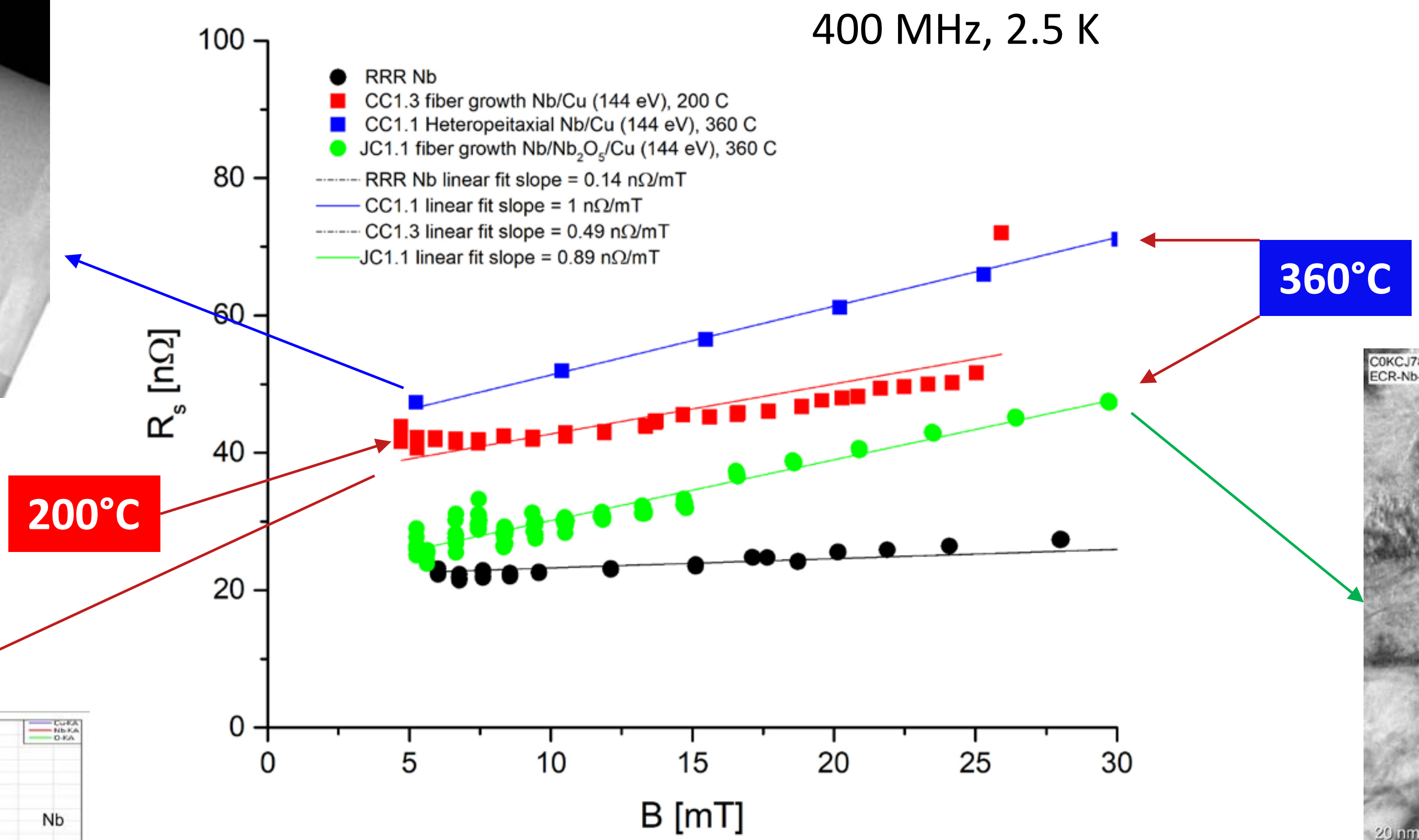


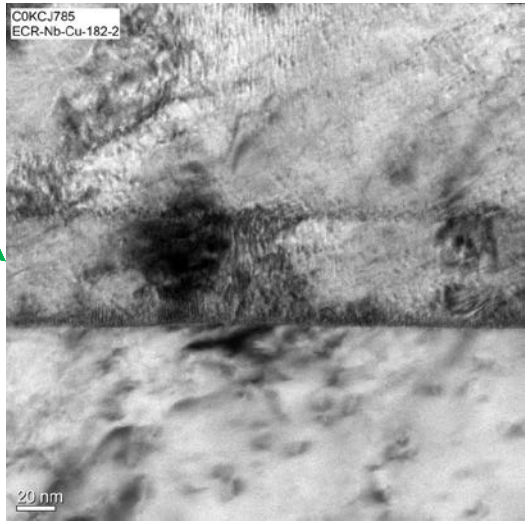
ECR Nb/Cu Film – Fiber Growth vs. Hetero-epitaxy

RF measurement at CERN: S. Aull, M. Arzeo, L. Vega Cid







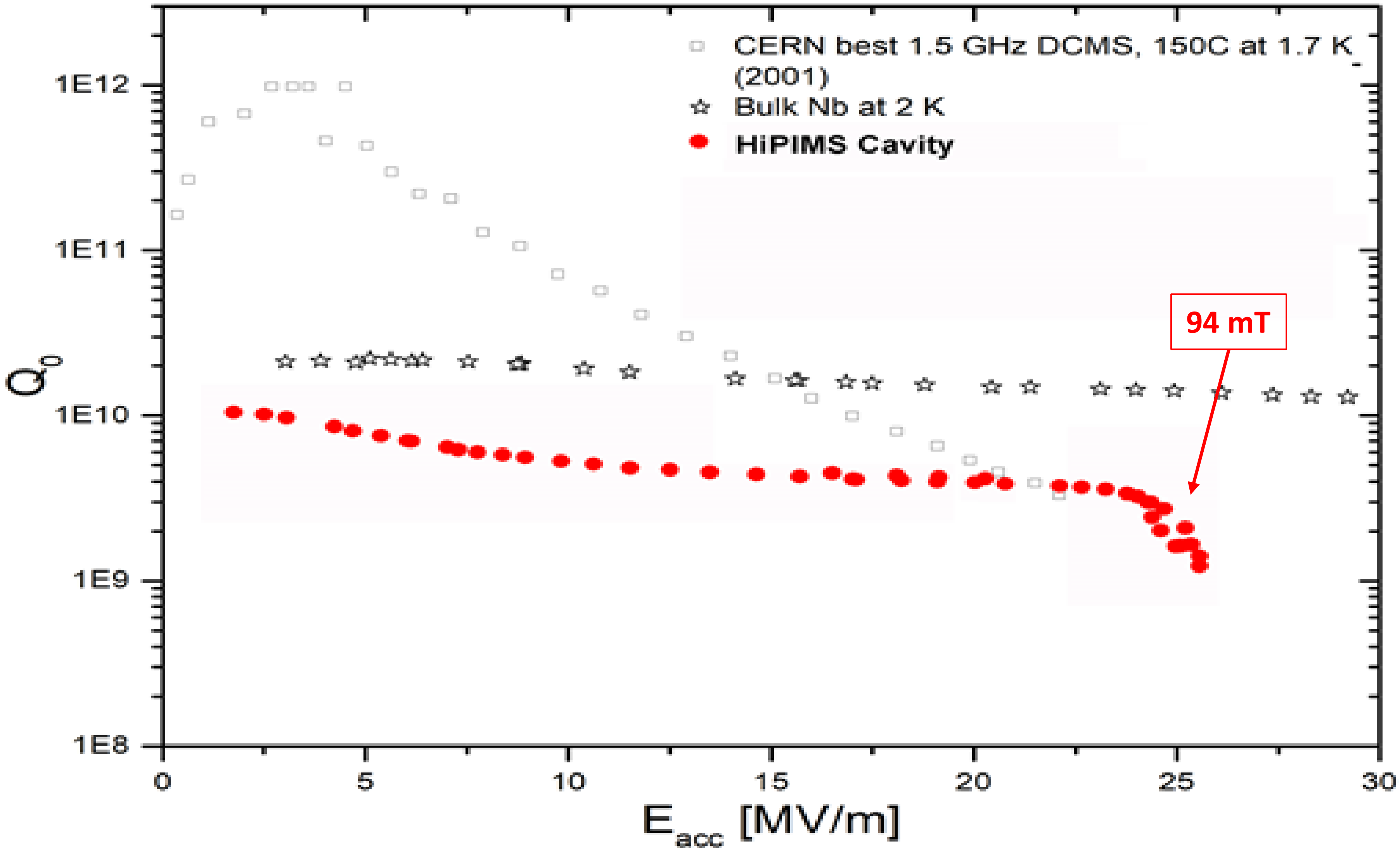


Fiber growth ECR Nb/Cu show better mitigation trend of the Q-slope

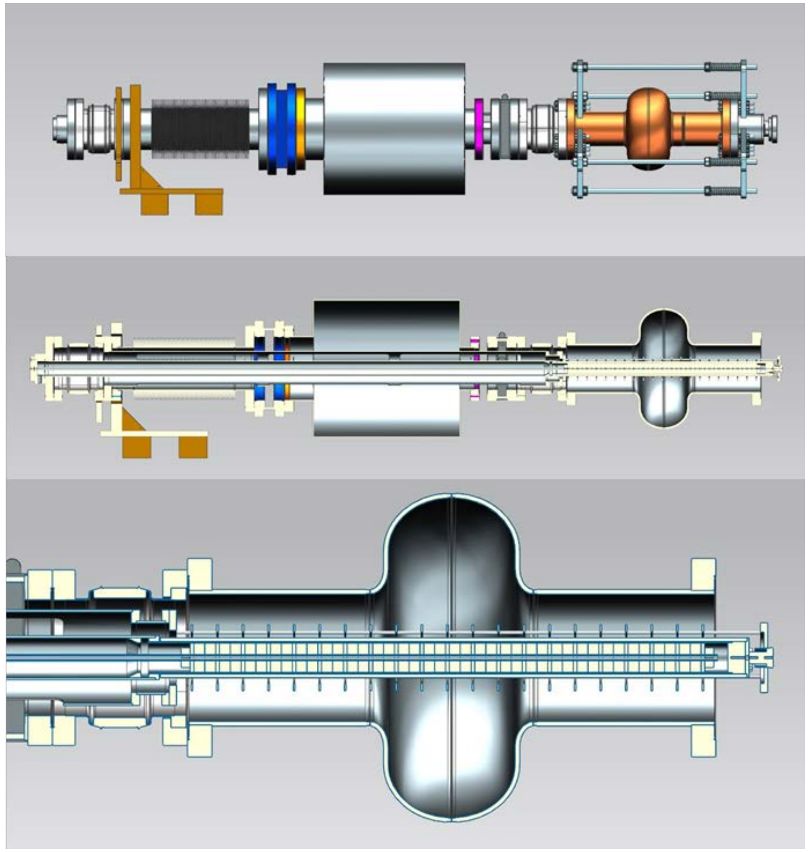
Insight on interface, coating temperature influence

Nb/Cu coated at 200°C with Nb_2O_5 interlayer waiting to be measured

HiPIMS Nb/Cu Film RF Results on 1.3 GHz cavities



Nb/Cu via Energetic Condensation - HiPIMS



- ***System completely rebuilt for maintenance:***
  - Expected due to Nb cathode material consumption during deposition process
  - Thick film created in main chamber peels off and requires periodic disassembly and cleaning
- ***System upgrades/modifications:***
  - New cathode design
    - Easy replacement of Nb sputter target with Nb sleeve
    - Cathode replacement now only requires 1 day compared to > 2 months
    - Cathode can be isolated under static vacuum
  - 952.6-800MHz cavity deposition capability
  - System reliability
    - Alignment, tolerances, vacuum, ease of operation…
  - Increased throughput & volume of data

Under recommissioning & pulser reassessment
Cavity work restarting in March

Nb/Cu via Energetic Condensation – next steps

Principal challenges at present

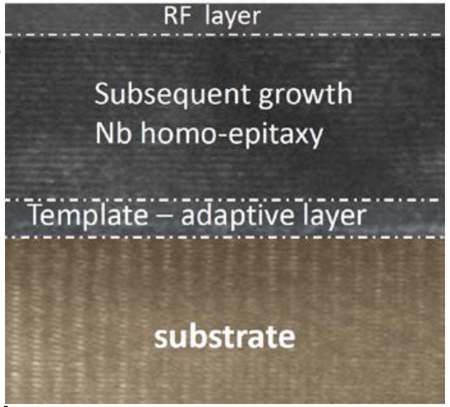
- ❑Establish adequate process controls
- ❑**Need better substrates**

  see Mondays talk
- ❑ **Need better chemical processes**

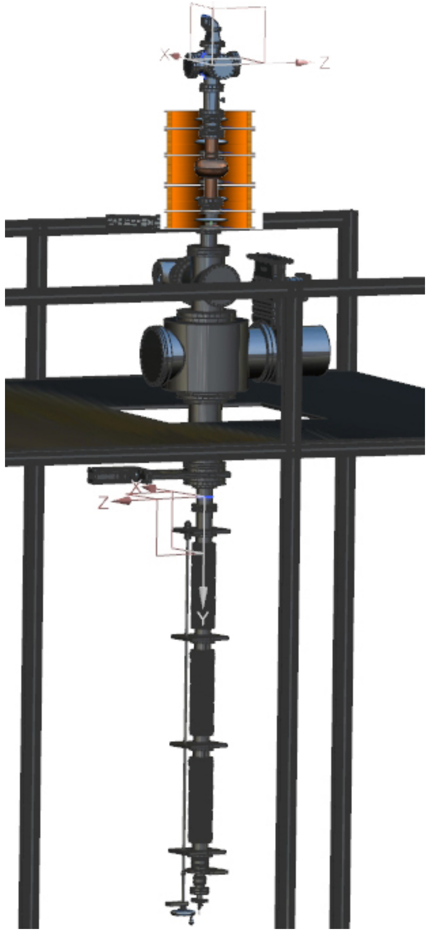
  ➡ EP development

II-VI

- ❑ "Turn the knobs" to truly engineer the SRF surface by manipulating the film growth conditions



- ❑ Deposition on JLEIC cavities (952.6 MHz)



ECR cavity deposition

Develop Nb/Cu cavity coating with energetic condensation for different frequencies (1.3 GHz, 952 MHz) for *bulk-like* RF performance

- Never been done before
- Vacuum design finalized
- Engineering challenges to produce pure Nb vapor with required density for sustained ECR plasma in a cavity
- Design iterations in progress of system core for ECR plasma
  - Enhanced ECR scheme for distributed plasma
  - Ducting ECR plasma into cavity (magnetic confinement/transport)

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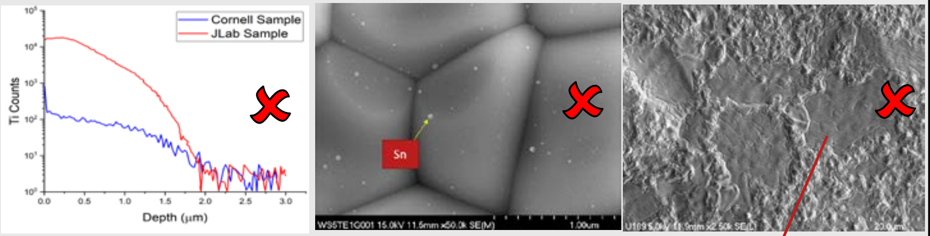
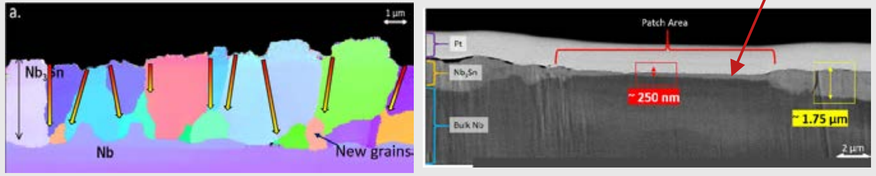
Nb_3Sn Development via Sn diffusion

U. Pudasaini, G. Eremeev et al.

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

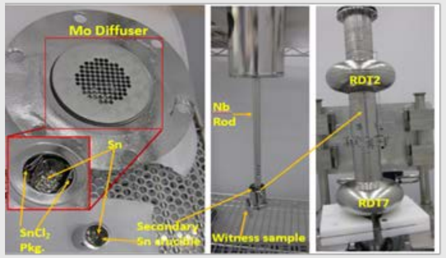


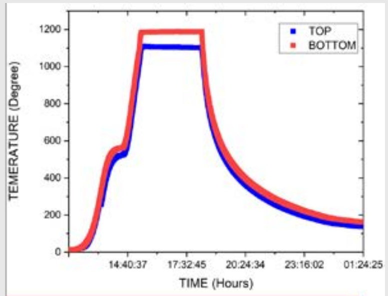
Potential factors contributing to recurrent Q-slopes in Nb_3Sn cavities



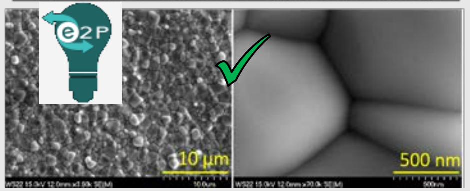
Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in RF-affecting thin regions.

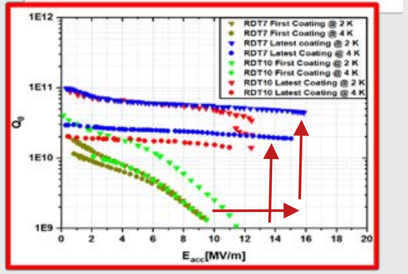
Process Development





No Sn-residues and uniform coating





Modification of coating process based on learnings from correlated material and RF studies of Nb_3Sn samples resulted in the removal of recurrent Q-slopes.

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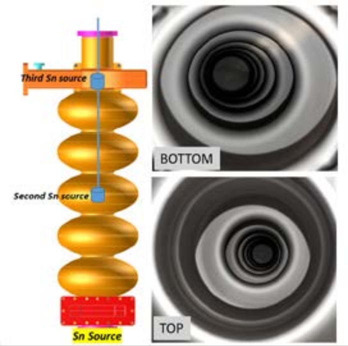
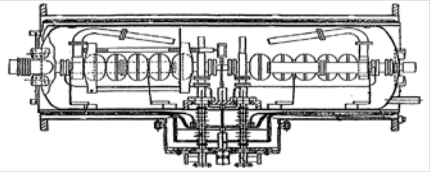
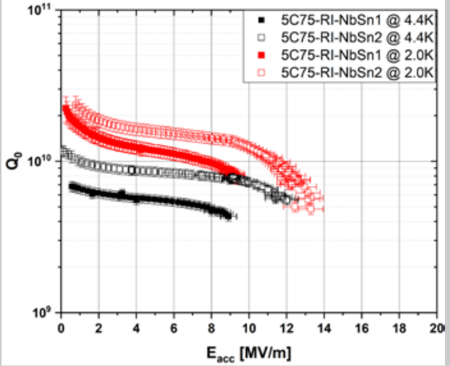
Multi-cell cavity coating for accelerator application

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

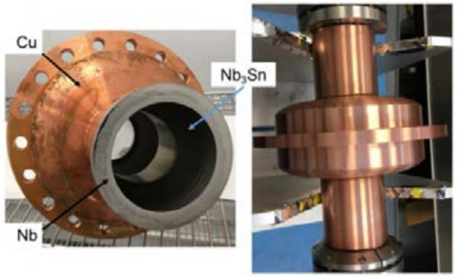


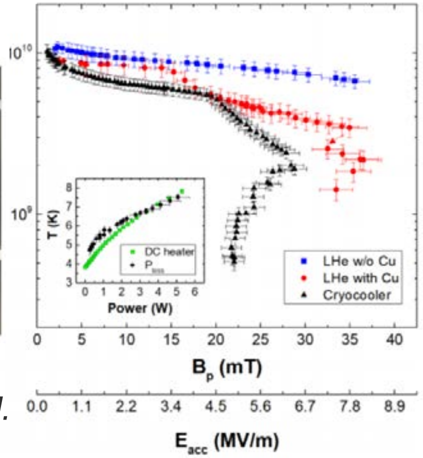




These cavities progress to quarter cryomodule for the first-ever beam test.

Multi-metallic conduction cooled Nb_3Sn-coated cavity





G. Ciovati *et al* 2020 *Supercond. Sci. Technol.* **33** 07LT01

- Materials such as Nb_3Sn 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_3Sn technology further.

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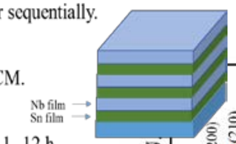
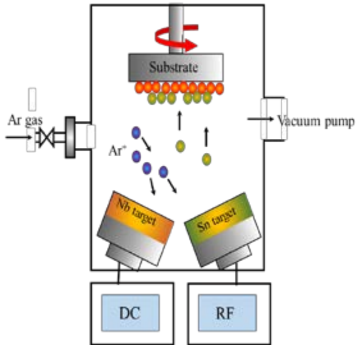
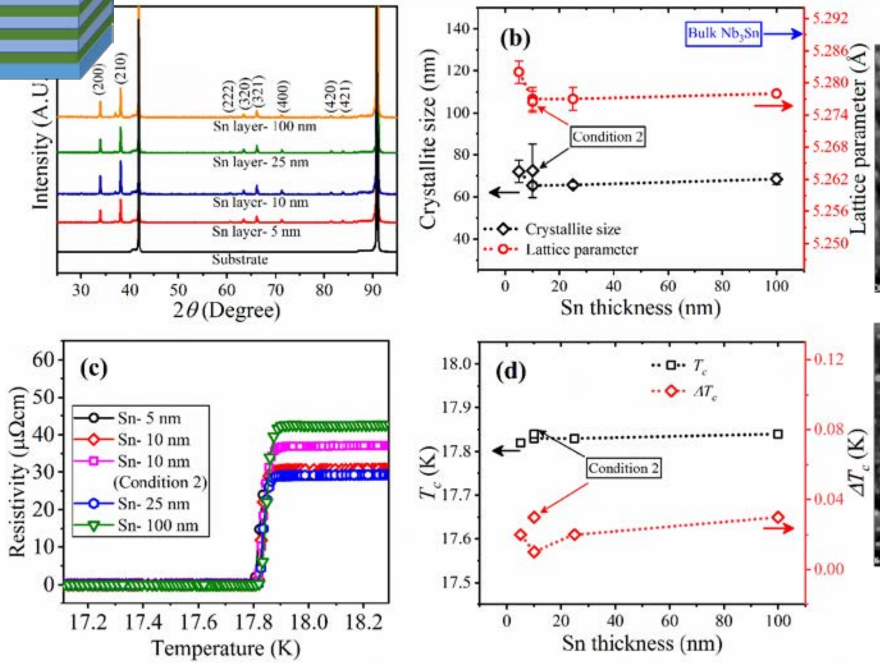
Nb_3Sn growth by sequential sputtering & post-diffusion

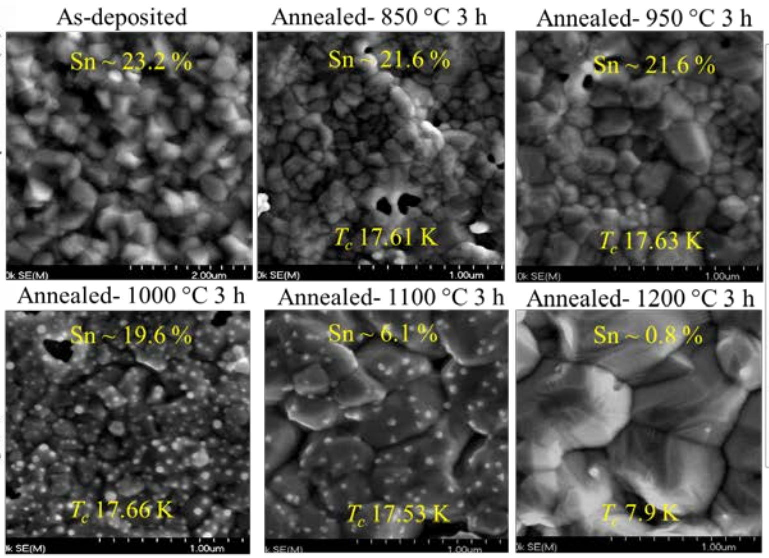
Md Nizam Sayeed
See talk on Wednesday

- Multilple layers of Nb and Sn sputter sequentially.
- Deposition rate: 1 Å/s.
- Sputtering pressure: 3 mTorr 20 SCCM.
- Substrate rotation: 30 rpm.
- Multilayers annealed: 850- 1200 °C, 1- 12 h.









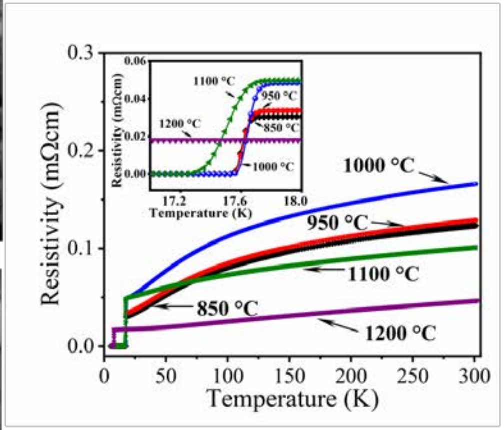
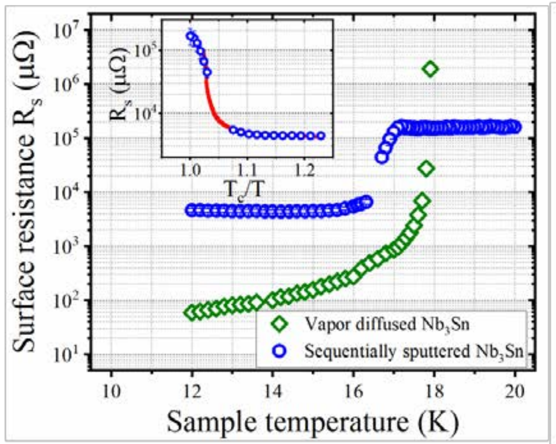
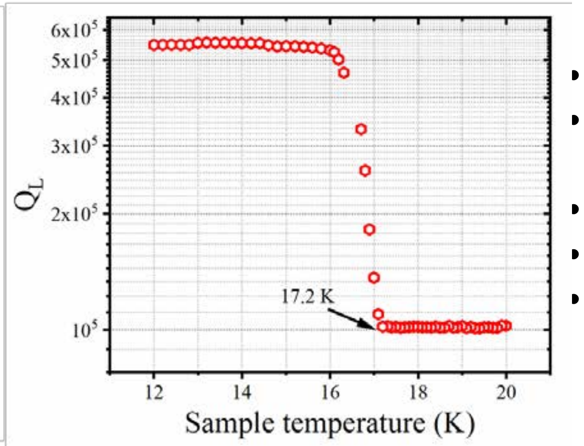


Figure: Resistivity vs temperature.

M.N. Sayeed et al. https://doi.org/10.1016/j.jallcom.2019.06.017



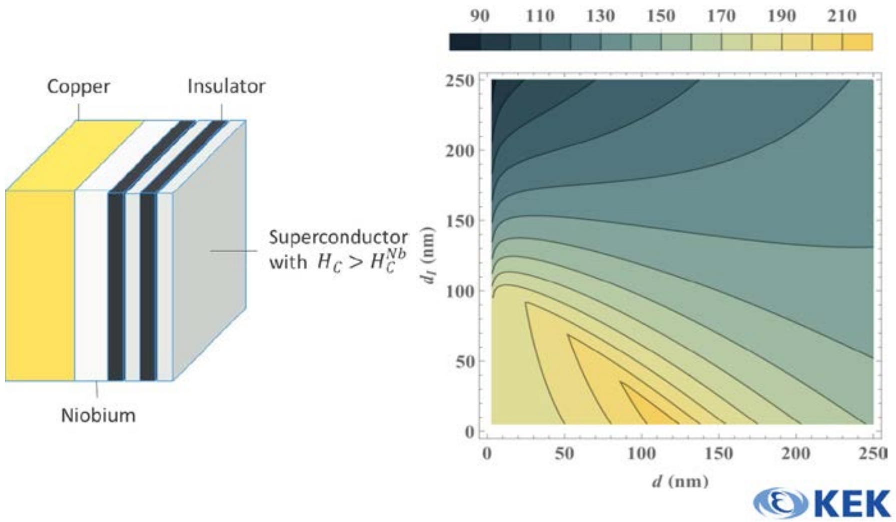


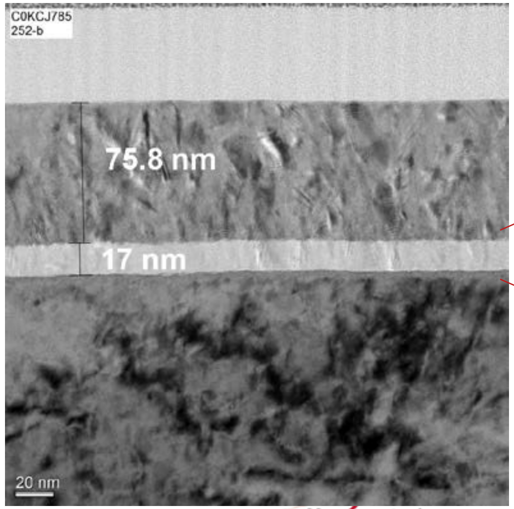
- Superconducting Nb_3Sn with a T_c up to 17.93 K have been achieved.
- Film morphology modified with niobium buffer layer and increased substrate temperature.
- Significant Sn evaporation above 950 °C.
- Sn evaporation was not affected by varied thickness.
- Layer thickness should be thin to avoid delamination.

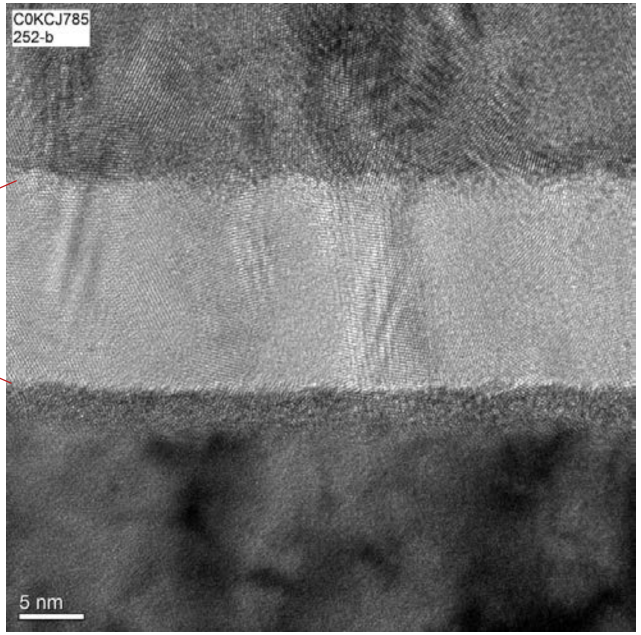
M N Sayeed et al 2020 IOP Conf. Ser.: Mater. Sci. Eng. 756 012014

Alternative Materials to Nb & Multilayered Structures

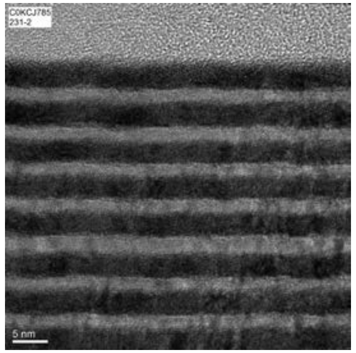
- Combination of superconducting materials with adequate dielectric material in multi-layered structures have been conceived as a performance enhancer for bulk Nb and Nb/Cu film cavities with delayed vortex penetration in Nb surfaces allowing them to sustain higher surface fields than any pure material.

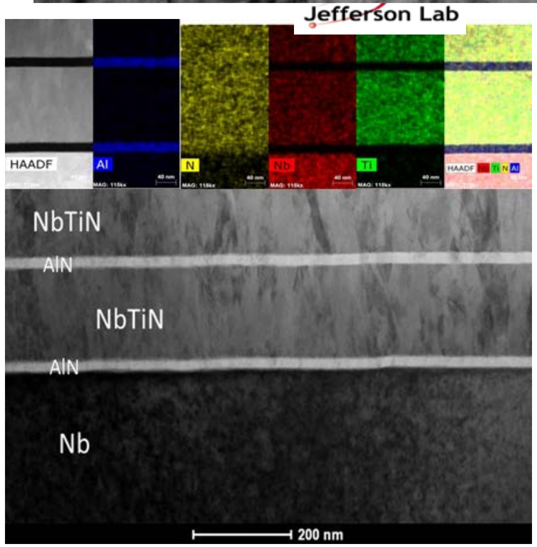






- Meta-materials for functional surfaces





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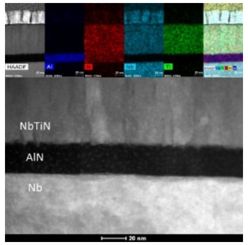
SIS Multilayered Structures based on NbTiN

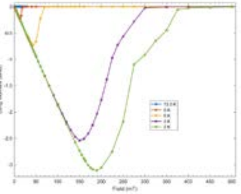
D.R Beverstock thesis

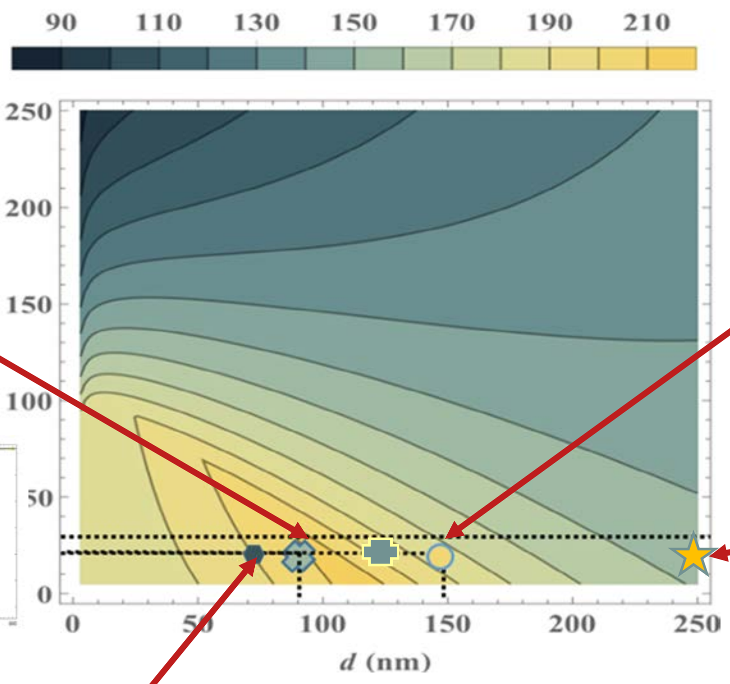
Contour plot calculated for NbTiN [T. Kubo]

DC/SQUID



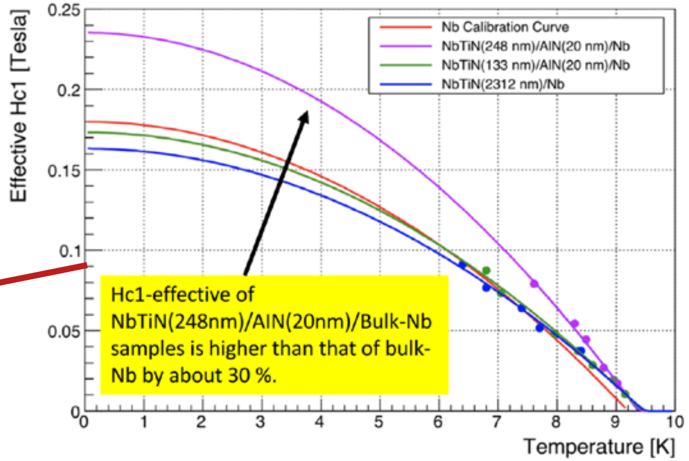
T_c=14.2 K
H_{fp} ~155 mT





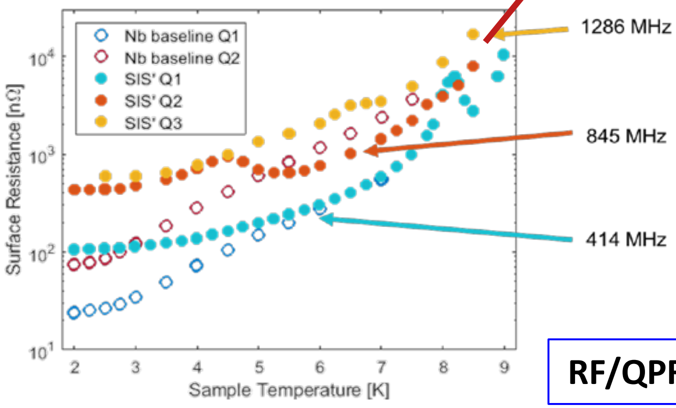
	Thickness [nm]	H_{c1} [mT]	T_c [K]
NbTiN/MgO	2000	30	17.3
NbTiN/AlN/AlN ceramic	145	135	14.8
NbTiN/AlN/MgO	148	200	16.7

Some NbTiN/AlN SI structures exhibit **H_{fp} enhancement** compared to bulk-like NbTiN film



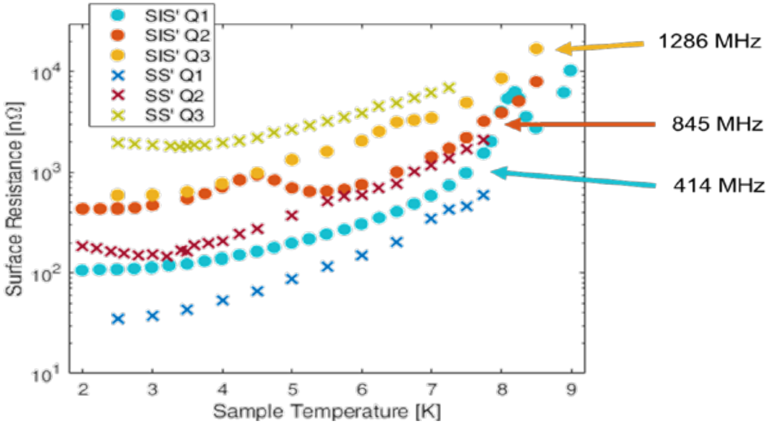
Courtesy T. Saeki et al.

75nm NbTiN / 15nm AlN / Nb @ 10 mT



RF/QPR

S-I-S´ : 75nm NbTiN / 15nm AlN / Nb
S-S´ : 70nm NbTiN / Nb



- **Hfp measurement by SQUID in agreement with QPR measurement.**
- **Contour plot calculated with values from references, need to be re-done with values extracted from films produced.**
- **The odd RF behavior observed may be due to the presence of a thin lossy NbN layer at the surface of the bulk Nb substrate.**
- **QPR deposition & measurement to be repeated in 2021.**

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SIS Multilayered Structures based on NbTiN

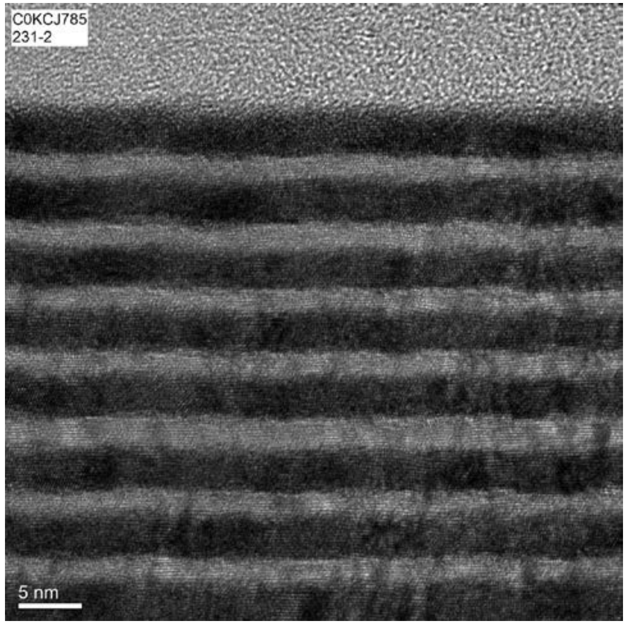
D.R Beverstock thesis

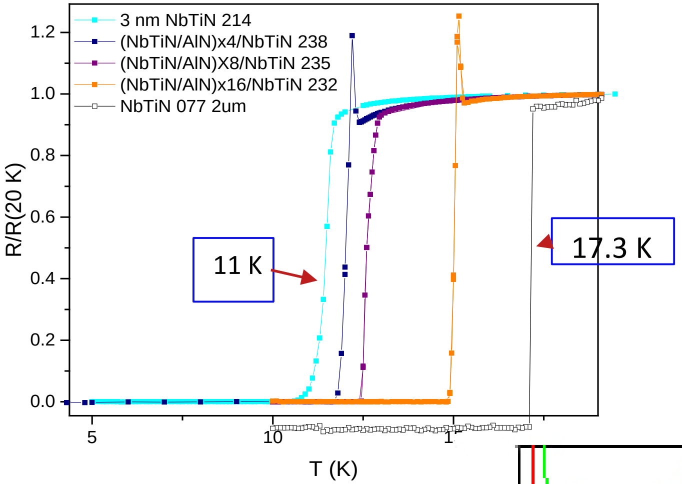
- **NbTiN/AlN interface development (metamaterials synergistic project,** DARPA-BAA funded)

  - Meta-materials for functional surfaces

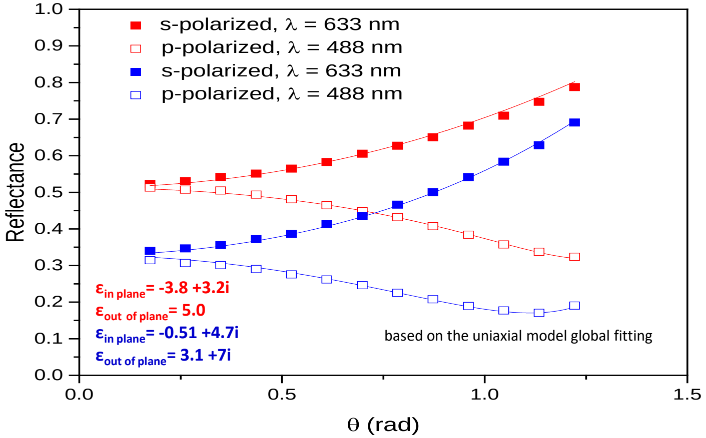
- Multilayer structure of NbTiN = 3.6/3/2 nm and AlN = 2/1.5/1 nm.

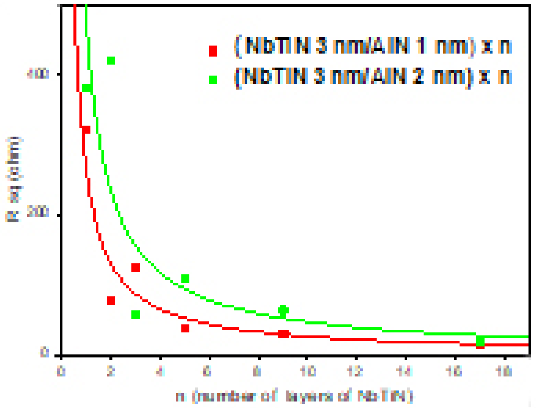
N bilayers deposited on NbTiN/MgO

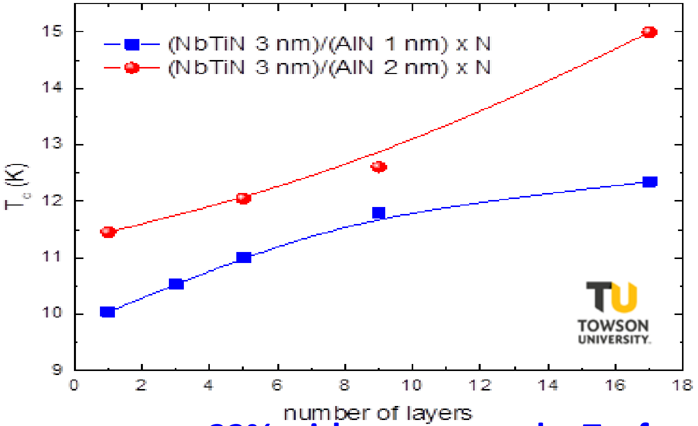




Nature Scientific Reports 6, Article number: 34140 (2016)





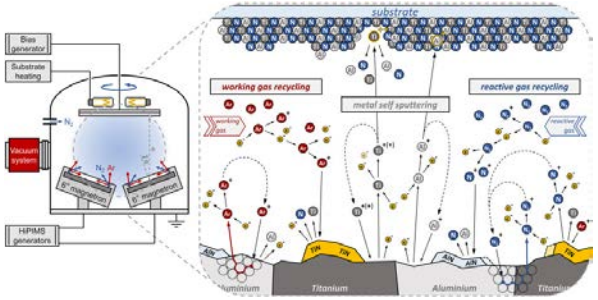


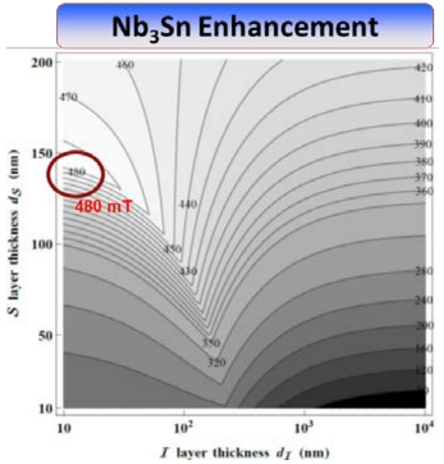
Metamaterial engineering shows hyperbolic behavior and increased the T_c of these multilayered structures up to 32% with respect to the T_c of a single ultrathin NbTiN layer. Enhancement limited by the small coherence length of NbtiN (ξ~3.8 nm).

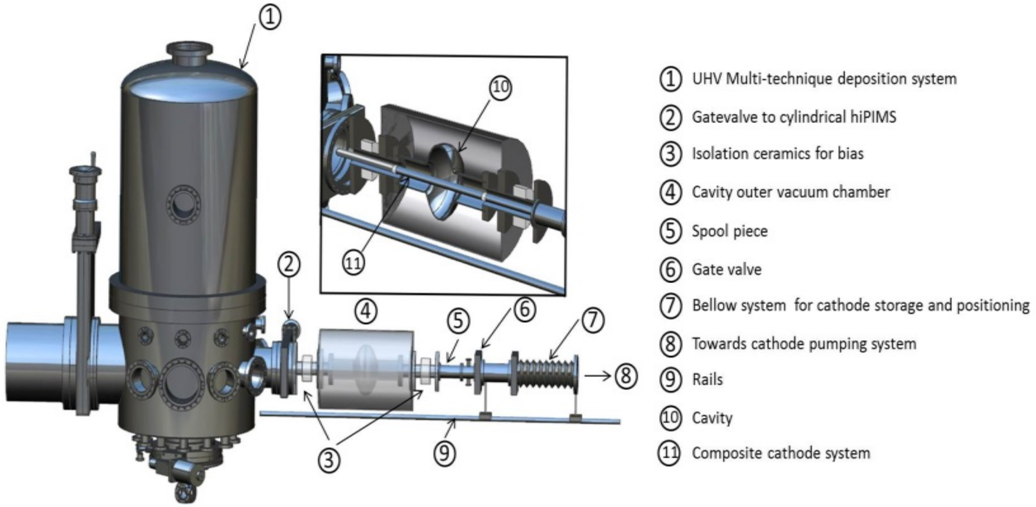
SIS Development - Next Steps

- Explore AlN dielectric layer thickness
- Substrate development
- new QPR samples
- Explore other dielectric materials ZrN and Al_2O_3
- Resume Re-HiPIMS
- 3rd harmonic setup under development in collaboration with CEA Saclay
- Development of A15 compounds (Nb_3Sn …) via energetic condensation
- Implement SIS cylindrical cavity deposition design

Re-HiPIMS







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Summary

Nb/Cu Development

- Manipulation of interface, bulk and final structure of Nb films
- Lower RF losses and mitigation of Q-slope seem to be achieved for fibre growth films at moderate ion energy

Convergence with other research programs results

- Ramp-up cavity development at different frequencies

Nb_3Sn films on Nb

- Persistent Q-slope and gradient limitation commonly observed proven to be not fundamental but process induced thus amenable to improvement.
- Alternative deposition approaches such as sequential, stoichiometric and co-deposition on Nb show promising results and could prove to push the Nb_3Sn technology further.

SIS Development

- Reactive DC-MS development complete with good layers and structures quality from 1.5 nm to 2 µm
- Refine structures performance with QPR samples
- Transfer to cavity deposition
- Develop A15 based multilayers

Coating for Ancillaries Development

starfire industries

HiPIMS Cu/stainless steel deposition development in collaboration with company for 12 GeV waveguides

Samples subjected to 400°C bake and LN2 quenching
No degradation or peel-off observed

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II-VI
TRIUMF
e2P
starfire industries
SLAC National Accelerator Laboratory
BTM Bailey Tool & Manufacturing "Positioned for the Future..."
Universität Siegen
HZB Helmholtz Zentrum Berlin
CERN
STFC ASTeC
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro
KEK
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Openings @ JLab

Looking for talented individuals to join in the development of SRF Thin Films and SRF in general:

- Post-Doc

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- SRF Accelerator Physicist II

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- Senior Accelerator Physicist

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