Overview Of Recent Progress On Thin Film Technologies

A.-M. Valente-Feliciano

ACKNOWLEDGEMENT

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OUTLINE

Recent progress in SRF thin film developments since SRF 2023

- ❑ Nb Thin Film Technology
- ❑ Beyond Nb – Alternate Materials
  - Nb_3Sn
  - NbTiN
  - MgB_2
- ❑ Beyond Nb – Multilayers
- ❑ SRF Thin Film Characterization
- ❑ Substrates

Disclaimer:

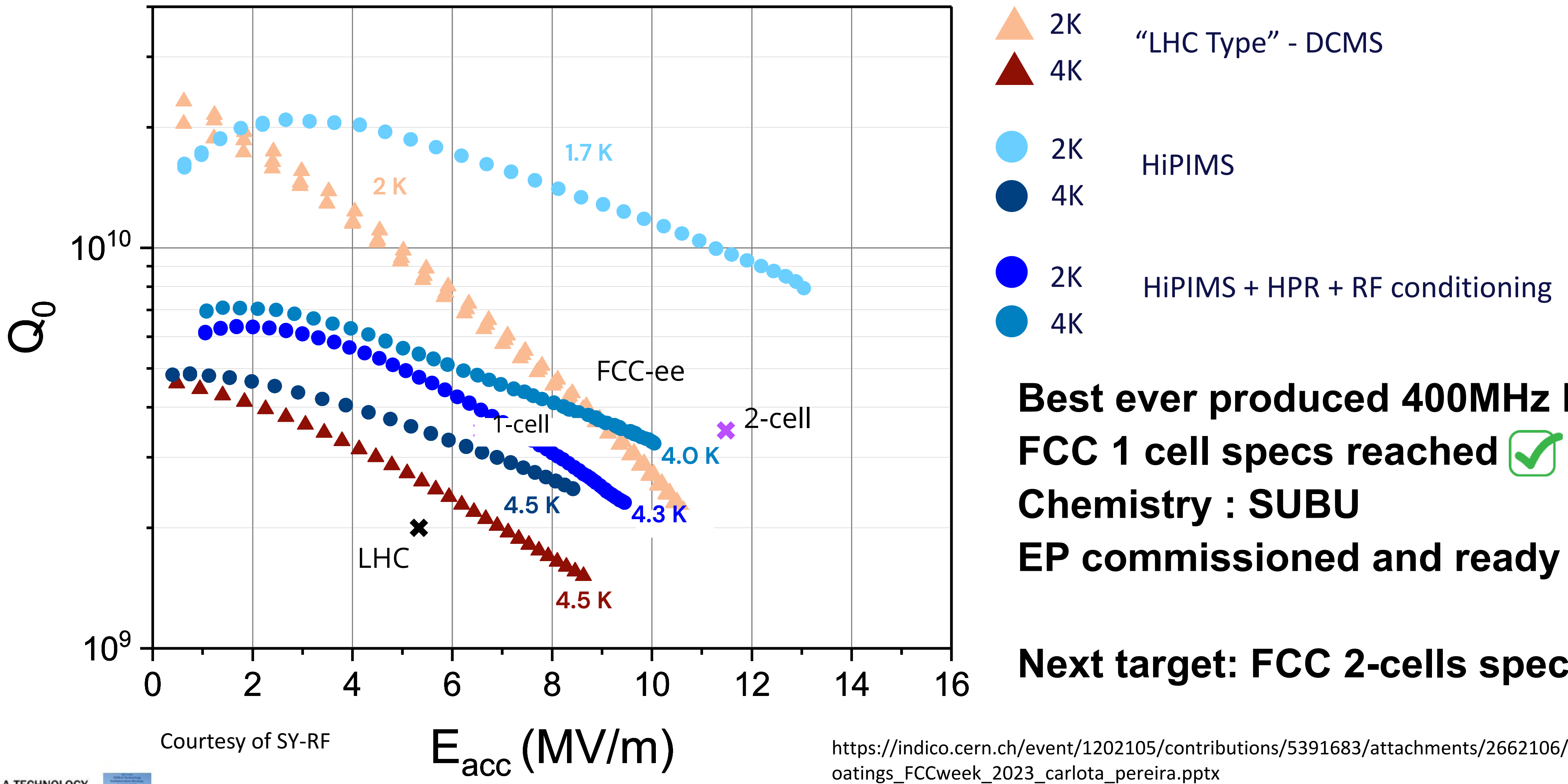
Non-exhaustive summary

Many more ongoing developments, awaiting results, validation…

Nb Thin Film Technology

400 MHz Nb/Cu cavities

G. Rosaz et al.



Courtesy of SY-RF

Best ever produced 400MHz Nb/Cu
FCC 1 cell specs reached ✅
Chemistry : SUBU
EP commissioned and ready for 2024

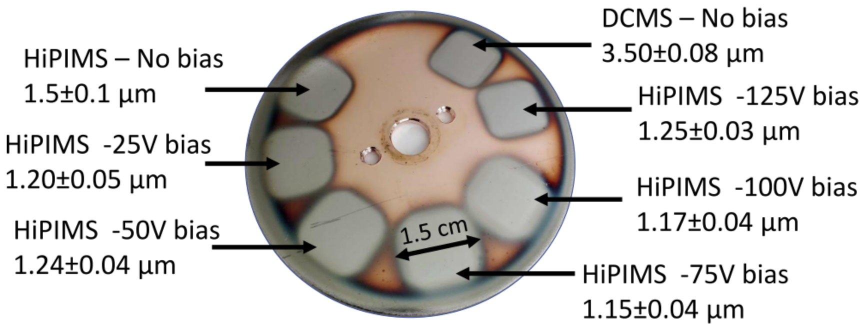
Next target: FCC 2-cells specs

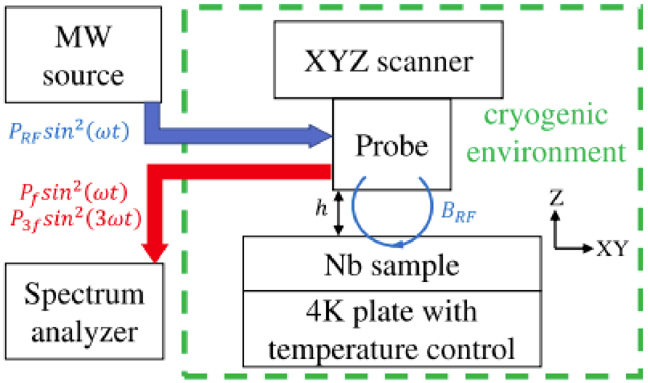
https://indico.cern.ch/event/1202105/contributions/5391683/attachments/2662106/4612074/HIPIMS%20Nb%20coatings_FCCweek_2023_carlota_pereira.pptx

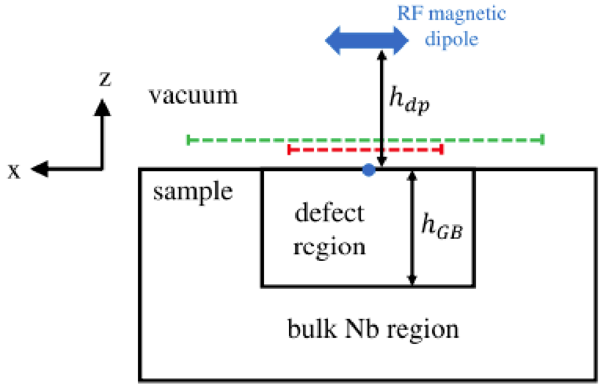
1.3 GHz Nb/Cu

https://arxiv.org/abs/2305.07746

Samples characterization by local microwave spectroscopy







Sample	ρ^{defect}	$h^{defect}_{penetration}$
HiPIMS, 125V bias	low	deep
HiPIMS, 100V bias	low	deep
HiPIMS, 75V bias	low	shallow
HiPIMS, 50V bias	high	shallow
HiPIMS, 25V bias	high	shallow
HiPIMS, no bias	N/A	
DCMS, no bias	N/A	

Optimum coating bias evaluated using local probe technique
Surface defects signal through P3f sample response
Optimum in agreement with VSM/Squid data

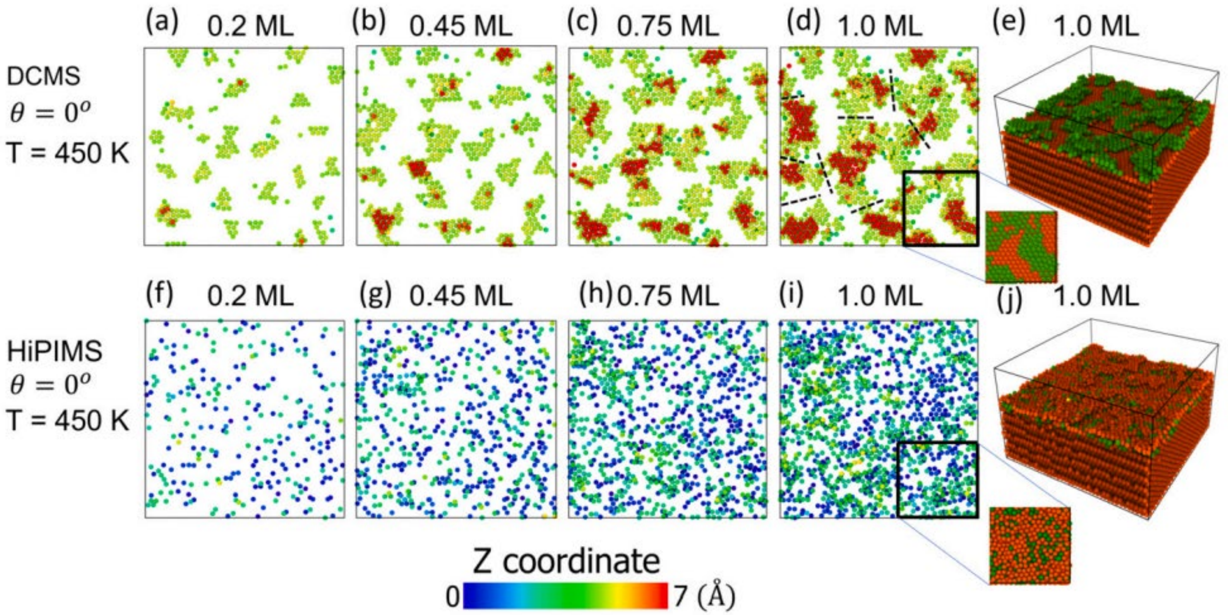
G. Rosaz et al.

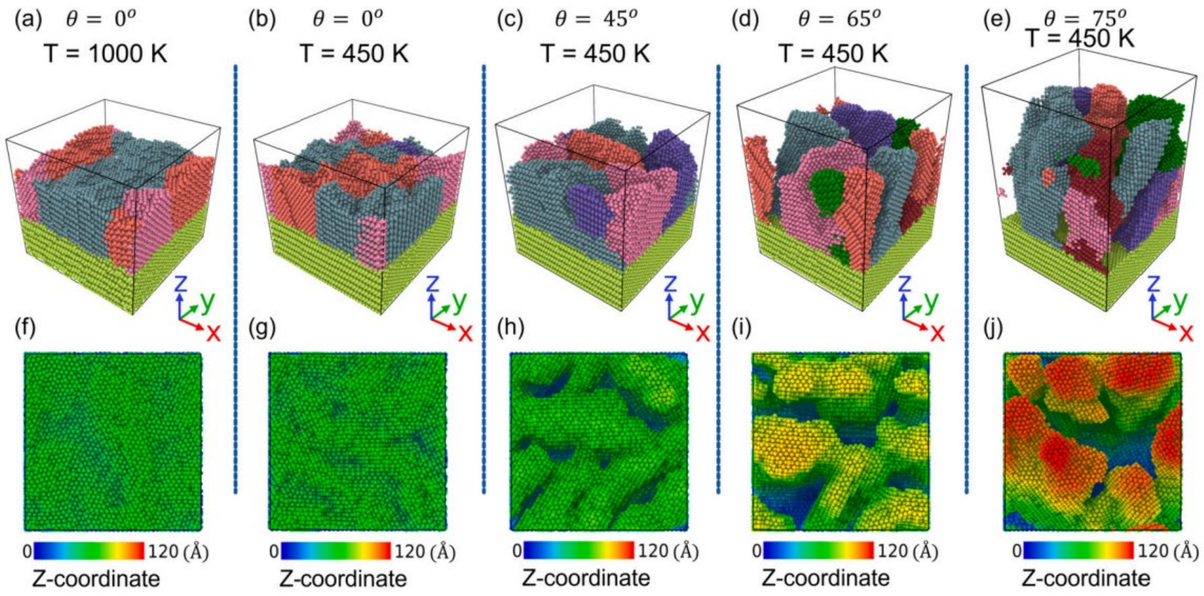
1.3 GHz Nb/Cu

https://doi.org/10.1016/j.surfcoat.2023.130199

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Molecular dynamic simulations





Confirmation of Cu presence on top of Nb films – confirmed by XPS analysis
Structure of the film studied as function of temperature and incidence angle

Next Step: Study defects formation and annihilation

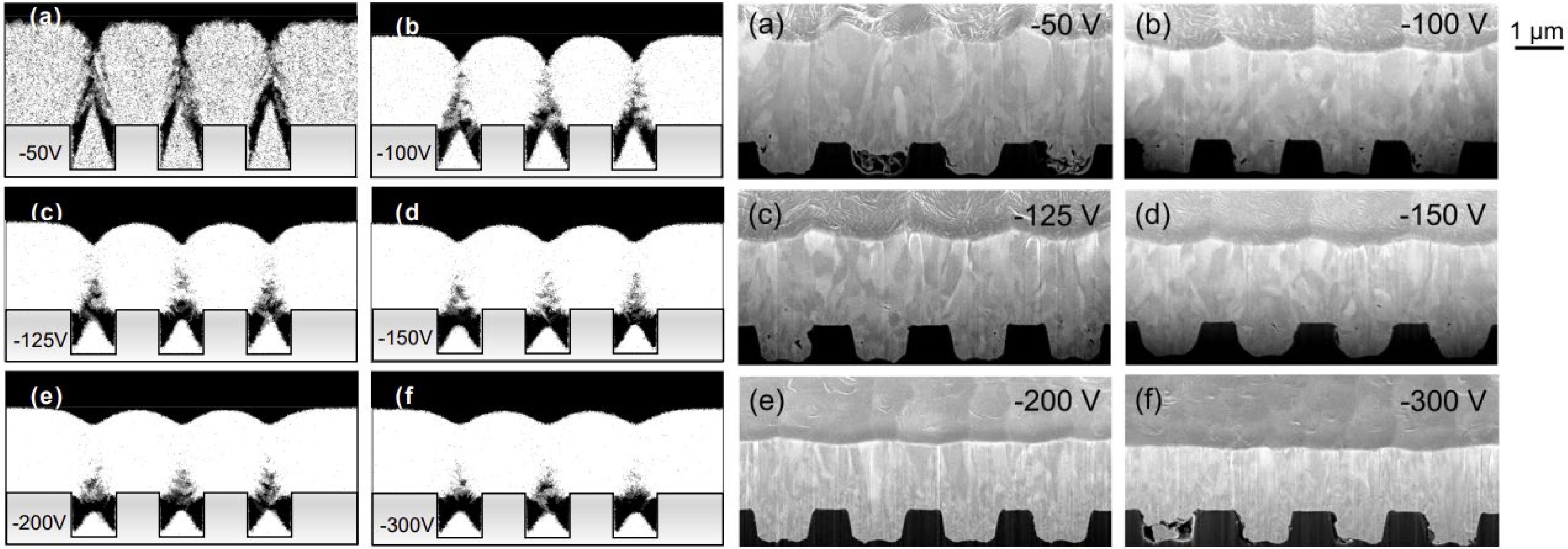
G. Rosaz et al.

Nb Thin Film Technology

1.3 GHz Nb/Cu

G. Rosaz et al.

Niobium film planarization



Simulations (SRIM, SIMTRA + NASCAM, 70% ionization)

Experimental results, Nb on trenched Si samples
Focus Ion Beam (FIB) measurements

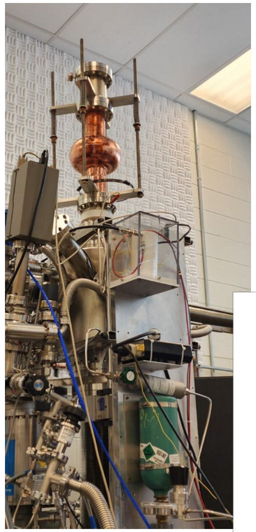
Suppression of substrate-induced defects by ion bombardment
To be tested on actual 1.3GHz cavities

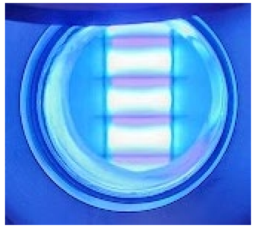
Nb Thin Film Technology

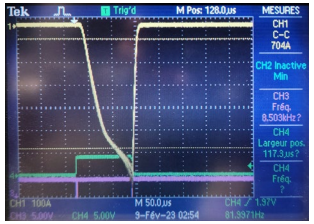
1.3 GHz Nb/Cu

Growth in sequential phases developed for ECR implemented on cavities with HiPIMS

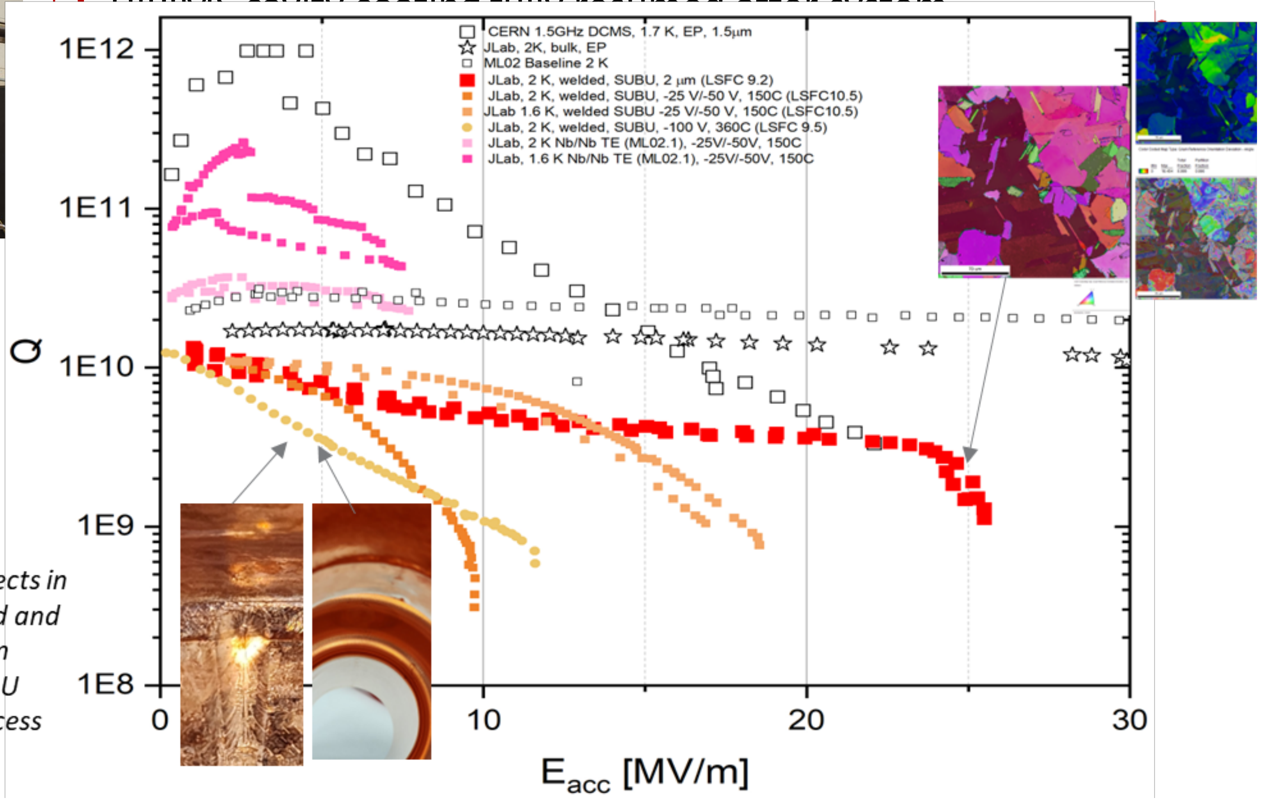
A-M Valente-Feliciano et al.





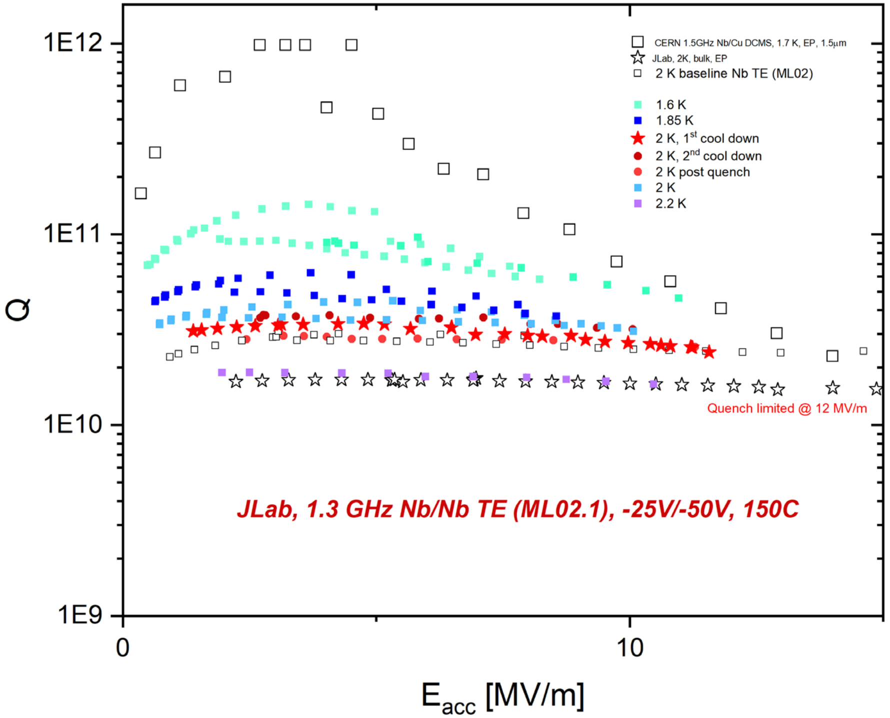


- HiPIMS cavity coating fully resumed after system



Defects in weld and from SUBU process

HiPIMS Nb/Nb 1.3 GHz TE cavity

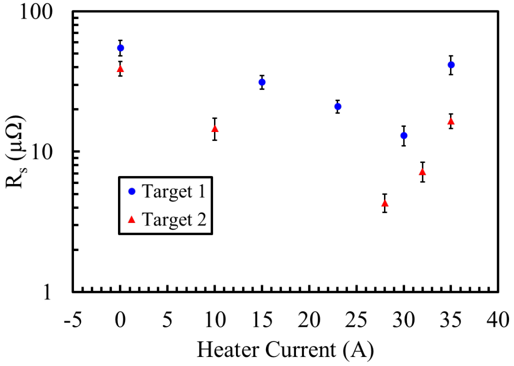


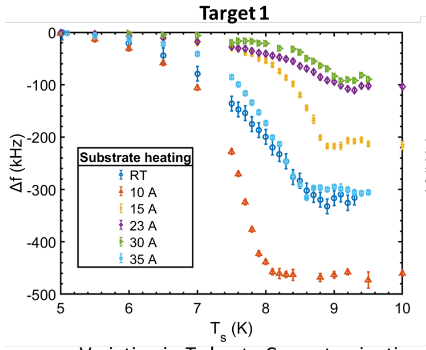
- lower frequency cavity deposition (952.6 & 800 MHz, substrates on hand)

Nb Thin Film Technology

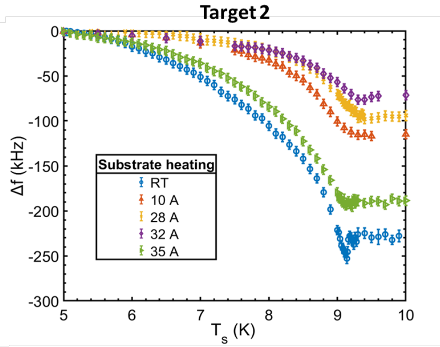
Science and Technology Facilities Council

Nb/Cu: surface resistance at 4.2 K



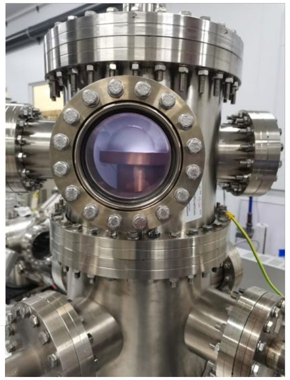


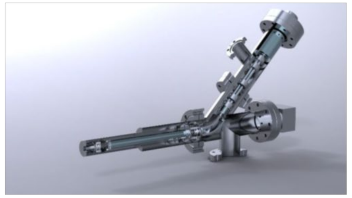
- Variation in T_c due to Cu contamination



- T_c as expected for all samples

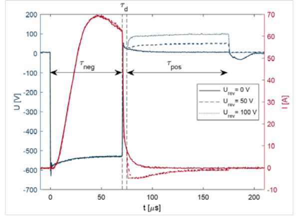
Plasma diagnostic study with Liverpool University





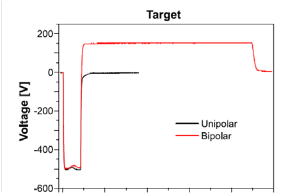
Bipolar HiPIMS discharge

Starfire Industries Impulse 2-2 Liverpool University



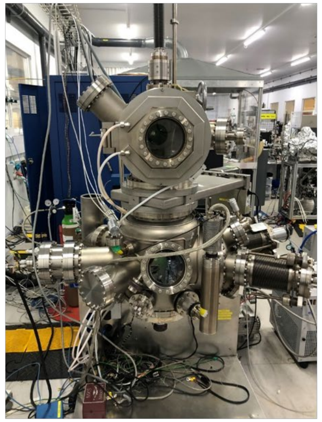
19/09/2022

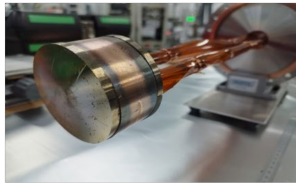
Ionautics HiPSTER Bipolar Viloan et. al.*



* https://doi.org/10.1016/j.surfcoat.2021.127487

1.3 GHz Cavity deposition system

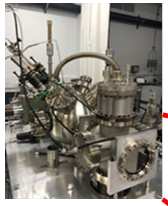




The system is equipped with load lock chamber, rotating arm that can turn and move up and down, the chamber wall is water cooled, fixed magnetron in the centre.
It will be positioned in an ISO 6 clean room with ISO 4 cabinet for final cavity preparation.

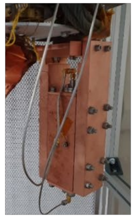
From planar samples to real cavities

Aim: Flat samples → split cavities → 1.3 GHz cavities



3 sets of samples:

1. Nb coated planar samples
   - Low power RF test with choke cavity
   - High power RF test with QPR
2. Split cavity deposited with planar magnetron & planar target
   - RF test
3. Split cavity deposited with cylindrical magnetron & tubular target
   - RF test

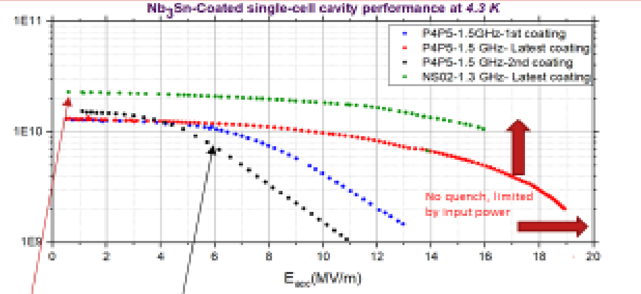


R. Valizadeh et al.

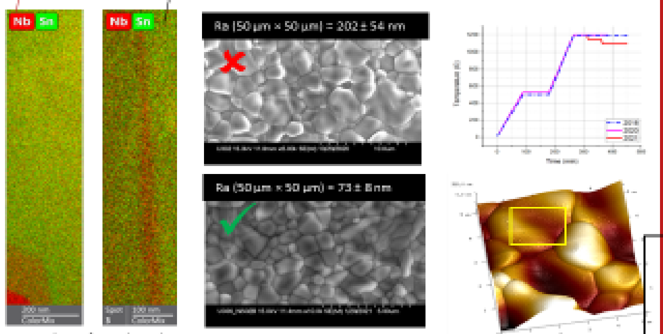
Beyond Nb: Alternate Materials Nb_3Sn

Jefferson Lab

Material studies and development of Nb_3Sn-coated cavities



Witness sample analysis correlating RF performance and coating parameters

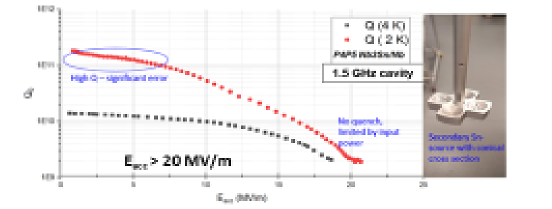


TEM analysis of grain boundaries with and without Q-slope

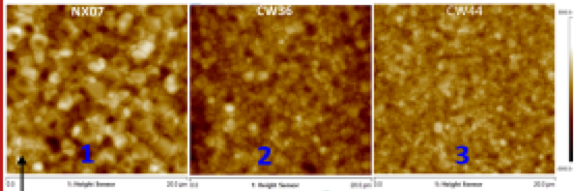
Grain size and roughness

Recurrent Sn residues contributing to residual resistance

- Coating with small grain sizes, smoother surfaces, and thinner (~ 1 µm) thinner coating with no Sn segregation or deficient grain boundary correlate with better-performing cavities.
- Further coating process optimization to enhance cavity performance is in progress.



Several cavities reached to ~ 20 MV/m, material studies and surface improvement is in progress to maintain high Q at high E_{acc}.



Expt	1200C	1150C	1100C	Ra (nm)	Grain size (um)	Thickness (um)
00	38 min	45 min	85 min	83.4± 3.1	1.15	-
01	10 min	45 min	85 min	69± 3	0.93	[illegible]
02	10 min	45 min		40± 1	0.75	1.0 +/- 0.2
05	10 min			27± 2	0.55	0.75
04	10 min		85 min	43.5± 1.5	0.6	1.02

- Several temperature profiles are identified to control roughness and thickness.
- Cavity coatings with selected profiles are in progress for potential improvement in RF performance.

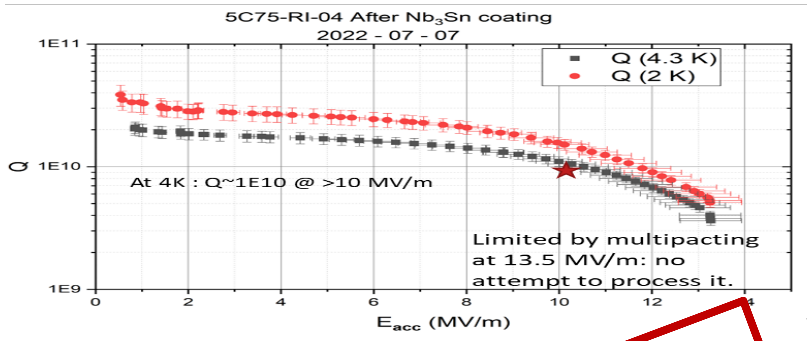
Jefferson Lab

G. Eremeev

Fermilab

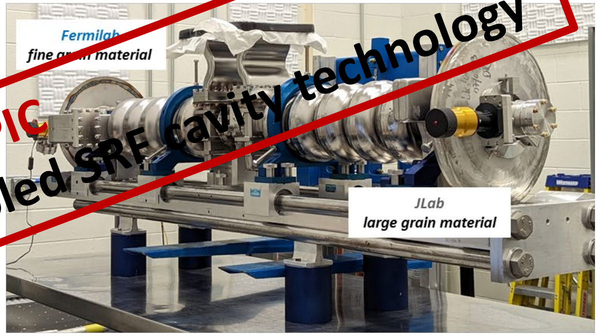
U. Pudasaini et al.

5-cells deposition towards implementation in CM

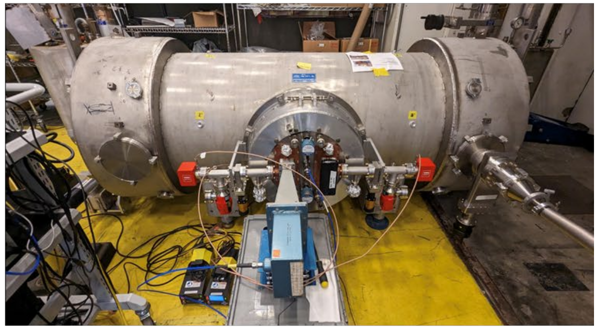


Progress with Nb_3Sn C75 Quarter Cryomodule

- One cavity was coated at Fermilab and another at Jlab
- Cavity assembled in the pair and subjected to disassembly because of a leak and assembled again with some degradation in the cavity performance.
- Quarter cryomodule assembly is completed.
- Test scheduled for Jan 2024.



Based on G. Eremeev's ECA, Jlab cavity work supported by R&D fund.



HOT TOPIC

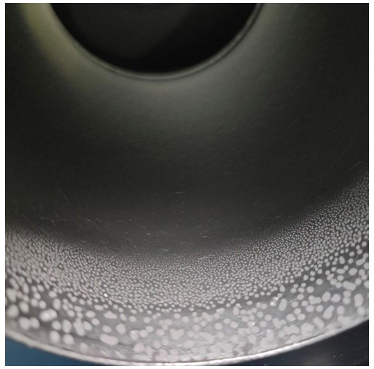
Challenges for conduction-cooled SRF cavity technology

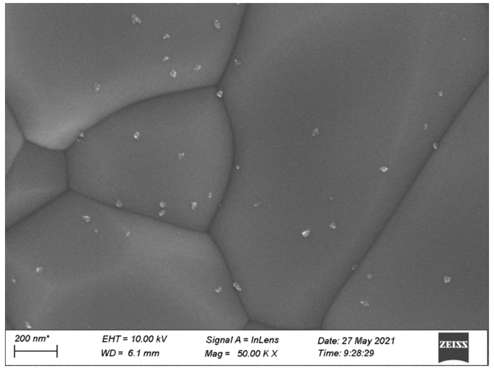
TESLA TECHNOLOGY TTC COLLABORATION

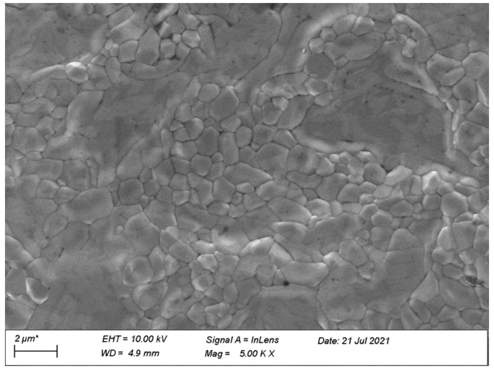
Jefferson Lab

Beyond Nb: Alternate Materials and Multilayer Structures Nb_3Sn

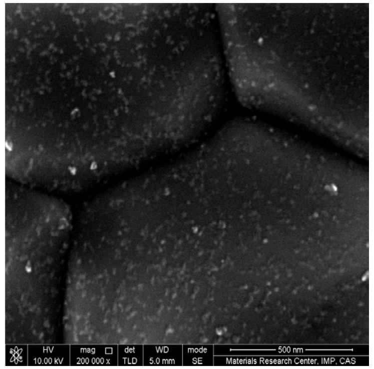
Optimization of Coating Process of Nb_3Sn SRF cavity by vapor diffusion method at IMP

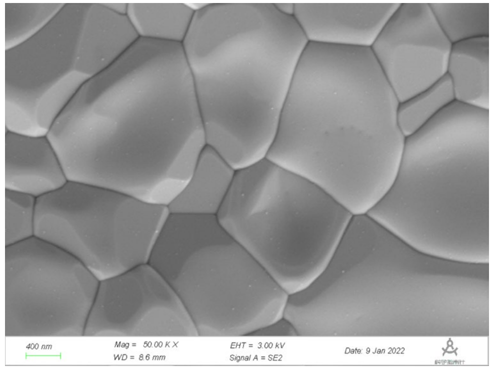


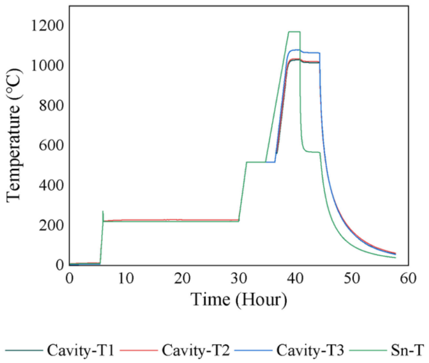




Limiting factors: Millimeter-scale Sn spots (left), Nanometer-scale Sn droplets (middle), Locally extremely thin patchy areas (right), the composition and causes of them were confirmed

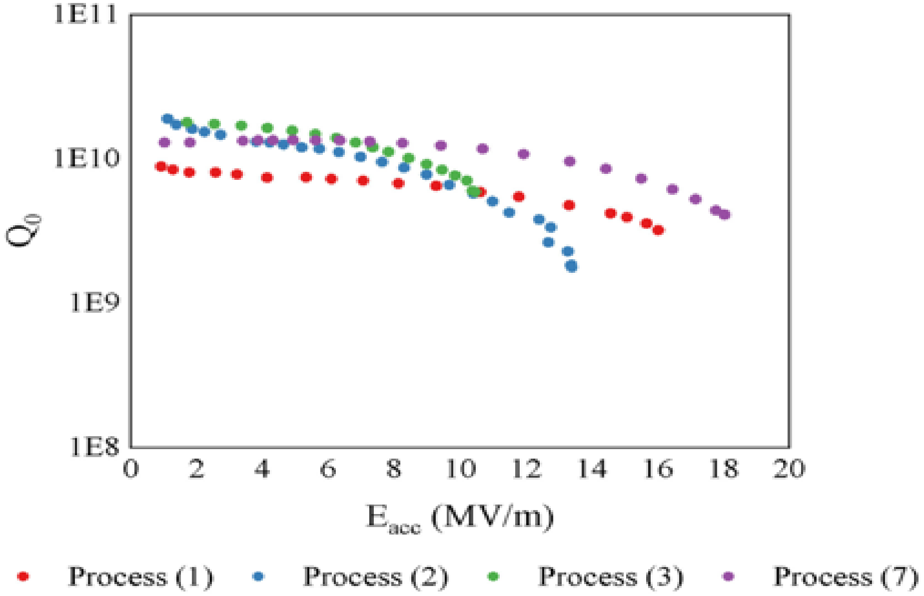






Optimization process: Denser Sn droplets from simply higher Sn flux (left), Free of Sn droplets from Sn vapor adsorption, Optimized recipe after exploration (right), under the premise of effectively inhibiting the condensation of Sn droplets, the Sn source temperature can be safely increased

T. Tan et al.



Key to high-performance Nb_3Sn film:

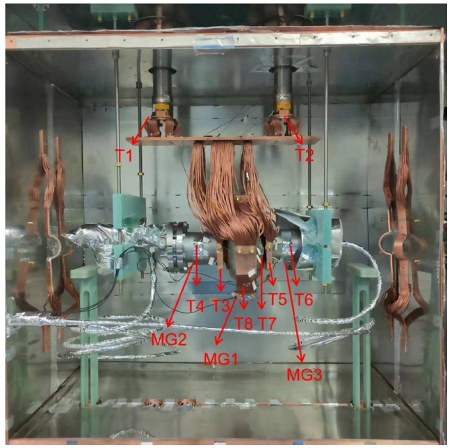
1. Temperature uniformity of cavity
2. Sufficient Sn vapor flux
3. Timely removal of residual Sn vapor before cooling

Development and Application of Nb_3Sn Thin Film SRF Cavity at IMP, Jiankui Hao (PKU) – Tues 12/6

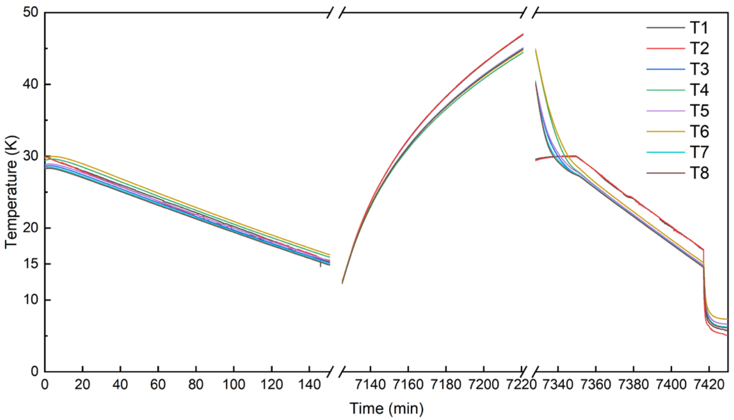
Beyond Nb: Alternate Materials and Multilayer Structures Nb_3Sn

Development of conduction-cooled LHe-free SRF technology

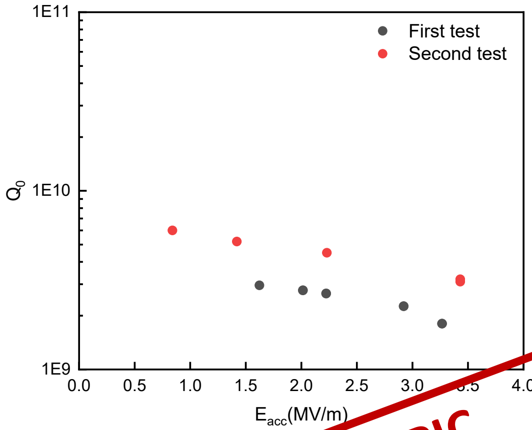
T. Tan et al.



Cernox sensors and magnetic flux gates



Two cooldown processes crossing 30-15K



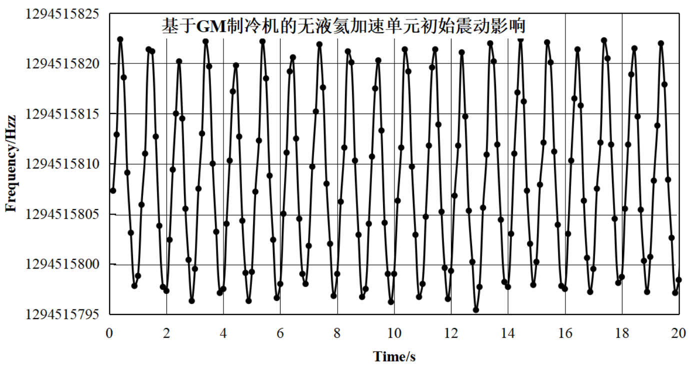
Improvement of RF performance after repeated cooldown process

Thermal cycle effect of conduction-cooled Nb_3Sn SRF cavity:

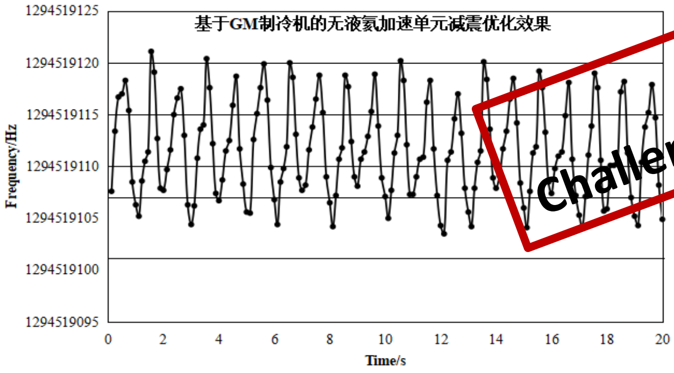
1. Uneven temperature distribution in the first slow-cooldown due to the local contact between the copper strip and the cavity,
2. Repeated cooldown has been shown to reduce non-uniformity

HOT TOPIC

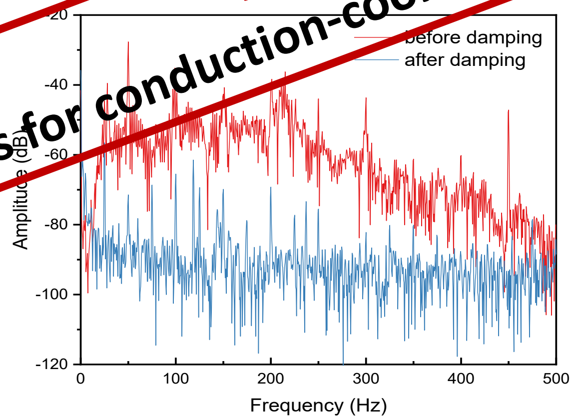
Challenges for conduction-cooled SRF cavity technology



Frequency vibration~**27Hz** in the case of vibrations transmitted to the top of module measured by frequency meter



Frequency vibration decreased to~**15Hz** after vibrations transmitted to the ground



The mechanical vibration of the cavity is obviously **suppressed** after optimization

Frequency vibration caused by GM cryocoolers and suppression:

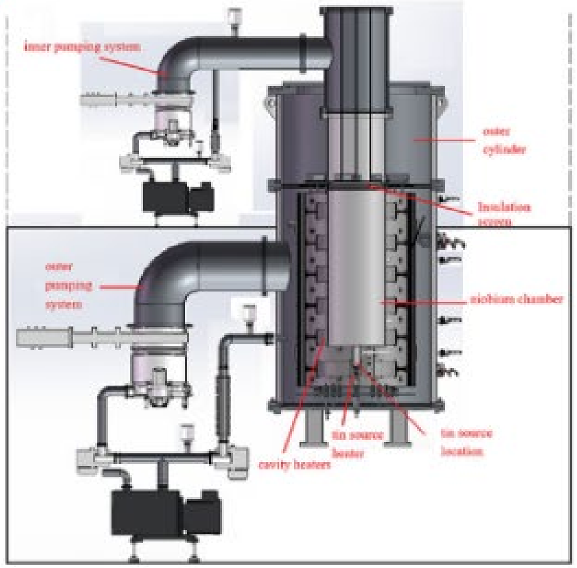
1. GM cryocoolers can cause frequency vibration of conduction cooled SRF cavity
2. Reasonable damping structure design can significantly reduce the impact of GM cryocoolers

See Dr. Ziqin Yang's Hot-topic slides on December 7 for more details

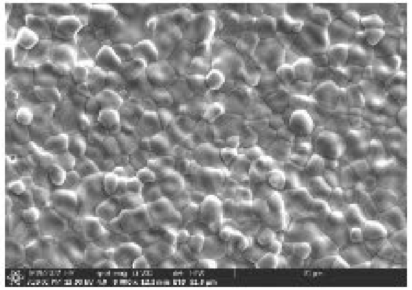
Beyond Nb: Alternate Materials

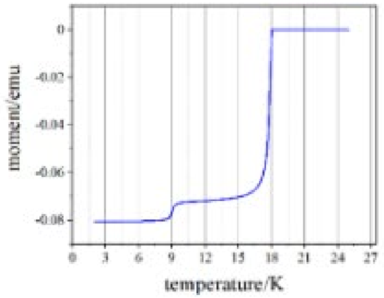
Nb_3Sn

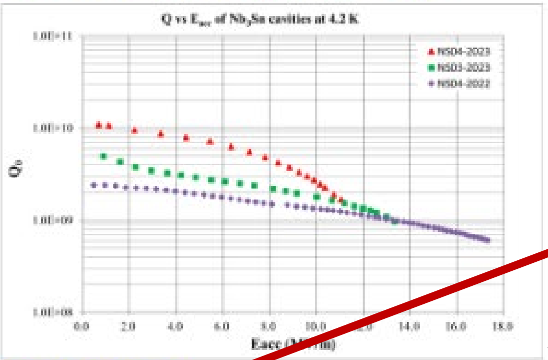
Nb_3Sn Cavities Coated by Tin Vapor Diffusion (Jiankui Hao, PKU)



3 tin sources

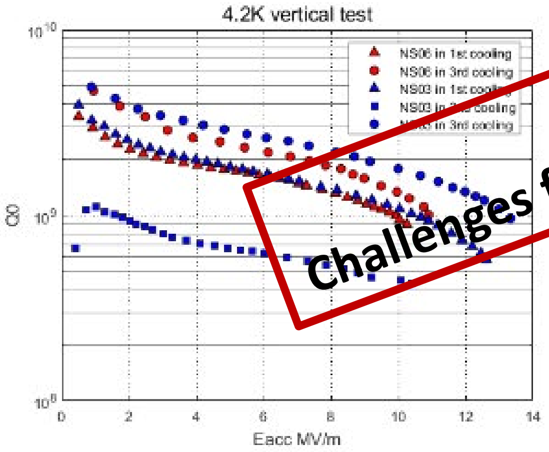






Coating: 1250°C, 120 min, Annealing: 1150 °C, 60 min

$Q_0 \sim 1.1 \times 10^{10}$ @4.2K @ low field, max. $E_{acc} \sim 17.3$ MV/m



Vertical Tests (2023)	T grad., cooling rate	Q_0 @ ~1.0 MV/m
NS03(1st, Oct. 17)	15.7 K/m, ~6 min/K	3.3E9
NS06(1st, Oct. 17)	15.7 K/m	3.0E9
NS03(2nd, Oct. 18)	110	1.1E9
NS03(3rd, Oct. 23)	2.7 K/m, ~10 min/K	4.9E9
NS06(3rd, Oct. 23)	2.7	4.7E9

Vertical tests at different cooling rate

HOT TOPIC

Challenges for conduction-cooled SRF cavity technology

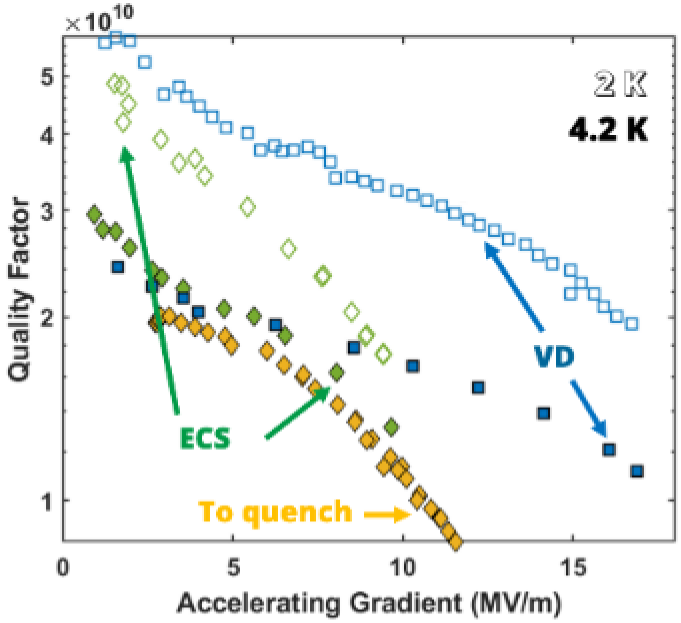
Electrochemical Synthesis

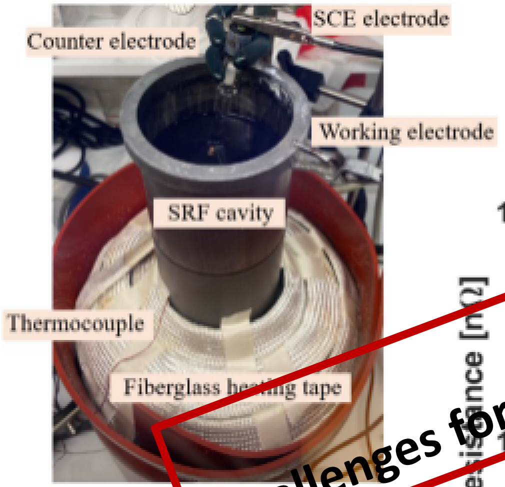
L. Shpani et al.

Achieve a smooth Nb_3Sn film with uniform thickness and stoichiometry

This alternative growth method provides uniform tin nucleation and sufficient Sn supply in critical times

⇒ **smoother** Nb_3Sn films with **little variation in Sn concentration with depth**.

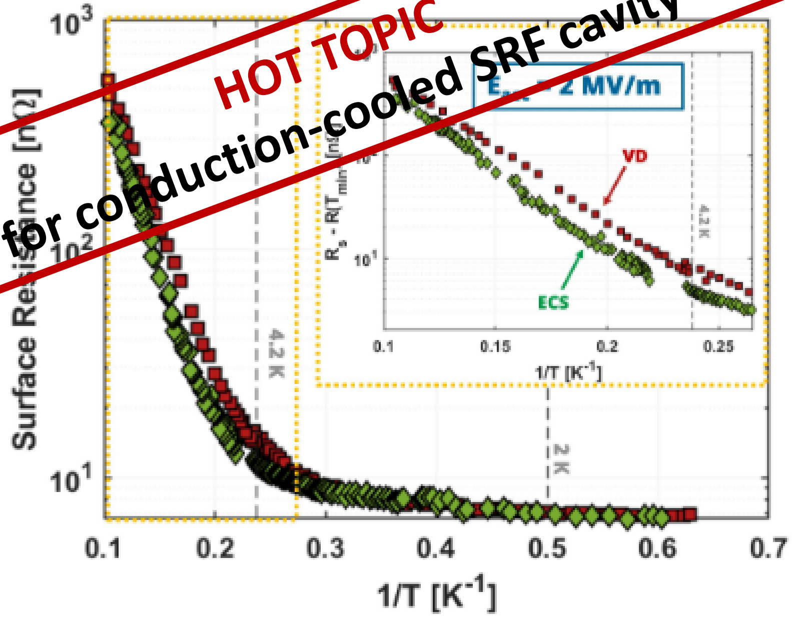




→ Very low BCS low resistance

HOT TOPIC

Challenges for conduction-cooled SRF cavity technology



→ First ever alternative growth method to vapor diffusion to achieve **quality factors >10¹⁰** at **4.2K**

Beyond Nb: Alternate Materials and Multilayer Structures Nb_3Sn

CVD Nb_3Sn Thin Film Performance

ULTRAMET ADVANCED MATERIALS SOLUTIONS

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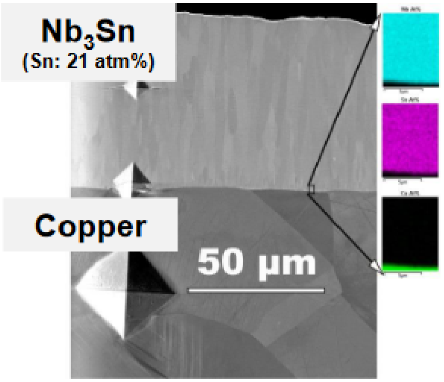
Ultramet | Pacoima, California

TESLA Technology Collaboration Meeting (TTC 2023)
Fermilab | Batavia, Illinois | December 5–8, 2023

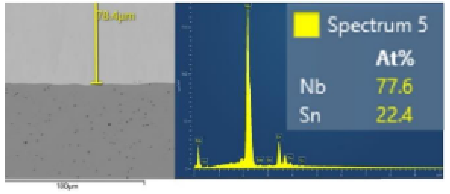
U.S. DEPARTMENT OF ENERGY | Office of Science

PROGRESS

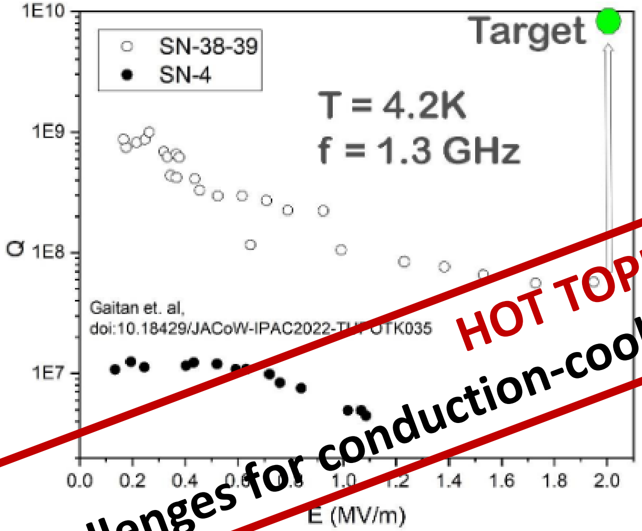
CVD Nb_3Sn coating on CVD niobium interlayer on welded (Niowave) copper cavity substrate



CVD Nb_3Sn coating on copper substrate: excellent adhesion



CVD Nb_3Sn on welded copper cavity



Q vs. E for first-of-kind CVD Nb_3Sn welded copper cavity SN38-39 and seamless copper cavity SN-4 with CVD Nb_3Sn coating on CVD niobium interlayer at 4.2 K

SN-4A, seamless copper cavity substrate (BTM, Inc.)

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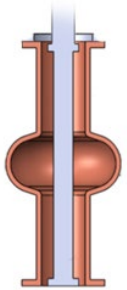
HOT TOPIC

Challenges for conduction-cooled SRF cavity technology

Nb_3Sn Coatings: Target Production

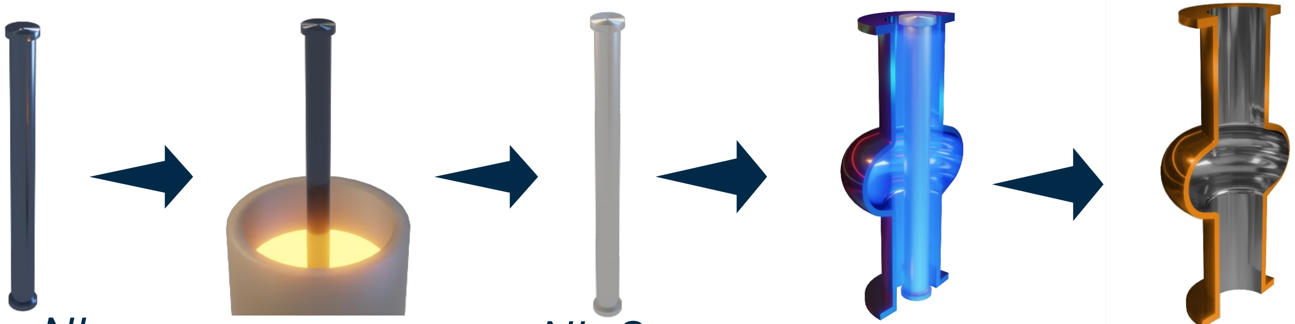
C. Pira et al.



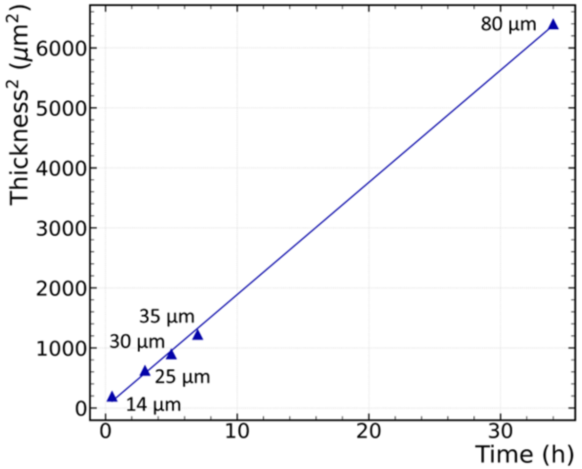
Single target configuration **easiest to scale** onto elliptical geometry

Nb_3Sn cylindrical target are not commercially available

LNL Strategy for Nb_3Sn cylindrical target production
(6 GHz cavities)

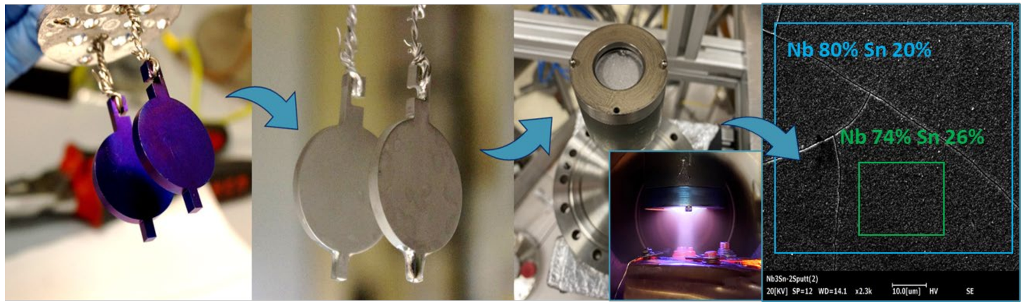


Raw Nb target → ***Dipping in liquid Sn*** → *Nb_3Sn cylindrical target* → ***Nb_3Sn Magnetron Sputtering*** → *Nb_3Sn on Cu cavity*



Nb_3Sn **thickness** related to **dipping time**

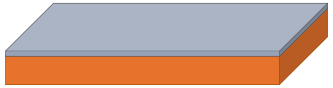
Possible **tin content modulation**



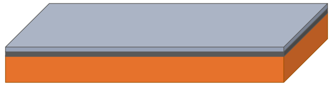
Proof of concept

Strategy to get the nominal Tc

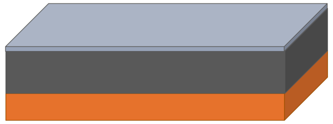
C. Pira et al.



Cu + 1 µm Nb_3Sn

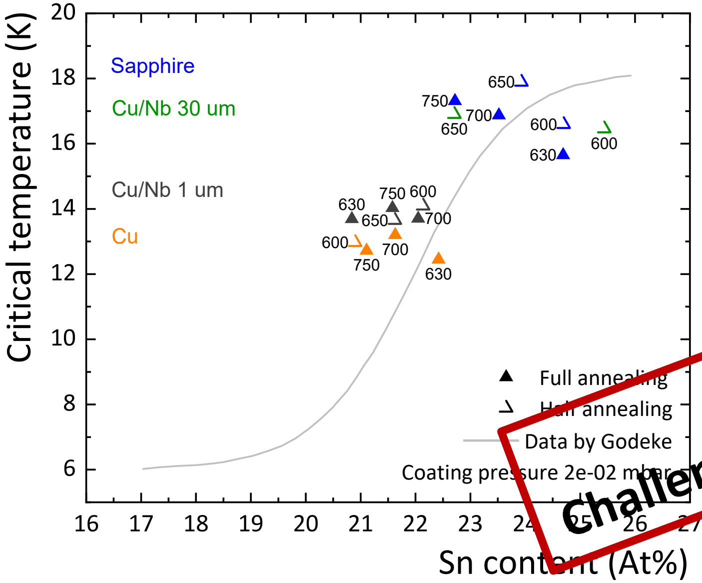


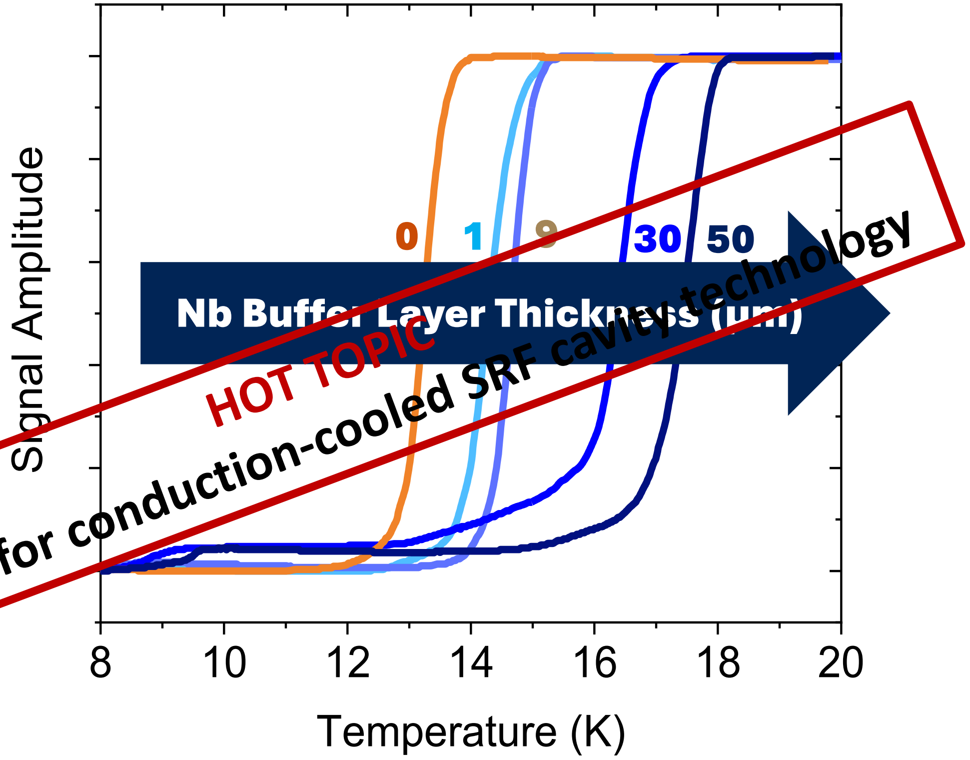
Cu + **1 µm Nb** + 1 µm Nb_3Sn



Cu + **50 µm Nb** + 1 µm Nb_3Sn

A very thick Nb barrier enhance dramatically Tc





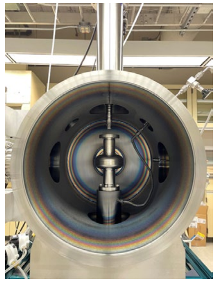
T_c = 17.33 ± 0.25 K on Cu + 50 µm Nb Buffer Layer at T_{dep} = 600 °C

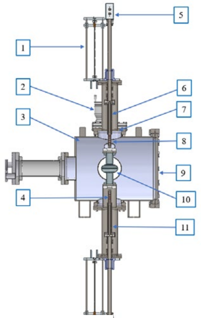
Beyond Nb: Alternate Materials

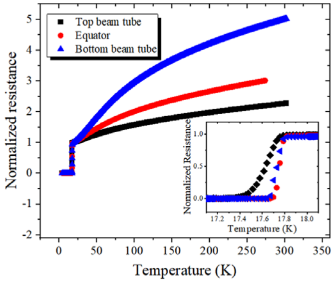
Nb_3Sn

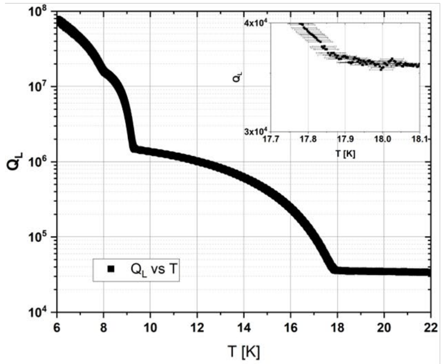
Frank Batten College of Engineering & Technology Old Dominion University | Fermilab | Jefferson Lab | Applied Research Center Old Dominion University

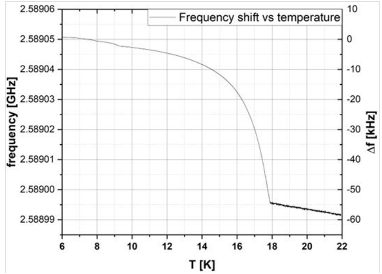
Nb_3Sn coating of a 2.6 GHz Nb SRF cavity using a Cylindrical Magnetron Sputtering System -*Sharifuzzaman Shakel, et al.*

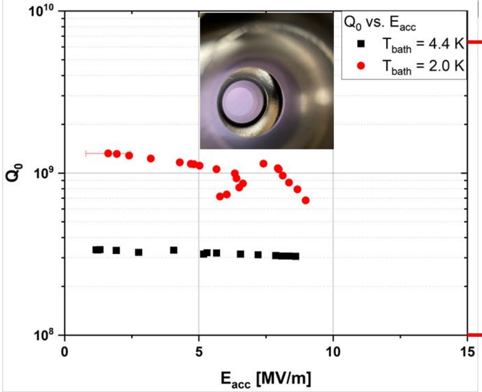










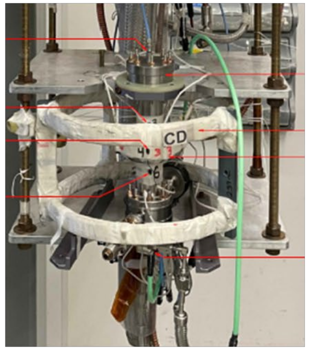


Q_0 with Acceleration gradient (E_{acc})

$Q_0 = 3.2 \times 10^8$ at $E_{acc} = 5$ MV/m, $T_{bath} = 4.4$ K
$Q_0 = 1.1 \times 10^9$ at $E_{acc} = 5$ MV/m, $T_{bath} = 2.0$ K

Nb $Q_0 \sim 7 \times 10^9$ @ $T_{bath} = 2.0$ K

Nb $Q_0 \sim 1 \times 10^8$ @ $T_{bath} = 4.4$ K



Nb_3Sn coating using cylindrical stoichiometric target

~20-22 um Nb_3Sn has been grown on Nb tube target of thickness of 0.1'' (OD 0.9'' x ID 0.8'').

Nb_3Sn has been grown on 4.5'' long Nb tube target using Sn vapor diffusion system in Jefferson Lab.

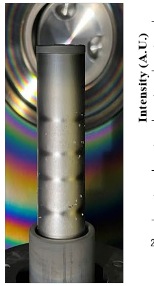
~148 hours of Sn vapor diffusion process produces ~20-22 um of Nb_3Sn on the surface of the tube.

Nb_3Sn tube target has been used to sputter deposit Nb-Sn film on Sapphire substrate using Cylindrical Magnetron Sputtering System.

Nb_3Sn target sputter discharged using the bottom magnetron

- 30 W DC power
- ~95-107 mA magnetron current
- 11 mTorr Ar background pressure
- 50 sccm gas flow rate.

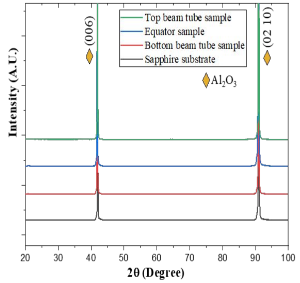
Positions	Total thickness (μm)
Top beam tube	~132 nm
Equator	~140 nm
Bottom beam tube	~127 nm



Nb_3Sn is depleted from the area against the magnets inside bottom magnetron, where the plasma is created.

Composition of as-deposited Nb-Sn films from stoichiometric Nb_3Sn tube target

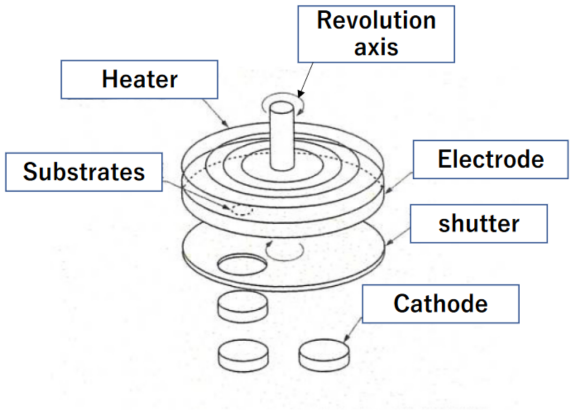
Sample Position	Nb (atm %)	Sn (atm %)
Top beam tube	74	26
Equator	73	27
Bottom beam tube	74	26



No crystalline Nb or Sn formation is observed in the XRD pattern of the as-deposited film. Only diffraction peaks from the sapphire substrates are observed.

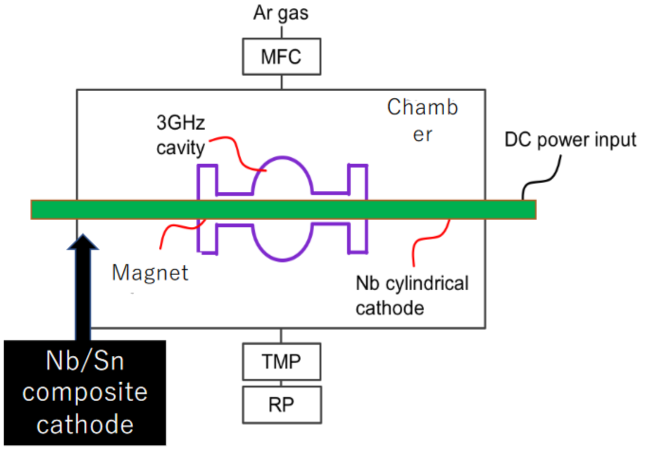
- As-deposited films will be annealed at 950 °C for 3 hours for Nb and Sn to interact for growing Nb3Sn.
- 1 μm Nb_3Sn film will be coated inside 2.6 GHz Nb cavity and annealed. The performance of the coated cavity will be tested.

Beyond Nb: Alternate Materials Nb_3Sn



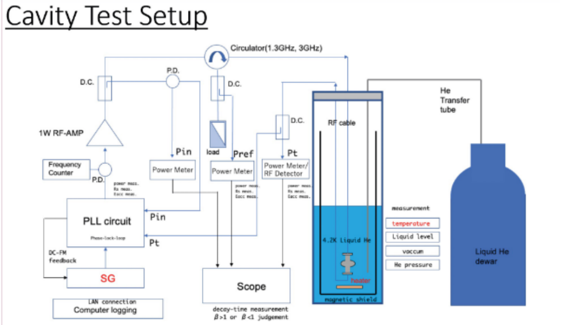
- KEK introduce the sputtering apparatus, SH-450 (ULVAC inc.).
- SH-450 is capable of Nb3Sn coating method almost same as developed by ULVAC-KEK collaboration.
  - In addition, temperature control of substrate is possible.
  - RF sputtering and HIPIMS are also possible only by replacing DC power sources.

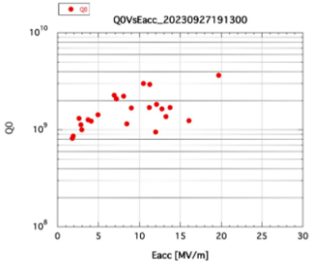
SRF multi-layer thin film R&D at KEK, Ryo Katayama , Wed 12/06



- Nb3Sn coating method can be applied to the inside of 3 GHz cavity.
- **Nb/Sn composite cathode** is the key.
- Development of the special cathode is ongoing.

T. Saeki, R. Katayama et al.





- This year, we prepared VT setup for 3 GHz cavity at KEK STF for evaluation of the cavity performance with S'IS structure.
- We performed the first VT of a 3 GHz cavity made of a pure bulk Nb on Sep 27.
  - Treatment
    - BCP and 120 °C bake for 48 h
    - No anneal (we missed)
- Problem
  - RF feedback system was unstable if Eacc is greater than 20 MV/m.
- We are developing new RF feedback system designed to be work stably.

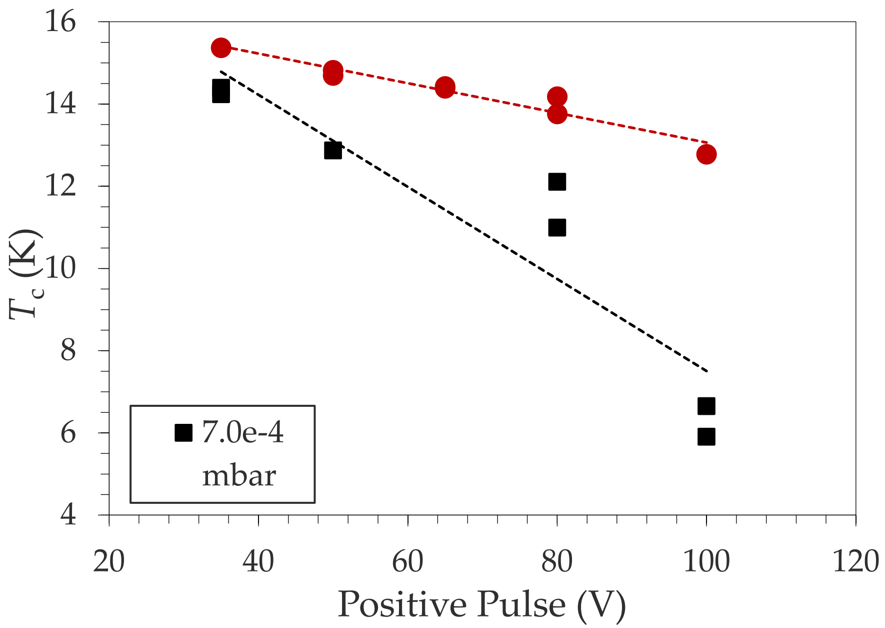
Beyond Nb: Alternate Materials Nb_3Sn

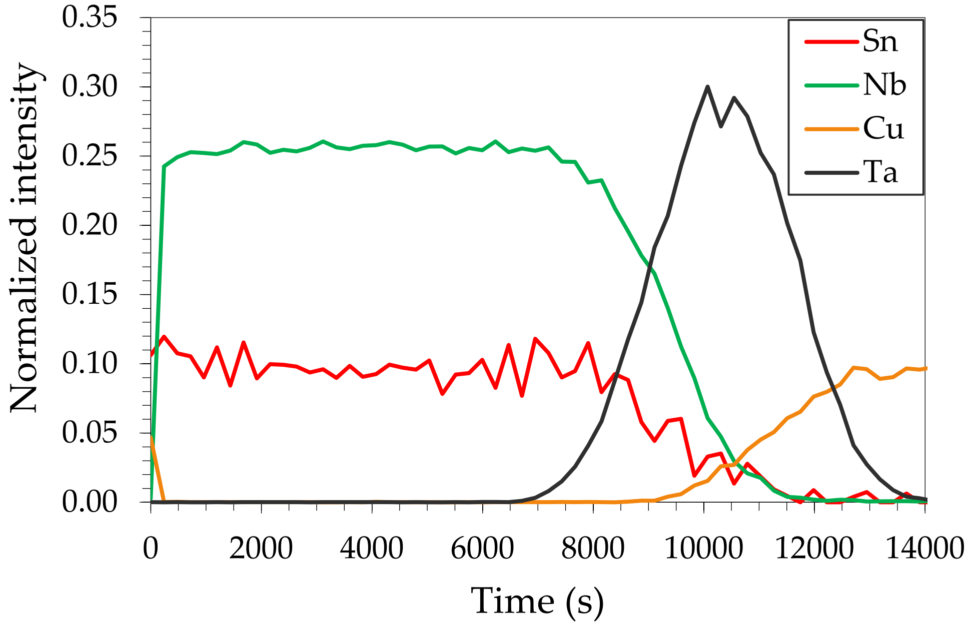
A15/Cu

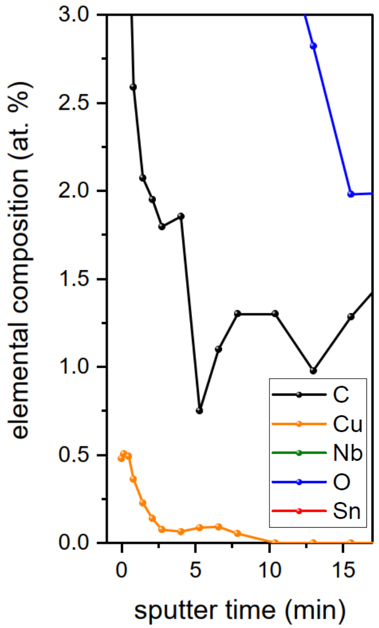
https://indico.jlab.org/event/535/contributions/10694/attachments/8476/12127/Recent%20advances%20with%20bipolar%20HiPIMS-deposited%20Nb3Sn%20films%20on%20Cu_S.%20Leith.pptx

G. Rosaz et al.

Choice to move to Bi-polar HiPIMS
- Q-slope mitigation proven on Nb/Cu
- Detrimental to long range order parameter (bombardment energy)







Sn composition: OK
T_c: still lower than the theoretical value
Cu surface contamination is a key issue

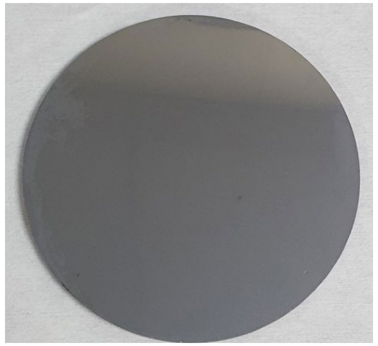
Recent RF measurements are very encouraging
Communication under preparation

Beyond Nb: Alternate Materials Nb_3Sn

Science and Technology Facilities Council

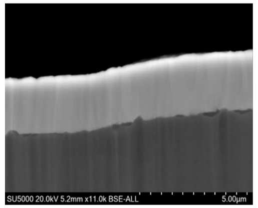
- 3 DCMS, 1 HiPIMS
- **Aim:** investigate effect of target power/deposition method
- **Substrate preparation:**
  - Diamond turned Cu disks – 10 cm diameter, 3 mm thick
  - Average roughness ~ 2-3 nm
- **Sample preparation:**

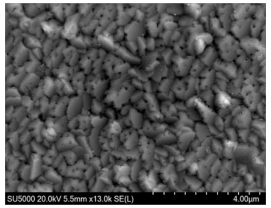
Parameter	DCMS	HiPIMS
Substrate heater current (A)	35 (~ 650 °C)	35 (~ 650 °C)
Target power (W)	200, 100, 50	100
Expected thickness (µm)	2.6	2.6

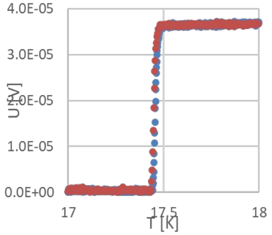


R. Valizadeh et al.

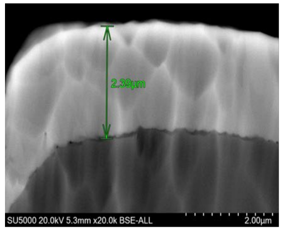
100 W DC Nb_3Sn on 50 and 100 mm diamond turned Cu

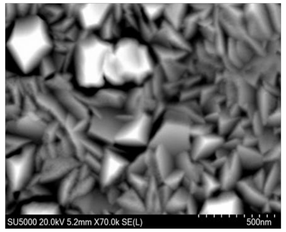


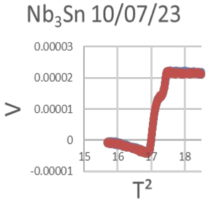




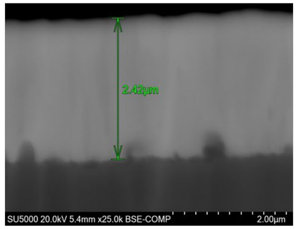
100 W HIPIMS Nb_3Sn on 50 and 100 mm diamond turned Cu

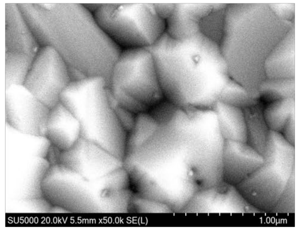


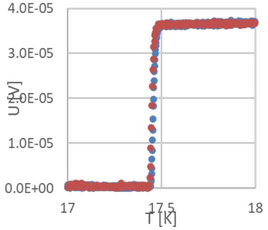




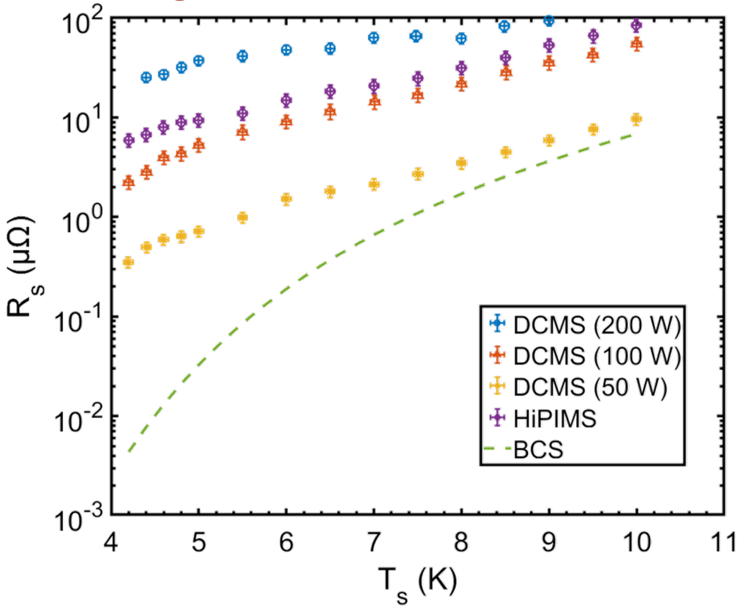
50 W DC Nb_3Sn on 50 and 100 mm diamond turned Cu







Nb_3Sn: surface resistance



T_c ~ 16.5 – 17 K from frequency shift

*BCS from SRIMP code (Parameters from: A-M Valente-Feliciano, *Superconducting RF materials other than bulk niobium: a review*)

TESLA TECHNOLOGY COLLABORATION

Jefferson Lab

Beyond Nb: Alternate Materials

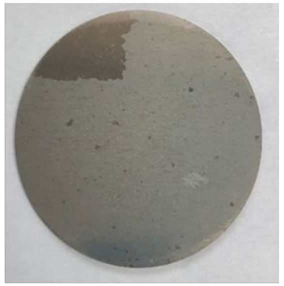
NbTiN

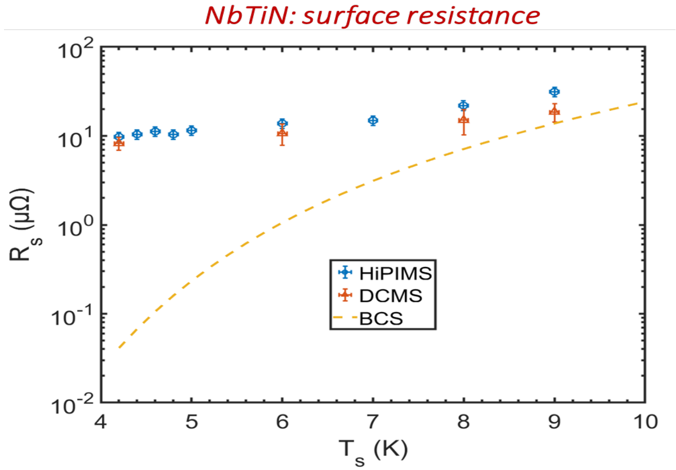
Science and Technology Facilities Council

Synthesis Of NbTiN As An Alternative Thin Film For SRF Cavity – *R. Valizadeh*

R. Valizadeh et al.

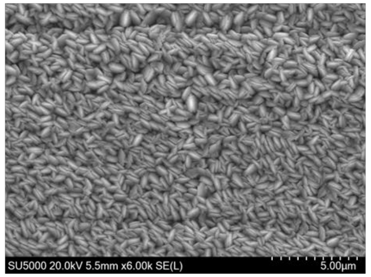
Parameter	DCMS	HiPIMS
Substrate heater current (A)	35 (~ 650 °C)	35 (~ 650 °C)
Target power (W)	300	300
Expected thickness (μm)	0.8	0.8

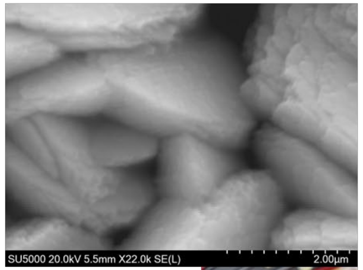




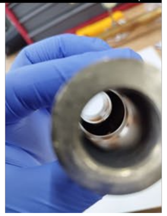
*BCS from SRIMP code (Parameters from: A-M Valente-Feliciano, *Superconducting RF materials other than bulk niobium: a review)*

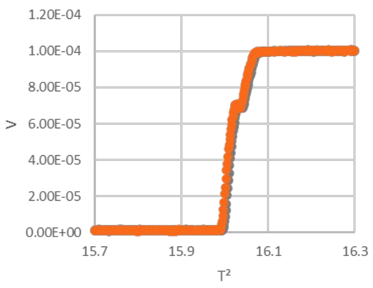
NbTiN from Nb Rod and Ti Wire



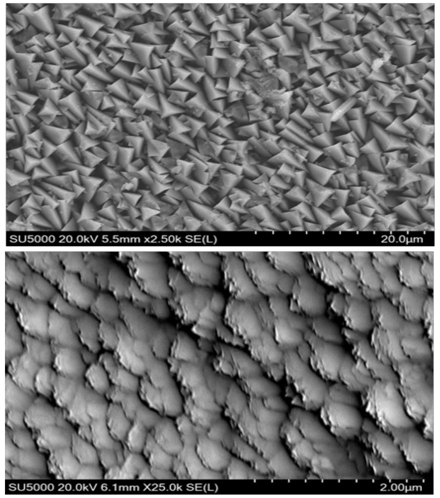


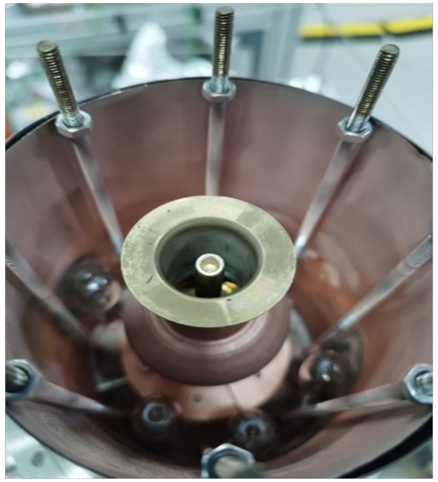
After several iteration of changing Ti wire loops composition of $Ti_{0.5}Nb_{0.5}$ reached





NbTiN from NbTi Rod

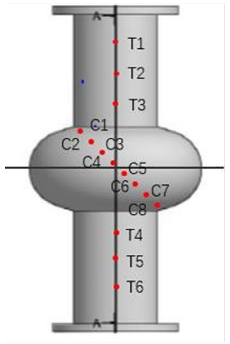


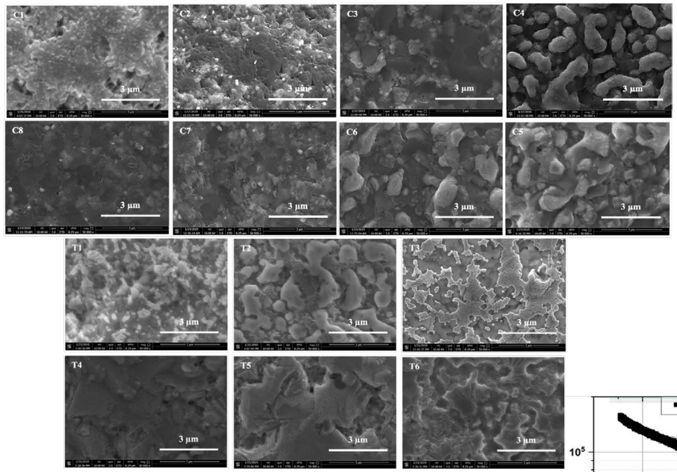


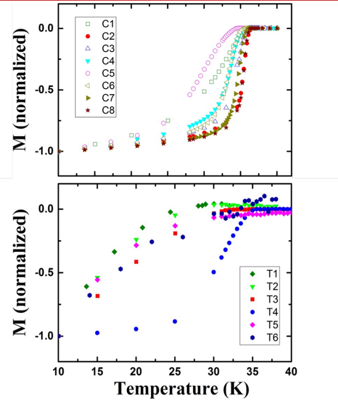
Composition is fixed $Ti_{63}Nb_{37}$

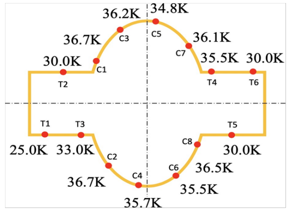
Other SC Materials beyond Niobium: MgB_2

X. Xi et al.

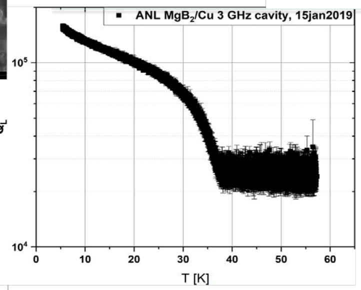


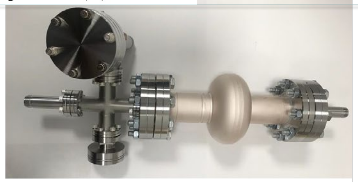


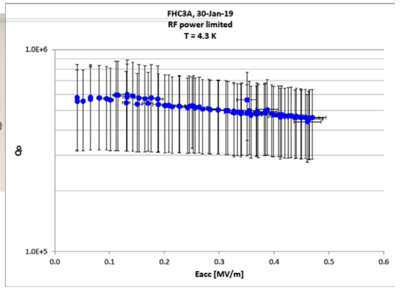




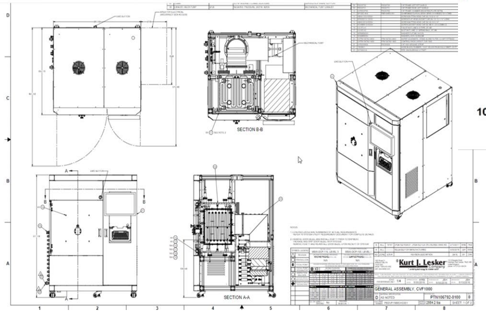
- All the samples show superconducting transition
- The transition temperature for MgB_2 films on cavity cell: around 34.8-36.7 K



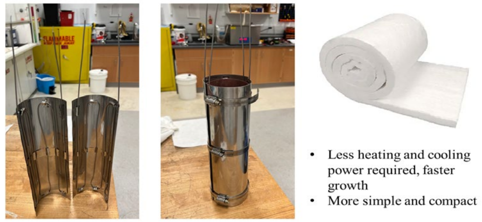




- RF test performed at JLab
- The 3.9 GHz MgB_2 thin film cavity show transition at around 36K.
- Q value is low (1E5 at 20 K and 1.5E5 at 5 K).

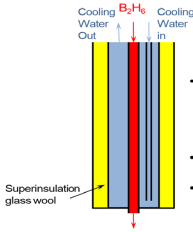


New direct-contact heater with superinsulation glass wool or castable ceramics to impede radiation and convection



- Less heating and cooling power required, faster growth
- More simple and compact

New B_2H_6 gas feed line design with superinsulation glass wool to impede radiation



- Superinsulation layer to lower thermal conduction between the hot outer tube and the water jacket
- Outer tube at similar T as the cavity
- Less Mg to condense on the outer tube

Previous results

- MgB_2 was coated on 3.9 GHz mock Cu cavities. Good superconducting property $T_c \sim 36$ K and surface morphology were observed.
- RF test performed shows low Q possibly due to poor connectivity of MgB_2 grains caused by incomplete reaction of B with Mg-Cu alloy. Longer deposition should help.

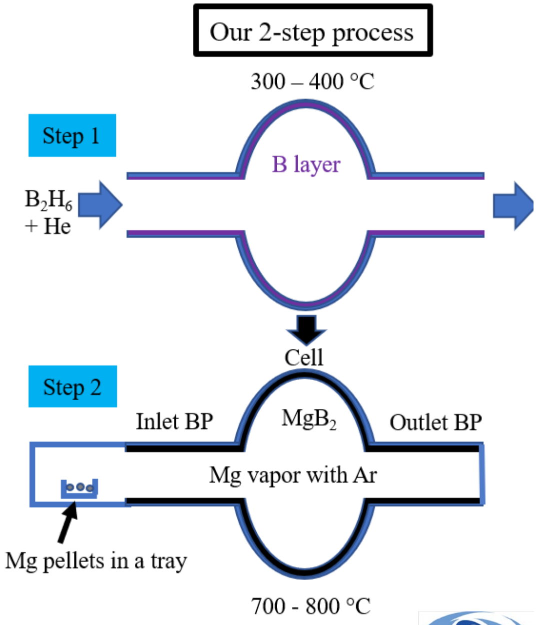
Current progress and plan

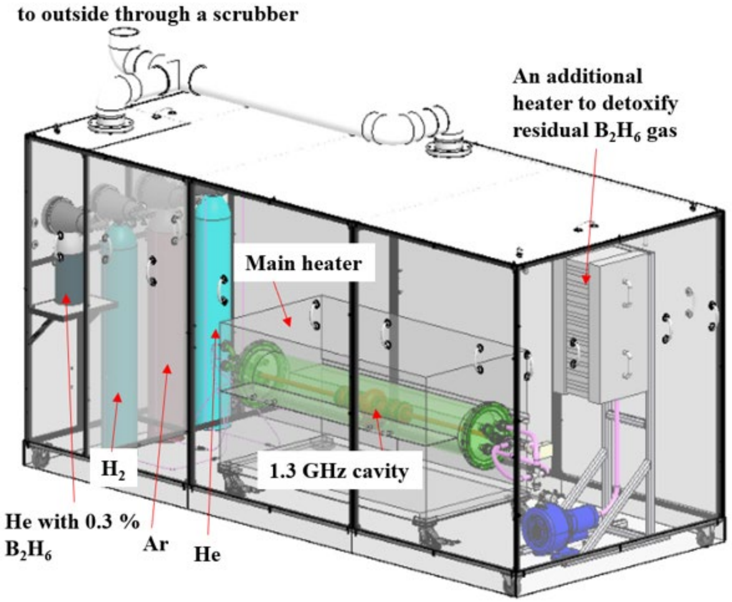
- MgB_2 to be coated on 1.3 GHz Cu cavities.
- Procuring a larger vacuum chamber.
- Cavity heater design is changed to direct-contact heating with superinsulation.
- Superinsulation replaces vacuum jacket to the B_2H_6 gas feeding line.

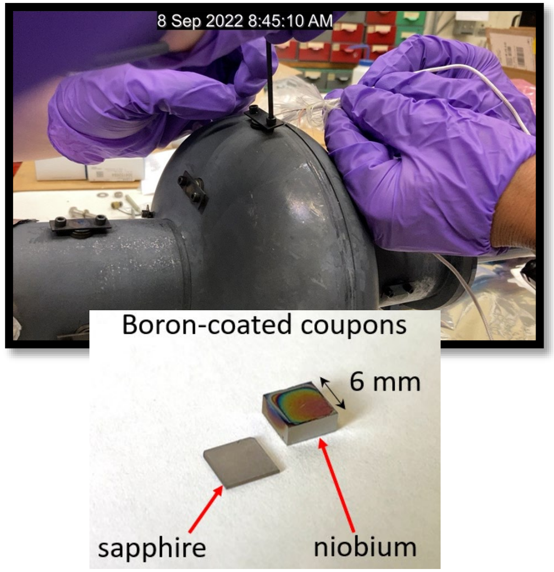
Other SC Materials beyond Niobium: MgB_2

LANL MgB_2 coating status [U.S. – Japan Science and Technology Cooperation Program]

- Cavity coating booth with ventilation constructed using LANL LDRD funding
- B coating system plumbing, installation of flow and gas detectors, and interlocks underway
- Using old B-coated coupons, B-Mg reaction tests were conducted and confirmed SC transitions, but not high quality with lower T_c and broader transition as shown on the next slide







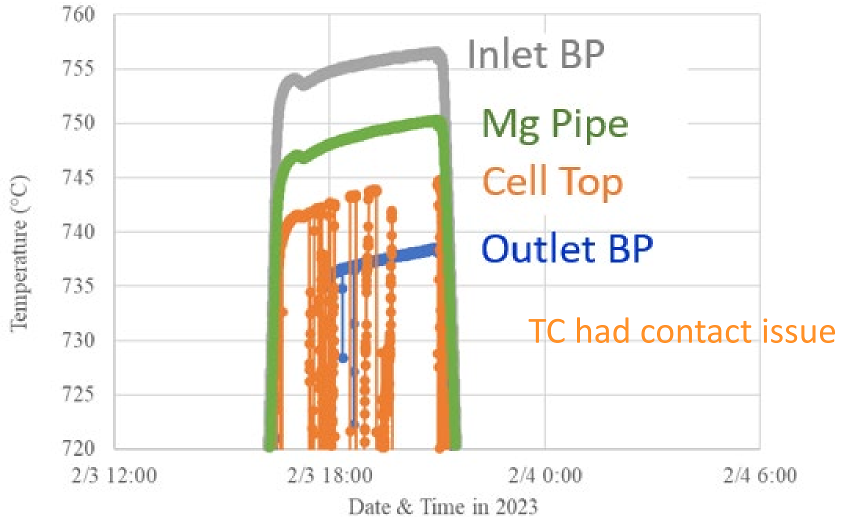
T. Tajima et al.

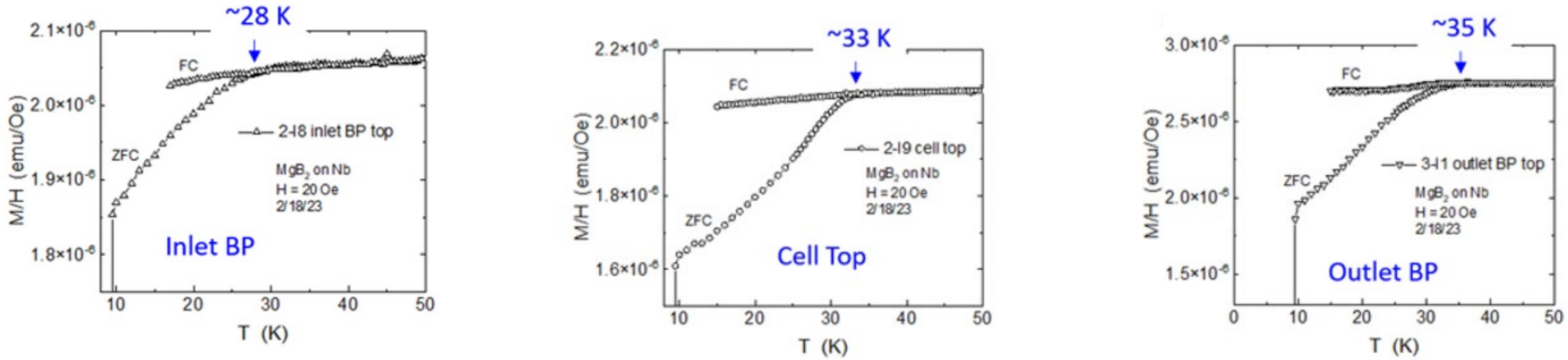
[IEEE Trans. Appl. Supercond. 33 (2023) 3500203]

Other SC Materials beyond Niobium: MgB_2

Plans to improve the quality of MgB_2 films

- Install an independent heater to control the temperature of Mg pellets section.
- Replace Vermiculite seals with metal seals at the cavity flanges, suspecting that these seals are the source of contamination.





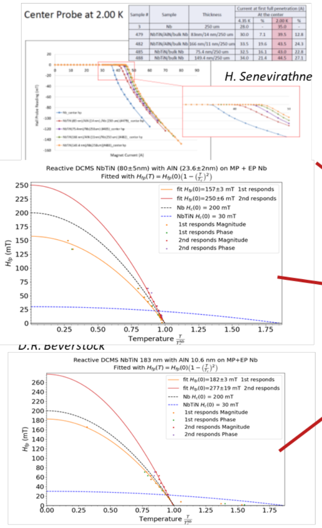
Magnetometer measurements results

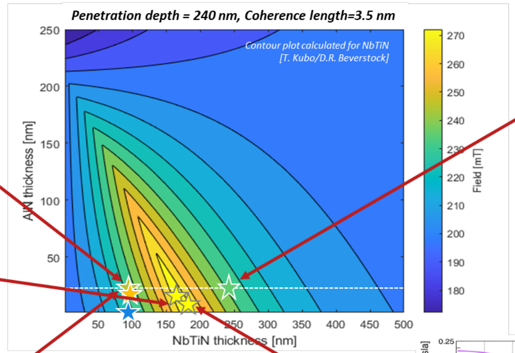
T. Tajima et al.

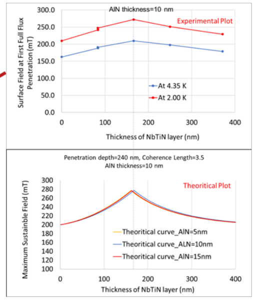
Beyond Nb: Multilayer Structures

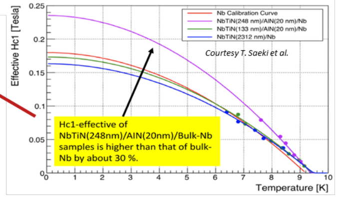
NbTiN/AlN

Measurement on NbTiN SIS structures on 1" & 2" Nb substrates

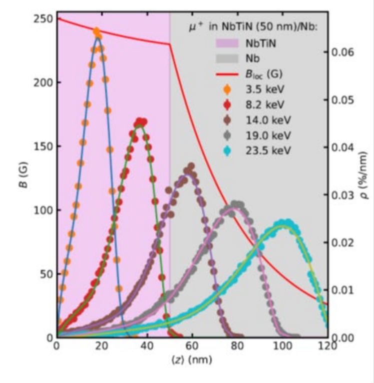








- *Deposited SIS structures fit the theoretical model*
- *3rd harmonic measurements show field enhancement up to 20-60% compared to base bulk Nb .*
- *Effect most sensitive to coherence length*

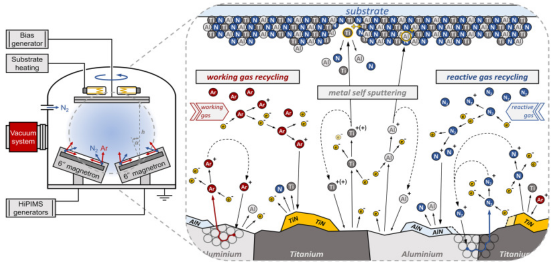


LE-μSR measurements on NbTiN/Nb

- *μSR measurements demonstrate the requirement of the dielectric layer in the SIS model*
- *High quality SIS structures for thicknesses all the way down to the nm level (Stack of 32 bilayers NbTiN/AlN/NbTiN/MgO is fully crystalline*

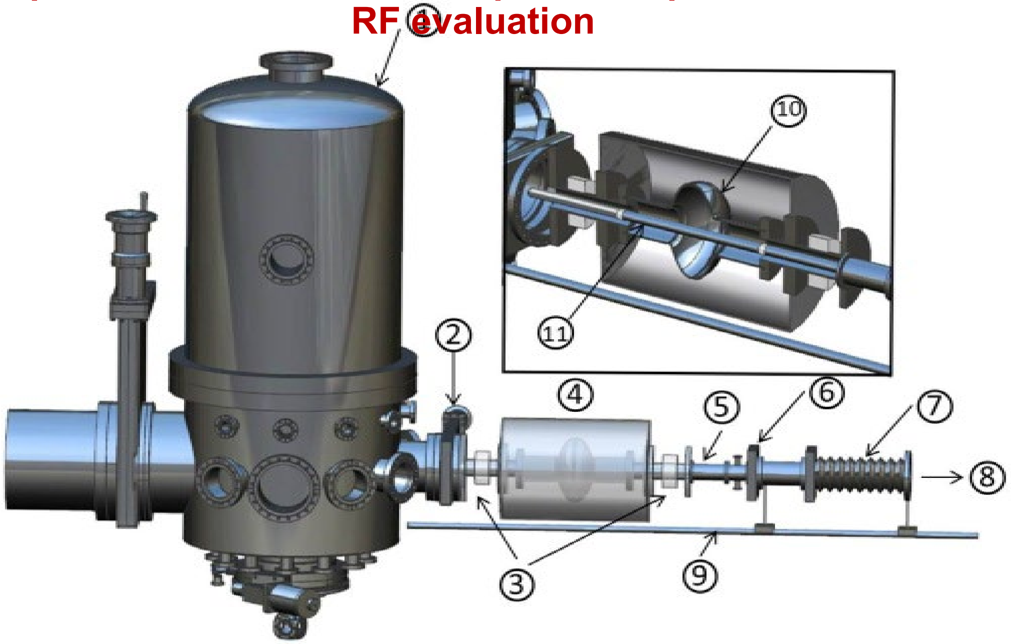
A-M Valente-Feliciano et al.

Re-HiPIMS



Refine deposition process for denser, more relaxed material in thin layers

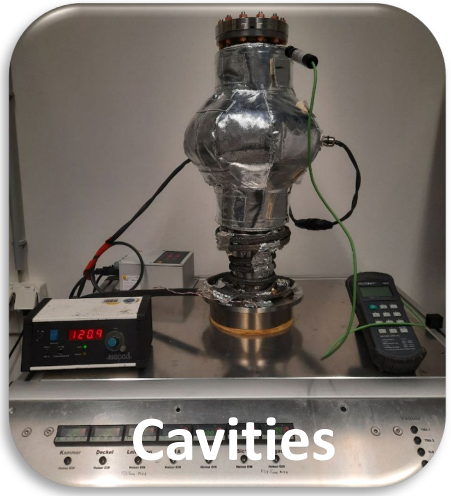
Implementation on QPR samples & elliptical cavities for RF evaluation



Development of Nb_3Sn Based SIS started

All under one roof: Coating & Testing - Samples & Cavities

M. Wenskat et al.



Thermal ALD

Several coated cavities by ALD of Al_2O_3.

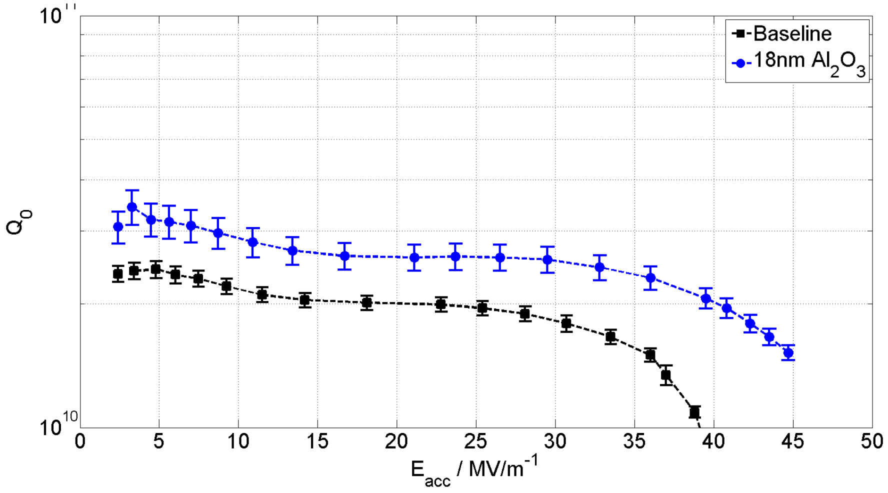
No deterioration of performances.

Maintaining E_{acc} above 40 MV/m for 2 out of 2 cavities.

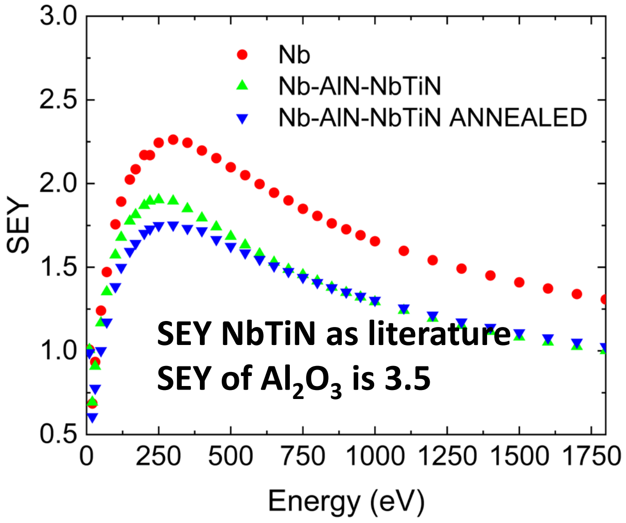
Plasma-enhanced ALD

PEALD of AlN/NbTiN multilayers.

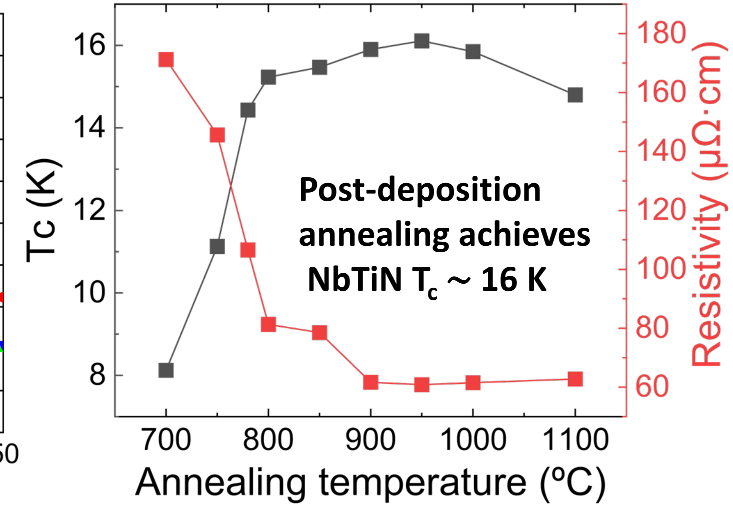
Characterization methods: ETO, VSM, SEM/TEM, SEY, XPS, etc.



[Wenskat, M. *et al.*, Supercond. Sci. Technol. 36 015010 (2023)]



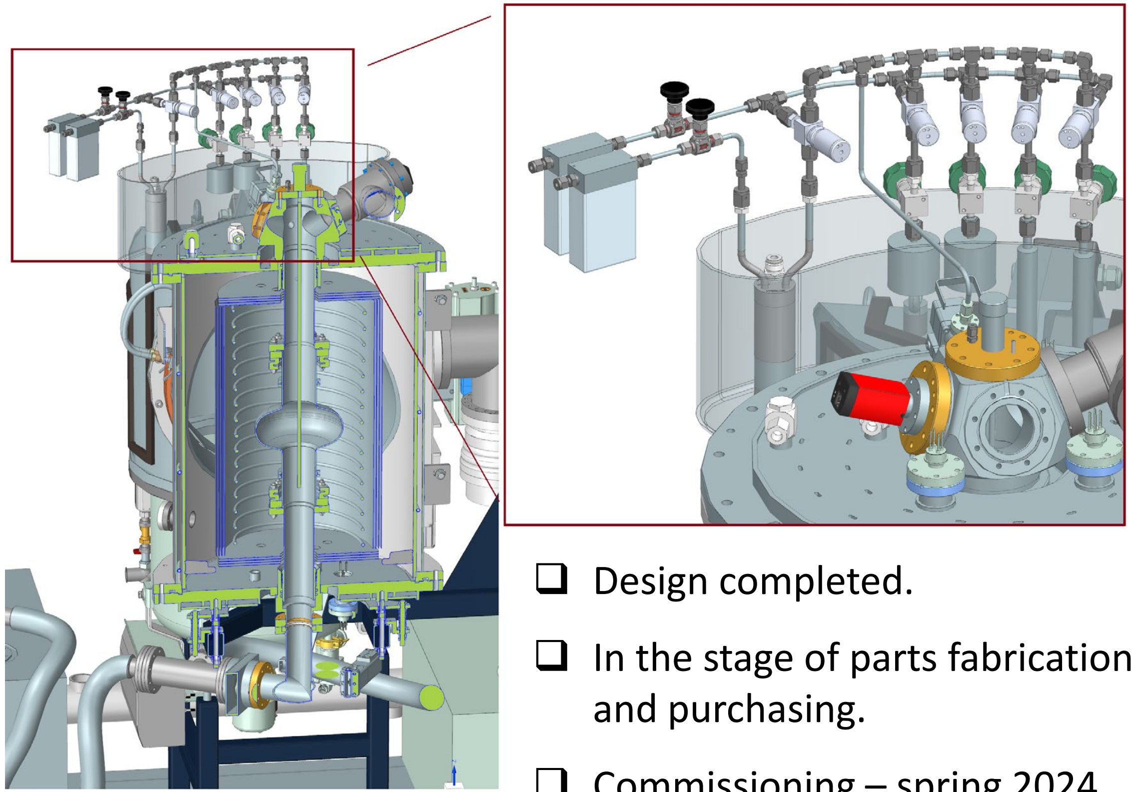
[Deneke, K. unpublished]



[González Díaz-Palacio, I. *et al.*, J. Appl. Phys. 134(3), 035301 (2023)]

Merge SIS sample results and cavity coating

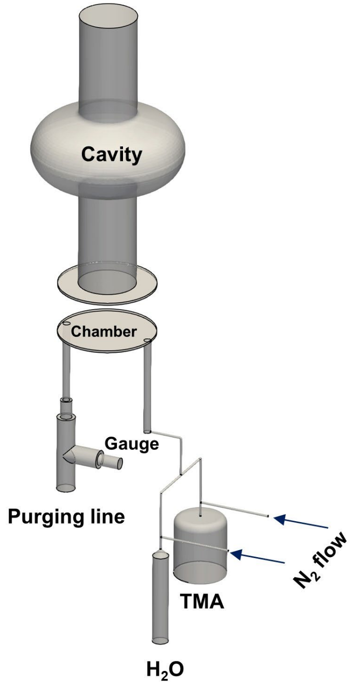
Plasma-Enhanced – Atomic Layer Deposition setup for single-cell cavities

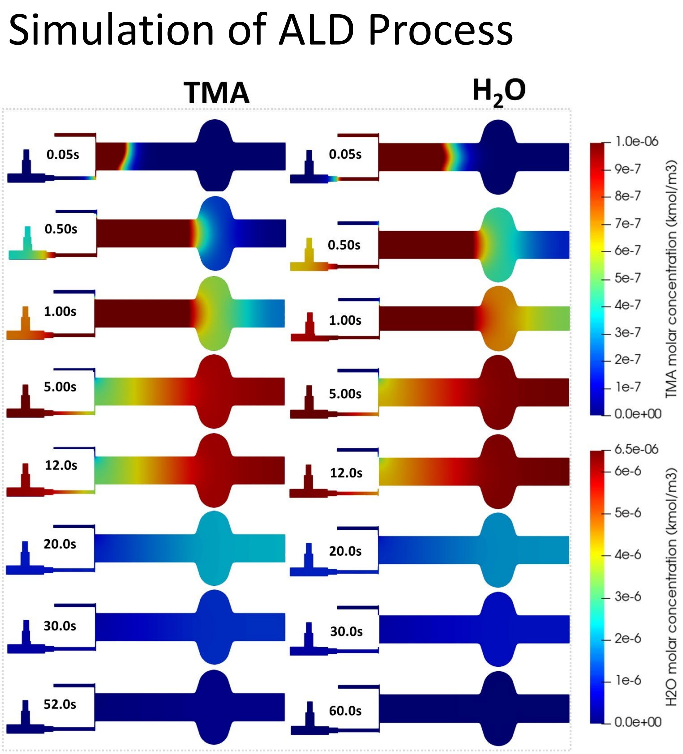


- ❑ Design completed.
- ❑ In the stage of parts fabrication and purchasing.
- ❑ Commissioning – spring 2024.
- ❑ First coatings planned for summer 2024.

M. Wenskat et al.

Thermal budget reduction of coating SRF cavities





- ❑ Significant time reduction and process optimization while maintaining quality.
- ❑ Excellent agreement of experiment and simulations of fluid dynamics and chemical reactions.

[Deyu, G. *et al.*, Chemical&Fluid Simulations on CavityCoating – to be submitted]

Further Characterization

M. Wenskat et al.

Flux Trapping

[Turner, D. *et al.*, MOPMB003, SRF2023]

Flux expulsion studies with CERN show Drastic **increase of expulsion efficiency** by continuous expulsion for each heat pulse even with **constant dT/dx**.

Thermal Resistance

[Saribal, C. *et al.*, MOPMB017, SRF2023]

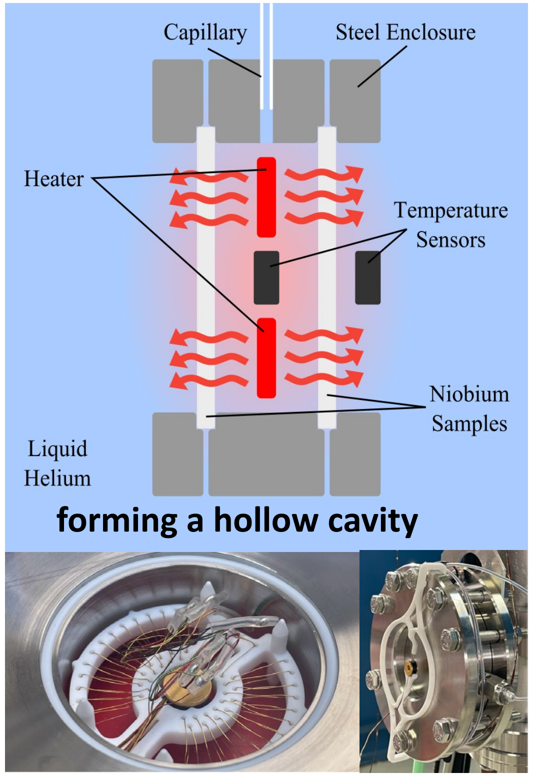
Thermal resistance of Nb-AlN-NbTiN shows no increase!

RF Measurements

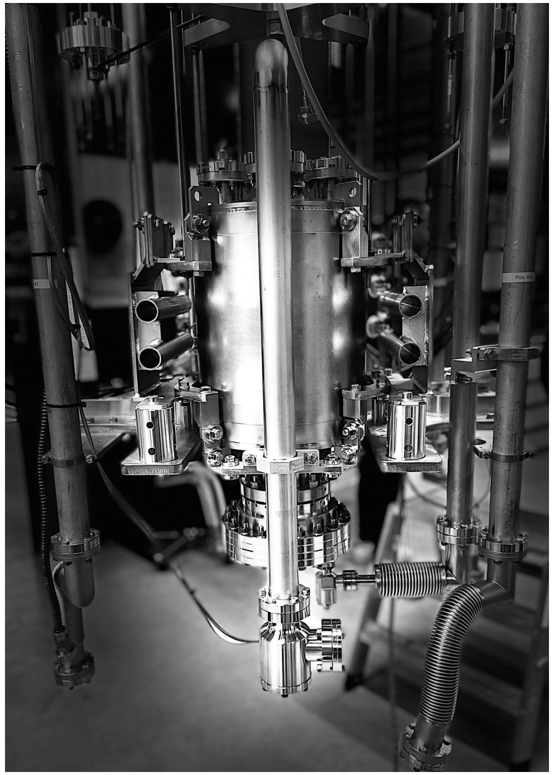
[Monroy-Villa, R. *et al.*, THCAA02, SRF2023]

QPR is now ready and 5 new samples for R&D are currently getting fabricated.

Thermal Resistance



QPR Setup for RF Measurements



SIS by ALD

Thin film R&D @ CEA

Y. Kalboussi, B. Delatte, C. Antoine, A. Four, F. Miserque, Y. Zheng, D. Hrabovsky, T. Junginger, N.Lochet , D.Bafia, L.Grasselino, T. Proslier

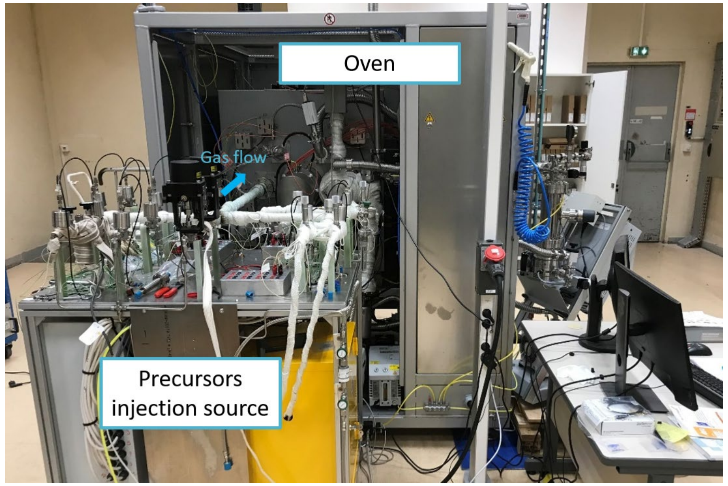
- New cooling techniques: 3D printing of 3.9 GHz cavities with closed loop cryocooler.
- Mitigating multipacting in SRF cavities by ALD and thermal treatments.
- Superconducting characterization of cavities and Qubits by tunneling spectroscopy.

✓Increased Q at low field for 3D superconducting resonators 1.3 GHz.

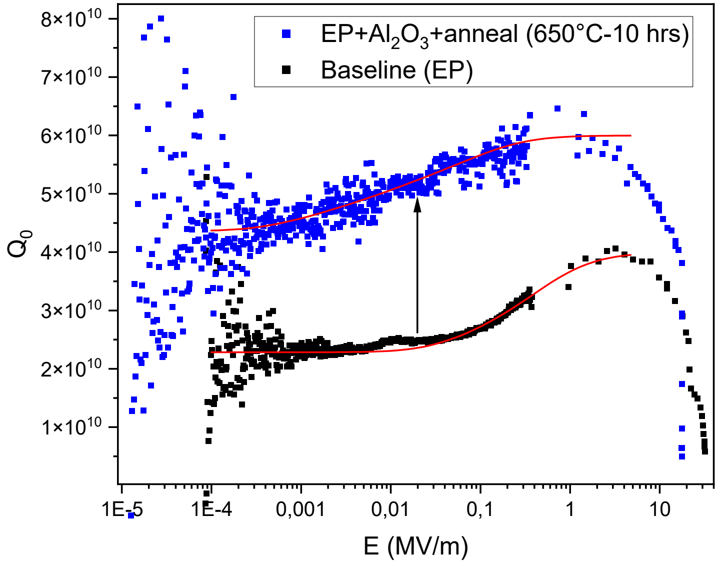
✓Increased penetration field on samples by 24%. First depositions of multilayers in 1.3 GHz cavities.

✓N doped cavity by ALD of NbN. Optimization underway. First depositions of multilayers in 1.3 GHz cavities.

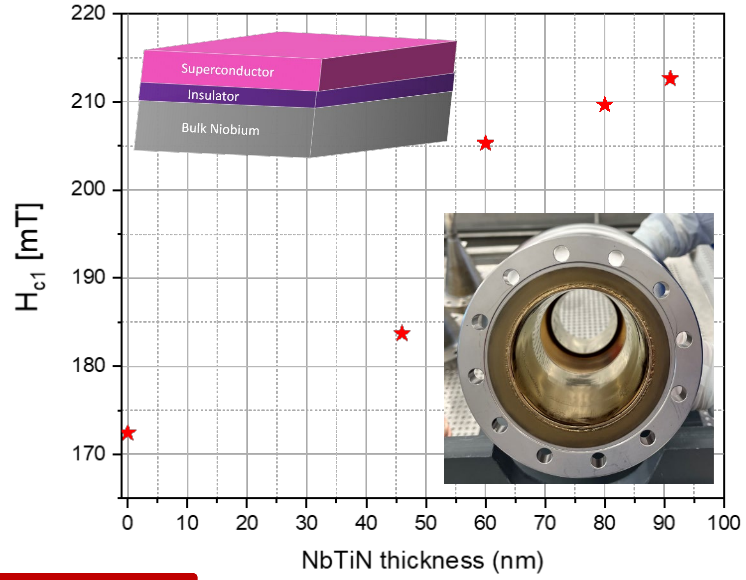
Home built Cavity deposition set up



High Q studies for Qubits and accelerators



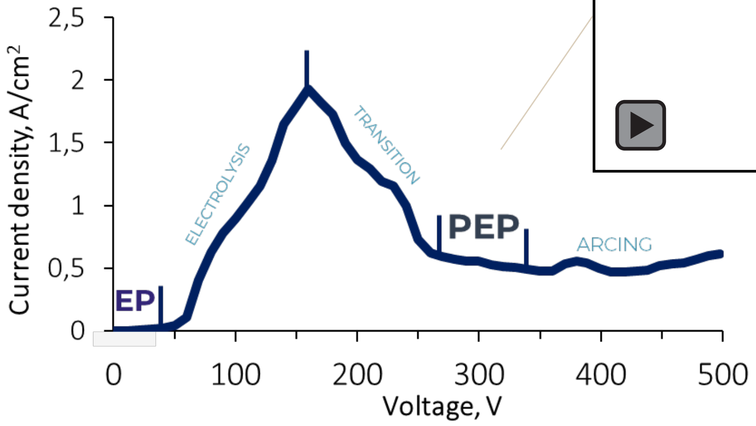
High Gradient for accelerators increased penetration field.

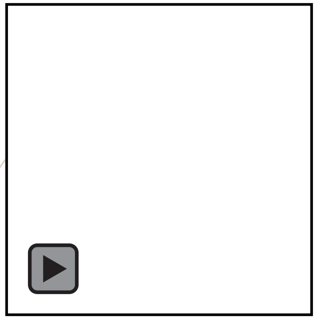


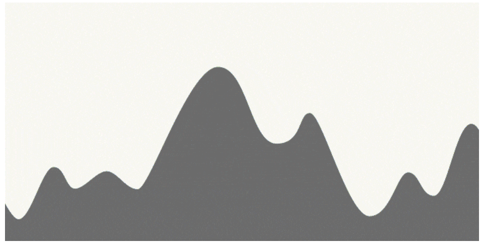
ALD surface engineering for SRF cavities , Y. Kalboussi, Wed 12/6

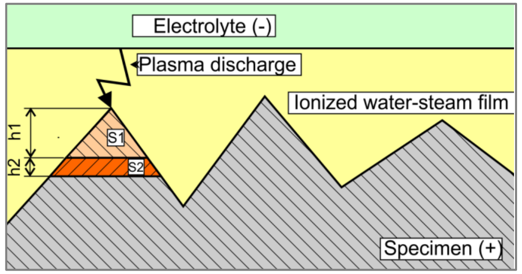
Plasma Electrolytic Polishing PEP

Mechanism

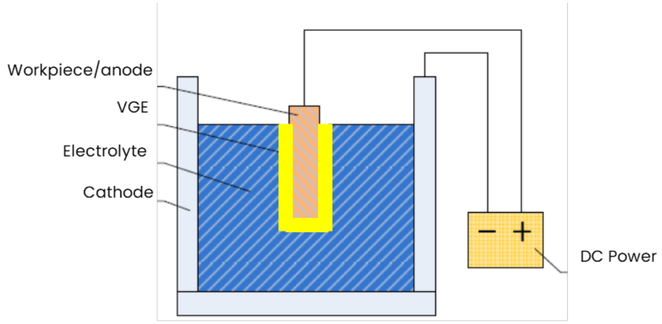






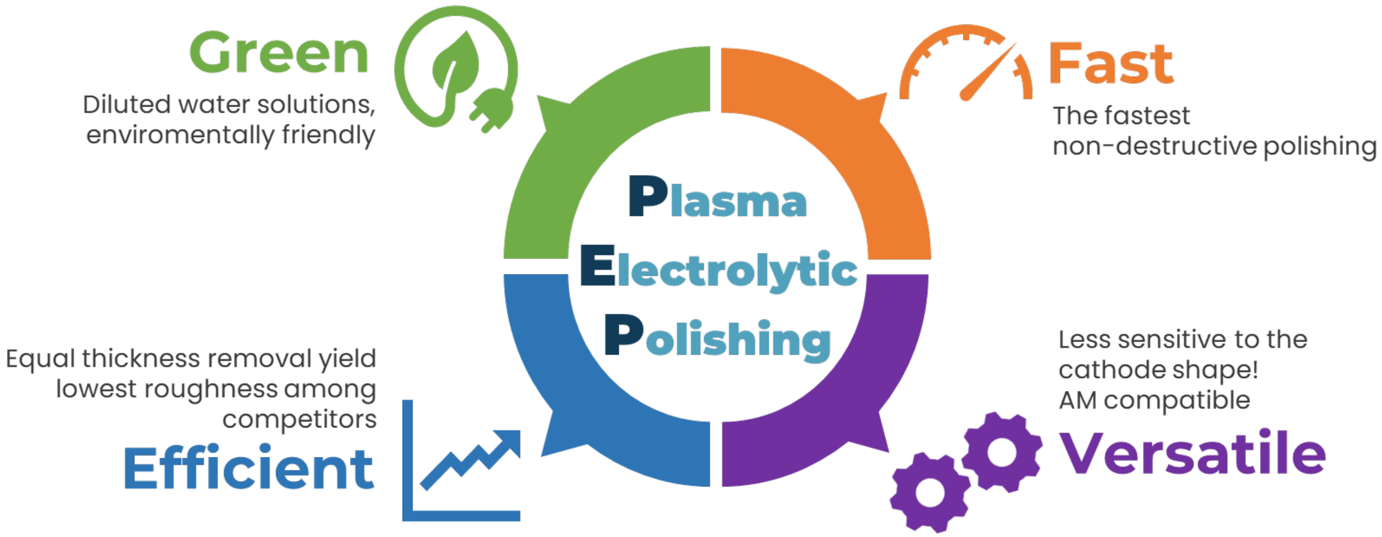


Same EP set-up -Different regime



J. Wang et al., AMR, 2012

Advantages

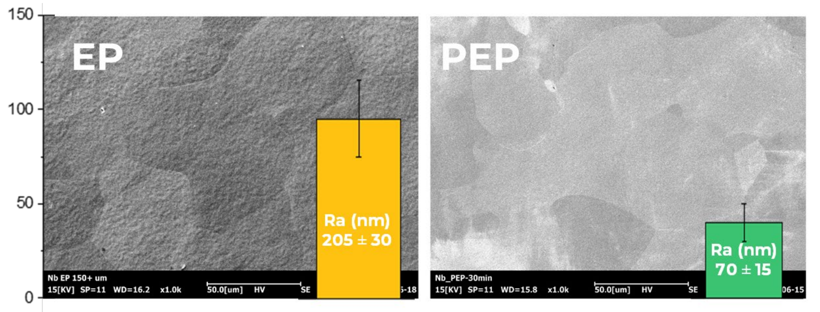


Advanced Substrate Preparation

Plasma Electrolytic Polishing PEP

SAMARA
INFN CSN5 EXPERIMENT

Results



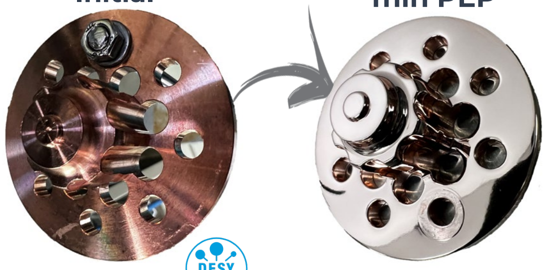
150 µm removed in ~ 5 h | 150 µm removed in ~ 40 min

1x Nb 3x Cu

Solution Patented by INFN

Ra ~ 8 nm!

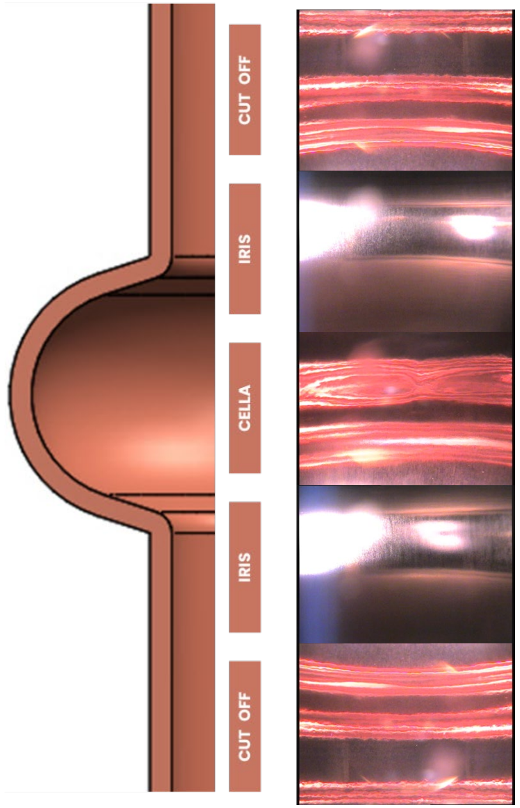
Initial **After 4 min PEP**



DESY. Photocathode

Cu QPR HZB Helmholtz Zentrum Berlin

6 GHz Cu cavity



No internal cathode

70 µm removed in 10 minutes

30 A (100 cm2 → 1.3 GHz ~ 300 A)

Plasma Electrolytic Polishing, Cristian Pira (INFN LNL), Tues 12/5

Thin film R&D @ CEA

Y. Kalboussi, B. Delatte, C. Antoine, A. Four, F. Miserque, Y. Zheng, D. Hrabovsky, T. Junginger, N.Lochet , D.Bafia, L.Grasselino, T. Proslier

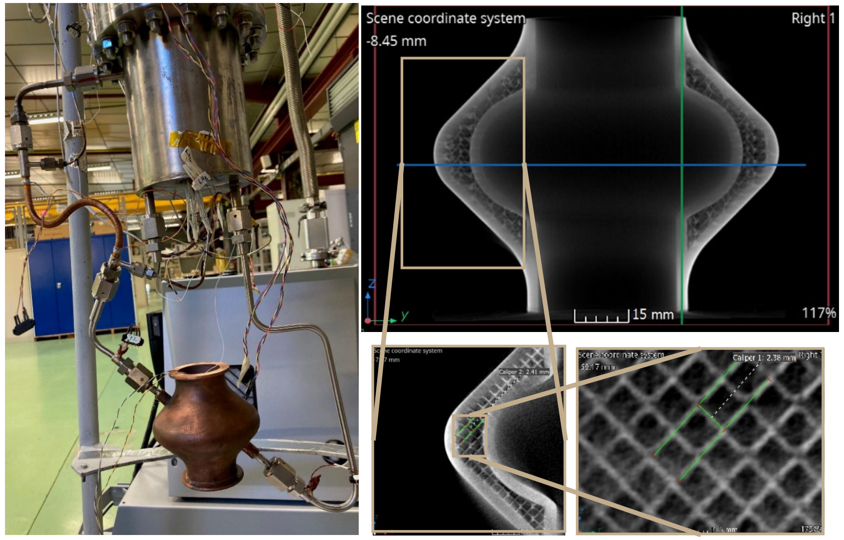
- Engineering superconducting surface for high Q operation by Atomic layer deposition (ALD) and thermal treatments.
- Engineering superconducting surface for high gradient operation by ALD and thermal treatments: Doping without chemistry and multilayers.

✓3D printed 3.9 GHz cavity cryocooled to 4.2K. Successful power dissipation studies.

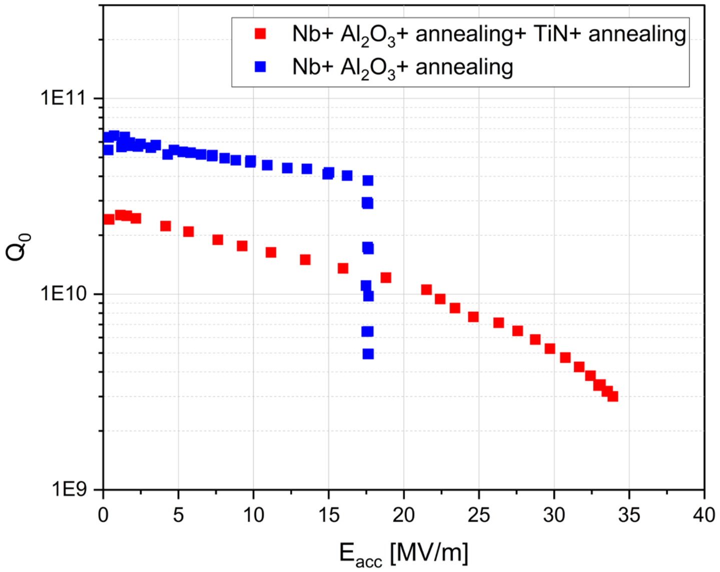
✓Successful multipacting mitigation in 1.3 GHz cavities by TiN deposition.

✓First samples measured: Nb_3Sn/Cu (CERN) and Nb/Ta resonators (USA).

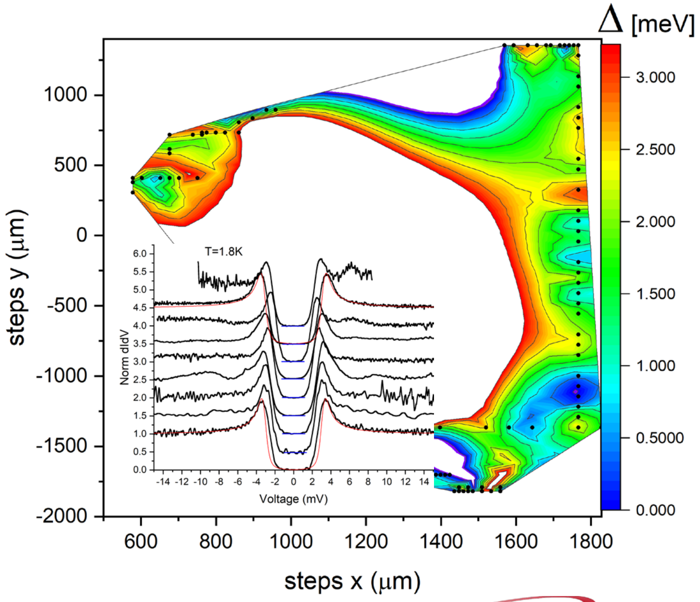
Cryocooled 3D printed Cu cavity



Multipacting mitigation by ALD of TiN



Tunneling spectroscopy of Nb3Sn/Cu



Summary

- **Nb Thin Film Technology**
  - Results on cavities at different frequencies
  - Demonstrations of Nb/Cu Q-slope mitigation
- **Beyond Nb: Alternate Materials**
  - Progress with Nb_3Sn by vapor diffusion towards cryomodules and conduction cooled cavities
  - Further development of alternate Nb_3Sn coating techniques HiPIMS, sputtering, CVD…
- **Beyond Nb: Multilayer Structures**
  - Further development on samples for characterization and RF measurement (QPR)
  - Development of concept from samples to cavities
- **Advance substrate fabrication & preparation**
- **SRF Film Characterization**
  - μ-SR, β-NMR, PCT, QPR, flux expulsion …
- **Superconducting TF applications beyond SRF keep expanding (devices, sensors quantum …)**
  - Nb/Al_2O_3 films for qubits
  - NbTiN Films for Superconducting Digital Logic
  - Film based cavities for Axion research (NbTi cavity, *INFN, C. Pira*)

Save the date

11th International Workshop on
Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

International Organizing Committee

C. Antoine (CEA Saclay, France)
A.- M. Valente-Feliciano (Jefferson Lab, USA)
C. Pira (INFN LNL, Italy)
A. Gurevich (Old Dominion University, USA)
W. Venturini (CERN, Switzerland)
R. Valizadeh (STFC, UK)
T. Saeki (KEK, Japan)

Will be held in 16-20 September 2024

In Paris Area, France
Hosted by CEA Saclay, Sponsored by iFAST Program