Report from the

TTC Thin Film Working Group

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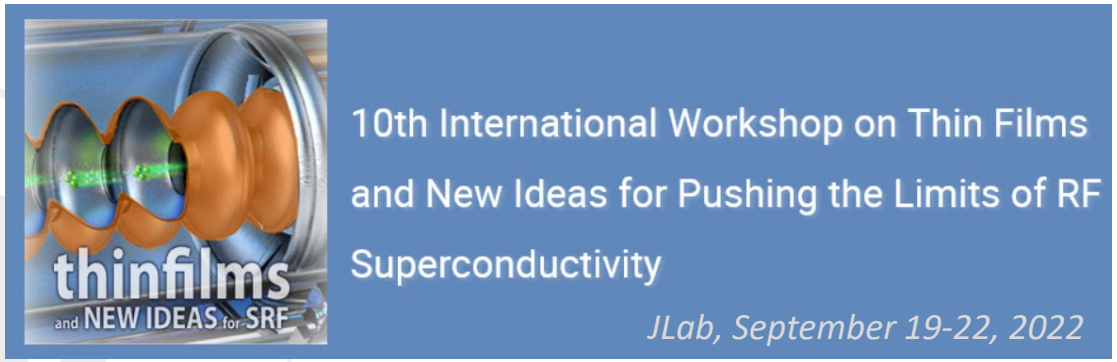


S. Keckert, M.Wenskat

A.-M. Valente-Feliciano

Update on Status of Thin Film Working Group

S. Keckert, M. Wenskat

- **Thin Films or more precisely „non-bulk niobium as RF surface“**
  - Re-established April 2021
  - Chairs:
    - Marc Wenskat (UHH) marc.wenskat@desy.de
    - Sebastian Keckert (HZB) sebastian.keckert@helmholtz-berlin.de
- Since then, 4 Meetings with chosen topics, elected speakers & discussion:
  - 04.21 SIS – *3 Talks*
  - 10.21 Nb on Cu – *2 Talks*
  - 03.22 MgB_2 – *2 Talks*
  - 08.22 Nb_3Sn – *4 Talks*
- Participation is >30 Persons & distributed over many labs/universities
- 5th meeting currently planed – picking up discussions from TF Workshop

Mailing list

Send „Subscribe ttc-wg-thinfilms NAME“ to sympa@listserv.dfn.de

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

Forum for new initiatives in innovative thin films and related technology to advance future generations of superconducting RF accelerators. Present superconducting RF accelerator technology is based on predominately bulk niobium, for which the state of the art in performance is reaching the theoretical limit.

Intensive and coordinated R&D effort is of decisive importance for the scientific community.

The primary aim of the workshop is to support this initiative by providing an opportunity to bring together individuals and institutions working in this effort and infusing expertise of specialists from related disciplines (superconductivity, plasma physics, material science, nanotechnology, RF engineering and industry).

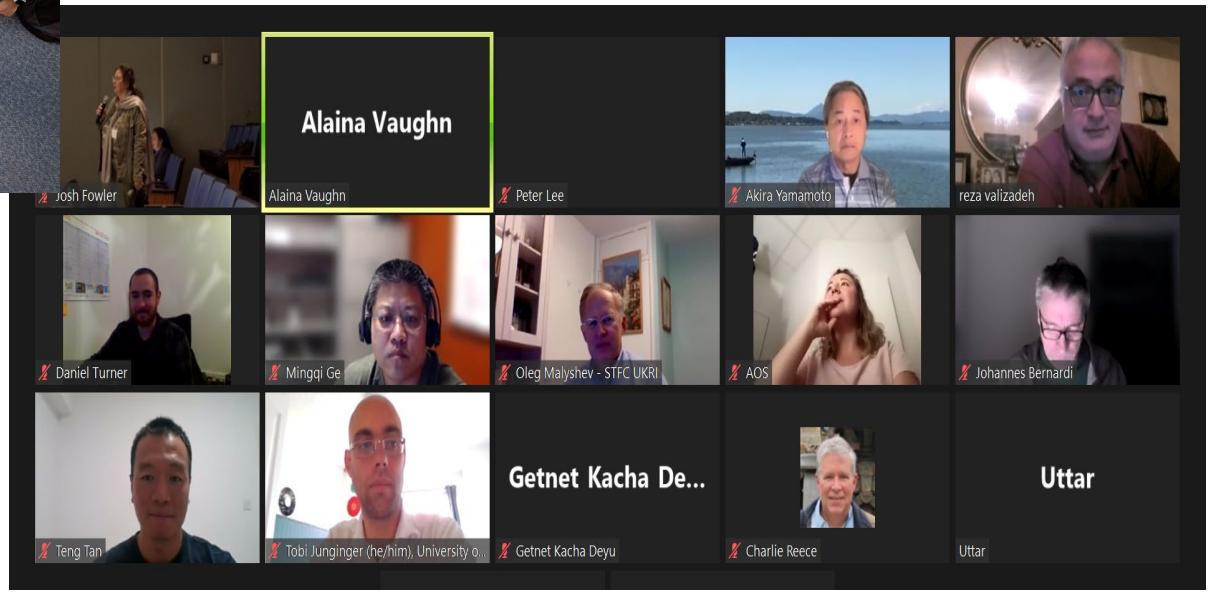
Aim to offer a **collaborative environment as open, inclusive and diverse** as possible.

- *The first event was organized at JLab in 2005, as a spin-off of the SRF conference (1.5 days).*
- *In 2006, Enzo Palmieri organized the 2nd edition under "International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity".*
- *Since then, the Workshop has taken place bi-annually.*
- *Virtual edition in March 2021 due to the Pandemic*

10th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

HYBRID EVENT @ JLab

- **63 Attendees***
- **31 In-Person**
- **32 remote**
- **34 Eu; 24 US; 5 Asia/9 countries total**



*Last in-person attendance in 2018:
65 Participants

TFSRF2022 Program

4 days / 14 sessions / Open discussions

https://indico.jlab.org/e/TFSRF2022

- Perspective of SRF Thin Film in International Projects
- Theoretical Approach for SRF Thin Films & Structures
- Nb Thin Film Technology
- Beyond Nb: Alternate Materials & Multilayer Structures
- Advanced Substrates
- SRF Thin Films Characterization: Cryogenic & RF Measurements, Materials, Surfaces & Structures
- Applications beyond SRF: Quantum & Devices

Meeting Friday 09/23 morning

Perspective of SRF Thin Films in International Projects

SRF Thin Film Technology in the International Context
Speaker: Anne-Marie Valente-Feliciano (Jefferson Lab)

The Thin Film Activities in the IFAST Program
Speaker: Claire Antoine (CEA)

INTERNATIONAL CONTEXT FOR SRF THIN FILMS

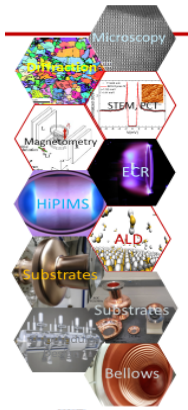
SNOWMASS & EUROPEAN STRATEGIES

A.-M. Valente-Feliciano

Jefferson Lab

See also S. Belomestnyk talk, Monday Plenary Session

Path Forward



Already well-established and fruitful international R&D collaborations
JLab, SLAC, ODU, CORNELL, FNAL, FSU, W&M, ANL, Temple U. ...
&
CEA Saclay, CERN, DESY, HZB, INFN-LNL, KEK, STFC, TRIUMF and other institutions
should be fully supported and expanded in the following areas of R&D:

- **Theoretical and material studies** to gain in-depth understanding of the fundamental limitations of thin film superconductors under radio-frequency fields
- **Advanced coating technology** for Nb/Cu and alternative materials, Nb_3Sn, V_3Si, NbTiN ...
  - Energetic condensation (electron cyclotron resonance (ECR), HiPIMS, kick positive pulse...)
  - Atomic Layer Deposition (ALD)
  - Hybrid deposition techniques
- **Cavity deposition techniques for development of superconductor-insulator-superconductor (SIS) nanometric layers** to further enhance the performance of bulk Nb and Nb/Cu
- **Improved cavity fabrication & preparation techniques**
  - electroforming, spinning, hydroforming, electro-hydro forming, 3D additive manufacturing
  - environmentally friendly electropolishing, diamond cutting, nano-polishing, plasma etching ...)
- **Cryomodule design** optimization
- Improvement of **accelerator ancillaries** with advanced deposition techniques
  - HiPIMS Cu coated bellows, power couplers...

TFSRF in the International Context: Snowmass & European Strategies - JLab, September 2022

Jefferson Lab

The Snowmass and European Strategies for particle physics are coherent with each other

Objectives for WP9 (task9.1)
Innovative superconducting cavities

Improve performance and reduce cost of SRF acceleration systems

- **We aim at building together a global strategy to be able to produce Superconducting RF (SRF) cavities coated with a superconducting films. Not only IFast, (informal) WW collaboration**
- **It includes pursuing the optimization and the industrialization:**
  - **Substrates preparation (Nb, Cu),** *e.g. PEP, metallographic polishing*
    - **Pre-and post treatment** *(laser, flash annealing)*
    - **The production of seamless copper cavities**
  - **The optimization deposition techniques: MS, PVD, ALD... to get Nb, NbN, Nb_3Sn, V_3Si... thick films (µm) and/or SIS Multilayers (nm)**
- **Produce and RF test prototypes of SRF cavities at 6 GHz: Easier to fabricate, handle, dissect to provide fast feedback**
- **Produce accelerator type 1.3 GHz cavities (feasibility assessment).**

6 Tasks

Task 9.2: Seamless elliptical copper cavities
Task 9.3 Cavity Coating and Evaluation
Planar Samples & QPR deposition
Task 9.4:Surface engineering by atomic layer deposition (ALD)
Task 9.5: Improvement of mechanical and superconducting
properties of RF resonator by laser radiation
Task 9.6: Optimization of flat SRF thin films production procedure
Baseline measurement on QPR samples

IFAST WP9:
- 9 countries
- 15 institutes
- >50 participants

	IFAST WP9 Partners	Leading	Participating
1	CEA (Saclay, France)	WP, Tasks 1 and 4	Task **1**, 2, **4**, 6
2	CNRS/IN2P3/IJCLab (Orsay, France)		Task 1, 4
3	IEE-SAS (Bratislava, Slovakia)		Tasks 2-6
4	INFN/LNL (Legnaro, Italy)	Task 2	Tasks 1, **2**, 3, 5, 6
5	*INFN/LASA (Milano, Italy)*		Tasks 2, 3
6	*Piccoli S.r.l. (Noale (VE), Italy)*		Tasks 2, 3
7	Helmholtz-Zentrum Berlin (Berlin, Germany)	Task 6	Tasks 1 and **6**
8	RTU (Riga, Latvia)	Task 5	Task **5**
9	University Siegen, (Siegen, Germany)		Tasks **2**, 3, 6
10	UKRI/STFC/ASTeC (Daresbury, UK)	WP, Tasks 1 and 3	Tasks 1, 2, **3**, 5, 6
11	*Lancaster University (Lancaster, UK)*		Tasks 1 – 3, 6
12	*Jlab (Newport News, Virginia, USA)*		Tasks 1, 2
13	*PTI (Physics-Polytechnic Institute, Minsk, Belarus)*		Tasks 1, 2
14	*MEPHI (National Research Nuclear University, Moscow, Russia)*		Tasks 1 - 3
15	*Helmholtz-Zentrum Dresden-Rossendorf (Dresden, Germany)*		Tasks 1 – 3, 5

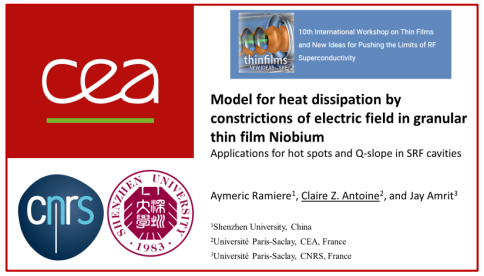
Theoretical Approach for SRF Thin Films & Structures

Model for heat dissipation by constrictions of electric field in granular thin film Niobium
Speaker: Claire Antoine (CEA)

Modelisation of Oxygen profile tailoring in bulk and thin film Nb
Speaker: Eric Lechner (Jefferson Lab)

Nonlinear Meissner effect in Nb3Sn thin film coplanar resonators
Speaker: Alexander Gurevich (ODU)

Thermal-conductivity-related New Strategy for Breaking the Eacc Limit
Speaker: Didi Luo (Institute of Modern Physics, Chinese Academy of Sciences)



Model for heat dissipation by constrictions of electric field in granular thin film Niobium

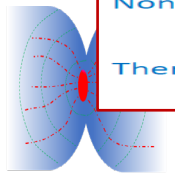
Applications for hot spots and Q-slope in SRF cavities

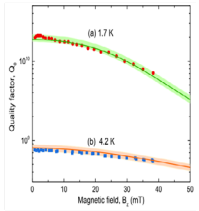
Aymeric Ramiere[1], Claire Z. Antoine[2], and Jay Amrit[3]

[1]Shenzhen University, China
[2]Université Paris-Saclay, CEA, France
[3]Université Paris-Saclay, CNRS, France

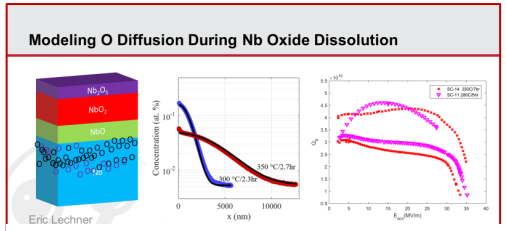
- *current crowding due to porosities (generating local electrical field)*

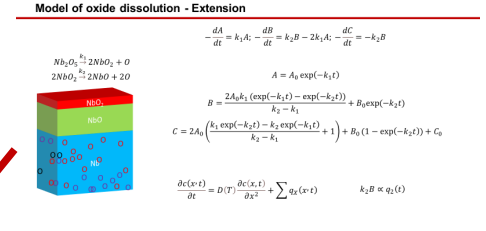
- A model for heat dissipation in thin film SRF cavities based on the constriction of electric field at grain boundaries is proposed
- The temperature of clusters of grain boundaries is derived
- Model gives a good description of Q-slope behavior with B_z *and should be considered in coexistence with other established models*
- Model must be further tested with future experimental data
- Need to better characterize the hot spot sizes in granular Nb : how ?
- Refinement of model – work for pure theoreticians

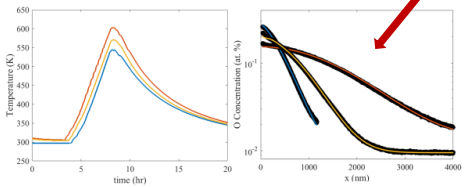




All results are presented in paper: PHYS. REV. ACCEL. BEAMS 25, 022001 (2022)

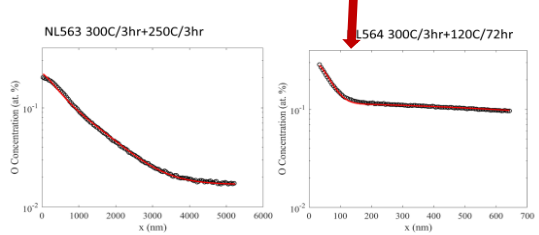






$$\frac{\partial c(x,t)}{\partial t} = D(T(t))\frac{\partial c(x,t)}{\partial x^2} + q(t,T(t))$$

$$-\frac{dA}{dt} \propto q = u_0 k(T(t)) \exp\left(-\int_0^t k(T(s))\,ds\right)\delta(x).$$



1. Start with the input of Ciovati's model for the first temperature and time
2. Re-oxidize the surface
3. Replenish the sources and advance the solution numerically.

$$\frac{\partial c(x,t)}{\partial t} = D(T)\frac{\partial c(x,t)}{\partial x^2} + q(t,T)$$

See also E. Lechner talk, Tuesday Afternoon WG1 Session

J. Makita, C. Sundahl, G. Ciovati, C.B Eom and A.Gurevich.
Phys. Rev. Research 4, 013156 (2022)

Nonlinear Meissner Effect in Nb_3Sn thin film coplanar resonators.

Alex Gurevich (NLME)

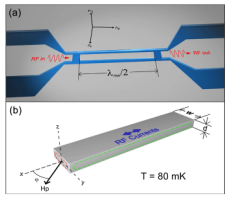
Old Dominion University, Norfolk, VA

Supported by DOE Grant DE-SC 100387-020.

- Unlike Nb the anomalous NLME in polycrystalline Nb3Sn is primarily determined by weakly-coupled grain boundaries
- GBs give an order of magnitude stronger field dependence of $\lambda(B)$ as compared to the conventional Meissner pairbreaking
- Quasi-linear increase of $\lambda(B)$ with B > 20 mT in Nb3Sn as opposed to the quadratic field dependence for the NLME in Nb
- NLME may contribute to the high-field Q slope
- NLME can contribute to the shift of the cavity frequency at high rf fields. If polycrystalline Nb3Sn films in Nb cavity exhibit a quasi-linear increase of $\lambda(B)$ with B, the GB anomalous NLME can dominate over the quadratic Lorentz detuning

Groll, Gurevich, Chiorescu PRB 81, R020504 (2010)

Half-wave thin film Nb stripline

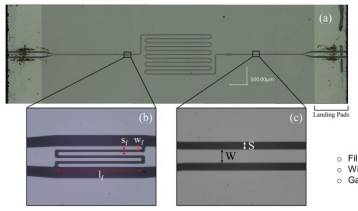


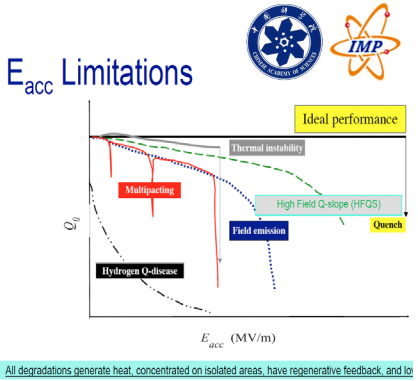
- 65 nm thick Nb thin film stripline w = 100 μm, s = 3mm
- resonance frequency f = 19.2 GHz
- dirty Nb with $\rho_N(T_c)$ = 26.3 μΩcm T_c = 7.25K, λ = 226 nm, ξ = 9 nm
- 3 coils enabled varying the dc field orientation (< 2T)
- NLME produced by dc field is probed by very weak rf currents (P_d < 10 pW)
- Total inductance is a sum of geometric and kinetic inductances $L = L_g + L_k(B)$

Measure the change of the resonance frequency $f = 1/2\pi(CL)^{1/2}$ as a function of a parallel dc magnetic field:

$$\frac{\delta f}{f} = \frac{L_k(0) - L_k(H)}{2L_0}$$

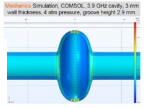
Nb_3Sn coplanar half-wave resonator

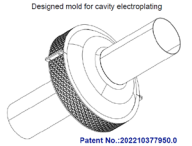




All degradations generate heat, concentrated on isolated areas, have regenerative feedback, and lo

1. EP/BCP/HPR/Plasma cleaning to remove defects
2. Increase thermal conductivity κ
3. Add high κ material outside: Cu-clad cavity
4. Increase contacting area/shorten the distance to liquid He(LHe)
5. Adding an extra thermal path: cavity inner wall





Starting with cavity degradations' appearance

Found 2 strategies to increase the cavity's thermal conductivity---the **outer-wall groove structure (OGS) and the inner-wall thermal conducting film (ITCF).**

Performed COMSOL simulations and they seem effective. We hope these two structures can improve the thermal conductivity, thus increasing the cavity's E_{acc} limit.

Nb Thin Film Technology

Study of the influence of the manufacturing process and thermal cycling on the RF performance of 1.3 GHz Nb/Cu SRF cavities

Speaker: Lorena Vega (CERN)

Ion energy analysis of a bipolar HiPIMS discharge using a retarding field energy analyser

Speaker: Felix Walk

SRF Thin Film Coating Development at IHEP

Speaker: Dr Ping He (IHEP)

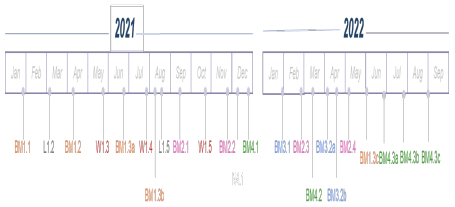
Characterization of TESLA-shaped single-cell Nb thin-film cavity with varying RRR values at low temperatures

Speaker: Bektur Abdisatarov

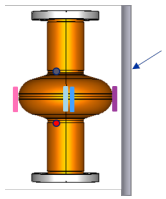
Nb film Technology – Discussion

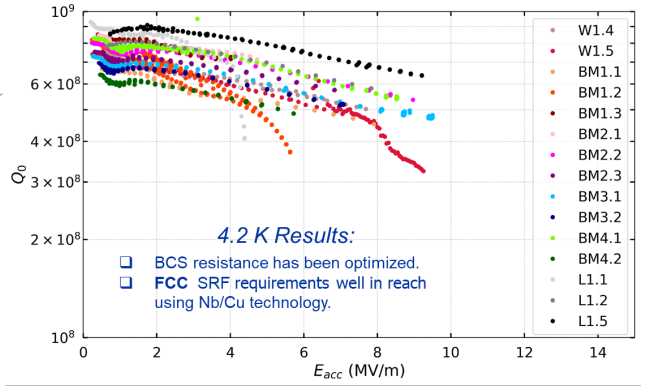
Nb Thin Film Technology

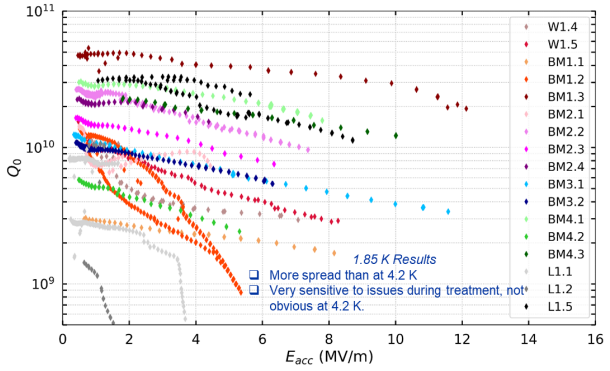
Study of the influence of the manufacturing process and thermal cycling on the RF performance of 1.3 GHz Nb/Cu SRF cavities – *L. Vega et al*




Machined cell







Characterization of TESLA-shaped single-cell Nb thin-film cavity with varying RRR values at low temperatures – *B. Abdisatarov et al.*

SRF cavity and Nb thin-film characteristics

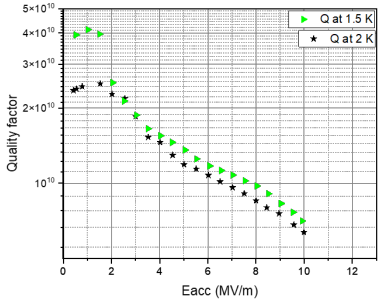

Nb cavity was designed and fabricated at Fermilab. Nb thin film was optimized and coated at CERN

Cavity parameters
- Type: TESLA-shaped single-cell Nb
- Frequency: 1.3GHz
- Beta: High
- Geometry factor: 273Ω

Thin-film deposition parameters
- Main pulse duration: 200us
- Bias voltage: -75V
- Power: 1200W
- Pressure: $3x10^{-3}$mbar
- Temperature: 150°C
- Deposition time: 6 hours
- Target: Nb RRR300
- Background gas: Kr
- Thickness: 6μm

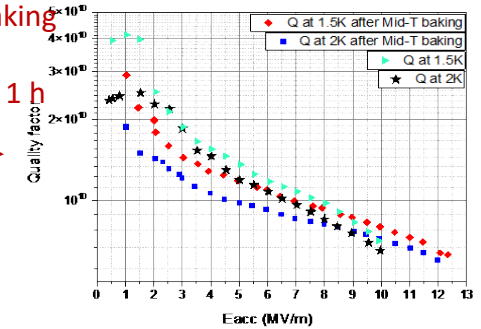
Data: CERN


A Bipolar HiPIMS thin film deposition system at CERN. (Image: CERN)



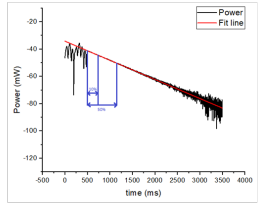
❖ The cavity was limited at Eacc ≈10.2 MV/m by a quench.

Mid-T baking @ 340˚C / 1 h



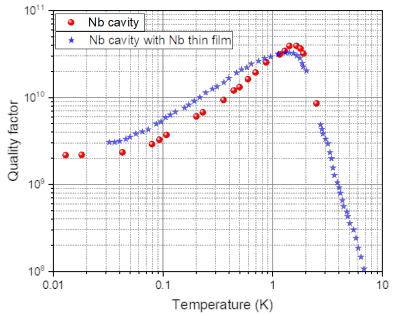
Motivation: The superconducting properties of niobium in microwave fields vary significantly with lattice defects and impurity content, where sub-at.% impurity level can reduce or increase microwave surface resistance.

Quality Factor and Frequency dependence as a function of Temperature



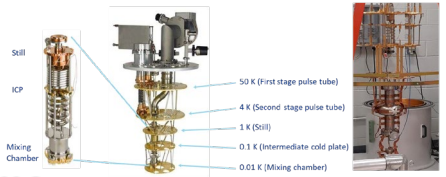
❖ The cavity was tested from 10K down to 40mK to measure the frequency and quality factor dependence as a function of temperature at low fields.

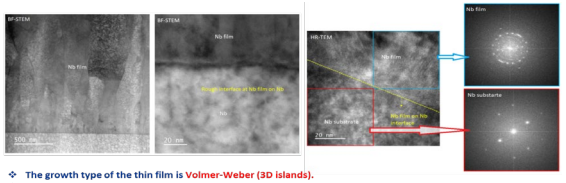
❖ The cavity performance was similar to that of bulk niobium cavities



Quality factor comparison of Nb cavity and Nb cavity with Nb thin film

Dilution Fridge (DR) cavity testing




❖ The growth type of the thin film is Volmer-Weber (3D islands).
❖ The oxygen layer prevents epitaxial growth.
❖ Nb films grow randomly on the Nb substrate.

Nb Thin Film Technology

Niobium Sputtering on Copper Cavities at IHEP

Ping He
On behalf of SRF Thin Film Coating Group
IHEP, CAS

10TH INTERNATIONAL WORKSHOP ON THIN FILMS AND NEW IDEAS FOR PUSHING THE LIMITS OF RF SUPERCONDUCTIVITY
JLAB, Newport News, VA, USA, 19-23 Sep 2022

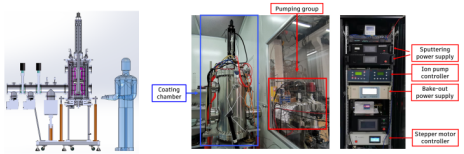
Substrate cavities
Copper surface preparation
- *SUBU chemical polishing*
- *Centrifugal barrel polishing*
- *Electrochemical polishing*

Inner surface inspections
DCMS coating

Magnetron sputtering system (DCMS)

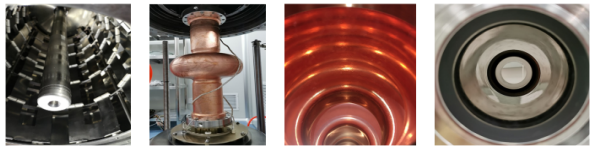
- DCMS sputtering system developed for 1.3GHz mono-cell cavity Nb coating
  - RF cavity placed in the vacuum chamber baking
  - Background vacuum inside the coating chamber: 3E-9 mbar
  - Diameter of niobium target（RRR~300）: 45 mm
  - 2 permanent magnetic rings (width: 20mm, 1.35 Telsa) with opposite poles placed concentrically inside Nb target, and can be freely moved up and down

IHEP



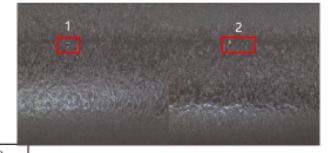
Nb coating

- Substrate baked at 400 degC for 48 hours, then cooled to 200 degC to start coating
- Background vacuum inside the coating chamber: 3 E-9 mbar
- Krypton pressure: 0.5 Pa
- Duty ratio 0.6, discharge current 3 A
- Magnet movement speed: 1 mm / s
- Niobium film thickness: 2 μm

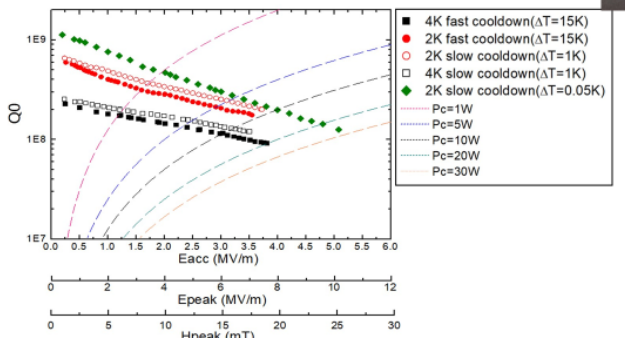


VT results

- Eacc reached 5 MV/m with Q0 > 1×10^8
- Defects on equator found in later inspections after VT



Nb/Cu 1.3GHz Single-cell VT



19

Ion energy analysis of a bipolar HiPIMS discharge using a retarding field energy analyser

10th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity

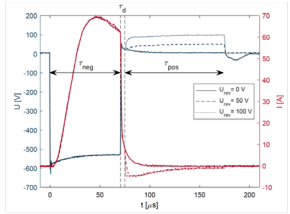
UNIVERSITY OF LIVERPOOL · The Cockcroft Institute of Accelerator Science and Technology · UKRI Science and Technology Facilities Council

Retarding Field Energy Analyser - RFEA

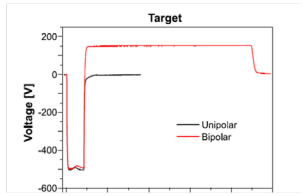
- Small form factor
- Simple design – home build
  - 2 grids, 1 ion collector plate
- Requires LP acquisition system and DC power supply
- Mass integrated
- IEDF
- Ion flux
- energy flux density

Bipolar HiPIMS discharge

Starfire Industries Impulse 2-2
Liverpool University

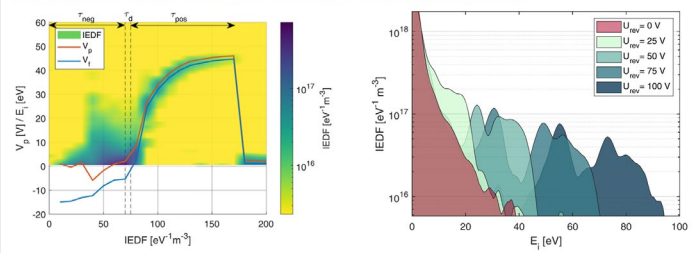


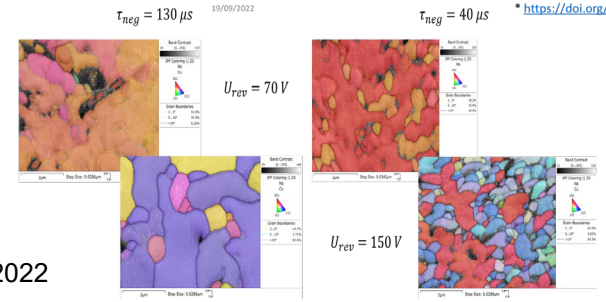
Ionautics HiPSTER Bipolar
Viloan et. al.*



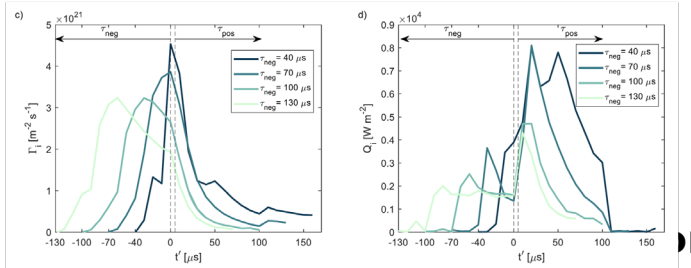
* https://doi.org/10.1016/j.surfcoat.2021.127487

Ion acceleration in substrate sheath





Change in negative pulse length



Beyond Nb: Alternate Materials and Multilayer Structures

Beyond Nb: Alternate materials and mulilayer structures: 1

Nb3Sn Coating of a 2.6 GHz SRF cavity using a cylindrical magnetron sputtering system
Speaker: Md Sharifuzzaman Shakel (Old Dominion University)

Recent advances with bipolar HiPIMS-deposited Nb3Sn films
Speaker: Dr Stewart Leith (CERN)

Nb3Sn thin films on Cu base materials using bronze routes
Speaker: Andre Juliao (Applied Superconductivity Center, NHMFL, Florida State University)

Nb3Sn Technology Development at JLab
Speaker: Uttar Pudasaini (Jefferson Lab)

Beyond Nb: Alternate materials and mulilayer structures: 3

6 Ghz Cavity Deposition with B1 Superconducting Thin Film at Astec
Speaker: Reza Valizadeh (STFC)

AlN-NbTiN multilayers deposited by PEALD for SRF cavity studies
Speaker: Isabel González Díaz-Palacio

Successful Al2O3 coating of superconducting niobium cavities by thermal ALD
Speaker: Getnet Kacha Deyu (Universität Hamburg | DESY)

Material engineering of ALD- deposited multilayer to improve the superconducting performances of RF cavities under intense RF fields.
Speaker: Yasmine KALBOUSSI (IRFU/DACM CEA Saclay)

Beyond Nb: Alternate materials and mulilayer structures: 2

Effect of Lower Temperature Annealing on Surface Properties of Vapor Diffusion Coating of Nb3sn.
Speaker: Jayendrika Tiskumara (Old Dominion University)

Nb3Sn on Cu Coating By Magnetron Sputtering From Target Synthesized via Liquid Tin Diffusion
Speaker: Cristian Pira (INFN LNL)

V3Si thin film deposition using HiPIMS and DC
Speaker: Francis Lockwood Estrin (University of Liverpool)

Pushing the CW beam current limit of TESLA SRF Cavities with Nb3Sn and NbTiN Coating of HOM Antennas
Speaker: Paul Plattner (JGU Mainz Institut für Kernphysik)

Beyond Nb: Alternate materials and mulilayer structures: 4

The Investigation of Sputtered S(I)S Structures for Srf Cavities
Speaker: A. Özdem Sezgin (University of Siegen)

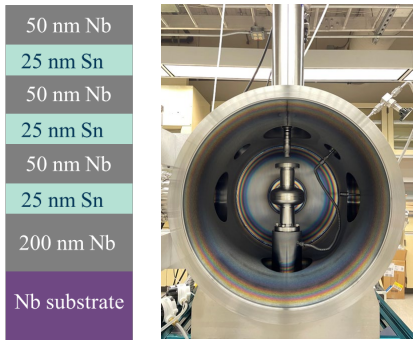
MgB2 Progress at Temple University
Speaker: Dr Ke Chen

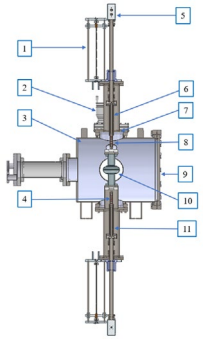
A new system for MgB2 coating R&D at LANL
Speaker: Tsuyoshi Tajima (Los Alamos National Laboratory)

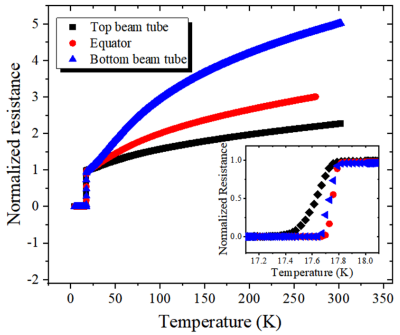
Beyond Nb: discussion

Beyond Nb: Alternate Materials and Multilayer Structures Nb_3Sn

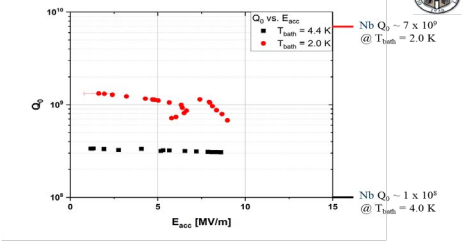
Nb_3Sn coating of a 2.6 GHz Nb SRF cavity using a Cylindrical Magnetron Sputtering System –*S. Shakel*







Cold test set up for cryogenic RF testing of the cavity in Vertical test stand



Results

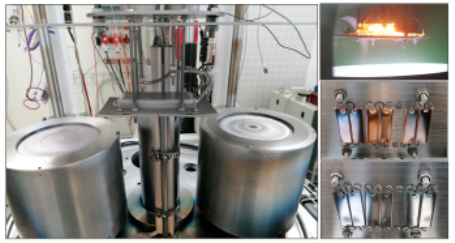
(Q_0) of 3.2 x 10^9 at E_{acc} = 5 MV/m at T_{bath} = 4.4

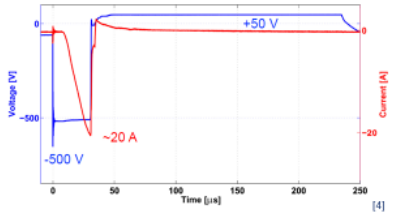
(Q_0) of 1.1 x 10^9 at E_{acc} = 5 MV/m at T_{bath} = 2.0

See also talk, Wednesday afternoon WG3 Session

Recent advances with bipolar HiPIMS-deposited Nb_3Sn films on Cu - *S. Leith et al.*

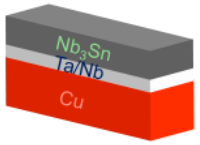
Bipolar HiPIMS Nb_3Sn/Ta/Cu





[4]

Process Gas:
Kr
Pressure:
$7 \cdot 10^{-4}$ … $5 \cdot 10^{-2}$ *mbar*
Positive Pulse:
35 … 100 V



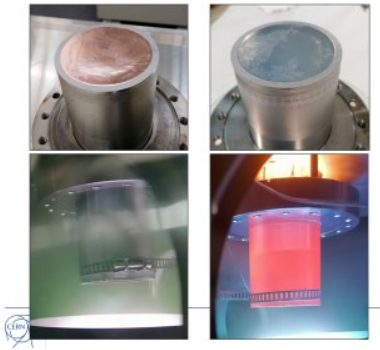
Reacted **During** Coating	
Coating temperatures	500 - 750°C
Additional Annealing (in-situ)	24 - 72 h

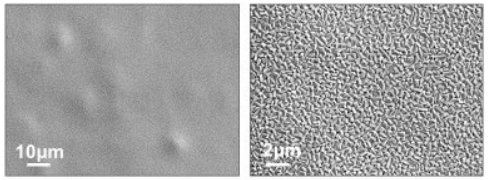
Reacted **After** Coating (Post-coating annealed)	
Annealing pressures	$5 \cdot 10^{-6}$ - $1 \cdot 10^{-7}$ mbar (ex-situ) $2.5 \cdot 10^{-2}$ mbar (in-situ)
Annealing temperatures	450 - 750°C (1 - 24 hrs)

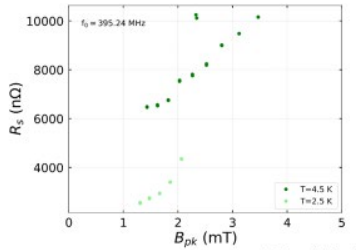
[4] F. Avino *et al* 2019 *Plasma Sources Sci. Technol.* **28** 01LT03

Superconducting Performance

QPR Coating for RF measurements
- Sn % = 26.08 ± 0.21 %
- T_c ~ 16 K
- CS ~ 120 nm, microstrain ~ $1.5 \cdot 10^{-3}$







Courtesy: L. Vega-Cid

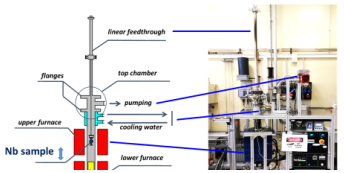
Performance likely limited by non-superconducting Cu surface contamination

- Reacted After Coating - consistently higher T_c
  - T_c pushed to 16.6 K
  - Similar to DC MS observations
- Surface Cu contamination
  - Decreased by reacting after coating
  - Optimisation required
  - Thicker films
- Deposition of further QPR samples required

Beyond Nb: Alternate Materials and Multilayer Structures — Nb_3Sn

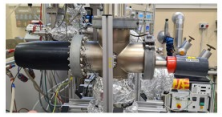
See also C. Pira talk, Wednesday afternoon WG.

Nb_3Sn target production by Liquid Tin Diffusion

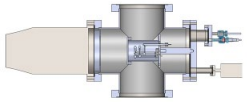


- Similar to **Tin Vapor Diffusion**
- Allows coating of **thick films**
- System designed in **2005**
- **UHV Inconel** chamber
- **Process improved** in 2021

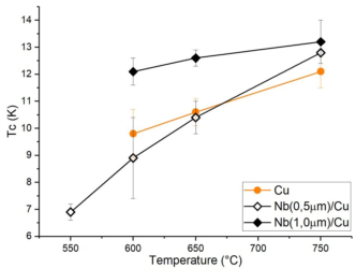
Experimental Set-up

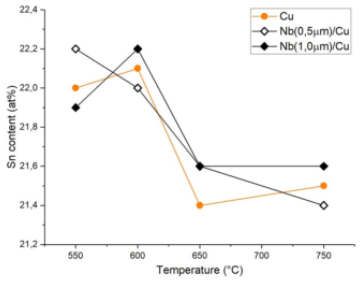


- Single 4" Nb_3Sn stoichiometric target (commercial)
- $P < 5*10^{-9}$ mbar
- I=0,25 A (3mA/cm²)
- V= 300-400 V

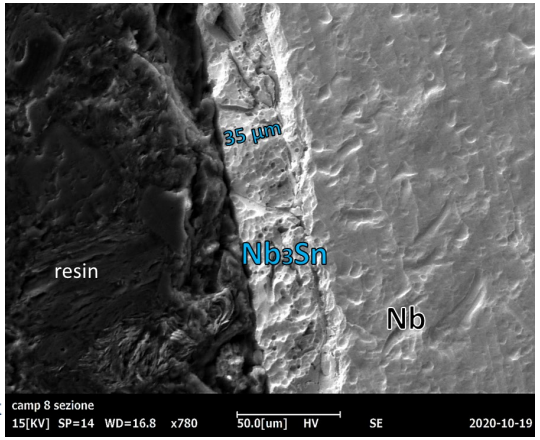


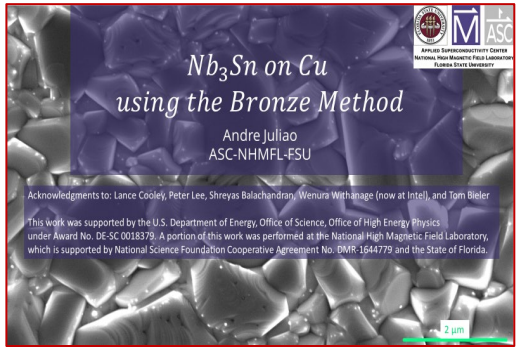
Temperature effect



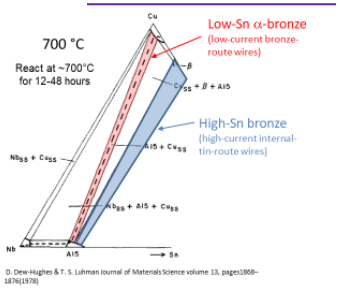


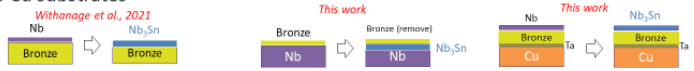
Temperature ↑ Long-range crystallographic order ↑ Sn content ↓

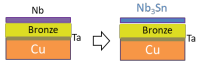




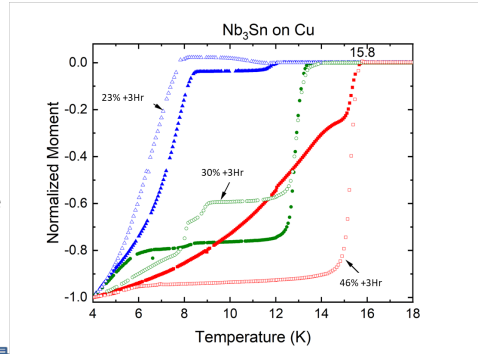
- Bronze route reaction temperature of ~700°C is compatible with Cu cavities
  - Cu melts at 1085°C, below the ~1100°C tin vapor method
  - Cu cavities facilitate conduction cooling and goals of DOE Accelerator Stewardship.
- We recently used a high-Sn alloy instead of the usual α-bronze to increase tin activity.
  - Increased tin activity is the key to success of Nb_3Sn wires for high-field magnets
  - Increased tin activity is vital to avoid tin-poor A15 with degraded superconducting properties
- Experiments began with Nb substrates then moved on to Cu substrates





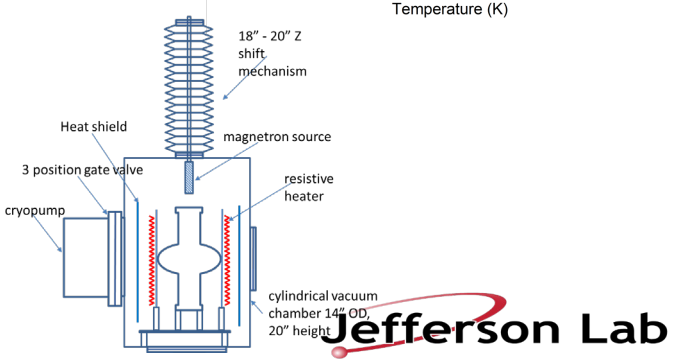


- Improvement in Tc for ~1 µm thick films
  - We do not attempt thicker films due to limitations of our system
- Improvement also for high-Sn bronze



How might the hot-bronze route be applied to a Cu cavity?

- A chamber with cylindrical magnetrons was envisioned by Withanage
- Ta deposition occurs below 250 °C – ok, similar to LEP cavities
- Bronze can be deposited or evaporated – need to prove
- Nb deposition at 700°C = a magnetron in an oven?
  - Divide along a longitudinal seam, deposit side away from heater
  - Will the seam heal when re-joined?

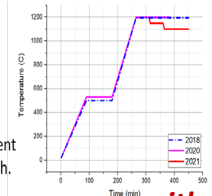


Beyond Nb: Alternate Materials and Multilayer Structures Nb_3Sn

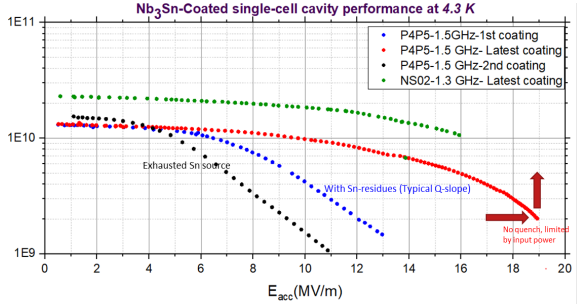
Nb_3Sn cavity coating development for accelerator applications at Jefferson Lab - *U. Pudasaini et al.*

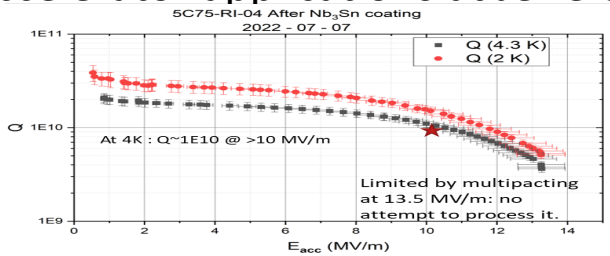
Jefferson Lab

- The coating profile update was guided by the witness sample analysis.
- The coating profile currently followed aims to obtain equivalent coating grown at 1200 °C for ~ 1 h.



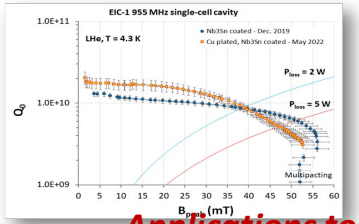
Improve coating process with single cells



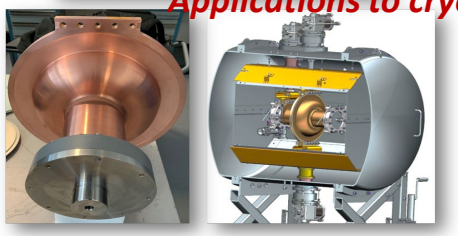


5-cells deposition towards implementation in CM

The goal is to install the QCM and test in JLab UITF (beam test.)



Applications to cryo-cooled cavity

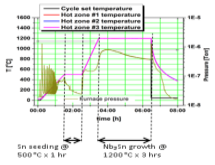


See also U. Pudasaini talk, Wednesday afternoon WG3 Session

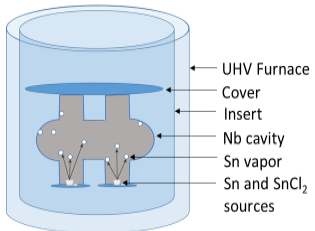
Effect of Lower Temperature Annealing on surface properties of Vapor Diffusion coating of Nb_3Sn - *Jayendrika K. Tiskumara*

Nb_3Sn coating of Twin axis cavity

- T_c ~ 18.3K & H_{sh} ~ 400 mT (twice of Nb)
- Promises higher **Q** and $\mathbf{E_{acc}}$
- Vapor diffusion coating
- Twin axis cavity-Two beam axis structures to improve the performance of the ERL
  T M_{110} rf dipole mode with 1497 MHz frequency



The temperature profile used for coating twin axis cavity[1].



Twin axis cavity coating setup

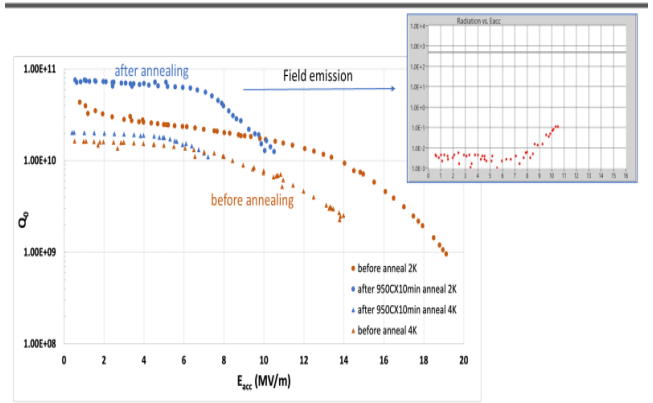
Appearance of the coating

1. G. Eremeev, W. Clemens, K. Macha, H. Park and R. Williams, "Commissioning of Nb_3Sn cavity vapor diffusion deposition system at JLAB"

Old Dominion University

Jefferson Lab

RF test results



RF performance of the coated cavity before and after anneal for 950 °C for 10 minutes.

Old Dominion University

Jefferson Lab

Nb_3Sn coating of Twin Axis cavity.
Performance limiting factors- Mechanical deformation, Sn residue.
Low Temperature annealing of the Nb_3Sn Samples.
Annealing the single cell cavity at 900 °C for 10 minutes and RF tested- Increased Quality factor at low fields.
Retest it and annealed again for another 10 minutes at 900 °C.

Other SC Materials beyond Niobium: V_3Si

V_3Si Thin Film Deposition using HiPIMS and DC – *F.Lockwood et al*

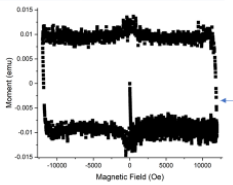
Science and Technology Facilities Council

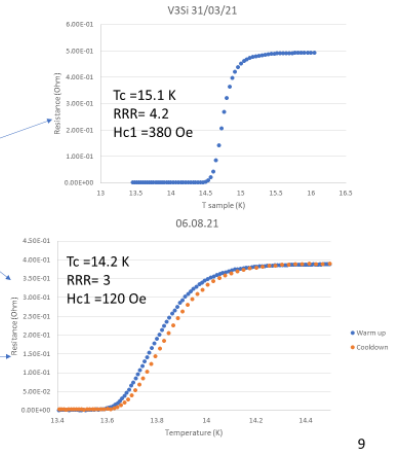
UNIVERSITY OF LIVERPOOL

The Cockcroft Institute

Higher temp.

Power supply	Heater current	Bias	Pulse and frequency	Tc (K)
Home-made	34.9 A	Earthed	200 Hz 100 us pulse length	15.1
Starfire	44.5 A	Earthed	100 us 200 Hz Pulse length	14.2
DC	44 A	Earthed		12





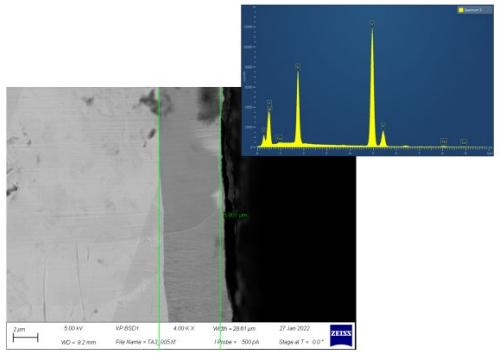
9

EDX

DC source on copper at max temp. Tc= 12 K

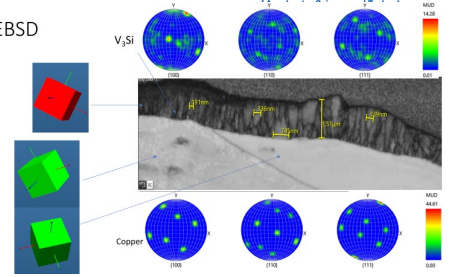
Element	Signal	Atomic %	σ
V		52.83	
C		18.92	
Si		18.04	
O		9.50	
Cu		0.71	

V:Si
74.7:25.3



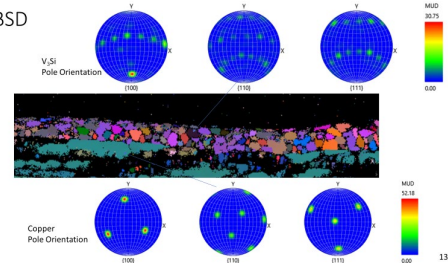
10

EBSD



11

EBSD



13

- HiPIMS increases the Tc of V_3Si samples by around 2-3 K e.g. 10K DC samples → 12-13 K HiPIMS samples
- Best performing HiPIMS supply seems to be The Home-made supply
- First penetrations of V_3Si is relatively low with 300 Oe being a good result Second penetrations is very high
- Increasing temp beyond 700 C with HiPIMS yields Tc up to around 15 K without the need for post-annealing
- EBSD reveals growth patterns
- Evidence that samples tarnish in air

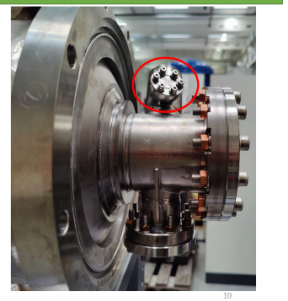
Pushing CW beam current limit of TESLA SRF Cavities with Nb_3Sn and NbTiN Coating of the HOM Antennas-*Paul Plattner et al.*

HIM Helmholtz-Institut Mainz

Refurbishment of the ALICE module

MESA Enhanced ELBE-type Cryomodules (MEEC):
- Helium port (Joule-Thomson valve)
- Faster DESY/Saclay tuner (higher beam currents)
  → diameter of Helium tank changed
- New HOM antennas
- Cavity contamination leads to field emission @7 MV/m

→ Clean room treatment!



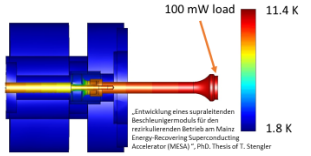
20/09/2022 10th Thin Films SRF Paul Plattner 10

HOM Couplers - Simulation

Goal:
Reduce heating of HOM Antenna
→Prevent quench of whole CM

How:
Antenna coating with Nb3SN/NbTiN on Nb/Cu Antennas

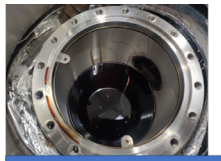
Ongoing CST simulation



Property	Nb	Nb3Sn
T_C [K]	9.2	18.3
κ_0(0K)	1.4	34
ξ_0 [nm]	39	5.7
λ_L [nm]	27	65-89

S. Keckert et al 2019 Supercond. Sci. Technol. 32 075004

20/09/2022 10th Thin Films SRF Paul Plattner 13



- HOM antennas with Nb_3Sn and NbTiN coating (Nb/Cu core)
- 2022 coated HOM antennas in Hamburg and Darmstadt

HOM tests in ALICE module

- Oil in Helium tank
- Disassembly of the ALICE Module

6 cell cavity:
- HPR treatment was successful!

→Successfull Cavity refurbishment

2021

- HPR and vertical cold test in 2022
- Acetone treatment for helium tank

2022

2023+

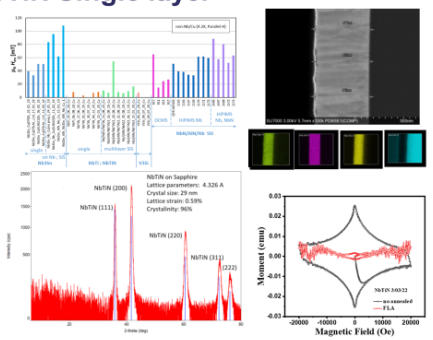
Other SC Materials beyond Niobium: NbTiN, NbN and SIS

Synthesis of NbTiN as an Alternative Thin Film for SRF Cavity – *R. Valizadeh*

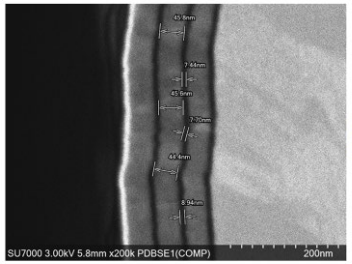
Science and Technology Facilities Council

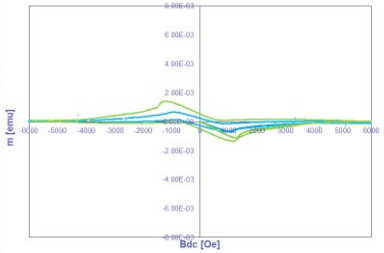
NbTiN Single layer

- The best superconducting phase only materialises at high Temperature.
- The higher the temperature the higher Tc, ranging from 14 K to 17 K.
- The best Tc and hysteresis was found to be on Cu substrate.
- Can be synthesised quite easily with both alloy target
- Both RBS and EDS showed good compositional uniformity for all the film.
- The XRD matched well with the published data with lattice parameter of 4.326 A and grain size of 29 nm.



NbTiN as multilayer SIS

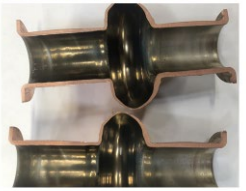




Defects are still present in individual layers, however due to the SIS structure their influence is reduced and no longer promote early Vx entry

Science and Technology Facilities Council

Deposition of NbTiN inside the 6 GHz



Deposition parameters:

Power 150 W
Current 0.23 A
Voltage 658 V
Dep Temp 650 C

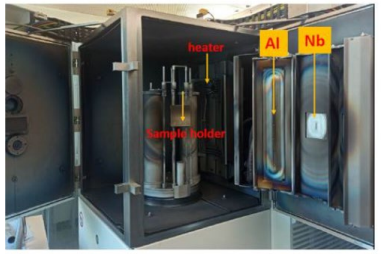
Pulsed DC
Frequency 350 KHz
Dual Time 1.1us
Deposition time 1 h 30 min
Dep pressure 2.6 x10^{-2} mbar
mag current 7.54 A

Science and Technology Facilities Council

Investigation of Sputtered S(I)S Structures for SRF Cavities - A.Ö. Sezgin

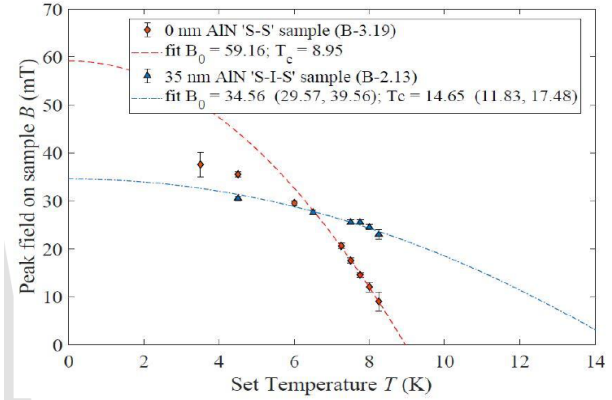
HiPIMS Coatings

CemeCon - CC800 at USI

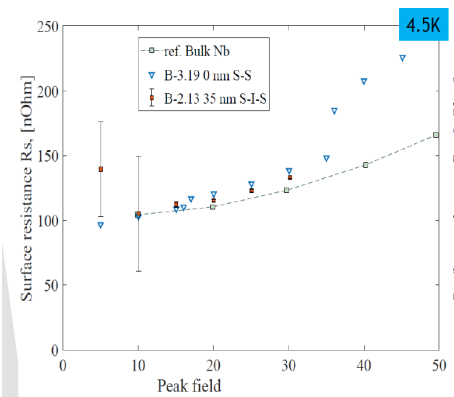


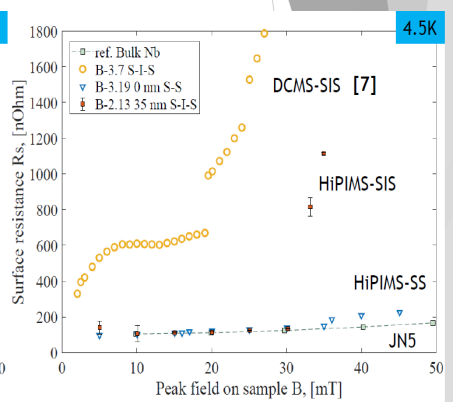
The unc
sample

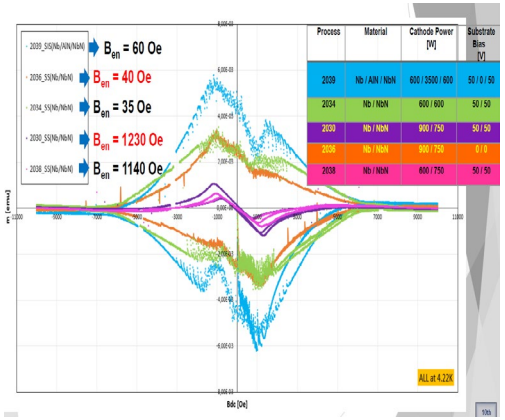
The HiF
(Nb/(AlN
Cu-QPF



Rs=(Bpeak) for the S(I)S structures vs the Bulk Nb (JN5):







Bundesministerium für Bildung und Forschung

UNIVERSITÄT SIEGEN

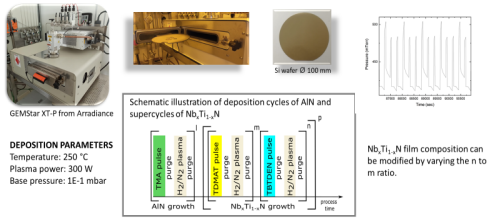
Jefferson Lab

Beyond Nb: Alternate Materials and Multilayer Structures

SIS by ALD

AlN-NbTiN multilayers deposited by PEALD for SRF cavity studies - *I. González Díaz-Palacio et al.*

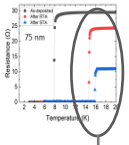
AlN - $Nb_xTi_{1-x}N$ PEALD: Supercycle approach



DESY · CHyN Centre for Hybrid Nanostructures · Bundesministerium für Bildung und Forschung · Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

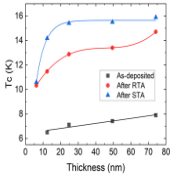
Different post-deposition thermal annealing for thicknesses

Post-deposition thermal annealing, rapid thermal annealing (RTA) and slow thermal annealing (STA), has been studied for $Nb_{0.75}Ti_{0.25}N$ films of different thicknesses.



Temperature (°C)	RTA	STA
1000	60 °C/min P_{base} E-3 mbar N_2	3.33 °C/min P_{base} 2.5 E-6 mbar N_2

- Highest T_c of **15.9 K** obtained for 75 nm $Nb_{0.75}Ti_{0.25}N$ after STA



14-15 K

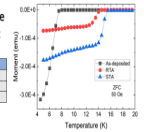
- EBSD: Electron back scatter diffraction patterns (Kikuchi lines) appear after thermal annealing, being especially noticeable after STA

DC magnetization using vibrating sample magnetometer (VSM)

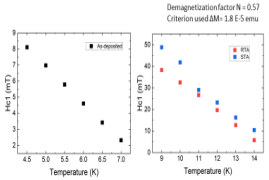
DC magnetization studies for 75 nm $Nb_{0.75}Ti_{0.25}N$ films as-deposited and after post-deposition thermal annealings (RTA and STA).

Temperature dependence of the magnetic moment

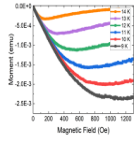
	Tc (K) VSM	Tc (K) ETO
As-deposited	7.5	7.9
After RTA	14.5	14.7
After STA	15.5	15.8



Temperature dependence of lower critical field H_{c1}



Field dependence of the magnetic moment

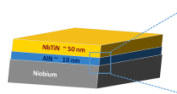


NEXT MEASUREMENTS IN ELLIPSOID GEOMETRY

ALD-deposited Multilayer to improve the superconducting performances of RF cavities - *Yasmine Kalboussi et al.*

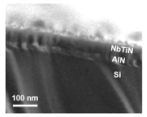
CEA SACLAY

NBTiN- ALN bilayer

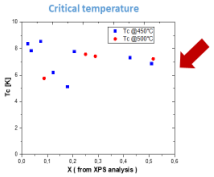


- Motivation: NbTiN has good superconducting performance (T_c = 17 K)
- AlN as an insulating layer.
- Chemistry: Combination of *TiN and NbN cycles:*

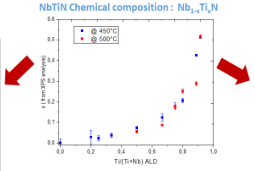
$n\ (TiCl_4 + NH_3) + m\ (NbCl_5 + NH_3) = Nb_{1-x}Ti_xN$



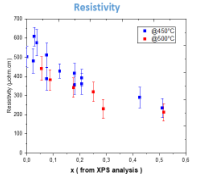
Critical temperature



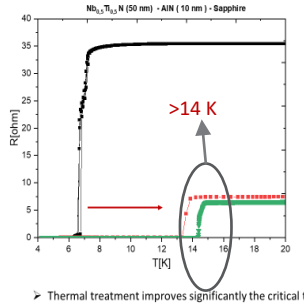
NbTiN Chemical composition : $Nb_{1-x}Ti_xN$

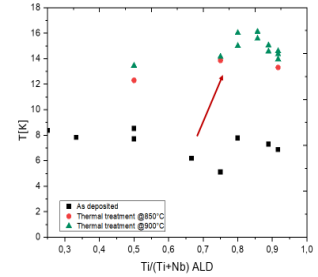


Resistivity

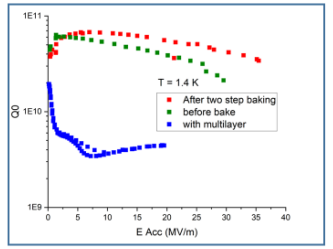


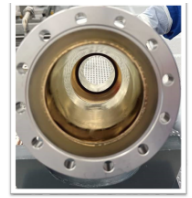
Optimizing the superconducting T… e





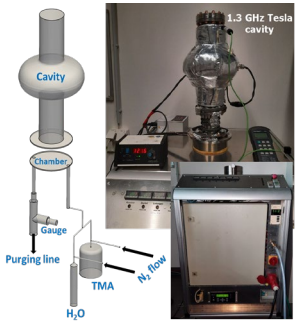
- Thermal treatment improves significantly the critical temperature.

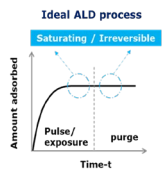


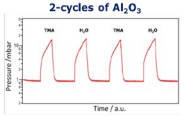


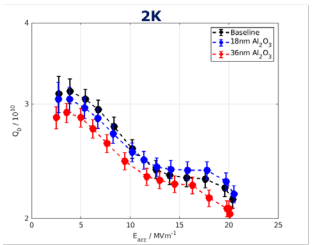
- First attempt: Lower Q and Emax
- Unexpected behavior during annealing on SRF cavity.
- Work in progress...

Successful Al_2O_3 Coating of Niobium Cavities with Thermal ALD - *Getnet Kacha Deyu*

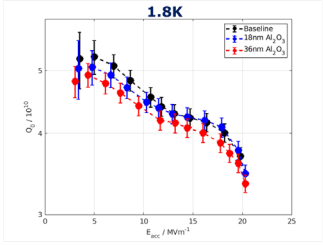




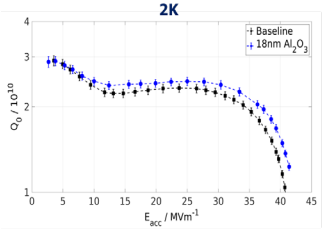




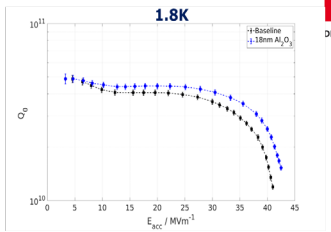
- no significant difference with baseline
- $\Delta R_{s,\ max}$ = +0.3 nΩ (18nm) & + 0.8 nΩ (36nm), which is below the measurement uncertainty
- no FE for both coatings



- no significant difference with baseline
- $\Delta R_{s,\ max}$ = +0.2 nΩ (18nm) & + 0.4 nΩ (36nm), which is below the measurement uncertainty
- no FE for both coatings



- Q_0→ slight increase above 10MV/m
- Slight increase in maximum quench field
- No deterioration was observed due to coating



- Q_0 increase more above 25 MV/m
- Max quench field slightly increased by (3 ± 1.5) MV/ m
- Preserve extraordinary cavity performance

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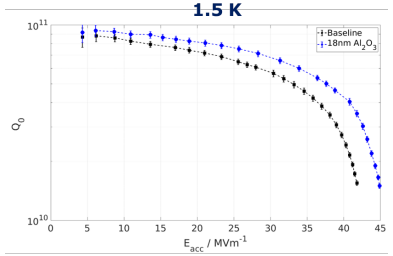
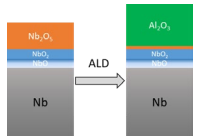
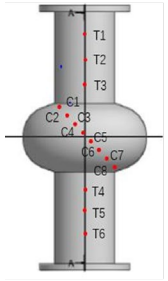
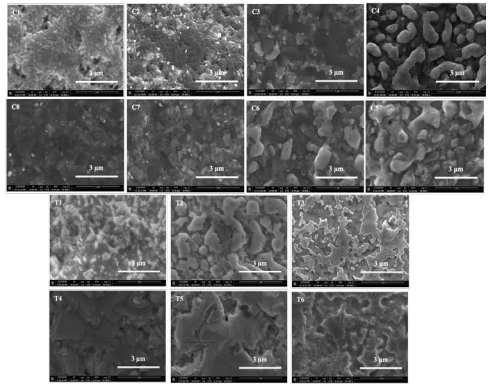
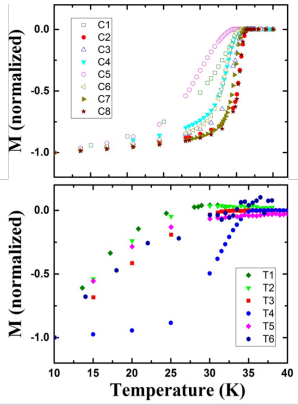


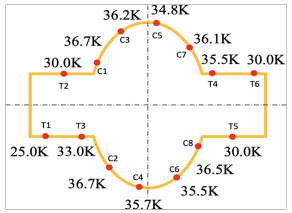


Other SC Materials beyond Niobium: MgB_2

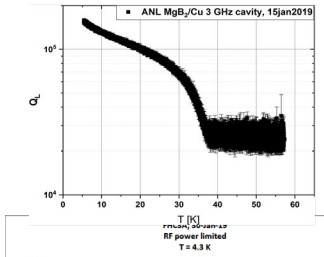


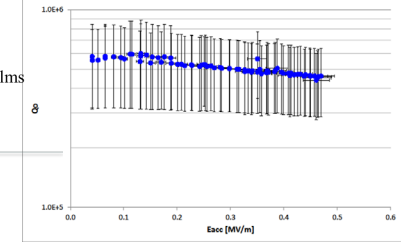


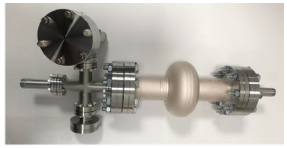




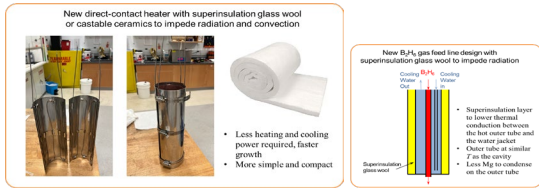
- All the samples show superconducting transition
- The transition temperature for MgB_2 films on cavity cell: around 34.8-36.7 K

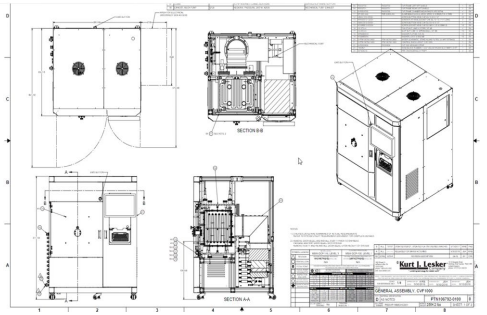






- RF test performed at JLab
- The 3.9 GHz MgB_2 thin film cavity show transition at around 36K.
- Q value is low (1E5 at 20 K and 1.5E5 at 5 K).



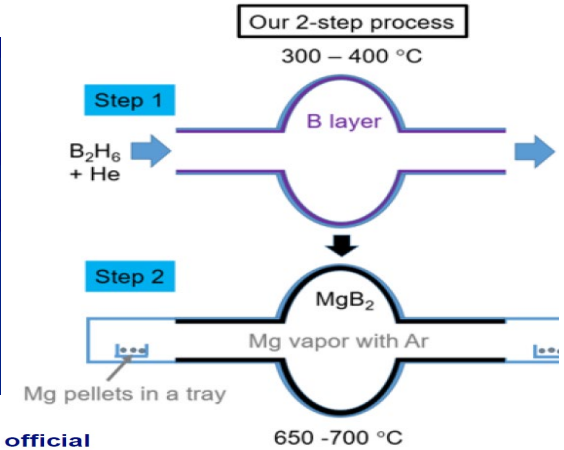


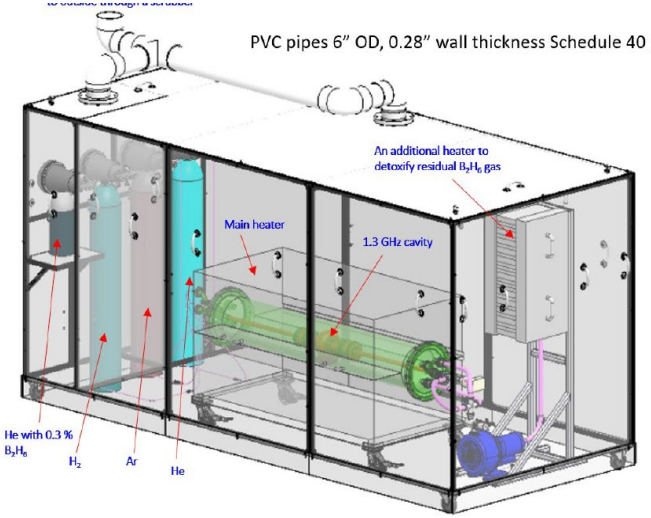
TEMPLE UNIVERSITY

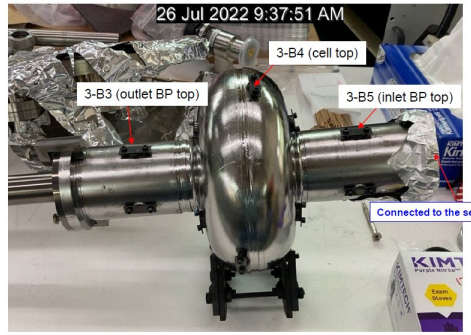
Los Alamos NATIONAL LABORATORY

A New System for MgB_2 Coating R&D at LANL

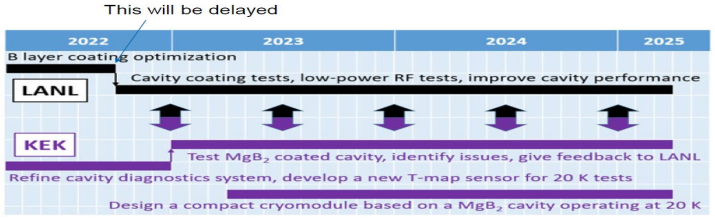
Tsuyoshi Tajima, Leonardo Civale, Torben Grumstrup, Dan Kelly, Maxim Mealy, Paolo Pizzol*, Anju Poudel, Harry Salazar, Roland Schulze (LANL, *now at SNS)
Hiroshi Sakai, Hayato Ito, Eiji Kako, Takafumi Okada, Kensei Umemori (KEK)







US-Japan Cooperation Project Schedule (in the official proposal). Mg-B reaction tests continue first.



Jefferson Lab

Advanced Substrates

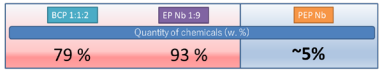
Recent advancements on Plasma Electrolytic Polishing technique
Speaker: Mr Eduard Chyhyrynets (LNL - INFN; University of Padua)

Additive Manufacturing for SRF copper cavities production and preliminary surface treatments on the printed prototypes
Speakers: Massimiliano Bonesso (INFN - Padua Section; Dept. of Industrial Engineering (University of Padova)), Cristian Pira (INFN - LNL)

Recent advancements on Nb Plasma Electrolytic Polishing –*E. Chyhyrynets et al.*

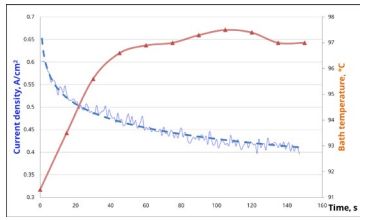
Motivation

- **Nb SRF cavity polishing requires hydrofluoric acid (HF)**
  - ➔HF is an extremely dangerous and poisoning acid
  - ➔Serious workers hazard risks
  - ➔Expensive procurement and disposal
  - ➔Expensive infrastructure for safe handling

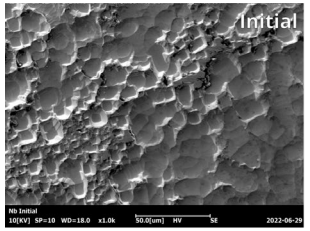


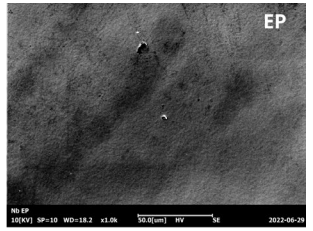
Ecology
- Greener approach
- No HF
- Less contamination
- Less wastes
- More secure

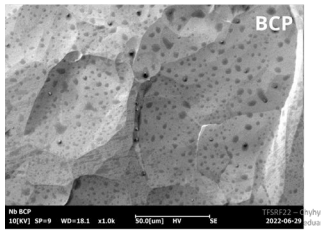
NH_4F – 3%
NaF – 0,5 %
Patent application number Ufficio Brevetti e Marchi, Italy 102022000009899

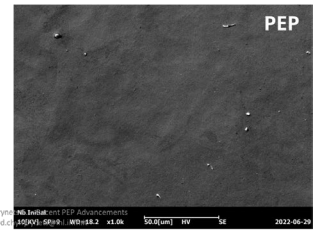


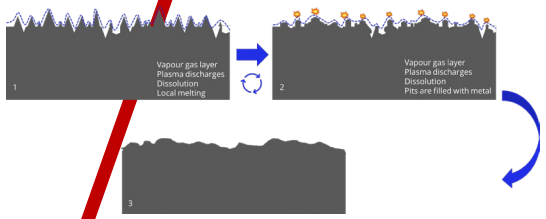
Cu process also in development (different chemistry of course)



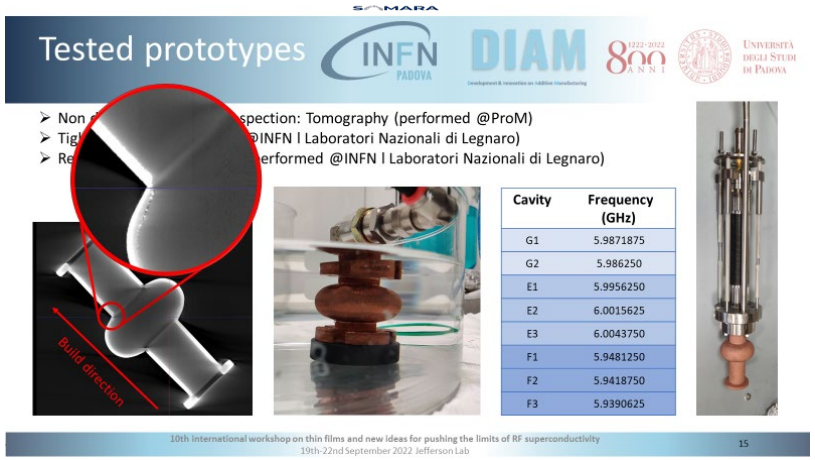








Additive Manufacturing for SRF copper cavities production and preliminary surface treatments on the printed prototypes-*Massimiliano Bonesso et al.*



By Laser Powder Bed Fusion (LBF)

- AM can overcome the issues encountered with traditional manufacturing techniques, single body cavities and even more sofisticated parts can be produced.
- Copper is succesfully printed only if powerful IR laser or green-blue lasers are adopted.
- Roughness is still limiting the quality of the 3D-printed parts.
- Post-processing is required.
- Further tests need to be done to evaluate how the 3D-printed parts work.

Nb process also in development

RF characterization for SRF films

SRF Thin Film Characterization: 1

Advanced characterization of SRF samples

Speaker: Sebastian Keckert (Helmholtz-Zentrum Berlin)

Optimization of Quadrupole Resonator geometry at JLab

Speaker: SARRA BIRA

RF Characterisation of Bulk Niobium and Thin Film Coated Samples at 7.8 GHz

Speaker: Daniel Seal (Cockcroft Institute, Lancaster University)

SRF Thin Film Characterization: 2

Temperature Mapping of Niobium-coated 1.3 GHz Copper Cavities

Speaker: Antonio Bianchi (CERN)

SPLIT SRF THIN FILM 6 GHZ CAVITIES

Speaker: Taaj Sian (Lancaster University)

Experimental evidence for counter current flow in superconductor-superconductor bilayers

Speaker: Md Asaduzzaman (University of Victoria, BC, Canada)

SRF Thin Film Characterization: 3

A DC magnetic field penetration facility for the characterization of planar multilayer structures for superconducting radiofrequency applications

Speaker: Daniel Turner (Lancaster University/Cockcroft Institute)

Development 3rd Harmonic Magnetometer at Jefferson Lab

Speaker: David Beverstock (Jefferson Lab)

Dc Magnetic Hall Probe Technique to Characterize the Materials for Accelerating Cavities

Speaker: Harshani Senevirathne (Old Dominion University)

SRF Thin Film Characterization: 4

Stress-induced omega (ω) phase transition in Nb thin films

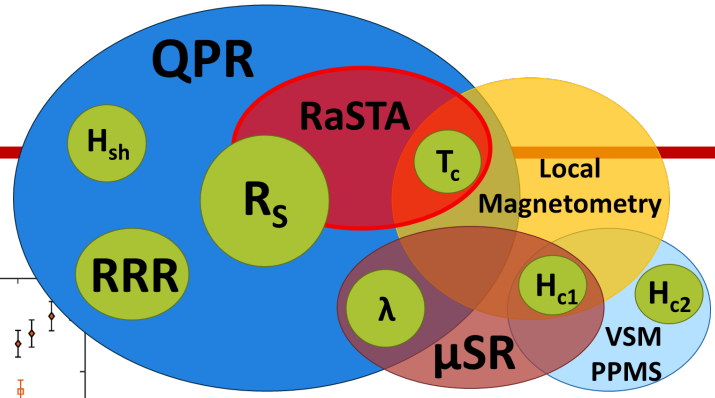
Speaker: Jaeyel Lee (Fermilab)

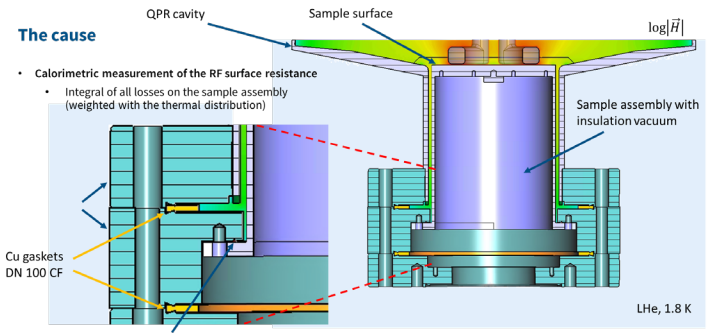
STM for SRF Thin Films

Speaker: Prof. Maria Lavarone

SRF Thin Films: Characterization: Discussion

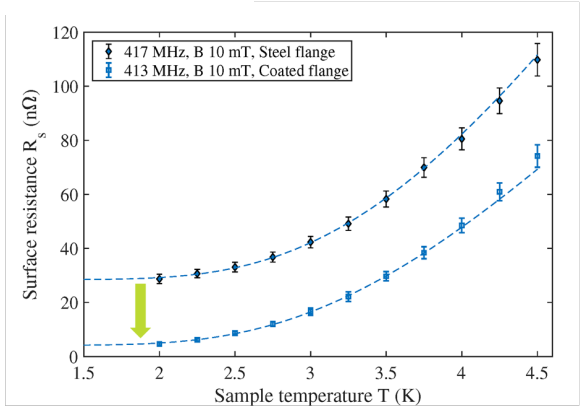
RF characterization for SRF films

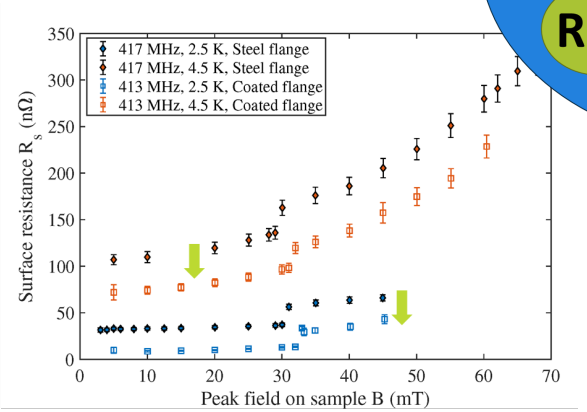




HZB Helmholtz Zentrum Berlin

Improve QPR Measurements





Measured ΔR = 24 nΩ

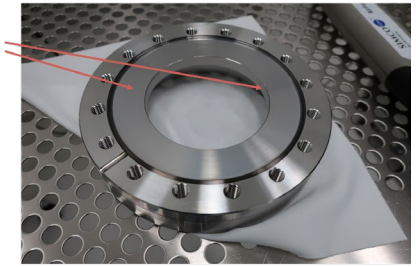
ΔR is independent of RF field and temperature → bias of R_{res} only

The solution

Thin film coating: Nb on stainless steel at University of Siegen

- HiPIMS coating of surfaces that are exposed to RF fields
- 4 … 12 µm → full screening
- CF knife edge covered during coating

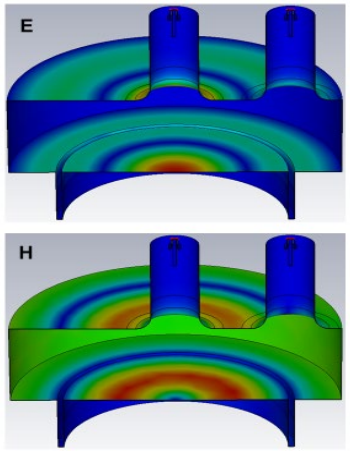
UNIVERSITÄT SIEGEN



Fast Measurements development – RF & Trapped Flux

RaSTA: „faster“ testing

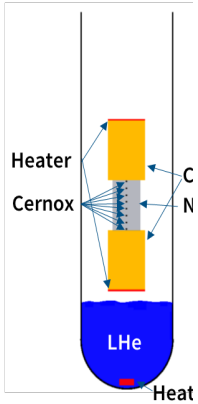
- Requirements
  - Use QPR samples
  - Calorimetric measurement → Thermal decoupling
- Pillbox-like design
- TM_{020} mode, f ≈ 4.8 GHz
- Possibility to operate without radiation safety → Limit: 5 kV
  - B_{sample} = 10 mT
  - P_{sample} = 0.5 W
  - P_{total} = 2 W
- German patent 10 2021 123 261



S. Keckert, thin films '22 15 HZB

miniVTS – trapped flux in samples

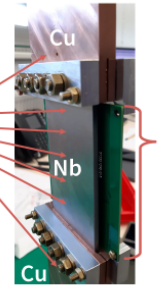
[F. Kramer, TUPOTK006, IPAC'22]



Sample: 100 x 60 x 3 mm³

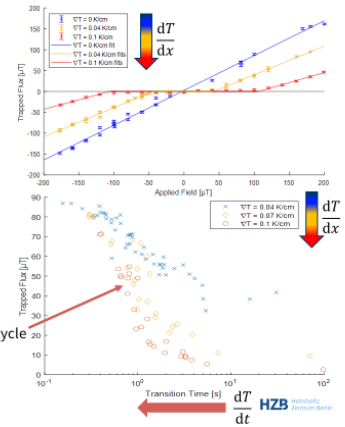
8 Cernox sensors for T-mapping and active heater control

3 heaters (top, bottom, LHe)



PCB with 5x3x3 AMR sensors

1 data point = 1 T_c cycle → ~100 cycles/day



→ Ongoing work: Nb thin film samples

S. Keckert, thin films '22 21

See also O. Kügeler talk, Wednesday afternoon WG3 Session

Jefferson Lab

RF characterization for SRF films

Optimization of Quadrupole Resonator geometry at JLab
- S. Bira et al.

	$\frac{\delta f = f_{dipole} - f_{quadrupole}}{f_{quadrupole}}$	$\frac{H_{Sample}}{H_{Max}}$	$\frac{E_{Max}}{H_{Sample}}$
rrod	(+)(-)	(+)	(-)(+)
Wloop	(+)(+)	(+)(-)	(+)(-)
rloop	(+)(+)	(+)(-)	(+)(+)
hloop	(+)(+)	(+)	/
ltran	(-)	(-)	(-)
lcone	(-)	/	(+)(-)
dloop	(-)(-)	(+)	(-)

Tab: Influence of increasing a single geometric parameter on the various RF figures of merit.
(+), (-) indicate whether a modest change in the geometric parameter influences the figure of merit.

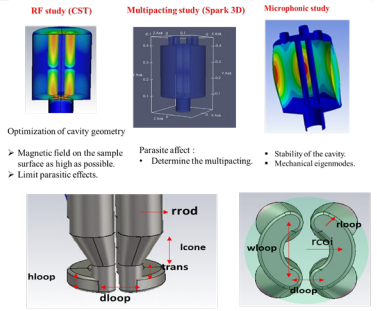


Figure: Parametrized model of the QPR. The length of the rods is not shown in this diagram.

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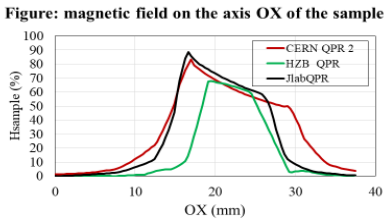
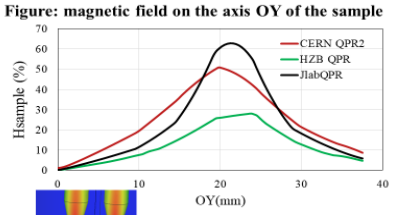
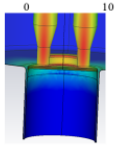
RF Study: Distribution of magnetic field on the sample

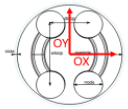




- The magnetic field distribution on the sample is homogeneous.
- The field within the coaxial gap is reduced.



Magnetic field distribution on the coaxial gap



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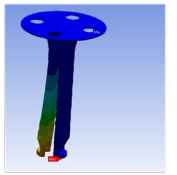
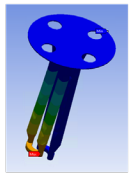
13

- Microphonic study with **ANSYS**



Mode 1: The displacement of rods is according to OX axis.



Mode 2: The displacement of rods is according to OY axis.

Mode	Frequency (Hz)
1	104
2	108
3	134
4	137
5	470
6	474
7	536
8	537
9	557
10	557

- Geometry optimization: homogeneity of magnetic field is increased.
- Overlapping of modes solved
- Microphonic effect minimized.
- QPR fabrication ready to resume at CERN.

Science and Technology Facilities Council · The Cockcroft Institute · School of Engineering · Lancaster University

RF Characterisation of Bulk Niobium and Thin Film Coated Samples at 7.8 GHz

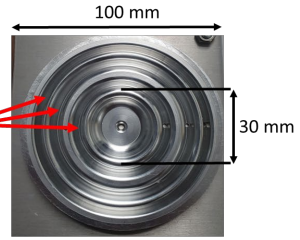
Daniel Seal
Lancaster University/Cockcroft Institute

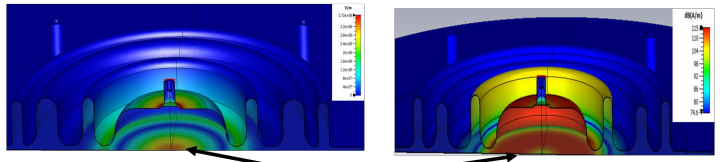
10th International Workshop On Thin Films And New Ideas For Pushing The Limits Of RF Superconductivity

thinfilms NEW IDEAS for SRF

3 Choke Bulk Nb Cavity

- Cavity frequency = 7.8 GHz
- TM_{010} mode
- An **RF choke** is designed to reflect the cavity's fundamental mode frequency back into the cavity

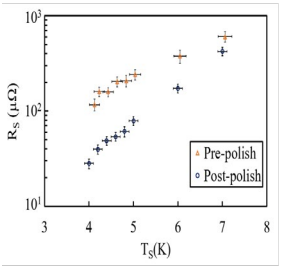


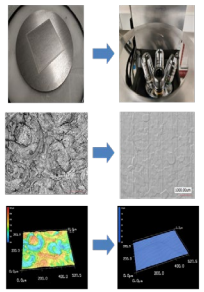


Sample sits under cavity with a small gap

From CST

Commissioning with Bulk Nb





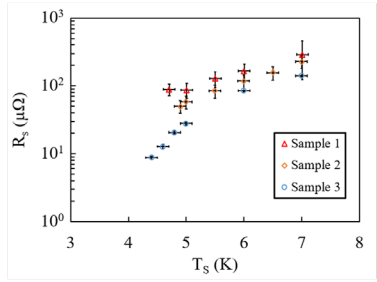
- Bulk Nb *RRR* = 400
- Sample measured before and after metallographic polishing at UCLab (Improvement in R_S)
- R_{BCS} (4.2 K) ~ 15.3 μΩ
- Aim to measure bulk Nb after full treatment procedure

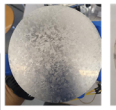
Ave roughness (Sa) = 4.2 μm
Height dev. profile (Sz) = 31 μm

Ave roughness (Sa) = 0.05 μm
Height dev. profile (Sz) = 1.2 μm

Courtesy of O. Hryhorenko, D. Longuevergne UCLab

Nb thin films on Cu





Sample 1 – 600°C, pulsed DC magnetron sputtering

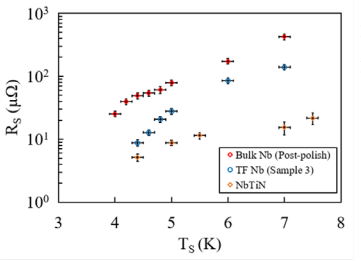
Sample 2 – room temperature, pulsed DC magnetron sputtering

Both polished with diamond abrasive

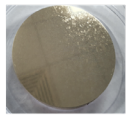
Sample 3 – polished with diamond turning, HiPIMS

Samples from R. Valizadeh, S. Wilde STFC DL

NbTiN thin film on Cu



- Comparison with best Nb on Cu and our bulk Nb
- T_c ~ 12.6 - 17 K (sensitive to N stoichiometry)

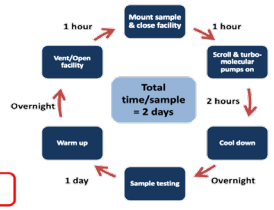


- Surface analysis and DC characterisation to be carried out on all samples
- NbTiN to be tested on cavity geometry soon and as a multilayer

Facility Operation

- **Current parameters:**
  - $f \approx 7.8$ GHz
  - Sample temperatures, $T_S \geq 4$ K
  - Sample $B_{peak} \leq 1.1$ mT
  - Low RF powers ≤ 1 W
- Simple to operate and change sample (1 PhD student!)
- Simple sample design (low cost)

2-3 sample tests per week!



RF test → Cut sample → DC Field penetration → Surface characterisation

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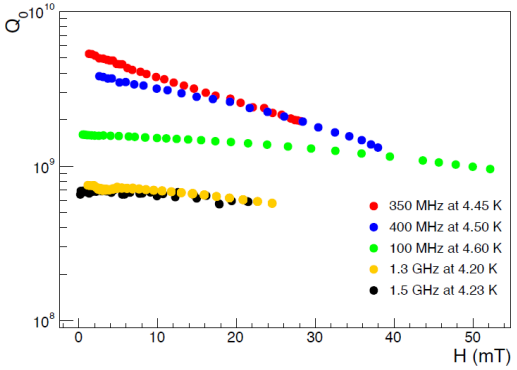
RF characterization for SRF films

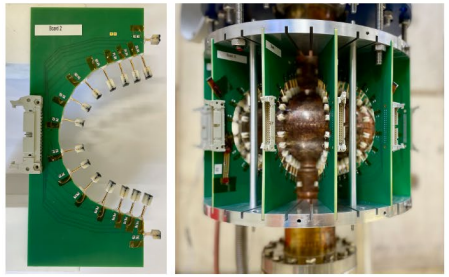
Temperature Mapping of Niobium-coated 1.3 GHz Copper cavities

Antonio Bianchi



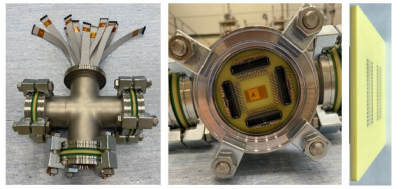
Temperature Mapping System for Nb/Cu cavities

Twelve boards (~200 thermometers):

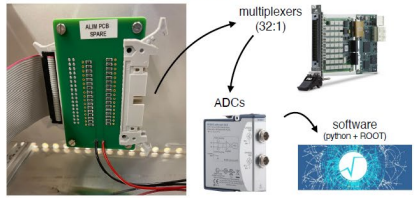


- **~200 thermometers**
- **~500 feedthroughs** in 3 SMT/SMD PCBs
- **6 multiplexers**
- **12 ADC channels** (maximum sampling rate: 100 kS/s)
  → possibility of **high-speed temperature mapping**

Five hundreds feedthroughs in three SMT/SMD PCBs:



Twelve PCBs for electrical circuit:

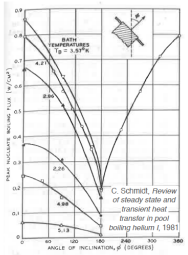


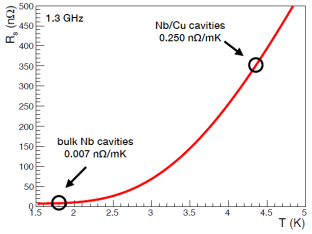
Engineering the Surface of Copper Cavities

Might we induce heat dissipation by nucleate boiling in the outer surface of Nb/Cu cavities?

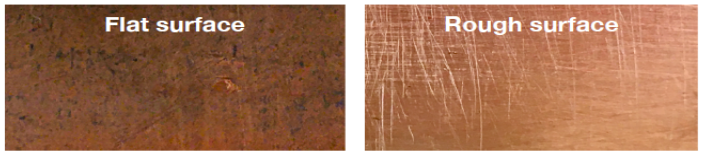
The heat dissipation between Cu cavities and He-I depends on several parameters. For example:
- surface orientation
- thickness of substrate
- external oxidation of substrate
- thermal conductivity of copper substrate
- etc

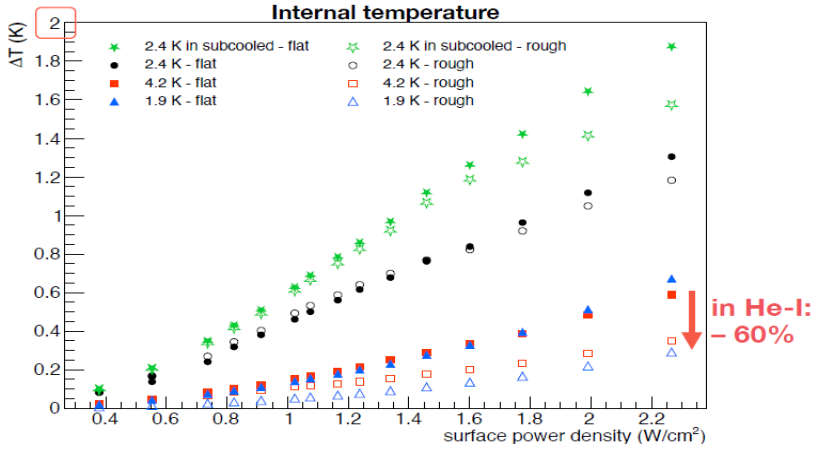
many constraints to be considered…





A small variation in the temperature of the film at 4.2 K (He-I) implies a high increase of surface resistance.





Temperature mapping system for niobium-coated copper cavities at CERN:

- used for thermal studies in LHe-I, where Nb/Cu cavities usually operate
- challenging because the heat conduction in copper is much higher than that in bulk niobium
- possibility to detect and localize heat losses (ohmic losses, field emitters, etc) at 2.4 K in saturated vapor pressure as well as in sub-cooled He

Heat dissipation of thin film cavities is not uniform

- observation of hotspots as expected, but also, surprisingly, cold areas
- several hints indicate that the cold area is in nucleate boiling regime

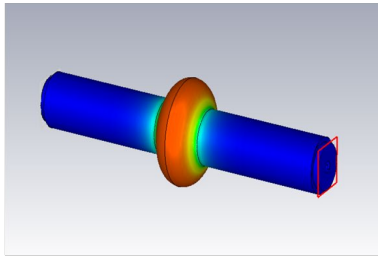
Engineering copper surfaces for thin film cavities

- roughness of copper substrate may improve the heat dissipation of cavities and, in turn, their performance (studies ongoing)

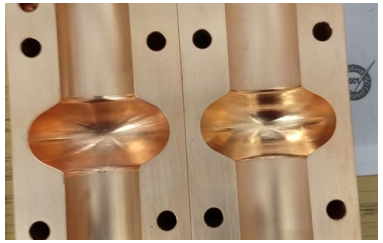
Characterization for SRF films: Cryogenic & RF

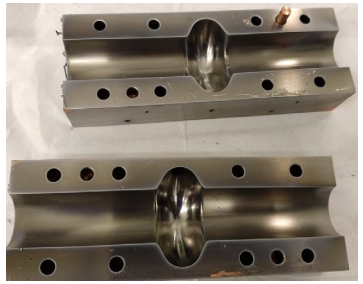
Split SRF Thin Film *6 GHz Cavities*

- For conventional cavities the weld is along a critical area with the highest surface current.
- The weld is usually where defects occur.
- Defects cause problems with thin films:
  - Increase surface resistance
  - Can be areas of inconsistency or delamination in the film



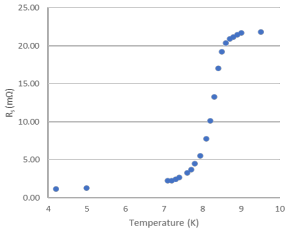
Contour plot of the surface current of at typical elliptical cavity. (Simulation using CST Microwave Studio)

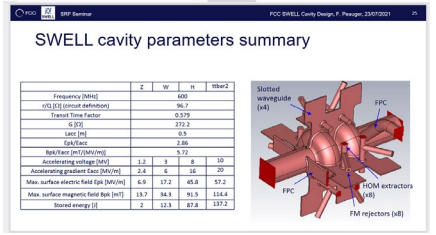




Cavity A Superconducting Preliminary Results

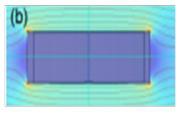
- Clear superconducting transition at the correct transition temperature range.
- Measured Rs =1.13 mΩ at 4.2 K .
- R_{BCS} = 1.15 × 10^{-2} mΩ.
- 2 orders of magnitude higher than theoretical Rs.
- Maybe due to imperfection of the thin film as it was a trial coating.
- This was the first RF cavity coated with a superconducting thin film at DL and in UK.
- The first RF test of thin film coated SRF cavity at DL.
- First split cavity coated and tested in UK



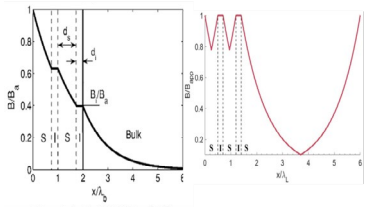


- Slotted Waveguide ELLiptical (SWELL) Cavity.
- Baseline design for FCC-ee RF system even though they have not been teste as they overcome one of the biggest problems in SRF.
- Welds away from the electric field in the HOM dampeners.
- Made as quarter cells.
- Slots reduce HOMs.
- Cavities planned (and simulated to) reach 20 MV/m.
- Bulk Nb or Nb coated Cu.

A DC magnetic field penetration facility for the characterisation of planar multilayer structures for SRF applications– D.Turner

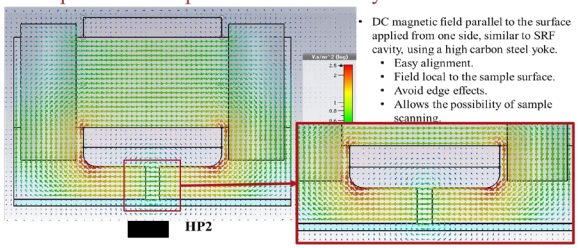


Junginger, T., et al. (2018). Physical Review Accelerators and Beams, 21(3), 32002.

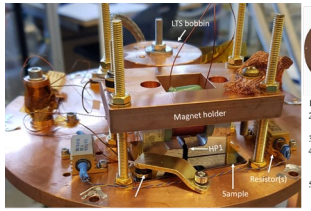


Gurevich. A., (2006) Appl. Phys. Lett. 88, 012511

Field penetration experiment at Daresbury

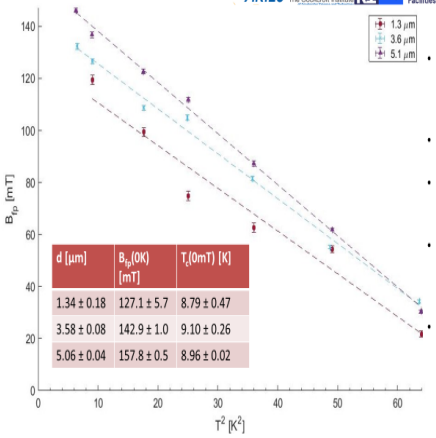


- DC magnetic field parallel to the surface applied from one side, similar to SRF cavity, using a high carbon steel yoke.
  - Easy alignment.
  - Field local to the sample surface.
  - Avoid edge effects.
  - Allows the possibility of sample scanning.



1. Resistors – Heaters
2. Brass posts to hold the magnet in position
3. Sample area
4. Hall Probes – 1 between the dipoles of the yoke, 1 under the sample
5. Thermometer

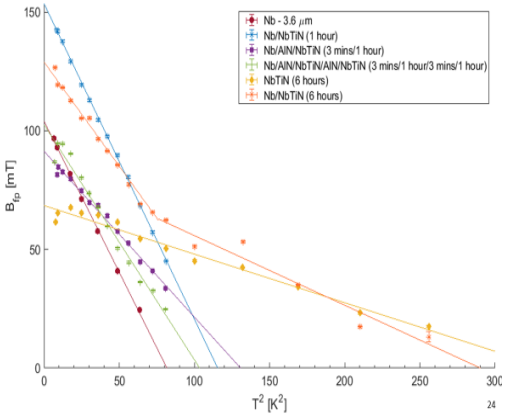
Nb sample



d [μm]	B_{fp}(0K) [mT]	T_c(0mT) [K]
1.34 ± 0.18	127.1 ± 5.7	8.79 ± 0.47
3.58 ± 0.08	142.9 ± 1.0	9.10 ± 0.26
5.06 ± 0.04	157.8 ± 0.5	8.96 ± 0.02

- The thickness dependence of Nb has been investigated (*Samples courtesy of Reza Valizadeh*).
- The samples were deposited by DC magnetron sputtering.
- It can be seen that thicker samples produce an increased B_{fp}.
- The thinner samples produce an increased amount of scattering compared to thicker samples.
- **B_{fp} is not B_{c1}.**

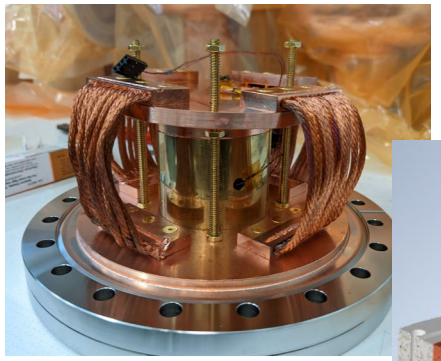
- Comparing $B_{fp}(T^2)$ shows films with AlN insulating layer produce no increase in B_{fp} at low T, but do at increased T.
- The thick NbTiN layer produces a lower B_{fp} than all samples.
- Thick bi-layer NbTiN produces two slopes:
  - T>Tc Nb, the slope is similar to that of NbTiN.
  - T<Tc Nb produces a line similar to that of Nb
- The Nb was not tested at the same T's, thus the B_{fp}(0K) is compared.
- Increase in B_{fp}(0K) from 104.0 mT (Nb) to:
  - NbTiN thin film: 153.6 mT
  - NbTiN thick film: 129.0 mT

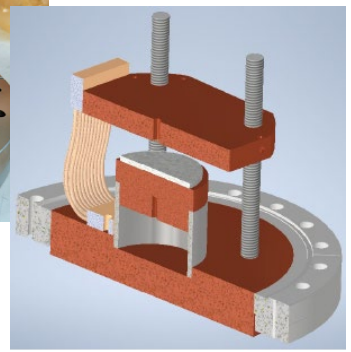


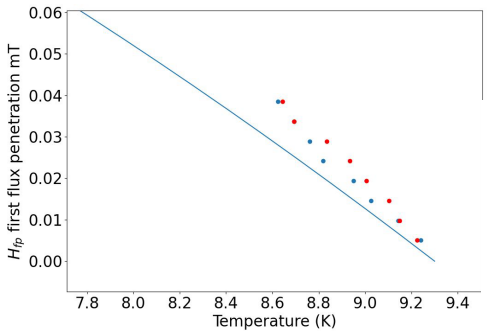
Jefferson Lab

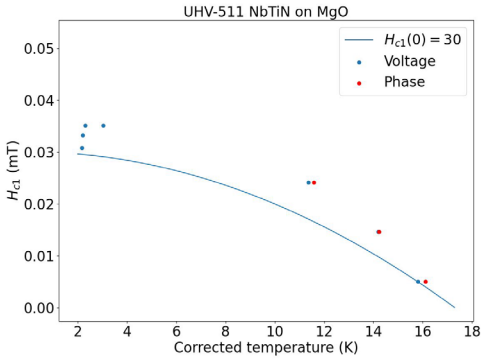
Characterization for SRF films: Cryogenic & RF

Development of 3rd Harmonic Magnetometer at Jefferson Lab – *D.R. Beverstock et al.*









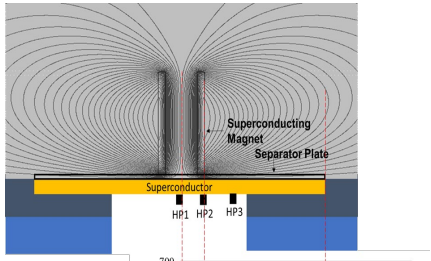
Current Limitations

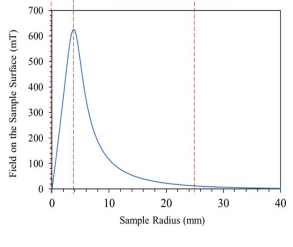
limited to 130 mT due to electronics overloading
thermal stability from coil becomes an issue around 50 mT

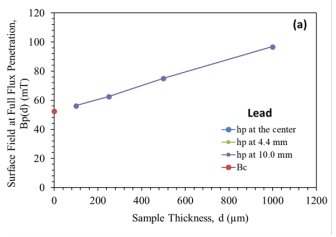
Future plans

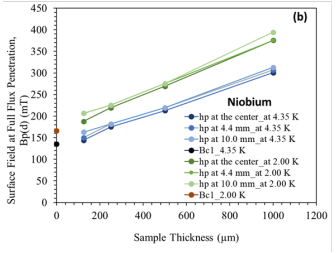
High watt heater on coil plate for more thermal control
Coil plate and sample holder to diminish eddy currents
Integration of data analysis and data collection programs
Hall probe to measure applied field, at top of coil
Samples with cut offs to measure edge effects.

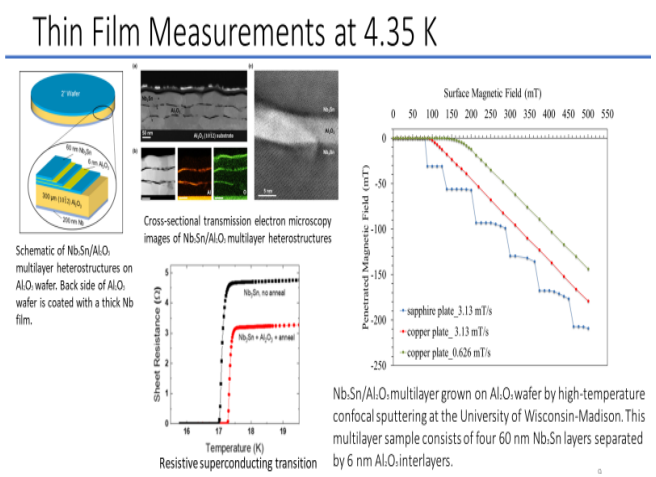
DC Magnetic Hall Probe Technique to Characterize the Materials for Accelerating Cavities – *H. Senevirathne et al.*

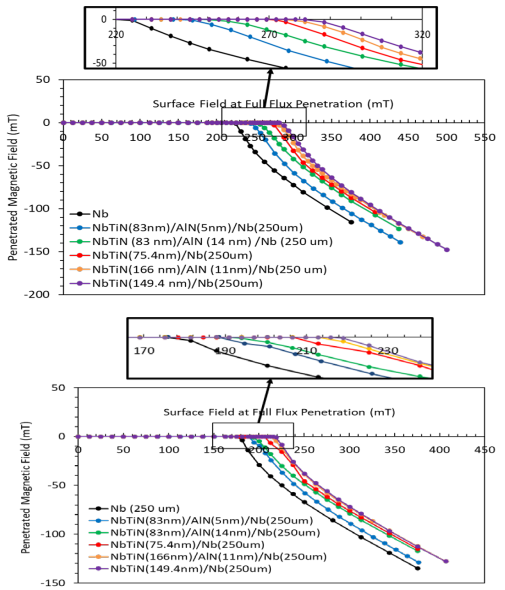










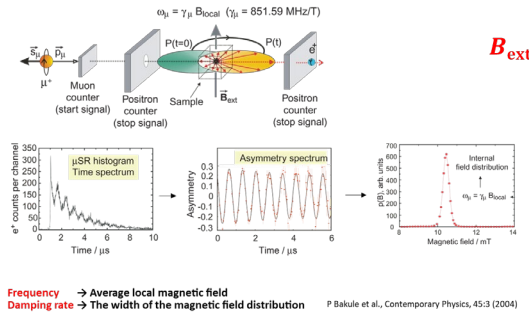


Sample #	Percentage increase % At 4.35 K	Percentage increase % At 2.00 K
1	7.5	10.3
2	8.9	12.9
3	19.6	24.3
4	16.1	22.9
5	21.4	27.1

RF characterization for SRF films

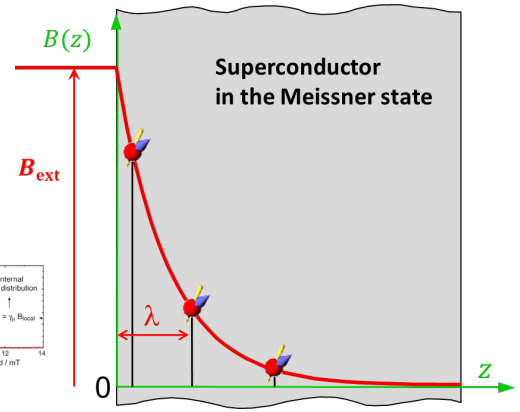
Experimental evidence of counter current flow in superconductor-superconductor bi-layers

Experiment: Low Energy Muon Spin Rotation (LE-μSR)



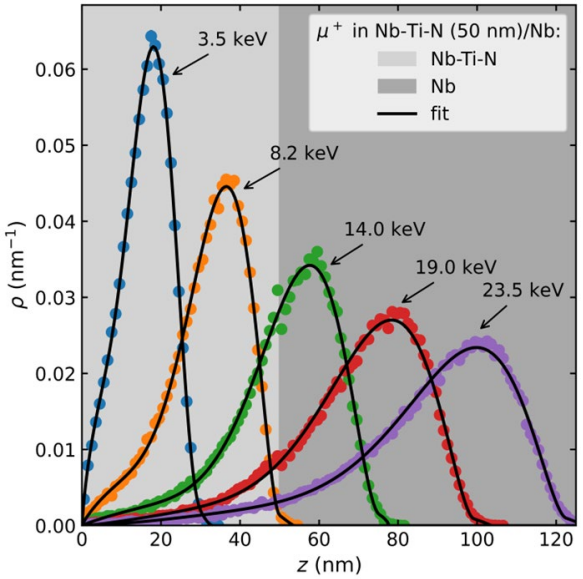
Frequency → Average local magnetic field
Damping rate → The width of the magnetic field distribution

P Bakule et al., Contemporary Physics, 45:3 (2004)

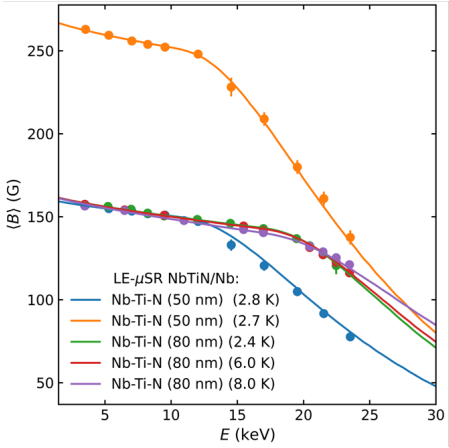


Frequency → Average local magnetic field
Damping rate → The width of the magnetic field distribution

- LE-μSR to measure the Meissner screening profile into SS bilayers.
- Data fits to counter current flow model yielded λ_(Nb−Ti−N) in good agreement with the literature in contrast to a naïve (bi)exponential model.
- Results imply the validity of counter current flow model in SS bilayers and that they are a viable means of exceeding the Nb field limits.
- No observation of bilayer behavior in Low Temperature Baked Nb. Meissner state field screening profile is just an exponential.



Global fit (counter current flow model) to the Meissner screening profile of
- Nb-Ti-N (50 nm)/Nb and
- Nb-Ti-N (80 nm)/Nb



Extracted penetration depths (at 0 K)

$\lambda_{Nb-Ti-N} = (201 \pm 4)$ nm
$\lambda_{Nb} = (50.4 \pm 2.2)$ nm

Extracted film thicknesses

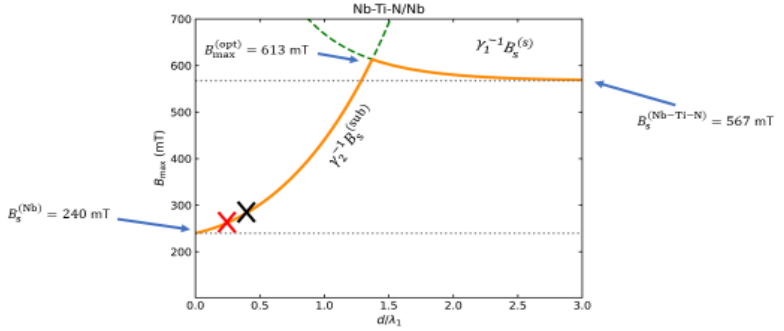
$d_{Nb-Ti-N} = (56.3 \pm 0.9)$ nm [50 nm]
$d_{Nb-Ti-N} = (83.3 \pm 0.8)$ nm [80 nm]

Predicted B_{max} in SS bilayers

Based on our experimental result

✗ → 50 nm Nb-Ti-N = 262 mT
✗ → 80 nm Nb-Ti-N = 284 mT

Here $\lambda_1 = 201$ nm, $B_s^{(S)} = 0.84 B_c^{(S)} = 567$ mT
$\lambda_2 = 50$ nm, $B_s^{(Sub)} = 240$ mT



T. Kubo, Supercond. Sci. Technol. 30 023001 (2017)

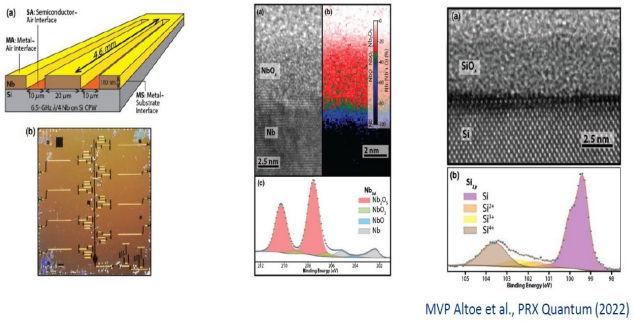
Material characterization for SRF films

Stress-induced omega (ω) phase transition in Nb thin films – J. Lee

Fermilab SQMS

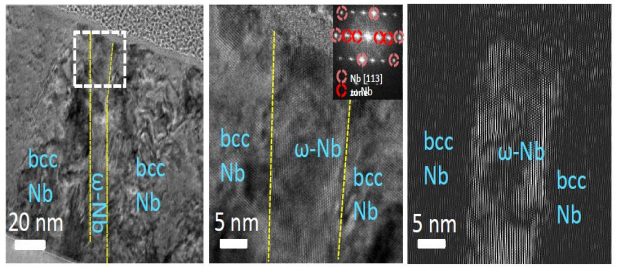
Nb thin film resonators for superconducting qubits

- Nb thin film 2D resonator shows ~10^6 of Q-factor significantly lower than 3D-resonator
- Understanding materials origins for the degradation of quality factor of Nb thin film resonators for superconducting qubits.



MVP Altoe et al., PRX Quantum (2022)

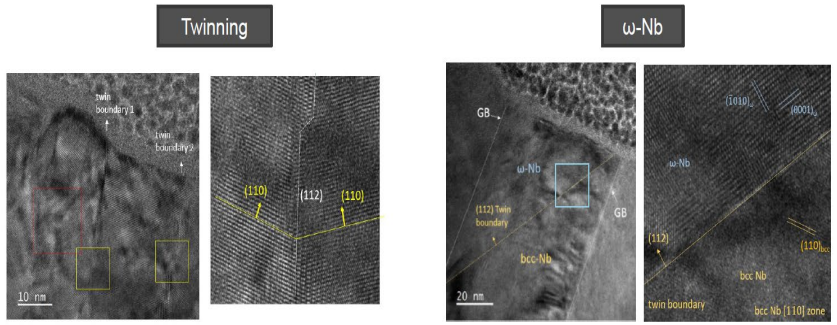
Nb films deposited by HiPIMS (Rigetti), RRR=5



- Size of omega phases is comparable to the coherence length of Nb (~40 nm): 10~100 nm
- Volume fraction: ~1 vol.%

Some of the omega phase in Nb thin film extend along the whole thickness of Nb thin film

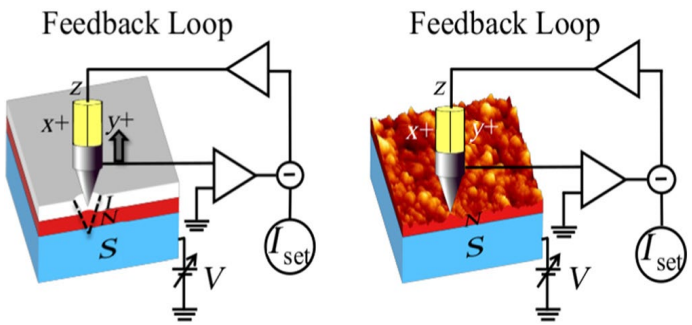
ω-Nb : bcc to hexagonal transition

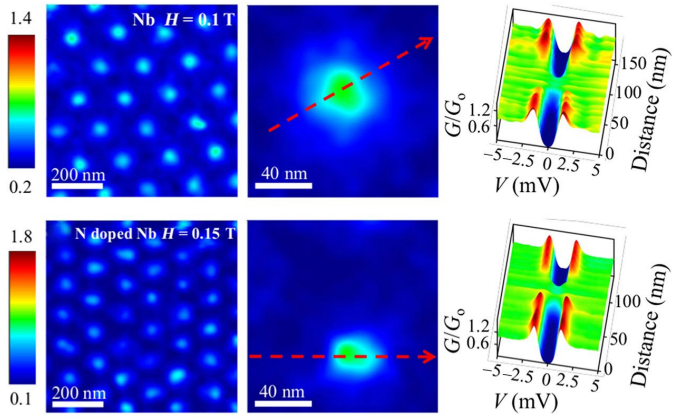


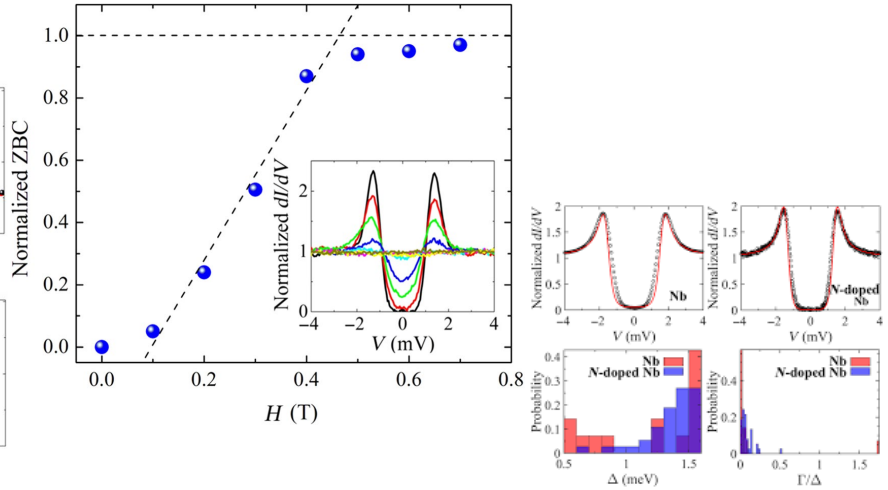
Why do they form?	(i) Nb is soft. Internal stress in Nb thin film possibly matter. (ii) Grain boundaries provide dislocations
Superconducting properties?	DFT calculations imply that omega phase may have degraded Tc etc.
How to control?	Controlling stress and grain size of Nb (substrate or heat treatment, etc)

STM for SRF Thin Films – *M. Iavarone*

TEMPLE UNIVERSITY







Phys. Rev. Applied 13, 044044 (2020)

Jefferson Lab

Superconducting film beyond SRF

Metamaterials based on NbTiN

Speaker: Anne-Marie Valente-Feliciano (Jefferson Lab)

Impact of Superconductors' Properties on the Measurement Sensitivity of Resonant-Based Axion Detectors

Speaker: Prof. Nicola Pompeo (Università Roma Tre, DIIEM and INFN, Sezione Roma Tre - Italy)

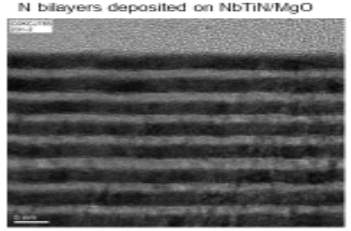
NbTiN/AlN Metamaterials Developments

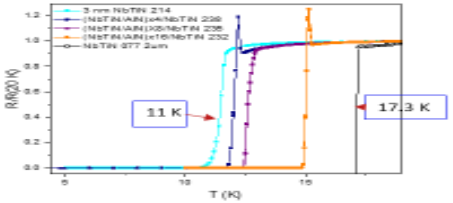
- **NbTiN/AlN interface development for Metamaterials** *(DARPA-BAA funded)*

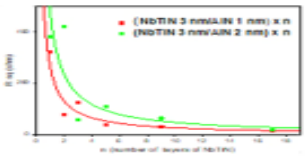
Meta-materials for functional surfaces

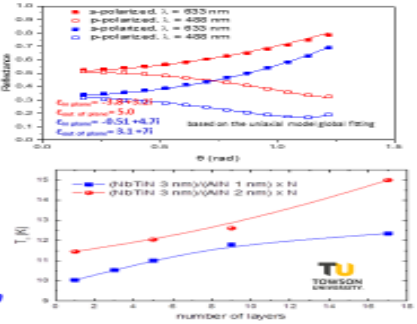
- Multilayer structure of NbTiN = 3.6/3/2 nm and AlN = 2/1.5/1 nm.

N bilayers deposited on NbTiN/MgO









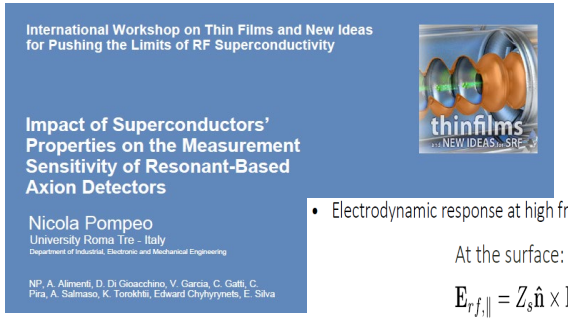
Metamaterial engineering shows hyperbolic ***behavior*** *and increased the T_c of these multilayered structures up to 32% with respect to the T_c of a single ultrathin NbTiN layer. Enhancement limited by the small coherence length of NbtiN (ξ~3.8 nm).*

Vera N. Smolyaninova, et al., "Effect of metamaterial engineering on the superconductive properties of ultrathin layers of NbTiN", ***Journal of Applied Physics*** ***130, 073901*** *(2021) https://doi.org/10.1063/5.0057663*

- **NbTiN for quantum devices & sensors**
- **Nb films on insulators for Q-bits & quantum devices**

Jefferson Lab

TOWSON UNIVERSITY



- Electrodynamic response at high frequency: surface impedance

At the surface: $\mathbf{E}_{rf,\parallel} = Z_s \hat{\mathbf{n}} \times \mathbf{H}_{rf,\parallel}$ $\quad Z_s = R_s + iX_s$ losses + screening

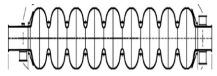
- Z_s : "performance" of mw cavities (+ other rf appl., e.g. next gen. particle accelerators beam screens)

$Q = \frac{2\pi\nu_0 W}{P_{diss}} \Rightarrow \frac{1}{Q} = \frac{R_s}{G}$ quality factor; dissipation

W: stored energy; P_{diss}: dissipated power; G: geometrical factors (computed | calibrated)

NbTi haloscope

Alesini et al. Phys. Rev. D 99 101101(R) (2019)



9-cell TESLA-type accelerator cavity

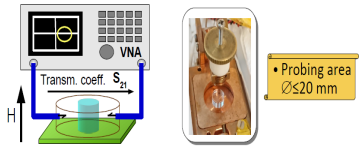
H. Padamsee, Supercond. Sci. Technol. 30 053003 (2017)

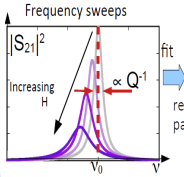
$R_s(H_{dc}, E_{rf} \to 0) \Rightarrow Q \Rightarrow$ Axion signal (linear regime)

$R_s(H_{dc} = 0, E_{rf}) \Rightarrow Q \Rightarrow E_{acc}$ (non linear regime)

- Z_s : probe for physical properties → input to theory and material engineering

Dielectric-loaded resonator (surface perturbation method).





fit → Q, ν_0 → resonator parameters → std. em theory

H-induced variations:

$\Delta R_s(H) = G\left(\frac{1}{Q(H)} - \frac{1}{Q(0)}\right)$

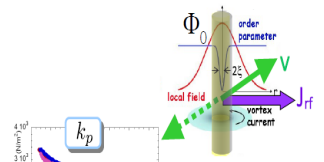
$\Delta X_s(H) = -2G\frac{\nu_0(H) - \nu_0(0)}{\nu_0(0)}$

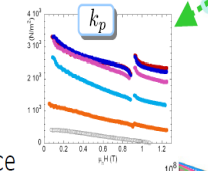
$\Delta Z_s(H) \Rightarrow \rho_{vm}$

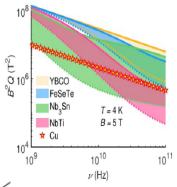
Various limits:
- thin film on insulator $Z_s \propto \rho$
- bulk $Z_s \propto \sqrt{\rho}$
- film on metal & thick film $Z_s(\rho)$

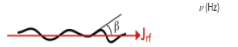
Alimenti et al. Meas. Sci. Technol. 30 065601 (2019)
Torokhtii et al, Acta IMEKO 9 47 (2020)
Pompeo et al, Measurement 184 109937 (2021)

- Surface impedance measurements in the mixed state: powerful probe for vortex physics
- Vortex dynamics studies on various superconductors
  - NbTi:
    - Collective pinning regime
    - Pinning frequency ν_p =5-6 GHz
  - YBCO, FeSeTe, Nb_3Sn: different pinning strengths and regimes
- Evaluation of superconducting haloscope performance
  - YBCO most promising, benefits from extensive APC optimization
  - FeSeTe potentially competitive
  - Nb_3Sn good results, would benefit from pinning optimization
  - NbTi mainly effective below 10 GHz
  - extended pins //H & J_{rf} could enhance "force free" effect









ROMA TRE UNIVERSITÀ DEGLI STUDI

thinfilms NEW IDEAS for SRF Report from

Jefferson Lab

Summary

- Strong collaborations across the community
- More institutions are joining in
- Enthusiastic, dynamic exchanges
- Progress in ongoing Nb and other materials films projects
- Demonstrations of Nb/Cu Q-slope mitigation and SIS concept
- Emergence and/or refinement of theoretical models
- New techniques for substrate fabrication and preparation, film analyses
- Superconducting TF applications beyond SRF keep expanding (devices, sensors, quantum …)
- The SRFTF field continues to gain momentum

Next Workshop Edition

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

thinfilms and NEW IDEAS for SRF

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 2024

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

In the mean time …

Let's continue the conversations and foster collaborations

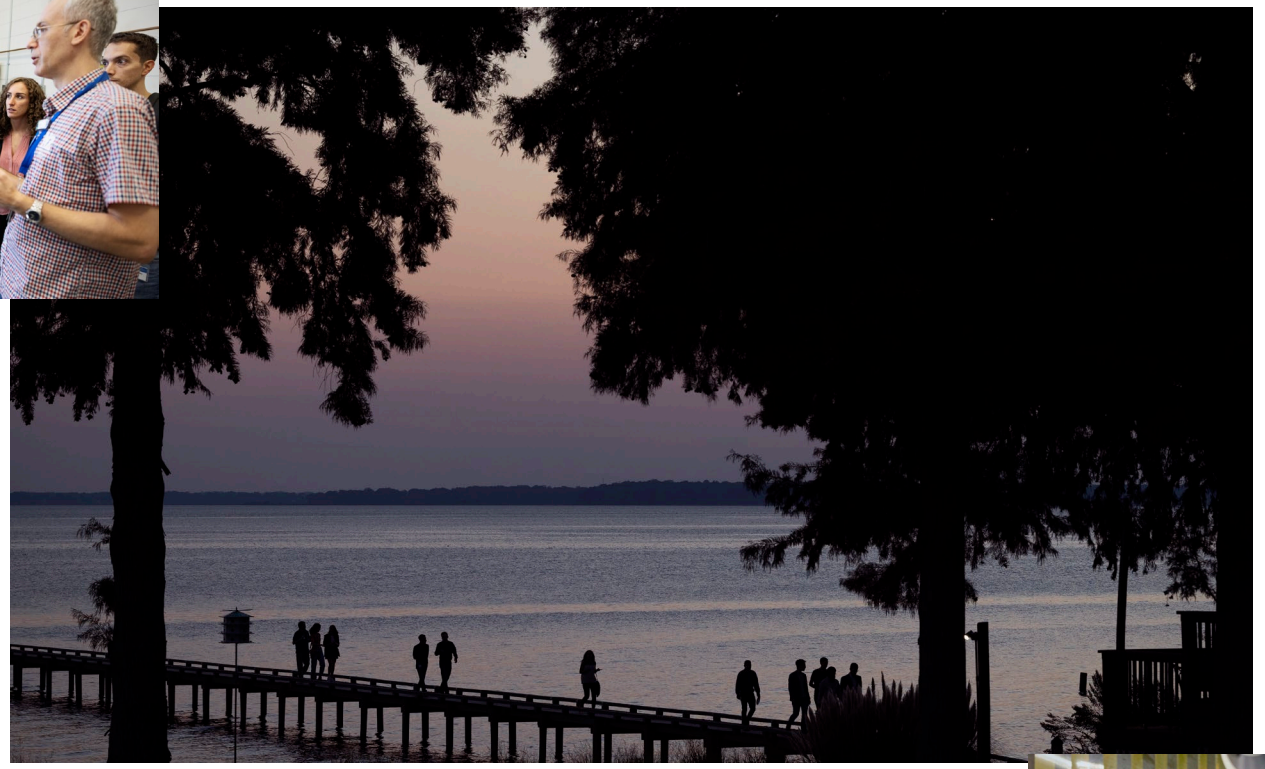
TTC working group „Thin Films" or „Non-bulk Nb as RF surface"

- Online meetings, one topic per meeting
- Open discussions, exchange of knowledge, ideas, problems, …
- Chairs
  Marc Wenskat , Sebastian Keckert

- Indico webpage: https://indico.cern.ch/category/6583/
- Mailing list: ttc-wg-thinfilms@listserv.dfn.de
  To subscribe send „Subscribe ttc-wg-thinfilms NAME" to sympa@listserv.dfn.de

- Next meeting not yet scheduled
  → possibility to continue discussions of this workshop

Both series of events are synergistic and complementary



ありがとうございました

THANK YOU