This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Innovative Superconducting Thin Film Coated Cavities

3rd Annual Meeting Paris, 18 April 2024

Cristian **Pira** INFN LNL

Reza **Valizadeh** UK RI Science and Technology Facilities Council

on behalf of iFAST ***WP9*** *Collaboration*

iFAST

I.FAST WP9 Collaboration

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M. Bertucci, R. Paparella (LASA)

O.B. Malyshev, R. Valizadeh, C. Benjamin, T. Sian, L. Smith, D. Seal

C.Z. Antoine, S. Berry, Y. Kalboussi, T. Proslier

D. Longuevergne, O. Hryhorenko,

S. Keckert, O. Kugeler, J. Knobloch

S. Prucnal, S. Zhou

X. Jiang, T. Staedler, A. Zubtsovskii

E. Seiler, R. Ries

A. Medvids, A. Mychko, P. Onufrievs

G. Burt, N. Leicester, S. Marks, D. Turner

W. Bradley, S. Simon

R. Berton, D. Piccoli, F. Piccoli, G. Squizzato, F. Telatin

Associated Partners

A. M. Valente Feliciano

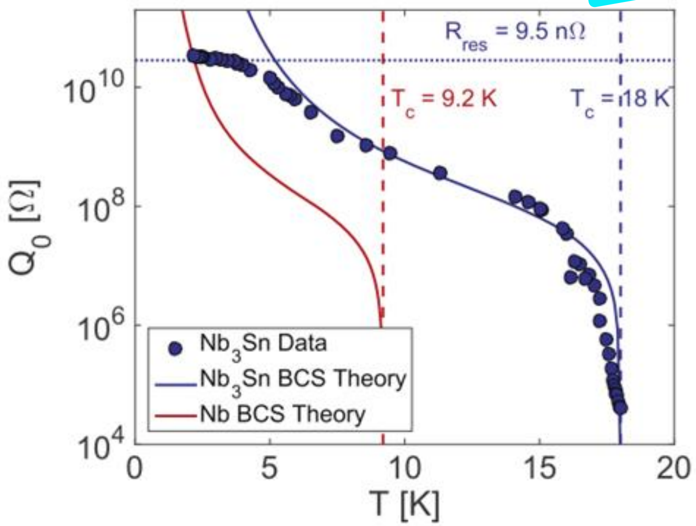
Informal Partners

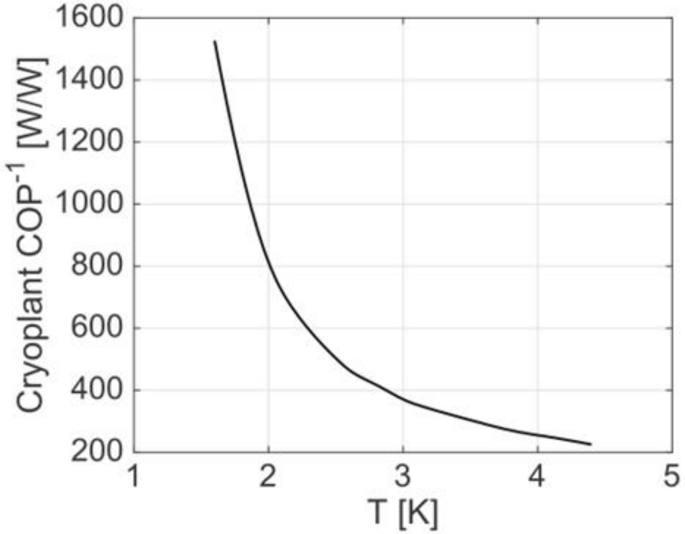
Goal of WP9

MAIN Deliverable (2025):
Produce a prototype of high performance 1.3 GHz thin film SRF elliptical cavity $Q > 1 \cdot 10^{10}$ @ 4.5 K

Energy saving *is mandatory fo* … ***ators***…

…***cryogenics*** *is one of the* ***larger*** … ***st*** *in modern SRF accelerators*





Move from bulk Nb @2K to Nb_3Sn @4.5 K

reduces cryogenic power by a factor of 3

cristian.pira@lnl.infn.it

Nb_3Sn on Cu: Multiple challenges

- A15 are Brittle materials
- Complicate Phase Diagram
- Low melting point substrate
- Substrate preparation
- Interface diffusion
- Target Production
- Coating Parameters
- Trapped Flux
- Tuning

Nb_3Sn on Cu: Multiple challenges

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Nb_3Sn on Cu: Multiple challenges

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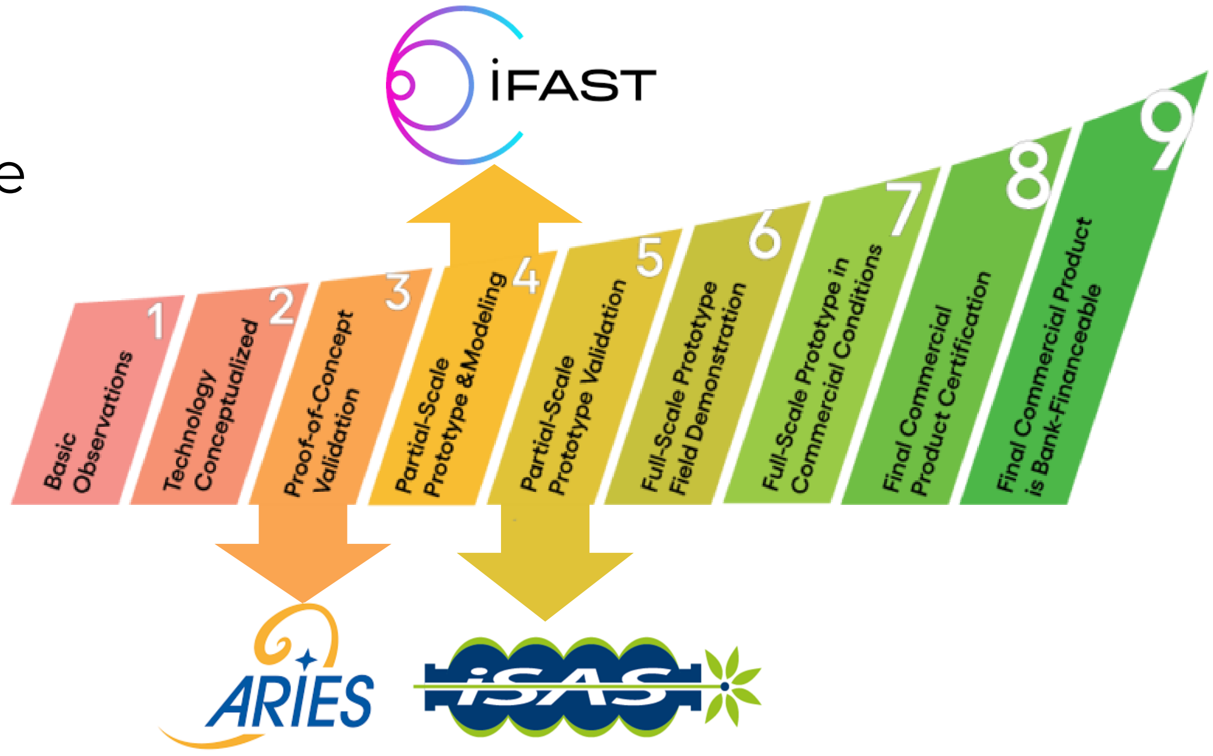
- **Target Production**
- **Coating Parameters**
- **Trapped Flux**
- **Tuning**

Started in March 2024



WP9 Structure

Task 9.1
Coordination and strategy
for innovative superconducting accelerating cavities

Task 9.2
Innovative SC accelerating cavity **prototype**
1.3 GHz cavity coating and testing

Task 9.3
Optimisation of process parameters and target development for SRF cavity coating with **A15 material**
6 GHz cavities

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
QPR and HWR

Task 9.1

Task Leaders: **Claire Antoine** *and* **Oleg B. Malyshev**

Coordination and Strategy for innovative SC accelerating cavities

WP9 Meetings every 3 months

On scopes:

- **Preparation of the ESPP R&D roadmap report:** ***done***
  - **implement our expertise in the organisation of future Intl thin film R&D**
- **Leading Implementation of TF SRF theme as a part RF Coordination Panel** **ongoing**
  - **aiming to gather all European TF activities together in a common project/collaboration**
- **Coordinating with DESY/CERN** **ongoing**
- **Coordinating with Thin films TTC group** **ongoing**
- **Snowmass letter of interest** **done**
- **Participating in in SRF 2023 Organising Committees** **done**

Organization of the 2024 Thin Film SRF workshop officially sponsored by IFAST (scientific committee + local organisation) **in progress**

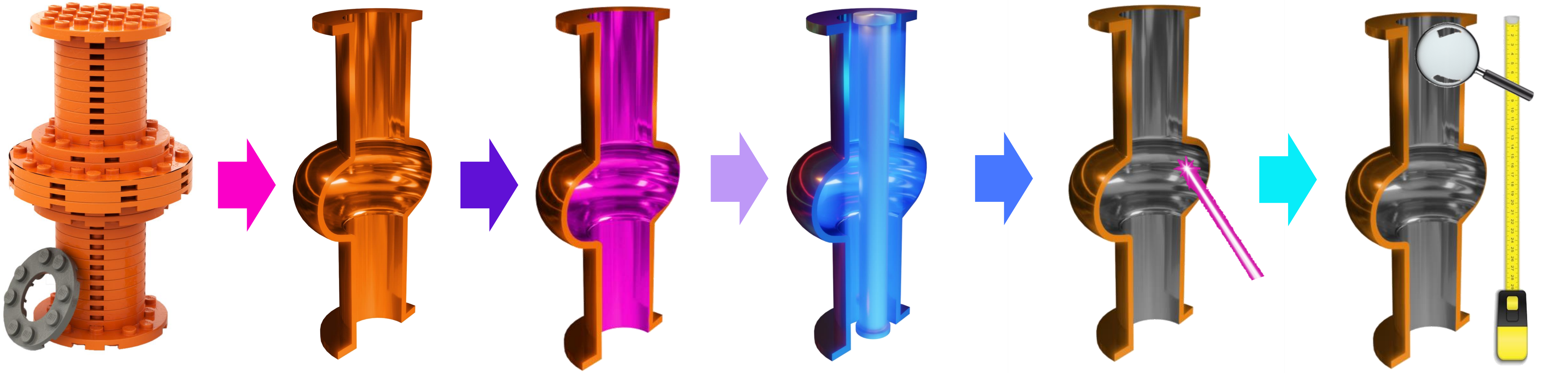
16–20 September 2024 - Université Paris-Saclay, France

Registration deadline is May 24, 2024

https://indico.cern.ch/event/1376902/

I.FAST WP9 R&D program
cover all the cavity production chain

Cavity Forming	Surface Polishing	layer by ALD	SC film coating	Post Treatments	SC property evaluation RF test



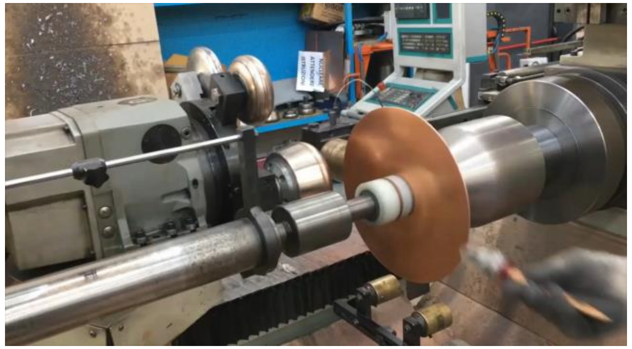
TASK 9.2	TASK 9.2	TASK 9.4	TASK 9.2 TASK 9.3	TASK 9.5	TASK 9.3 TASK 9.6

Cavity forming

Task 9.2
Task Leader: **Cristian Pira** INFN

Seamless Spinning

Forming technology adopted to produce 1.3 GHz (task 9.2) and
6 GHz (task 9.3) elliptical seamless Cu R&D substrates to all partners



PRIMARY GOAL:

High internal surface quality

OPTIMIZED PRODUCTION PROTOCOL:

- CNC machine
- Reduced Annealing Temperature (400 °C, previous 500 °C)
- New intermediate Deep Drawing Step

LAST YEAR RESULTS

- New design for dies
- Testing of new dies
- OFE Copper procurement finished
- Ready for 1.3 GHz production

New 1.3 GHz Die for Spinning produced by Piccoli

Cavity Forming

Surface Polishing

Task 9.2

Task Leader: **Cristian Pira** INFN

Methallographic Polishing

As received samples

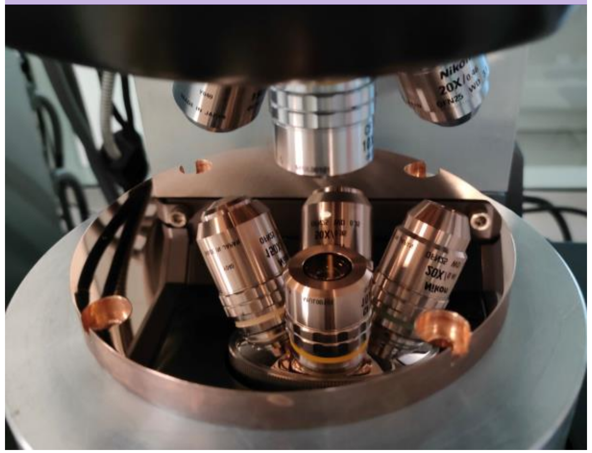
BCP

Machining

MP polished Nb QPR

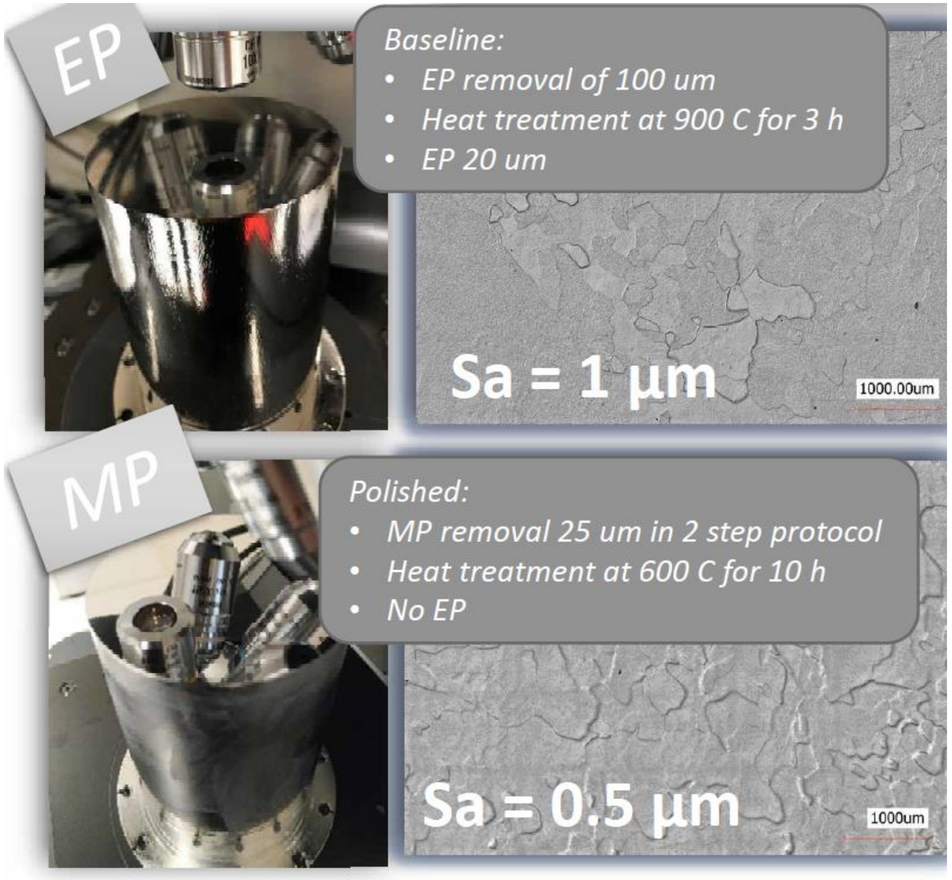
MP polished Nb RF disk

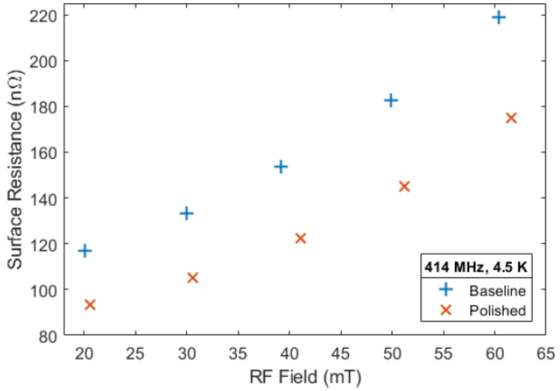
MP polished Cu RF disk

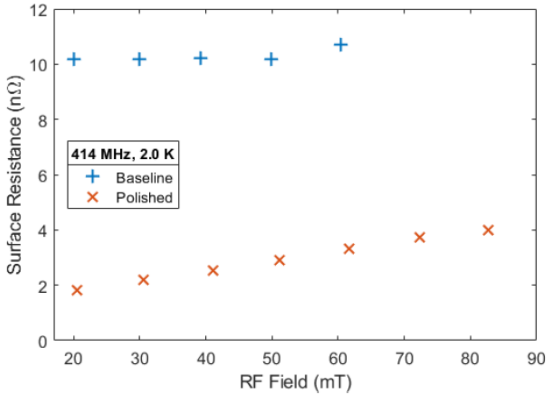


Courtesy of Oleksandr Hryhorenko, Claire Antoine and David Longuevergne

Methallographic Polishing







RF test on QPR done in the framework of

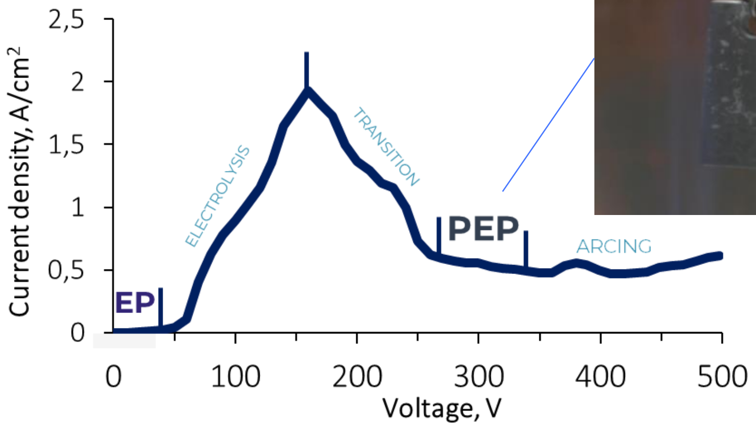
Task 9.5

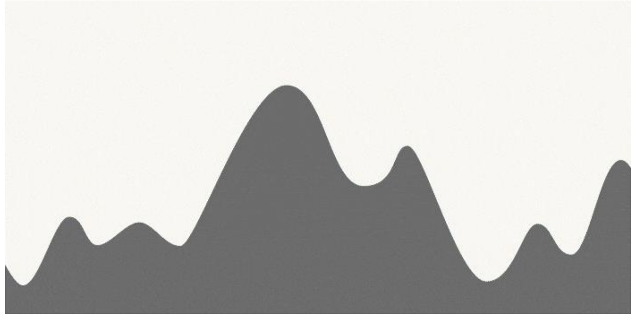
- Improved surface preparation pushed the RF fields above 80 mT
- Measurement of R_{res} resistance below 1 nOhm
- Reproducible results (x2 QPR so far)

Courtesy of O. Hryhorenko, C. Antoine, D. Longuevergne, O. Kugeler and S. Keckert

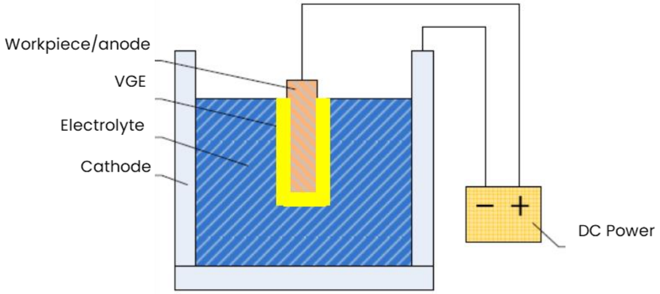
Plasma Electrolytic Polishing PEP

Mechanism



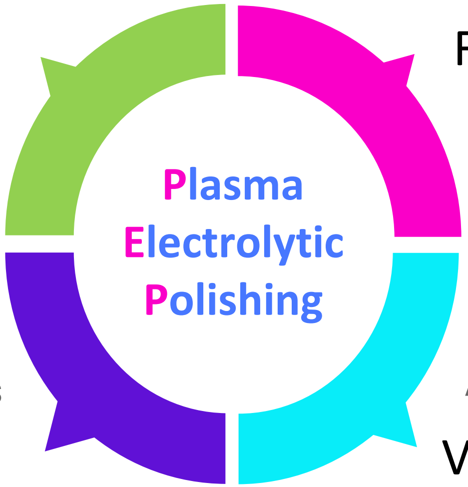


Same EP set-up
Different regime



J. Wang et al., AMR, 2012

Advantages



Green
Diluted water solutions, enviromentally friendly

Fast
The fastest non-destructive polishing

Efficiency
Equal thickness removal yield lowest roughness among competitors

Versatility
Less sensitive to the cathode shape!
AM compatible

Courtesy of E. Chyhyrynets

Plasma Electrolytic Polishing PEP

Results

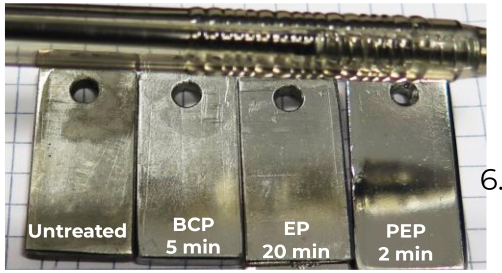
1x Nb 3x Cu
Solution Patentees by INFN

Additive Manufacturing (WP10)

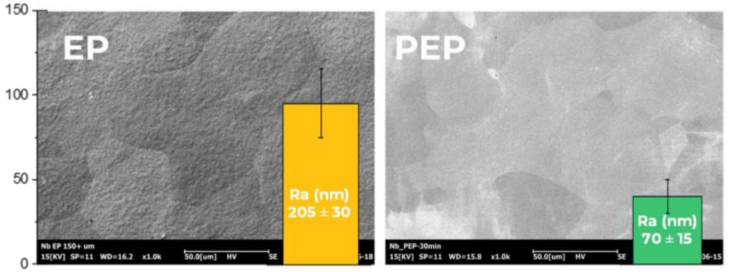
Initial
Ra= 13 μm

PEP 30 min
Ra= 1.5 μm

Planar samples



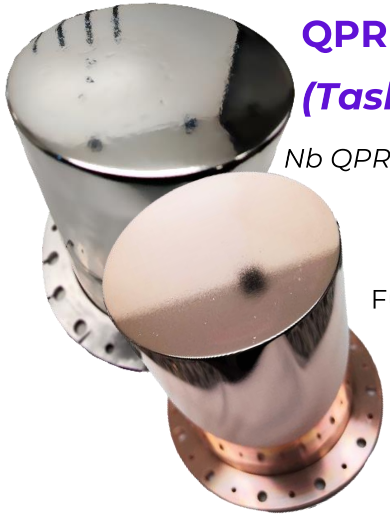
6.5 μm removed



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

QPR Samples (Task 9.5) HZB Helmholtz Zentrum Berlin

Nb QPR polishing optimizaztion on-going



Full Cu QPR ready for coating

Cu Photocatodes

Ra ~ 8 nm!!!

6 GHz Cu cavity

No internal cathode!
70 μm removed in 10 minutes
30 A (100 cm2 → 1.3 GHz ~ 300 A)

Courtesy of E. Chyhyrynets

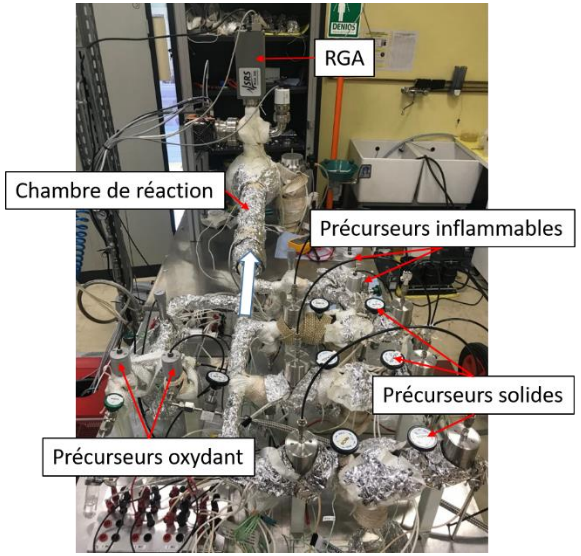
Surface Polishing

Atomic Layer Deposition

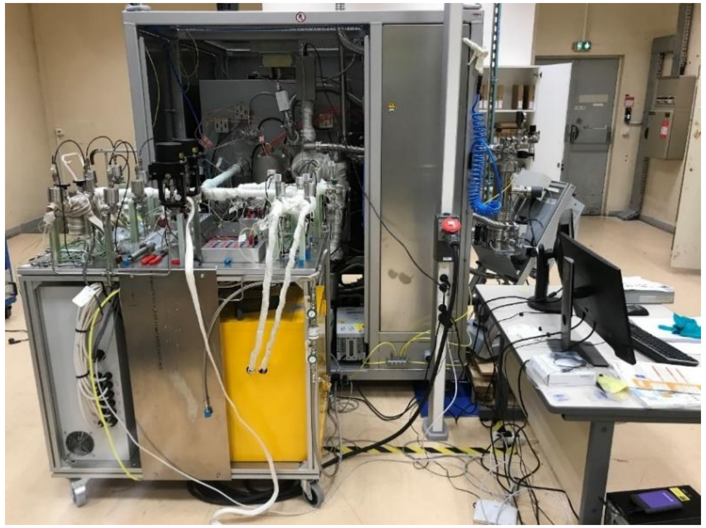
Task 9.4

Task Leader: **Thomas Proslier**

Atomic Layer Deposition Coatings



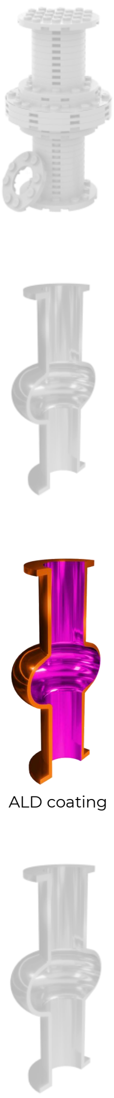
Atomic Layer Deposition Research Scale Reactor



Atomic Layer Deposition Development Scale Reactor

- *High vacuum oven ØxL: 50x110 cm.*
- *Temperature: 30-450°C*
- *8 precursor lines : 4 solids, 2 liquids, 2 gases.*
- *Chamber adaptation (cavités, QPR).*
- *In situ: RGA.*

- Engineering superconducting surface for **high Q operation** by Atomic Layer Deposition (**ALD**) and thermal treatments
- Engineering superconducting surface for **high gradient operation** by ALD and thermal treatments: Doping without chemistry and multilayers

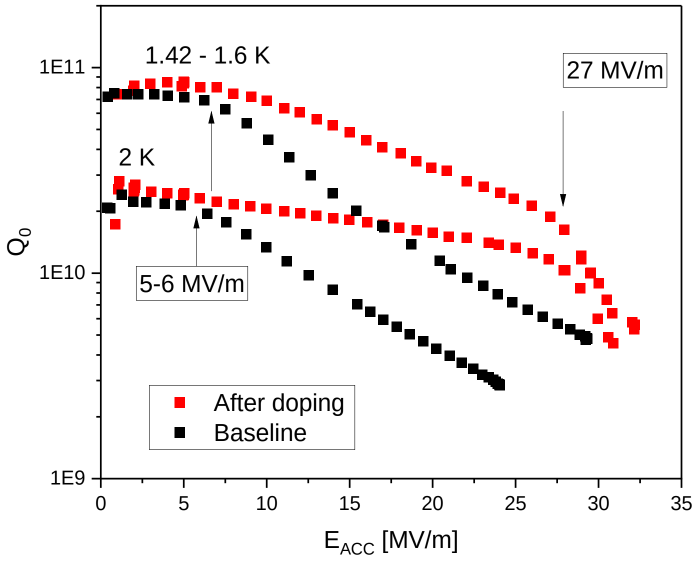


Courtesy of Y. Kalboussi, B. Delatte, C. Antoine, A. Four, F. Miserque, Y. Zheng, D. Hrabovsky, T. Junginger, N.Lochet , D.Bafia, L.Grasselino, T. Proslier

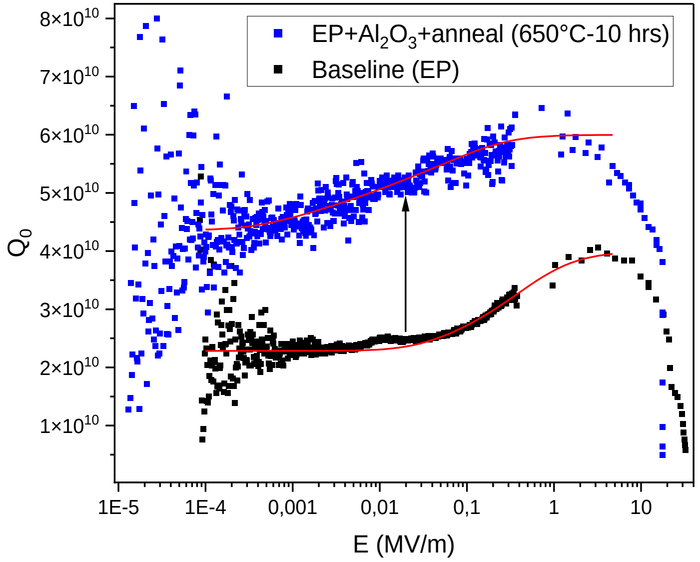
Atomic Layer Deposition Coatings

- ✓ **Increased Q at low field** **for 3D superconducting resonators 1,3 GHz.** Publication + patent
- ✓ **Increased penetration field** **on samples** by 24%. First depositions of multilayers in 1.3 GHz cavities
- ✓ **N doped cavity by ALD** **of NbN**. Optimization underway.
  First depositions of multilayers in 1.3 GHz cavities

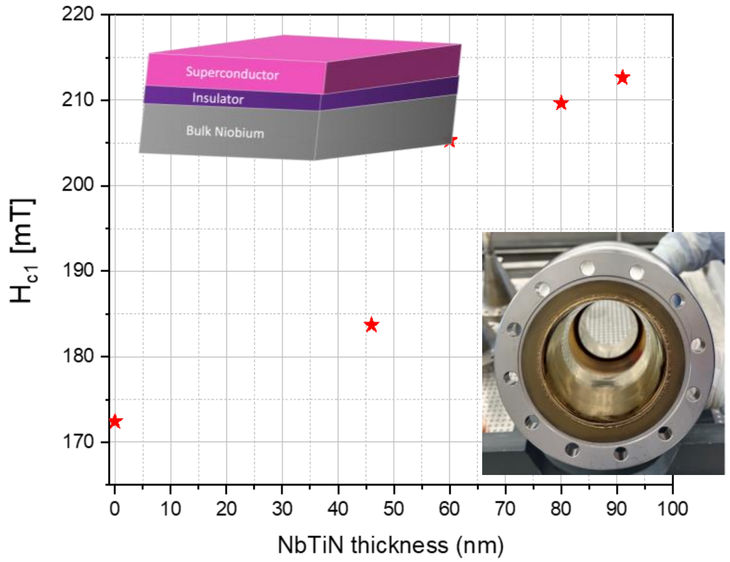
Doping by ALD: NbN (5nm) + thermal treatment

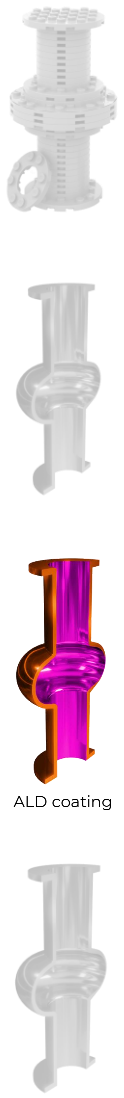


High Q studies for Qubits and accelerators

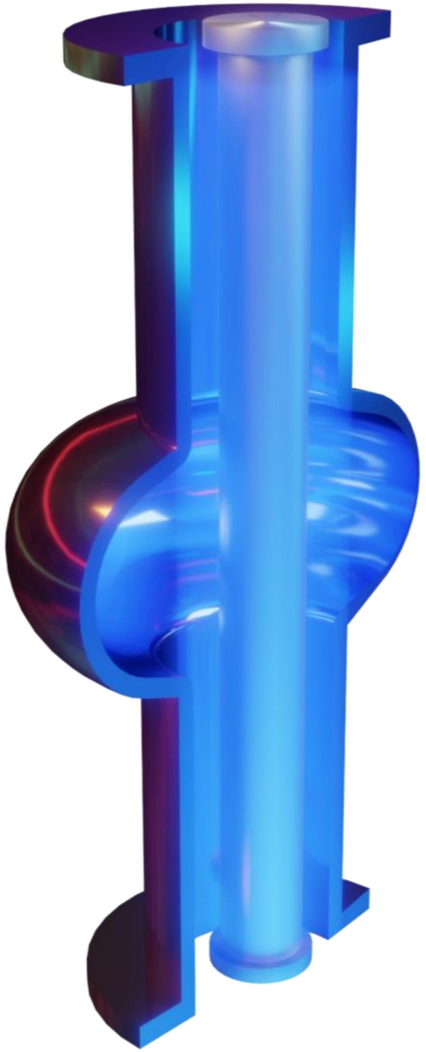


High Gradient for accelerators increased penetration field





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



SC Thin Film Development

Task 9.2
Task Leader: **Cristian Pira** INFN

Task 9.3
Task Leader: **Reza Valizadeh** UKRI Science and Technology Facilities Council

NbTiN Coatings

UNIVERSITÄT SIEGEN

LOT Lehrstuhl für Oberflächen- und Werkstofftechnologie

From **NbN** to **NbTiN** by HiPIMS

Goal: **SS or SIS structure** by PVD+ALD

NbTiN	S
DCMS-**AlN**	(I)
HiPIMS-**Nb**	S
Cu	

IOP Publishing — Supercond. Sci. Technol. 34 (2021) 025006 (12pp)

Superconductor Science and Technology — https://doi.org/10.1088/1361-6668/abc7

Superconducting NbN thin films for use in superconducting radio frequency cavities

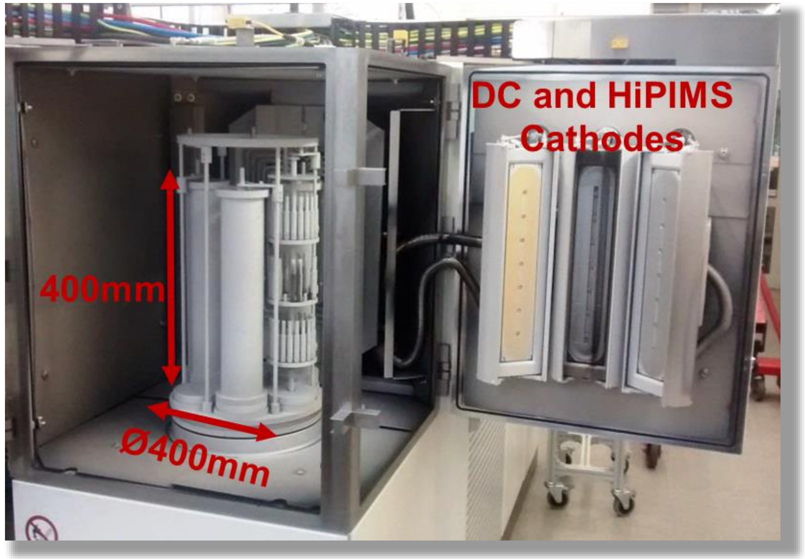
S Leith[1], M Vogel[1], J Fan[1], E Seiler[2], R Ries[2] and X Jiang[1]

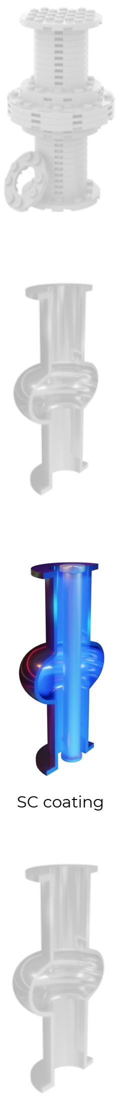
[1] Institute of Materials Engineering, University of Siegen, Siegen, Germany
[2] Institute of Electrical Engineering, SAS, Bratislava, Slovakia

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK016

HiPIMS-COATED NOVEL S(I)S MULTILAYERS FOR SRF CAVITIES

A.Ö. Sezgin[1], I. Gonzales Diaz-Palacio[3], X. Jiang[1], S. Keckert[4], J. Knobloch[4,5], O. Kugeler[4], R. Ries[2], E. Seiler[2], D. Tikhonov[4], M. Vogel[1], R. Zierold[3]





SC coating

Courtesy of A. Zubtsovskii

NbTiN Coatings
by DC/HiPIMS co-sputtering

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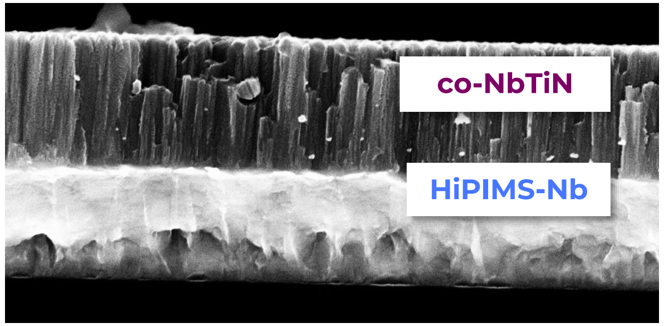
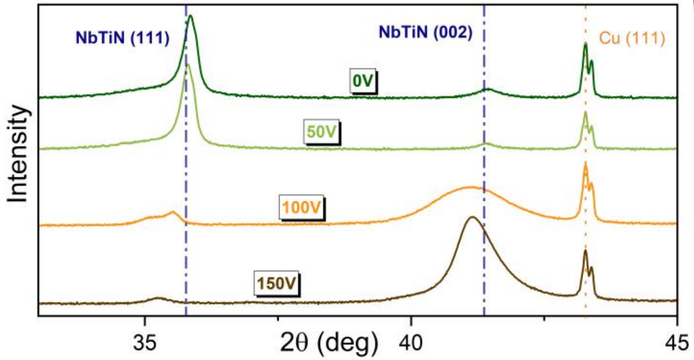
SS multilayer structure
co-NbTiN / HiPIMS-Nb / Cu



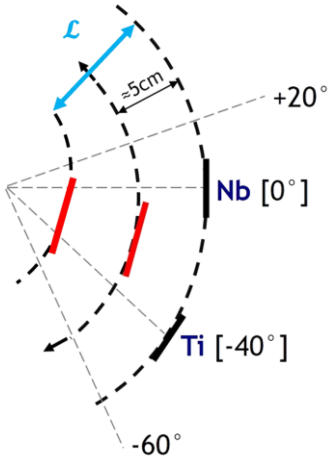
co-NbTiN:
Parameter Optimization:

Substrate bias:



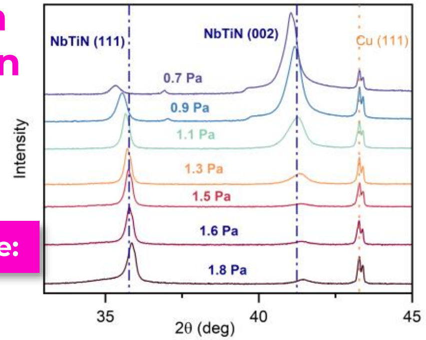
Deposition Angle (composition)

"$Nb_{0.73}Ti_{0.27}N$" at 1.3 Pa → Tc = 14.3 K
"$Nb_{0.82}Ti_{0.18}N$" at 1.1 Pa → Tc = 15.1 K

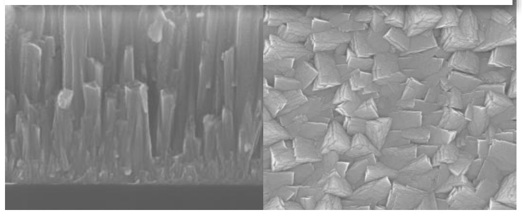


Deposition pressure:

Decreased pressure leads to film densification

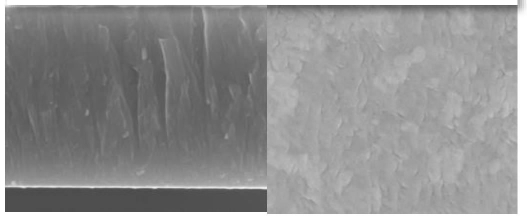


Deposition pressure: 1.8 Pa



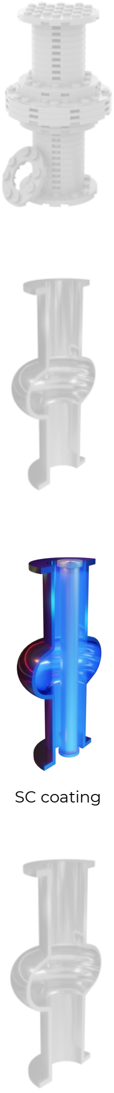
Pronounced columnar structure - Rough surface

Deposition pressure: 1.2 Pa



Nanocrystalline structure - Denser grain packing

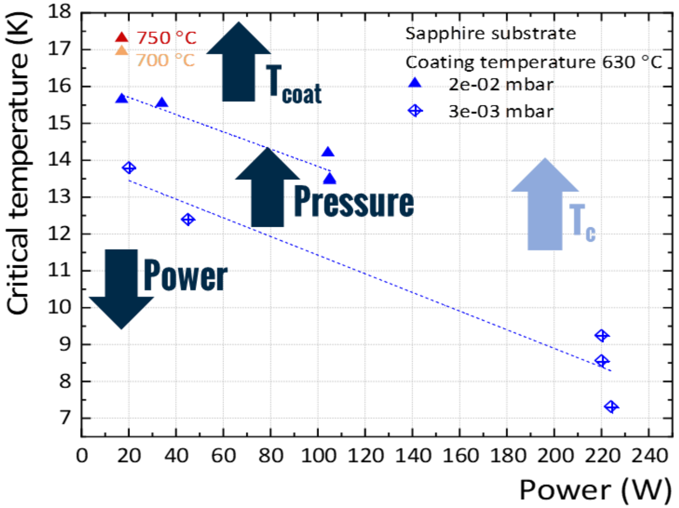
Courtesy of A. Zubtsovskii

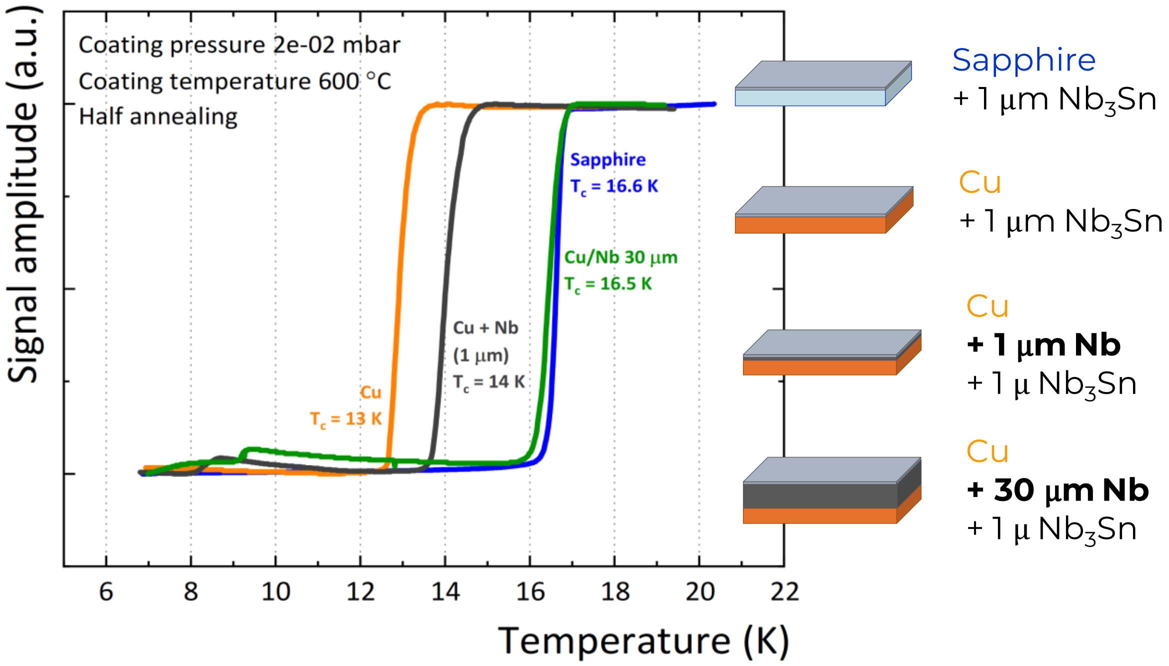


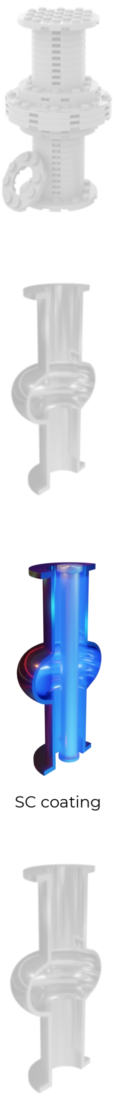
SC coating

Nb_3Sn Coatings

Long R&D phase on PVD Parameter Optimization







Optimized Coating Recipe

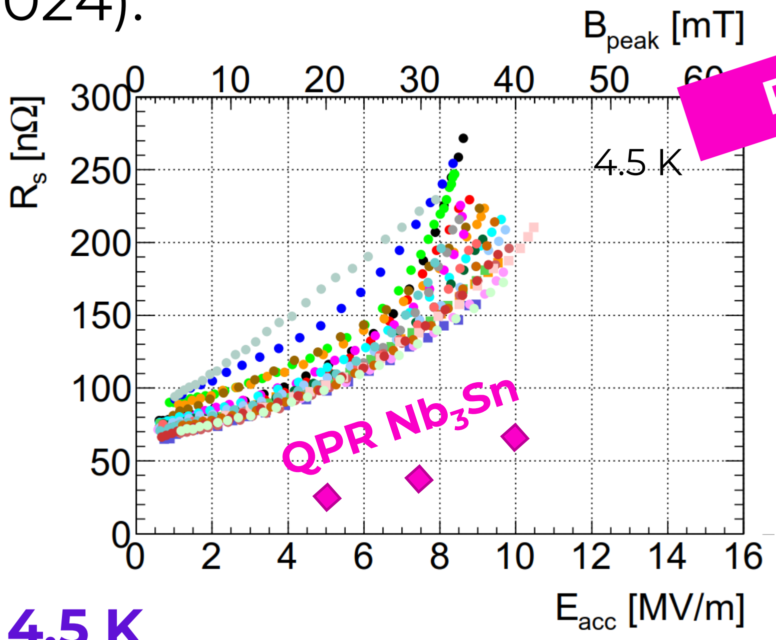
- Nb Thick Barrier Layer > 30 um
- Coating Parameters:
  - Pressure = $2*10^{-2}$ mbar
  - Power = 16 W
  - T substrate ≥ 600 C

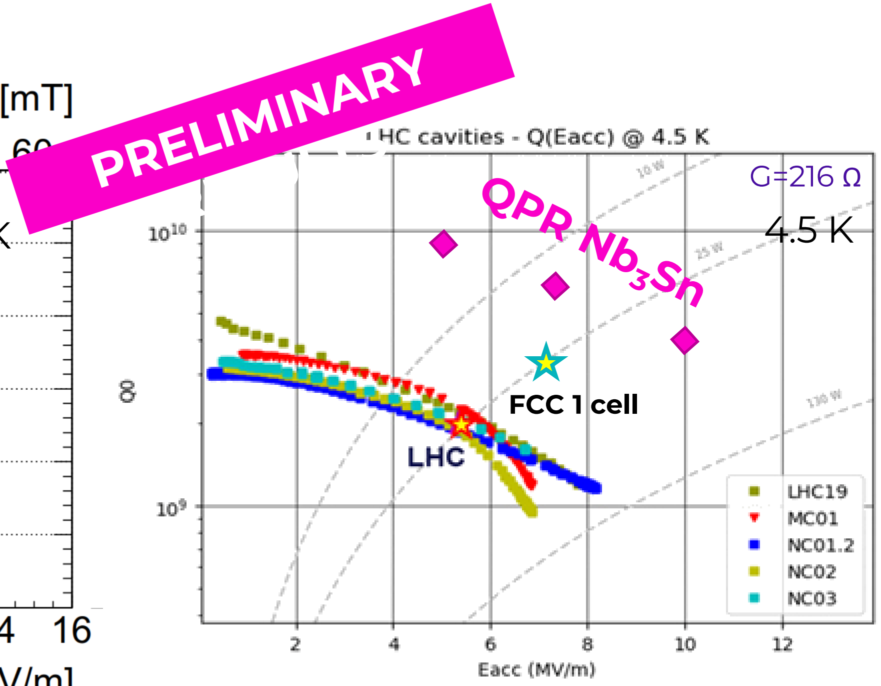
A thick Nb buffer layer accommodate the Nb_3Sn coating

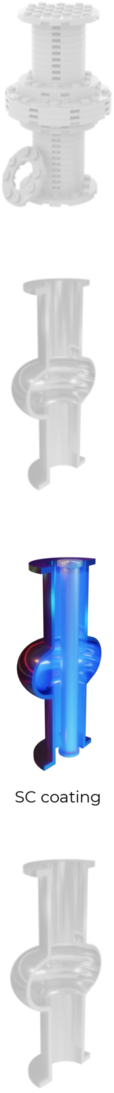
Coating performance validation on Nb substrate

Nb_3Sn Coatings

Last results (March 2024):







Rs of 23 nΩ @ 20 mT @ 4.5 K
Quench >70 mT @ 4.5 K

Data of LHC cavities from: W. Venturini, TTC Meeting 2018, Milan (Italy)

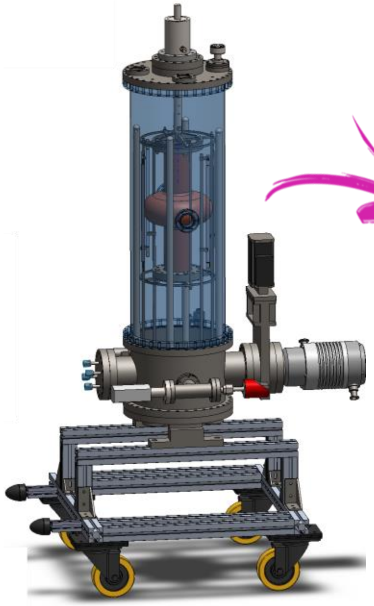
HZB Helmholtz Zentrum Berlin

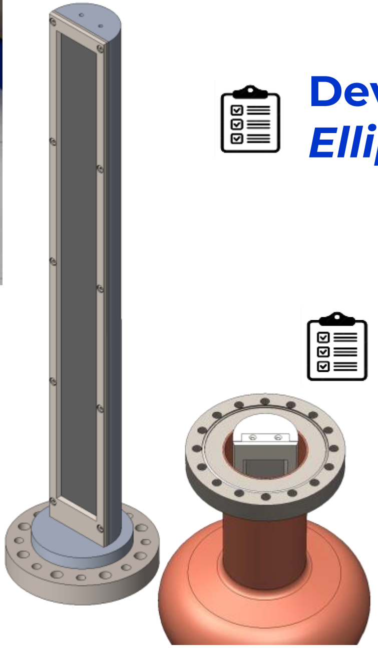
RF test on QPR done in the framework of
Task 9.5

Equivalent to a Q of $9*10^9$ @5 MV/m @4.5 K
Almost 1 order of magnitude better than LHC!!!
Room for improvement

Nb_3Sn Cathode and System Development

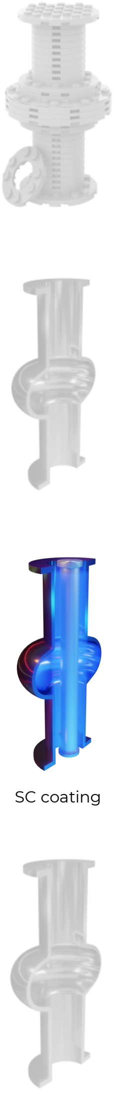
Path to final prototype





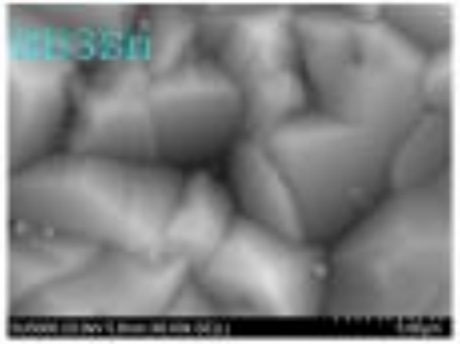
- **Nb_3Sn on bulk Nb to validate coating performances** ✓
- **Develop Nb thick coating *on 1.3 GHz Elliptical Cavities***
- **Nb_3Sn on Cu with thick Nb coating *on 1.3 GHz Elliptical Cavities***

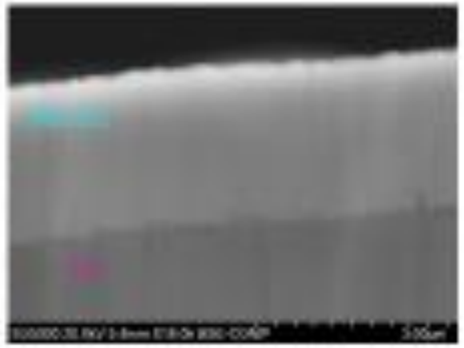
- **1.3 GHz Vacuum system ready**
- **Magnetron source commisioned**

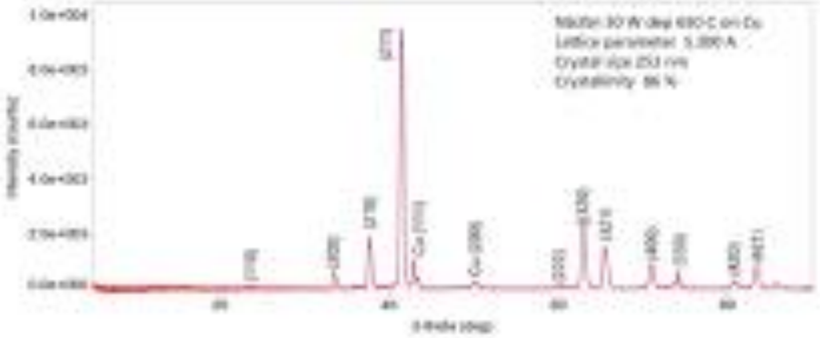


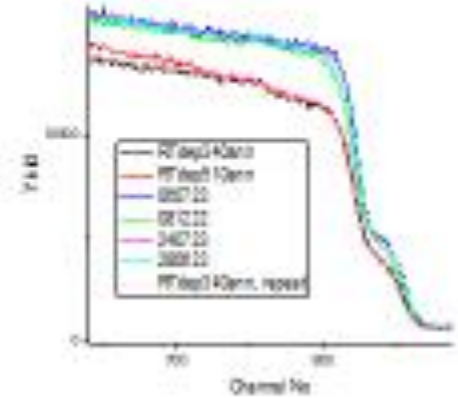
SC coating

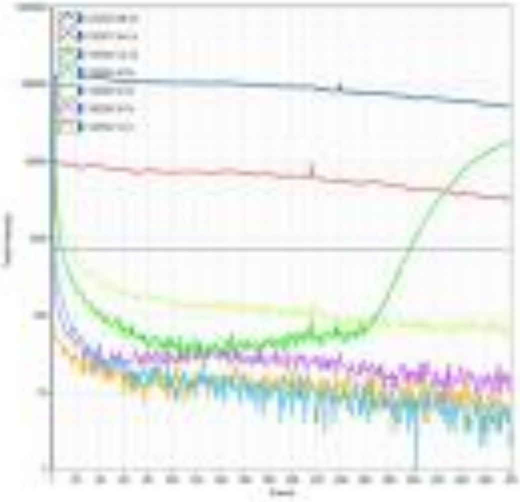
Nb_3Sn Coatings

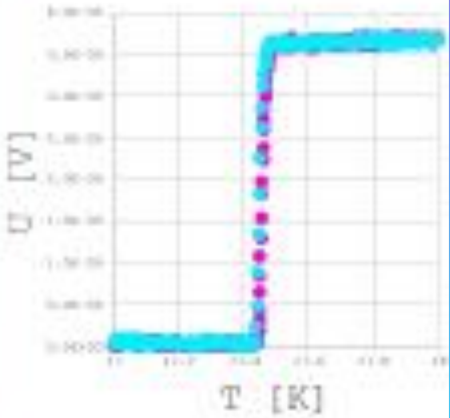


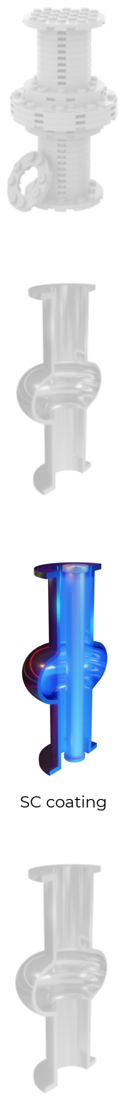








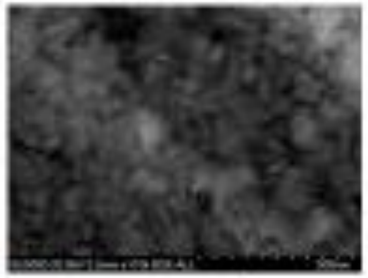




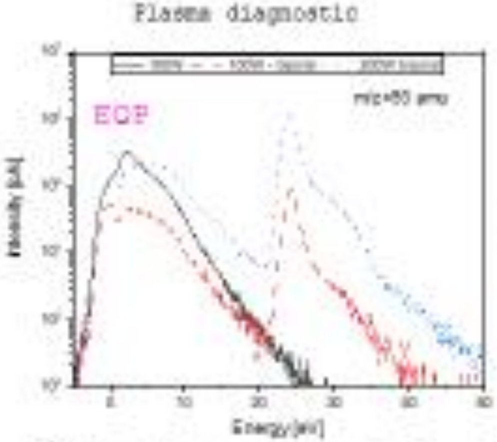
reza.valizadeh@stfc.ac.uk

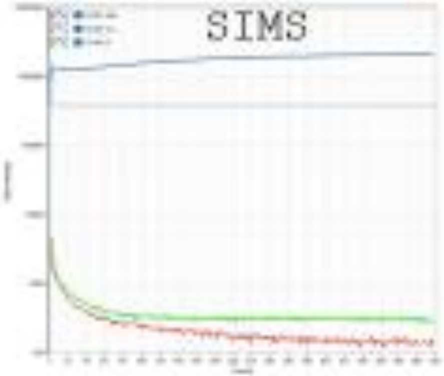
Cavity Coatings 1.3 GHz and 6 GHz

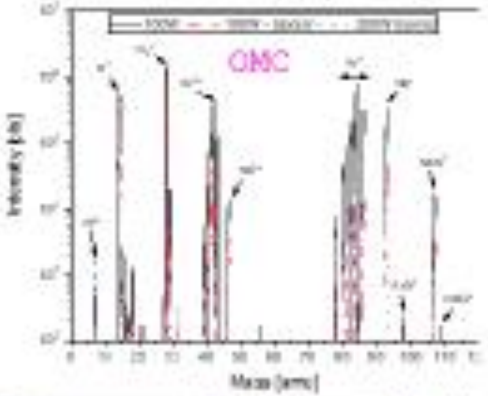
Science and Technology Facilities Council

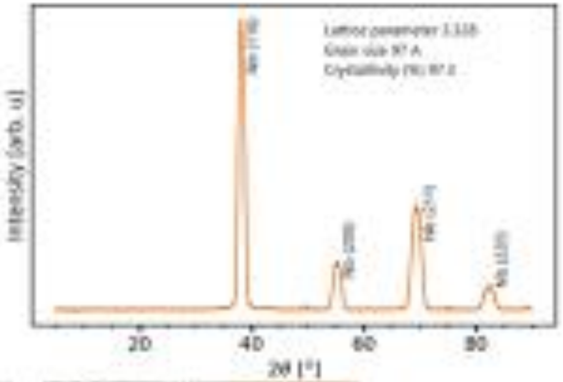


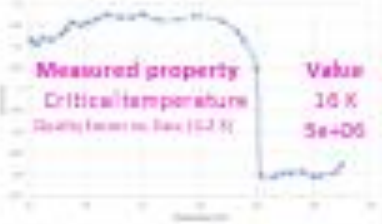
1.3 GHz Cavity deposition system

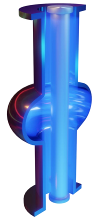








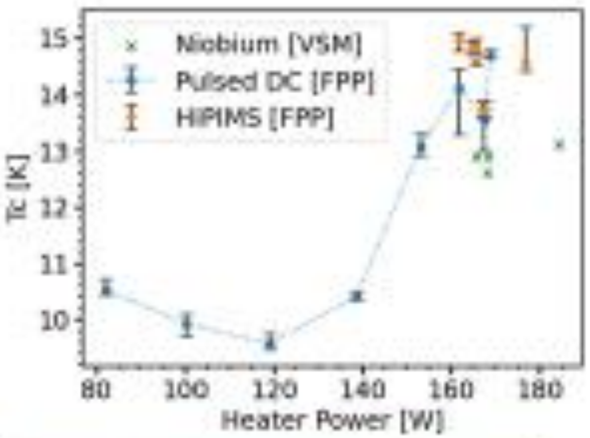


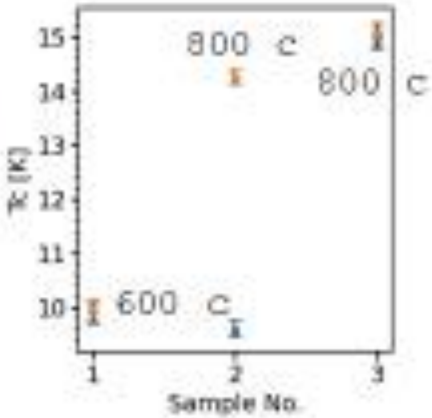


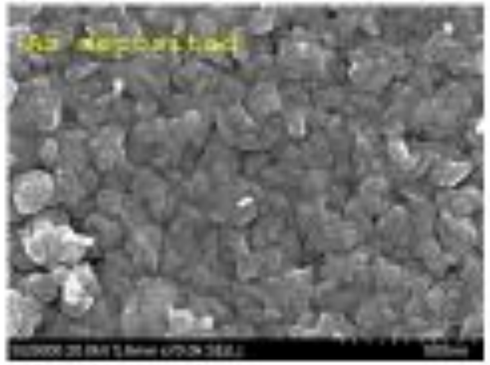
SC coating

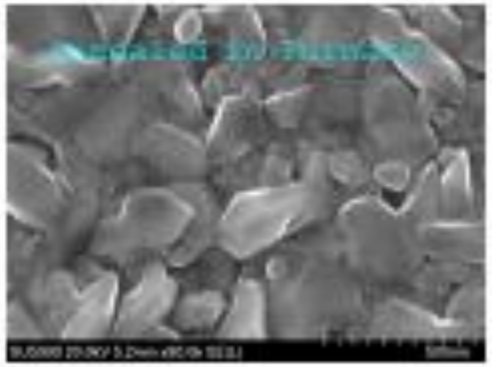
V_3Sn Coatings

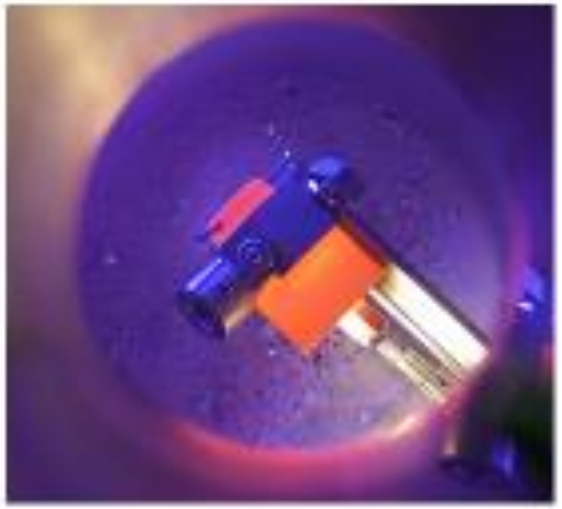
Science and Technology Facilities Council

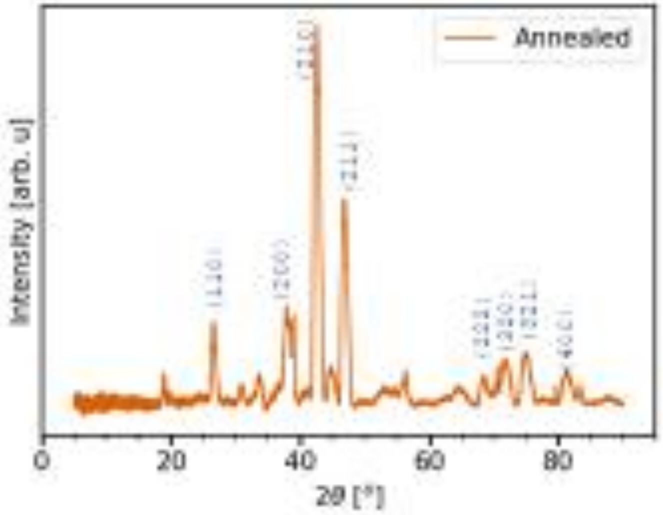


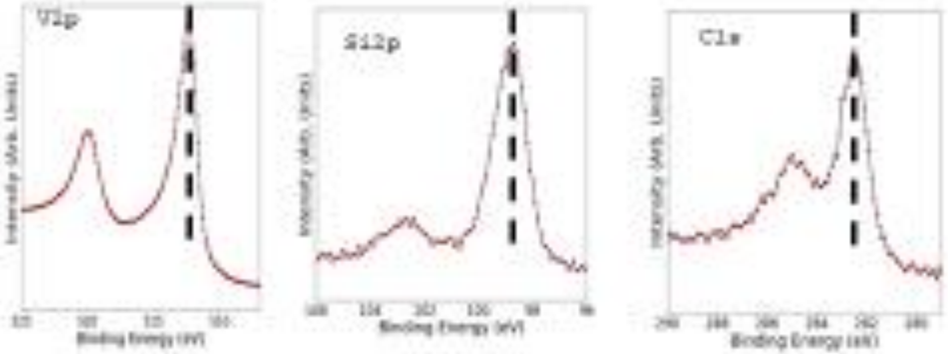




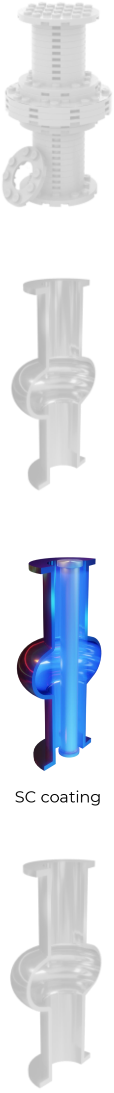


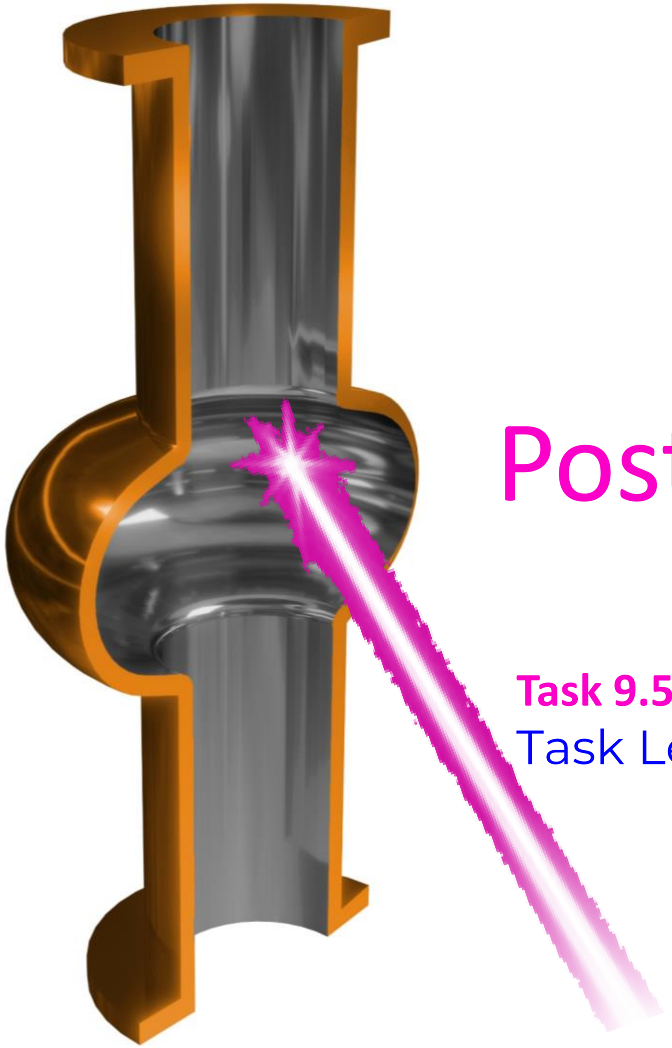






Oxygen present on the surface but not present after sputtering. Carbon present after sputtering.



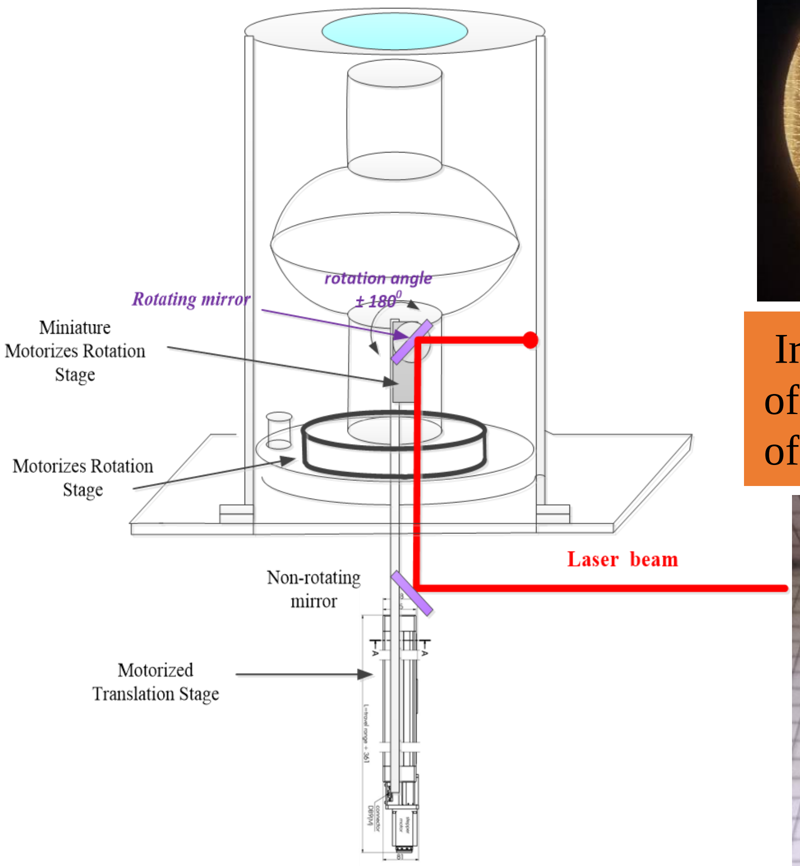


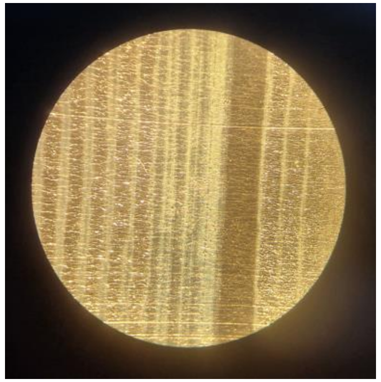
Post Processing

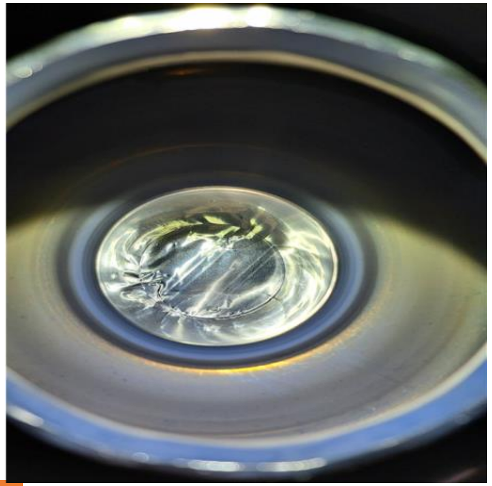
Task 9.5

Task Leader: **Arturs Medvids**

Laser Annealing

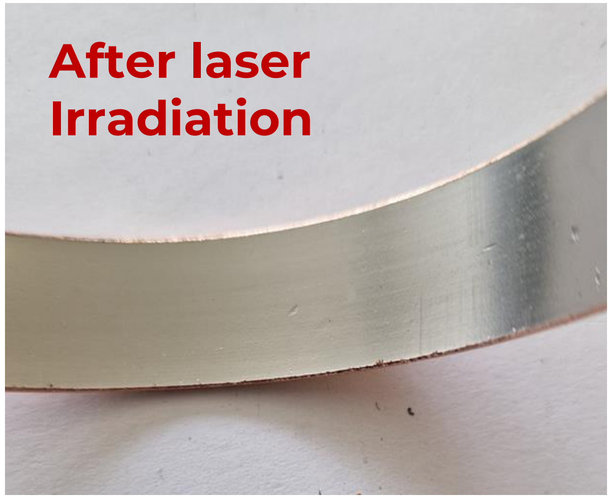






Irradaition lead to an increase of Nb hardness and a decrease of Cu hardness

1.3 GHz cavity prepared at INFN and Coated UKIR delivered to RTU



Courtesy of A. Medvids

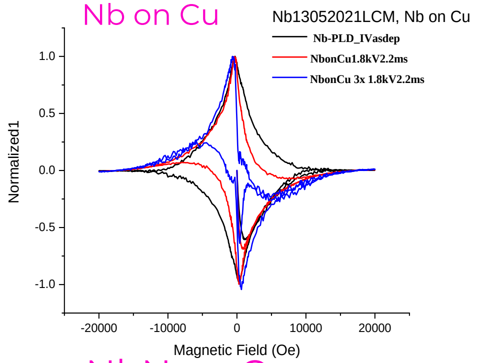
ms-Flash Lamp Annealing
(IFAST Innovation Fund Project)

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

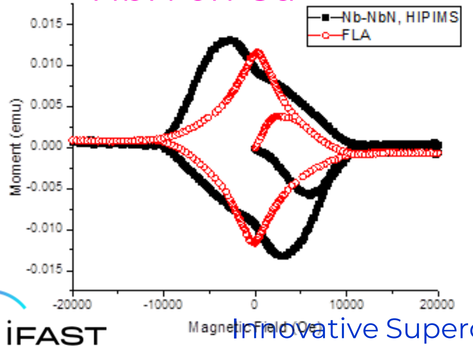
Material crystallinity improved
in all thin film superconductor tested

- On Nb and NbN coatings FLA produce a narrower hysteresis curve
- On Nb_3Sn coatings FLA improve lattice parameter (closer to bulk values)

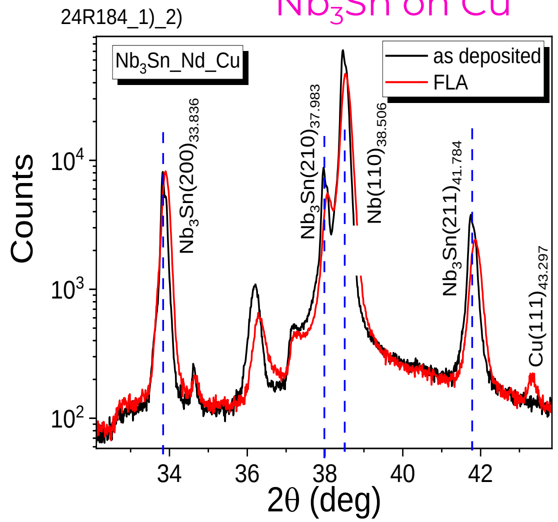
Nb on Cu



NbN on Cu

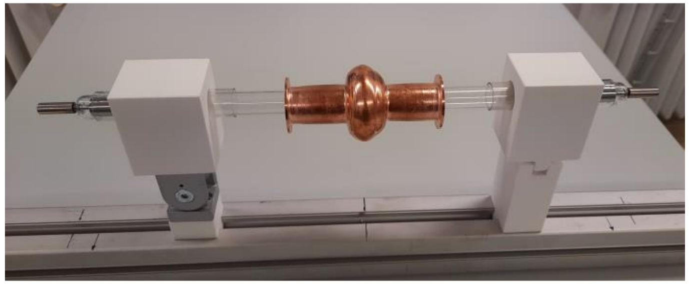


Nb_3Sn on Cu

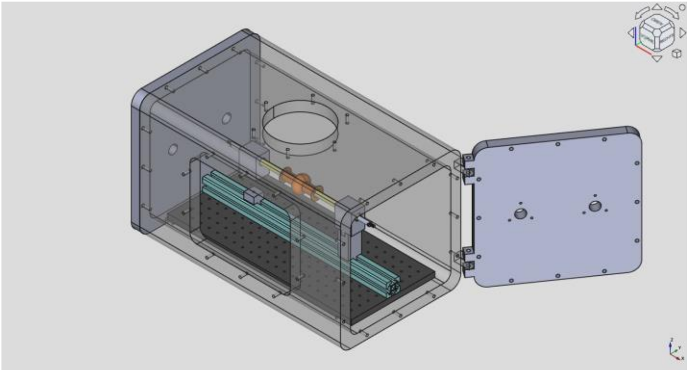


FLA system for 6 GHz cavities

- Holding System Ready
- Vacuum system commissioned



Holding system for the flash lamp and cavity



3D design of the complete system

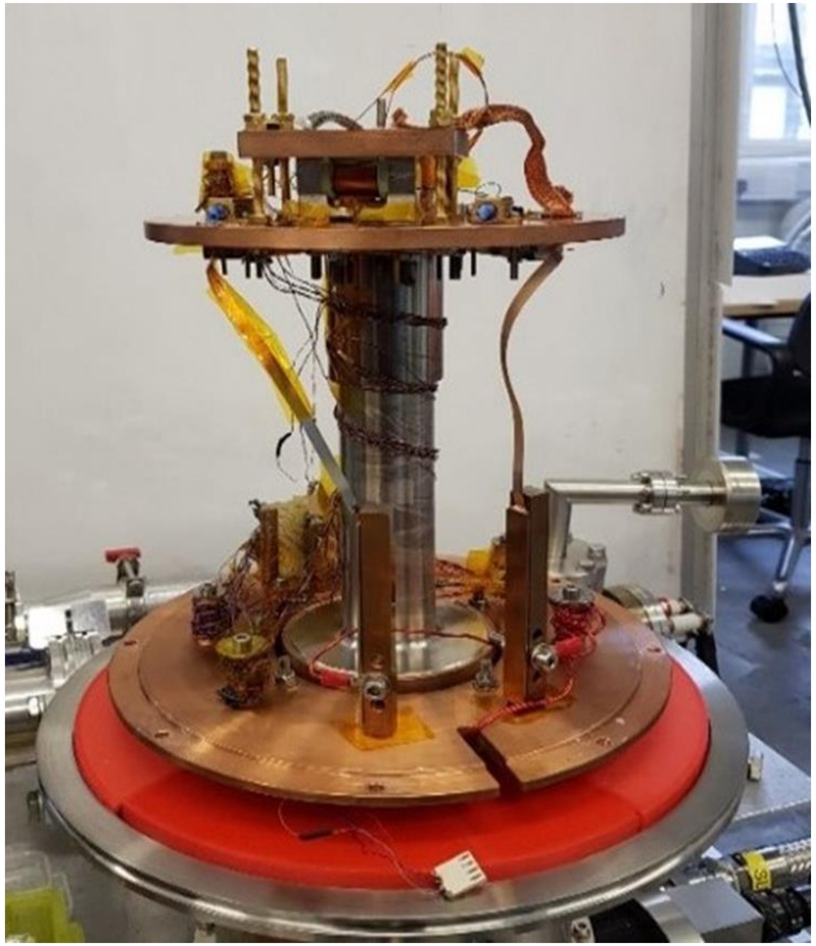
Courtesy of S. Prucnal and S. Zhou

SC Properties Evaluation

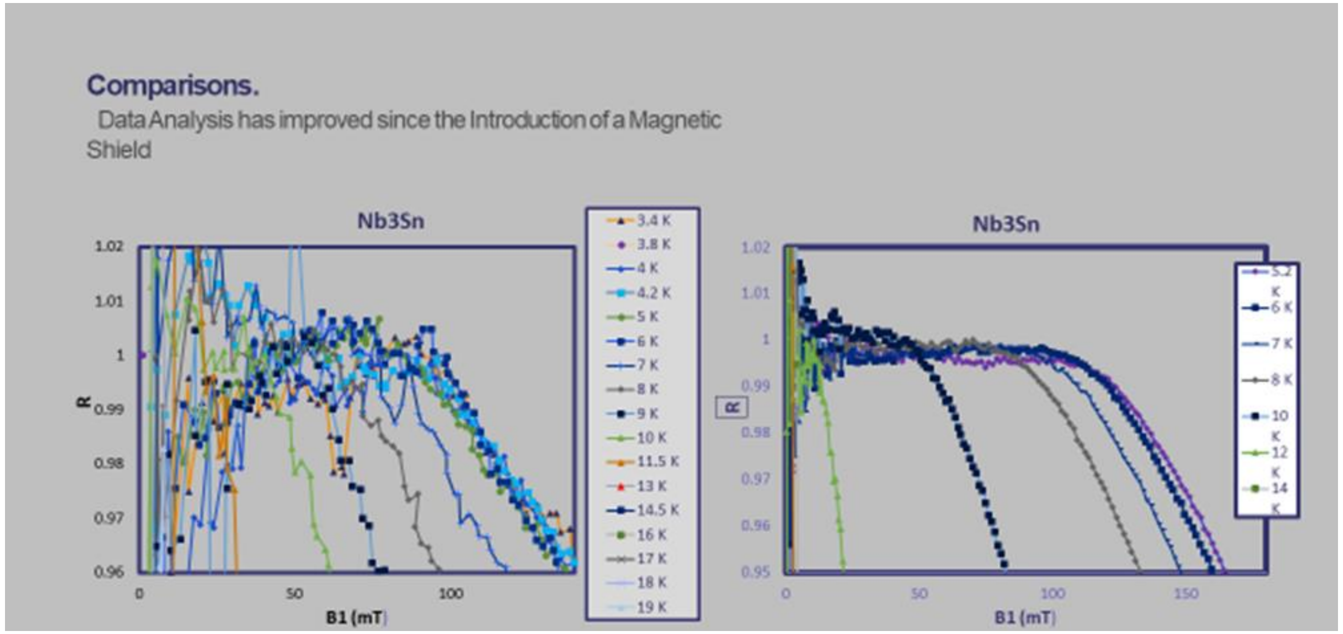
Task 9.3

Task Leader: **Reza Valizadeh** Science and Technology Facilities Council

Magnetic Field Penetration



- Larger sample up to 10 cm diameter can examined
- No indentation on the film in centre
- Magnetic shield made hudge improvement in result quality



Courtesy of L. Smith

DC/AC Superconducting Properties Evaluation

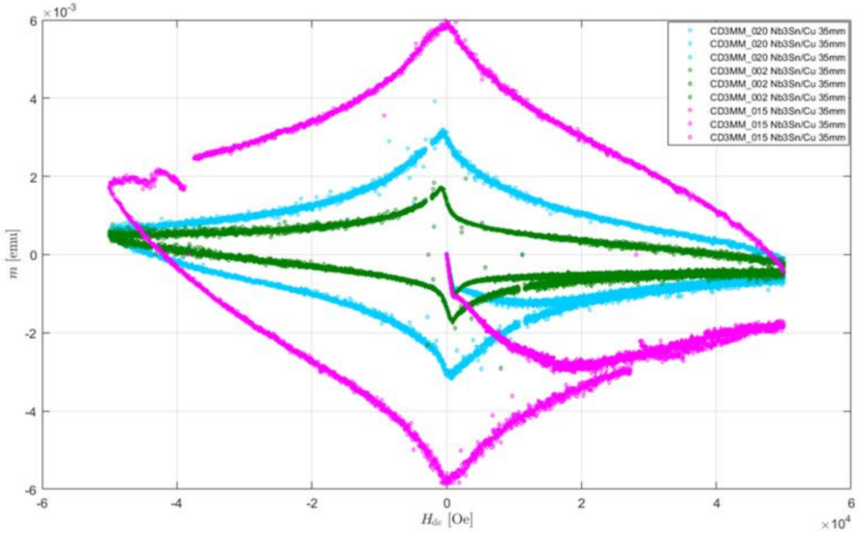
DC magnetisation measurements

Vibrating Sample Magnetometer

Small planar samples (~ 2x2 mm – *cutting*)

AC magnetisation measurements

- *Susceptibility – temperature scans*
- Tc of different films in Multilayer and SIS samples

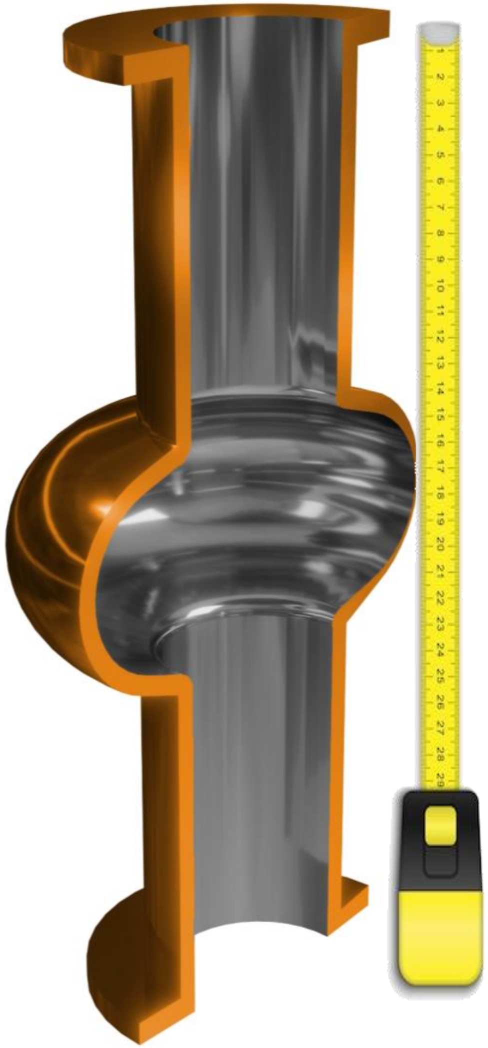


Nb3Sn Substrates: Cu, Sapphire STFC 1.12.2023 series Reza	Cu_28_06_23	160	17
	Cu_06_07_23	530	16.5
	Cu_24_07_23	350	17
	Cu_08_12_23	300	16.7
	Sapp_28_06_23	50	17.5
	Sapp_06_07_23	60	17.5
	Cu_RTdep_510C	430	14.7
	Sapp_24_07_23	930	17.5
	Cu_RTdep_340C	-	-
Nb3Sn Substrate: Cu 12.1.2024 series STFC D.Seal	Cu_CD3MM-020	610	16.8
	Cu_CD3MM-002	740	16.8
	Cu_CD3MM-015	580	16
Nb3Sn Substrate: Cu, Sapphire 8.2.2024 series INFN Dorothea Fonnesu	Cu_Run33	300	13.2
	Cu_Run33_50Nb	700	9.3 + 16.8
	Sapp_Run33	860	16.8

A quality control check for all the samples made within IFAST WP partners

Courtesy of L. Smith

SC Properties Evaluation

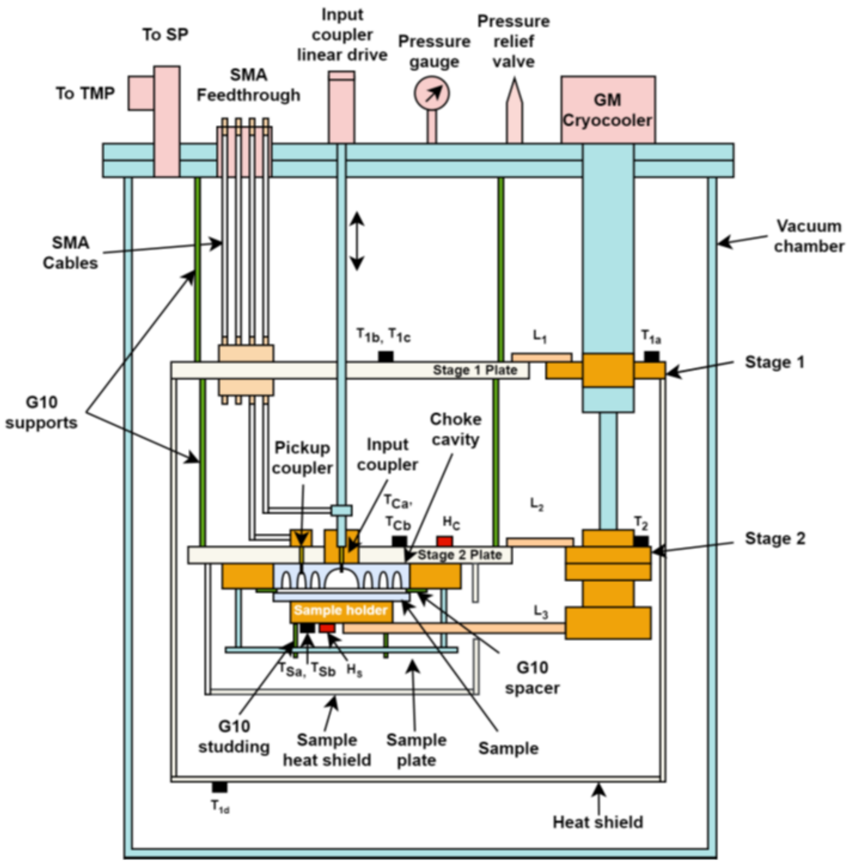


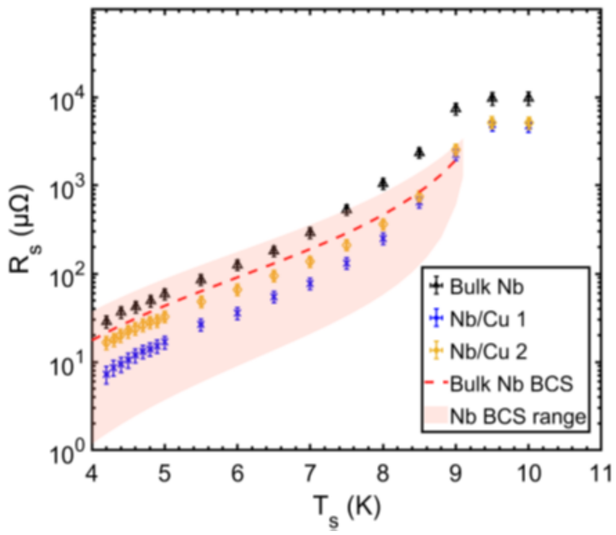
RF Measurements

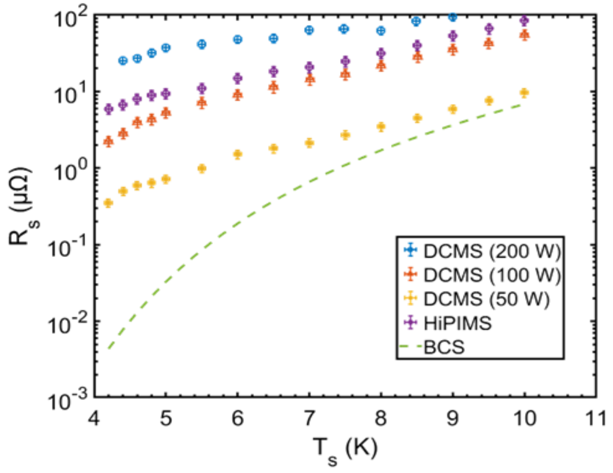
Task 9.6

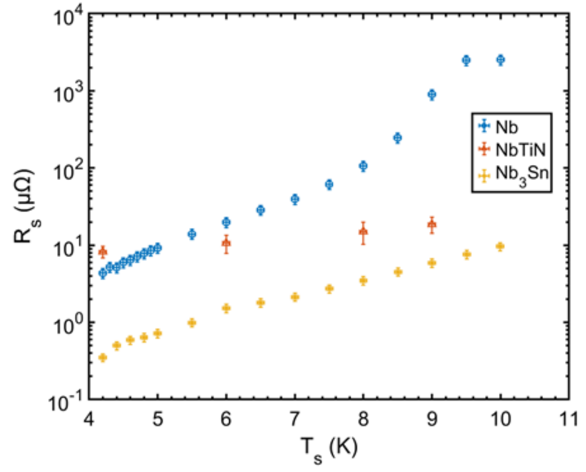
Task Leader: **Oliver Kugeler** HZB Helmholtz Zentrum Berlin

Sample RF test
with 7.8 GHz Choke cavity







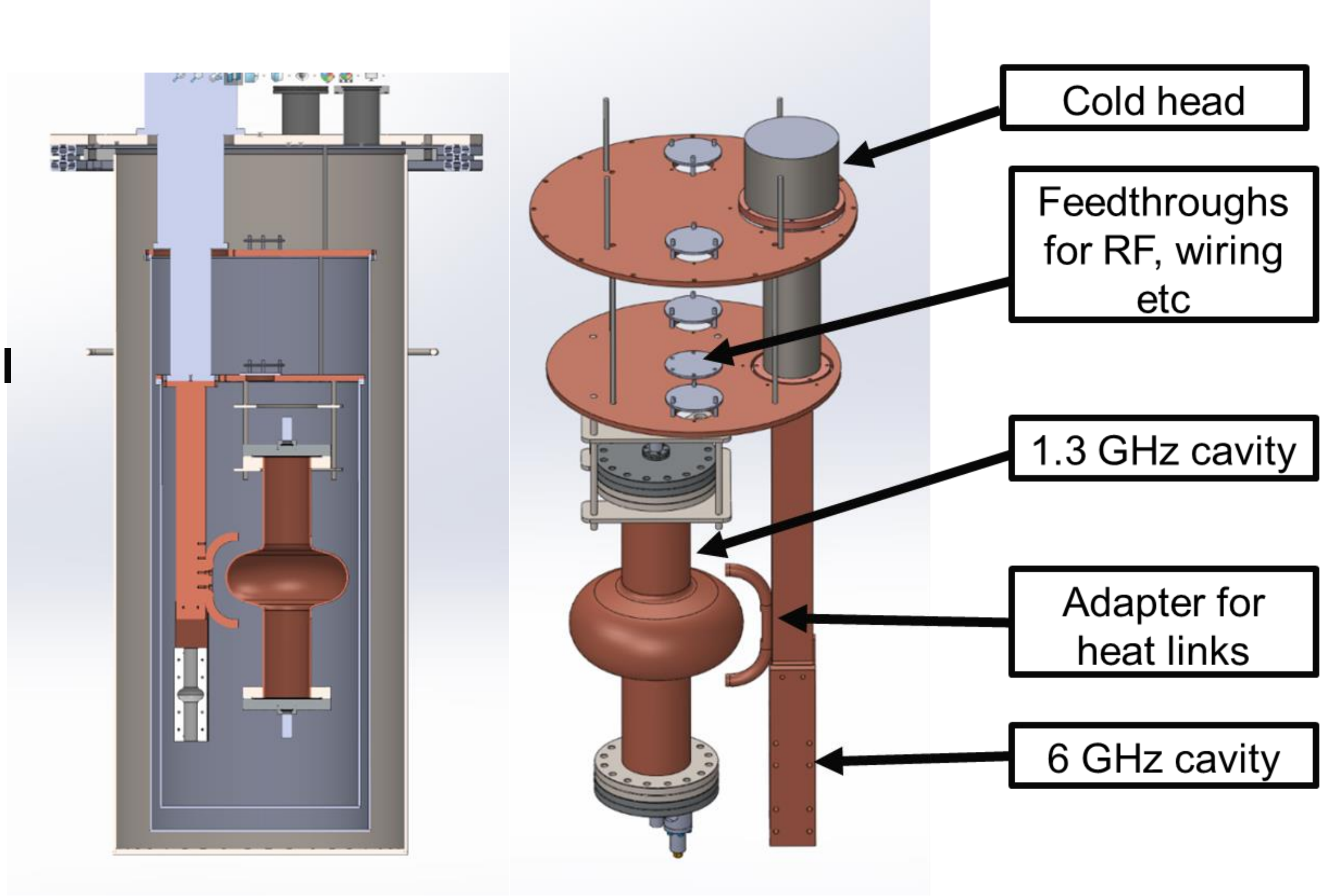


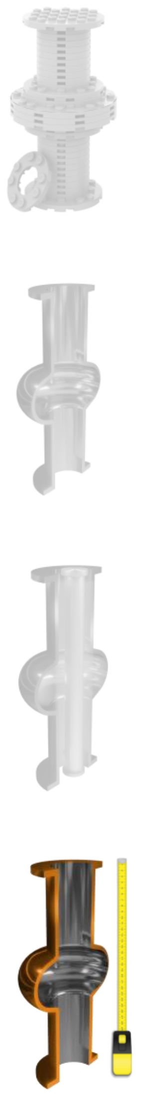
Courtesy of D. Seal

RF measurements

Low Power SRF Test

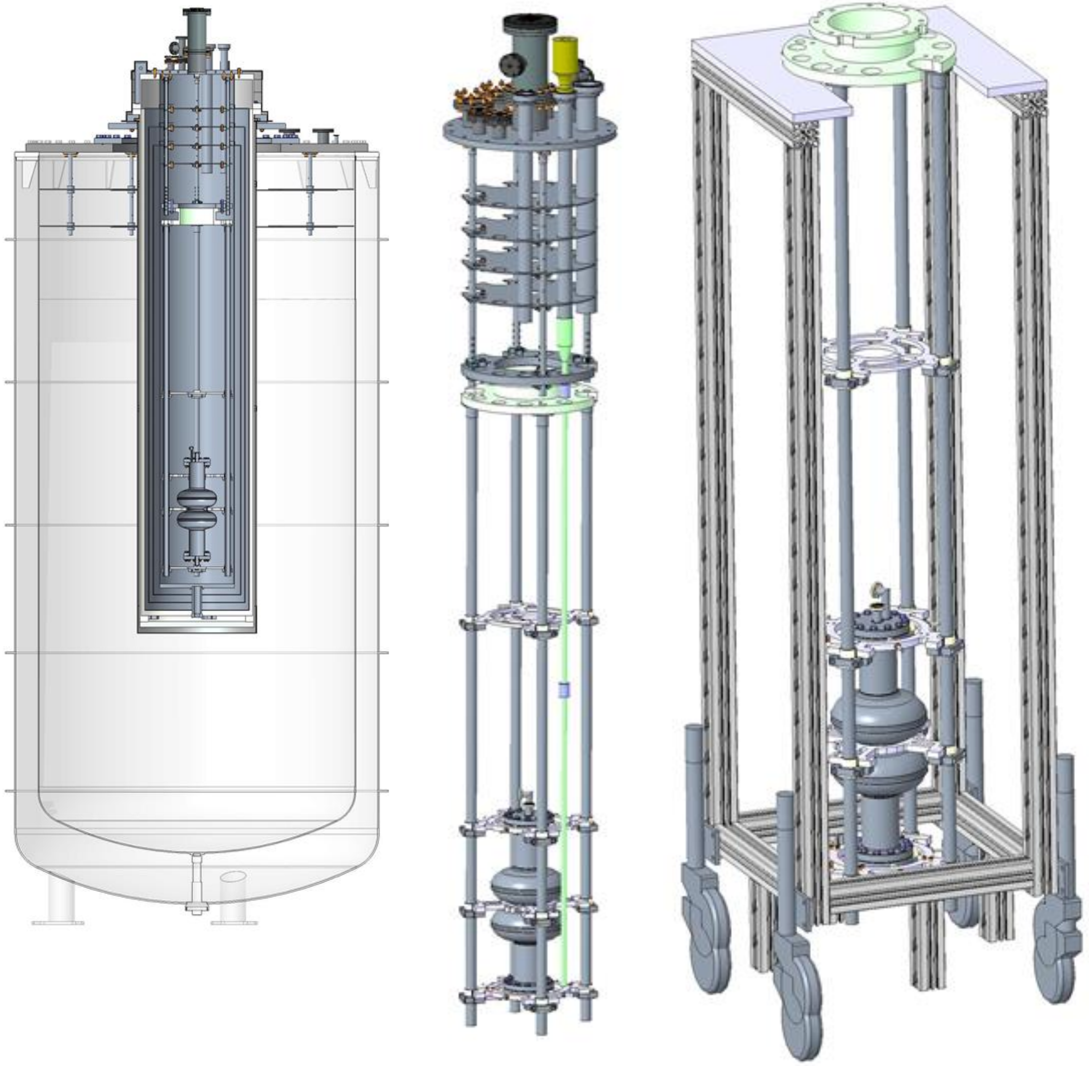
- **All main components manufactured and delivered**
- **Aim to begin vacuum & cryo tests by end of April**
- **RF System to be developed**
  A single system for 1 – 8 GHz
  New LU postdoc to be in charge of this from next week




RF measurements

1.3 GHz High power RF Facilities

- **Designs completed & in manufacturing stage**
- **RF System:**
  A single system for 650 MHz, 700 MHz and 1.3 GHz
  P ≤ 200 W
- **Aim to commission in June/July with 2-cell bulk Nb 1.3 GHz cavity previously tested at Fermilab**



RF measurements

WP9 Status

IFAST WP9 Milestones		
MS	**Description**	**Month**
37	International thin film workshop organisation in Sep. 2024 (web site + Report) (Postpone to data mistake in Grant Agreement)	28 ↓ **42** (Oct. 2024)
38	First seamless copper 1.3 GHz cavity produced as substrate for the coating of the SC film (Report)	12
39	Coating facility built and tested at STFC, USI and INFN (Report)	12
40	Construction and operation of the cavity dedicated ALD system (Report)	24
41	A facility for laser operation for complex 3D treatment is tested on 1.3 GHz cavity (Report) (Postpone to technical challenges)	36 ↓ **43** (Nov. 2024)
42	ARIES samples prepared for renewed SC film deposition (Report)	6

IFAST WP9 Deliverables		
D	**Description**	**Month**
9.1	Thin-Film SRF roadmap report. Summaries of the results obtained within the workpackage and prospective inspired from WP advances as well as discussions at TF-SRF 2022. (Postpone to data mistake in Grant Agreement)	35 ↓ **45** (Jan 2025)
9.2	RF test on coated resonant cavity. Resonant cavity coated and tested with an alternative material to Niobium with a $Q_0 > 10^9$ at 4.2 K and 1.3 GHz. (Postpone to technical challenges)	46 ↓ **48** (Jan 2025)
9.3	First 6 GHz cavity coated and characterised. Results from the morphological **and SC characterisation of first coated cavity** with an alternative material to Niobium. (Postpone to technical challenges)	36 ↓ **42** (Oct 2025)
9.4	Deposition of superconducting multilayers on cavities. 1.3 and 3 GHz Nb and Cu cavities coated and tested with multilayers.	46
9.5	1.3 GHz Nb-coated cavity irradiated by laser in Ar atmosphere and RF tested. Increasing of the field of magnetic flux entry in Nb coated 1.3 GHz cavity irradiated by laser in argon atmosphere. Standard RF testing	45
9.6	Test of thin-film samples. Four thin film samples reprocessed by 4 different techniques and tested with QPR.	46

WP9 Outputs in 2023

Disseminations

IPAC23

Plenary Talk
Claire Antoine - R&D in Superconducting RF: Thin Film Capabilities as a Game Changer for Future Sustainability

Posters from partners

SRF 2023 GRAND RAPIDS

Plenary Talks
Cristian Pira – Progress in European thin film activities
Oleksandr Hryhorenko - Recent advances on metallographic polishing for SRF application
Yasmine Kalboussi - Surface Engineering by ALD for Superconducting RF Cavities **(Early Career Inv. Award Winner)**

Posters from partners
Daniel Seal "Optimisation Of Niobium Thin Film Deposition Parameters For SRF Cavities **(3rd prize Best Student Poster)**

Various Workshop and Seminar Talks

Publications

2 Publications in International Journals

More than 20 conference proceedings

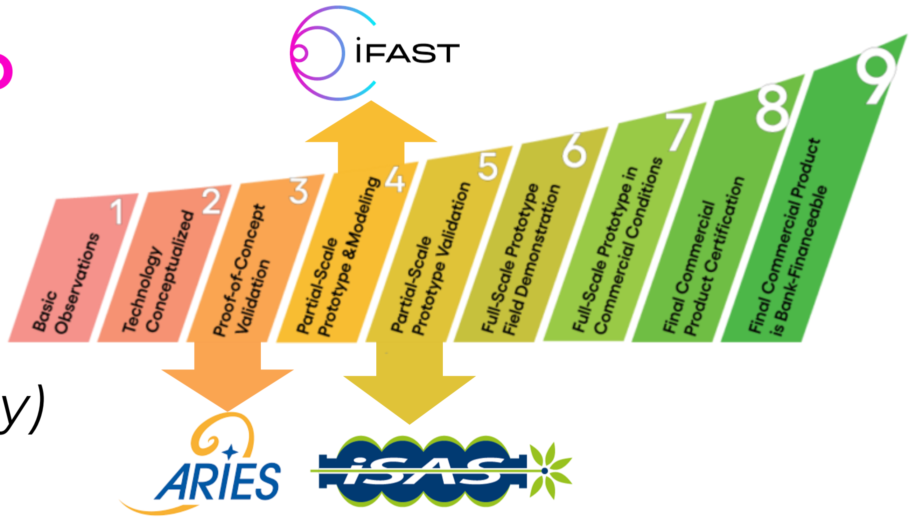
Conclusions

- **On track** with Deliverables and Milestones
  (minor delays due to technical challenges)

- WP9 Collaboration Team demonstrate:
  - **Optimum partners collaboration** within each task and between the tasks
  - **Collaboration extended** to new partners (HZDR, CERN, DESY)

- **Creating new opportunities to continue the R&D** on thin film cavities and move it to **higher TRL**

- **Strongly potential interest of industry** on Nb_3Sn for SRF
  (see Michael Pekeler's presentation on Wednesday)



2024 Thin Film SRF workshop, 16–20 September 2024, Paris

https://indico.cern.ch/event/1376902/

iFAST

WP9 Innovative Superconducting Thin Film Coated Cavities

Thank you!

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.