Final IFAST meeting
21-22/10/2025

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WP9 coordinators

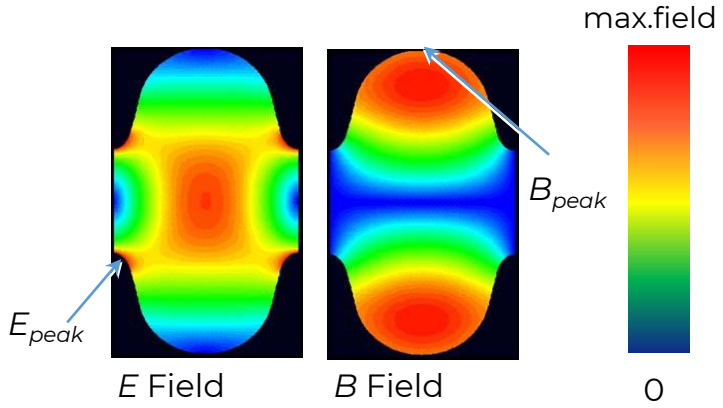
on behalf of WP9 team

Introduction

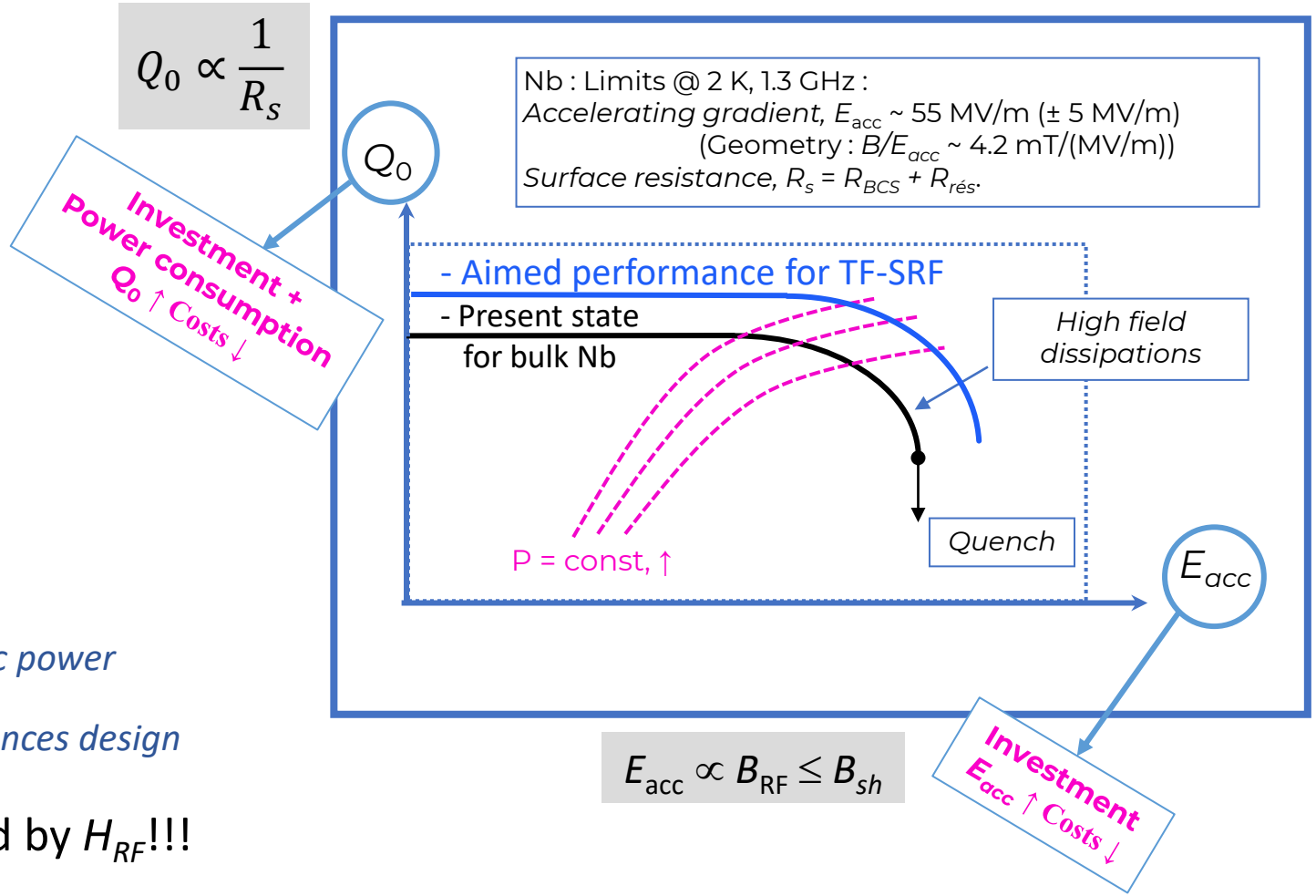
Recalls on SRF cavities

From Bulk Nb to Thin-Film coated RF cavities

- Nb/Cu applications at low accelerating field only until recently



- Figures of merit:
  - $E_{acc} \propto H_{RF}$ *limitation = magnetic transition*
  - $Q_0 \propto 1/R_S$ *limitation = thermal transition*
  - Duty cycle (=> 100%): *limitation = cryogenic power*
  - $\beta = \frac{v}{c}$ (particle speed /light speed): *influences design*
- At $f < 3$ GHz: cavities are mainly limited by H_{RF}!!!

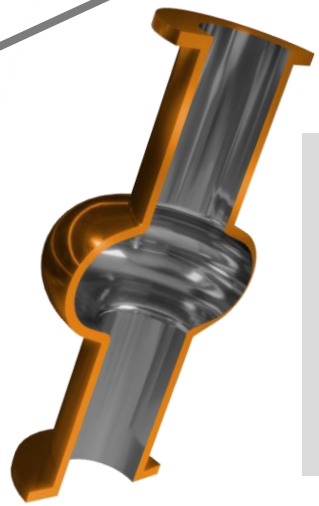


Superconductors for TF-SRF

Material	T_C (K)	$\mu_0 H_{SH}$ (mT)@ 0 K
Pb	7,1	100
Nb	9,2	219
NbN	**17,1**	**214**
NbTiN	**17.3**	**214**
V_3Si	**17.0**	**490**
Nb_3Sn	**18.3**	**425**
Nb_3Al	18.5-19.1	
MgB_2	39.0	170,0

High B_{sh} → High E_{acc} → fewer cavities → shorter accelerating tunnel

↓ Infrastructure cost



Why thin film on copper?

- Cheaper than Nb
- Higher thermal conductivity
- Easily machinable

High T_c → High Q_0 → less cooling

↓ Cryogenic operation cost

Best alternative: Nb_3Sn/Nb from Sn vapour diffusion – Q_0 ~ 10^{10}, E_{acc} ~ 20 MV/m at T = 4.2 K instead of 2 K

↓ Cryogenic infrastructure and operation cost

What past has taught us ?

- Huge number of parameter have to be explored
  - Not achievable without cooperation and work sharing
  - Still relatively few research teams and limited resources
- Paramount importance of substrate quality (pre/post treatments)
  - We knew it, but there is still room for improvement
- Thick and thin films are very sensitive to crystalline defects, but not all defects are troublesome.
  - Need for characterisation: structural, superconducting, RF.
  - For now, still no overlapping with techniques =>
    - predictions are difficult, R&D required

IFAST WP9

WP9 objectives

- Define a strategy for innovative superconducting RF (SRF) cavities coated with a superconducting film.
  - Deposition techniques: PVD and ALD
  - Superconducting films: Nb, NbN, Nb_3Sn, V_3Si (and others) and SIS
  - Optimization of flat SRF thin films production procedure
- Optimise and industrialise the production of seamless copper cavities and of the deposition techniques.
- Produce and test prototypes of SRF (single-cell elliptical) cavities:
  - Initially with pre-prototypes with f = 6 GHz
  - Scaling up for f = 1.3 GHz.
- Produce and test a new laser treated of Nb coated RF cavity.

➢ **Main goal**:

- Improving the performance and reducing the cost of acceleration systems
  - both production and operation

I.FAST WP9

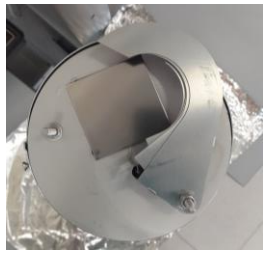
Surface preparation
- Cleaning, etching,
- Polishing, passivating

Cu sample polishing

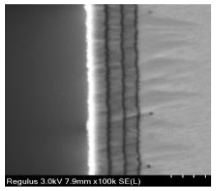
Thin film deposition
- **PVD**: DC, pulsed, HIPIMS…
- (PE)CVD, (PE)ALD
- **Nb, NbN, Nb_3Sn**, MgB_2, etc.
- FLA and Laser treatment of Nb films

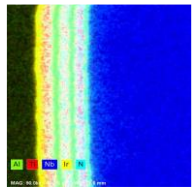
Film characterisation
- SEM, FIB, AFM,
- XPS, XRD, RBS, TEM…

Film deposition



SEM and EDS images of SIS film

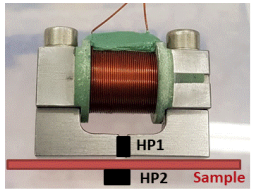


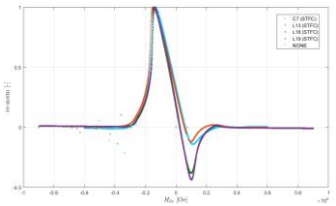


Superconducting properties measurement

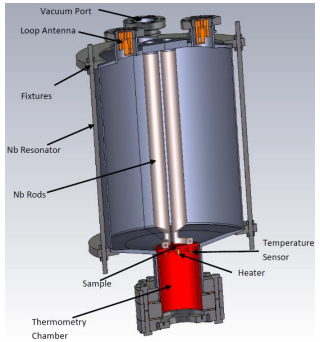
DC magnetic susceptibility,
RRR, H_c, H_{fp}, H_{sh},
Field penetration

DC magnetisation



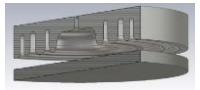


QPR



Superconducting RF properties evaluation
- QPR at CERN
- QPR at HZF
- HW cavity at ASTeC

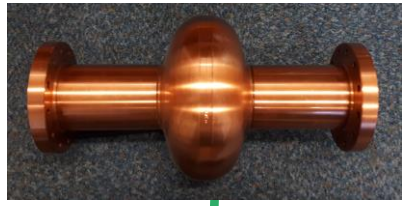
HW test cavity



Real RF cavity measurement
- Cavity deposition and testing

The main emphasis was on applying the result of ARIES to RF cavity deposition and testing

1.3 GHz cavity for STF deposition



WP9 tasks

- **Task 9.1**: Coordination and strategy for innovative superconducting accelerating cavities
  - *CEA, INFN, HZB, UKRI, USI, JLab MEPHI, PTI.*
- **Task 9.2**: Innovative SC accelerating cavity prototype
  - *INFN-LNL, INFN-LASA, PICCOLI, UKRI, USI, CEA, IEE, HZB, PTI, MEPHI*
- **Task 9.3** : Optimisation of process parameters and target development for SRF cavity coating with A15 material
  - *UKRI, INFN, IEE, USI, HZB, MEPHI*
- **Task 9.4**: Surface engineering by atomic layer deposition (ALD)
  - *CEA, CNRS*
- **Task 9.5**: Improvement of mechanical and superconducting properties of RF resonator by laser radiation
  - *RTU, UKRI, INFN, IEE, HZB*
- **Task 9.6**: Optimization of flat SRF thin films production procedure
  - *HZB, INFN, UKRI, USI, CEA*

	IFAST WP9 Partners	Leading	Participating
1	CEA (Saclay, France)	WP, Tasks 1 and 4	Task **1**, 2, **4**, 6
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
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

WP9 Tasks

Task 9.1 (Coordination and strategy)

- **Task 9.1**: Coordination and strategy for innovative superconducting thin film coated superconducting RF cavities (TF-SRF)
  - *CEA, INFN, HZB, UKRI, USI, JLab MEPHI, PTI.*
    - *Coordinated by Claire Antoine (CEA) and Oleg B. Malyshev (UKRI)*

1. Coordination of the overall activities of the WP
2. Strategy:
   - Overview existing and explore future directions in development of TF-SRF.
   - The ultimate goal is to obtain TF-SRF cavities with enhanced performances:
     - higher E_{acc}
     - with lower cryogenic power consumption
     - at lower production costs in comparison to bulk Nb.
     - Various high T_c materials (Nb_3Sn, V_3Si, NbN, NbTiN, MgB_2, and multilayer structures) to be explored.
   - Bring together the experts from EU and overseas institutions involved in R&D, production and operation of TF-SRF accelerating cavities organising
     - regular video-conferencing, satellite meetings at conferences, and dedicated **workshops**, etc.

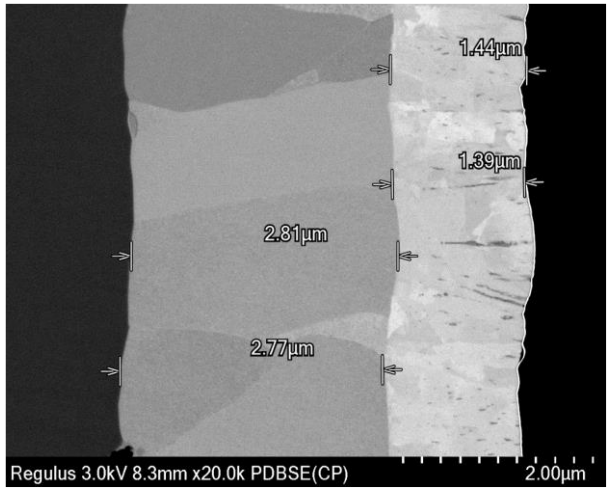
D9.1: Thin-Film SRF roadmap report. *Summaries of the results obtained within the workpackage and prospective inspired from WP advances as well as discussions at TF-SRF 2022.*	M35

MS37: International thin film workshop organisation	M28

Task 9.3 (Development) as planned

- **Task 9.3** : Optimisation of process parameters and target development for SRF cavity coating with A15 material
  - *UKRI, INFN, IEE, USI, HZB, ~~MEPHI~~*
    - *Coordinated by Reza Valizadeh (UKRI)*
  - *Seamless (INFN - Piccoli) or split (UKRI) cavities made of OFHC copper,*
  - *f = 6 GHz*
    - *Coated with non-Nb and SIS thin films and tested at INFN and/or UKRI*
  - *Planar copper samples*
    - *Coated with non-Nb and SIS thin films and characterised at INFN, UKRI and USI*
    - *Tested at IEE, MEPHI and UKRI*
  - *QPR samples (in coordination with Task 9.6)*
    - *Polished at INFN,*
    - *Deposited at INFN, UKRI and USI*
    - *Tested at HZB*

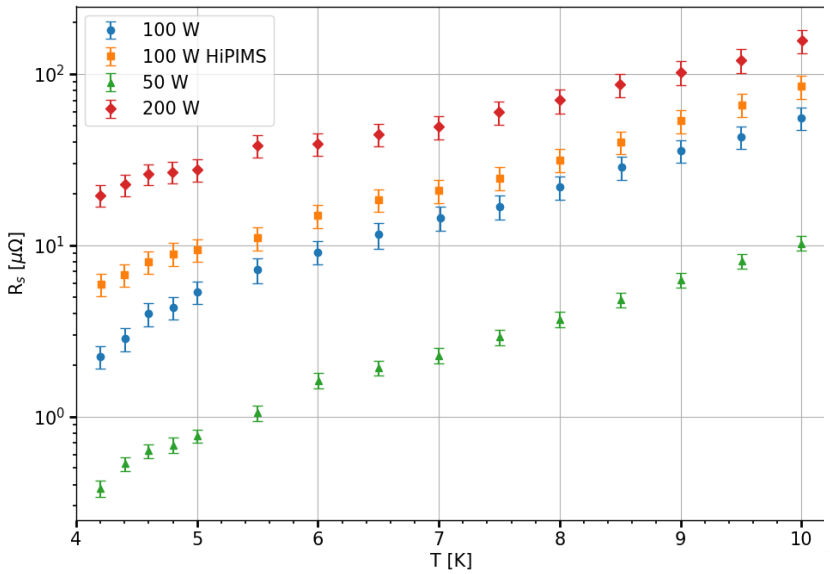
X-section SEM of Nb_3Sn with a Nb underlayer as double structure on copper. Courtesy to R. Valizadeh (UKRI)



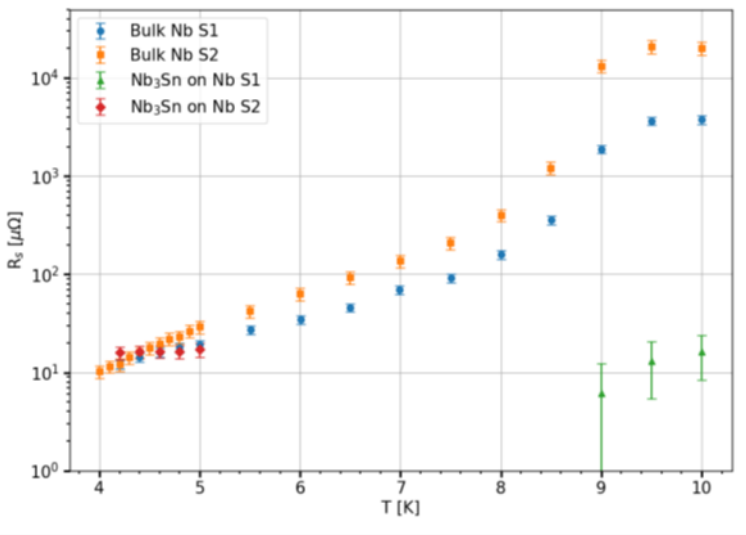
MS39: Coating facility built and tested at STFC, USI and INFN (Report)	**M12**	**D9.3:** First 6 GHz cavity coated and characterised. *Results from the morphological and SC characterisation of first coated cavity with an alternative material to Niobium.*	M36

Task 9.3 (Development) delivered

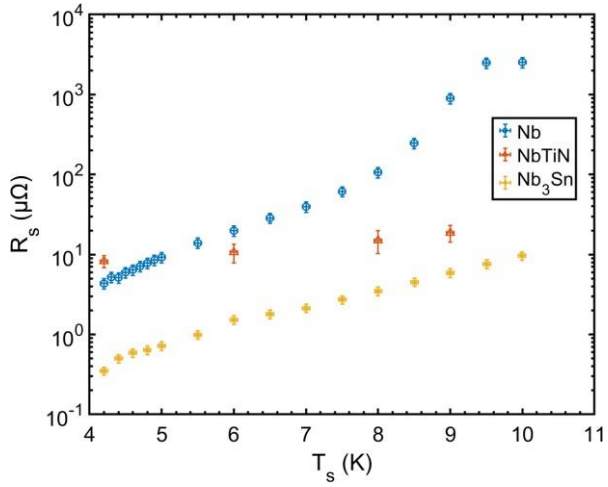
Surface resistance at 7.8 GHz of SRF thin film of Nb_3Sn and NbTiN deposited on planar samples



Optimisation of deposition power for Nb_3Sn on Cu

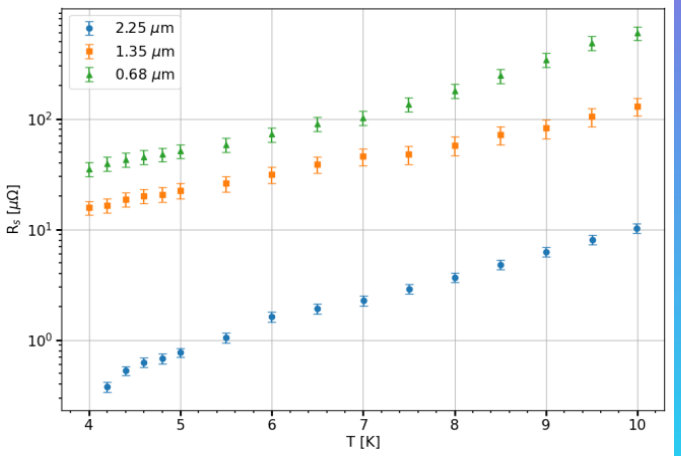


Surface resistance on Nb with different surface roughness surface preparation



Surface resistance of different SC thin film on Cu

- Optimum deposition power for Nb_3Sn is stablished at 50 W DC power
- Film Thickness dependence of Nb_3Sn on Cu
- Best surface resistance so far is achieved on Nb substrate
- For high T_c, Nb_3Sn seems to be more suitable candidate for 4-K operation having lower R_s than NbTiN.



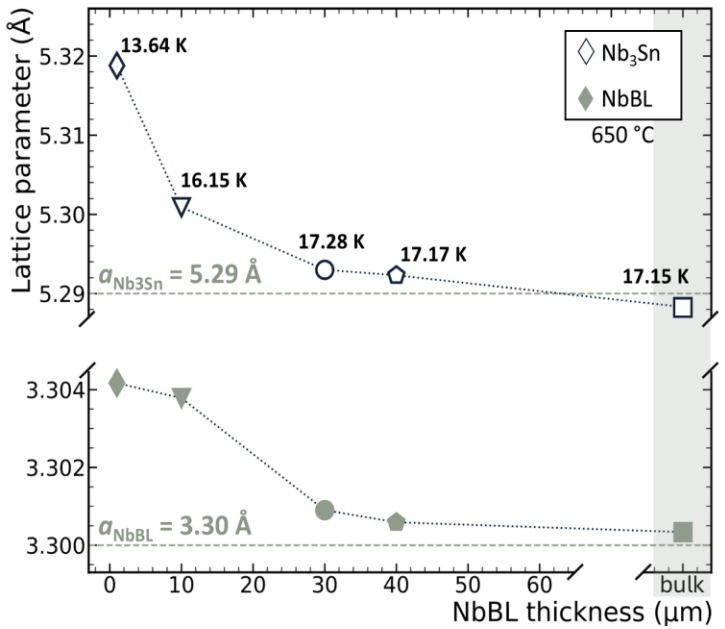
Surface resistance of different thickness on Cu

Courtesy to UKRI team

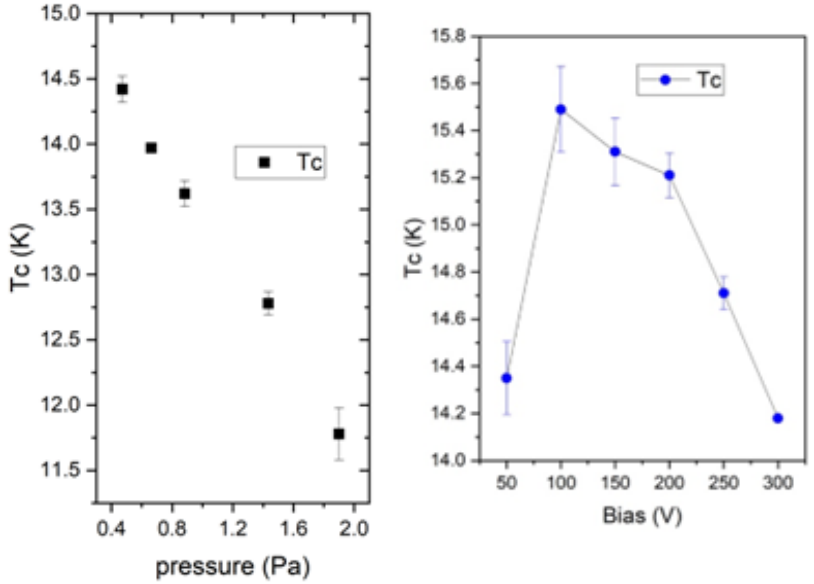
MS39: Coating facility built and tested at STFC, USI and INFN (Report)	**M12**

Task 9.3 (Development) delivered

Nb_3Sn and NbTiN deposited on planar samples

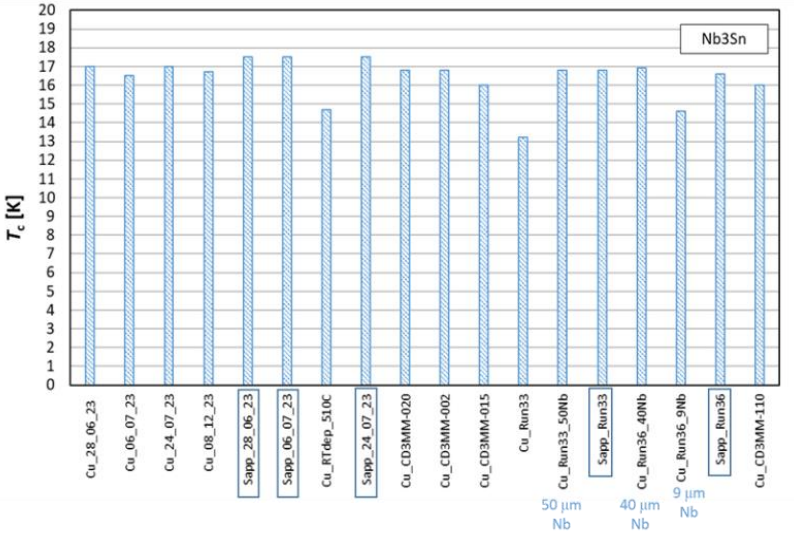


Optimisation of Nb3Sn deposition using Nb bilayer at INFN. Courtesy to INFN team

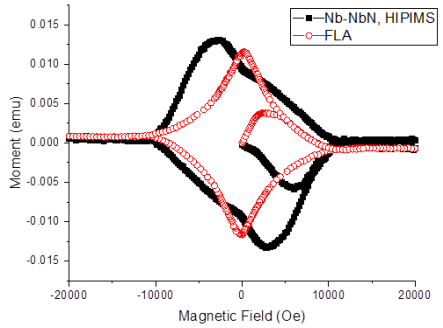


NbTiN study at University of Siegen

T_c as a function of bias and deposition pressure. Courtesy to USI team



T_c measurement of Nb_3Sn deposited on various substrate at ElU. Courtesy to ElU team



Flash annealing at HZDR of NbN/Nb/Cu deposited at STFC. Courtesy to HZDR team

- to be more suitable candidate for 4 K operation having lower R_s than NbTiN.

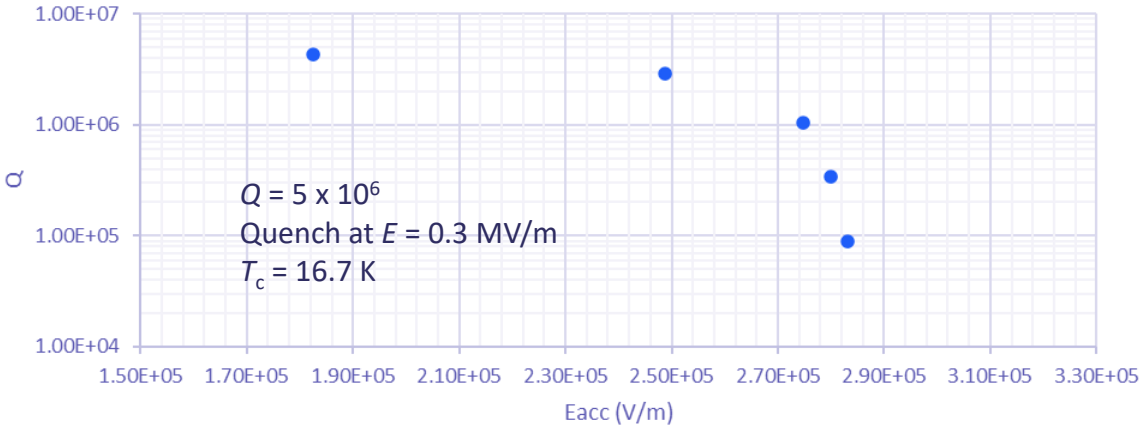
MS39: Coating facility built and tested at STFC, USI and INFN (Report)	**M12**

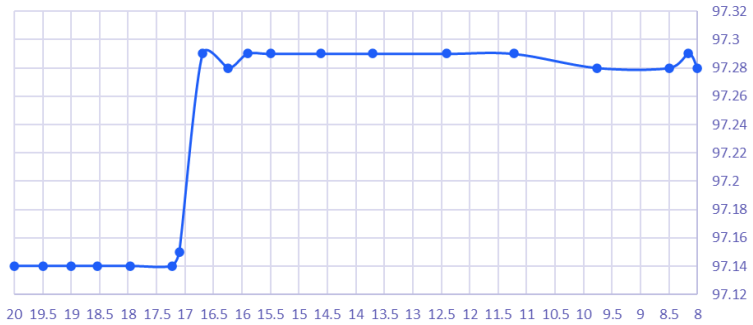
Task 9.3 (Development) delivered

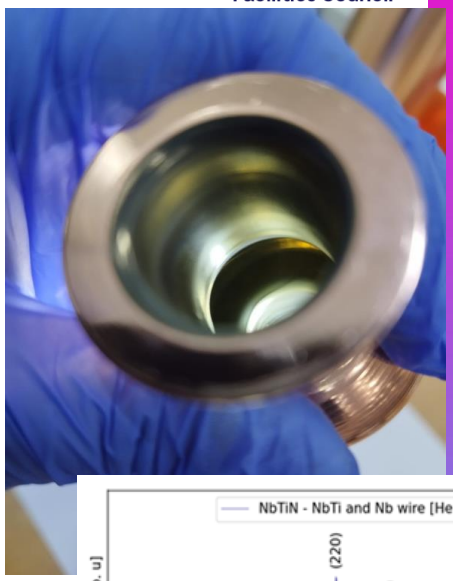
Science and Technology Facilities Council

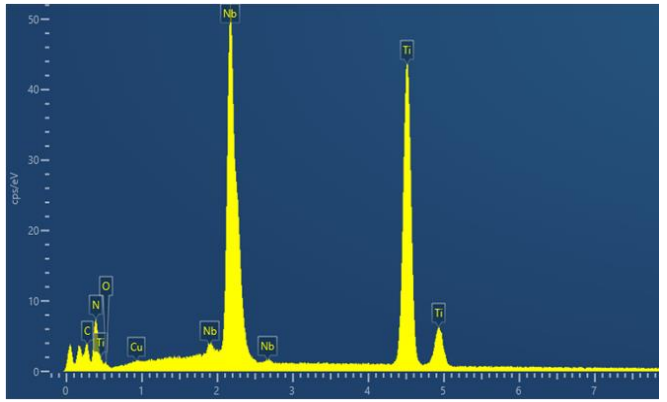
6 GHz cavities

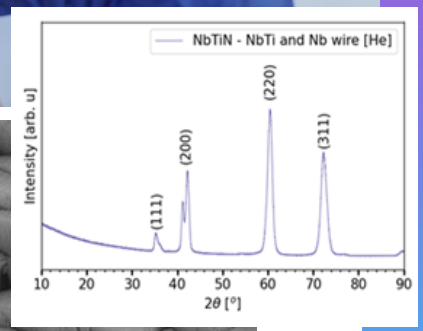
- Produced and polished by Piccoli/INFN
- Deposited and characterised at STFC
- RF tested at INFN

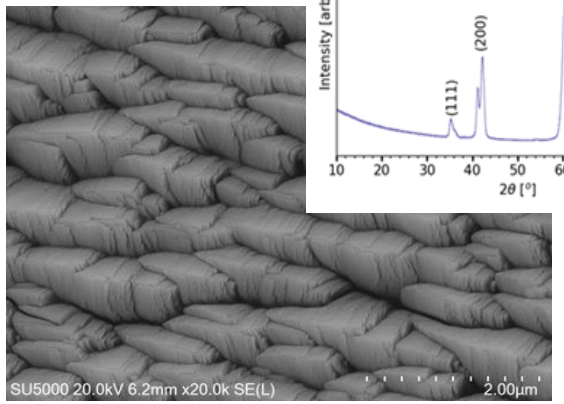










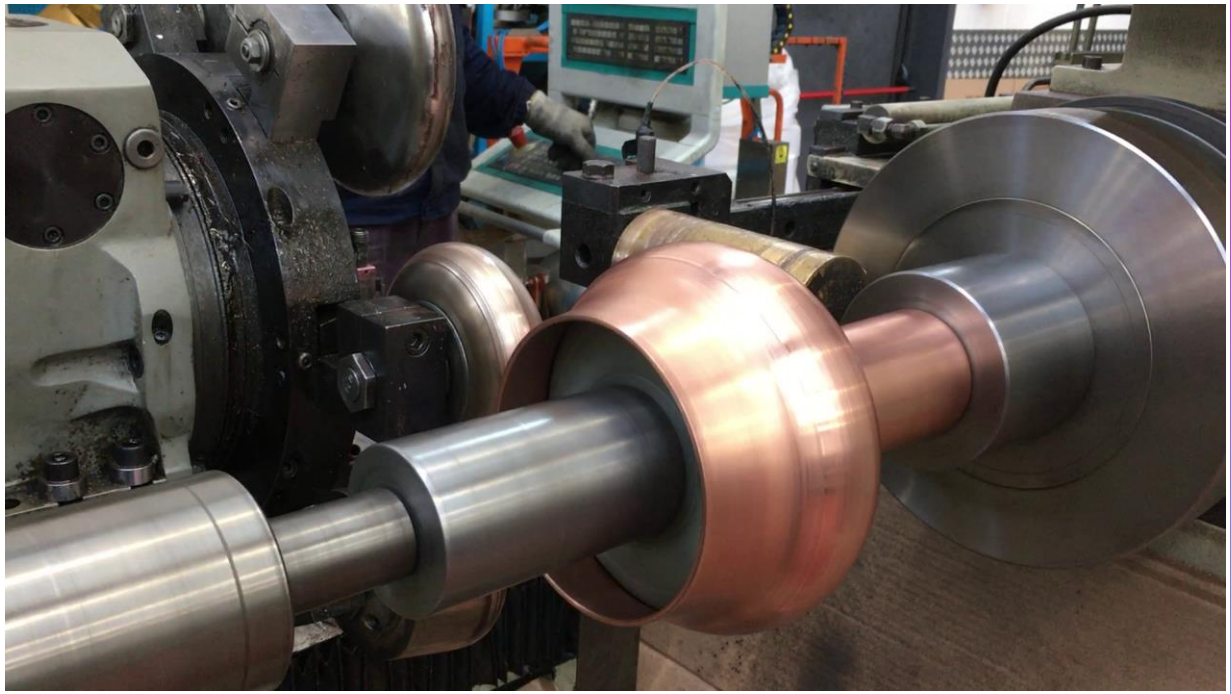


MS39: Coating facility built and tested at STFC, USI and INFN (Report)	**M12**	**D9.3: First 6 GHz cavity coated and characterised.** *Results from the morphological and SC characterisation of first coated cavity with an alternative material to Niobium.*	~~M36~~ M48

Task 9.2 (Prototype) as planned

- **Task 9.2**: Innovative SC accelerating cavity prototype
  - *INFN-LNL, INFN-LASA, PICCOLI, UKRI, USI, CEA, IEE, HZB, ~~PTI, MEPHI~~*
    - *Coordinated by Cristian Pira (INFN-LNL)*
  - *Seamless (INFN - Piccoli) and EB welded (PTI) cavities made of OFHC copper*
  - *f = 1.3 GHz*
  - *Coated with non-Nb and SIS thin films at CEA, JLab, INFN, UKRI and USI*
  - *Tested at INFN, UKRI, CEA, HZB and JLab*

Production of a seamless cavity from OFHC copper.
Courtesy to Cristian Pira (INFN)



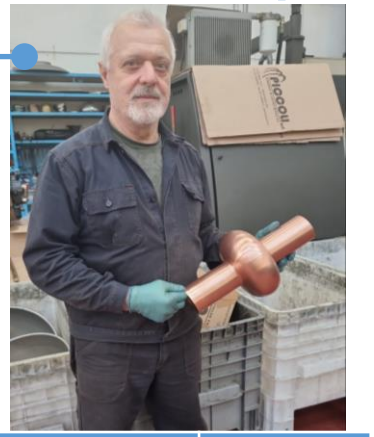
MS38: First seamless copper 1.3 GHz cavity produced as substrate for the coating of the SC film (Report)	**M12**	**D9.2:** RF test on coated resonant cavity. *Resonant cavity coated and tested with an alternative material to Niobium with a $Q_0 > 10^9$ at 4.2 K and 1.3 GHz.*	M46

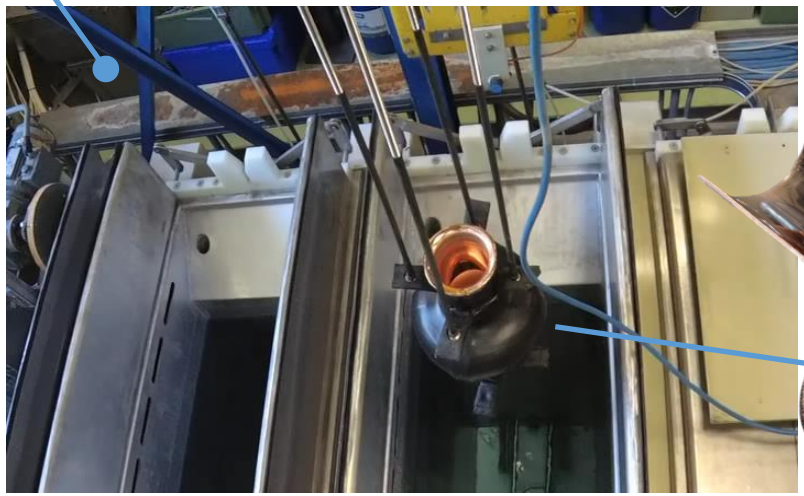
Task 9.2 (Prototype) delivered

ACHIEVEMENTS

- Piccoli Srl, in collaboration with INFN, has **developed a new semi-automated protocol for the manufacture of seamless Cu cavities via CNC**
- Developed a **new fully seamless design**
- **A new surface treatment based on Plasma Electrolytic Polishing has been developed.** Compared to traditional treatments, it offers removal speeds that are **10 times faster** and has a **lower environmental impact**

Courtesy to INFN/Piccoli team



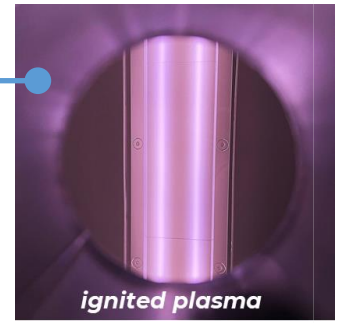


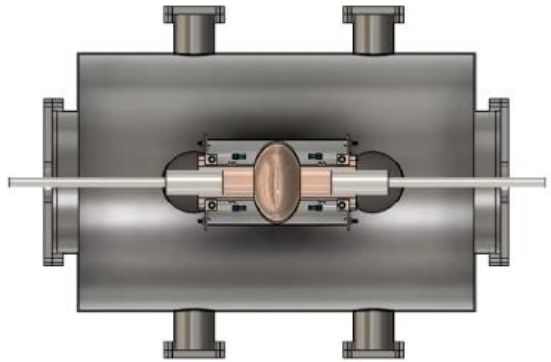
MS38: First seamless copper 1.3 GHz cavity produced as substrate for the coating of the SC film (Report)	**M12**

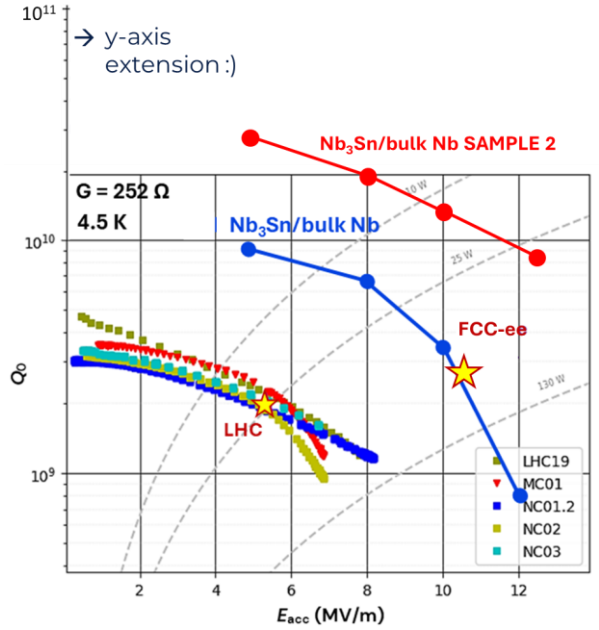
Task 9.2 (Prototype) delivered

ACHIEVEMENTS

- **Two new facilities** optimized for Nb_3Sn coating via PVD have been **designed and built** at INFN and UKRI
- **Innovative magnetron source is under testing** at INFN
- UKRI define a deposition protocol for 1.3 GHz cavity and **coat successfully the first cavity with Nb_3Sn** on bulk Nb cavity prepared by CEA. The cavity is at HZB and **RF test ongoing** *(results expected by end of October)*
- **The results** obtained from QPR RF test at 400 MHz **are currently state-of-the-art for Nb_3Sn films** produced via PVD







D9.2: RF test on coated resonant cavity.
First 1.3 GHz cavity coated with Nb_3Sn thin film *and ready for RF test by end of October 2025.*

~~M46~~ M52

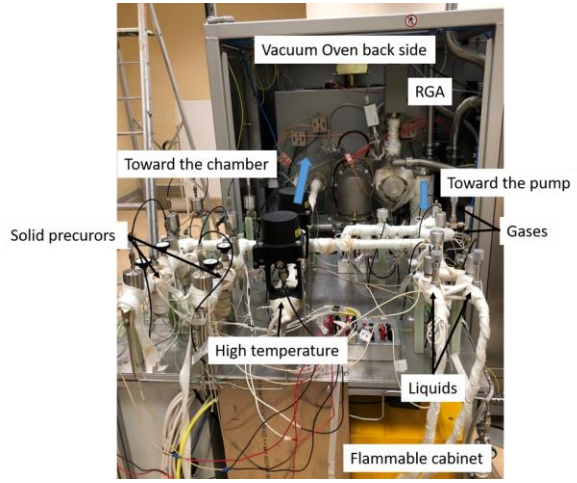
Task 9.4 (Development) as planned

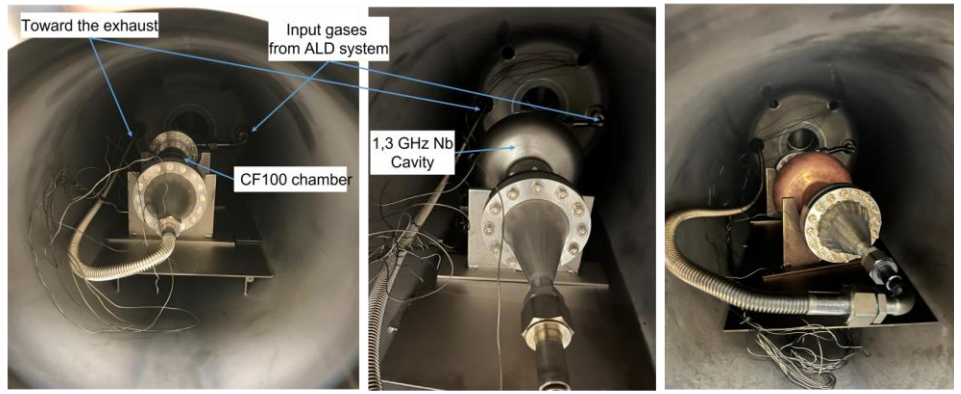
- **Task 9.4**: Surface engineering by atomic layer deposition (ALD)
  - *CEA, CNRS*
    - *Coordinated by Thomas Proslier (CEA)*
  - *Cavities made of OFHC copper or niobium*
  - *f = 3 and 1.3 GHz*
  - *Nb cavity coated with SIS thin film by ALD.*
  - *Cu cavity coated with Nb or non-Nb and SIS thin films by ALD*
  - *Tested at CEA*

MS40: Construction and operation of the cavity dedicated ALD system **(Report)**	**M24**	**D9.4:** Deposition of superconducting multilayers on cavities. *1.3 and 3 GHz Nb and Cu cavities coated and tested with multilayers.*	M46

Task 9.4 (Development) delivered

- **Construction and use of an ALD system dedicated to cavity coatings**
  - *The cavity ALD system is operational and in use since end 09/22.*





  - *Over twelve 1.3 GHz (10 Nb and 2 Cu) cavities have been coated and tested in collaboration with CERN, FNAL and JLAB.*
  - *Coatings and RF tests results have seeded new projects in Qubits and space applications.*

MS40: Construction and operation of the cavity dedicated ALD system (Report)	**M24**	**D9.4:** Deposition of superconducting multilayers on cavities. *1.3 and 3 GHz Nb and Cu cavities coated and tested with multilayers.*	M46

Task 9.4 (Development) delivered

- *Nb cavity coated with dielectrics and SIS thin film by ALD.*
  - *Two Niobium cavities have been coated with AlN/NbTiN multilayer: Delamination occurring during post annealing step -> found mitigation on coupons. Will attempt again on a cavity.*
  - *eight Niobium cavities coated with dielectrics layers (Ta_2O_5, Al_2O_3, ZrO_2) and post-annealing in HV:* ***World record, air stable Quality factor at low fields.***
  - *One Niobium cavity coated with multilayer: dielectric + TiN:* ***efficient suppression of multipacting.***
- *Cu cavity coated with dielectrics*
  - *Two Cu cavities coated with Al_2O_3 by ALD and with Nb by HiPIMS at CERN: RF test shows* ***efficient suppression of thermo-currents.***
- *Nb cavity and QPR surface treatments:*
  - *One Nb cavity from STFC have been HPR, leak tested and sent back to STFC. Two are being processed for Nb_3Sn coatings. See Task 9.2.*
  - *4 Nb QPR from Hamburg university and DESY have been processed at CEA. They show* ***record low surface resistances****. See Task 9.6*
- *RF Test at CEA:*
  - *For more than 3 years now RF tests are in degraded mode with He dewar transfer; in a few months the new liquefier will be operational.*
  - *RF tests have been on hold since January 2025, awaiting for ASN (French nuclear safety agency) for the authorisation to run tests in accelerator mode. Special authorization for low field measurements have been given in August 2025.*

Task 9.5 (Development) as planned

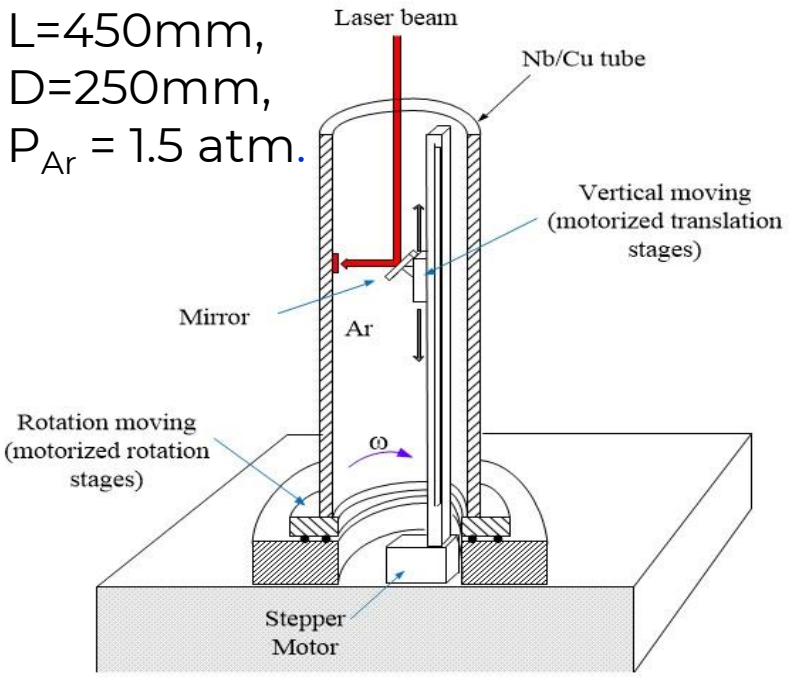
- **Task 9.5**: Improvement of mechanical and superconducting properties of RF resonator by laser radiation
  - *RTU, UKRI, INFN, IEE, HZB*
    - *Coordinated by Arturs Medvids (RTU)*
  - *Continue further development of laser treatment of Nb films on planar samples made of OFHC copper*
    - *Deposited at INFN or UKRI*
    - *Laser treated at RTU*
    - *Tested at IEE and UKRI*
  - *Development of a facility at RTU for laser treatment of Nb films deposited on*
    - *Copper tubes deposited with Nb (from INFN or UKRI)*
    - *1.3 GHz copper cavities made of OFHC copper and deposited with Nb (INFN)*
    - *RF tested at INFN or UKRI*

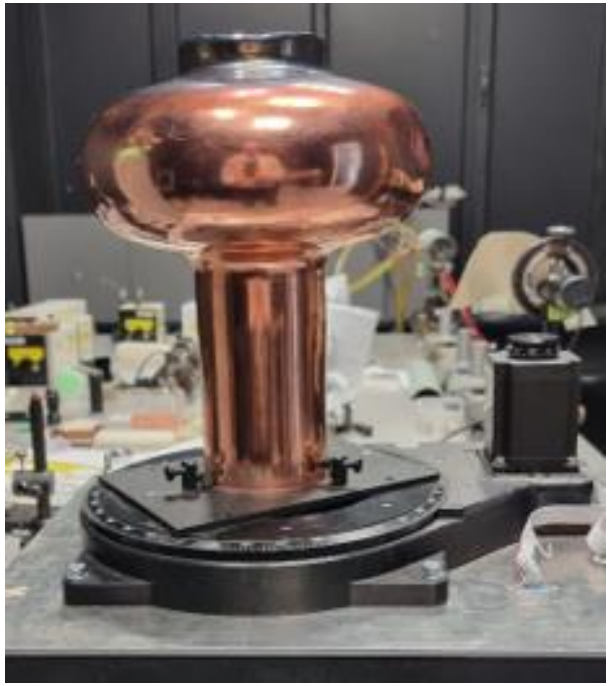
MS41: A facility for laser operation for complex 3D treatment is tested on 1.3 GHz cavity **(Report)**	M36	**D9.5:** A 1.3 GHz Nb-coated cavity irradiated by laser in Ar atmosphere and RF tested. *Increasing of the field of magnetic flux entry in Nb coated 1.3 GHz cavity irradiated by laser in argon atmosphere. Standard RF testing.*	M45

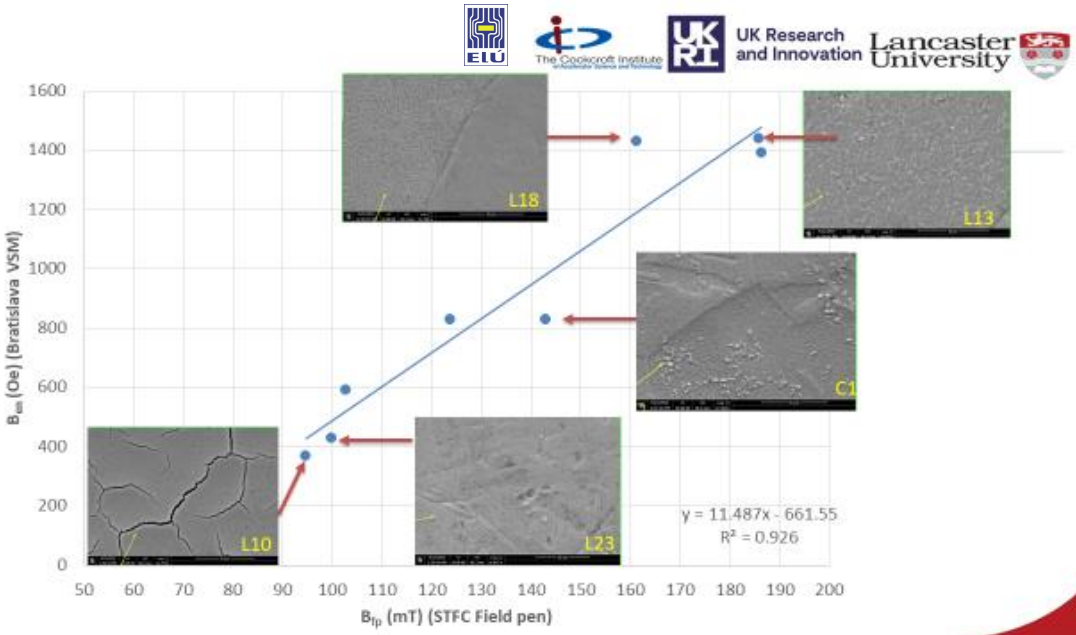
Task 9.5 (Development) delivered

Laser treatment facility:
1) Designed **2) Built** **3) Tested with Nb coated samples**

L=450mm,
D=250mm,
P_{Ar} = 1.5 atm.







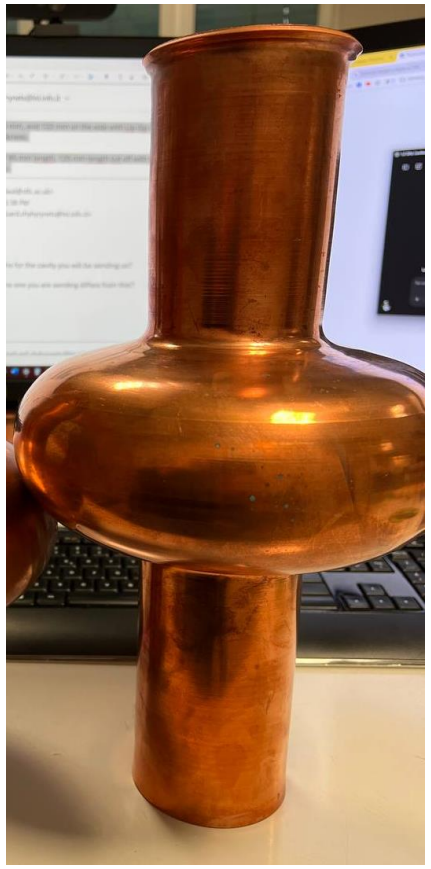
Courtesy to Arturs Medvids (RTU)

MS41: A facility for laser operation for complex 3D treatment is tested on 1.3 GHz cavity **(Report)**	M36

Task 9.5 (Development) delivered

1.3 GHz RF civility:

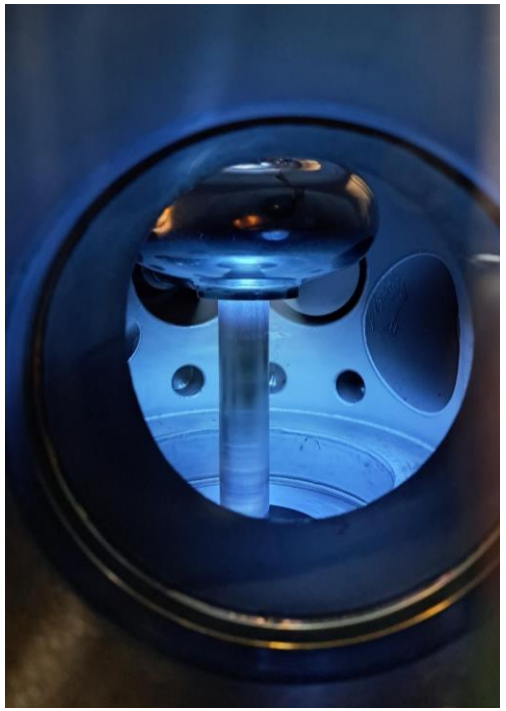
(4) 2 seamless cavities produced and polished at INFN/Piccoli



Courtesy to Cristian Pira (INFN)

(5) Coated with Nb TF at UKRI

Science and Technology Facilities Council



Courtesy to Reza Valizadeh (UKRI)

(6) Laser treated at RTU

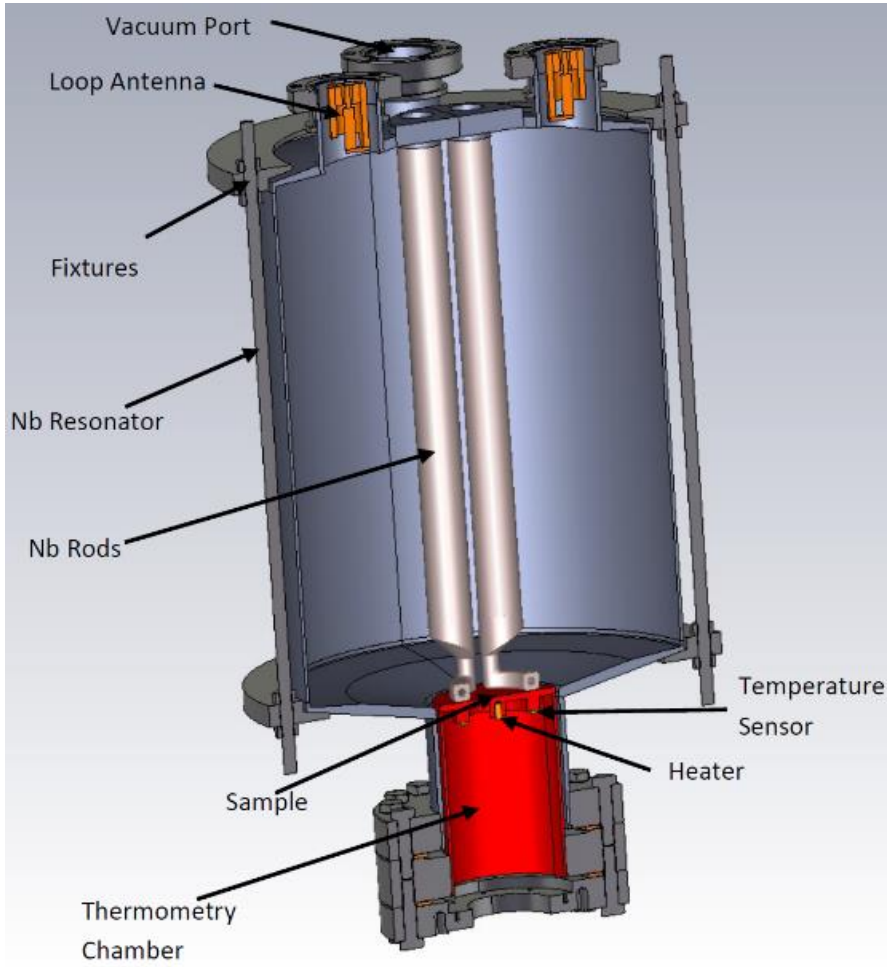
Courtesy to Arturs Medvids (RTU)

(7) Delivered to UKRI for RF testing in a new facility in early 2026

D9.5: A **1.3 GHz Nb-coated cavity irradiated by laser in Ar atmosphere** and ready for an RF test.	~~M45~~ M48

Task 9.6 (Development) as planned

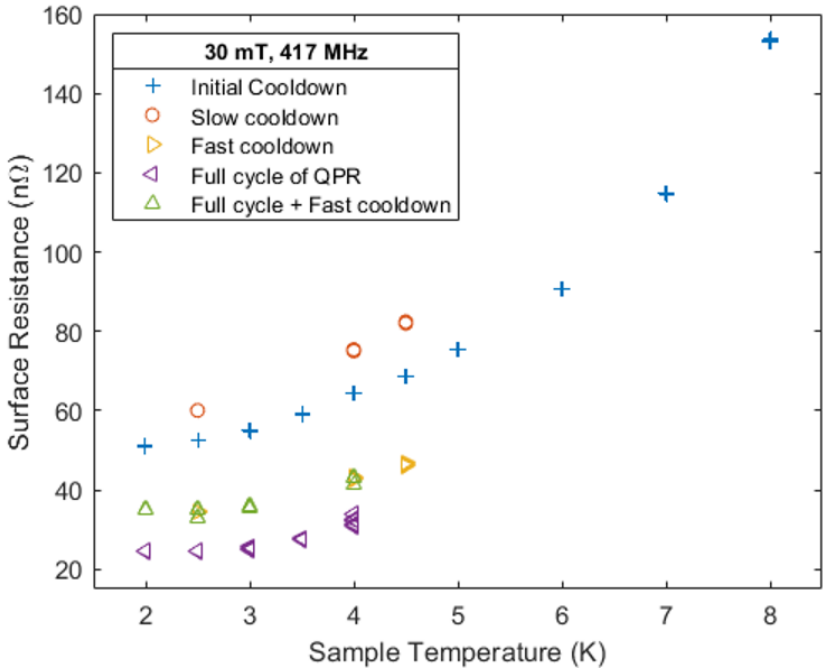
- **Task 9.6**: Optimization of flat SRF thin films production procedure
  - *HZB, INFN, UKRI, USI, CEA*
    - *Coordinated by Oliver Kugeler*
  - *Continue further development of non-Nb and SIS films on planar QPR samples made of OFHC copper*
    - *Deposited at CEA, INFN, UKRI and USI*
    - *Tested at HZB*



MS42: ARIES samples prepared for renewed SC film deposition	**M6**	**D9.6:** Test of thin-film samples. *Four thin film samples reprocessed by 4 different techniques and tested with QPR.*	M46

Task 9.6 (Development) delivered

Sample	Origin	Main Findings
Nb_3Sn on Nb	INFN Legnaro	Best performance: **$R_s \approx 25$ nΩ @ 4 K**; **$T_c = 17.7$ K**; strong flux expulsion.
Nb_3Sn on Nb	STFC Daresbury	$R_s \approx 90$ nΩ @ 4 K; $T_c \approx 16$ K; contamination & non-uniformity observed.
Nb-on-Cu	Univ. Siegen	Excellent film quality: **$R_s \approx 20$ nΩ @ 2 K**, $H_{quench} \approx 260$ mT; threshold $\Delta T/\Delta t > 20$ K/min for flux expulsion.
Nb_3Sn on Nb-on-Cu	HZB (bronze route)	First trial: $T_c \approx 15.5$ K, $R_s \approx 76$ nΩ @ 2 K; stoichiometric inhomogeneity, needs process refinement.



Courtesy to Oliver Kugeler (HZB)

Testing Conditions

- Frequency: 416 - 417 MHz
- Temperature range: 1.8 - 20 K
- Cryogenic cooldown dynamics strongly affect R_s (flux trapping).

MS42: ARIES samples prepared for renewed SC film deposition	**M6**	**D9.6: Test of thin-film samples.** *Four thin film samples reprocessed by 4 different techniques and tested with QPR.*	M46

Task 9.6 (Development) delivered

Key recommendations after QPR tests:

- **INFN Legnaro:** Process mature — ready for implementation for cavity coating.
- **STFC:** Required improving vacuum in deposition system.
- **Siegen:** Nb-on-Cu coating fully developed, reproducible, suitable for implementation forcoating curved surfaces.
- **HZB (bronze route):** Promising path toward Nb_3Sn-on-Cu; needs optimisation in stochiometry and phase purity.

Impact

- Confirms viability of **Nb_3Sn** and **Nb-on-Cu** as high-performance SRF alternatives to bulk Nb.
- Demonstrates significance of **cooldown dynamics** and **film homogeneity** for minimising RF surface resistance.
- Provides foundation for upscaling thin-film techniques to **SRF cavity geometries**.

Courtesy to Oliver Kugeler (HZB)

MS42: ARIES samples prepared for renewed SC film deposition	**M6**	**D9.6: Test of thin-film samples**. *Four thin film samples reprocessed by 4 different techniques and tested with QPR.*	M46

Lessons learned

- WP9 includes majority of European labs with TF SRF activities
  - ✓Intense collaboration, coordination, frequent meetings enhance a progress in R&D and TRL
    - ➢ Variety of knowledge and skill
    - ➢ Intense sample exchange
    - ➢ Wide range of material characterisation methods and superconductivity testing techniques
  - ✓Building a WP9 team with at least two partners with similar capability
    - ➢ Reduces risks for the project
      - Three partners with similar capability would be event better
  - ✓Faster progress requires more funding for personnel and equipment
    - ➢ Dedicated grants for PhD students and PostDocs would be nice
  - ✓Involvement of partners outside of accelerator labs
    - ➢ Exploring new technologies from experts in a different fields, e.g.: FLA (HZDR) and lasers (RTU)
- R&D Tasks are essential for further progress even at industrialisation stage
  - ➢Depositing thin films is a multi-parametric task that requires continuous R&D and optimisation
- Involving industry is difficult
  - ➢TF SRF is a relatively low-capacity business, and hard to plan ahead
  - ➢Challenge to keep an expertise in industry without a flow of contracts

Conclusions

Scientific and technological results

- First Nb_3Sn coated cavity produced and ready for RF testing (STFC, CEA, HZB)
- Progress in technologies for TF SRF:
  - Seamless copper cavity production by spinning (INFN/Piccoli)
  - Copper polishing (INFN, CEA, STFC)
  - Deposition targets development (INFN, STFC)
  - ALD and PVD Deposition facilities built and being used (CEA,INFN, STFC)
  - Post-deposition treatments with laser (RTU) and FLA (HZDR) exploration

Outcome

- Next steps:
  - Coating with Nb_3Sn on Cu cavities
  - Multilayers coatings and other SC materials
  - More single and multi-cell cavities,
  - Different frequencies
- Involving industry
  - EPITA bid with 3-4 industries involved

Impact

- Higher *Q* leads to lower operation cost
- Higher *E* leads to lower construction and operation cost
- Operating at $T = 4.2$ K instead of 2 K reduces cost of cryogenic system and running cost by a factor 3

iFAST

Thanks for your attention

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