Thin Films SRF 2024

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

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

Nb_3Sn/Cu by Magnetron Sputtering for SRF cavities at INFN-LNL

Dorothea Fonnesu

17.09.2024

INFN
LNL

Work supported by INFN CSN5 experiment SAMARA and INFN CSN1 experiments SRF and RD_FCC

This project has received funding from the European Union's Horizon-INFRA-2023-TECH-01 under GA No 101131435 – iSAS and from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730 – I.FAST

Outline

- Nb_3Sn/Cu challenges
- INFN-LNL goal
- Deposition recipe optimization
- Nb_3Sn R&D projects timeline
- Conclusion

Our partners

cea

LOT Lehrstuhl für Oberflächen- und Werkstofftechnologie

UNIVERSITÄT SIEGEN

HZB Helmholtz Zentrum Berlin

INFN LNF

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

ROMA TRE UNIVERSITÀ DEGLI STUDI

POLITECNICO DI TORINO 1859 1906

ELÚ

1862 RĪGAS TEHNISKĀ UNIVERSITĀTE

UNIVERSITAS STUDII PADUANI MCCXXII

CERN

UKRI Science and Technology Facilities Council

Fermilab

Jefferson Lab

Nb_3Sn on Cu: multiple challenges

- A15 are brittle materials
- Complicated phase diagram
- **Low melting point substrate (Cu)**
- **Interface diffusion**
- **Tuning of coating parameters**
- **Substrate preparation**
- **Target production/magnetron design**
- **Trapped flux**
- **Cavity tuning**

iFAST

SRF cavities R&D for FCC-ee

INFN Accelerators European Strategy Program

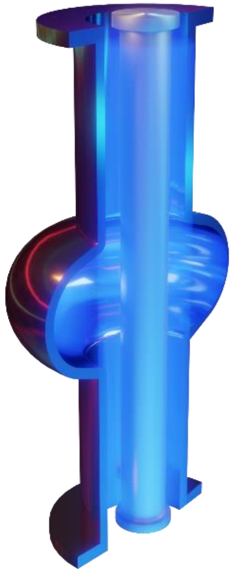
iSAS

ESPP Accelerator R&D Roadmap

dorothea.fonnesu@lnl.infn.it

INFN-LNL goal

Main R&D activities



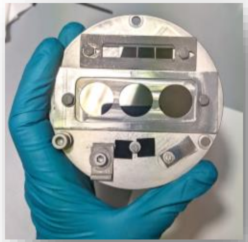
1.3 GHz elliptical Nb_3Sn/Cu prototype cavity
How?

DCMS with stoichiometric single target (small samples)

Easy and validated

(e.g. LHC Nb/Cu)

cylindrical target production via **LTD** (6 GHz cavities)



DC **M**agnetron **S**puttering

Deposition recipe must be optimised

Liquid **T**in **D**iffusion

Deposition recipe optimization

1

tuning of deposition parameters based on T_c of small film samples

2

production and RF test of quadrupole resonator (QPR) sample

3

apply 1&2 again for the deposition and RF test of 1.3 GHz prototype

1

T_c-driven parameter optimization

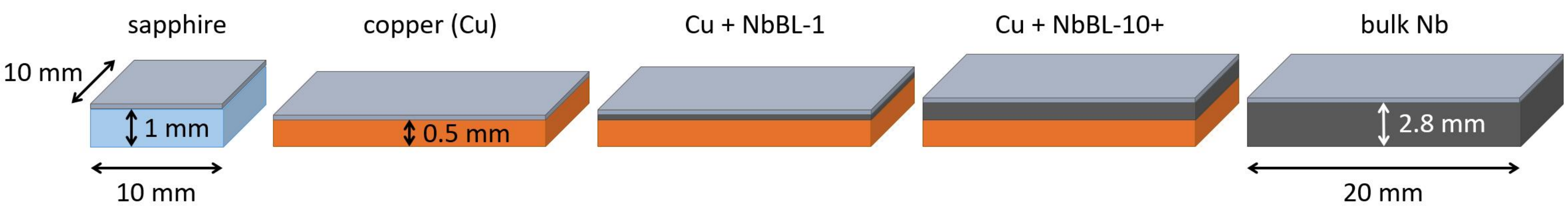
Sample production

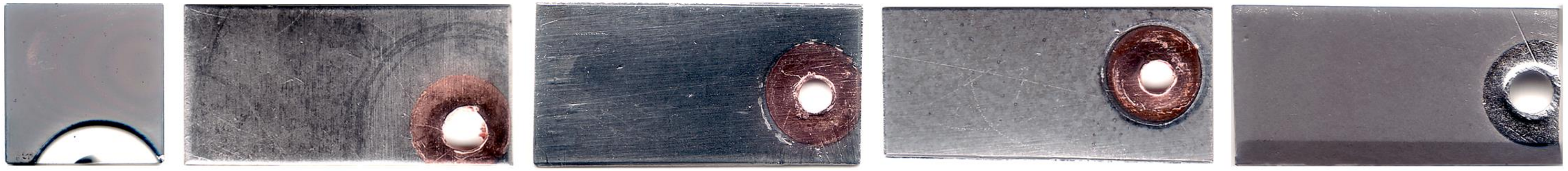
Tight-feedback driven standardized process:

deposition > characterization > parameter adjustment

Films are deposited on different substrates:

- **sapphire** for reference as substrate does not affect the film
- **copper without and with a niobium buffer layer** (NbBL) of variable thickness
- **bulk Nb**





Deposition temperature limit

Limited by weakening point of copper

- Cu starts weakening at ~ **450 °C** (Nb_3Sn requires > **930 °C**)
- **softening of 6 GHz cavity flanges observed at 650 °C**

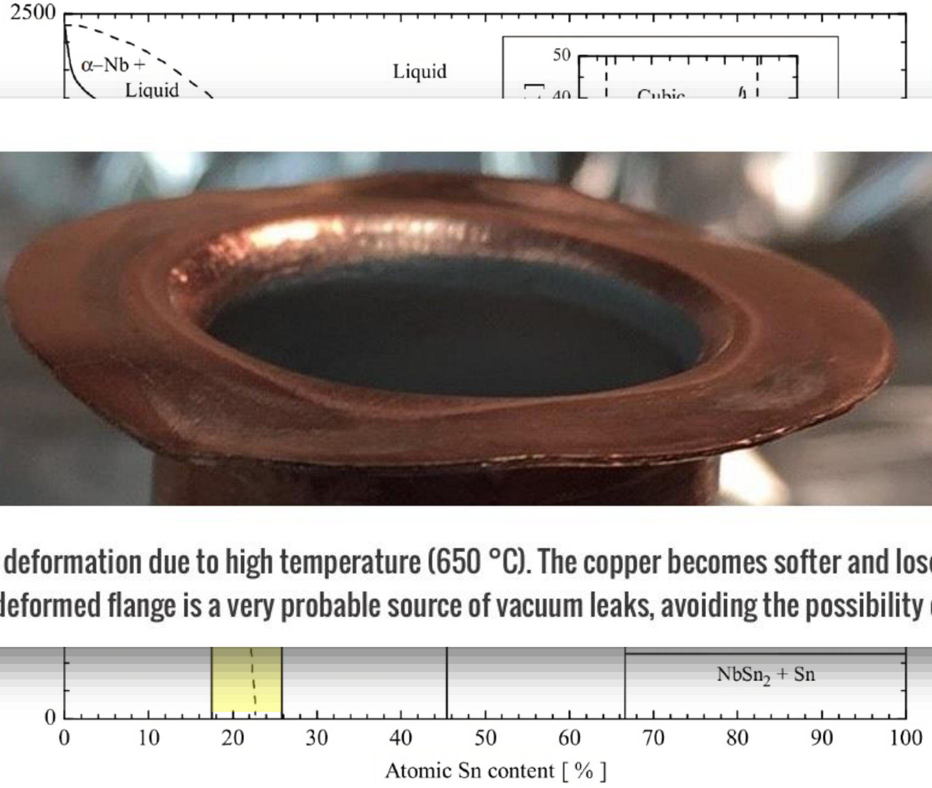
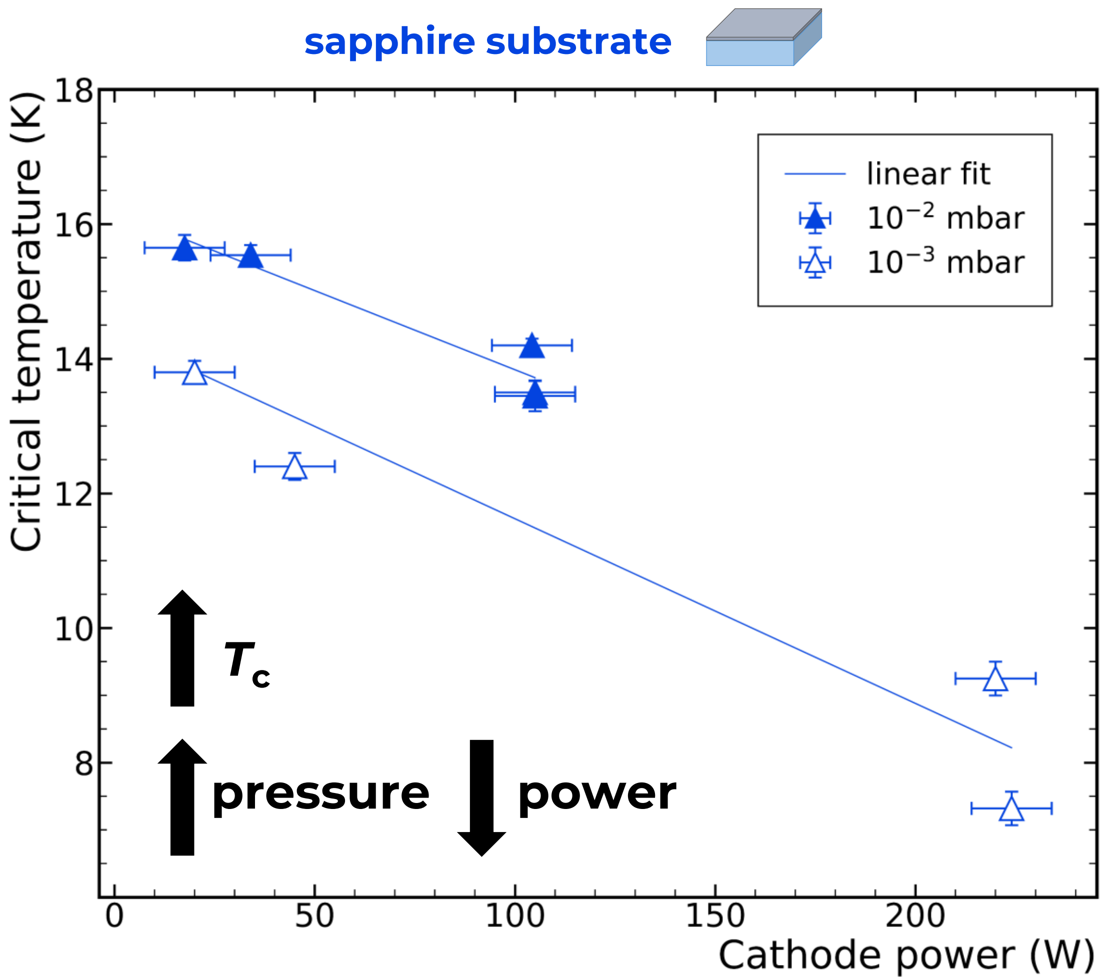
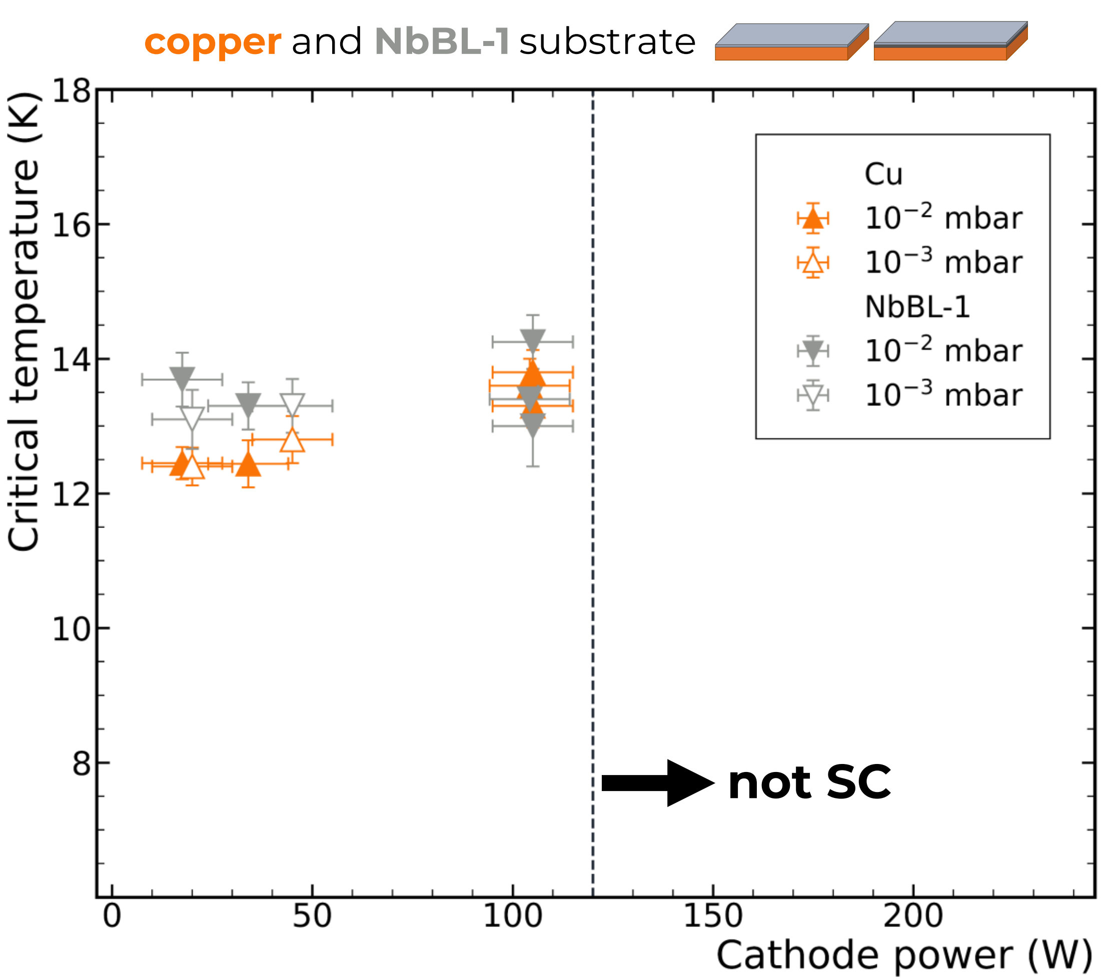


Figure 7.10 Flange deformation due to high temperature (650 °C). The copper becomes softer and lose his mechanical properties. A deformed flange is a very probable source of vacuum leaks, avoiding the possibility of the rf test.

Pressure and cathode power

Deposition temperature = 630 °C

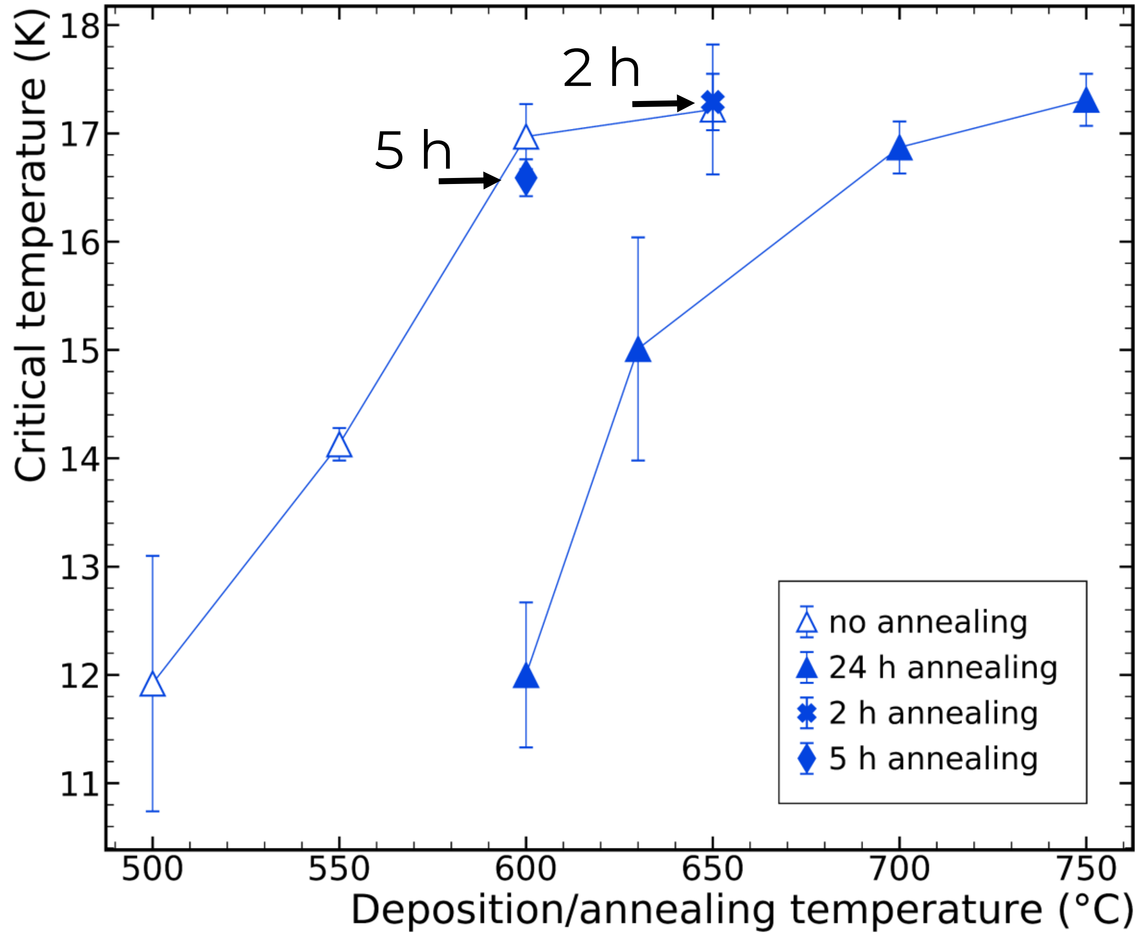




dorothea.fonnesu@lnl.infn.it

Temperature and annealing time

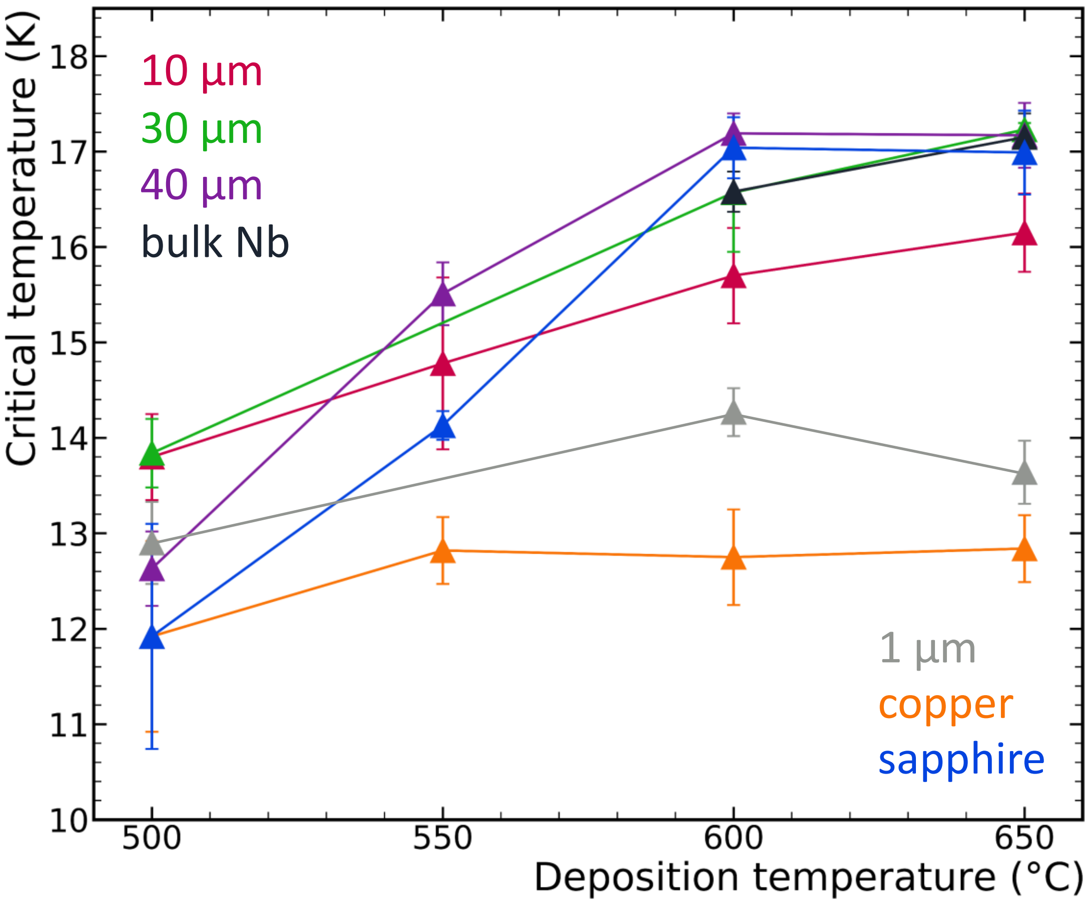
sapphire substrate



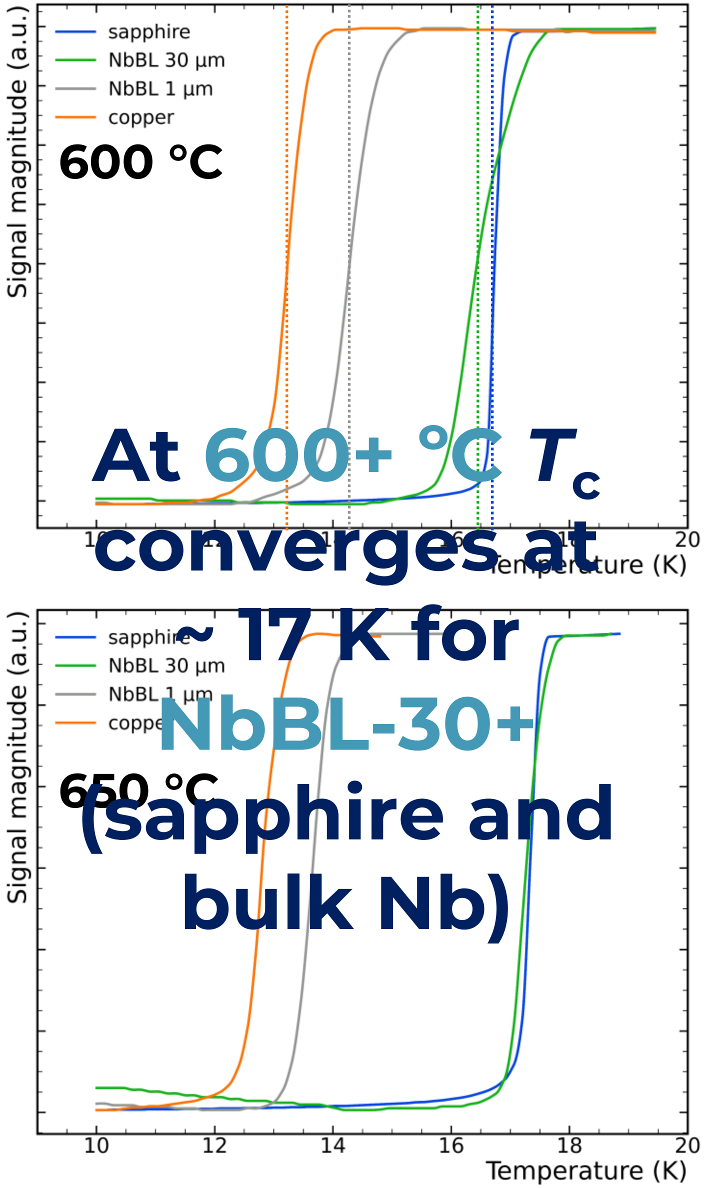
Annealing detrimental for T_c

Role of the NbBL

No annealing



Inductive measurement of SC transition



At 600+ °C T_c converges at ~ 17 K for NbBL-30+ (sapphire and bulk Nb)

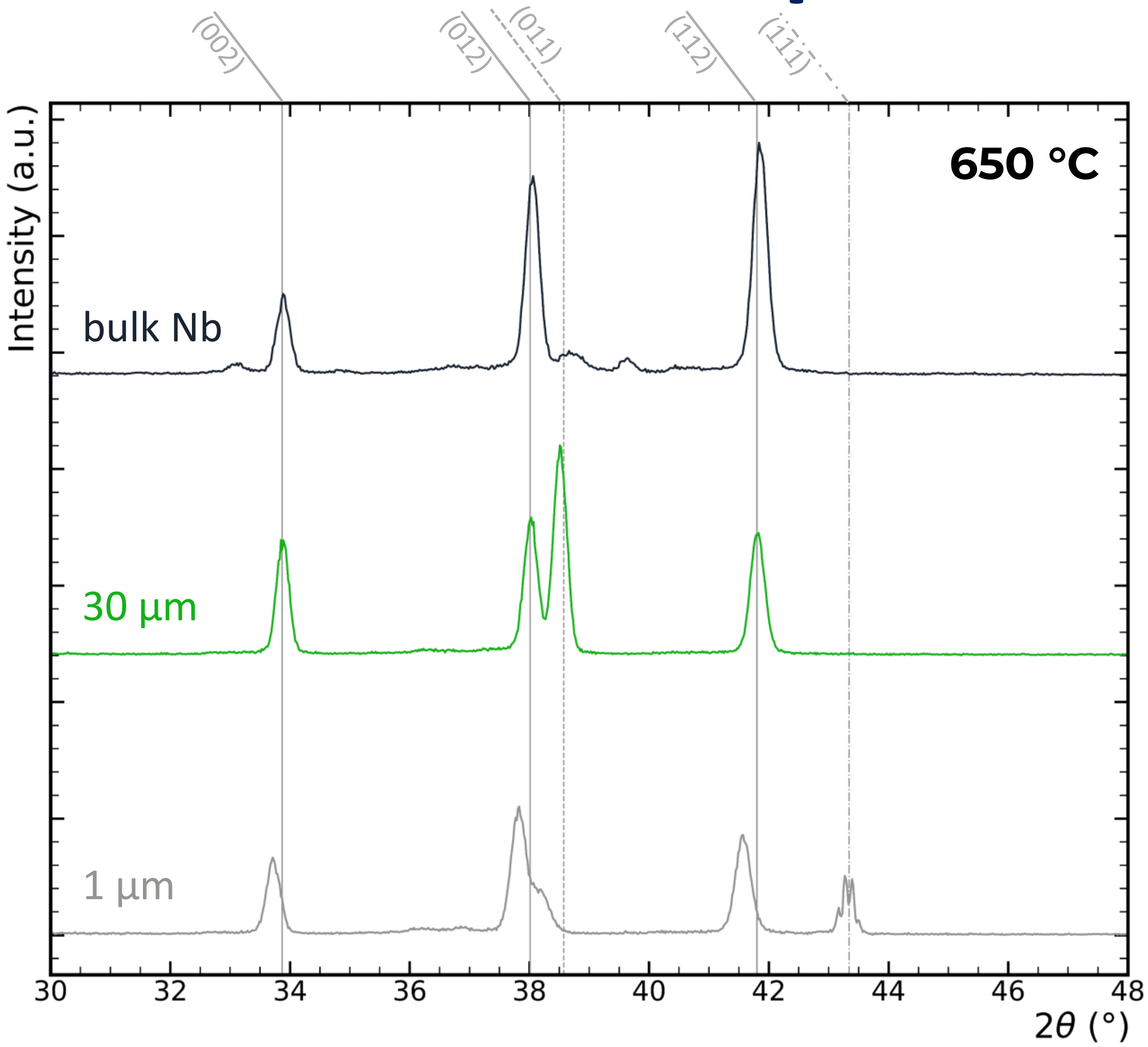
Recap: Nb_3Sn base recipe

- **Based on the observed results**
  - Low cathode power **< 20 W**
  - Deposition pressure **2 x 10^{-2} mbar**
  - **No annealing**
  - Deposition temperature **600 °C – 650 °C**

- **NbBL thickness plays a major role**

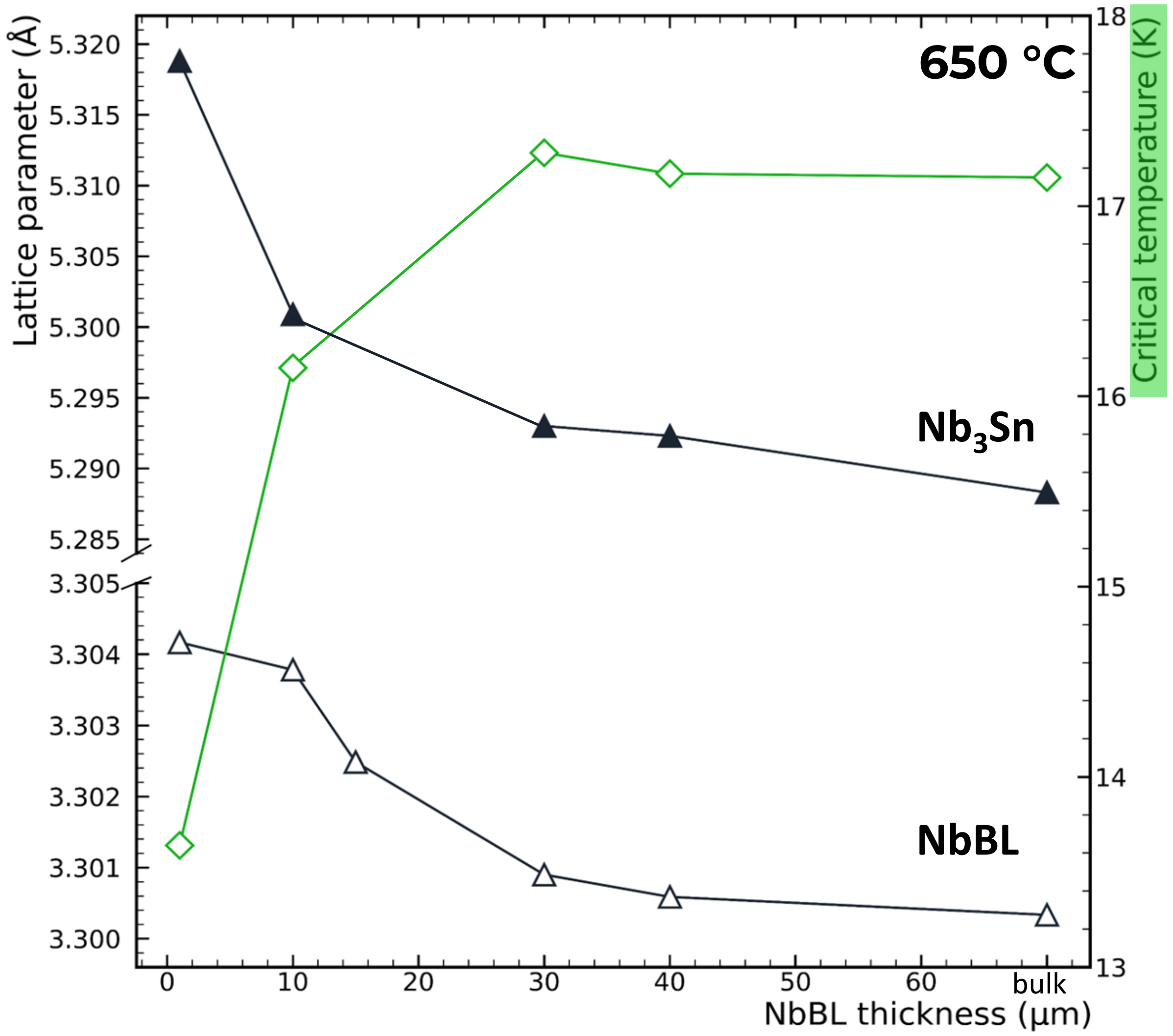
NbBL effect on lattice parameter

X-Ray Diffraction spectroscopy (XRD)



Peaks shift toward nominal values

NbBL effect: accommodation



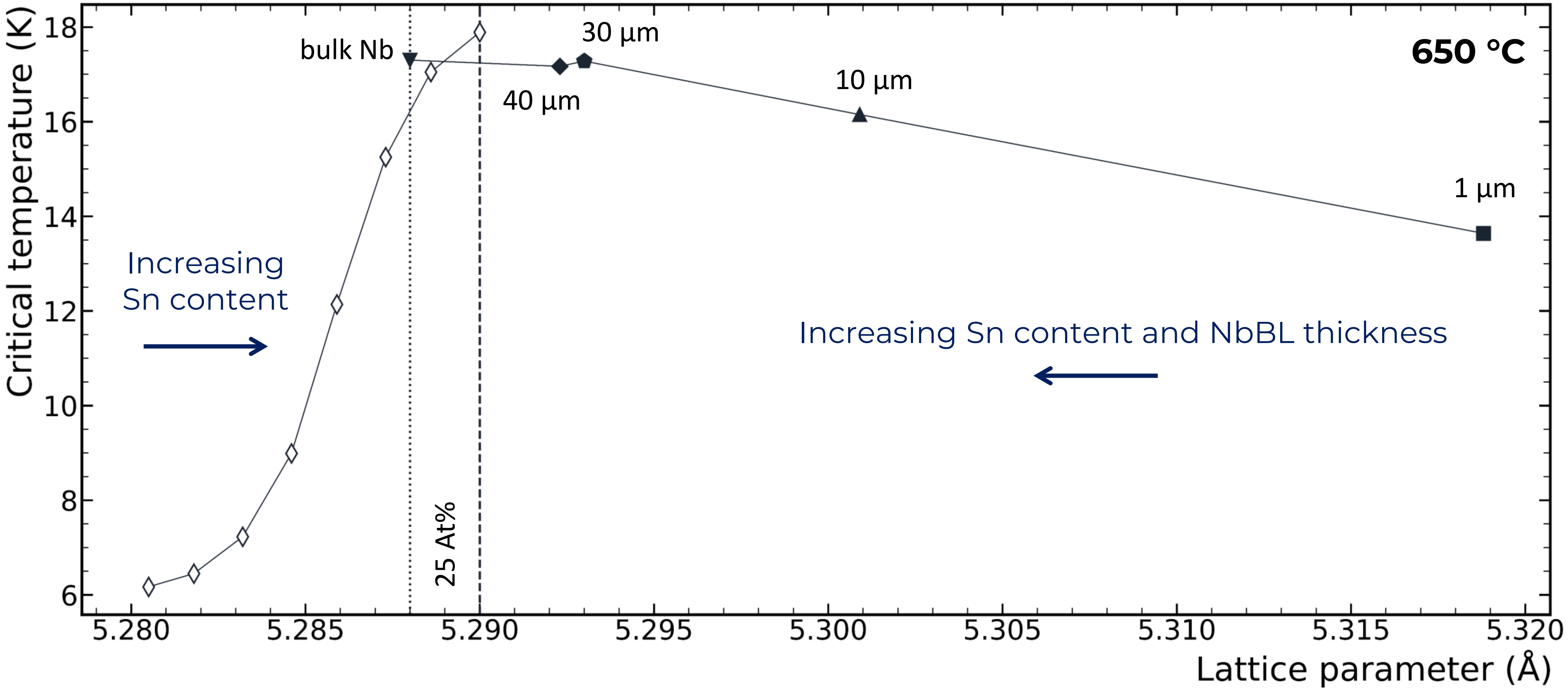
A thicker NbBL promotes the formation of the A15 phase (see T_c)

30+ µm is the "saturation" thickness

dorothea.fonnesu@lnl.infn.it

NbBL effect: accommodation

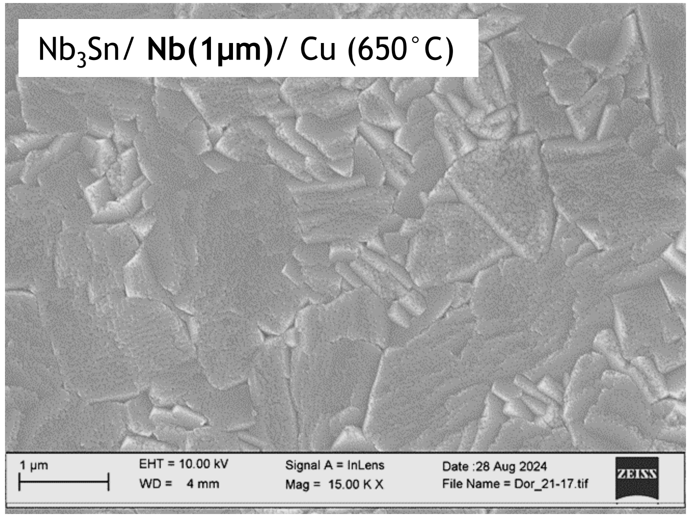
DCMS data comparison to literature data ◊ [A Godeke 2006 *Supercond. Sci. Technol.* 19 R68]



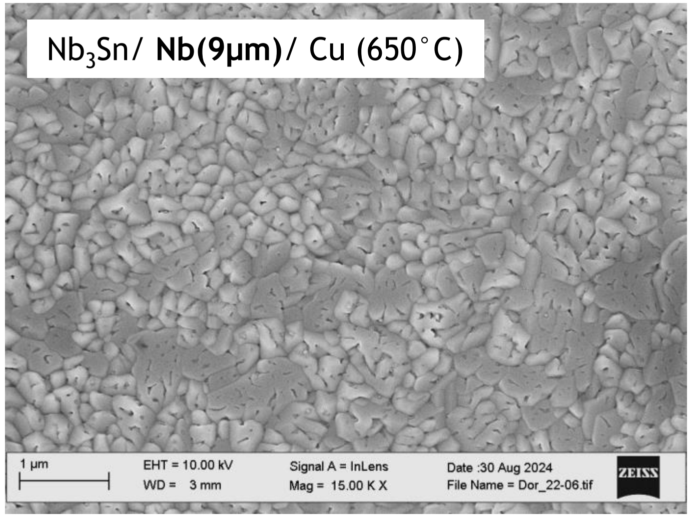
NbBL effect: morphology

LOT Lehrstuhl für Oberflächen- und Werkstofftechnologie

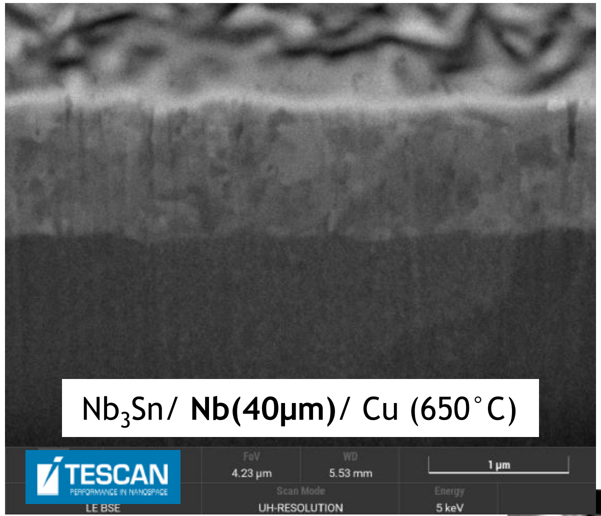
Scanning Electron Microscopy (SEM)



Nb_3Sn/ **Nb(1µm)**/ Cu (650°C)

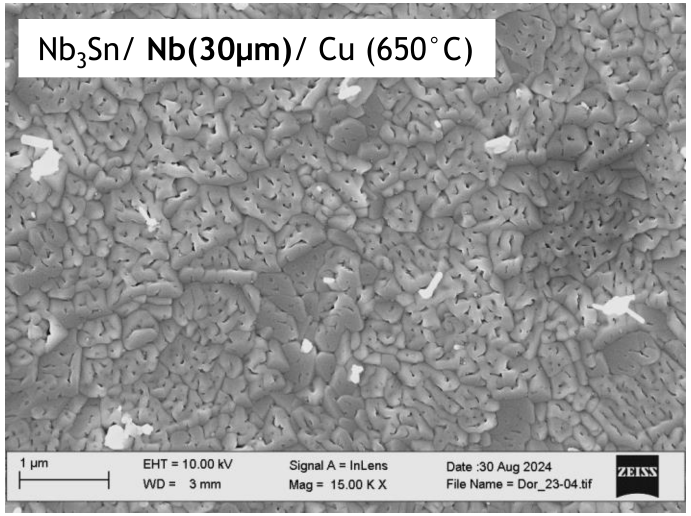


Nb_3Sn/ **Nb(9µm)**/ Cu (650°C)

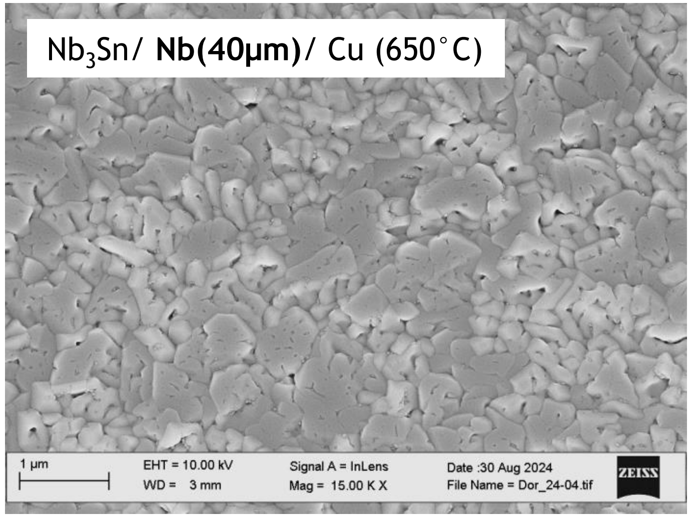


Nb_3Sn/ **Nb(40µm)**/ Cu (650°C)

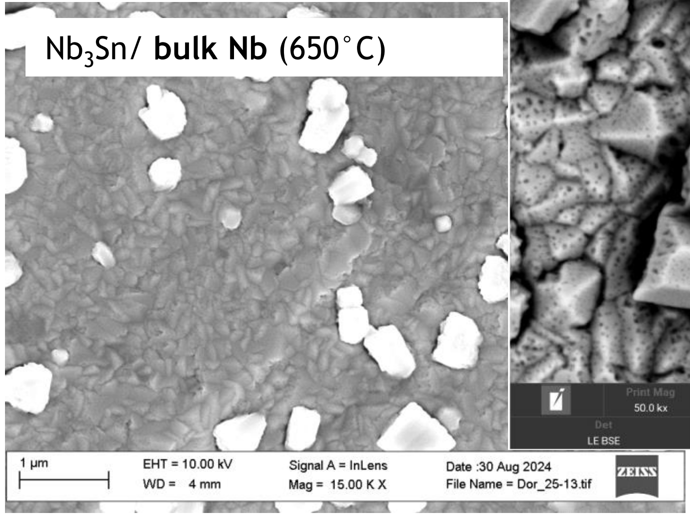
1µm



Nb_3Sn/ **Nb(30µm)**/ Cu (650°C)

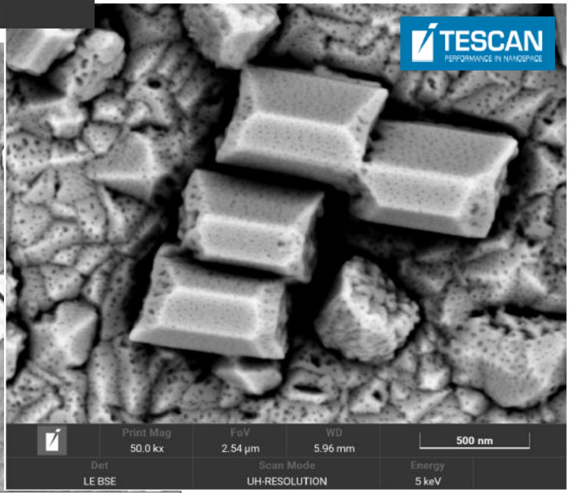


Nb_3Sn/ **Nb(40µm)**/ Cu (650°C)



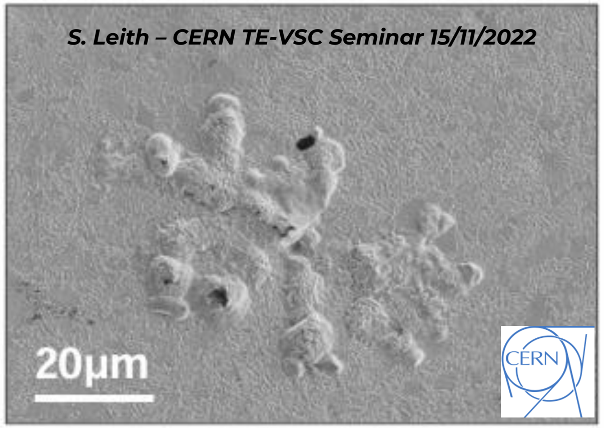
Nb_3Sn/ **bulk Nb** (650°C)

500 nm

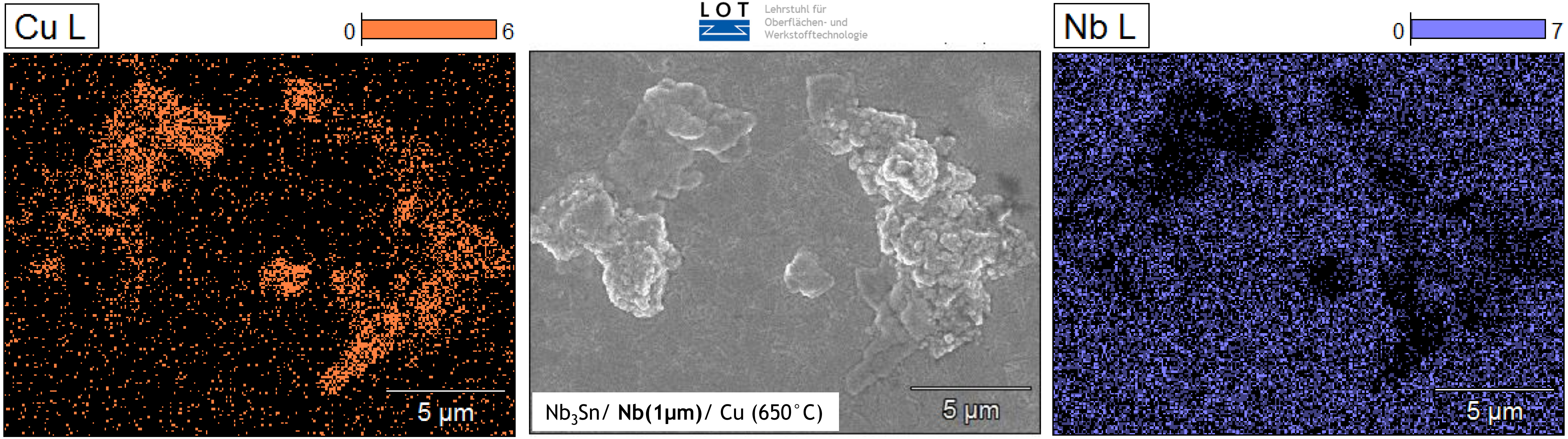


NbBL effect: morphology

Copper inclusions on film deposited on 1 µm NbBL



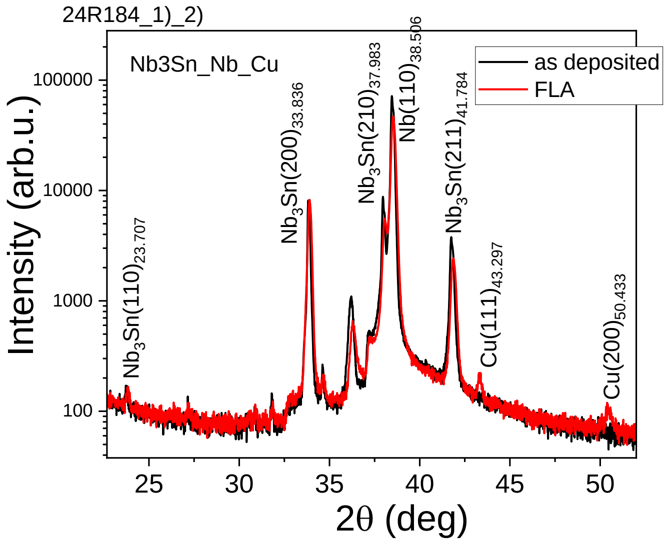
Scanning Electron Microscopy (SEM) + Energy Dispersive X-ray spectroscopy (EDX)

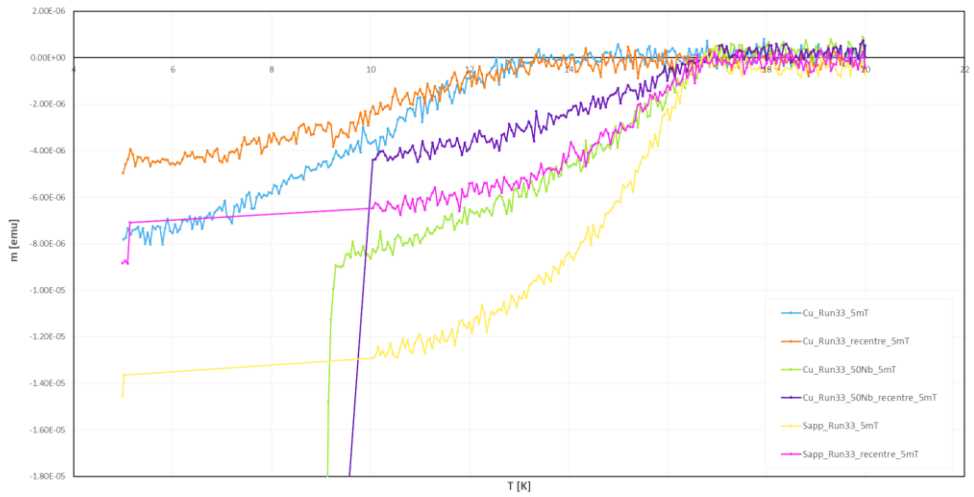


Additional studies

P. Vidal Garcia's talk later this morning!

- Magnetometry
- **RF surface impedance in high/low DC magnetic field**
- Superconducting gap
- Flash Lamp Annealing (FLA)
- laser treatment





2

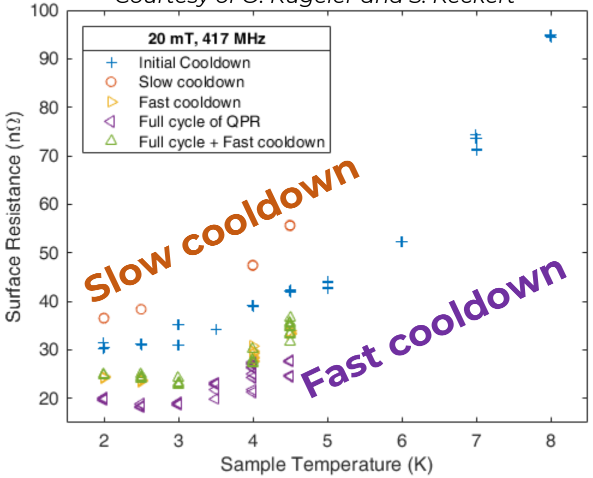
RF test results

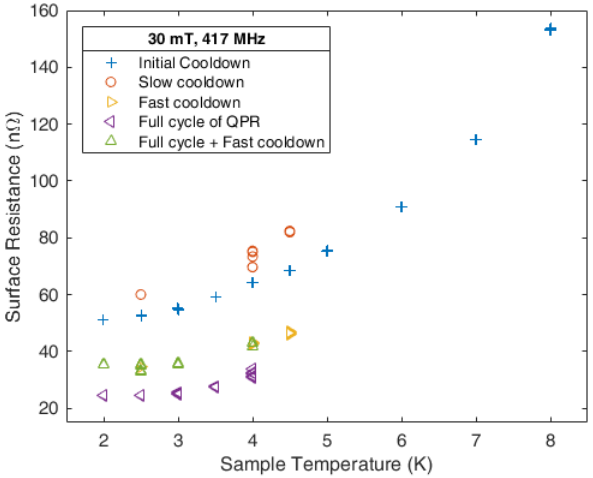
Nb$_3$Sn/bulk Nb QPR test

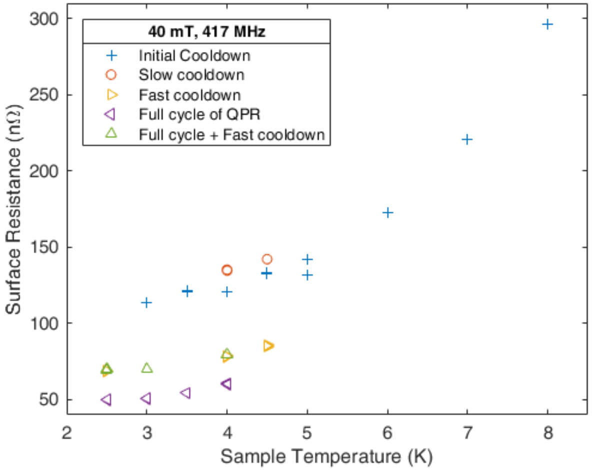
QPR = Quadrupole Resonator

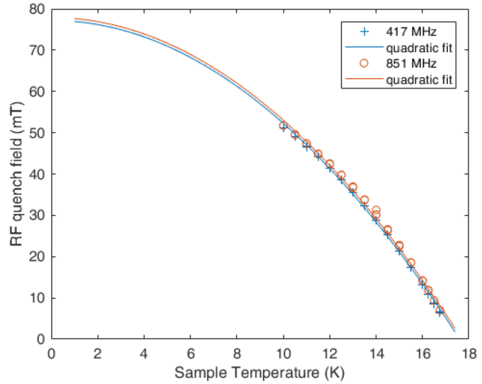
HZB Helmholtz Zentrum Berlin

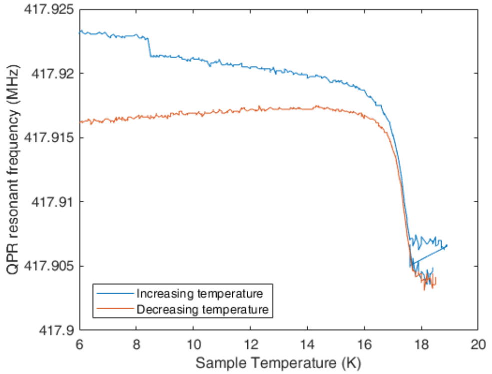
Courtesy of O. Kugeler and S. Keckert







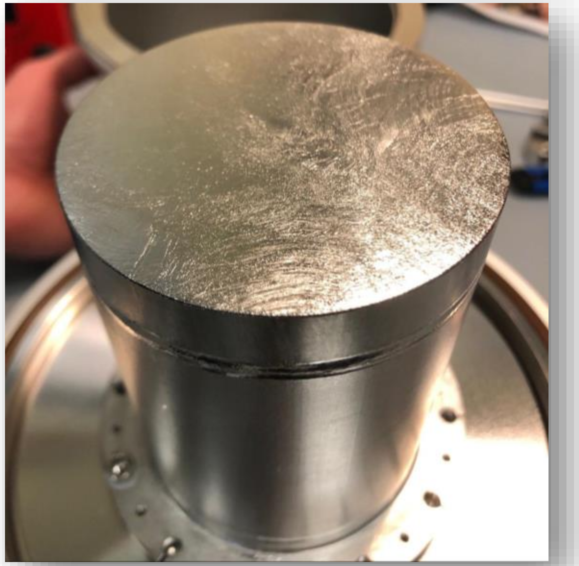




R_s ~ 23 nΩ @ 4.5 K, **20 mT**

Quench > 70 mT @ 4.5 K

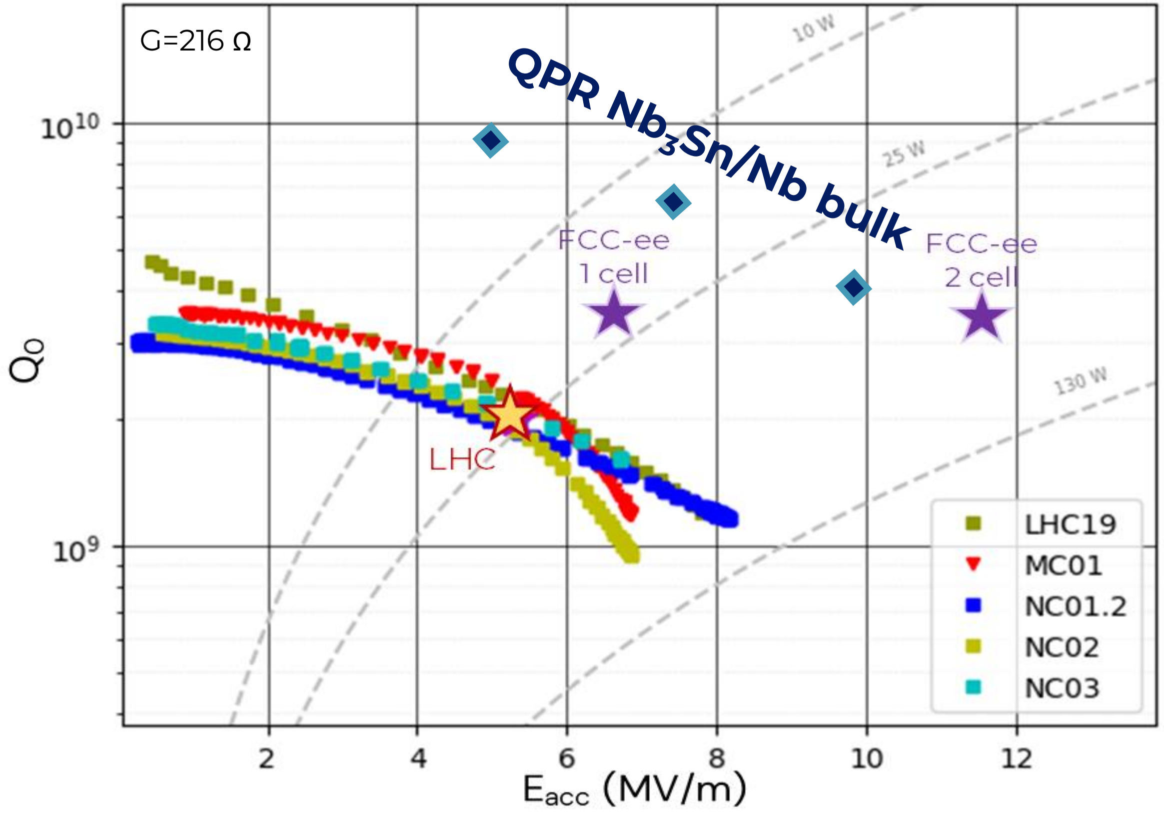
- **Nb$_3$Sn coating suffers from flux trapping**
- **Cooldown procedure influence R_s**



Nb_3Sn/bulk Nb QPR test

Comparison to LHC baseline: Q_0 vs. E_{acc} @ 4.5 K

LHC cavities
Nb/Cu 400 MHz

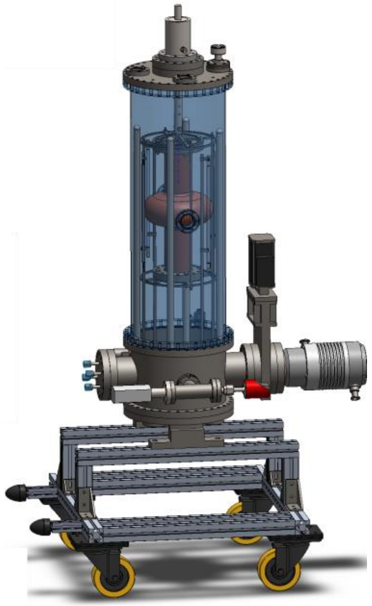


Equivalent to
Q_0 ~ 9 x 10^9
@ 5 MV/m
@4.5 K

3

Coating system for 1.3 GHz prototype

Nb_3Sn/Cu 1.3 GHz final prototype

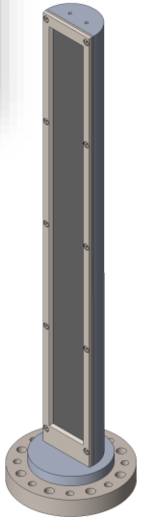


Nb_3Sn on bulk Nb to validate coating performances *on 1.3 GHz Elliptical Cavities (2025)*

Develop Nb thick barrier/accommodation layer *on 1.3 GHz Elliptical Cavities (2025)*
(proof of concept on 6 GHz cavities already done)

Nb_3Sn on Cu with thick Nb coating *on 1.3 GHz Elliptical Cavities (2026-2028)*

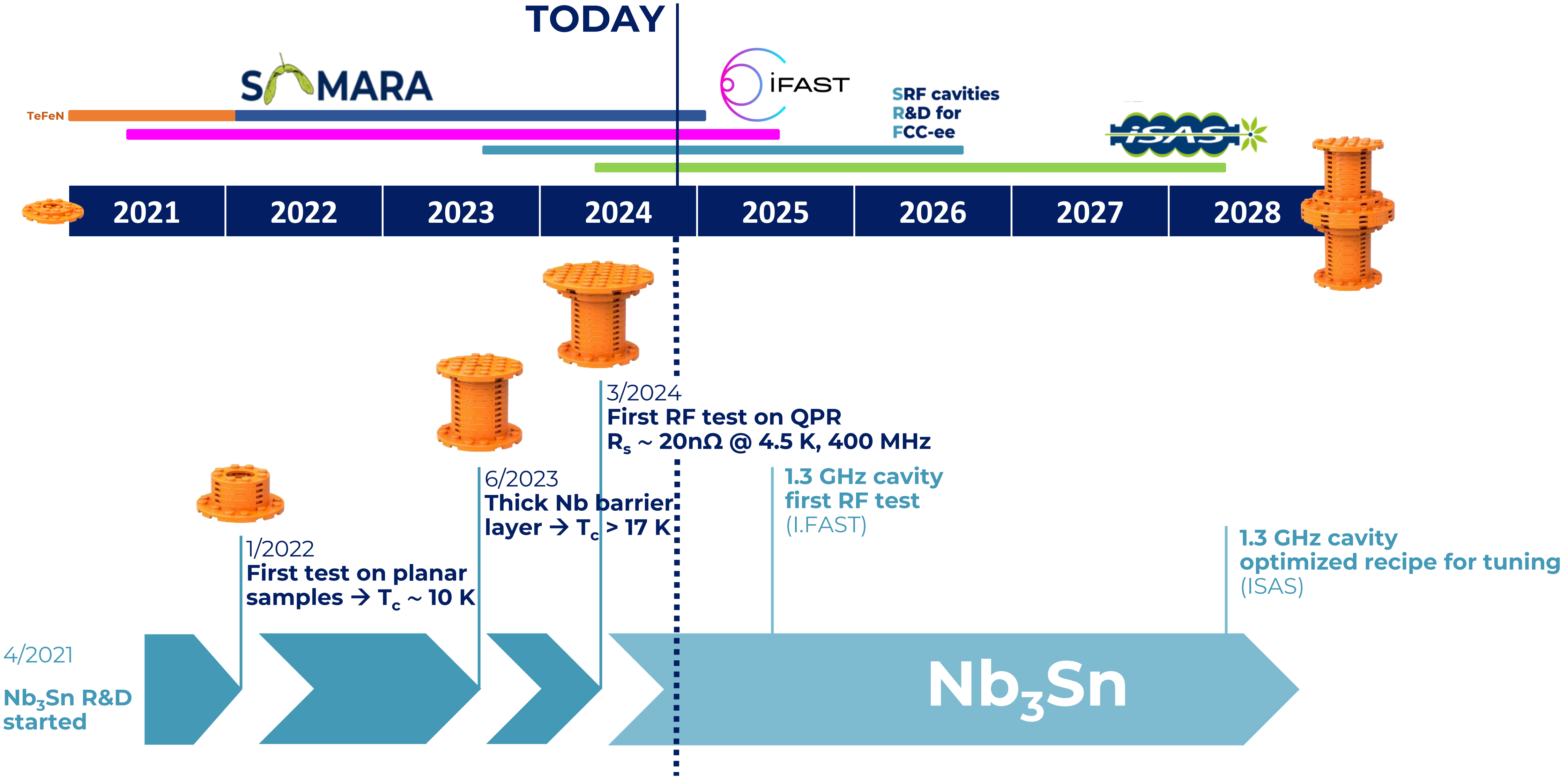
- 1.3 GHz vacuum system ready
- Magnetron source **commissioned**



In parallel:

- Study on alternative buffer layer
- Study on flux trapping

Timeline


TODAY
SAMARA
iFAST
SRF cavities
R&D for
FCC-ee
iSAS
TeFeN
2021
2022
2023
2024
2025
2026
2027
2028
3/2024
First RF test on QPR
R_s ~ 20nΩ @ 4.5 K, 400 MHz
6/2023
Thick Nb barrier layer → T_c > 17 K
1.3 GHz cavity
first RF test
(I.FAST)
1/2022
First test on planar samples → T_c ~ 10 K
1.3 GHz cavity
optimized recipe for tuning
(ISAS)
4/2021
Nb_3Sn R&D started
Nb_3Sn

Conclusion

- the optimization of **Nb_3Sn deposition recipe via DCMS** is at an advanced stage on small samples
  - ***T_c* ~ 17.5 K**
  - deposition temperature **600 °C - 650 °C**
  - thickness of **NbBL 30+ µm** → accomodation effect
- first RF test for film deposited on **bulk Nb on QPR sample**: promising **R_s ~ 23 nΩ** @ 4.5 K, 20 mT
- parallel work on **coating system for 1.3 GHz** with rectangular magnetron

Thank you!

dorothea.fonnesu@lnl.infn.it

Standard production process

(1) Set parameters:

Cathode power P

Deposition pressure p_{dep}

Deposition temperature T_{dep}

(2) 1 µm Nb_3Sn

Sapp
hire

Cu + **1 µm** Nb buffer layer (BL)

C
u

+ 24 h annealing

(3) Characterisation:

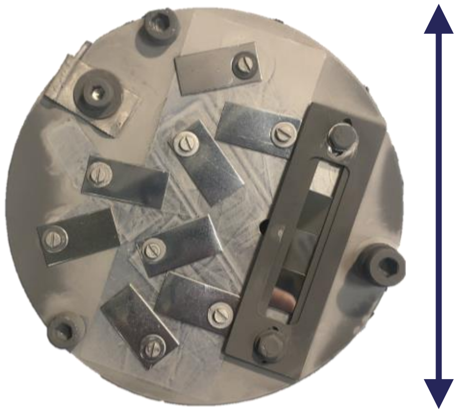
T_c measurement

SEM + EDS (Sn composition)

XRD

Tune next parameters based on trends (step 1)

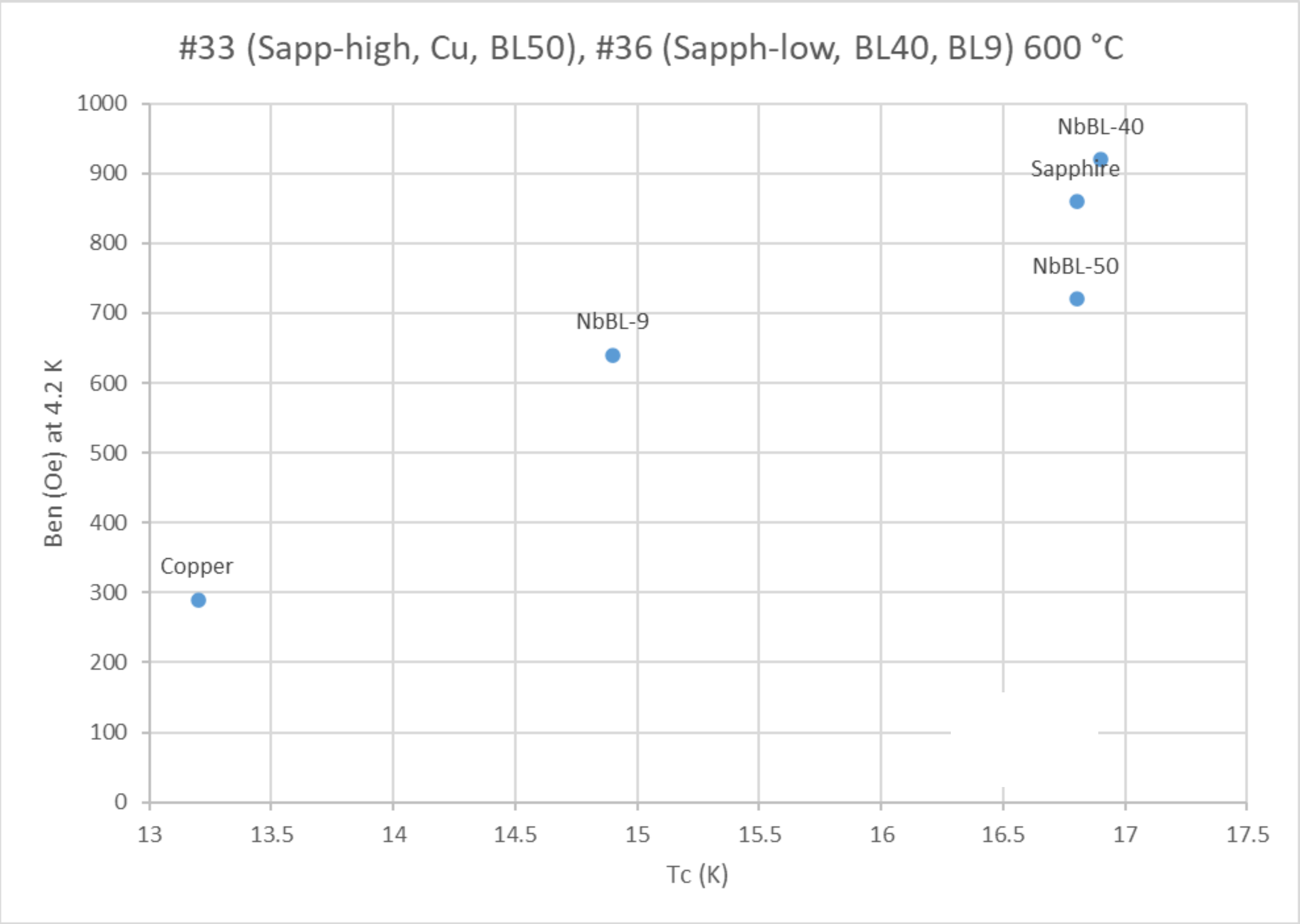
small samples on holder plate



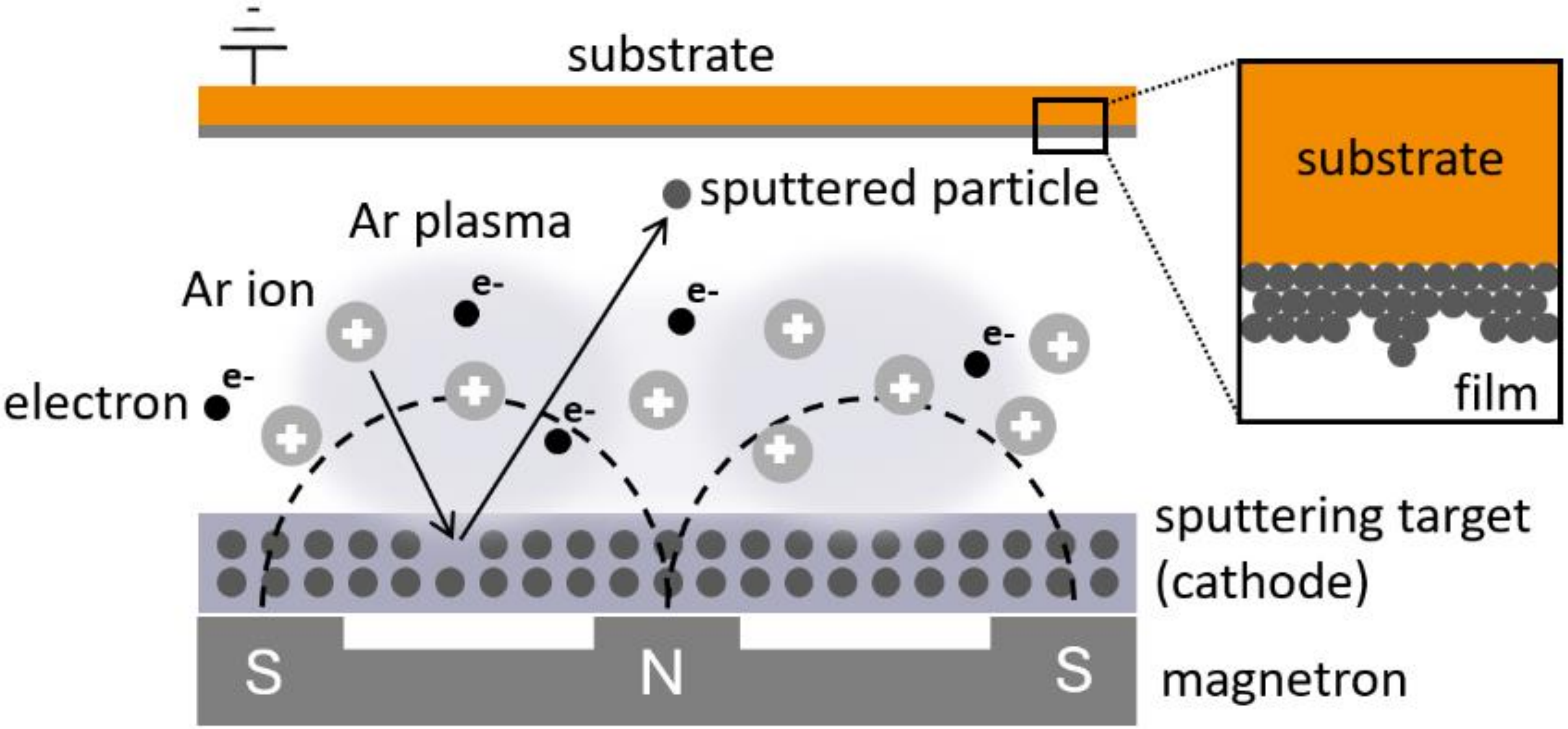
10 cm

Film properties

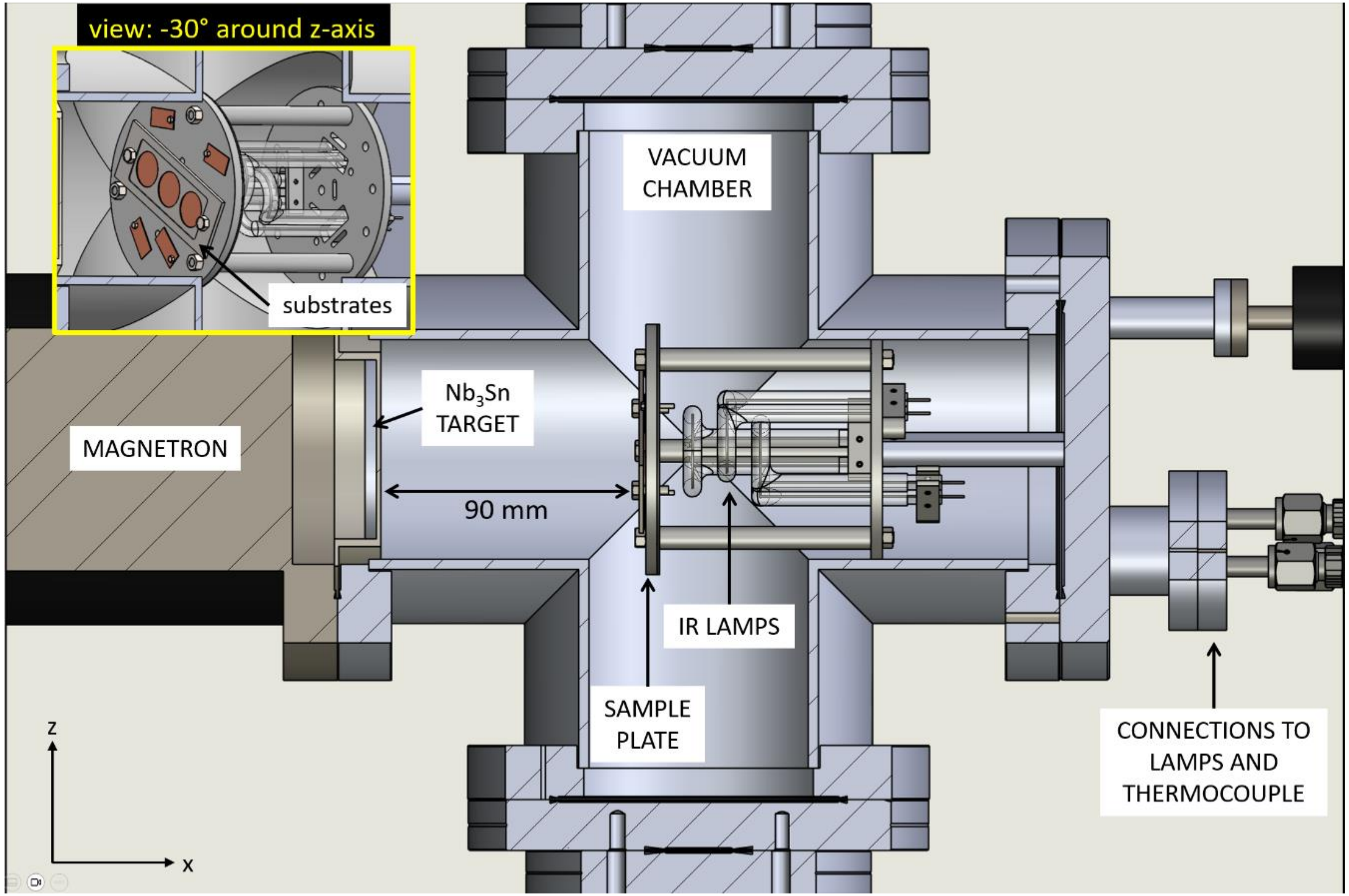
Field of first flux entry B_{en}



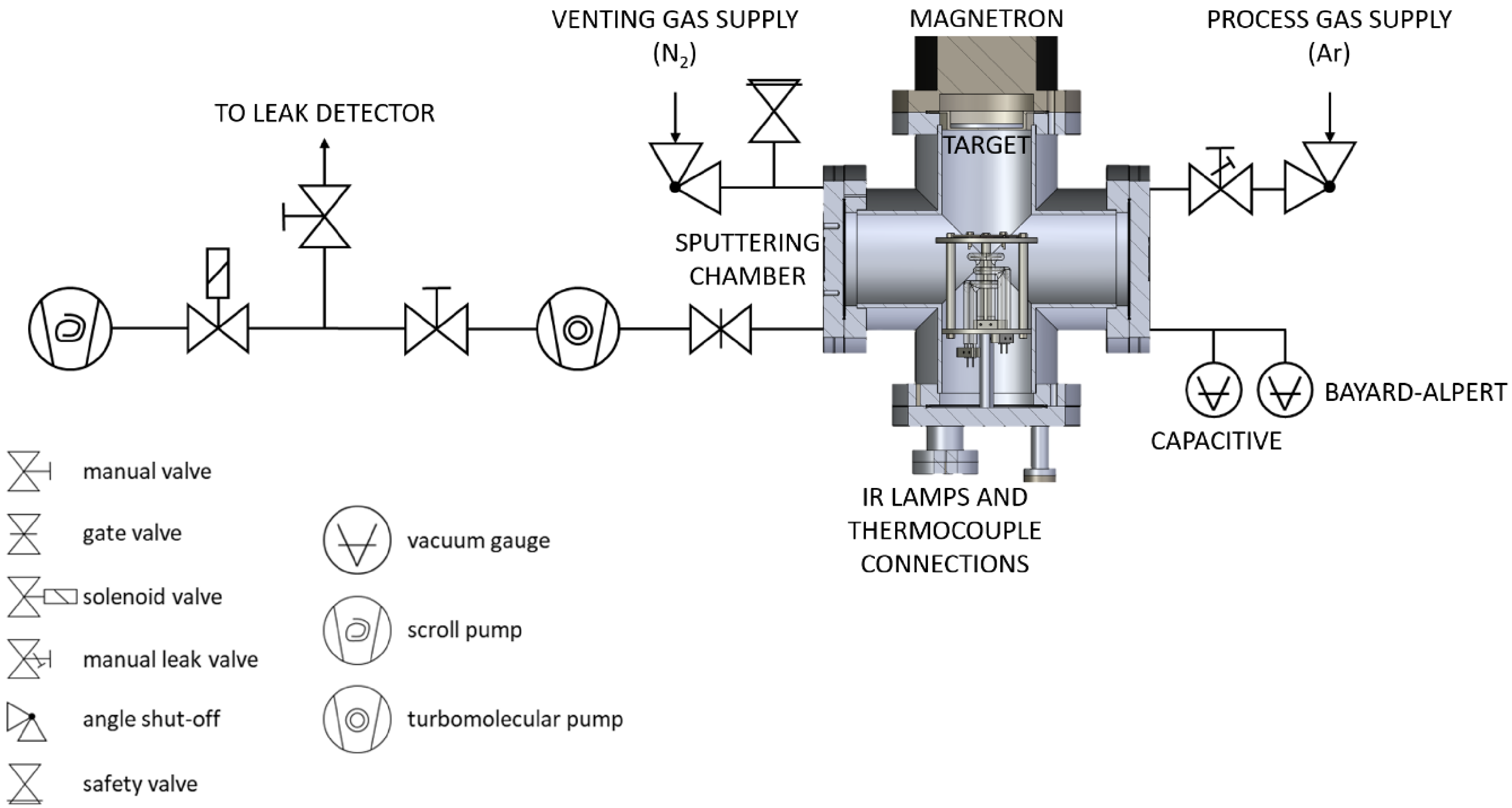
DC Magnetron Sputtering



Nb_3Sn deposition system



Nb_3Sn deposition system



Projects and partners:

- SAMARA (INFN CSN5)
  - INFN – LNL, INFN – TO, PoliTO, INFN – Roma3, INFN – LNF, Uni Roma 3, INFN – MI, INFN – LASA
- I.FAST WP9 (EU's Horizon 2020 Research and Innovation programme GA101004730)
  - IEE – SAS, RTU, Piccoli S.R.L., Uni Siegen, LOT, HZB, HZDR, CEA, IJC, UKRI, Uni Lancaster, Uni Liverpool, UniPD; INFORMAL: CERN, DESY; ASSOCIATED: JLab
- SRF (INFN Board for FCC R&D)
- ISAS (EU's Horizon Europe Research and Innovation programme GA101131435)
  - IEE – SAS, RTU, Piccoli S.R.L., Uni Siegen, LOT, HZB, HZDR, CEA, IJC, UKRI, Uni Lancaster, Uni Liverpool, UniPD, CERN, DESY, JLab, Fermilab
- SuperMAD (INFN CSN5)
  - INFN – LNL, INFN – TO, PoliTO, INFN – Roma3, INFN – LNF, Uni Roma 3, ENEA