Matteo Lazzari
INFN – Legnaro National Laboratories · Università degli Studi di Padova
on behalf of the LNL Surface Treatments & Superconductivity Team
◆ *PhD scholarship fully funded by Zanon Research & Innovation*

Nb_3Sn thin film development on 1.3 GHz cavities

12th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, 21–25 September 2026 Chester, United Kingdom

SUPPORTED BY

EU Horizon — iSAS (GA 101131435) & I.FAST (GA 101004730).
INFN CSN5 SuperMAD · CSN1 SRF, RD_FCC.

PROJECTS & COLLABORATIONS

EPITA · iFAST · iSAS · SuperMAD · SRF cavities R&D for FCC-ee (INFN Accelerators European Strategy Program) · RD_FCC (INFN CSN1 Experiment)

ACKNOWLEDGEMENTS

LNL SRF R&D — a collaborative effort

EU HORIZON PROGRAMMES

EPITA · iFAST · iSAS

INFN ACCELERATOR R&D

SRF cavities R&D for FCC-ee
INFN Accelerators European Strategy Program

RD_FCC
INFN CSN1 Experiment

SuperMAD

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- **HZDR**
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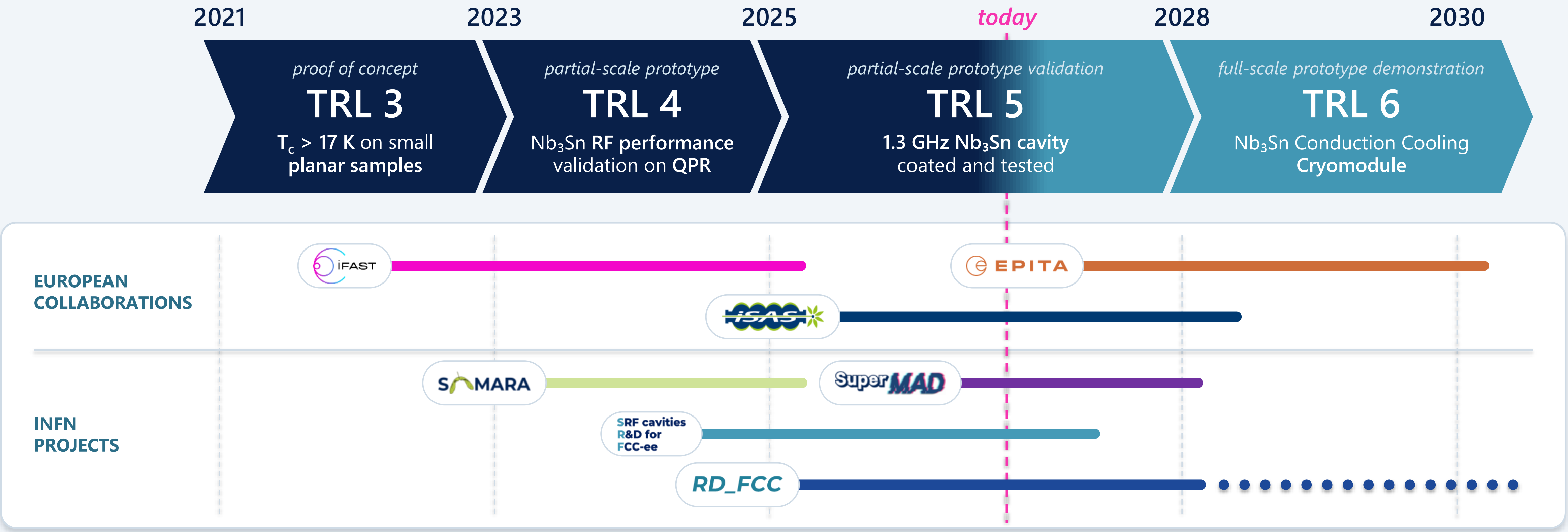
- **Riga Tech. Univ. · Piccoli**
  A. Medvids · R. Berton, D. Piccoli, F. Piccoli, G. Squizzato, F. Telatin

TECHNOLOGY READINESS LEVEL

Each EU project, a step up in TRL

Nb_3Sn-on-Cu has climbed the TRL ladder through successive European programmes.



TRL SCALE

1	2	3	4	5	6	7	8	9
Basic principles	Concept	Proof of concept	Lab validated	Relevant env.	Demonstrated	Operational prototype	Qualified	Proven in operation

OVERVIEW

Outline

01 **Nb_3Sn on a cavity**
Commissioning the coating system and first depositions on a mock-up cavity

02 **Future improvements of the system**
A rotating cavity: from design to construction

03 **Possible new film interface**
ALD oxide interlayers

→ **Next steps** — from the mock-up to an RF-tested Nb_3Sn cavity

PART 01

Nb_3Sn on a cavity

Commissioning the coating system and first depositions on a mock-up cavity

01

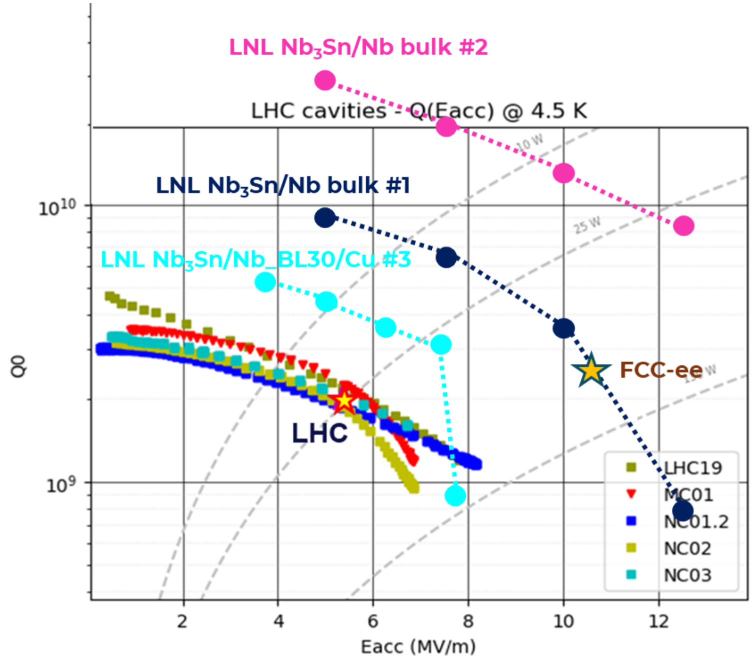
Moving the recipe onto a 1.3 GHz cavity

The recipe — validated on flat samples & QPR *

DCMS from a single stoichiometric Nb_3Sn target, T_c > 17 K on Cu

1. **Low cathode power** ~250 mW/cm²
2. **High deposition pressure** 2×10^{-2} mbar
3. **Deposition temperature** 600–650 °C
   → Heat the cavity in vacuum during coating, below the Cu limit
4. **No post-annealing**
   → A15 phase formed in situ: one single, hot deposition step
5. **Nb buffer layer** ~30 µm
   → Accommodation and diffusion barrier

QPR RESULTS



Sample #2	T_c	B_{peak}	R_s
Nb_3Sn on bulk Nb	17.45 K	> 85 mT	< 9 nΩ

* *D. Fonnesu et al., Recipe optimization and SRF test of Cu-compatible Nb_3Sn films by DCMS, Sci. Rep. 16, 3539 (2026).*

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THE LNL 1.3 GHz COATING SYSTEM

Magnetron inside the cavity

Full coating system

- **Fixed planar magnetron** — rectangular target on the axis
- **Rotating cavity** — turns around it for an even coating
- **Heated UHV chamber** — substrate up to ~670 °C

* *D. Fonnesu et al., Recipe optimization and SRF test of Cu-compatible Nb_3Sn films by DCMS, Sci. Rep. 16, 3539 (2026).*

Magnetron operating window & first depositions

STABLE OPERATING WINDOW

- **100 – 1500 mA** discharge current
- **$7.5\times10^{-3} - 6\times10^{-2}$ mbar** Ar pressure
- **up to 670 °C** substrate temperature

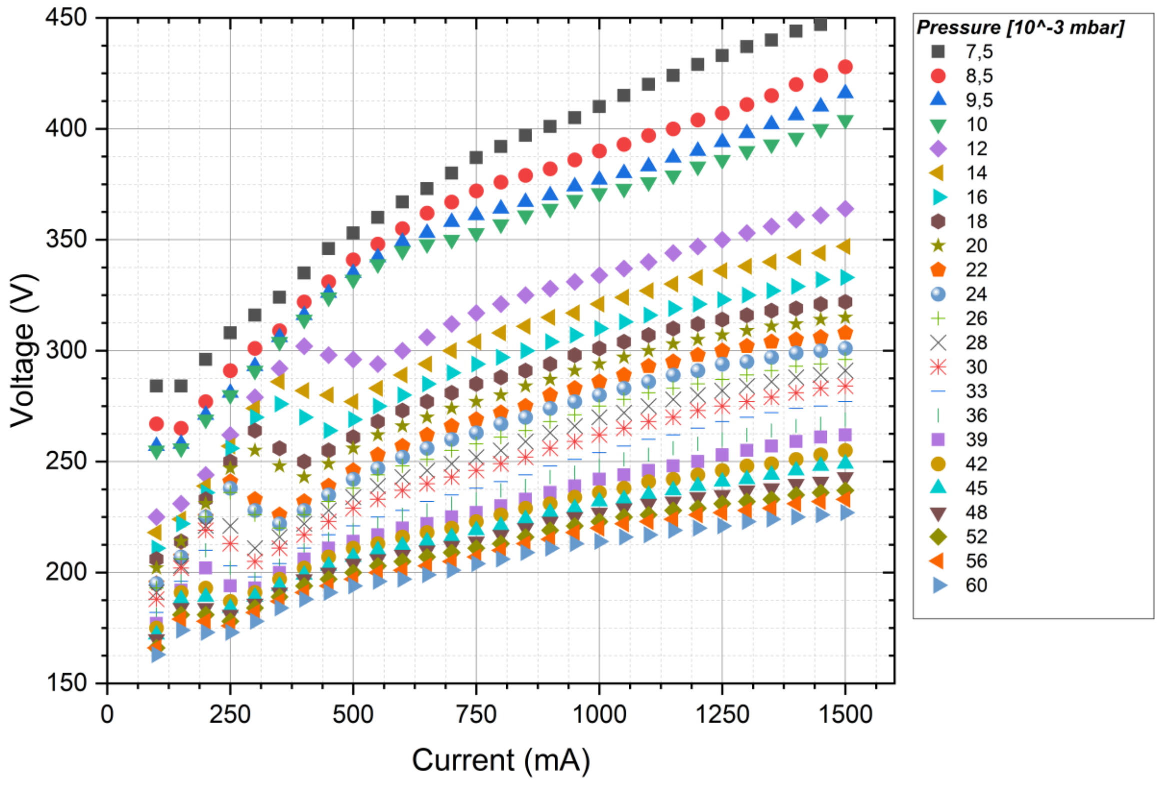
DEPOSITIONS TO DATE

12

8 × Nb
Runs for testing the magnetron set-up

4 × Nb_3Sn
First runs for parameter scaling/optimization study

DISCHARGE V–I CURVES



One curve per Ar pressure

A mock-up cavity with seven sample positions

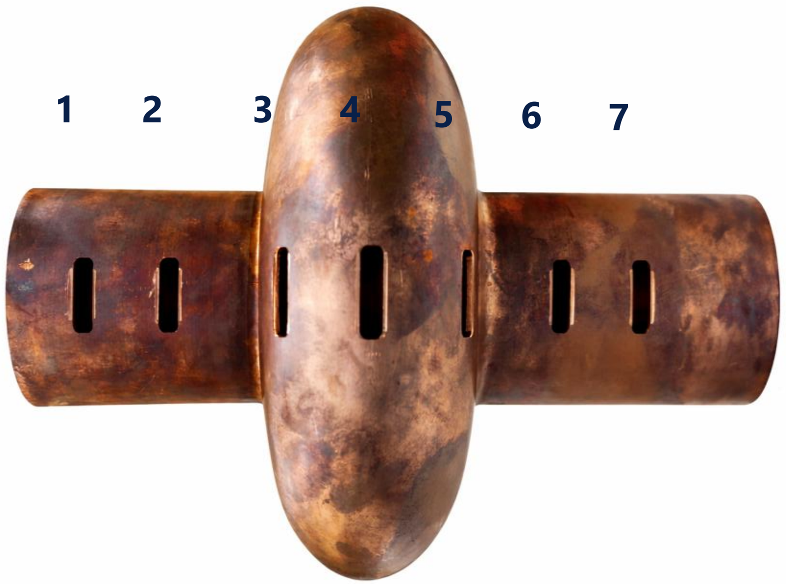
Seven positions studied separately

2 cut-off, 3 cell, 2 cut-off

- **Cavity-like conditions** — same pressure and temperature distribution as inside a real cavity
- **Fast testing** — samples analysed without coating a full cavity
- **Same target distance** — films compared under equal geometry
- **Repeatability** — controlled, identical starting conditions

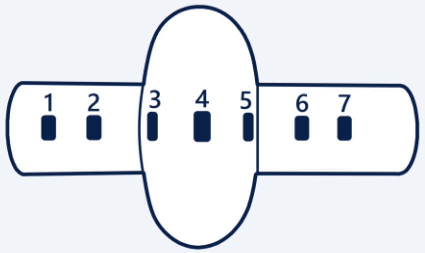
Why not real cavities?

Each cavity has its own substrate conditions (grain size, machining stress, actual distance from the target, batch variations)

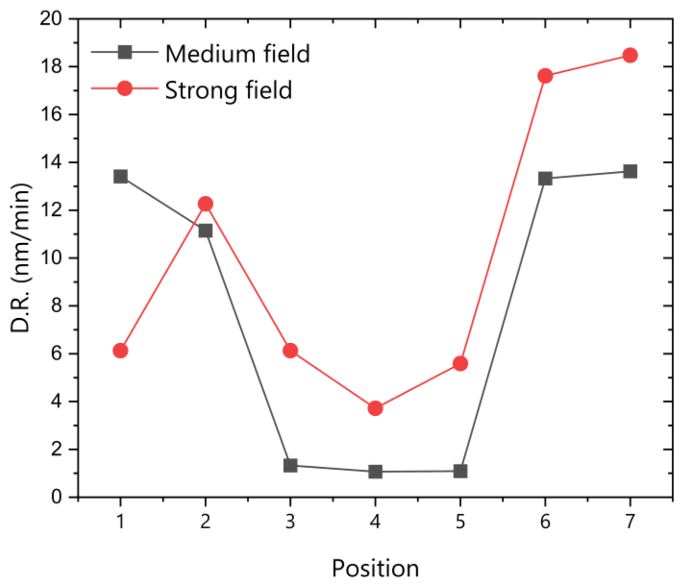


1–2, 6–7: cut-off (beam tubes), 3–5: cell

Magnet choice and process conditions

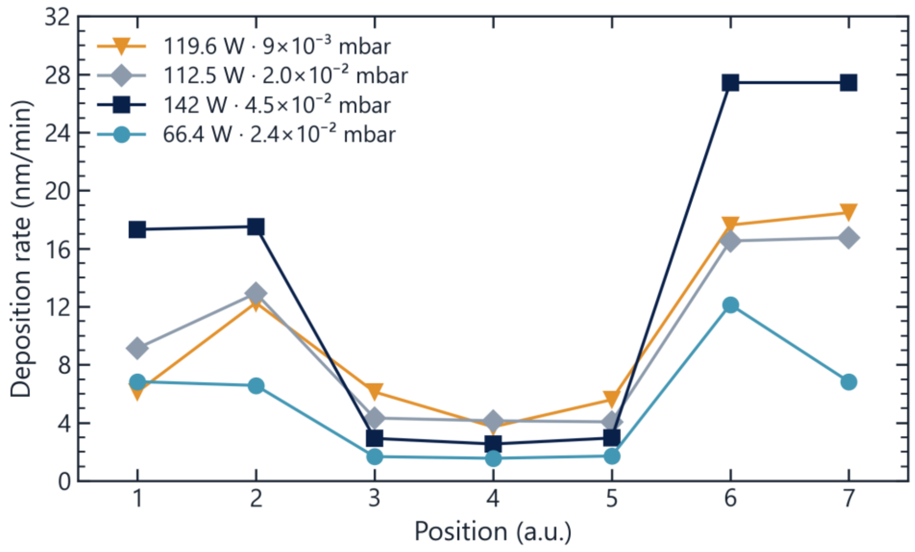


1 MAGNET CONFIGURATION



Two magnet configurations tested → **strong field** chosen: higher deposition rate.

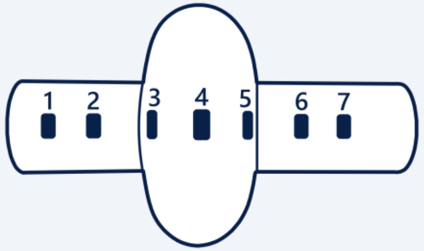
2 RATE PROFILE vs PROCESS CONDITIONS

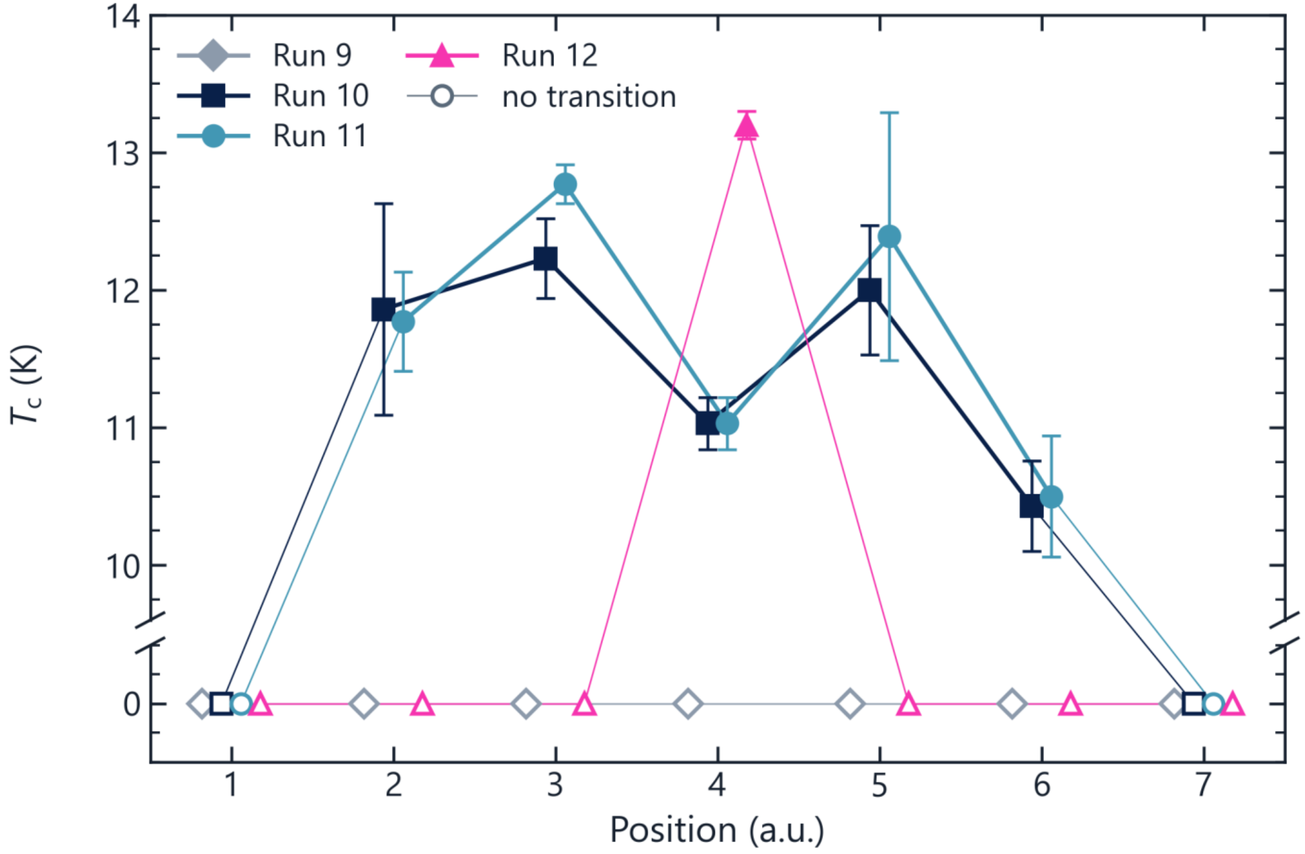


Deposition time set for a safety thickness on the cell (≈ 10 × Nb_3Sn London penetration depth), without an overly thick, stressed film at the cut-offs.

1 µm on the cell (@ ■ 2.8 nm/min) ≈ **6 h**

Different process conditions, similar T_c





Points offset along x for readability , T_c measurements: F. A. Costanzo

DEPOSITION PARAMETERS

	P (mbar)	T_s (°C)	Power (W)
◆ **Run 9**	2.0×10^{-2}	600	112.5
■ **Run 10**	4.5×10^{-2}	650	142
● **Run 11**	2.4×10^{-2}	650	66.4
▲ **Run 12**	1.2×10^{-2}	–	70.8

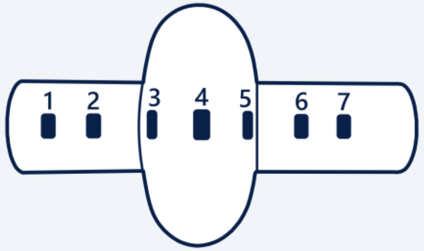
Key observations

Wide spread of process parameters (pressure, mean power), yet only small changes in T_c.

Broad, poorly defined transitions — hint at large variations of pressure and substrate temperature along the cavity.

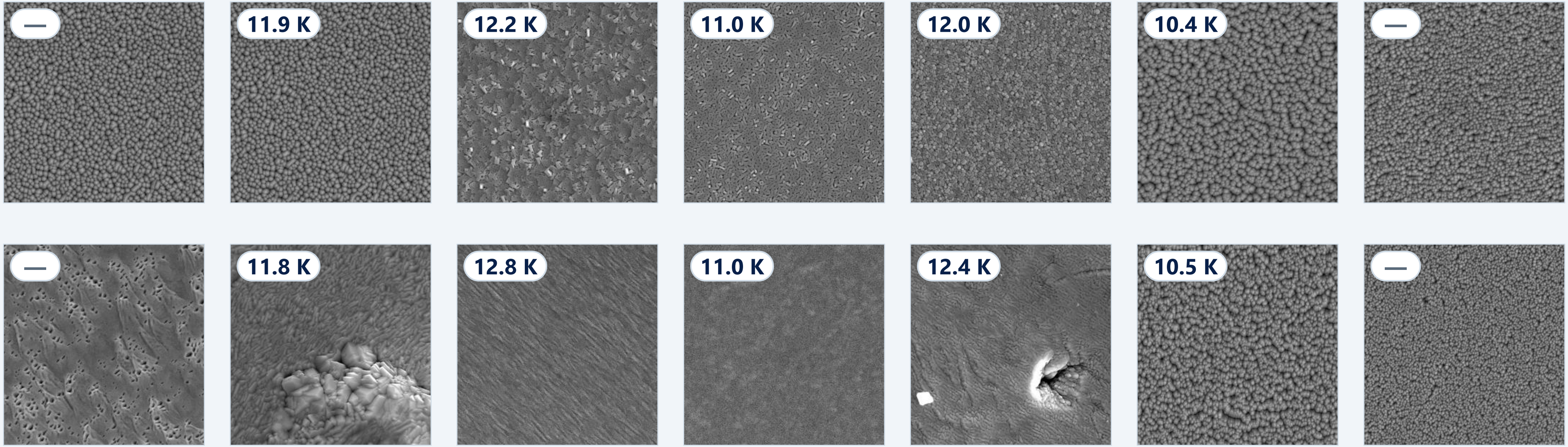
Run 9: no transition at any position.

Morphology, position by position



01 · Nb_3Sn **on a cavity**

	CUT-OFF 1	CUT-OFF 2	CELL 3	CELL 4	CELL 5	CUT-OFF 6	CUT-OFF 7
Run 10 142 W 4.5×10^{-2} mbar	—	11.9 K	12.2 K	11.0 K	12.0 K	10.4 K	—
Run 11 66.4 W 2.4×10^{-2} mbar	—	11.8 K	12.8 K	11.0 K	12.4 K	10.5 K	—



SEM, SE 15 kV · all images at the same scale · T_c above each image (— : no transition)

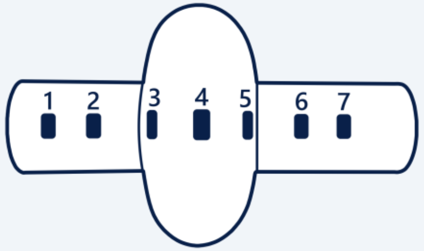
5 µm

Several morphologies along the cavity
Causes under investigation: pressure gradient, temperature gradient

Same region, different structure when parameters change
Can we reach a uniform film along the whole cavity?

SEM ANALYSIS

Morphology, compared with past samples



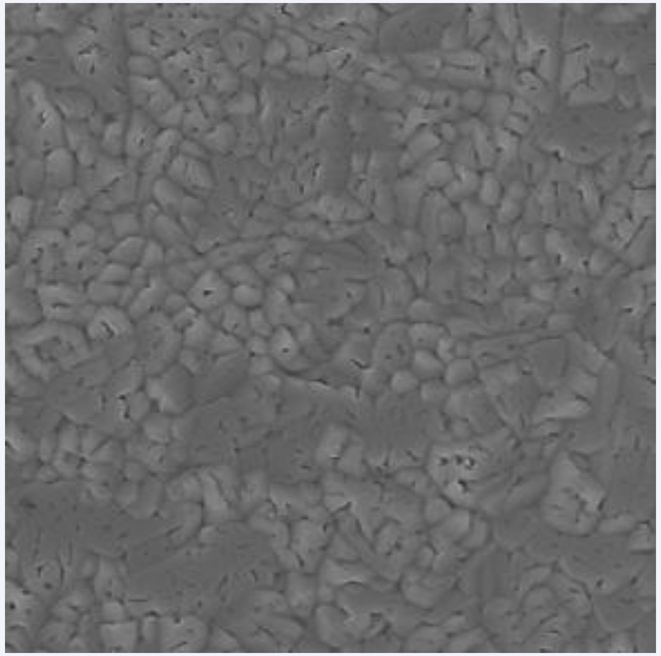
01 · Nb_3Sn on a cavity

SMALL SAMPLE

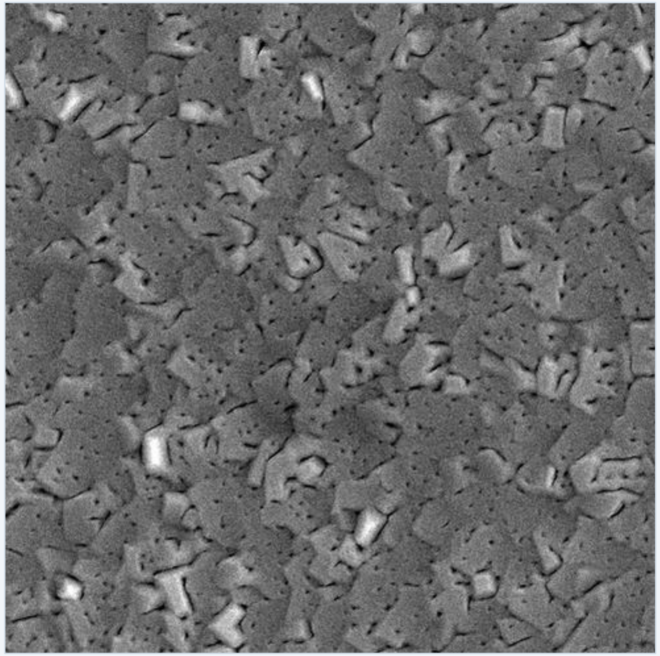
Cu + 15 µm Nb buffer layer

Flat sample, 2024

SEM InLens · 10 kV · ×15k



1 µm



1 µm

MOCK-UP CAVITY

Sapphire

Run 10 · position 3 (cell)

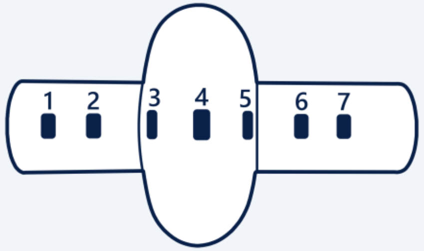
SEM SE · 15 kV · ×10k

Same scale: *both images cropped to a 4.9 × 4.9 µm field (originals taken at ×15k and ×10k)*

Comparison in progress
Small samples we already have vs. new films deposited in the cavity

Morphology as a process indicator
Mainly for temperature and pressure consideration

Similar T_c on different substrates



SUBSTRATE AT EACH POSITION

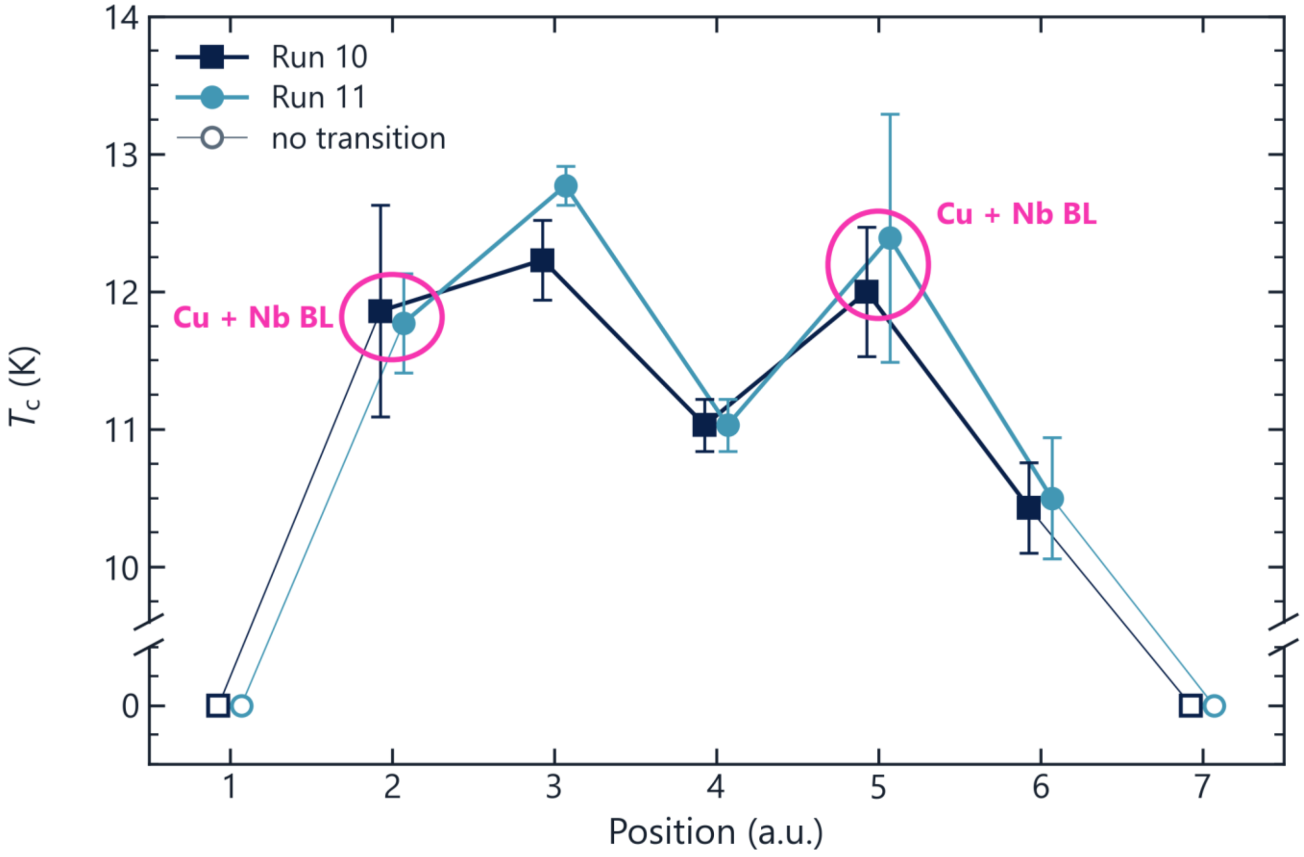
Position	■ Run 10	● Run 11
1	Sapphire	Sapphire
2	Sapphire	**Cu + Nb BL 15 µm**
3	Sapphire	Sapphire
4	Sapphire	Sapphire
5	Sapphire	**Cu + Nb BL 15 µm**
6	Sapphire	Sapphire
7	Sapphire	Sapphire

Same T_c, different substrate

Pos. 2: 11.9 K (sapphire) vs 11.8 K (Cu + Nb BL)

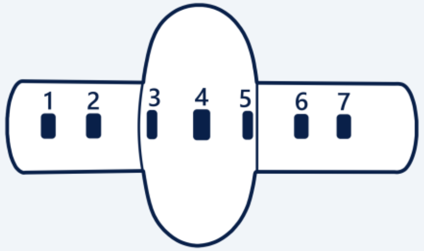
Pos. 5: 12.0 K (sapphire) vs 12.4 K (Cu + Nb BL)

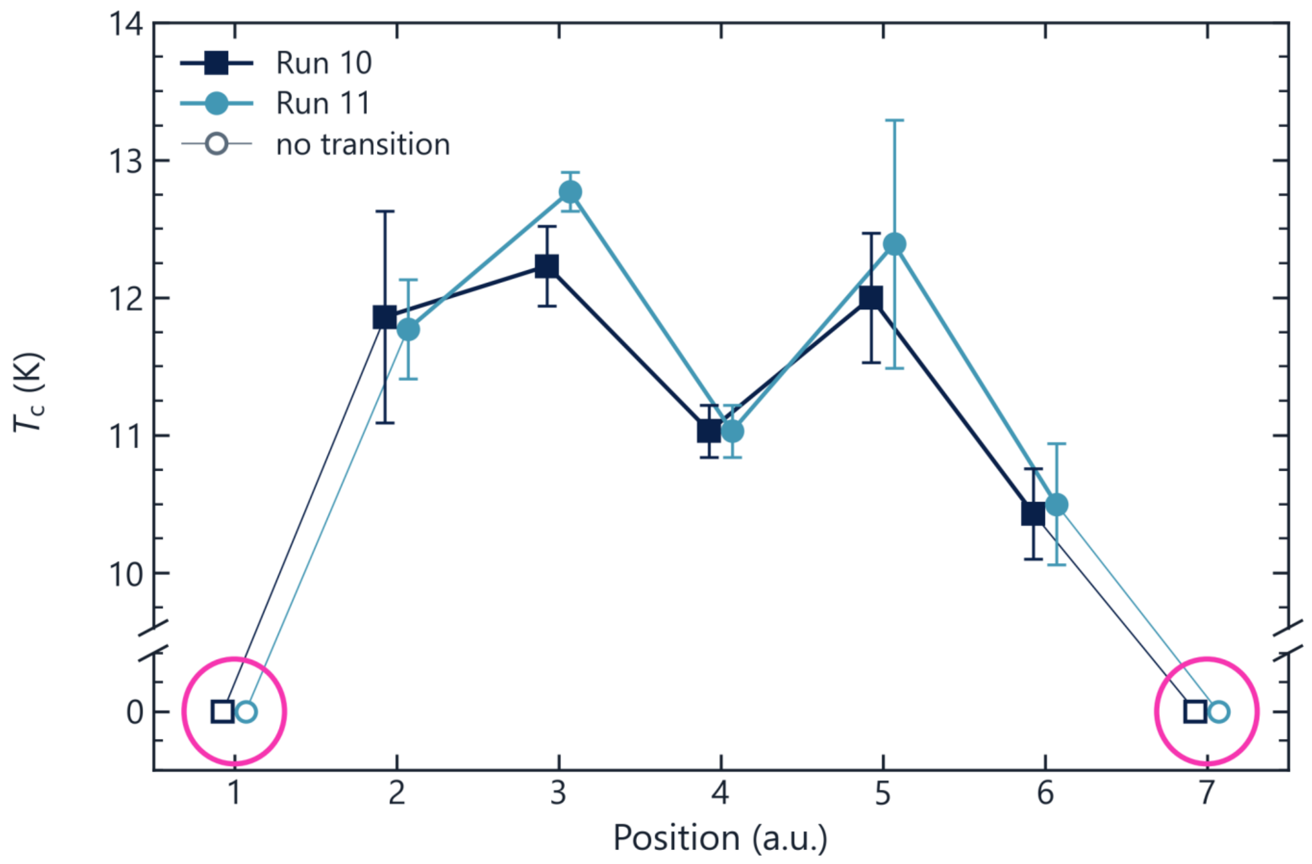
The driver doesn't seem to be the sputtering parameters alone, but their **uniformity along the cavity axis**.



Circled: Run 11 on Cu + Nb BL (15 µm), all others on sapphire. Open symbols: no measurable transition

T_c follows the position; no transition at the ends





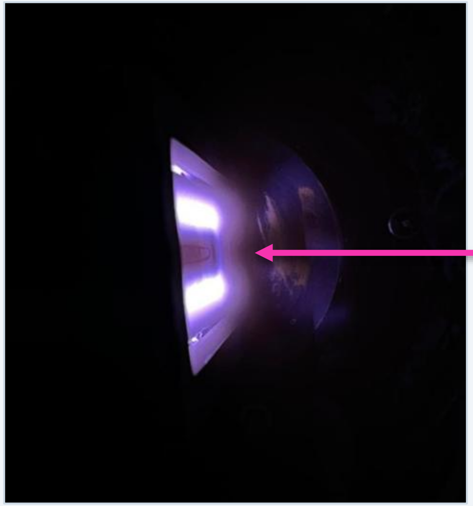
Circled: end positions 1 and 7 — no measurable transition in either run

Key observations

Same position → similar T_c in both runs: the target–substrate distance seems to dominate.

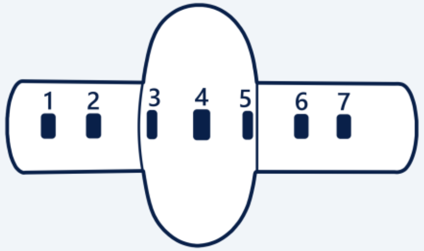
No transition at the ends (pos. 1, 7), likely where the magnetic field no longer closes the plasma.

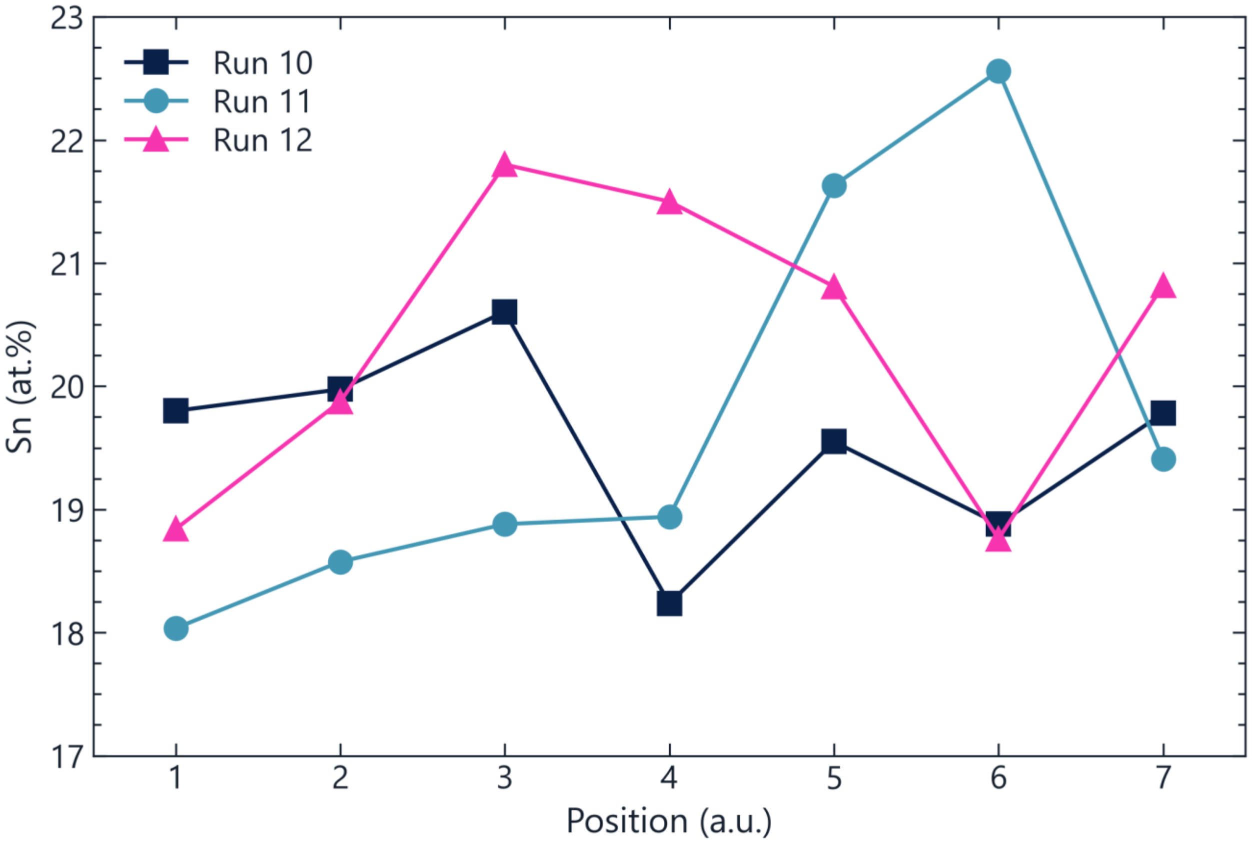
Same thickness in the cut-off



Plasma not closing
no-plasma region

Sn content along the cavity





Sn content measured by EDX at each of the seven positions

Sn CONTENT PER RUN

Required Sn % > 24%

■ Run 10

mean **19.5** at.%

range **18.2 – 20.6**

● Run 11

mean **19.7** at.%

range **18.0 – 22.6**

▲ Run 12

mean **20.3** at.%

range **18.8 – 21.8**

All within the A15 range (18–26 at.%), yet Sn-poor

SUMMARY

Lessons learned and further investigations

1

The system works and also the testing procedure

Stable magnetron from 0.1 to 1.5 A and 7.5×10^{-3} to 6×10^{-2} mbar, up to 670 °C, 12 depositions (8 Nb, 4 Nb_3Sn).

2

Geometry counts

Deposition rate and T_c depend on the position along the cavity.

3

Substrate temperature and pressure

Uniformity has to be investigated along the cavity and also good thermal contact

PART 02

Future improvements of the system

A rotating cavity: from design to construction

02

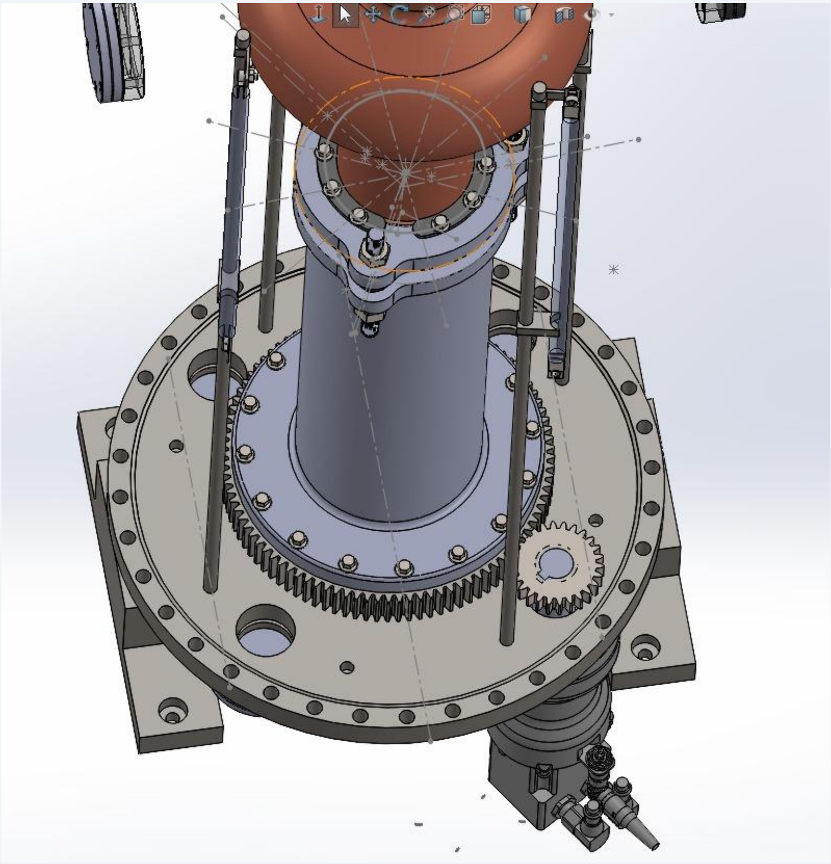
Rotating the cavity: from design to construction

FOUR REQUIREMENTS

1. **Clean rotation** — no lubricant inside the vacuum
2. **x–y adjustment and tilt** — to align the rotation axis with the magnetron axis
3. **Thermal shielding** — of the upper parts of the system
4. **Motor outside the vacuum** — slow rotation, < 10 rpm

STATUS

- ✓ **Design review** — done
- ✓ **Design phase** — completed
- → **Parts ordered** — construction by the end of 2026



Design and mechanical calculations: T. Subasinghe

PART 03

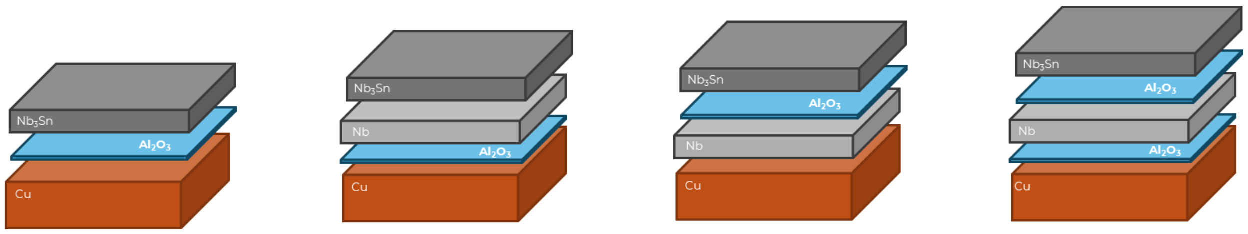
Possible new film interface

03

ALD oxide interlayers

CEA adaptive layer between Cu and the Nb buffer

SCHEMES TESTED WITH CEA



✗ **No Nb buffer** ✓ **ALD under Nb** **ALD above Nb** **ALD both sides**

Low T_c without the Nb buffer · $T_c \approx 17$ K with the adaptive layer between Cu and Nb

T_c BY BUFFER LAYER

Buffer layer	T_c (K)	ΔT_c (K)
✗ No buffer layer	13.8	0.3
16 µm Nb	16.5	0.6
30 µm Nb	16.7	0.5
✓ 30 µm Nb + 18 nm Al_2O_3	16.3	0.5
✓ 30 µm Nb + 25 nm $AlZrO_x$	16.9	0.2
✓ 30 µm Nb + 5 nm Al_2O_3 + 22 nm ZrO_2	16.8	0.2

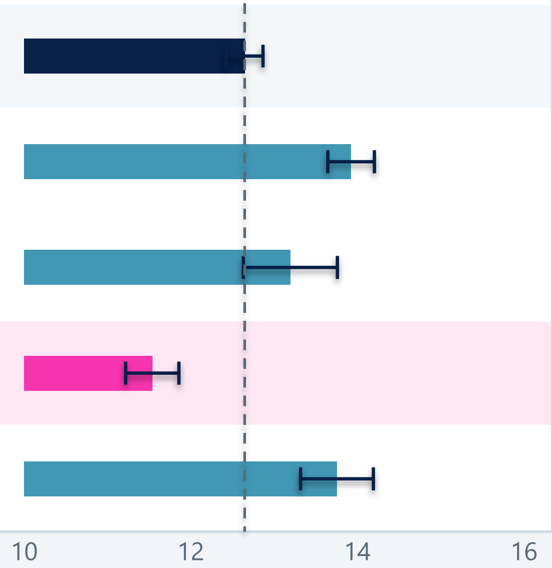
INFN LNL × cea

TWO GOALS

1. **Reduce or completely avoid the thick Nb buffer layer**
2. **Stop the thermoelectric currents between the layers**

First T_c without a Nb buffer layer

Sample · ALD interlayer	T_c (K)
Cu 30 µm (control)	**12.65** ± 0.22
✓ AlZrO (1:4), 48 cycles (≈4.8 nm)	**13.93** ± 0.28
✓ Al_2O_3, 180 cycles (≈18 nm)	**13.20** ± 0.57
✗ **Al_2O_3 50 cy + ZrO_2 270 cy (≈32 nm)**	**11.54** ± 0.32
✓ ZrO_2 · 270 cycles (≈27 nm)	**13.76** ± 0.44



T_c (K), dashed: Cu control (12.65 K)

! A run below par

This run went wrong — the value is not representative

✓ Single layers perform alike

Al_2O_3, ZrO_2 and AlZrO: T_c 13.2–13.9 K, above the Cu · 30 µm control

✗ The mixed stack lags behind

Al_2O_3 + ZrO_2: 11.5 K, the lowest of the series

Next: XRD, EDS

Next steps

From the mock-up to an RF-tested Nb_3Sn cavity

2026 — ◆ *we are here*

Mock-up cavity
system commissioning and first Nb_3Sn films

End 2026 – 2027

Small-sample optimisation
+ construction of the rotation system

2027

First coatings on Nb cavities
higher temperatures allowed, easy RF baseline before/after coating

End 2027 – 2028

First Nb_3Sn-coated Cu cavity
full RF test campaign

Thank you

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LNL Surface Treatments & Superconductivity Team · INFN–LNL
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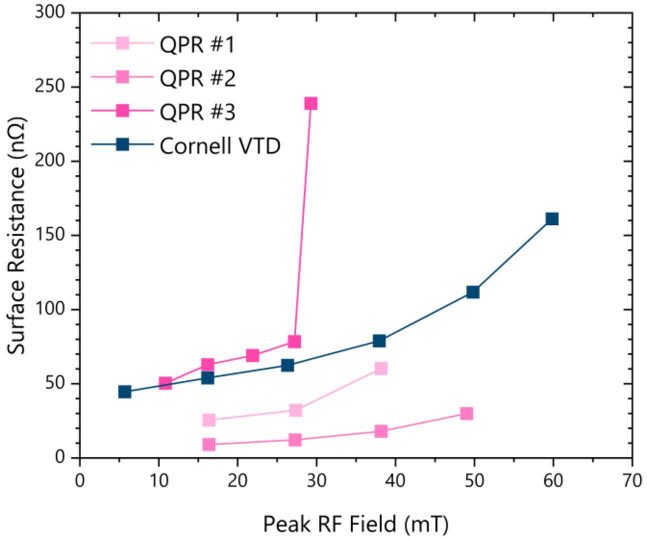
D. Ford, F. A. Costanzo, T. Subasinghe, G. Cassarà, E. Chyhyrynets, E. Tochukwu, F. Stivanello, O. Azzolini, C. Pira

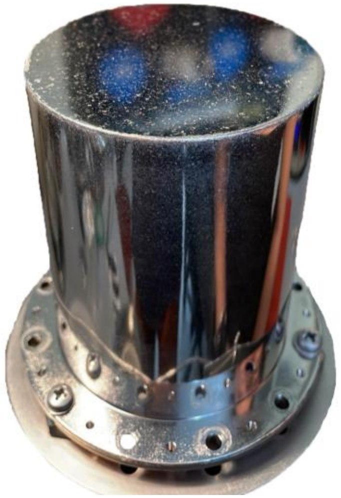
RF VALIDATION

Recipe confirmed on QPR samples

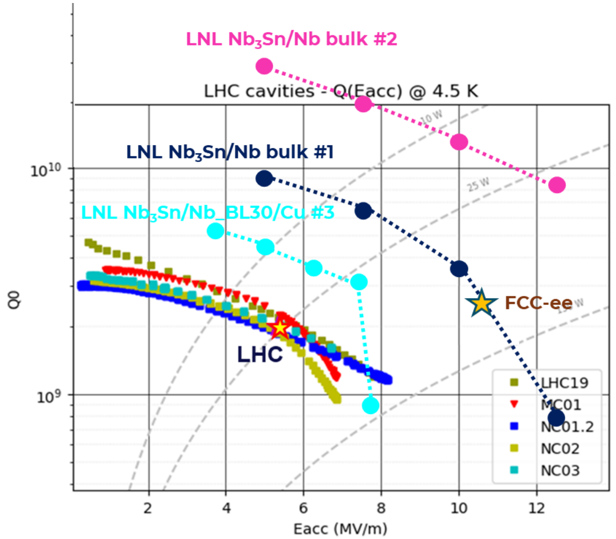
R_s vs peak RF field



Defects during NbBL deposition



Q vs Eacc · *reaching the FCC-ee target*



Sample	Tc	Quench	Rs @ 4K	vs VTD
Sample #1 · bulk Nb · BCP	17.2 K	> 70 mT	~ 25 nΩ	≈ to 40 mT
Sample #2 · bulk Nb · EP + pol.	**17.45 K**	> 85 mT	**< 9 nΩ**	better, ≤ 50 mT
Sample #3 · full Cu · NbBL30	prelim.	—	—	first on Cu

4 K · 400 MHz · courtesy O. Kugeler, S. Keckert (HZB)

Surface preparation matters

EP (#2) cuts low-field R_s >2× and lifts quench vs BCP (#1); Q ≈ 10× LHC.

#3 — first full-Cu QPR coating: very preliminary.