Nb_3Sn/Cu for SRF cavities

V. Giglia, S. Leith, G. Rosaz, C. P. A. Carlos, S, Pfeiffer, A. Moros, A.-T. Perez-Fontenla, L. Vega-Cid, K. Brunner, W. Venturini-Delsolaro, J. Bernardi, A. Steiger-Thirsfeld, M. Eisterer, M. Asiyaban, J. Gruber, M. Himmerlich, V. Petit

Outline

1. Context
2. Experimental setup
3. Feasibility
4. Some process parameters' effects
5. RF tests
6. Scale-up

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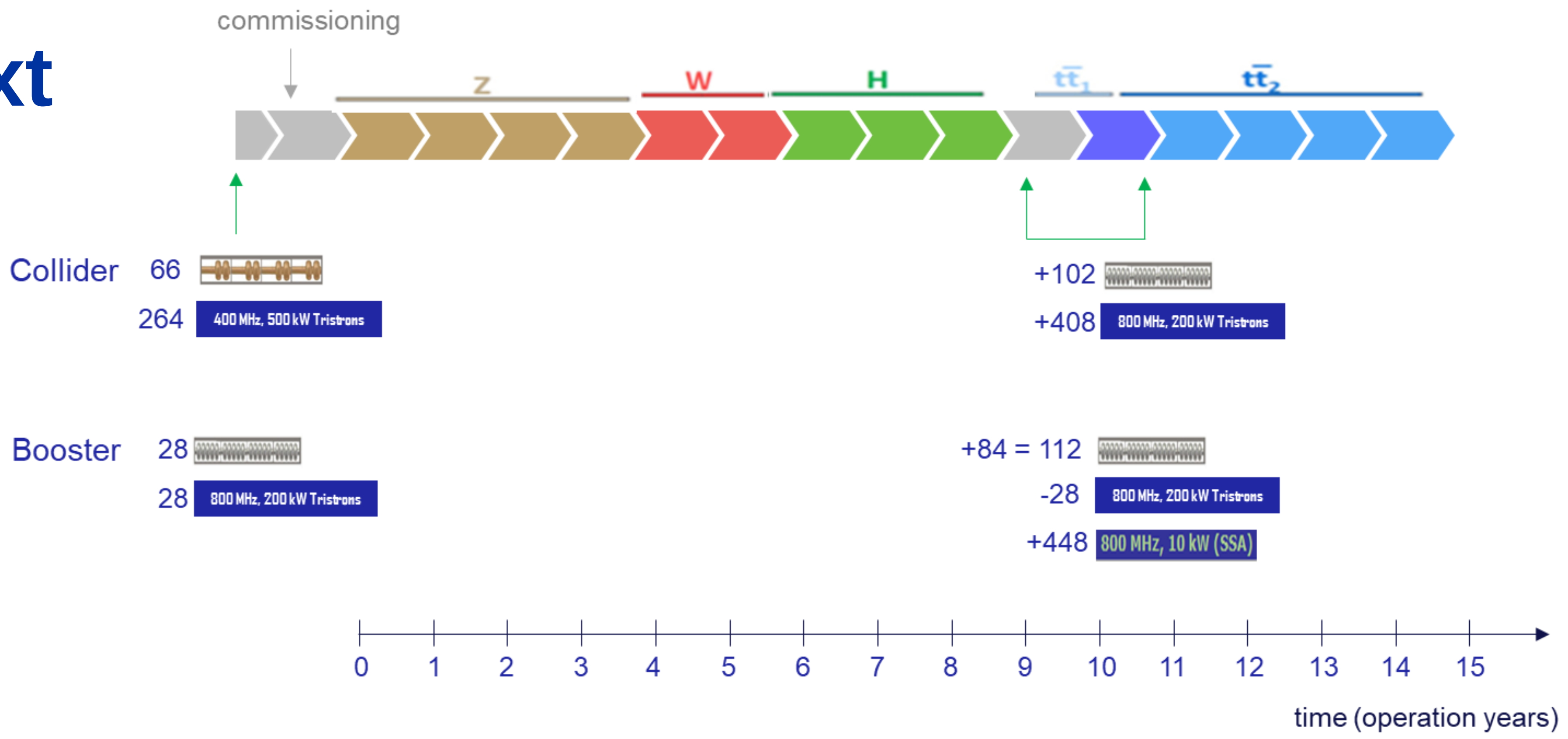
Context



FCC needs 100's of bulk Nb cavities for booster and collider operation

Currently foreseen to operate at 2K

Could it be operated at 4.5K? Could we switch to Cu substrates?

Nb_3Sn / Cu appears as a promising alternative

	Nb	Nb_3Sn
Tc (K)	9.2	**18.3**
R_{BCS} (nΩ)	45	**0.4**
H_{sh} (mT) @4.2K and 500MHz	220	**425**
Max th. Eacc (MV/m)	50	**100**

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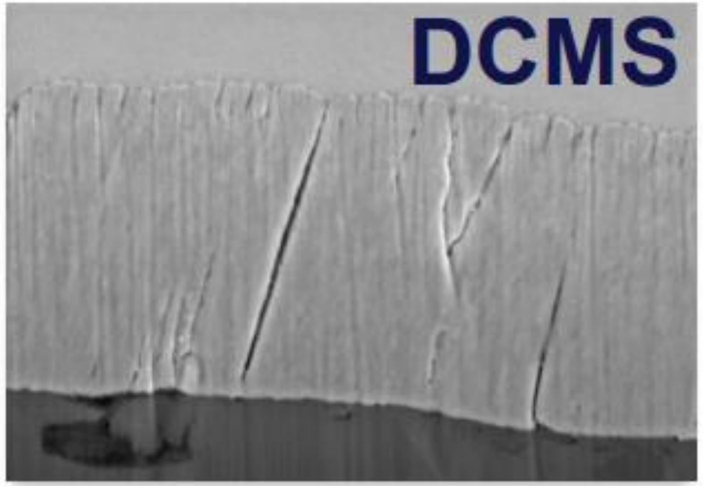
Experimental Setup

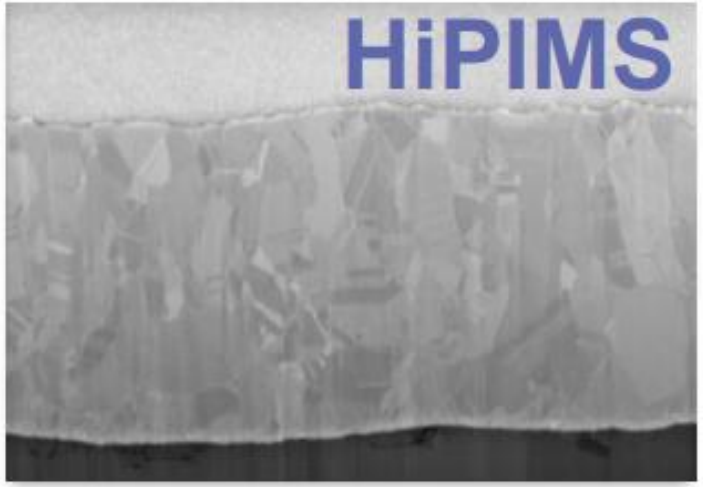
Our point of view:

Experimental Setup

Our point of view: HiPIMS is a MUST (driven by density mainly)



Direct current magnetron sputtering



High Power Impulse Magnetron Sputtering

Experimental Setup

Our point of view: HiPIMS is a MUST

However:

- Nb_3Sn forms at rather low energy level (~750°C) vs HiPIMS bias (10's eV)
- Biasing is prompt to damage the lattice
- Bias is needed for smoothness, density control
- Heat treatment is required to form proper A15 phase AND to recover defects

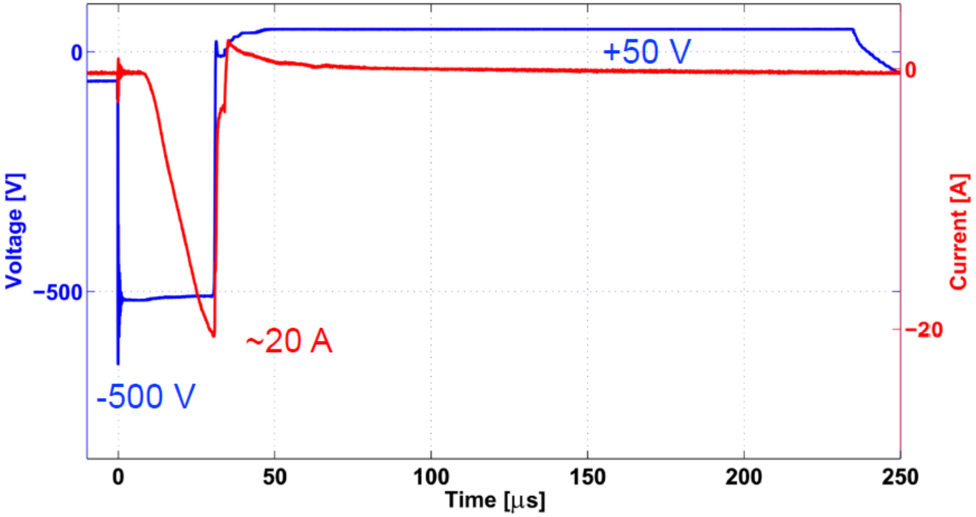
Experimental Setup

Bi-Polar HiPIMS (Energy Pulse Systems)

- Two magnetrons 150mm diameter
- Working distance (100mm)
- Base pressure ~10^{-10} mbar after BO
- Target: alloyed Nb_3Sn
- Heater: resistive, home-made

Coating parameters:

- *Gas:* Kr
- T_s: 500 … 750°C
- *P:* $7 \cdot 10^{-4}$ … $5 \cdot 10^{-2}$ *mbar*
- *PP:* 35 … 100 V
- *Post anneal:* 0 … 72 hrs



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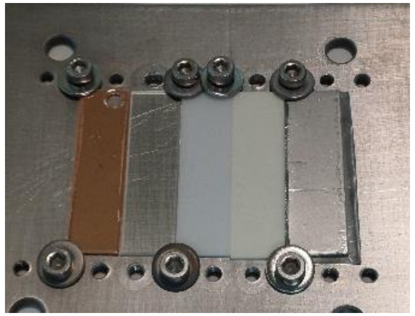
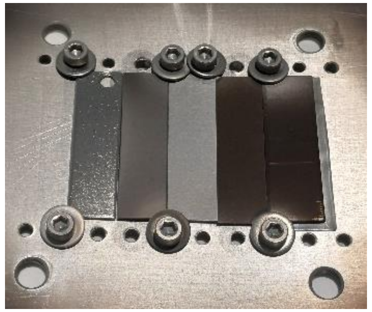
Feasibility - T_c

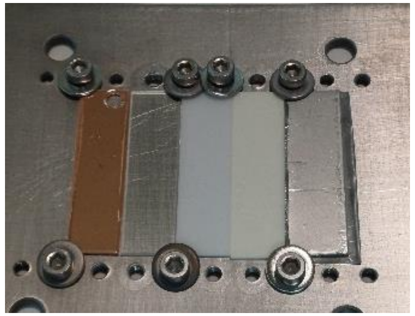


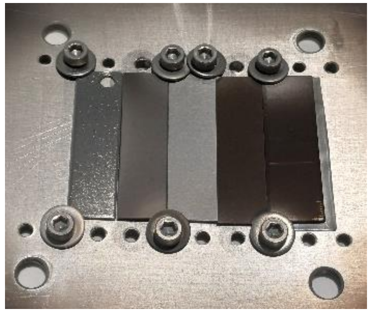


Can we elaborate high quality Nb_3Sn films?

Can we reach 18.3K Tc? First good sign of longe range order within the material lattice

Feasibility - T_c





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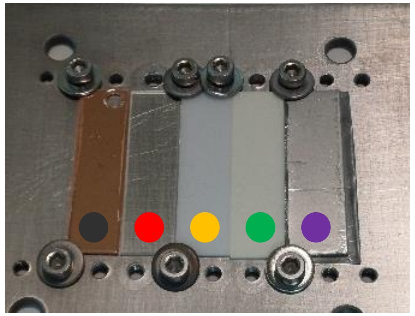
DCMS

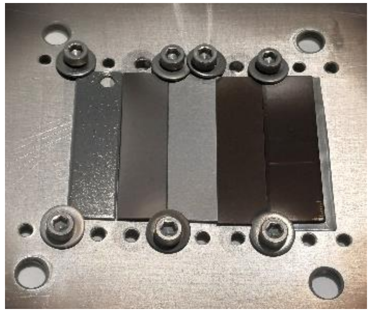
Table 1. Influence of the substrate on critical temperature of the Nb_3Sn films.

	Critical temperature (K)	
Process pressure	Copper substrate	Ceramic substrate
$P = 1 \times 10^{-3}$ mbar	14.7 K	17.5 K
$P = 5 \times 10^{-2}$ mbar	15.5 K	17.4 K

https://doi.org/10.1088/1361-6668/aaf61f

Feasibility - T_c





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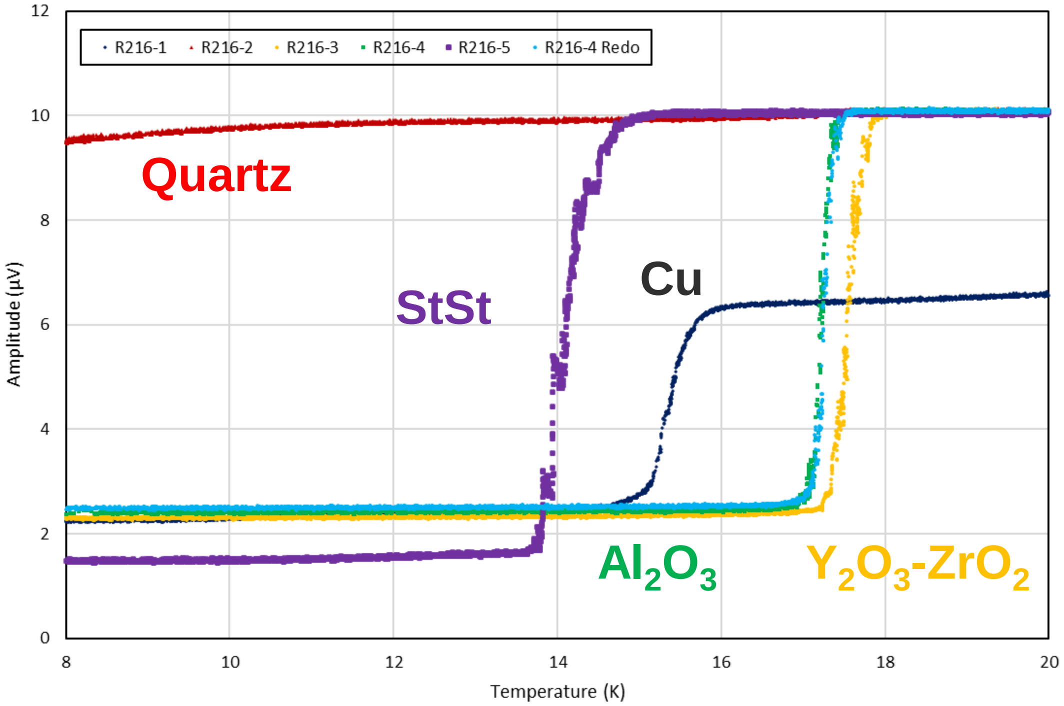
HiPIMS



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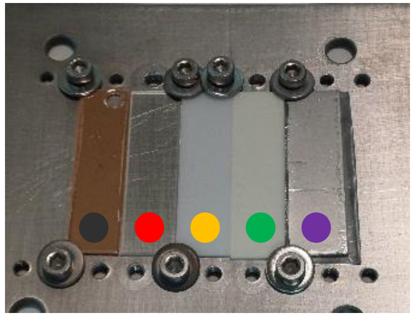

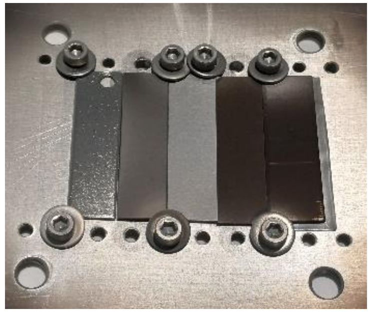

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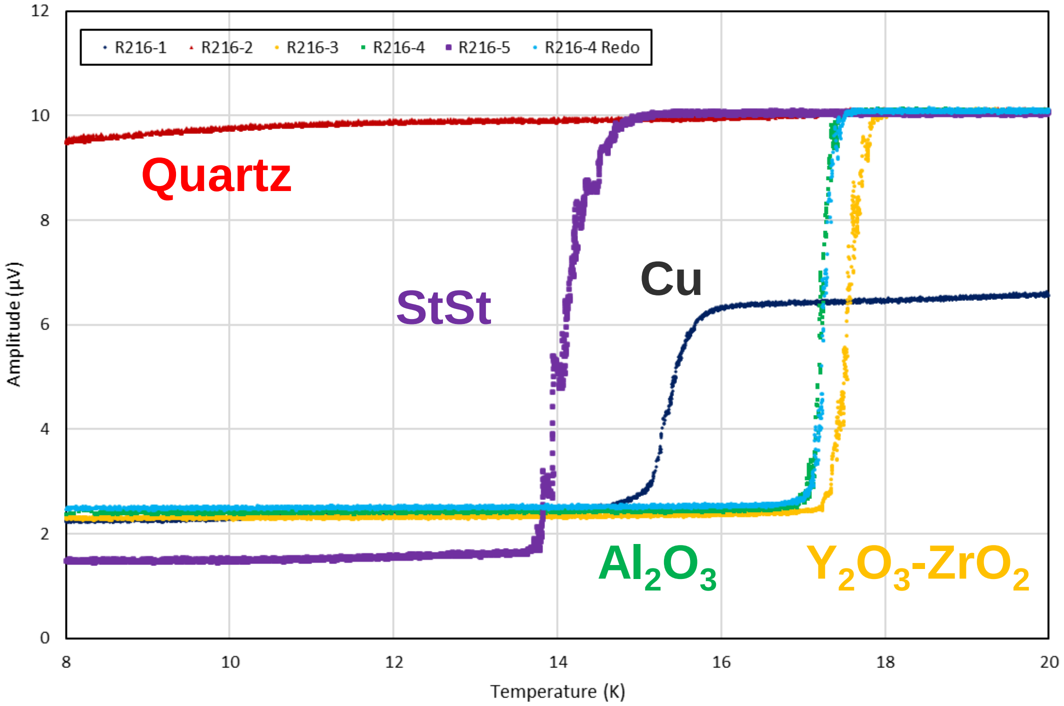
SUBSTRATE'S THERMAL EXPENSION COEFFICIENT DRIVES THE RESIDUAL STRESS → LRO → Tc

HiPIMS



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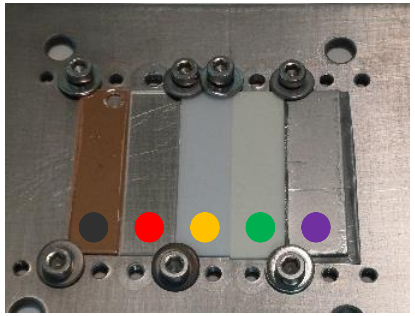

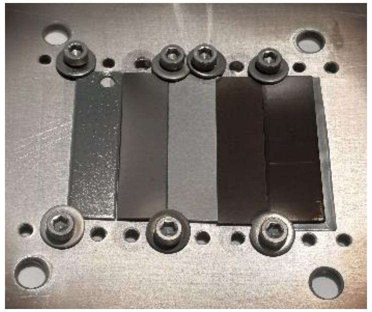

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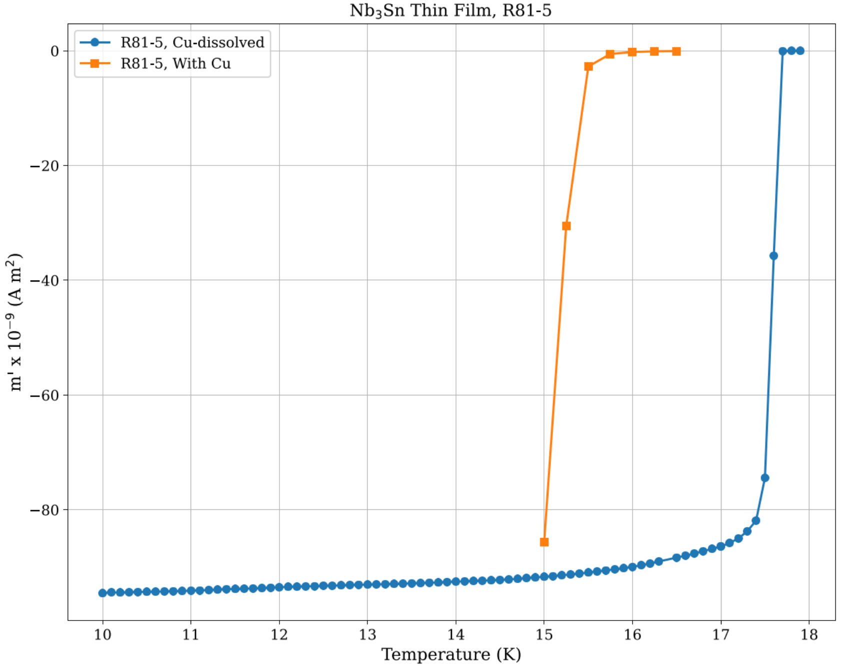
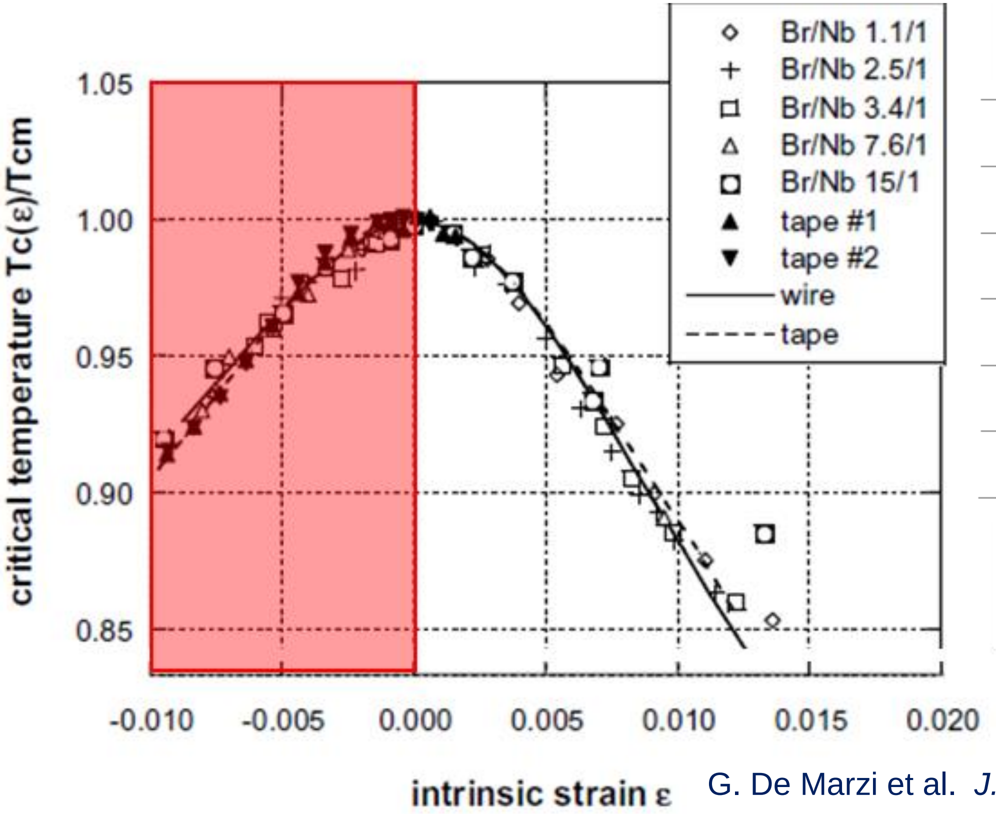
Also reproduced by TU-Wien ATI



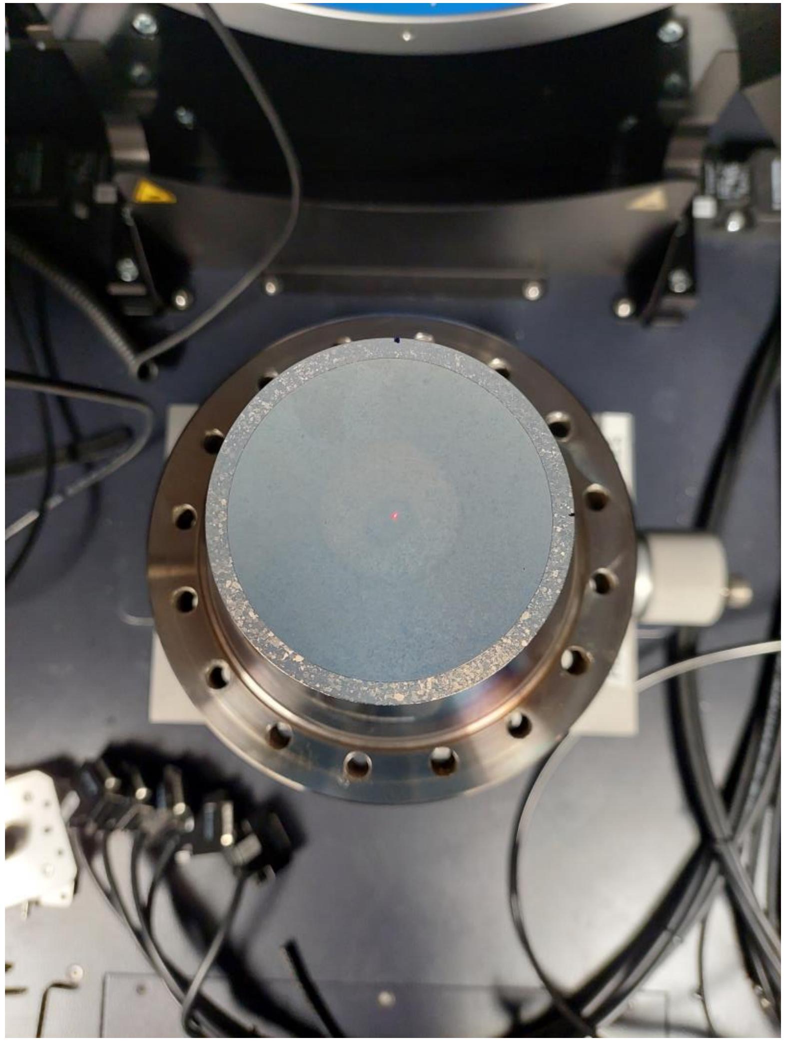
Residual stress

Quantification by X-ray diffraction

Compressive residual stress



Residual stress by XRD (MPa)
Centre #1: -888 ± 20
Centre #2: -760 ± 20
Outer #1: -975 ± 19
Outer #2: -949 ± 13
Outer #3: -1236 ± 17



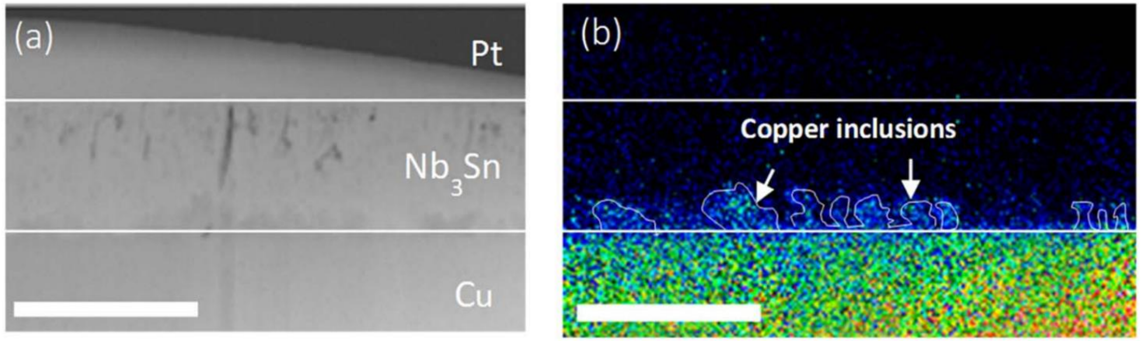
G. De Marzi et al. *J. Phys.: Condens. Matter* **25** (2013)

Feasibility – Cu

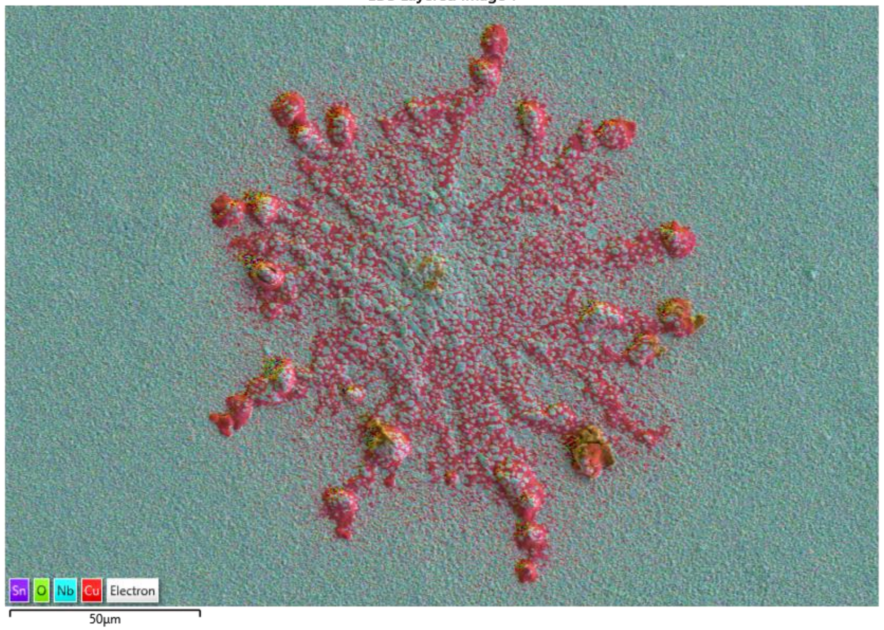
How problematic is Cu?

Interdiffusion → NC spots at the RF surface

Also promoting the A15 phase formation



EDS Layered Image 1



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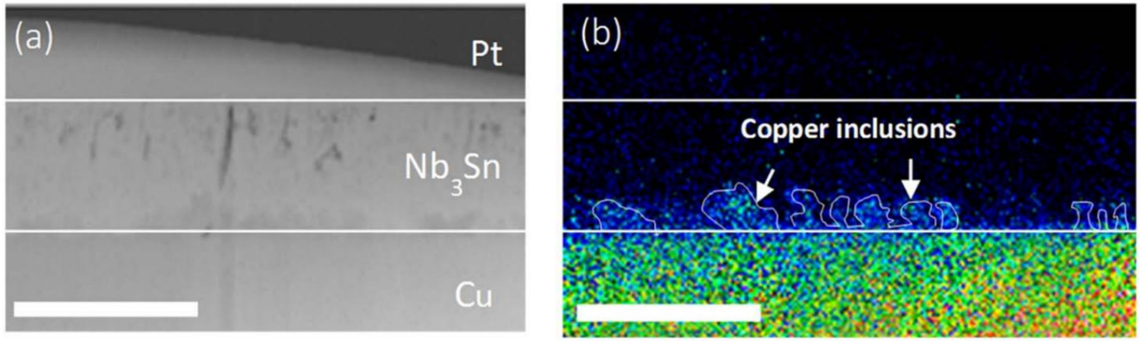
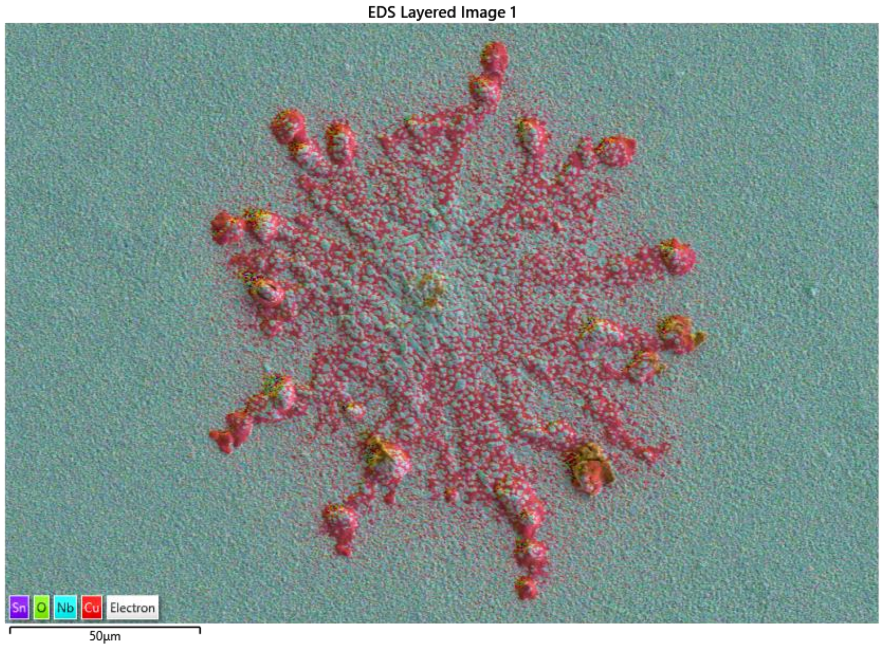


How to block it?

Diffusion barrier layer (Ta, HEA …)

Ta: requires a very specific crystalline phase (α)

HEA: promising, needs more investigations, amorphous even at high T



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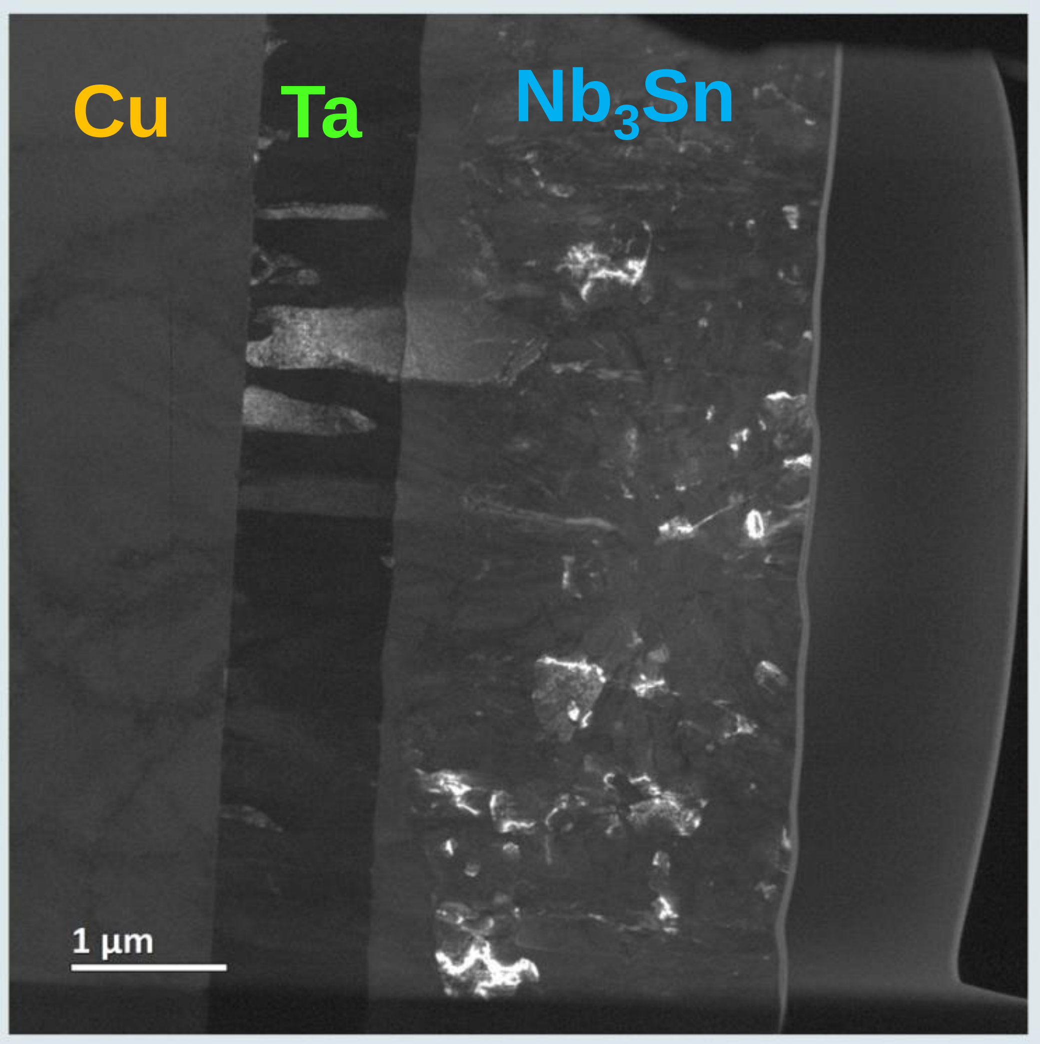

Cf J. Bernardi's talk (https://indico.cern.ch/event/1408515/timetable/#200-tem-analysis-of-coatings-f)

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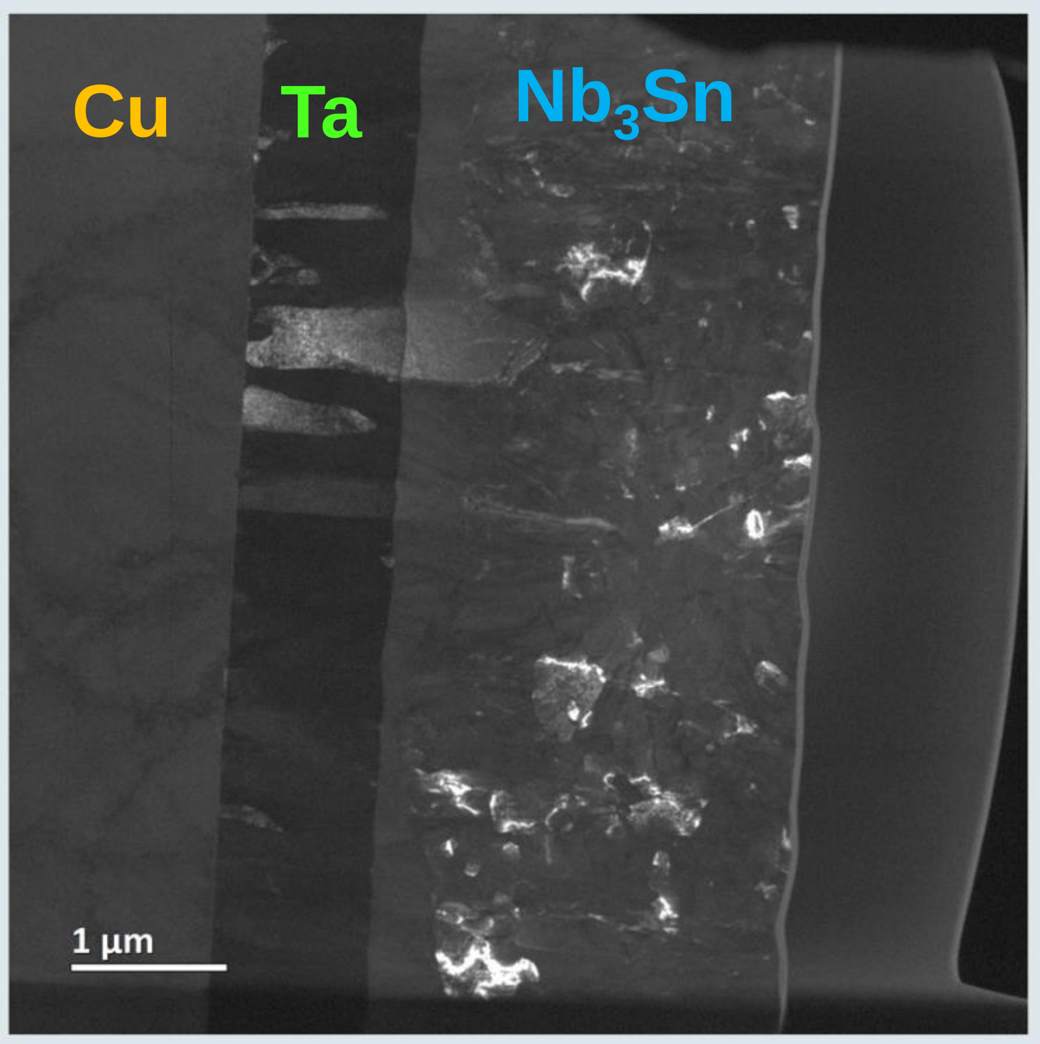
Then… the surface is absolutely free of Cu?



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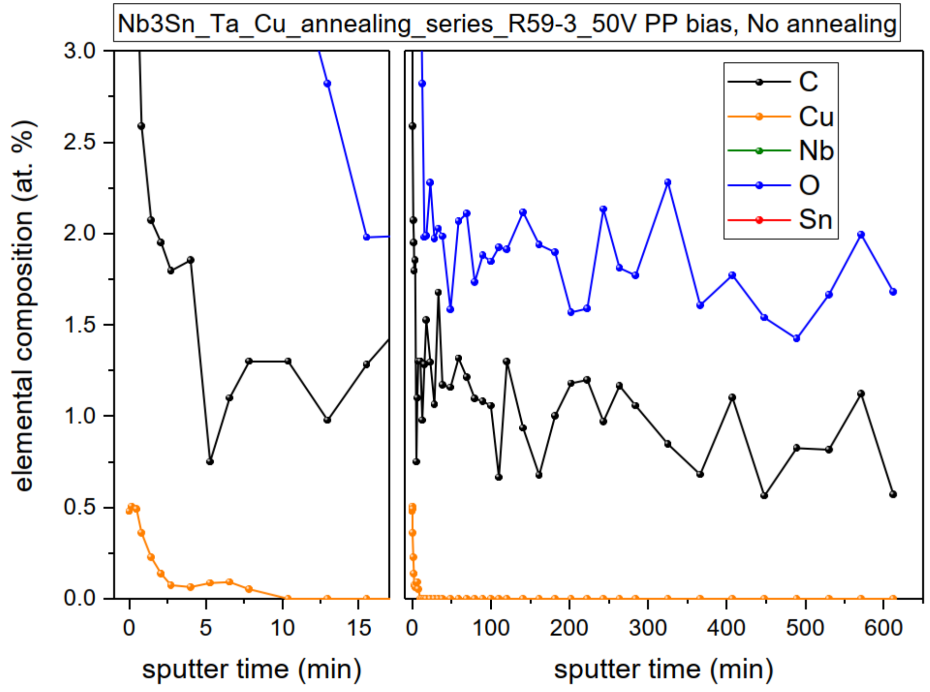
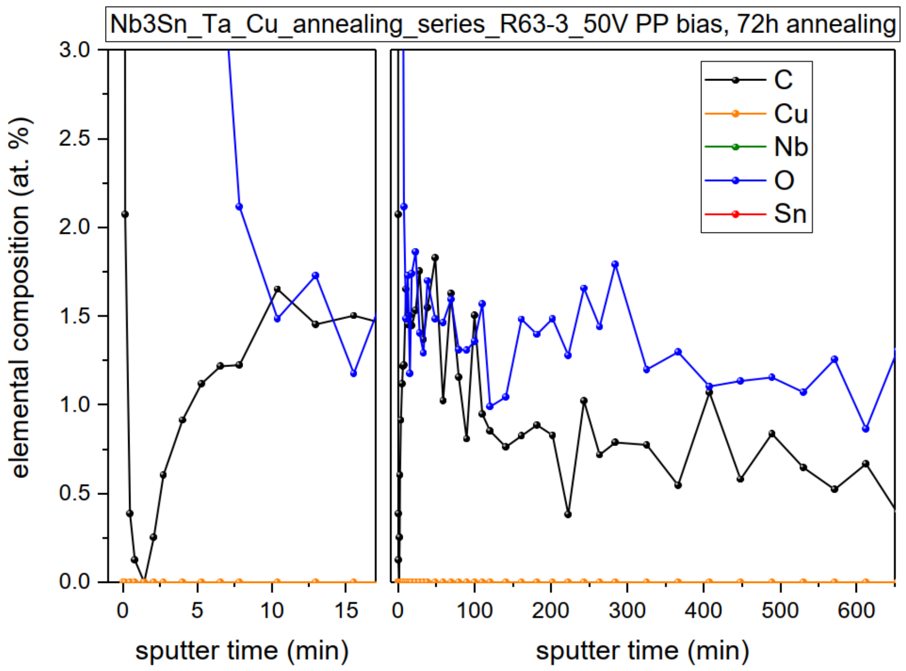
No

Surface contamination.

Disappears after HT.





Feasibility – Cu

Also observed:

A careful setup cleaning reduces surface Cu contamination.
Surface diffusion from samples
A problematic already known with dramatic industrial consequences

For future applications and scale-up

How to manage this contamination?

Curative approach: post coating Cu wet etching : Ammonium persulfate

Cu at. %	Pre Rinse	Post Rinse
Sample 1	3.9	0.6
Sample 2	5.3	1.6

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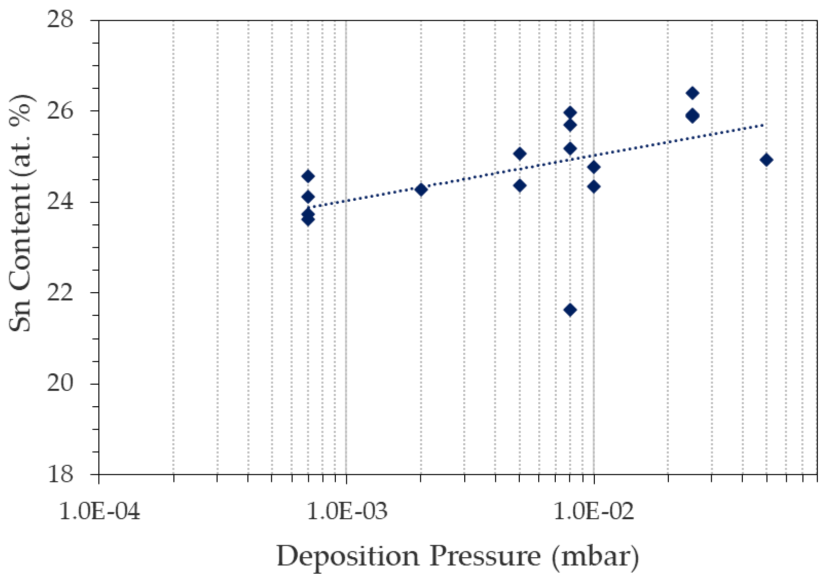
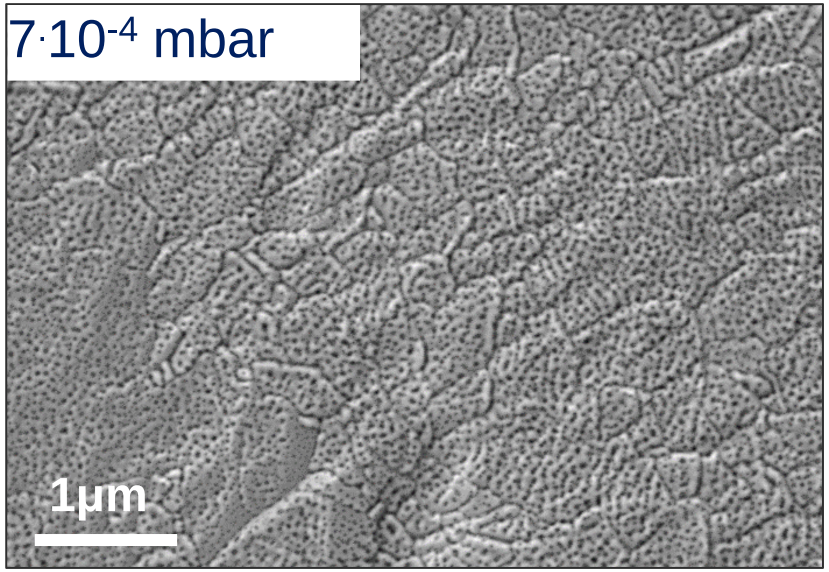
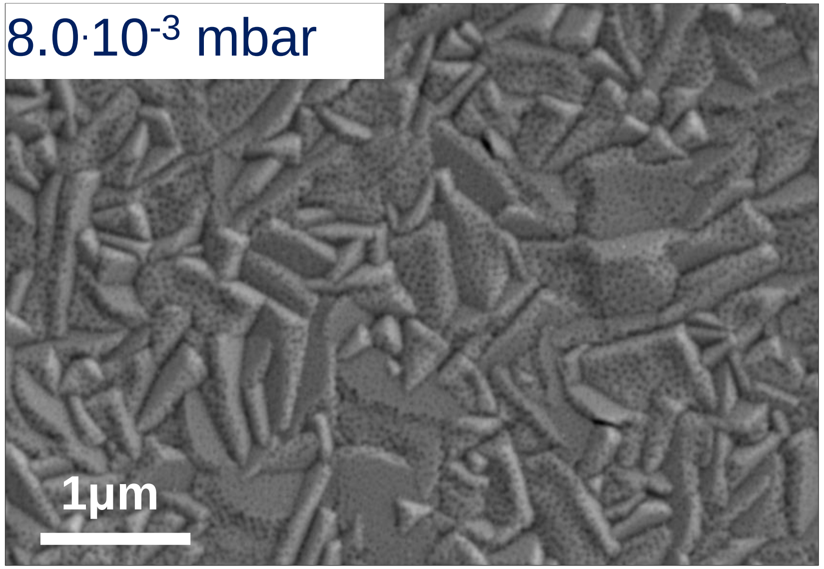
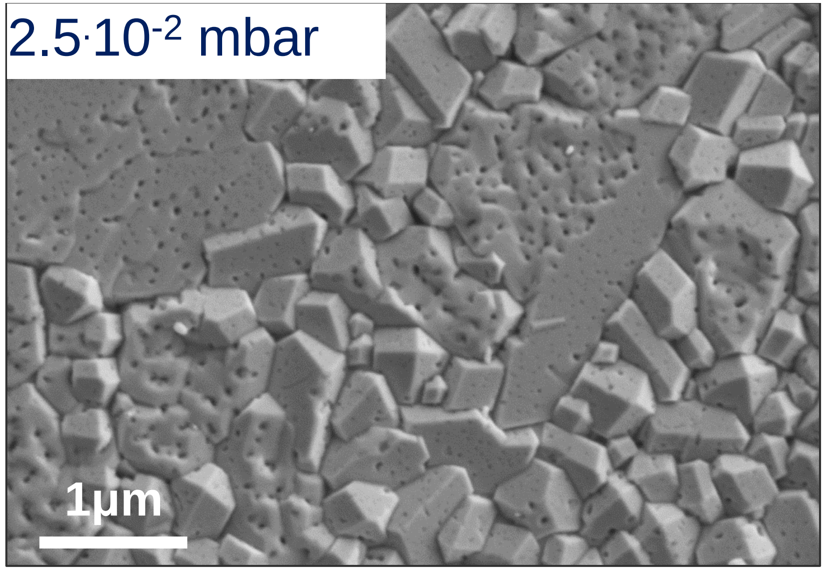
Some process parameters' effects

Coating pressure:
- Smoother at lower pressure (less gas phase collisions)
- Composition: Sn content increases with P
- An optimal has to be found between composition and roughness
- Films look as well more crystalline at high P (XRD quantitative analysis to be performed)





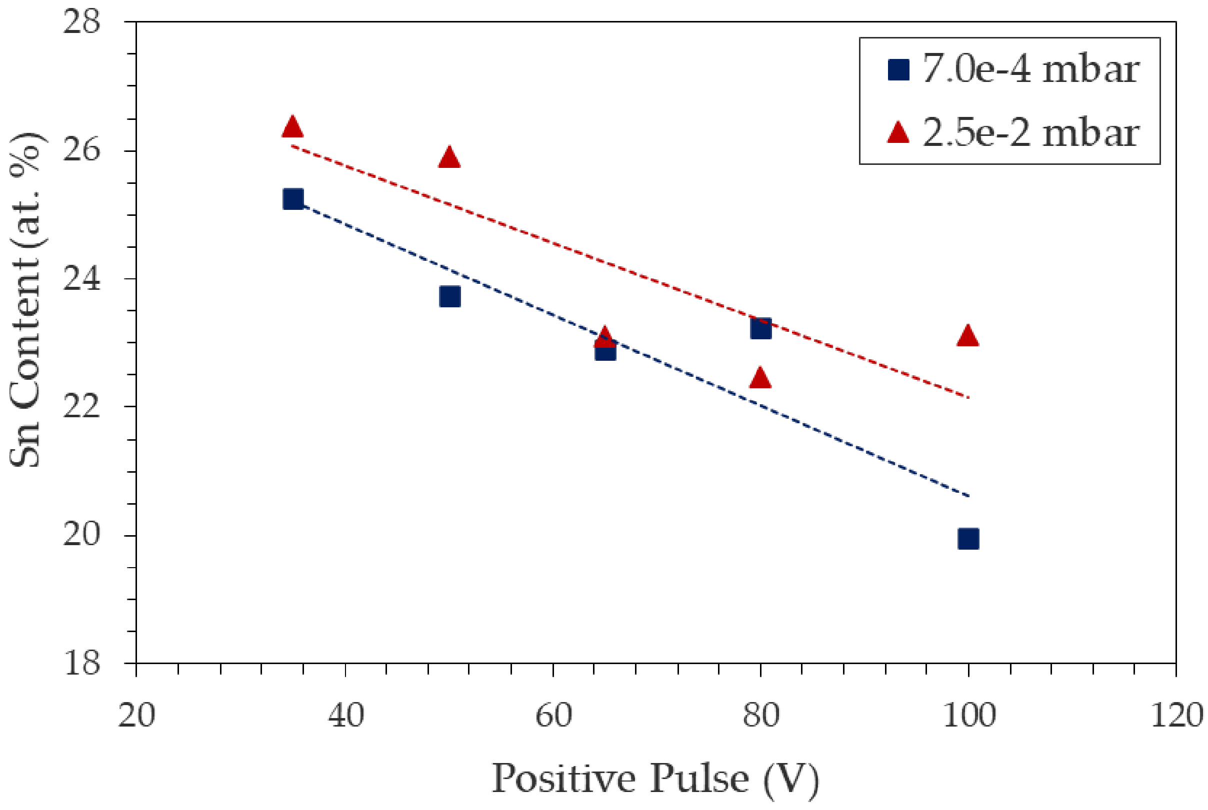




Some process parameters' effects

Positive Pulse:

- Sn very sensitive to re-sputtering
- Sn content decreases with positive pulse voltage
- Composition and density evolve on an opposite trend

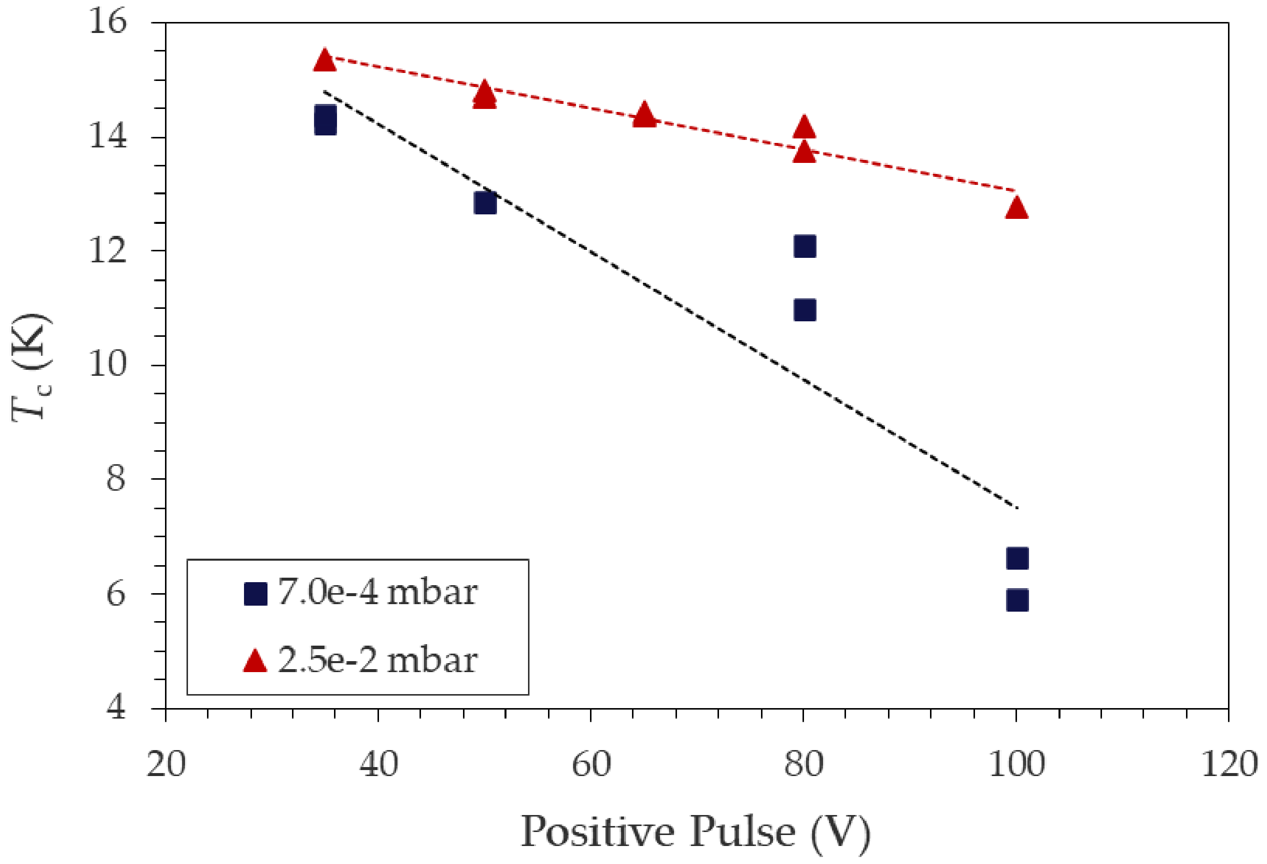


Some process parameters' effects

Effect on the Tc

- Increase in pressure → increase in Sn content → increase in T_c

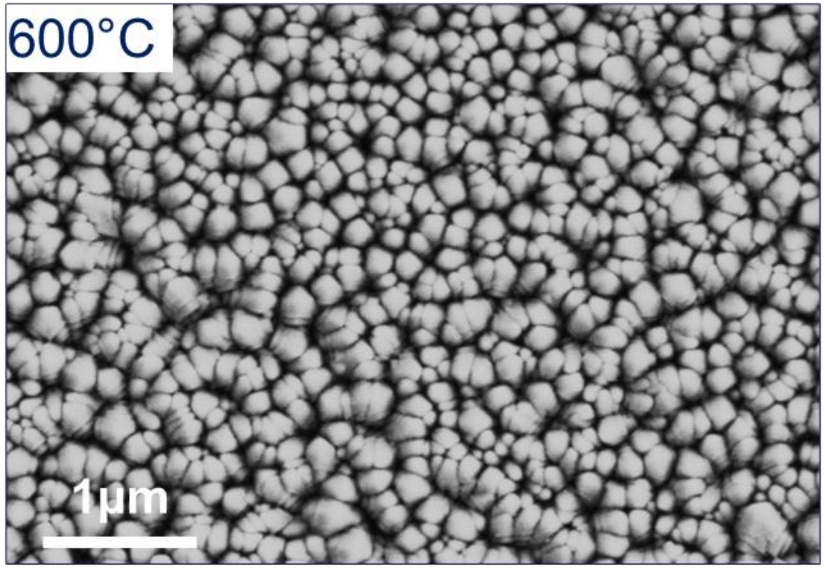
- Increase in PP → decrease in Sn content → decrease in T_c

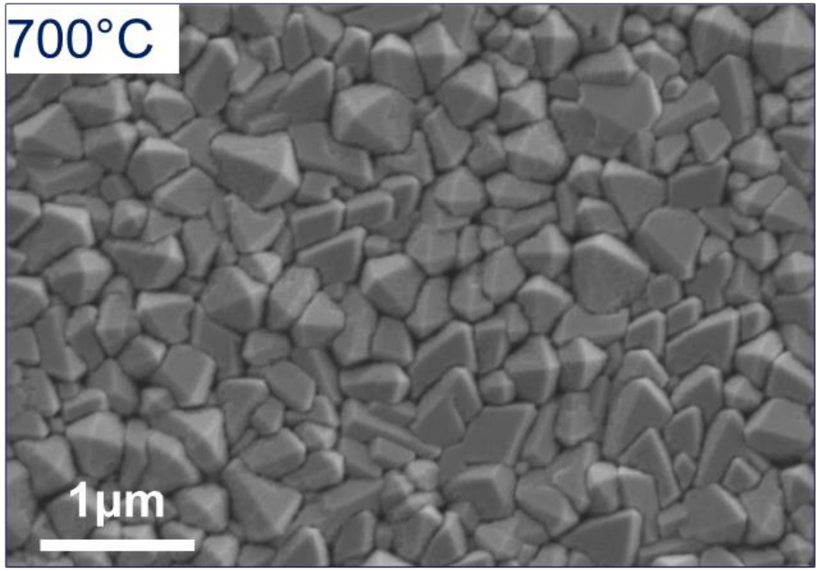


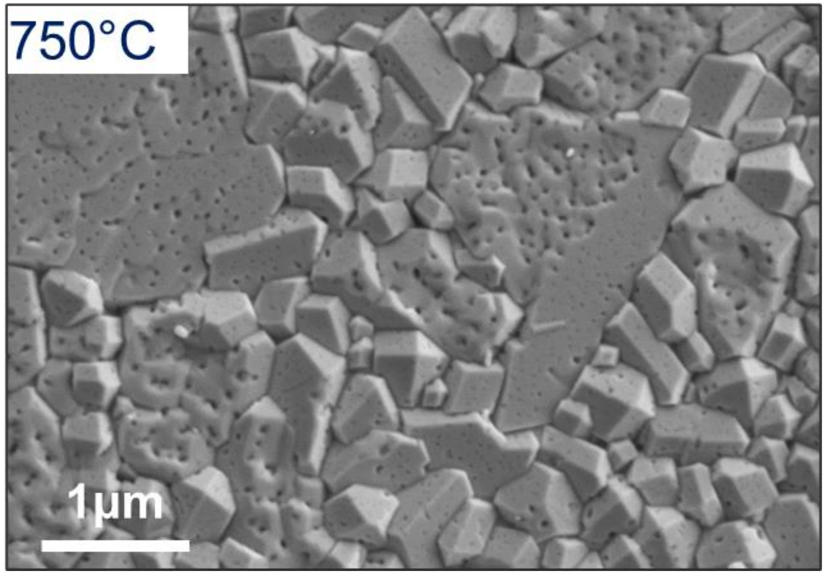
Some process parameters' effects

Coating temperature

- For a given coating recipe
- Lower temperature → lower adatoms mobility
  - Porous layer
  - Layer appears much less crystalline





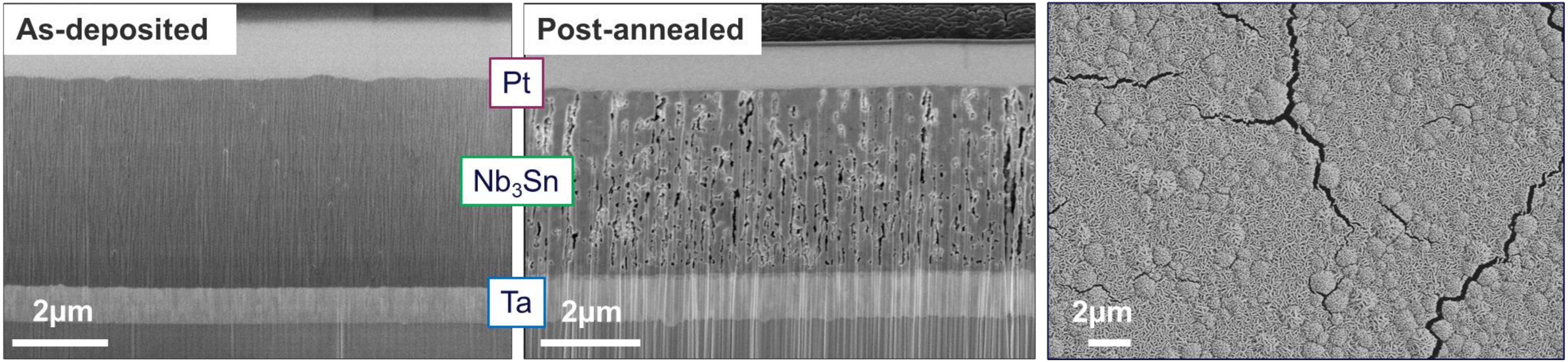


Side Note

Coating at low T and reacted after coating

SYSTEMATICALLY LEADS TO FILM CRACKING

This option is for the moment put aside as a potential process route



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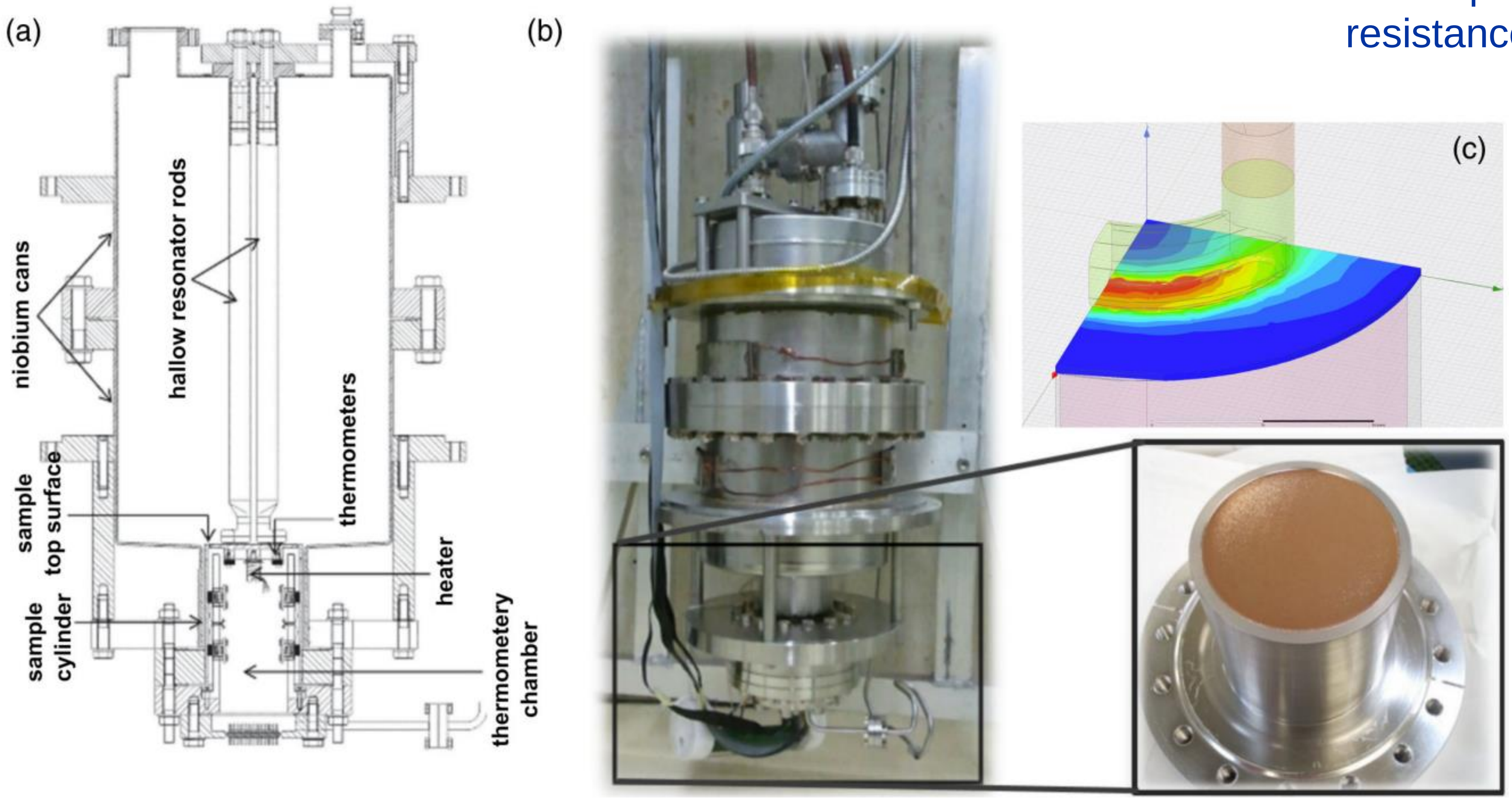
Quadrupolar Resonator



Calorimetric technique for superconductor surface resistance measurement

Flat (and light) sample

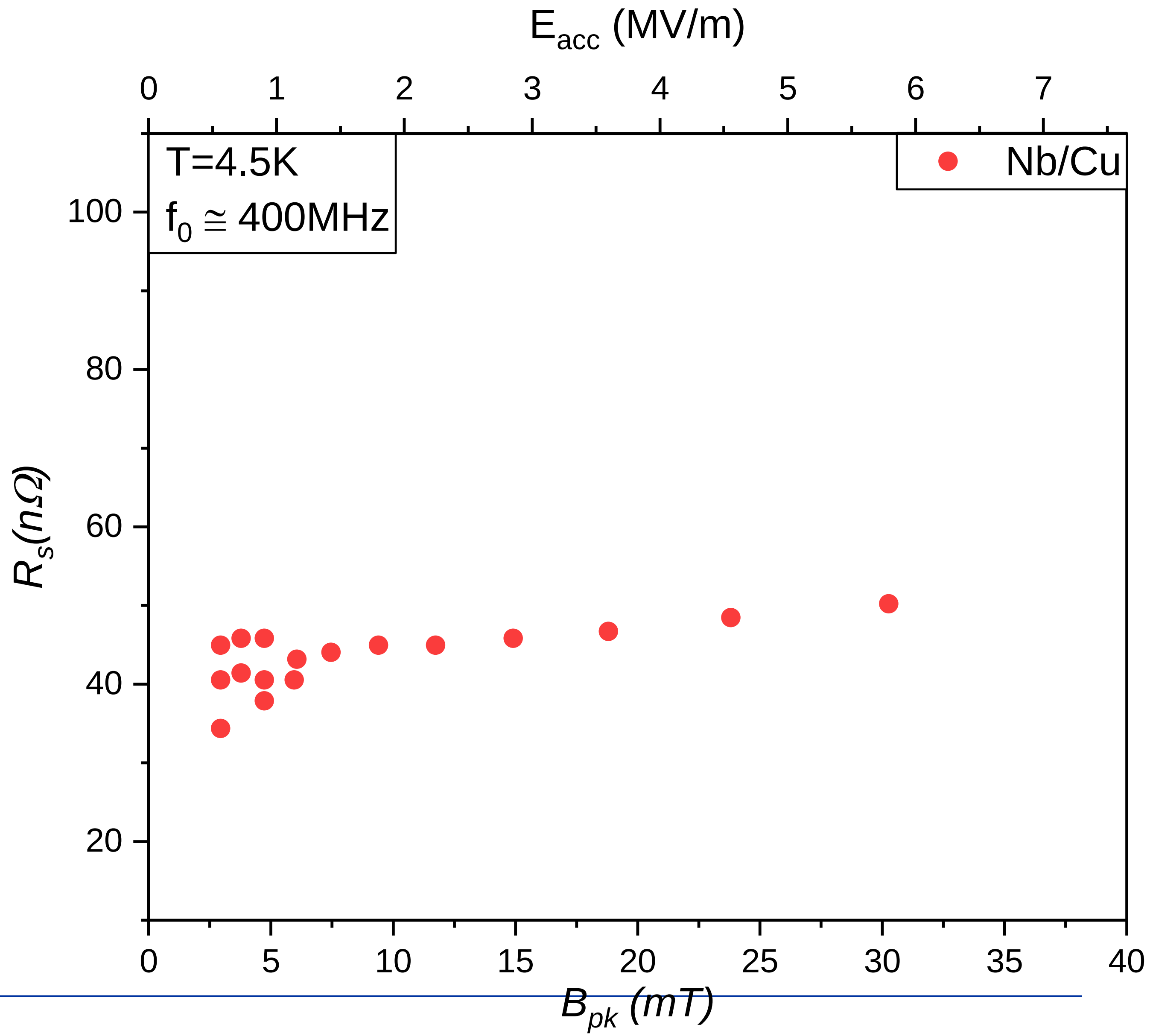
3 frequencies
400MHz
800MHz
1200MHz

Temperature dependancy

Field dependency

400 MHz

Comparison with Nb/Cu layers:



400 MHz

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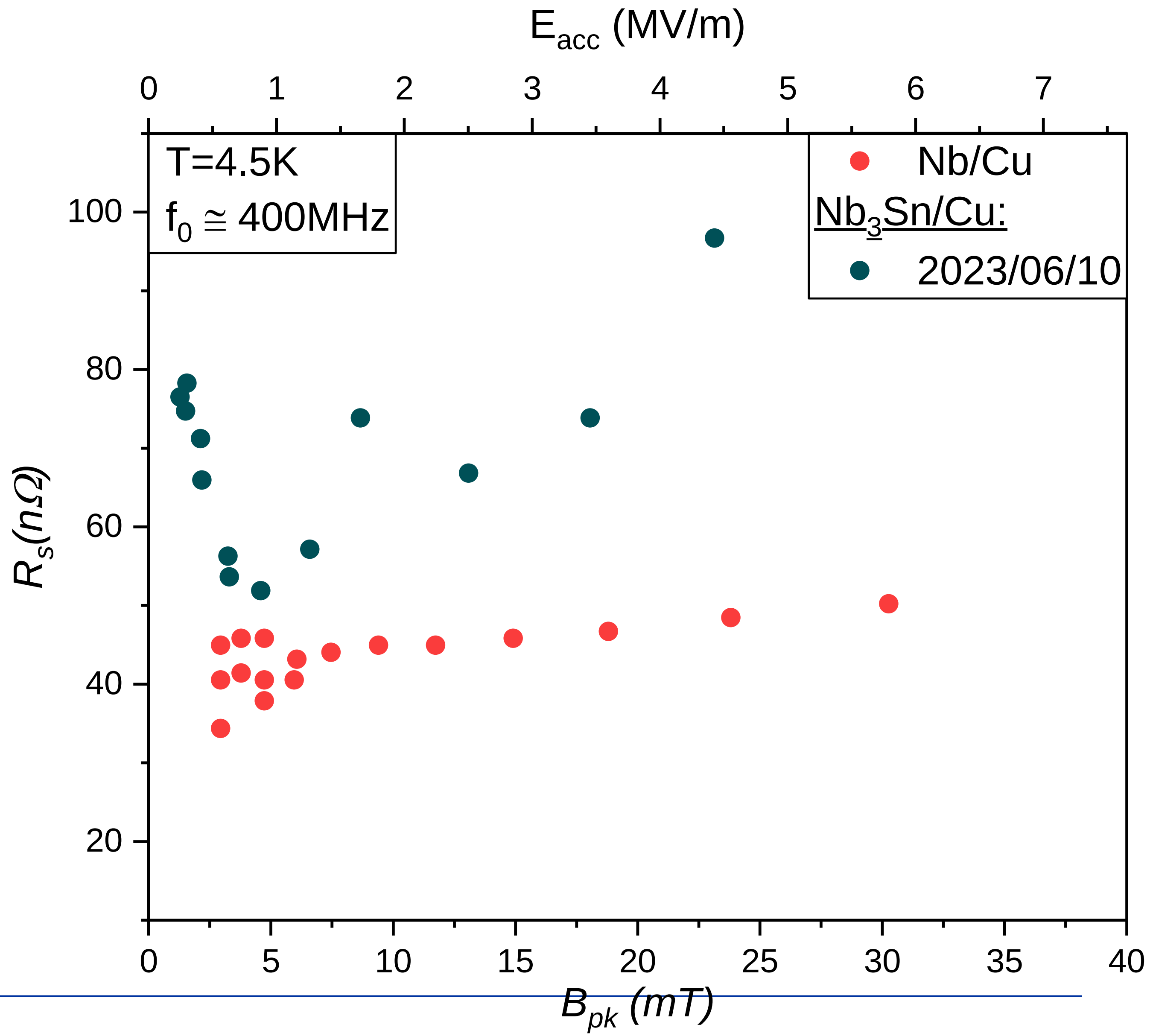

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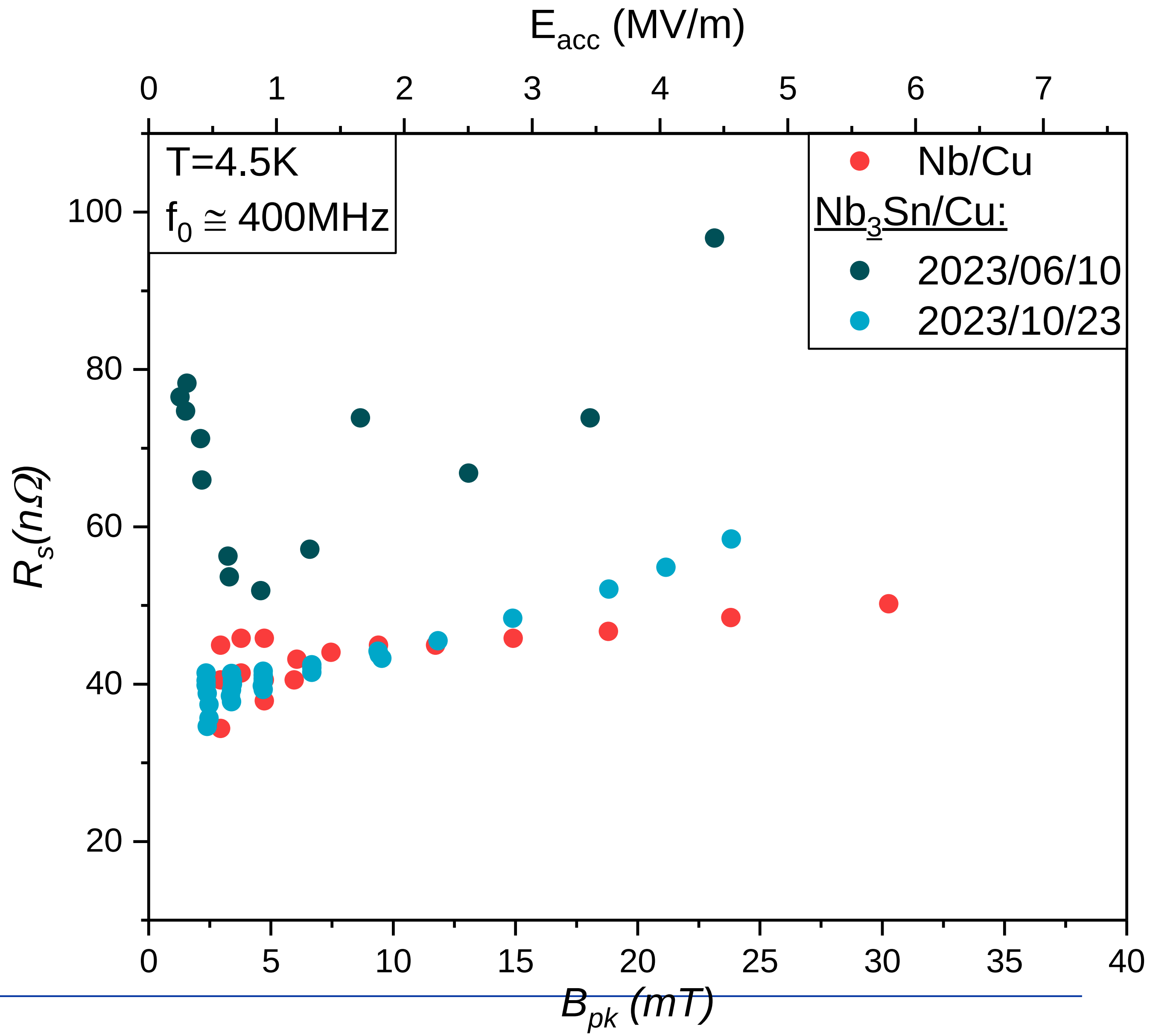
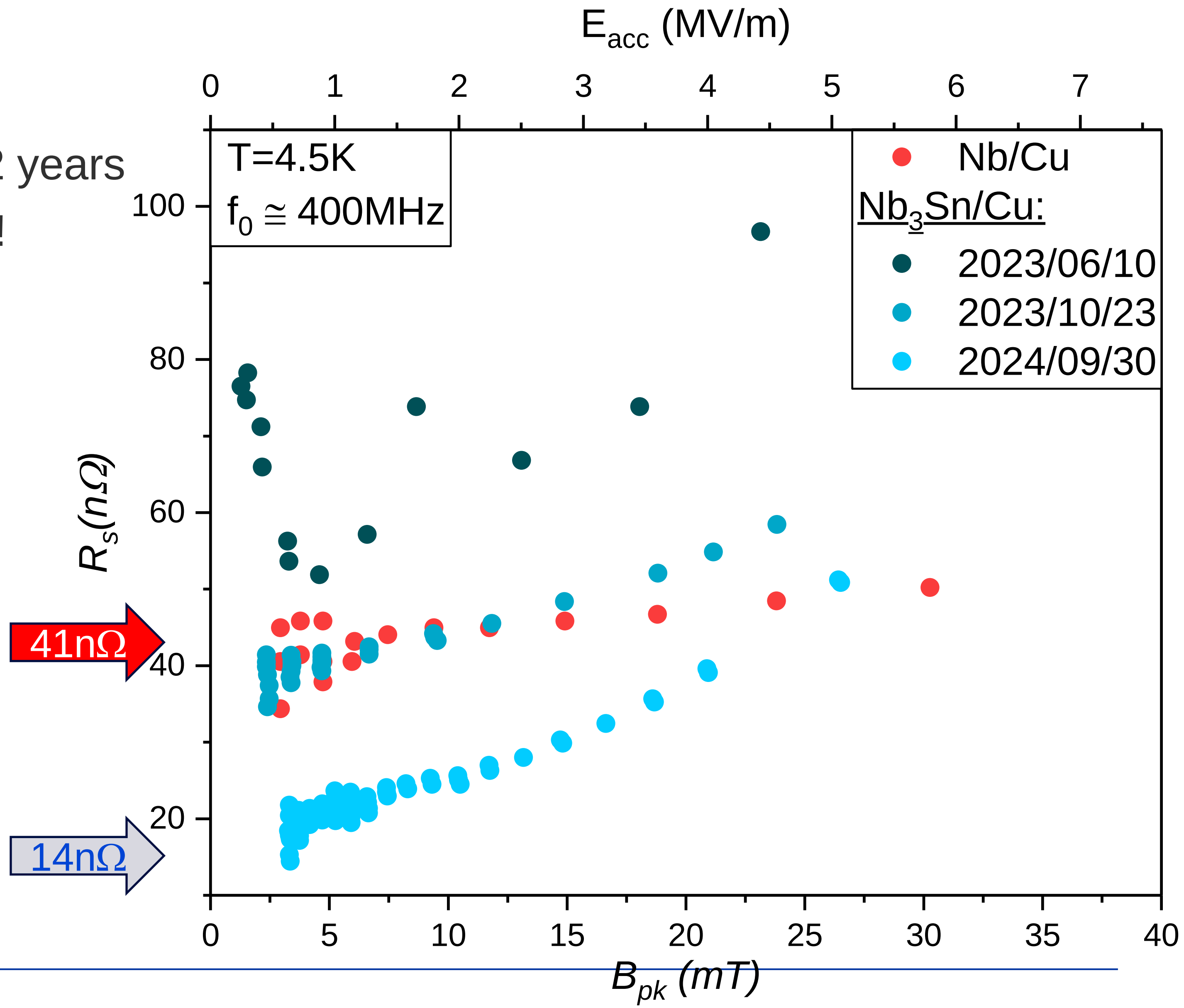


400 MHz

Comparison with Nb/Cu layers:

- Significant improvements these past 2 years
- R_s 2-3 times lower for Nb_3Sn vs Nb !!!!



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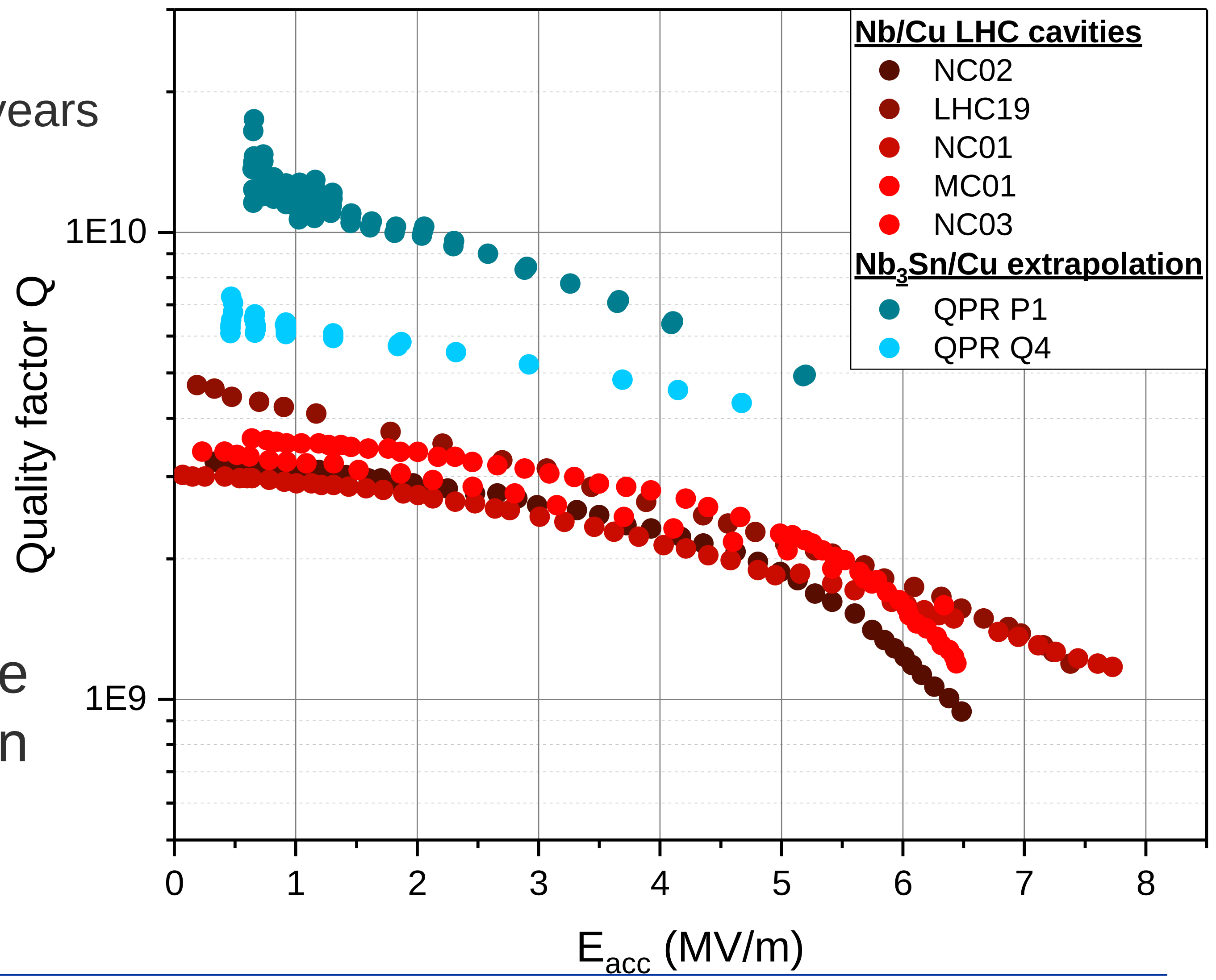
Comparison to LHC cavities

4.5K

10^{10} Q-factor in reach

Not yet at the factor 10 improvement we are looking for… margin for optimization



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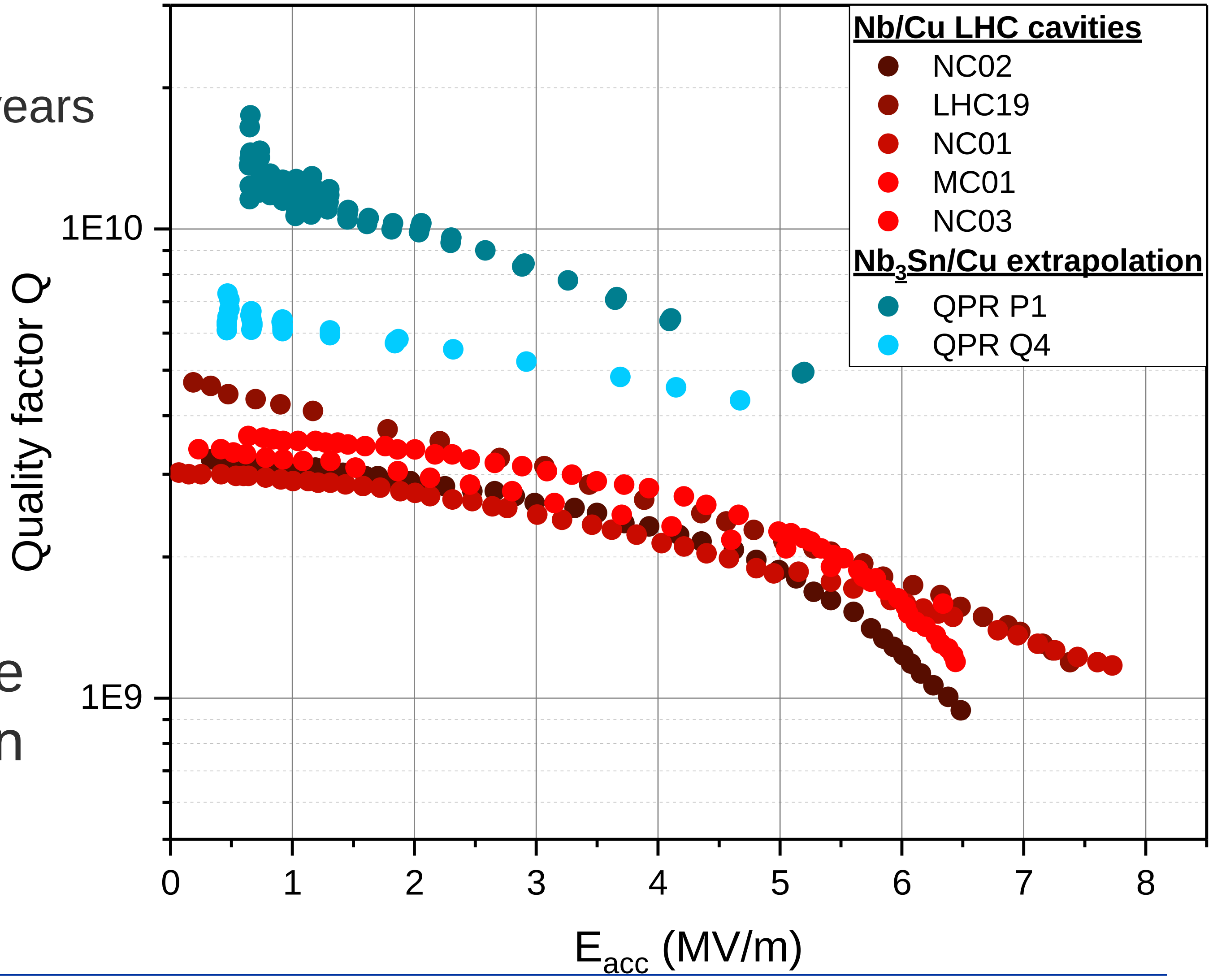
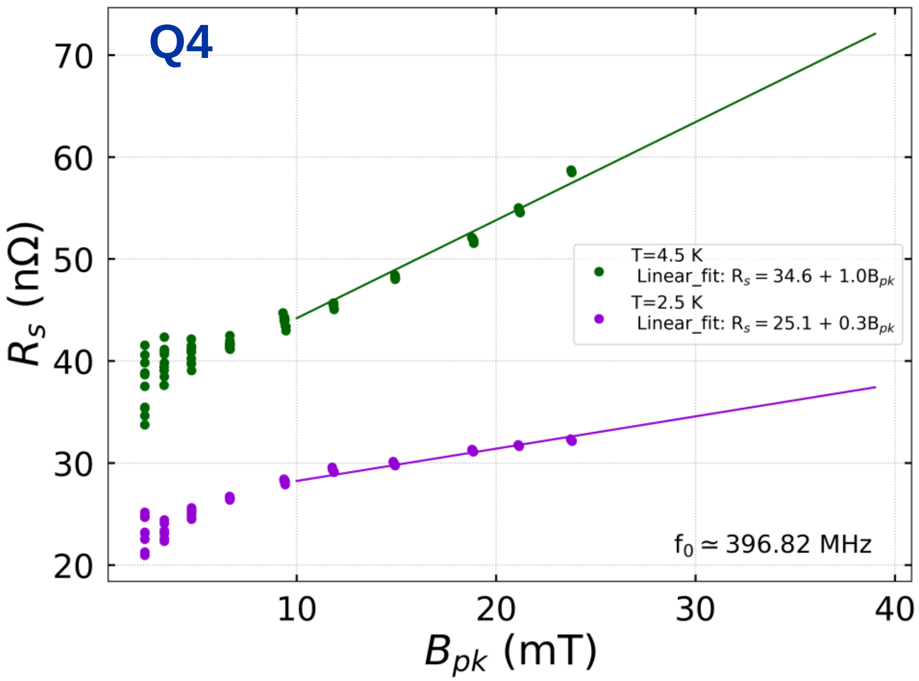
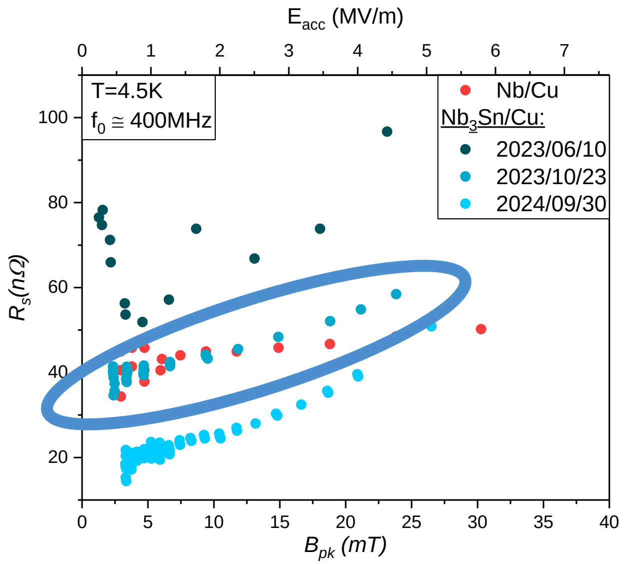
Objective: 800MHz…. What about it?



800 MHz

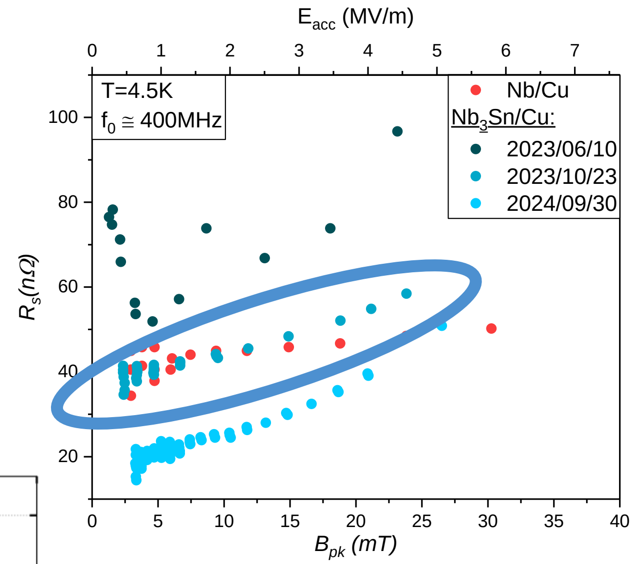

Q4
T=4.5 K
Linear_fit: $R_s = 34.6 + 1.0B_{pk}$
T=2.5 K
Linear_fit: $R_s = 25.1 + 0.3B_{pk}$
$f_0 \simeq 396.82$ MHz
R_s (nΩ)
B_{pk} (mT)

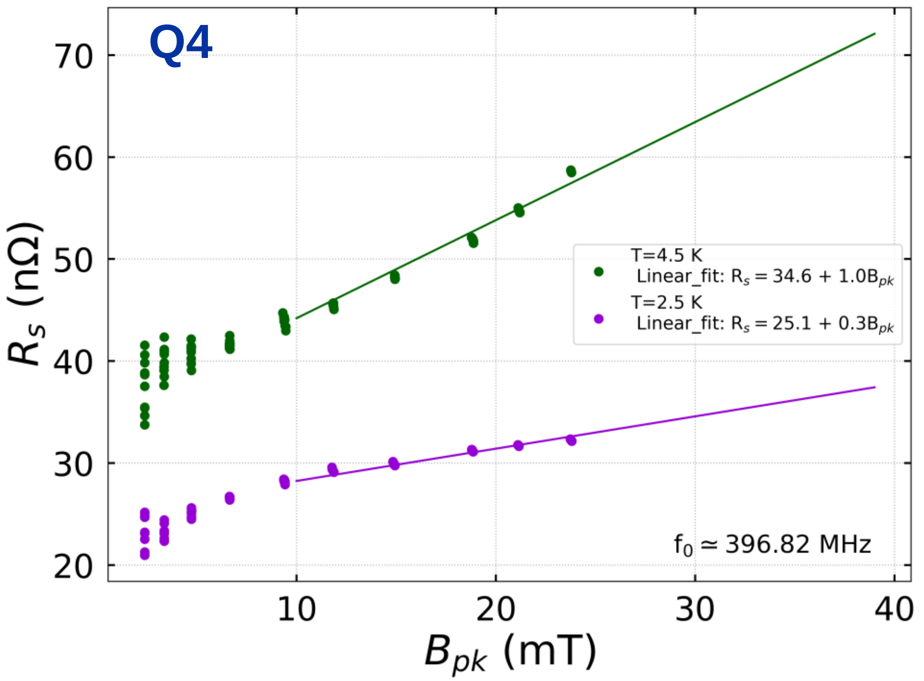

E_{acc} (MV/m)
T=4.5K
$f_0 \cong 400$MHz
Nb/Cu
Nb_3Sn/Cu:
2023/06/10
2023/10/23
2024/09/30
$R_s(n\Omega)$
B_{pk} (mT)

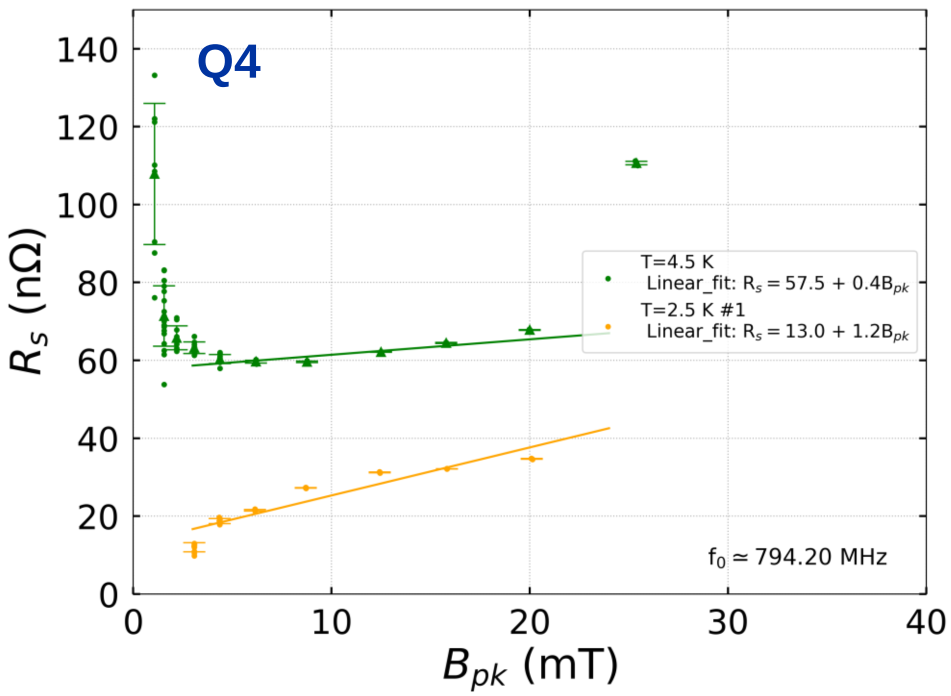
800 MHz

Frequency dependancy does not follow f²

800MHz surface resistance much lower than could be extrapolated !







Outline

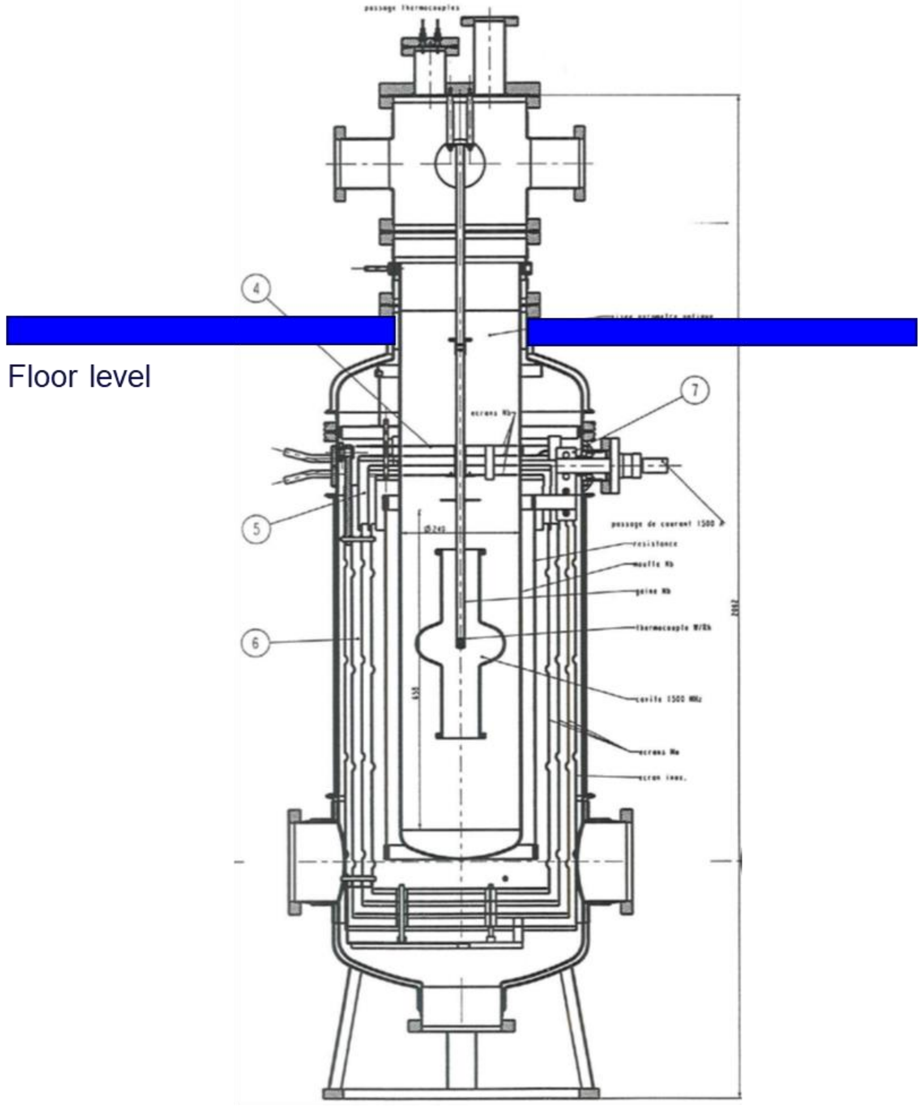
1. Context
2. Experimental setup
3. Feasibility
4. Some process parameters’ effects
5. RF tests
6. **Scale-up**

Challenges / technical proposals

High temperature deposition (750°C):

- Requires large furnace
- **Cu cavities must be upgraded**:
  - Increased cavity thickness
  - Rigid support structure inside the furnace ?
  - Alternative materials?

6-cells 800MHz FCC cavity schematic



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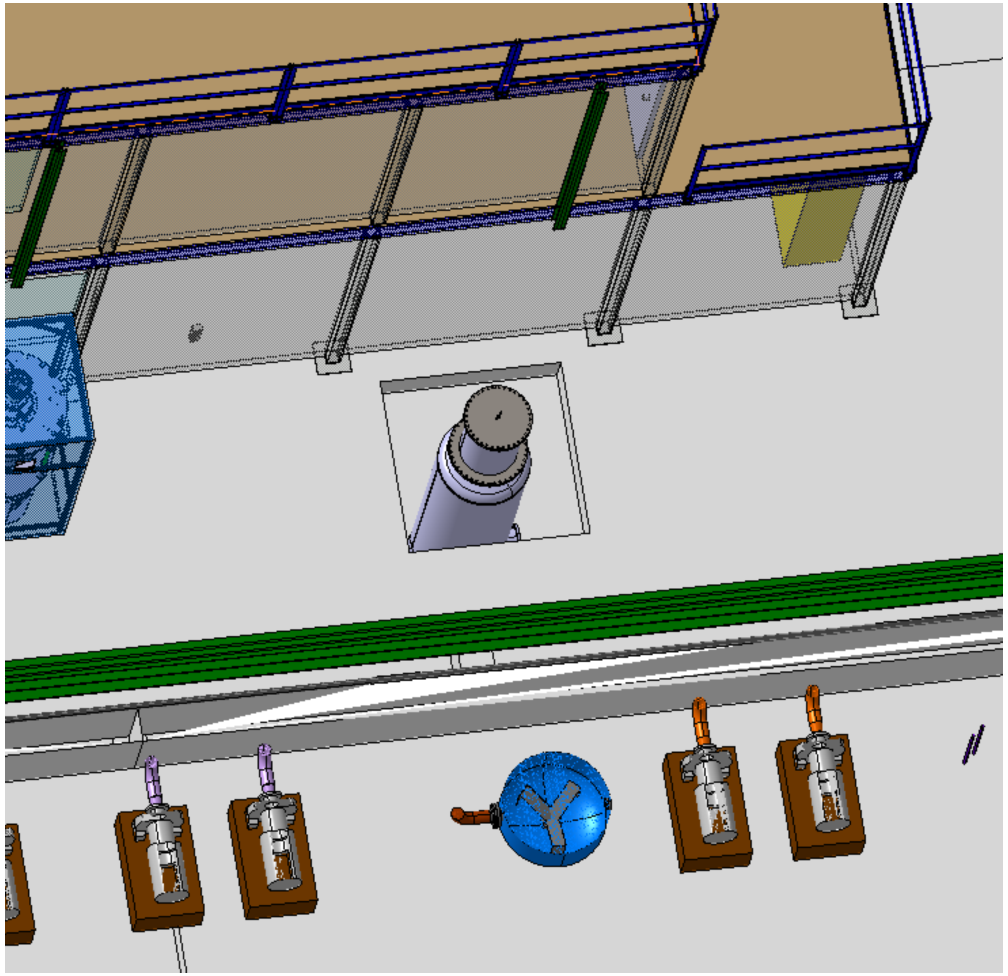


3D isometric view for the Nb_3Sn coating furnace integration in SA18 building

Towards cavity coating: Limitations

Nb_3Sn target specifications:

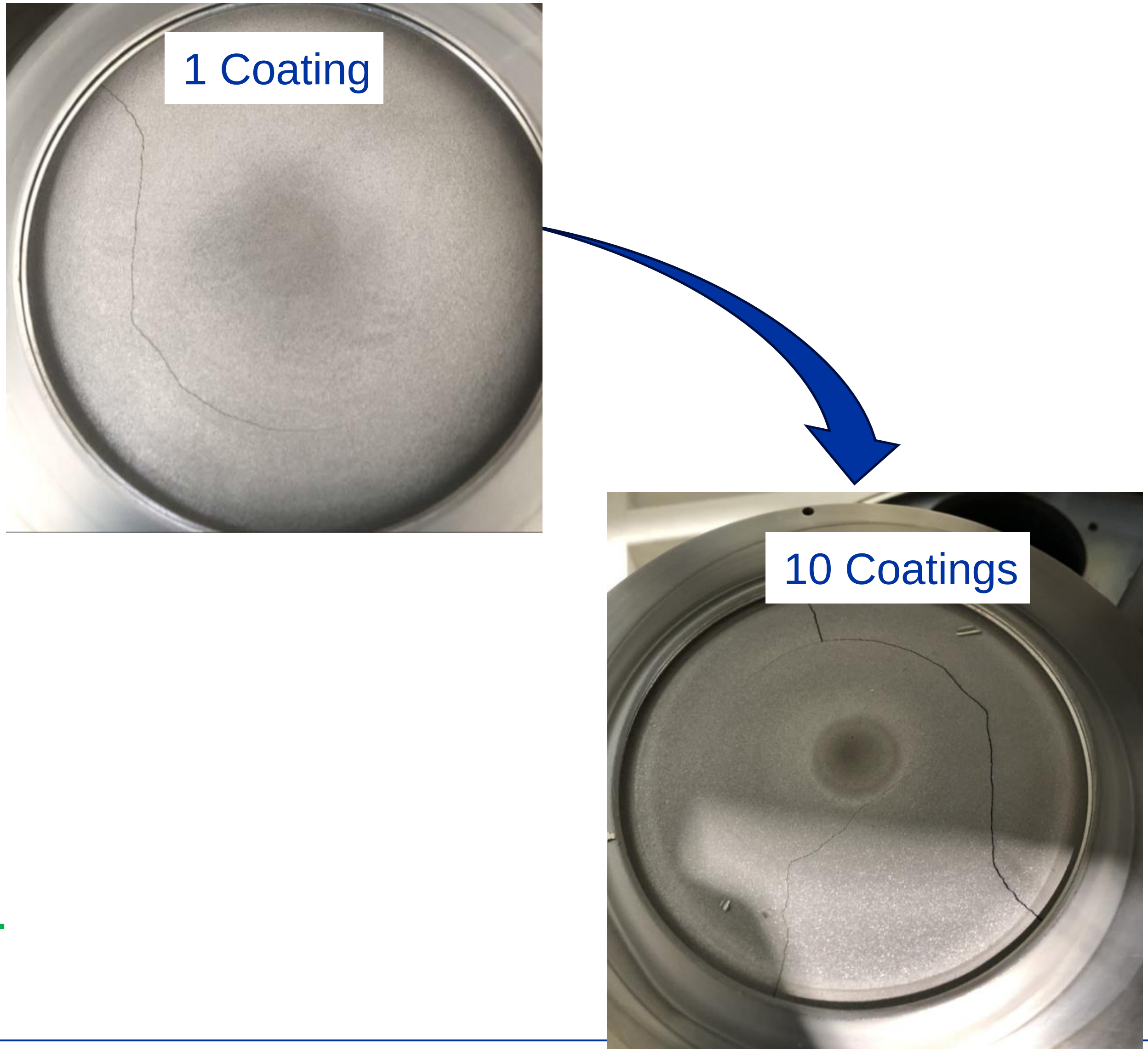
- Alloyed target
- Limitation to 2 targets:
  - One for diffusion barrier layer
  - One for Nb_3Sn

Nb_3Sn target undesired properties:

- Fragile and prompt to cracking
- Dust creation
- Not compatible with cylindrical shapes

Root cause identification:

- Thermal cycles, power ramp rate, **max power**
- The cracking is unavoidable



Towards cavity coating: Solution

G. Girod (EN-MME)

Most promising solution:

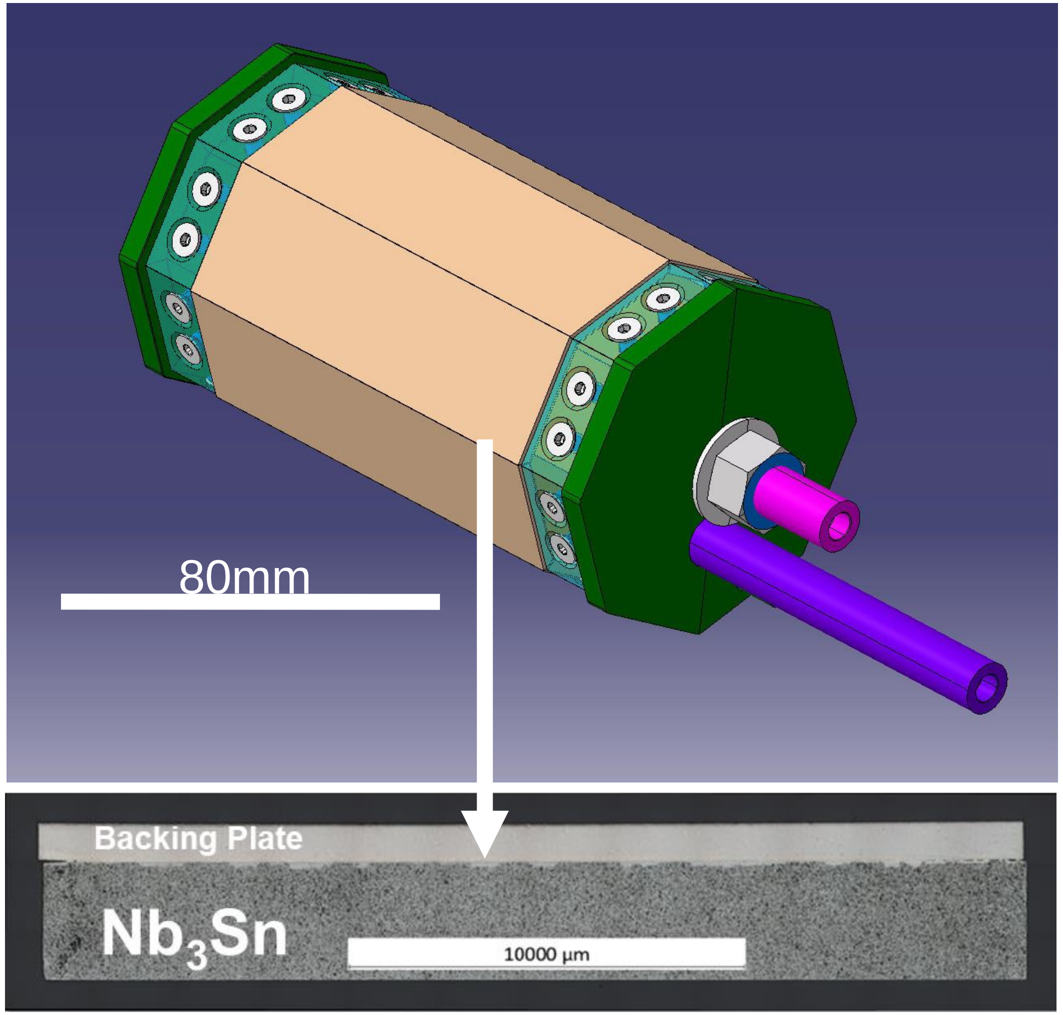
- Bonding on backing plate
- Same CTE as Nb_3Sn

First tests on small target:

- **Positive** on Ø 20mm target
- Ongoing for Ø 50mm target (then 150mm)

New magnetron design:

- Sealed magnet
- Dark space shields mandatory
- Cooling liquid bath for:
  - Magnet
  - Target through BP



V. Sibue and M. Crouvizier (EN-MME)

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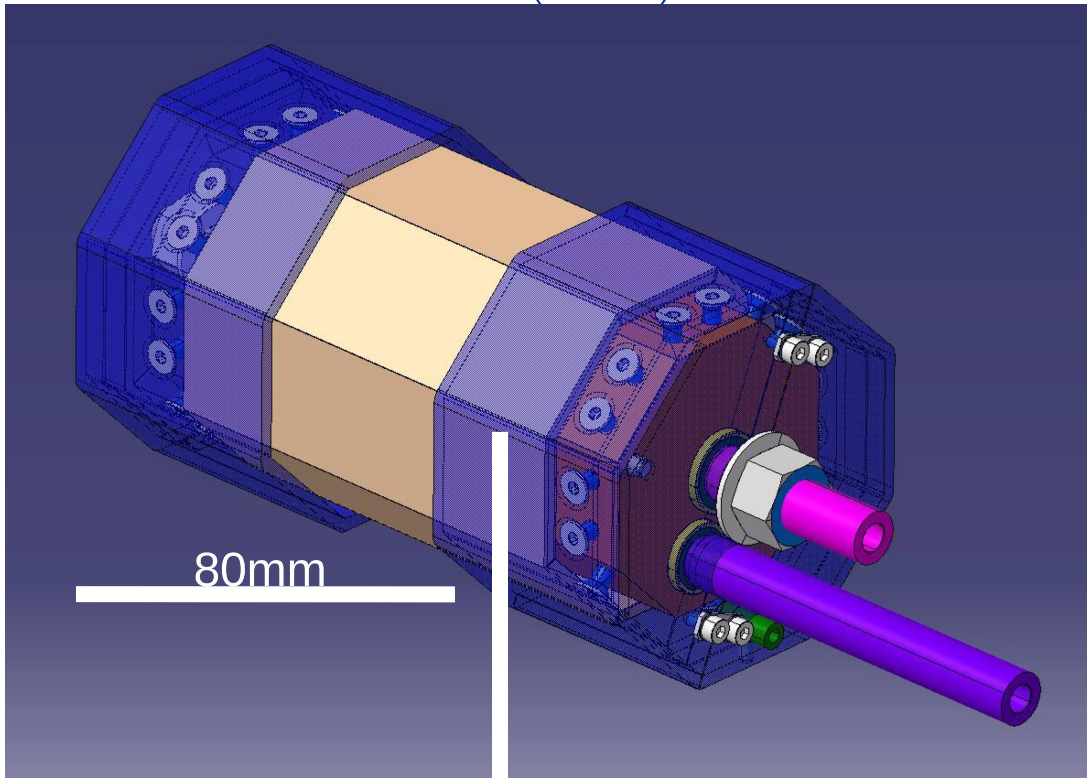

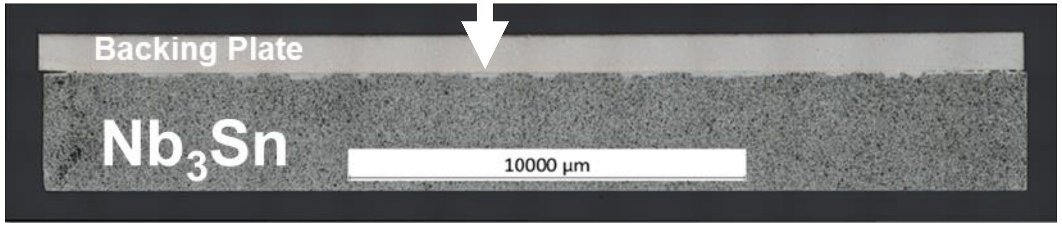

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Scale-up strategy at CERN

1. One have to push farther the competitiveness of Nb_3Sn/Cu wrt Nb/Cu
2. Continue with QPR testing and process optimization
3. Objects to be coated: last SRF CERN workshop consensus on moving on straight to 800MHz cavities. (potentialy compatible with 1.3GHz)
4. The cost of such a coating hardware will be > 500kCHF : one should target for success
5. Sub-components (target) shall be comissioned and validate prior full integration
6. New CERN SRF building to be «furnished» in 2029

Outlook

- Nb_3Sn/Cu is an attractive system to compete with Nb/Cu
- 800MHz performance appear promising
- Linear thermal dilatation coefficient difference between substrate and film remains an issue : look for another substrate?
- Cu interdiffusion can be controlled/mitigated. Does not appear yet as a showstopper.
- High temperature is a pre-requisite DURING coating
- Target fragility has to be handled for a proper scale-up: could be a showstopper
- RF tests on QPR are showing better performance than Nb/Cu
- Scale up to 800MHz cavities on its way

Thank you

Danke schön