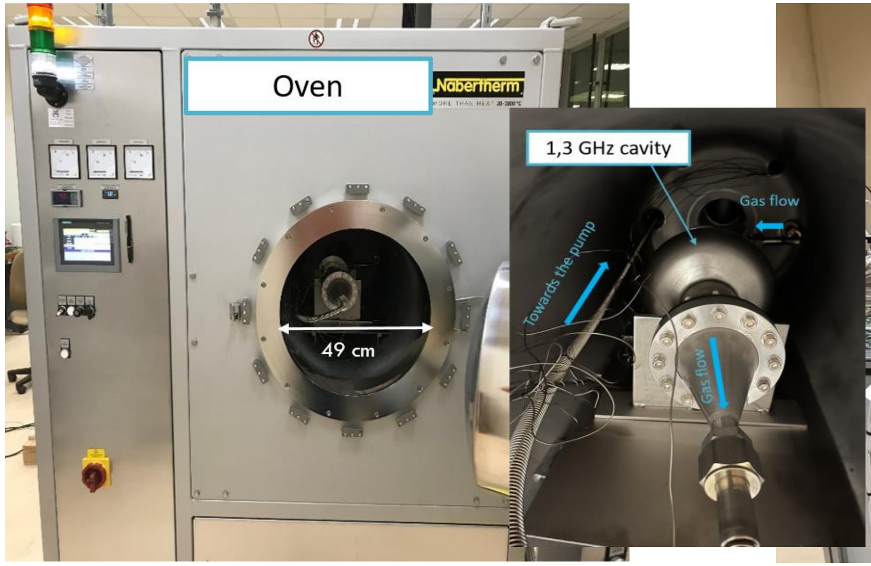
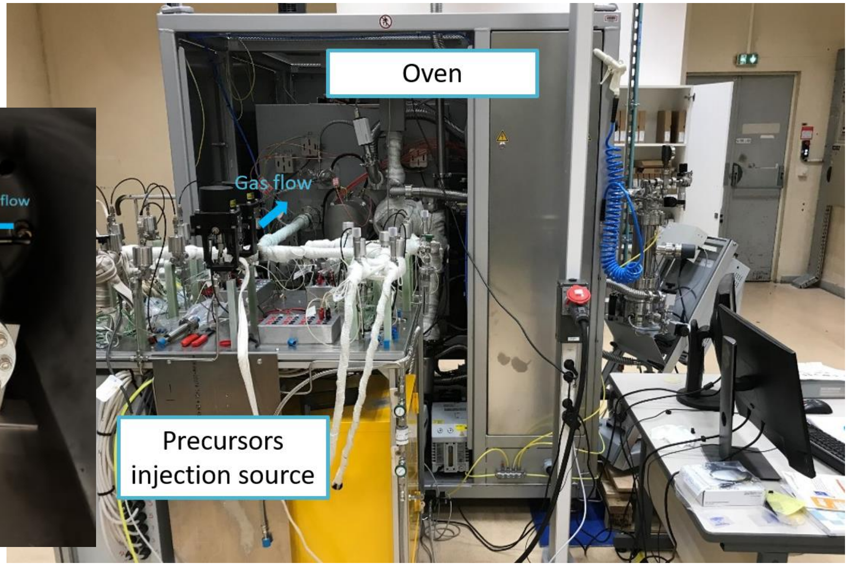
Surface engineering by Atomic Layer Deposition for SRF cavities WP 9.4

Team

- Yasmine Kalboussi: Research Staff – Atomic Layer Deposition (Qubits and cavities)
- Ivana Curci: Ph.D. Student CEA-USA – Tunneling spectroscopy for Qubits and cavities.
- Mathieu Benko: Engineer Student - Atomic Layer Deposition (Qubits and cavities-Y. Kalboussi).
- Fabien Eozenou: Chemist (EP, ninja cathode, Nb, Cu, Al…)
- Gregoire Jullien: Chemistry, clean room assembly etc…
- M. Baudrier, J. L. Maurice: RF tests
- P. Sahuquet, Q. Bertrand, B. Baudouy : Cryogeny
- F. Miserque: XPS
- M. Walls, N. Brun: TEM (Paris-Saclay University – LPS)
- Claire Antoine : Research director - magnetometry
- Thomas Proslier : Research staff – ALD and Tunnel spectroscopy

The lab – Deposition Lab

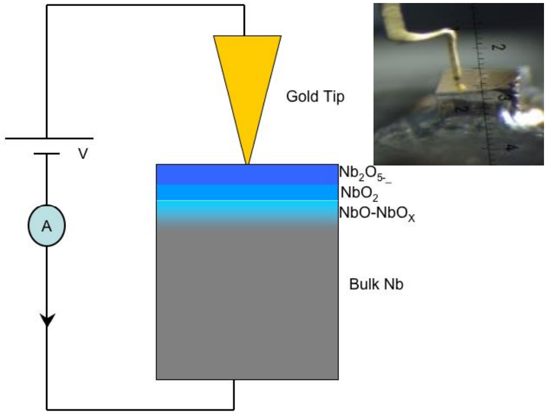




- Two ALD deposition systems:
  - Research scale: small samples (Φ = 5 cm , L = 40 cm) - New chemistries
  - Development scale: Macroscopic objects (Φ = 49 cm , L = 110 cm). 1.3, 0.7 GHz cavities

- Future:
  - HIPIMS deposition system for A15 on 1.3 GHz cavities and large coupons.
- Thématiques:
  - Superconductors (cavities, QuBits), multipacting, Corrosion, Filtration…

The Lab - Characterization



- Tunneling spectroscopy (Superconducting properties: gap, local Tc, Mapping – 1,5 K – 1x1 cm^2)
- Transport measurements (Tc, RRR)
- Projects:
- Collaboration USA (thesis, measurements)
- Collaboration with CERN (Nb_3Sn/Cu…)
- Research area:
- Qubits, cavities, ALD…

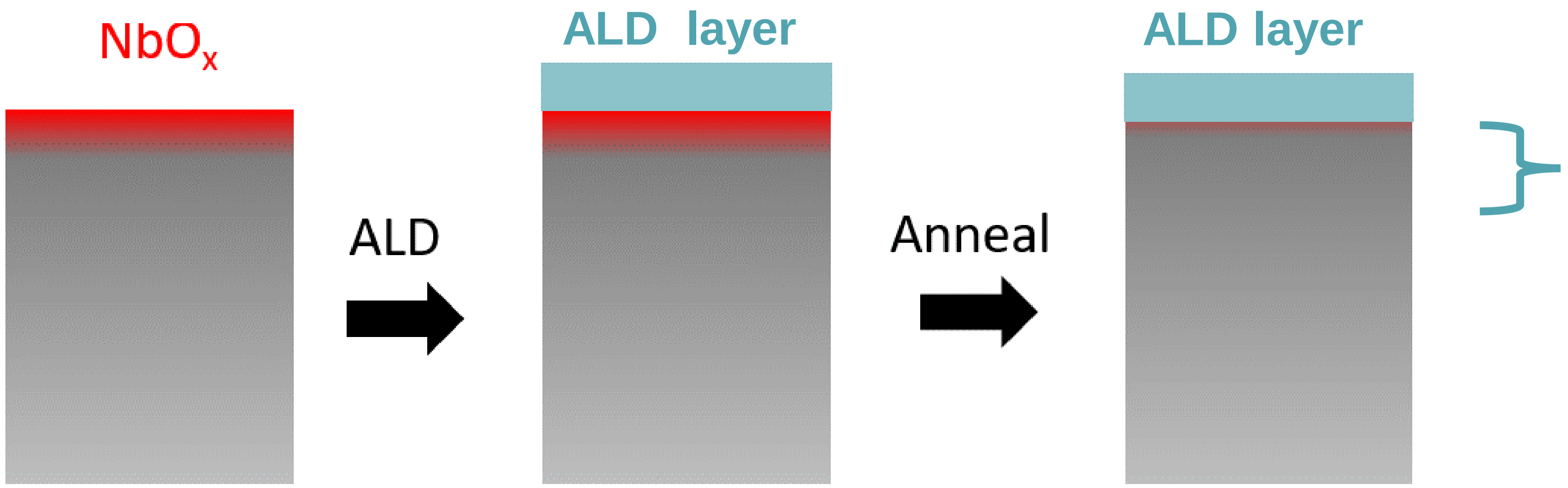
Part I

Reducing losses due the native oxide layer.

SRF cavities as detectors/Qubits

To replace niobium native oxides with ALD-deposited protective layer [1]

1) Deposit ~ 10 nm oxide layer by ALD (Al_2O_3 …) onto Niobium.
2) Perfom a subsequent thermal treatement to dissolve niobium native oxide underneath (vacuum levels 10^{-6} mbar)

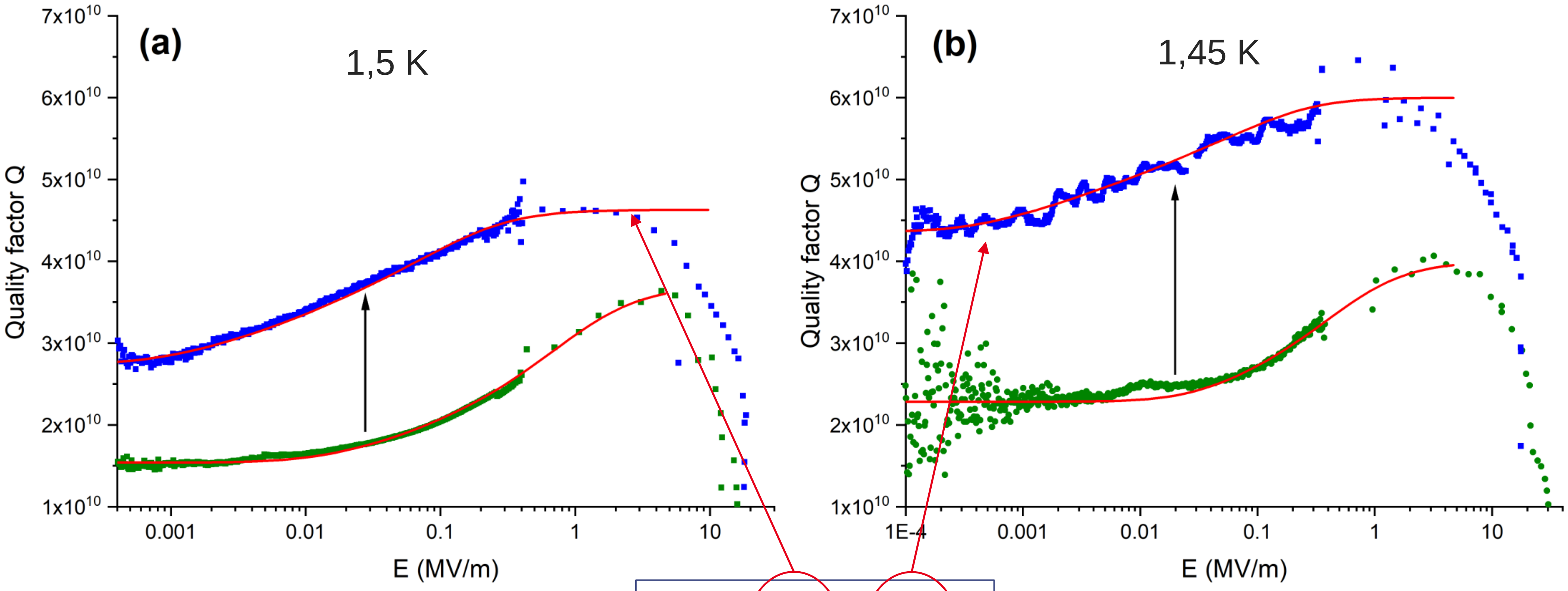


The oxide layer must be **thermally stable** and **have low dielectric** losses.

SRF cavities as detectors/Qubits

First experiment

Second experiment

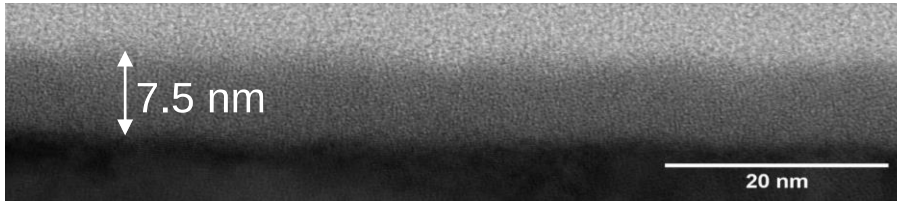


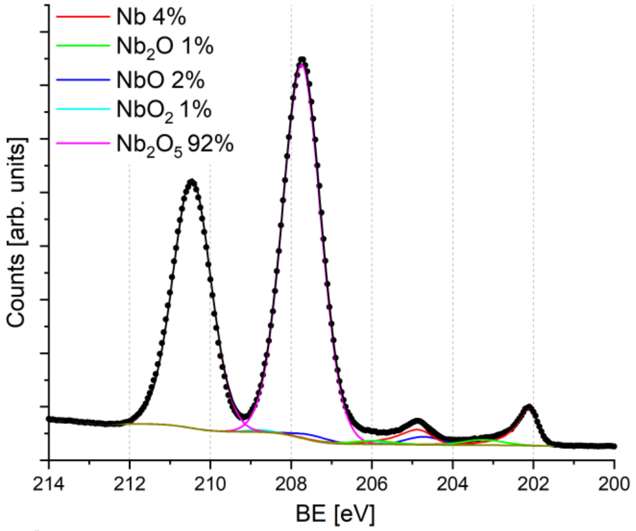
$$\frac{1}{Q} = \frac{1}{Q_{QP}} + \frac{1}{Q_{TLS}}$$

- The 10 nm Al_2O_3 film + annealing significantly improves the quality factors of the Nb cavity in the low field regime.

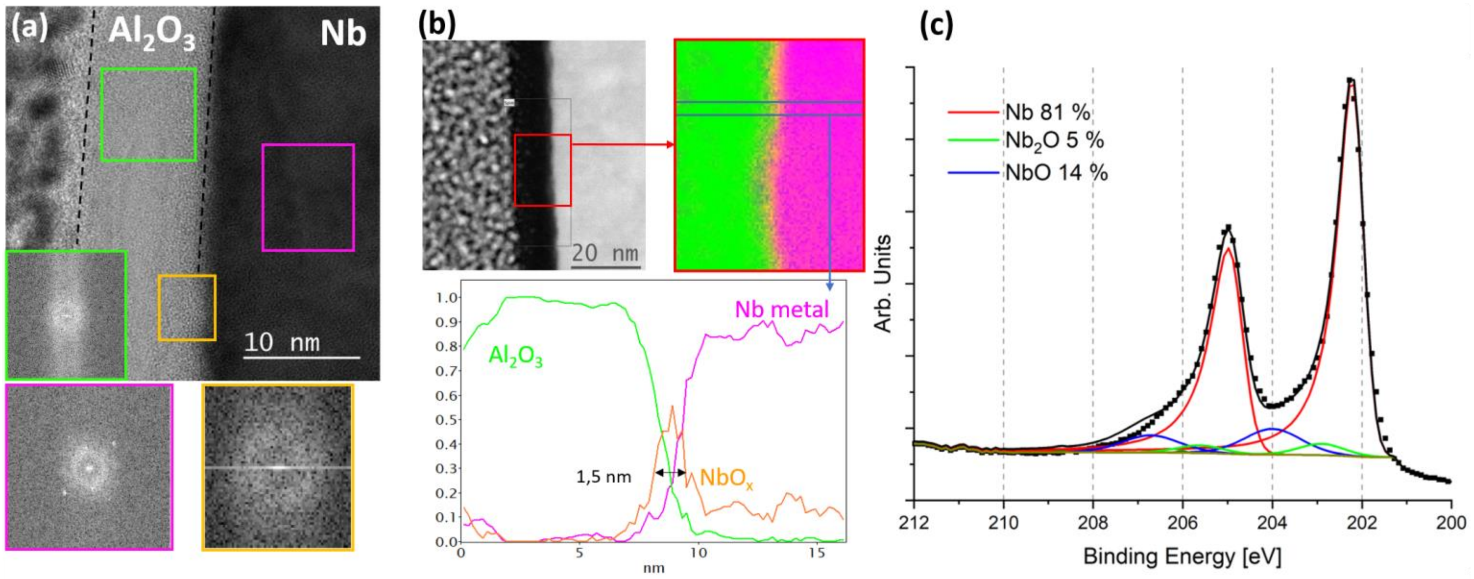
Electronic microscopy analysis

- Nb EP + HPR



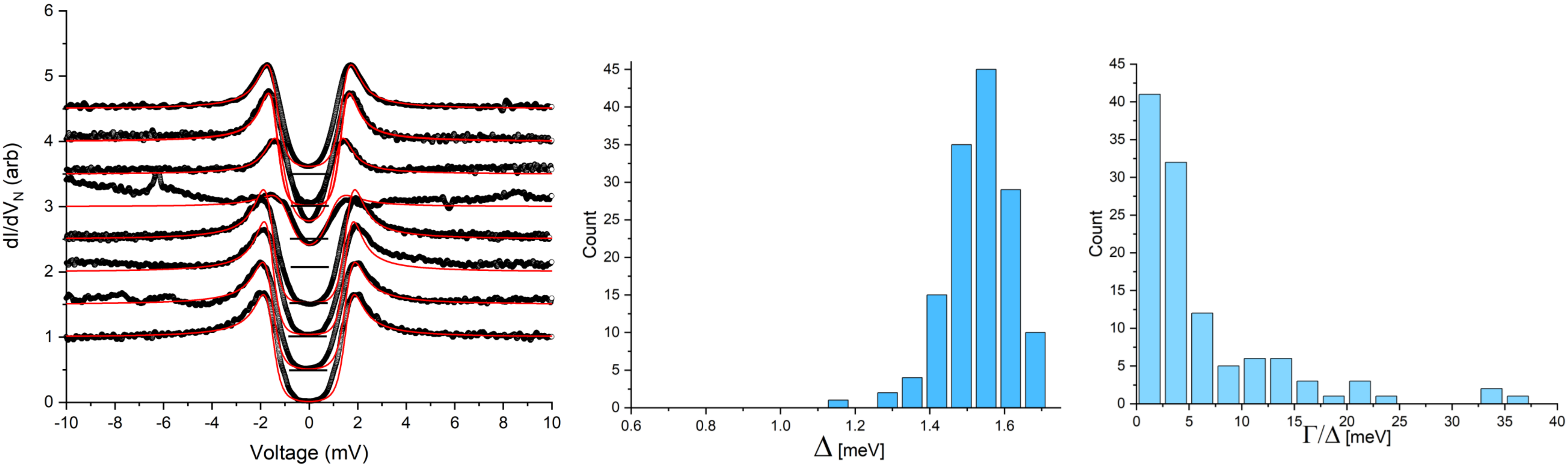


- Nb EP + HPR + Al_2O_3 ALD + 650°C-10hrs



- Removal of Nb_2O_5 -> increase of Q at low fields.
- Method to explore TLS losses with other materials, thicknesses and thermal treatments.
- Patent pending and publication *Appl. Phys. Lett.* 124, 134001 (2024).
- More tests with FNAL and CEA

Tunneling spectroscopy analysis Al_2O_3/Nb



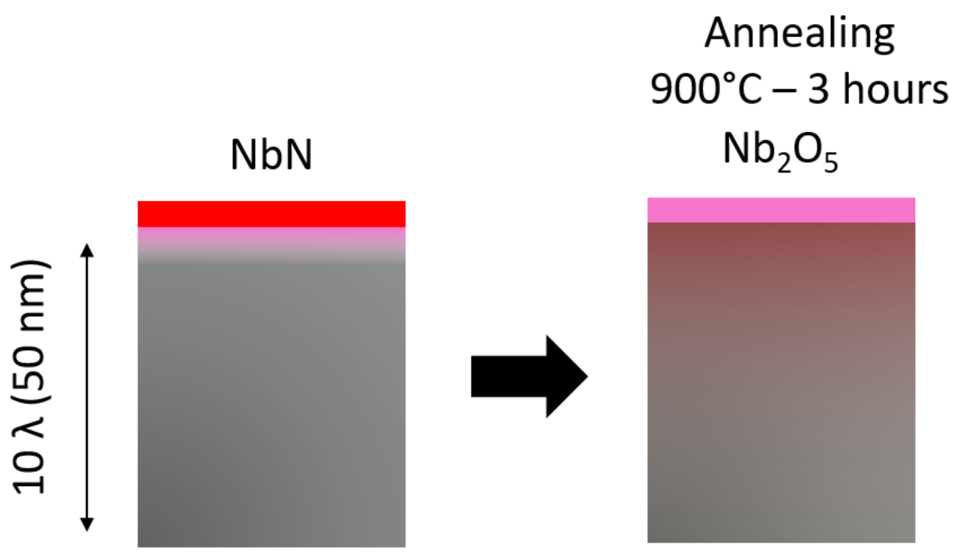
- High quality superconducting Junctions with high Δ and low Γ/Δ values.
- Responsible for increased Q_{QP}

Part II

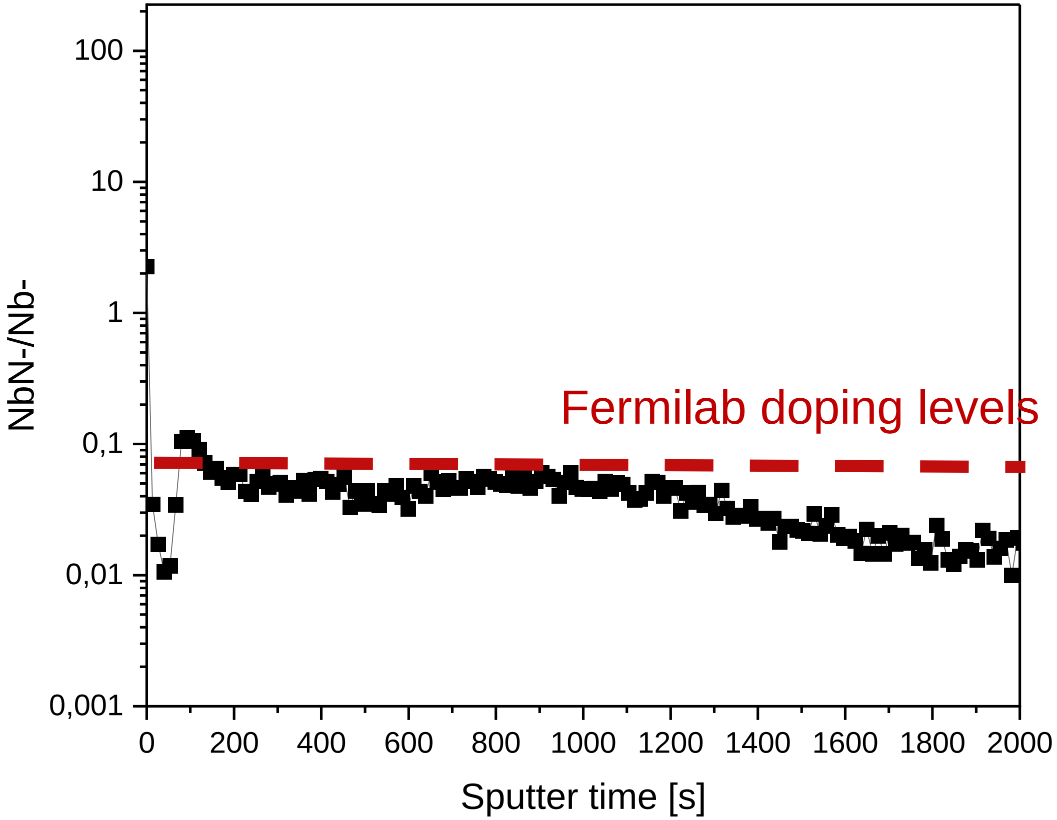
Doping Niobium cavities.

Doping

- 5 nm of NbN + annealing 900°C- 3 Hours - UHV



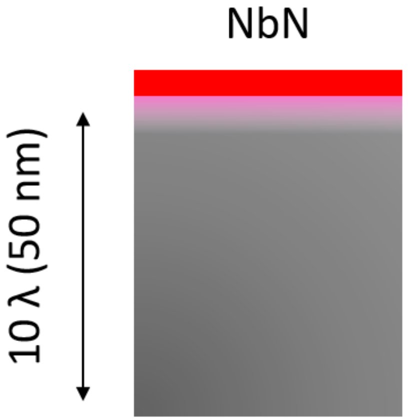
TOF-SIMS Profiling

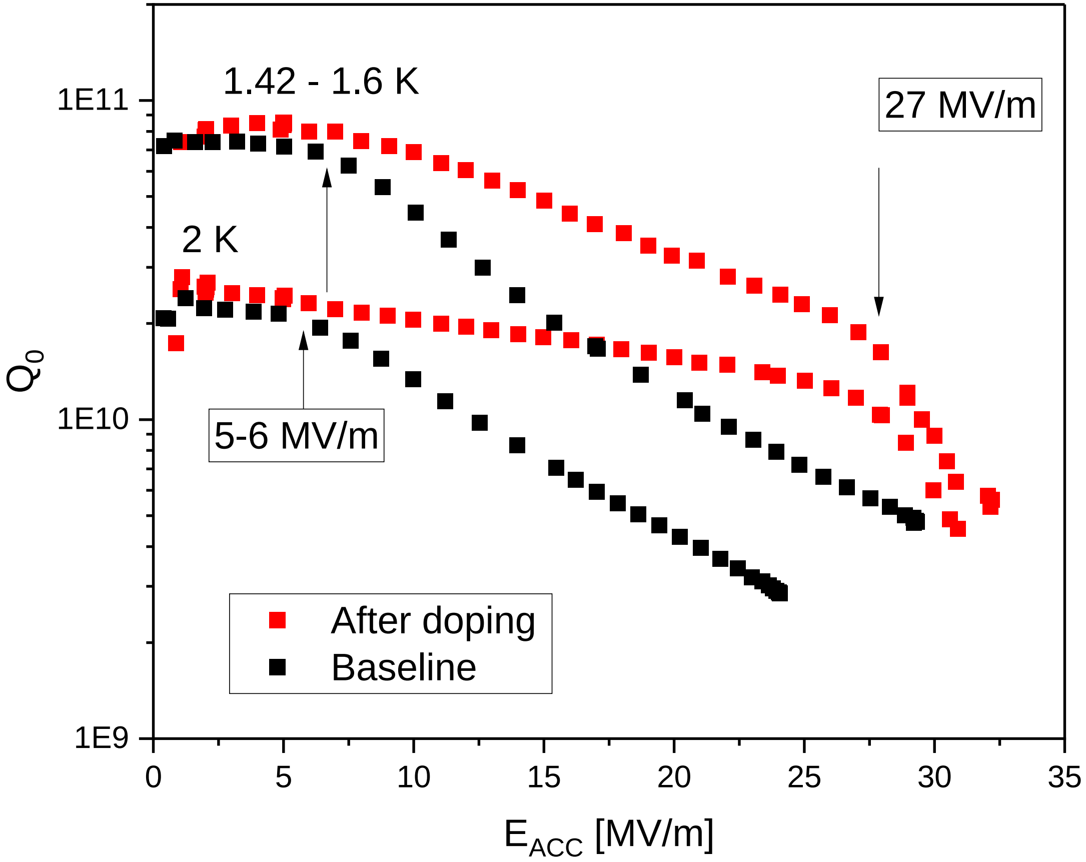


- Doping levels comparable to observed at Fermilab without electropolishing.

Doping

- The cavity was coated with 5 nm of NbN + annealing at 900°C-3 hours.
- No electro-polishing have been preformed.





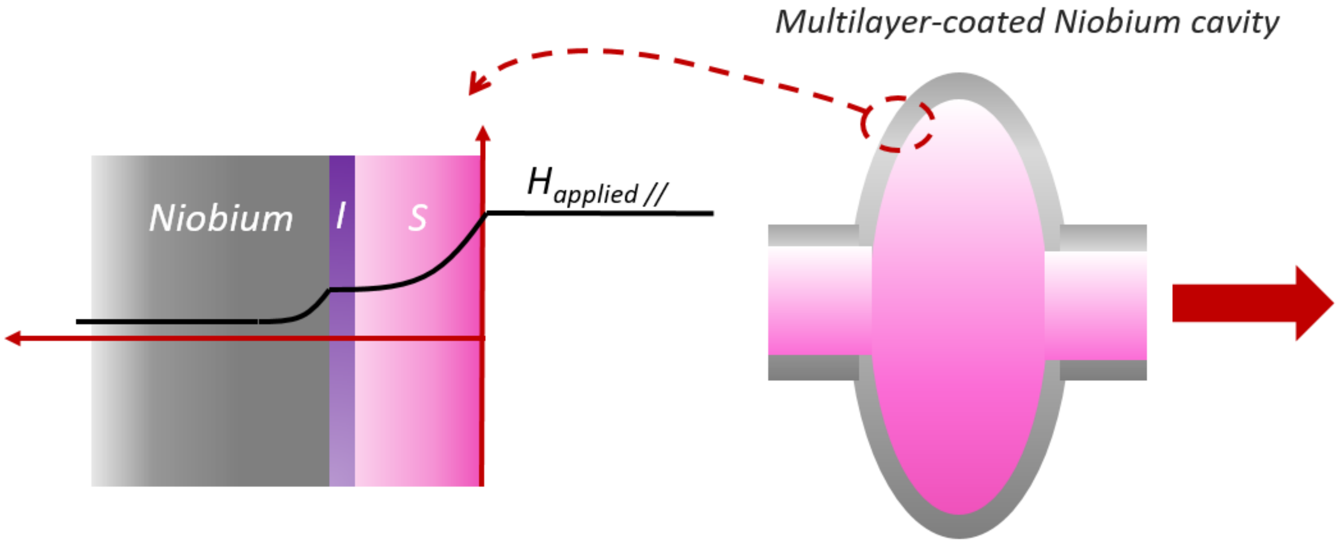
Thermal treatment and RF testing by Fermilab

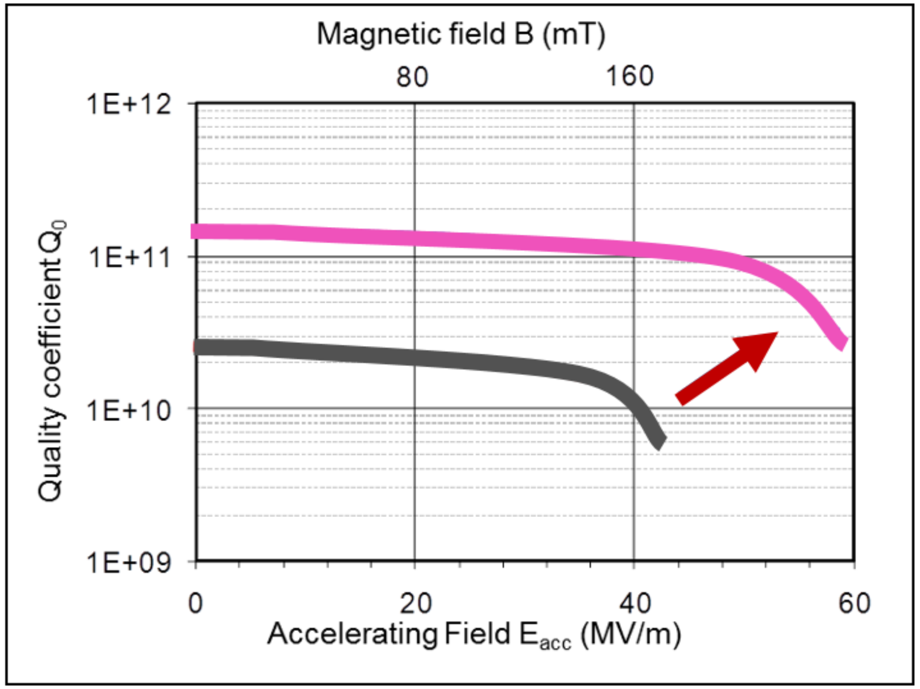
- ➢ The second test shows improvement over the baseline performances.
- ➢ Collaboration with FNAL. More tests to come

Part III

ALD-depositied multilayer to improve the superconducting performances of SRF cavities

Multilayers





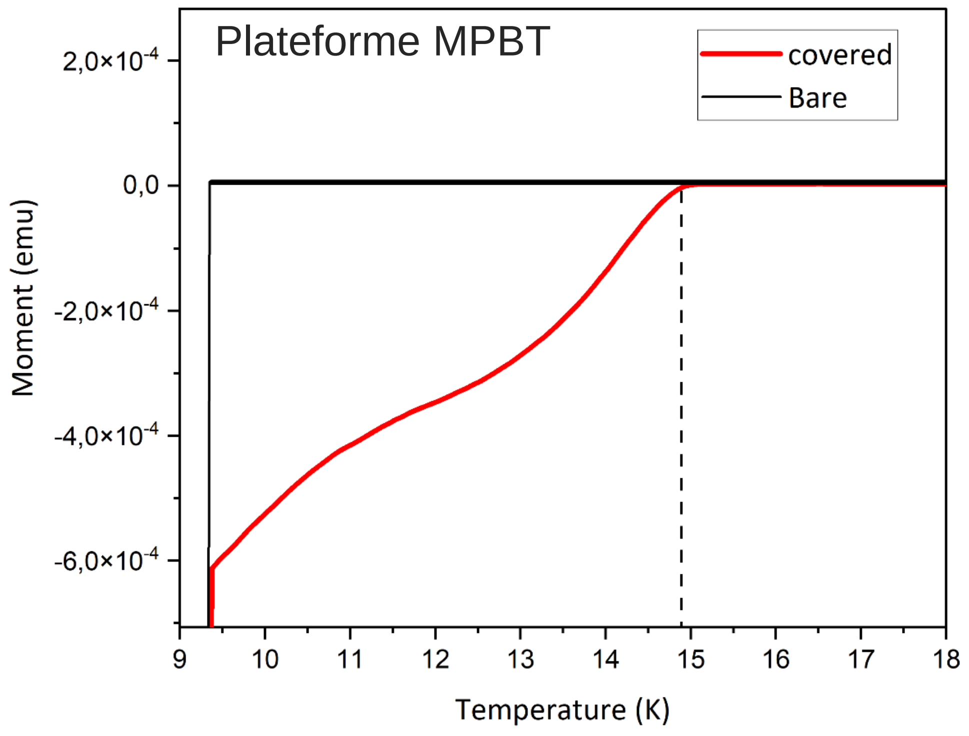
- A theoretical approach proposed by A. Gurevich (2006) to improve RF cavities through depositing a superconducting multilayer to screen the magnetic field.
- The thickness of the superconductor must be lower than its penetration depth.
- The superconducting layer must have higher T_c than Nb.

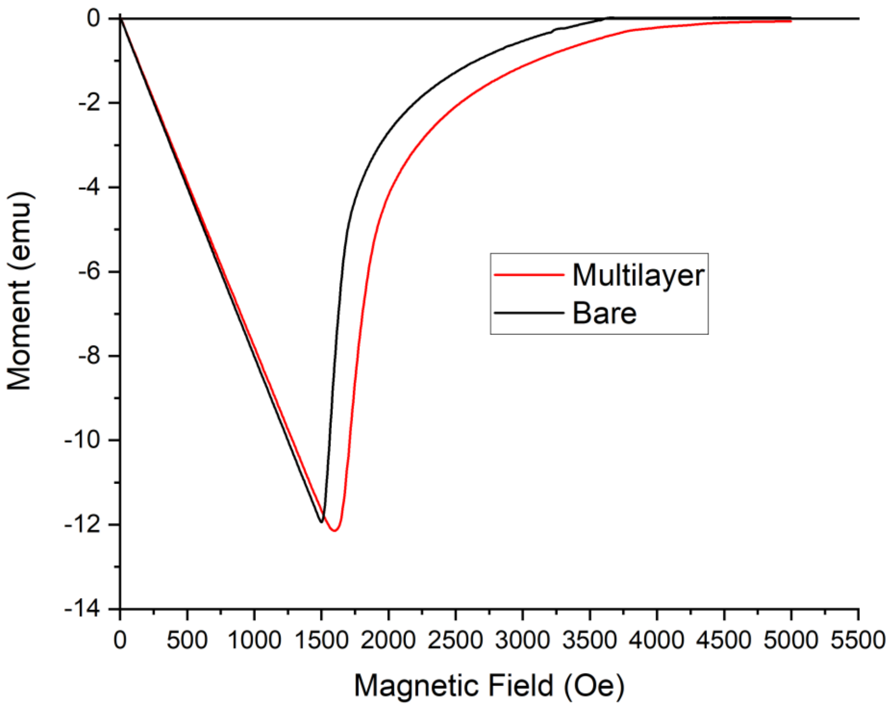
Multilayers

To enhance the superconducting performances of NbTiN films, several thermal treatments have been tested. The best results on Nb coated samples were obtained with:

- A first ramp of 6 °C/ minute up to 800°C
- A second ramp of 18°C/minute up to 900°C

NbTiN (45 nm) –AlN (10 nm) – Niobium

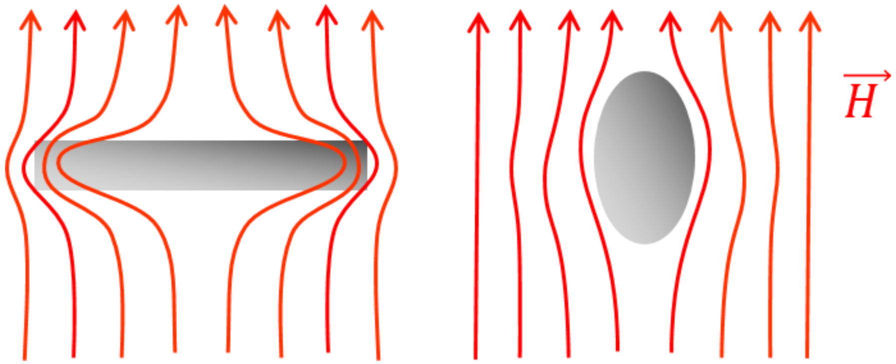




- T_c is similar on Niobium and Sapphire substrate.

Multilayers

➢ The Niobium ellipsoid was coated and annealed with the optimized NbTiN-AlN bilayer recipe.

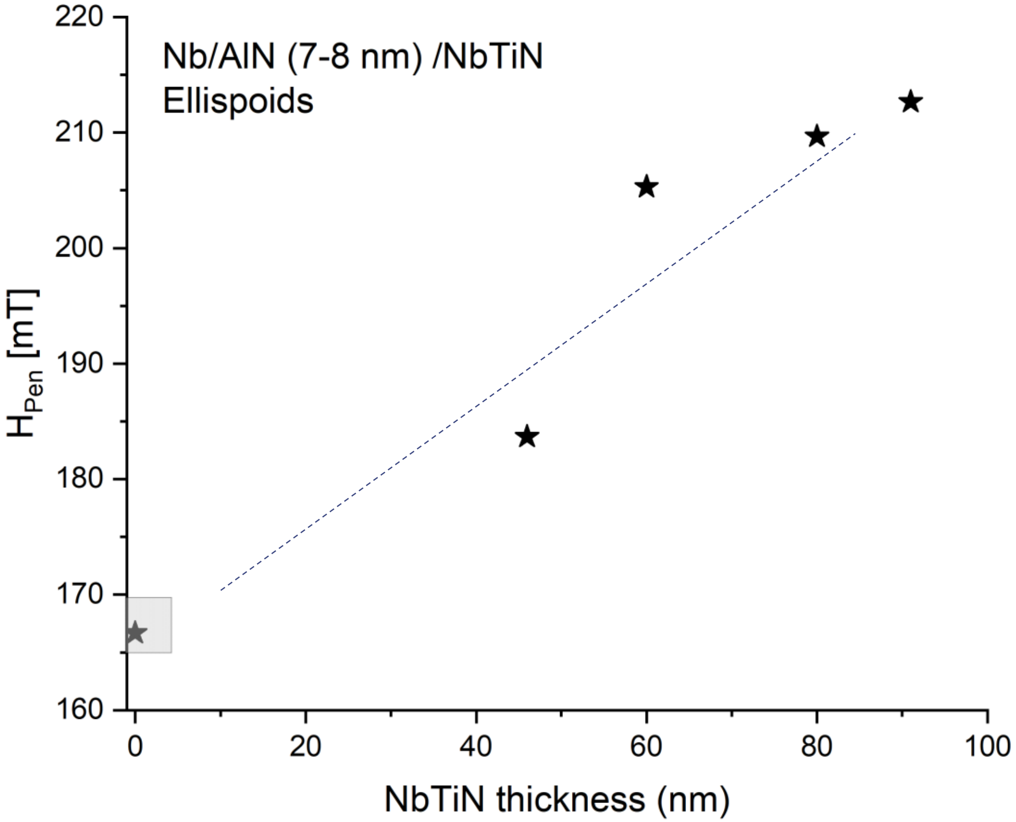


Demagnetisation factor N=0.13

$$H_{equator} = \frac{H_{applied}}{1 - N}$$

Before

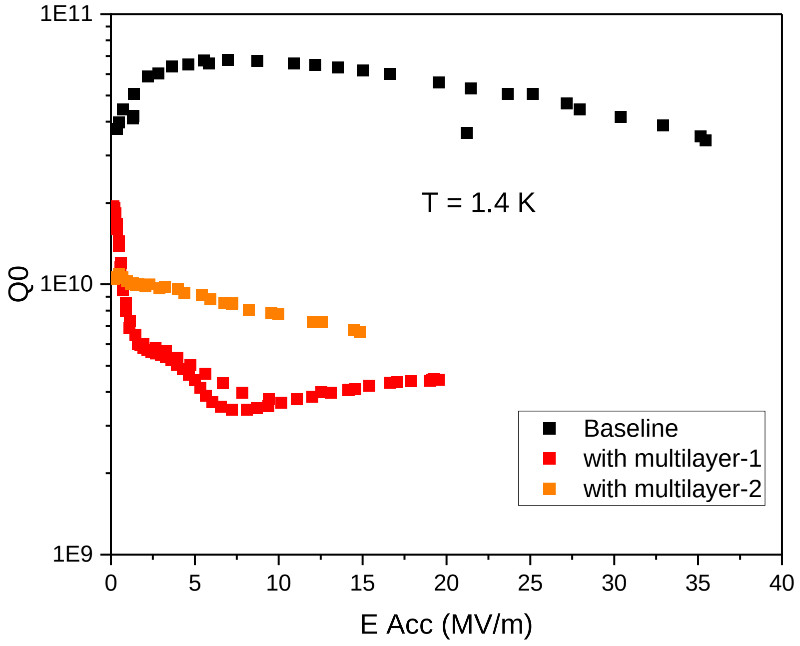
After

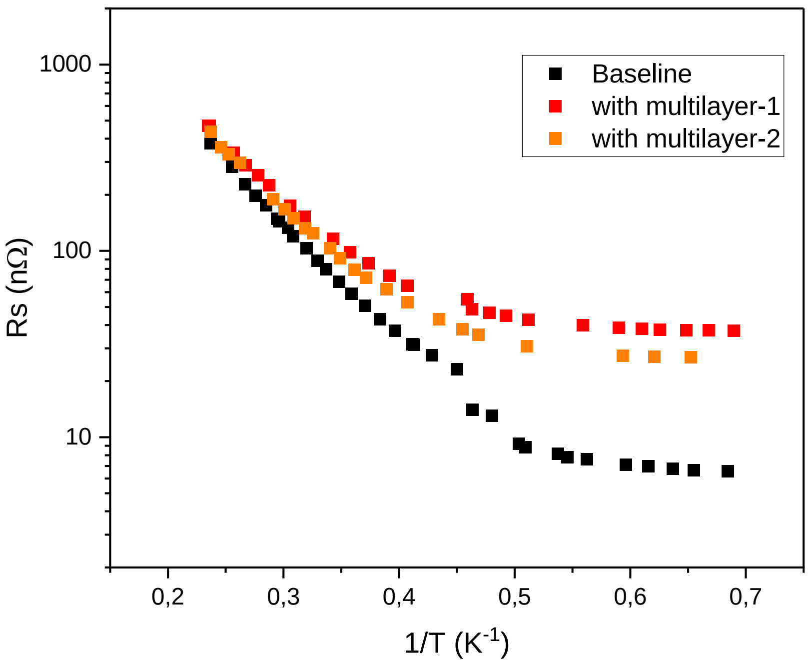


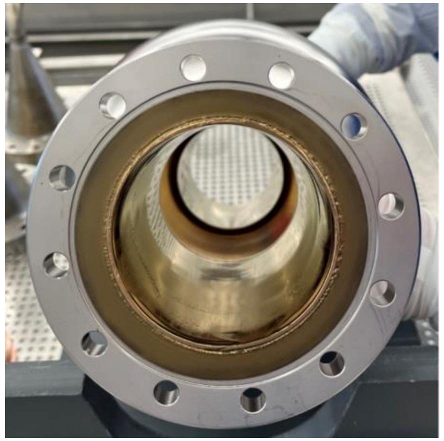
- The first vortex penetration field is enhanced by 30 mT after bilayer coating.

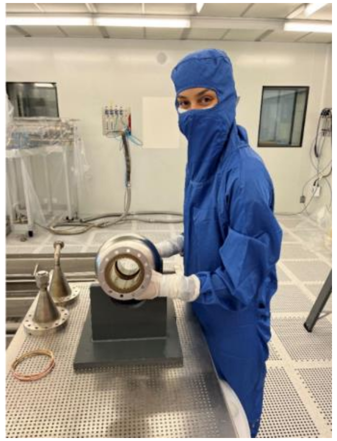
Multilayers

- The Niobium cavity was coated with the optimized AlN- NbTiN bilayer recipe .









- Coating had a bright golden and uniform color after ALD deposition.
- The cavity was annealed @ 900°C.
- Vacuum degradation during the annealing step on the first test.
- (P>10^{-5} mbar)
- Observed delamination in the beam tubes after annealing.

➢ A degassing step is necessary.

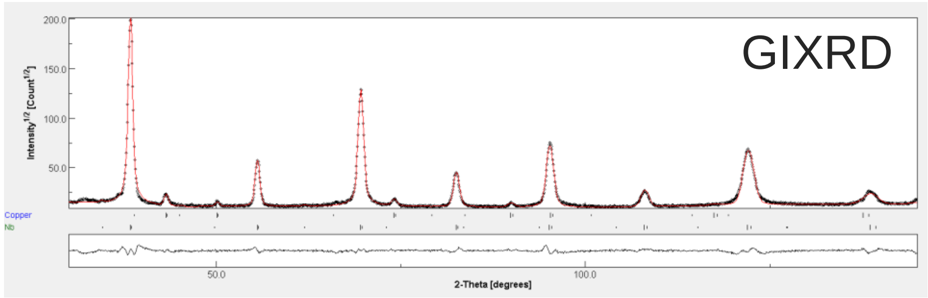
Part IV

Thermo-current mitigation: ALD on Cu for deposition Nb

ALD Al_2O_3 on Cu samples

C. Pereira, S. Leith, G. Rosaz, S. Pfeiffer

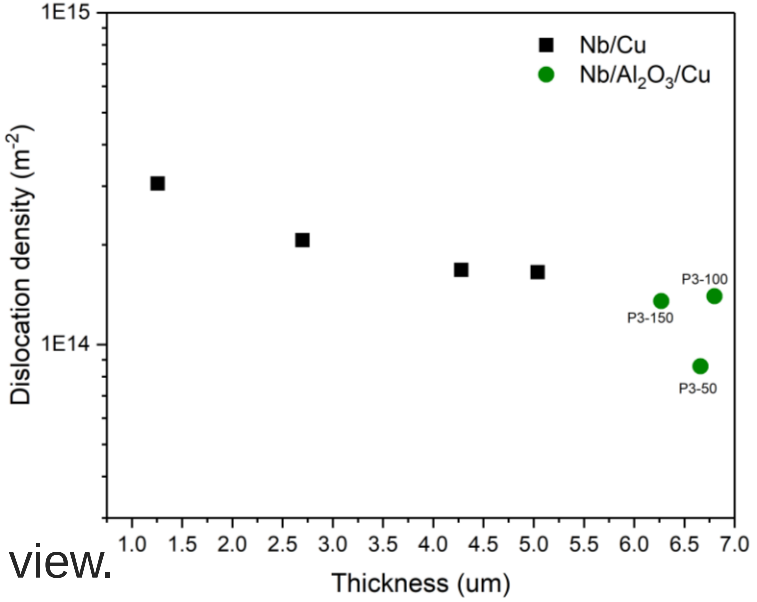
<u>Baseline coating recipe</u>
1.2kW avg
100Hz, 200us HiPIMS pulses
-75V bias voltage
150C
$2.5.10^{-3}$ mbar Kr



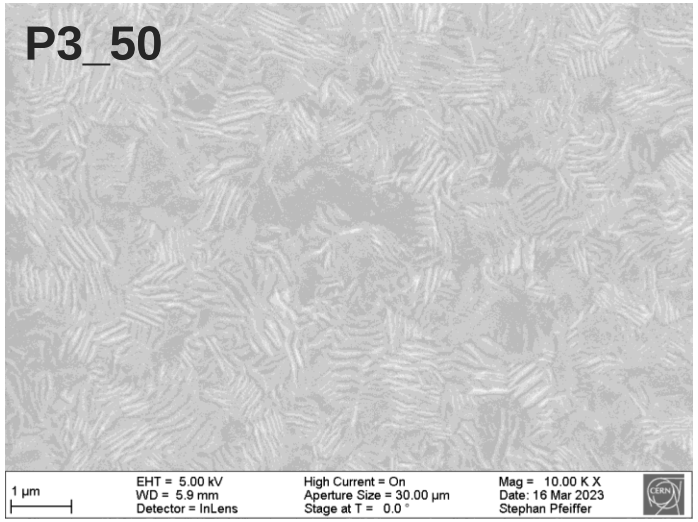
crystallite size, D
microstrain, ε
lattice parameter, a

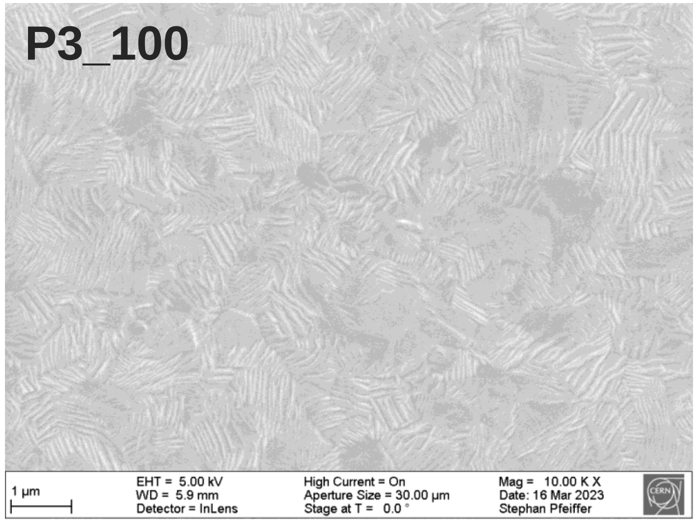
Dislocation density, ρ_D

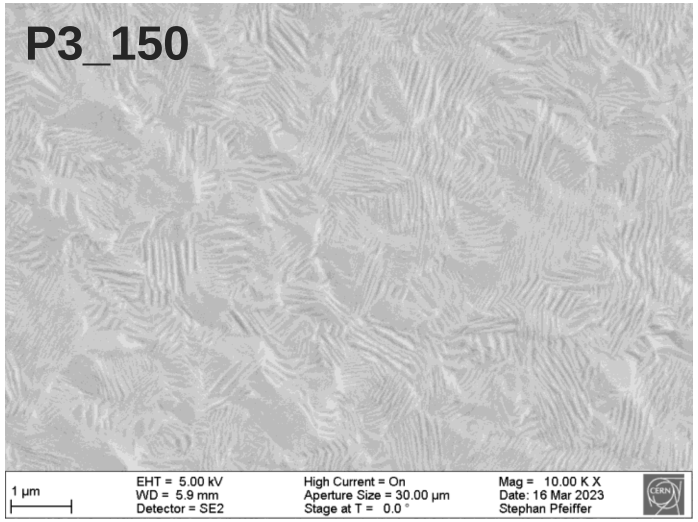
$$\rho_D = 2\sqrt{3}\frac{\langle \varepsilon^2 \rangle^{1/2}}{D \times b}$$



Nb/Cu and Nb/Al_2O_3/Cu do not show any difference from a defect content point of view.
The lower dislocation density can be explained by the thicker layer.





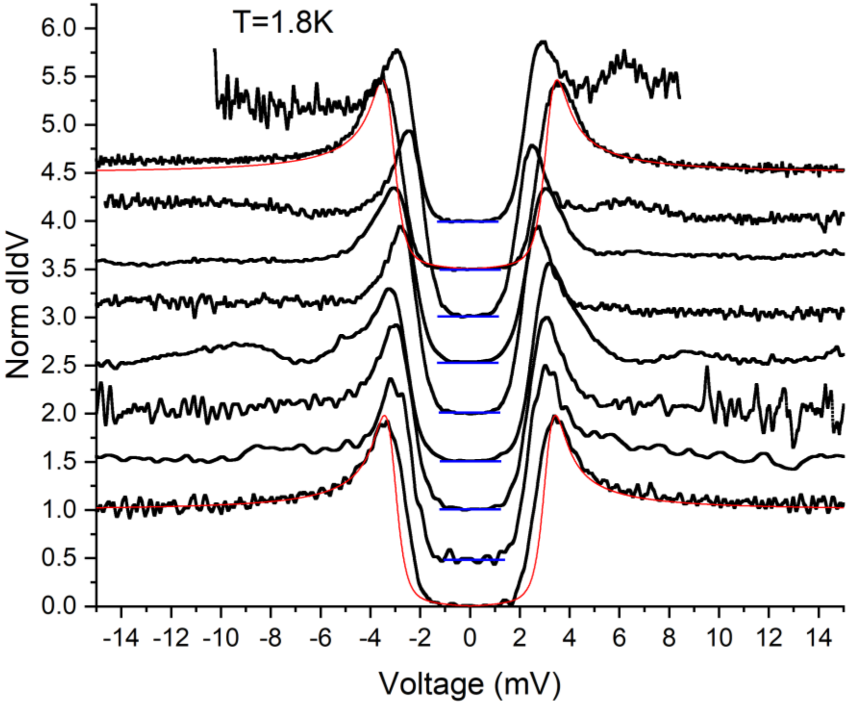


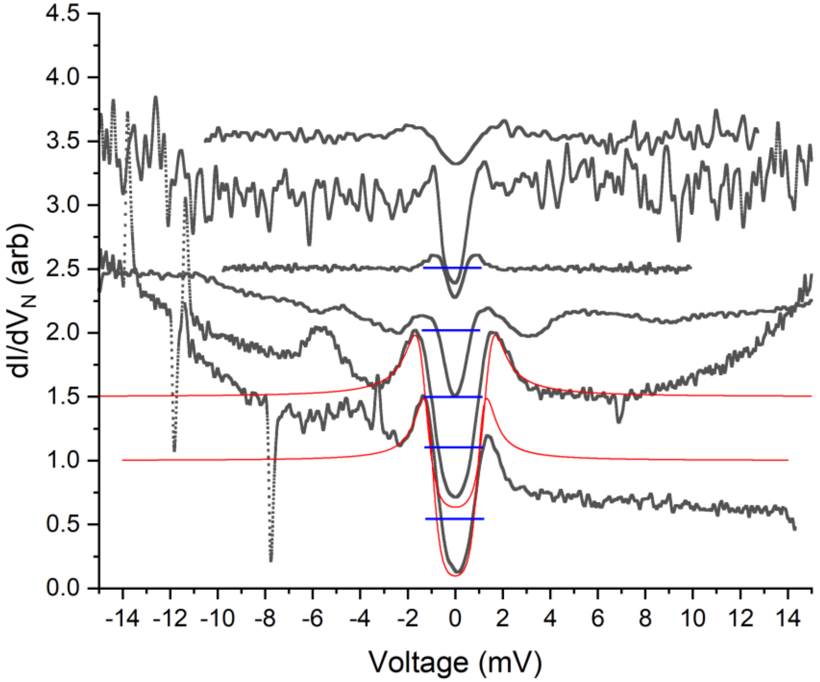
Part V

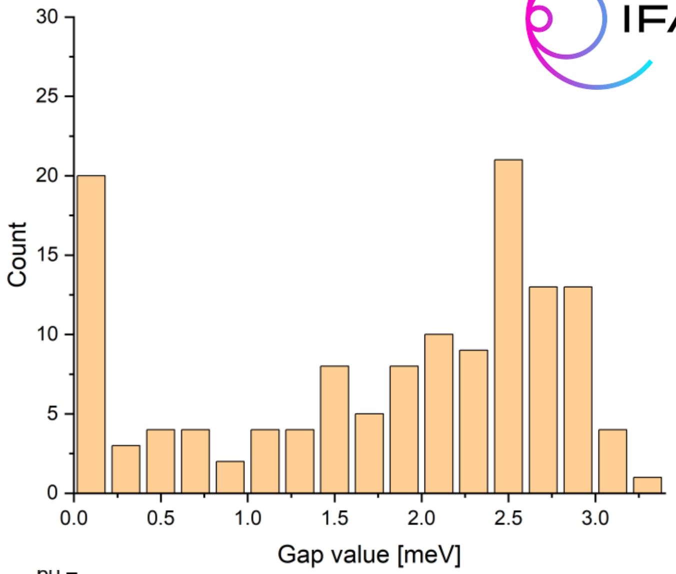
Tunneling spectroscopy Nb_3Sn - Cu

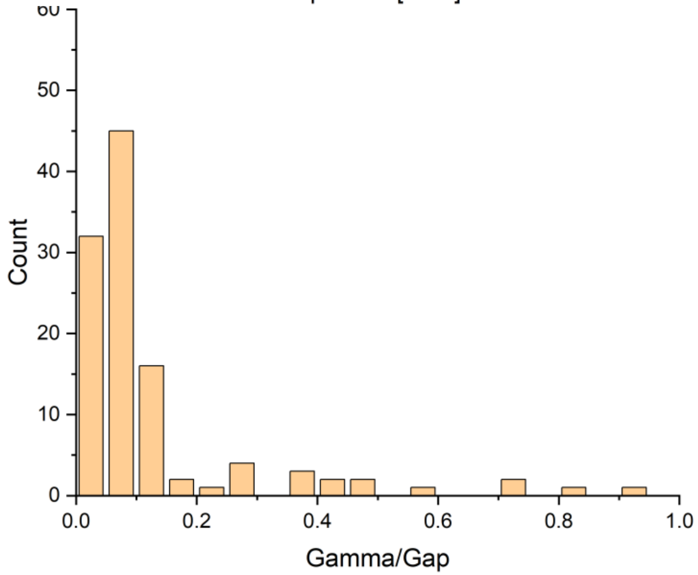
Nb_3Sn by Tunneling spectroscopy

- Nb3Sn-Ta-Cu (CERN)









- Some very nice tunnel junctions (low Γ/Δ values).
- Large distribution of superconducting gap values
  -> indicates different Sn concentration to be confirmed.

- Future measurements for INFN Nb_3Sn/sapphire

Part VI

Conclusion

Conclusion

- Multilayers: 1/ Find optimal NbTiN thickness. 2/ Future 1.3 GHz cavity coating (avoid delamination).
- Qubits: Engineering the surface oxide and decrease the TLS losses - Vary thicknesses and alloys.
- Doping: Repeat same deposition and vary the post annealing treatment.
- Thermo-current: ALD for thick superconducting films deposition: Nb HIPIMS/Al_2O_3…scale up to cavity (CERN).
- Tunneling Spectroscopy: Nb3Sn on Sapp/Cu, Nb surface treatments for cavities and Qubits.

Thank You for your attention !

Any questions ?