Characterization of TESLA-shaped single-cell Nb thin-film cavity with varying RRR values at low temperatures.

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September 19, 2022

Superconducting Quantum Materials and Systems Center

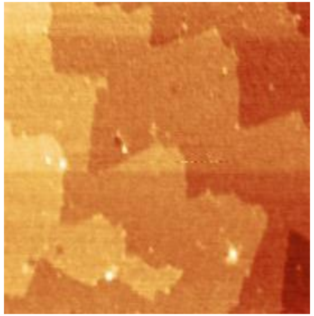
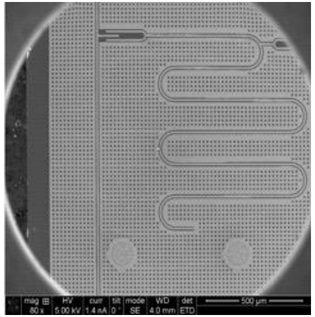
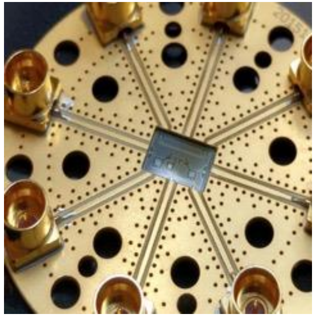
With the **Superconducting Quantum Materials and Systems** Center (SQMS), we propose to bring the power of DOE laboratories, together with industry, academia and other federal entities, to achieve transformational advances in quantum technologies for computing and sensing"

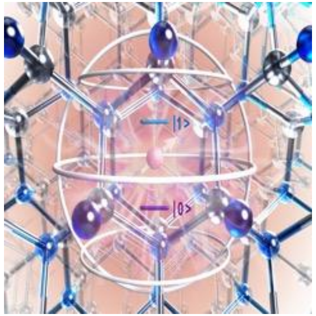
20 Institutions
>275 Collaborators

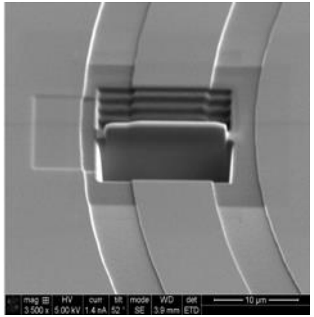
❖ **We have the ambitious goal of building the first quantum computer at Fermilab**

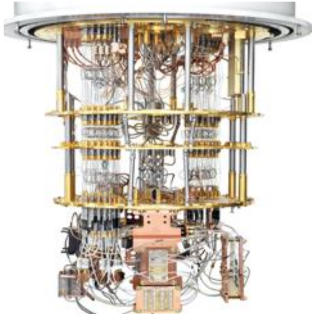
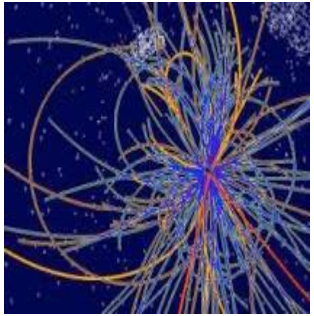
SQMS S&T Innovation Chain: from material discovery to quantum advantage

Materials Discovery → High Coherence Devices → Systems Integration → New quantum computing and sensing platforms → Quantum Advantage





SRF cavity and Nb thin-film characteristics

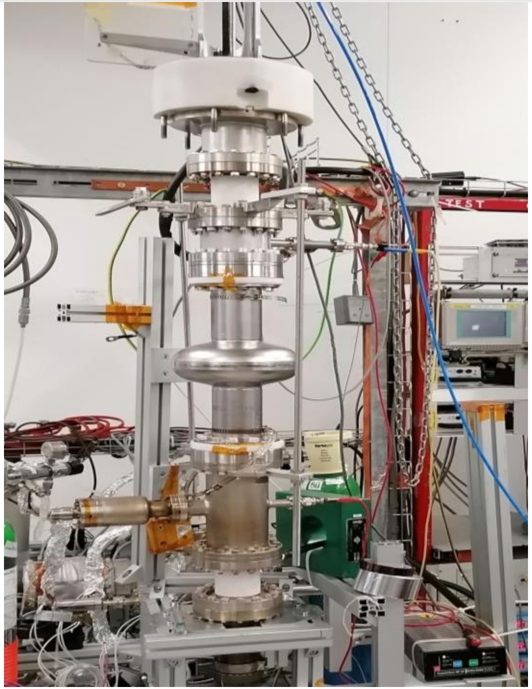
Cavity parameters

- Type: TESLA-shaped single-cell Nb
- Frequency: 1.3GHz
- Beta: High
- Geometry factor: 273Ω

Thin-film deposition parameters

- Main pulse duration: 200us
- Bias voltage: -75V
- Power: 1200W
- Pressure: 3x10^{-3}mbar
- Temperature: 150°C
- Deposition time: 6 hours
- Target: Nb RRR300
- Background gas: Kr
- Thickness: 6µm

Data: CERN

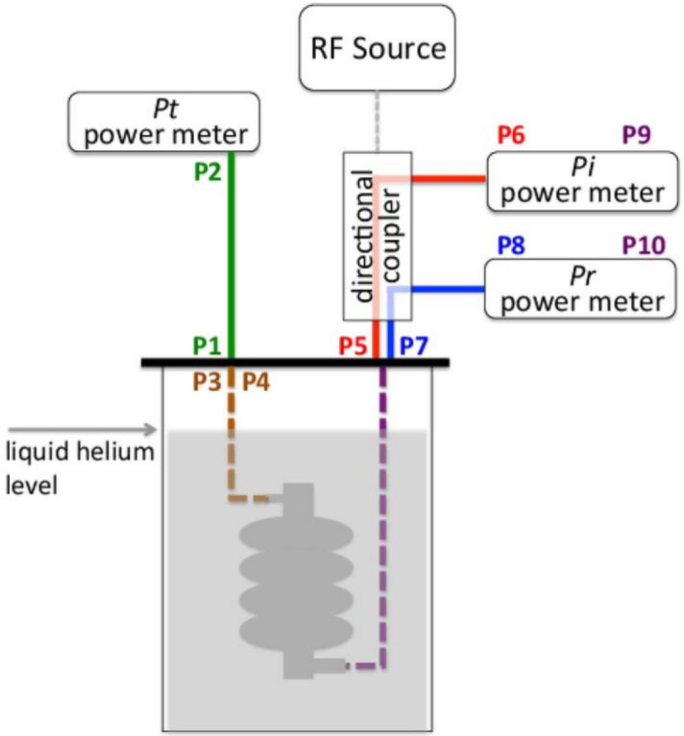


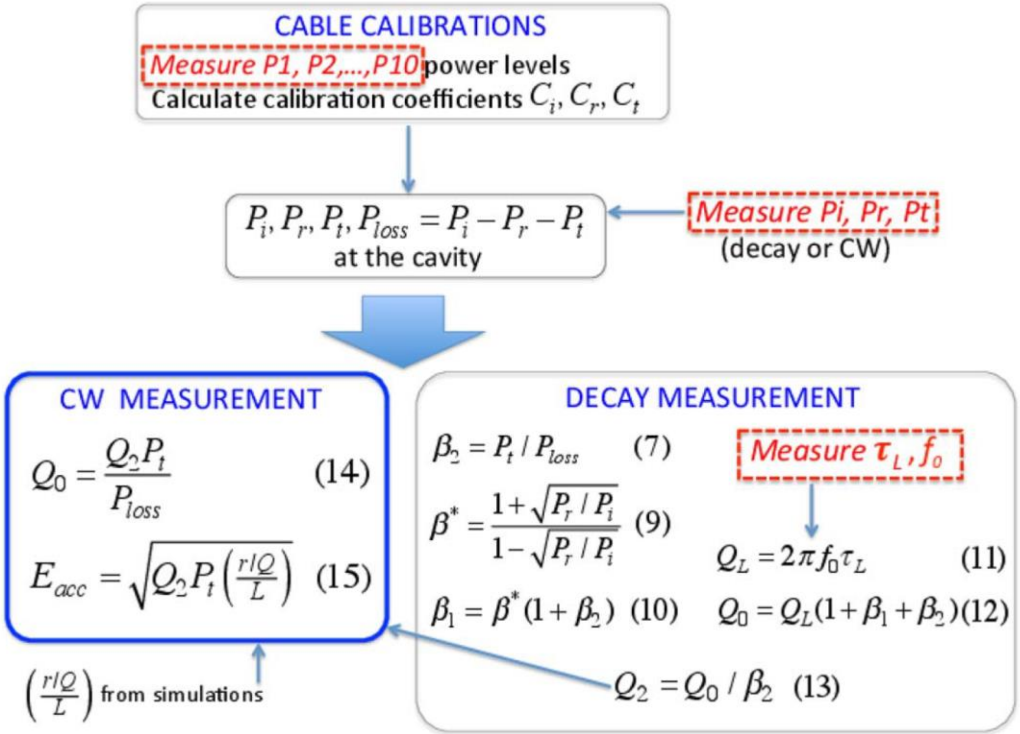
Nb cavity was designed and fabricated at Fermilab. Nb thin film was optimized and coated at CERN

A Bipolar HiPIMS thin film deposition system at CERN. (Image: CERN)

Motivation: The superconducting properties of niobium in microwave fields vary significantly with lattice defects and impurity content, where sub-at.% impurity level can reduce or increase microwave surface resistance.

Vertical Test Stand (VTS) cavity testing

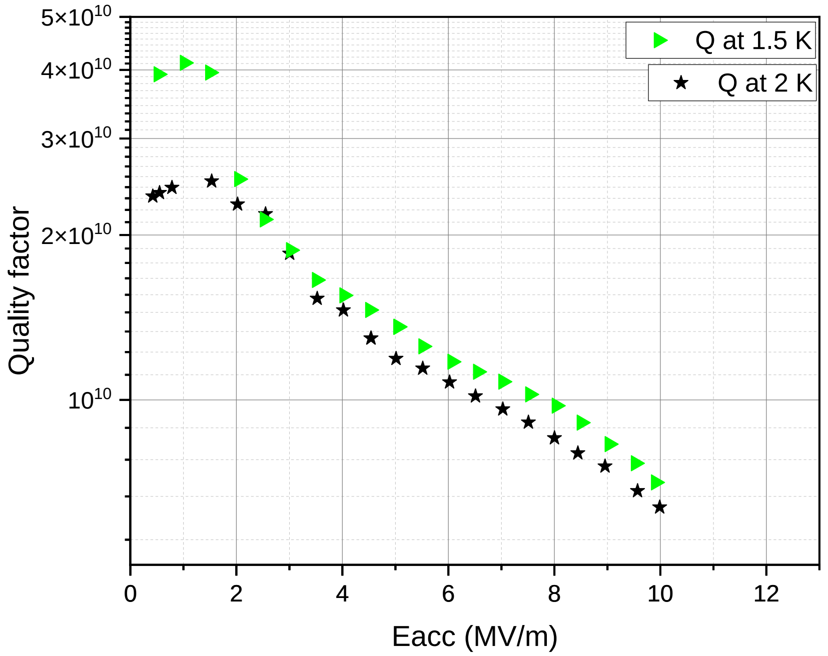




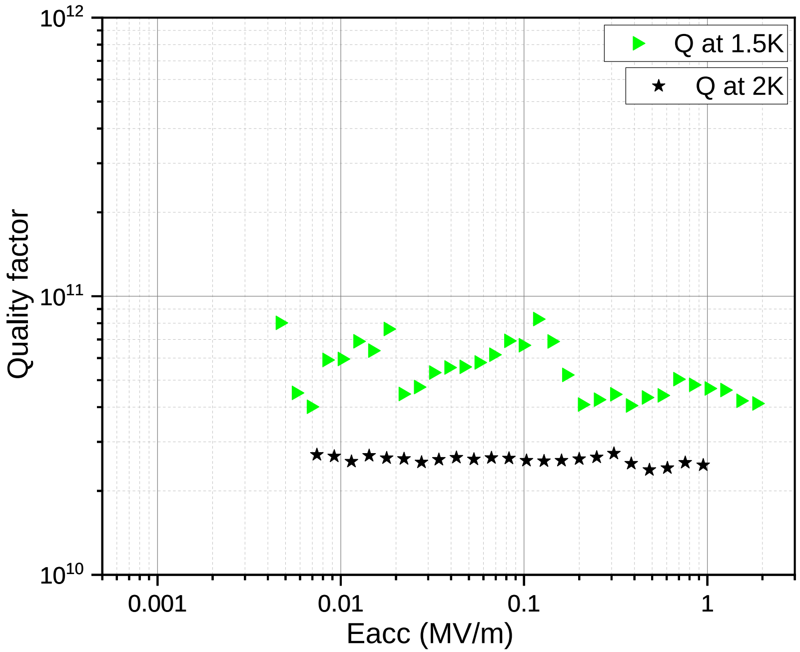
O. Melnychuk, A . Grassellino, A. Romanenko "Error analysis for intrinsic quality factor measurement in superconducting radio frequency resonators"

VTS measurements

Accelerating gradient vs Quality factor



Accelerating gradient vs Quality factor at low field



- **The cavity was limited at Eacc ≈10.2 MV/m by a quench.**

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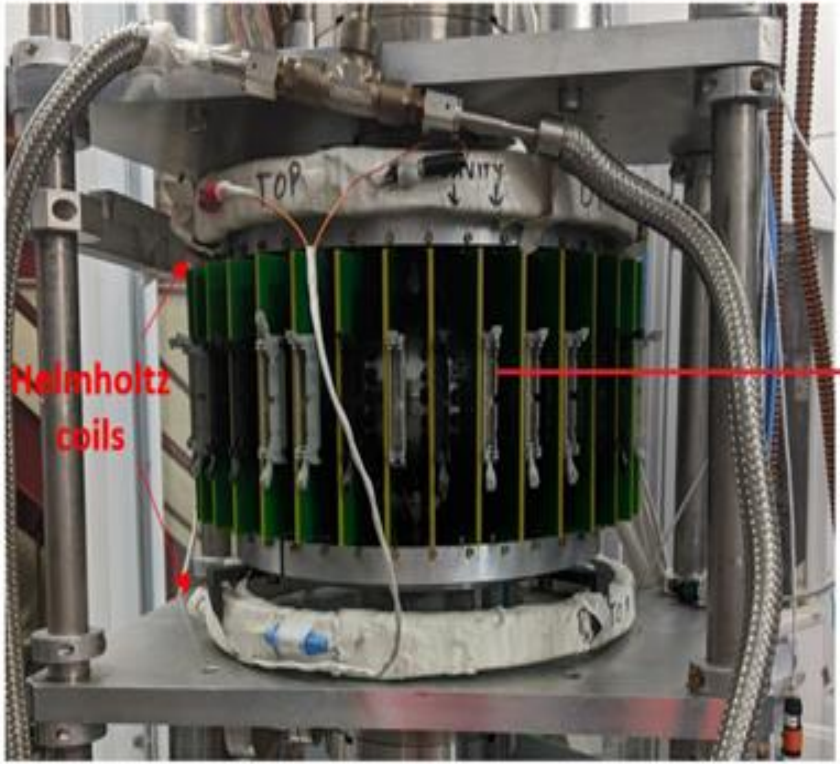
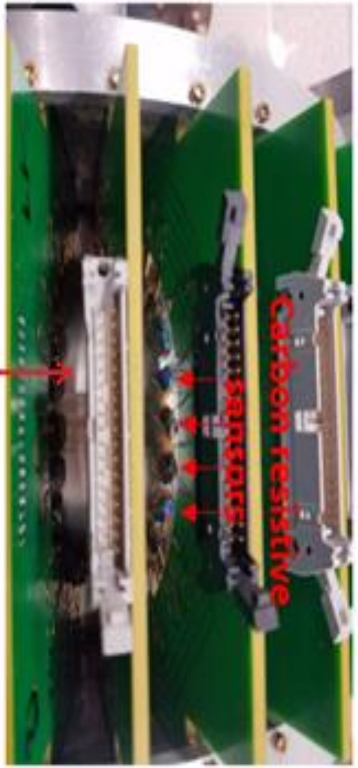
Thermometry Mapping





TMAP system

- 36 boards
- 16 carbon resistive sensors (576 sensors)
- Measurement efficiency %35

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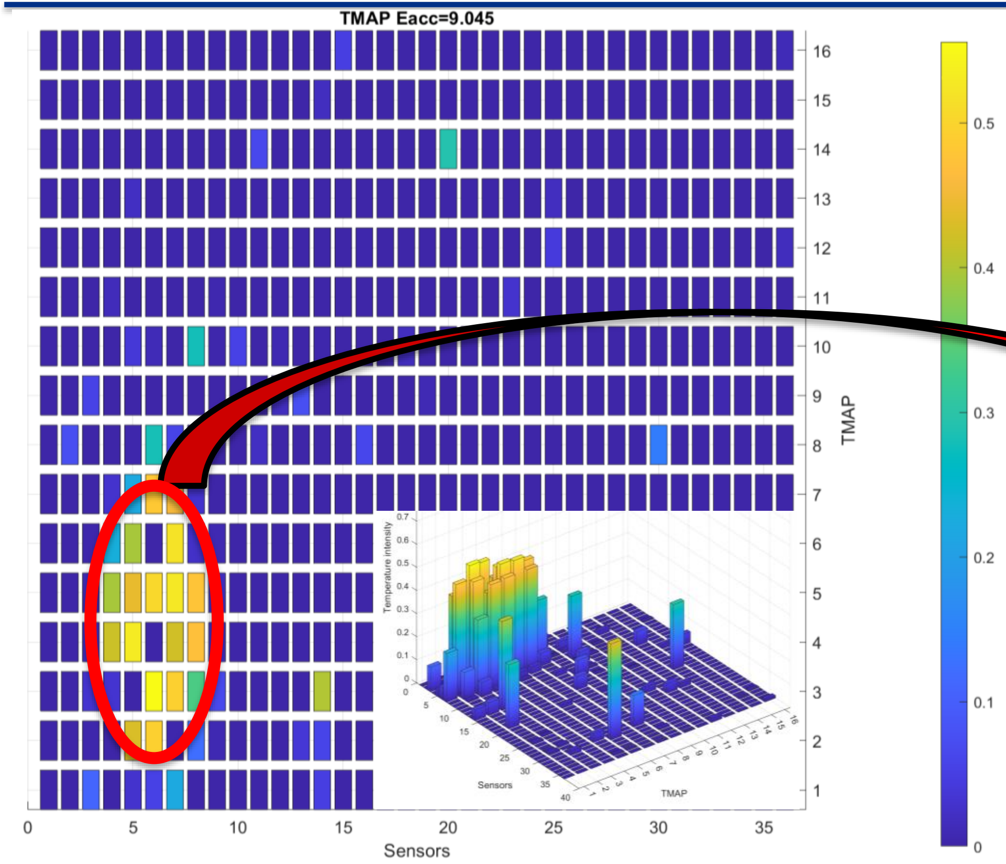
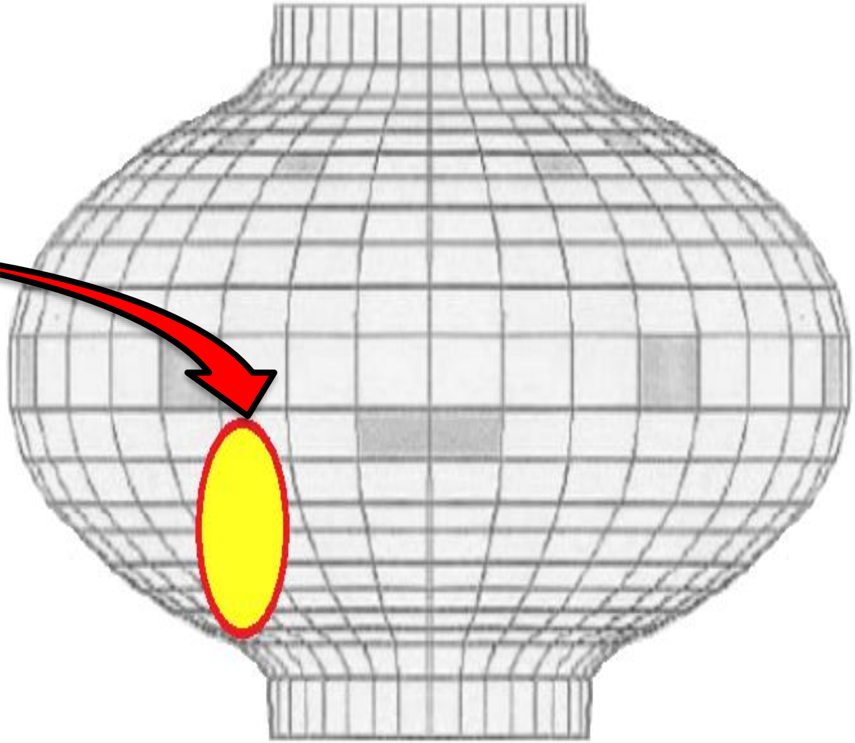
Thermometry MAP





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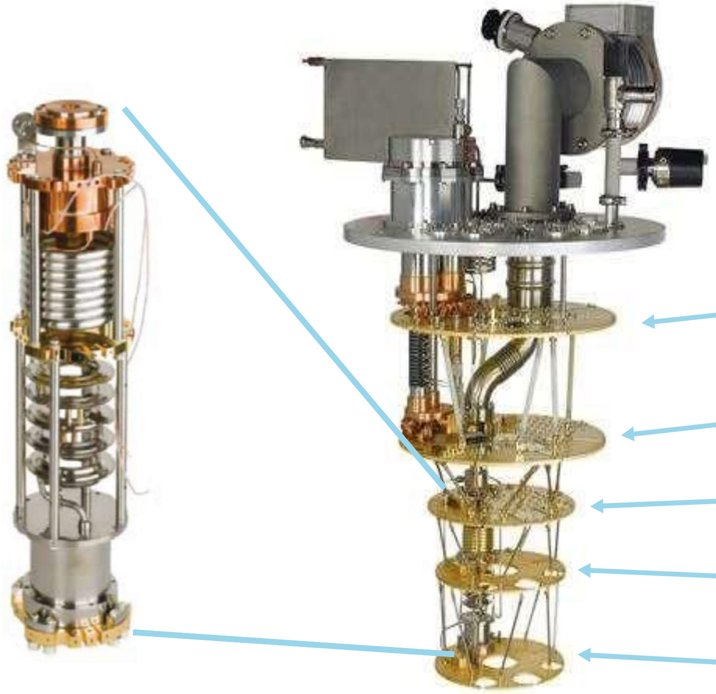
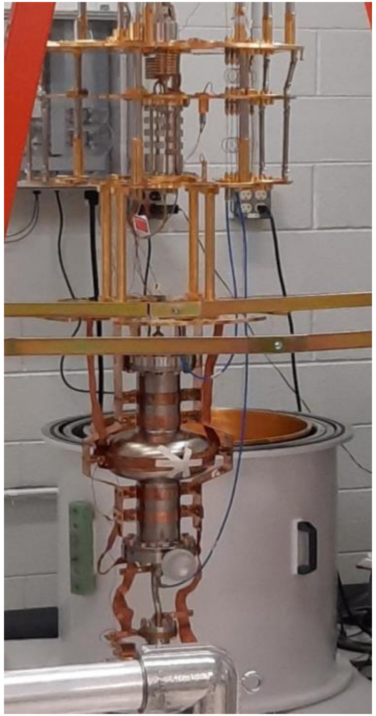
Dilution Fridge (DR) cavity testing

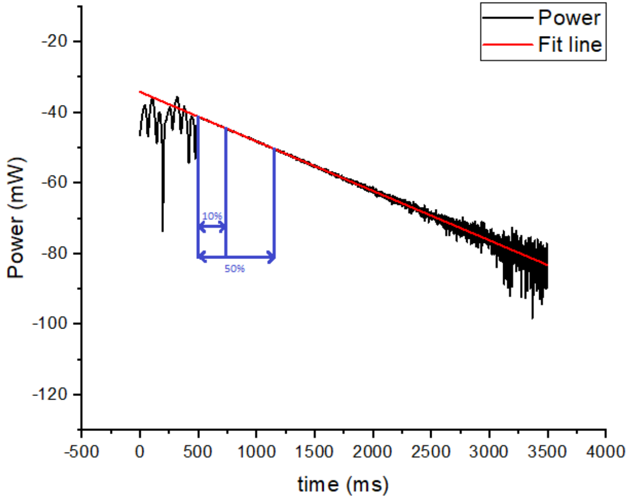


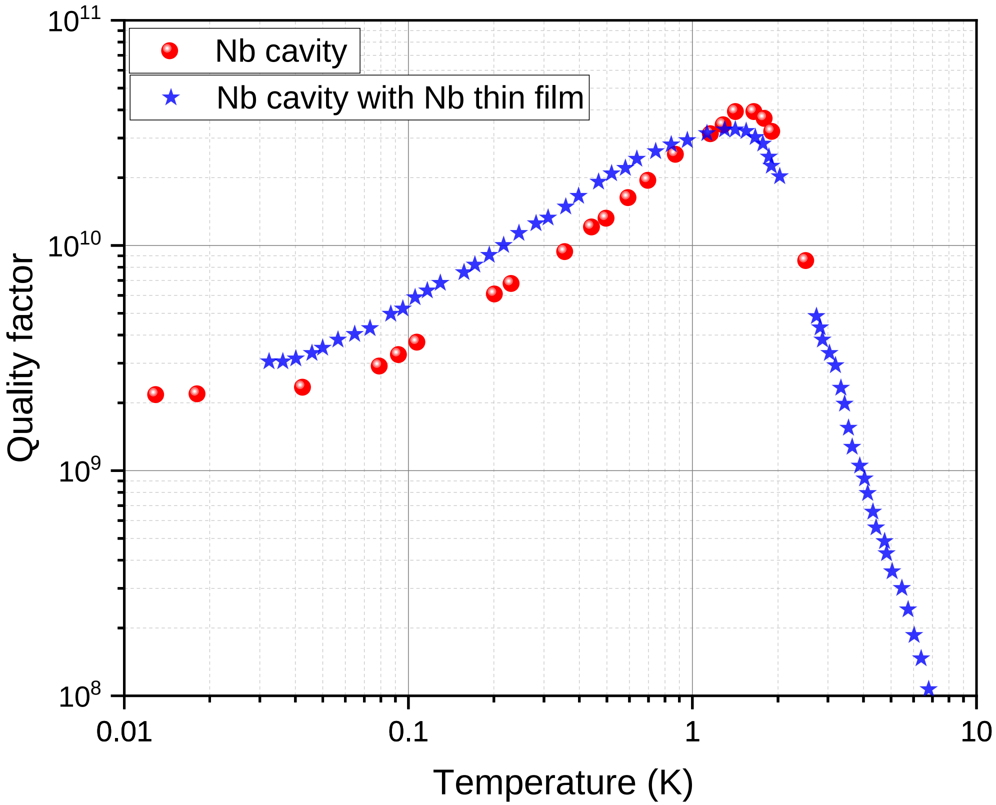
Images: Oxford Instruments



BlueFors dilution fridge system at Fermilab

Quality Factor and Frequency dependence as a function of Temperature

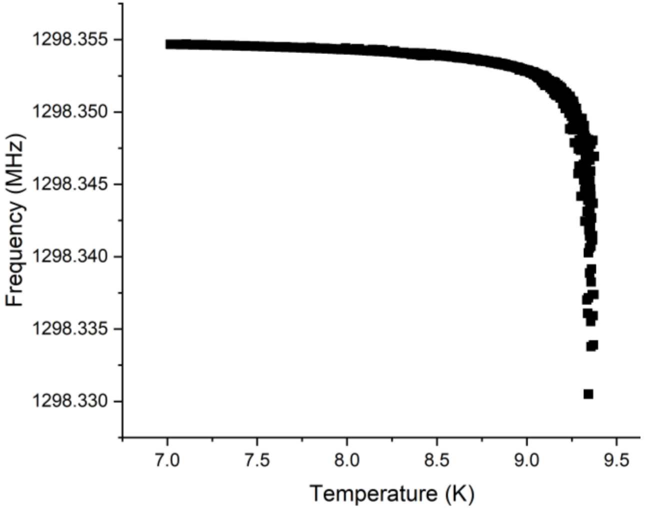




Quality factor comparison of Nb cavity and Nb cavity with Nb thin film

- **The cavity was tested from 10K down to 40mK to measure the frequency and quality factor dependence as a function of temperature at low fields.**
- **The cavity performance was similar to that of bulk niobium cavities at the quantum regime.**

BCS Halbritter fitting MFP of Thin Film Nb on 1.3GHz Nb Cavity



Frequency versus Temperature

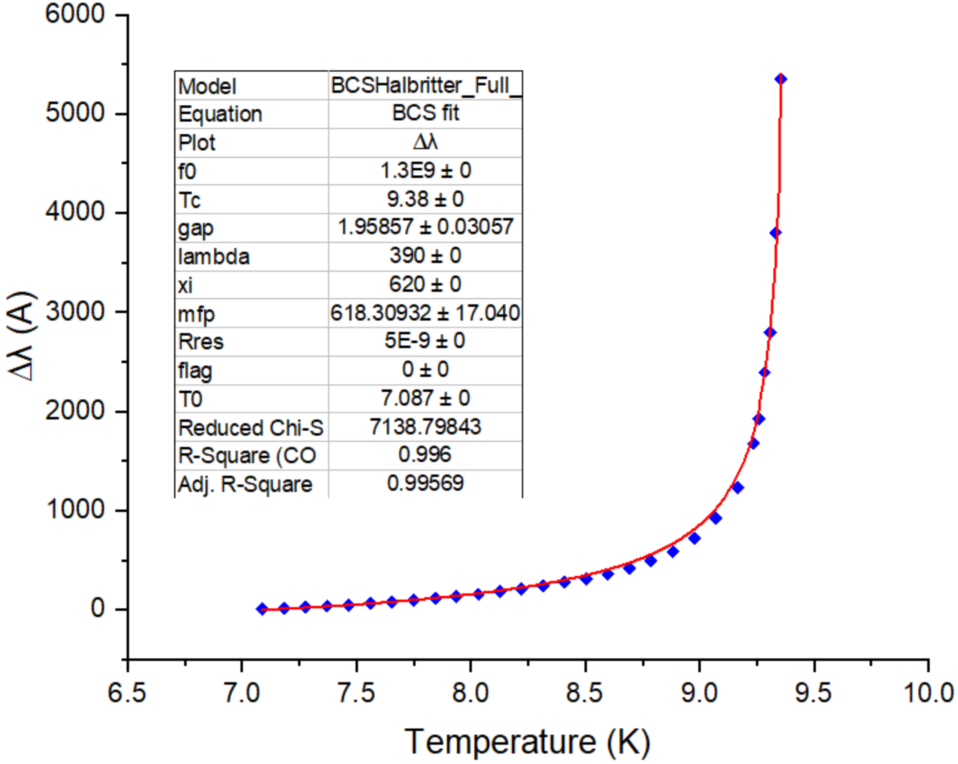
$$\Delta\lambda(T) = -\frac{G\Delta f_0(T)}{\mu_0 \pi f_0^2(T_0)}$$

$\Delta\lambda$ is the shift in the penetration depth

$\Delta f_0(T) = f_0(T) - f_0(T_0)$

is the shift in the resonant frequency

$T_0 \approx 7$ K for niobium



Model	BCSHalbritter_Full_
Equation	BCS fit
Plot	Δλ
f0	1.3E9 ± 0
Tc	9.38 ± 0
gap	1.95857 ± 0.03057
lambda	390 ± 0
xi	620 ± 0
mfp	618.30932 ± 17.040
Rres	5E-9 ± 0
flag	0 ± 0
T0	7.087 ± 0
Reduced Chi-S	7138.79843
R-Square (CO	0.996
Adj. R-Square	0.99569

BCS fitting on shift in penetration depth

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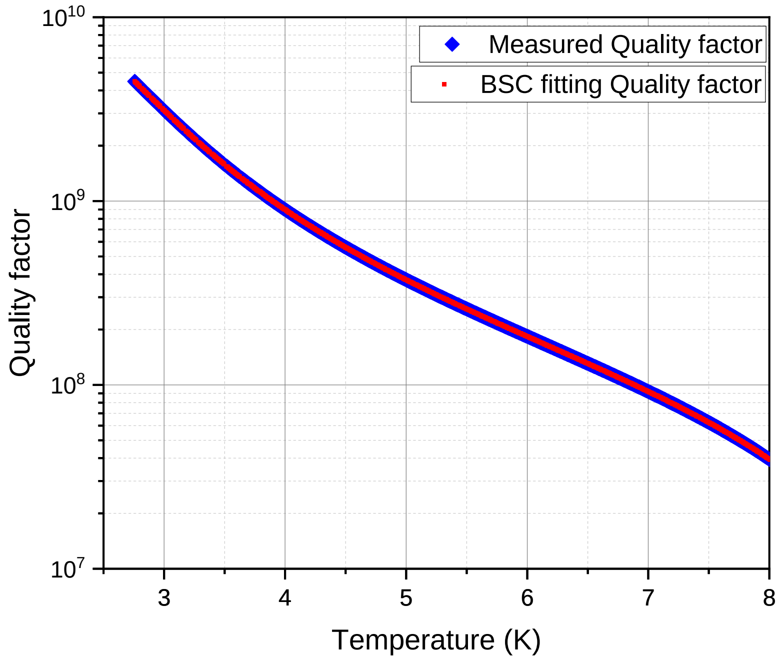
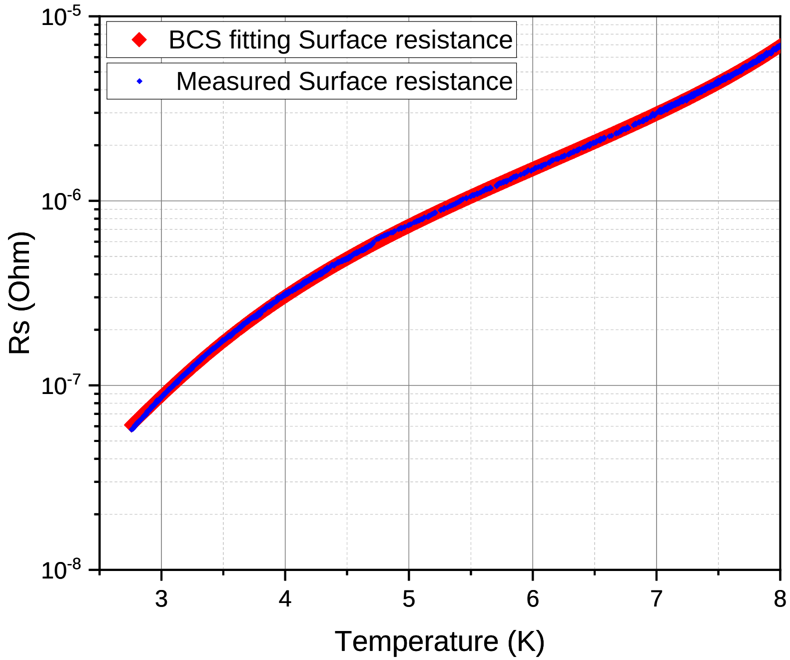
Measured and Calculated Q and Rs comparison

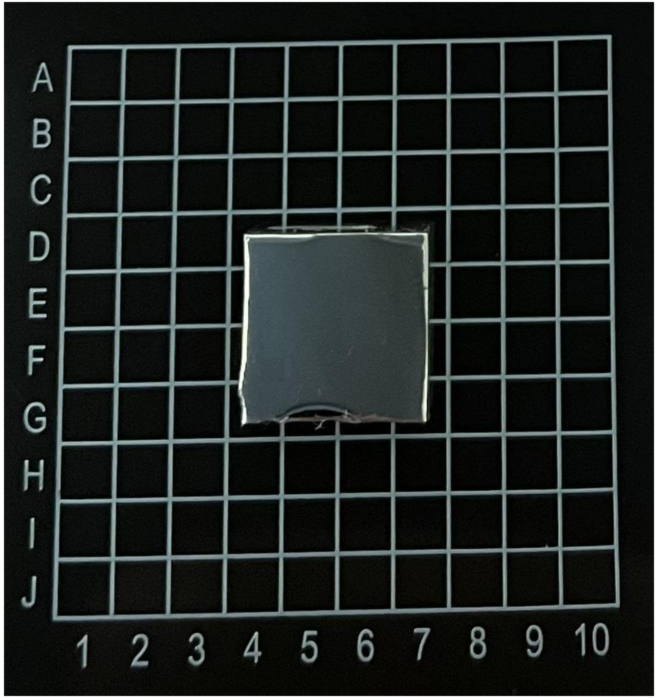




$$R_s = \frac{G}{Q}$$ where G is a geometry factor. (G=273Ω)

Characterization of Nb films.
(microstructure, surface morphology, microwave properties, etc…)

Nb thin film on Nb substrate



Thin-film deposition parameters

- Main pulse duration: 200us
- Bias voltage: -75V
- Power: 1200W
- Pressure: $3x10^{-3}$mbar
- Temperature: 150^{o}C
- Deposition time: 6 hours
- Target: Nb RRR300
- Background gas: Kr
- Thickness: 6µm
- Substrate: Niobium (200)
- Substrate size: 1cm X 1cm

Data: CERN

- **Nb thin films deposited on Nb substrates by using Bipolar HiPIMS with the same parameters at CERN.**

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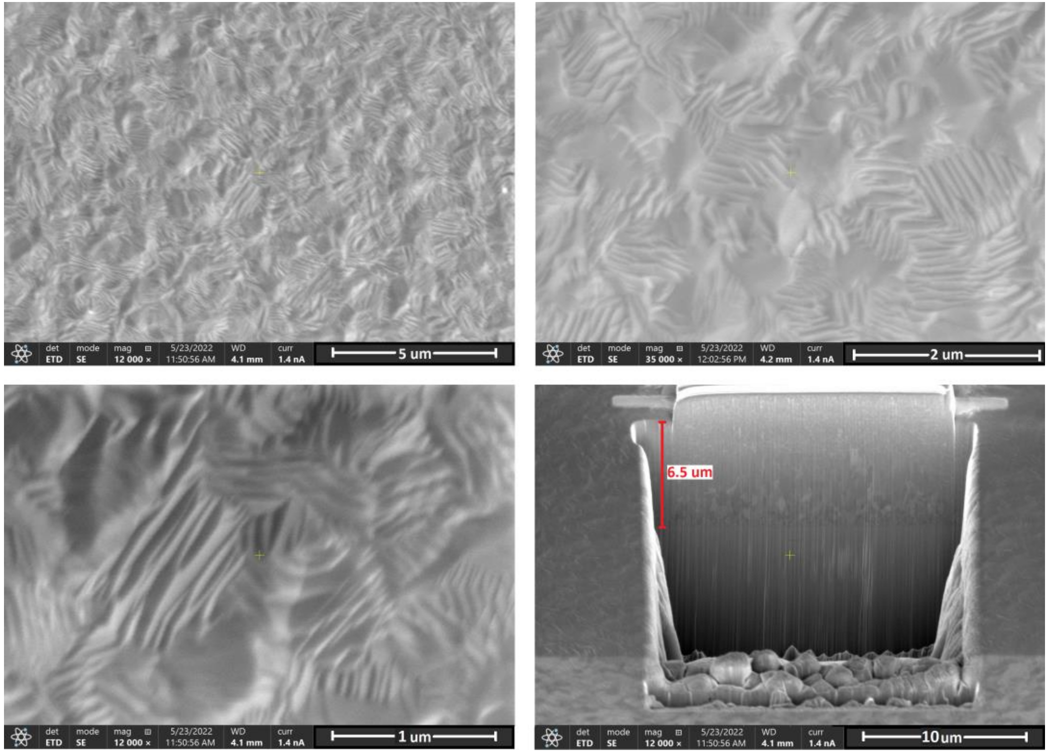
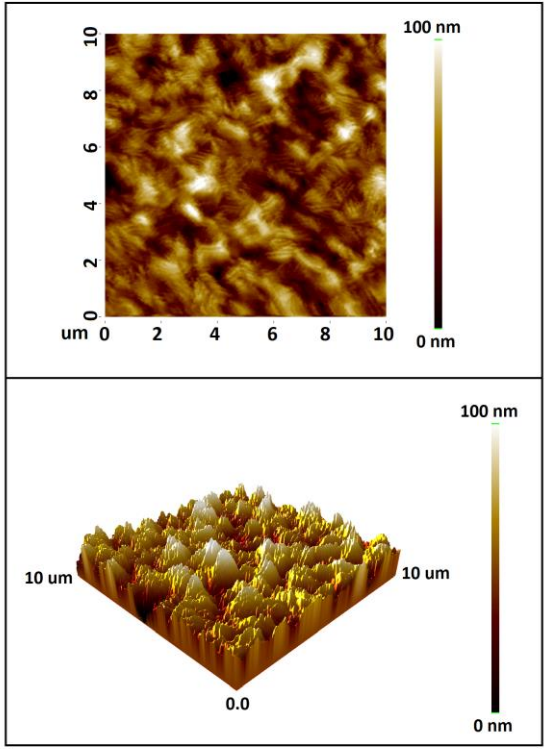
Surface morphology and thickness





- ❖ RMS surface roughness is 13.4 nm (scanned area 10 µm X 10 µm)
- ❖ Thickness is 6.5 µm

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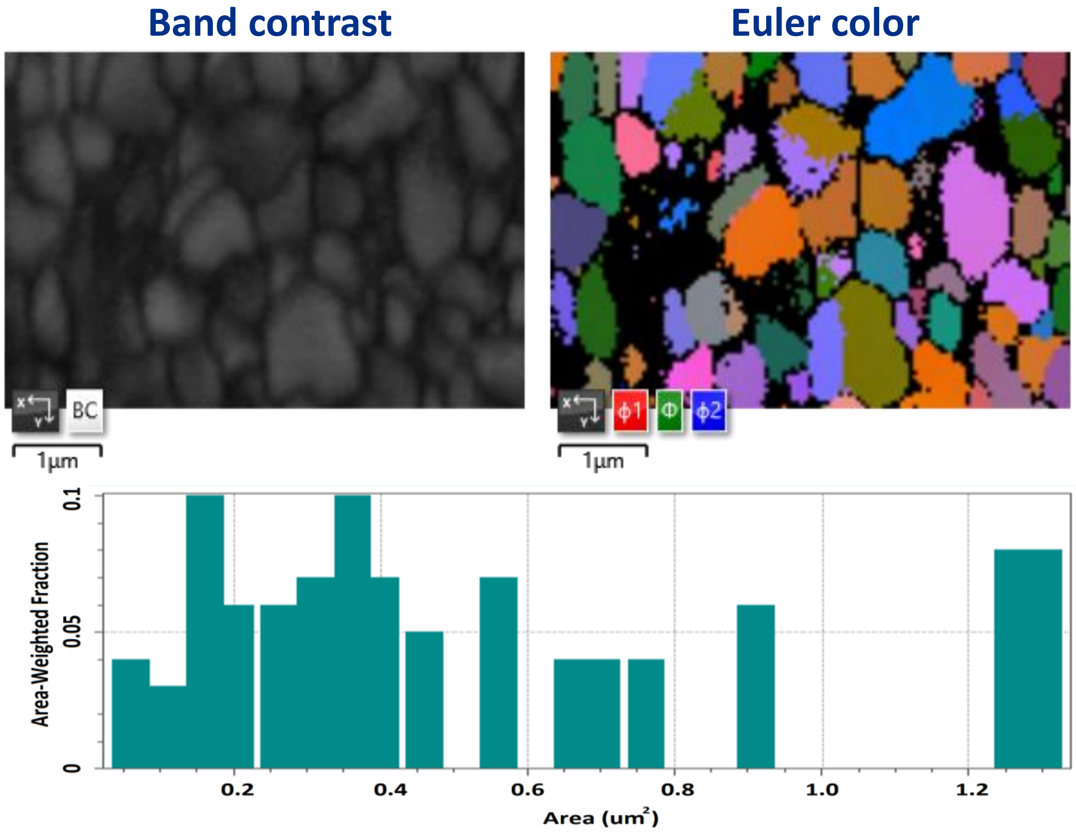
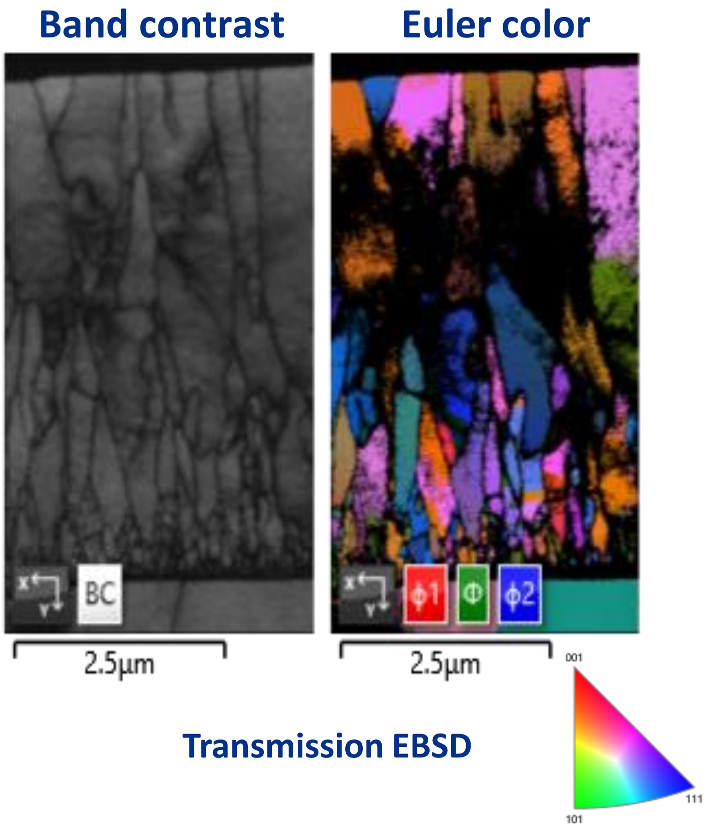
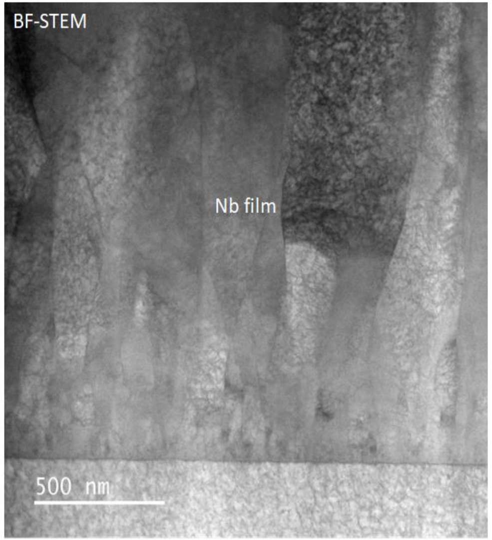
Grain size and orientations

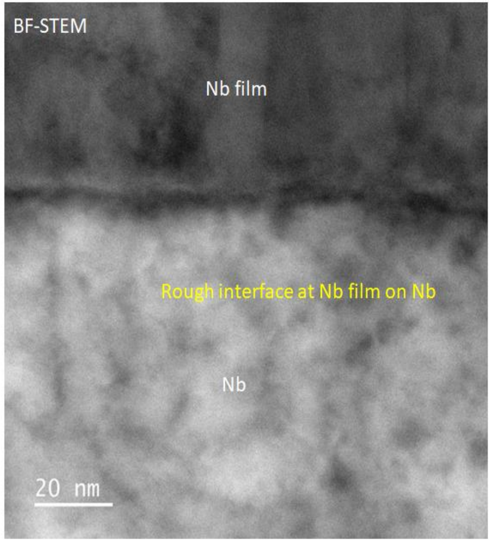


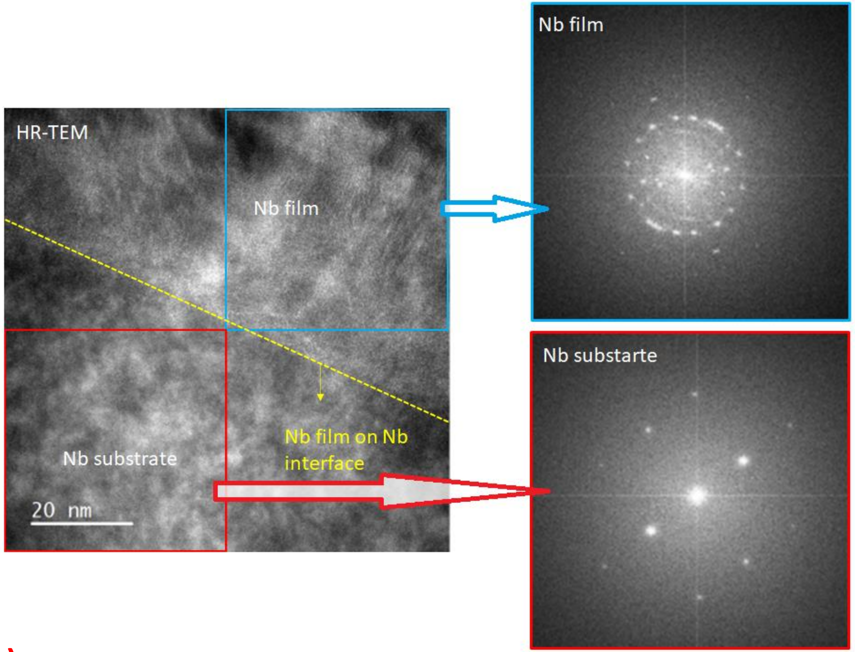


Transmission EBSD

Oxygen layer detected by high-resolution TEM







- The growth type of the thin film is **Volmer-Weber (3D islands).**
- The oxygen layer **prevents epitaxial growth.**
- Nb films grow **randomly** on the Nb substrate.

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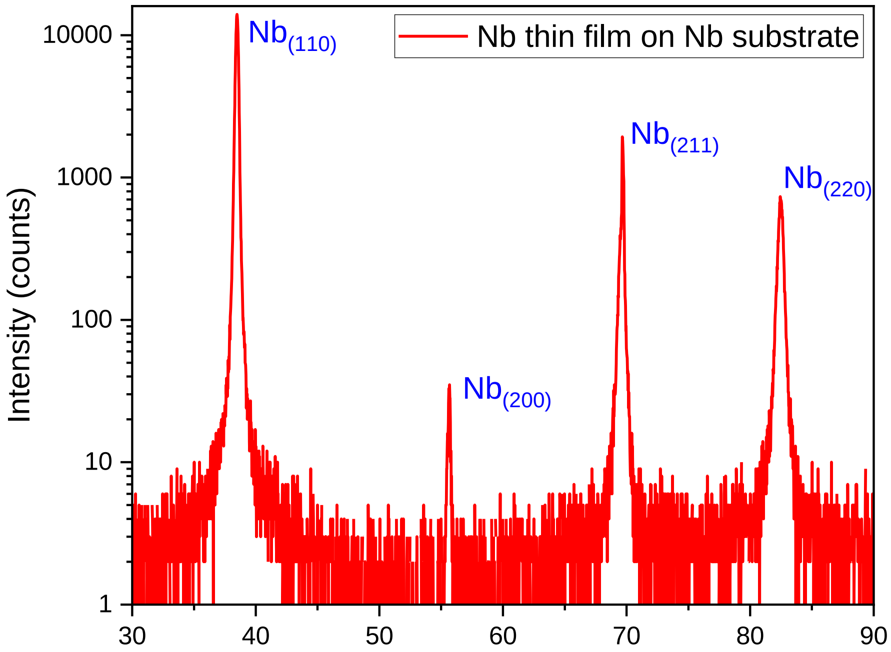
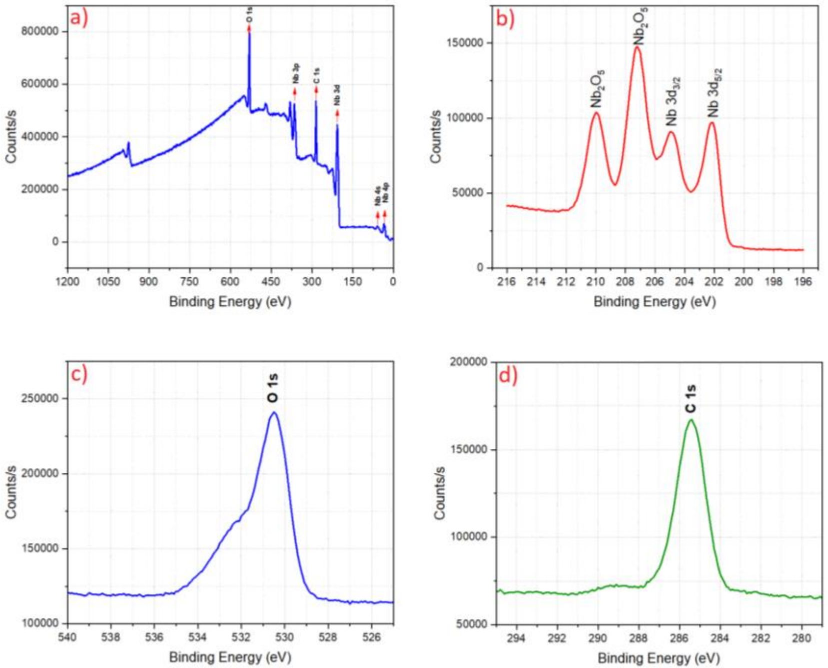
Crystallographic orientation and concentration of the elements





- ❖ **The thin film was polycrystalline dominated by Nb (110) orientation. Nb (200), Nb(211), and Nb (220) oriented structures were detected**
- ❖ **The concentration of elements showed that C, 52.51%; O, 32.06%; and Nb, 15.43% on the surface**

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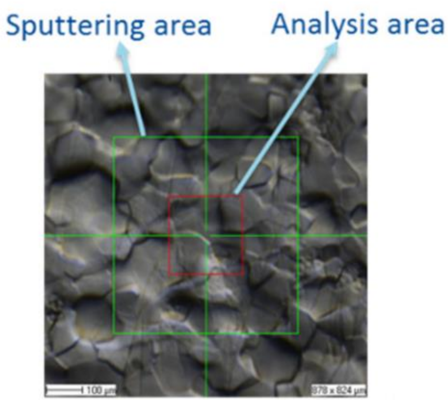
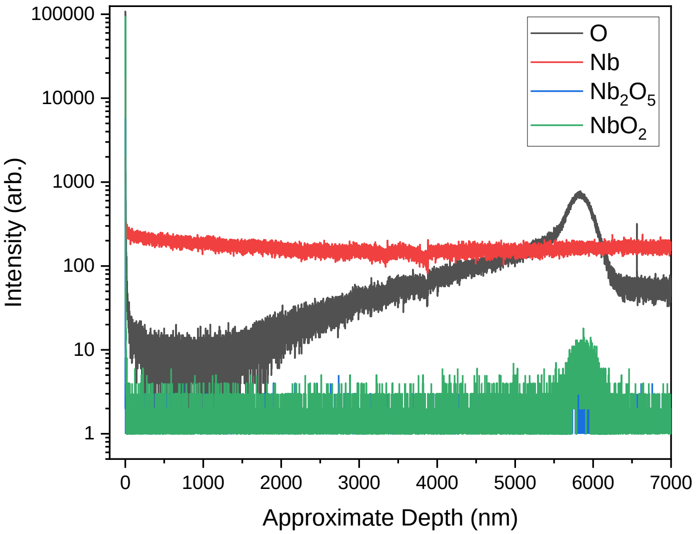
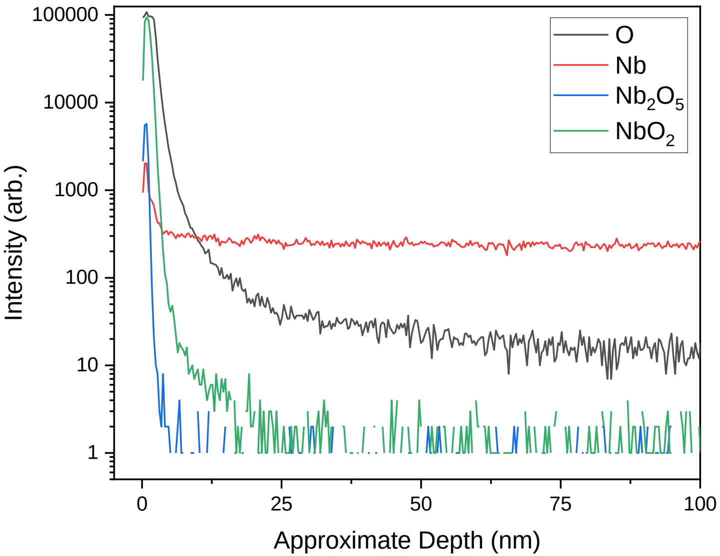
High concentrated oxygen layer on the surface and at the interface

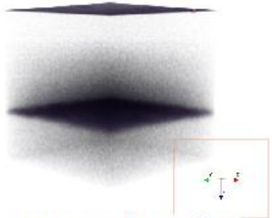




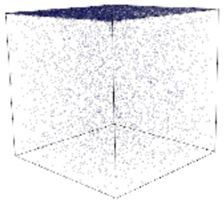


- **500 um x 500 um sputter area**
- **200 um x 200 um analysis area**

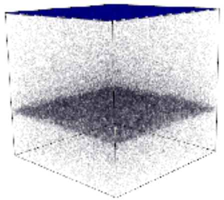
3D render of Nb



3D render of O



3D render of Nb_2O_5

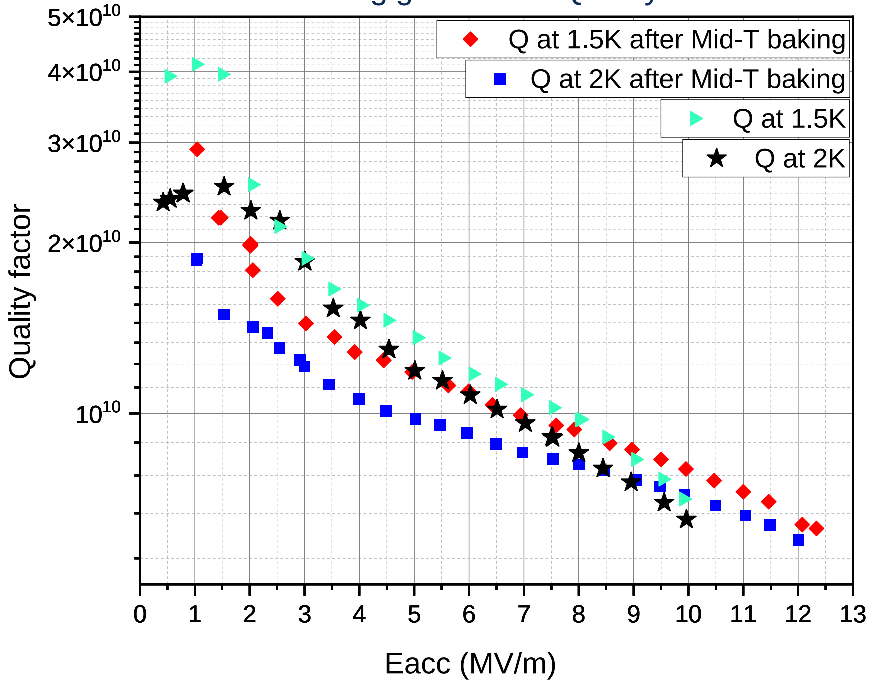


3D render of NbO_2

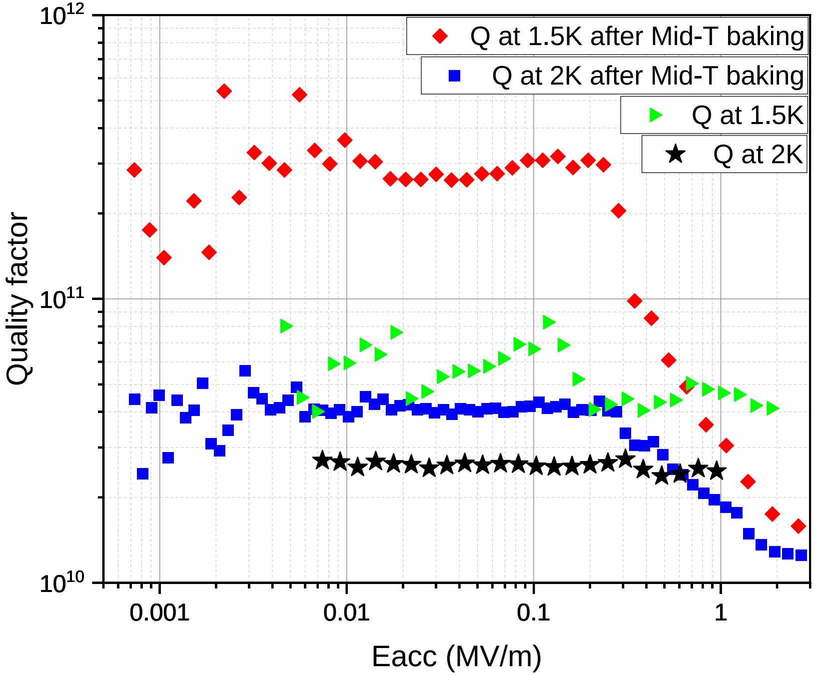
Cavity performance after Mid-T baking at 340˚C for 1 hour.

What changed after Mid-T baking?

Accelerating gradient vs Quality factor

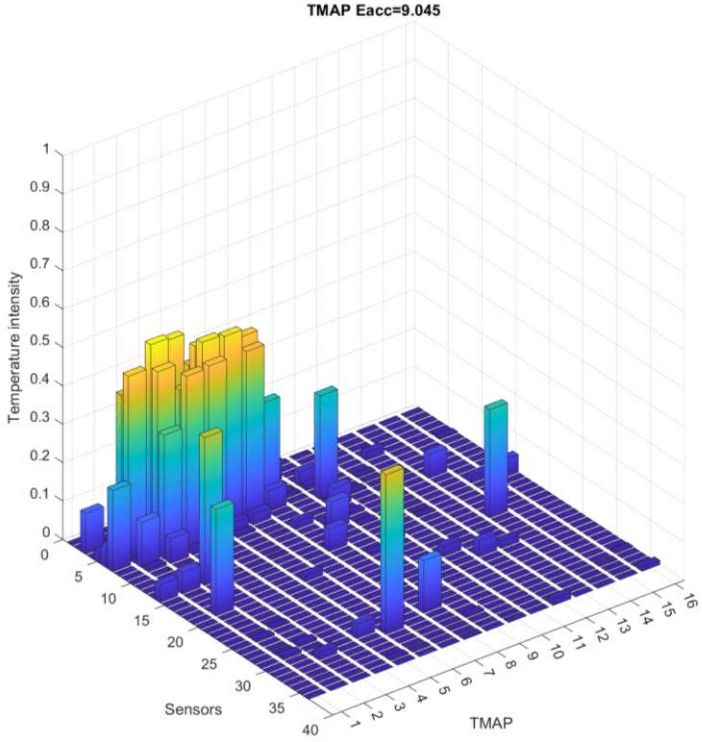


Accelerating gradient vs Quality factor at low field

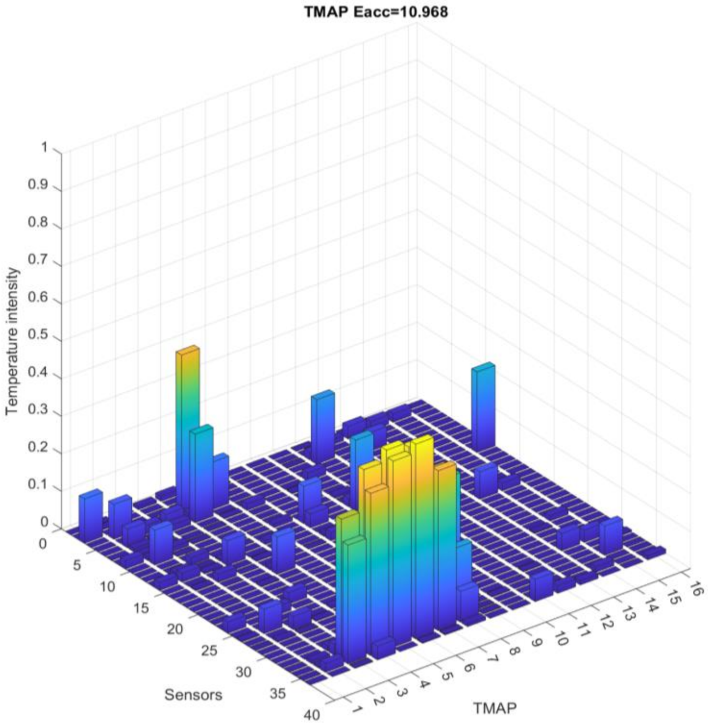


- After "*in-situ*" Mid-T baking at 340˚C for 1 hour, the cavity was limited at Eacc ≈12.8 MV/m by a quench.
- Quality factor increased by factor 10 at the low field at 1.5K after Mid-T baking.

Thermometry MAP

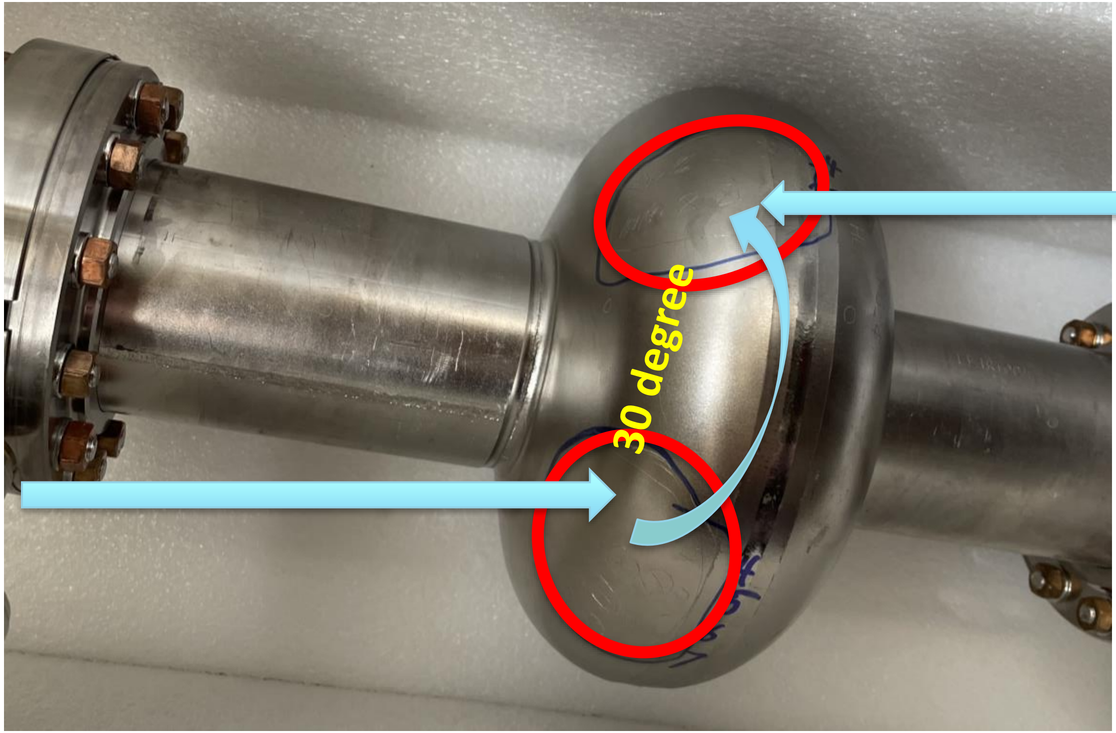


Hot spot area before Mid-T baking



Hot spot area after Mid-T baking

Hot spot area on the cavity



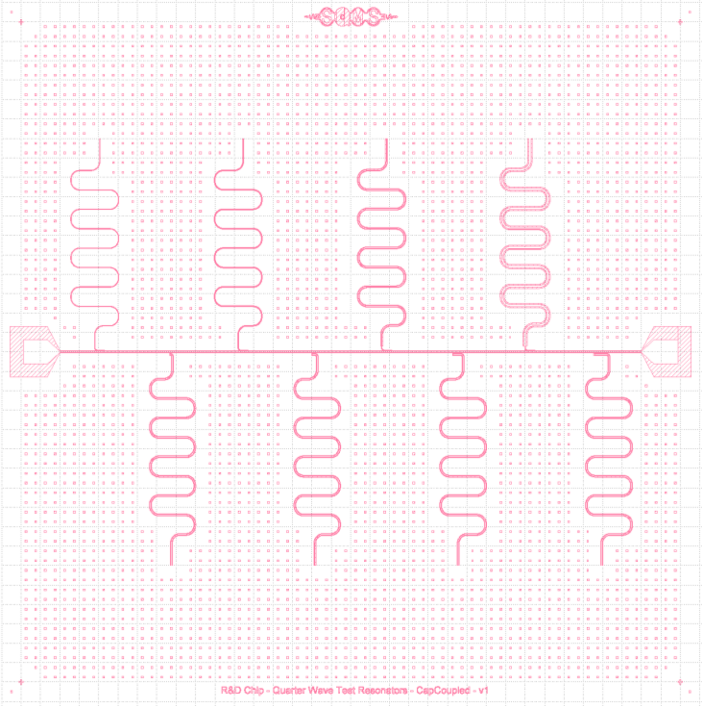
After Mid-T baking

Before Mid-T baking

What is next?

- ❖ Dilution fridge (DR) test after Mid-T baking.
- ❖ Nitrogen doping treatment.
- ❖ VTS and DR tests after Nitrogen doping treatment.

- ❖ Create coplanar quarter wave 2D resonators by using Nb (RRR300) thin films deposited on sapphire substrates with different PVD systems.



Designed quarter-wave resonators inductively coupled with a single 50Ω feedline.

Jefferson Lab
Thomas Jefferson National Accelerator Facility
INFN
Istituto Nazionale di Fisica Nucleare
CERN

Conclusion

- The cavity performance was similar to that of bulk niobium cavities at the quantum regime. At mid and high field, the quality factor of the Nb thin film cavity was lower than the bulk Nb cavity.
- Nb Thin film was polycrystalline dominated by the Nb (110) orientation. Nb (200), Nb(211), and Nb (220) structures were detected. The root mean square (RMS) of surface roughness is 13.4 nm.
- The conventional method of concentration of elements showed that C, 52.51%; O, 32.06%; and Nb, 15.43% on the surface. At the surface of the film and the intersection, an oxide layer was observed. The oxide layer at the intersection prevented epitaxial thin film growth.
- The cavity was limited at Eacc ≈10.2 MV/m by a quench. After Mid-T baking, it increased to Eacc ≈12.8 MV/m. The heated local area is not at the equator as expected. After Mid-T baking, it moved to a different area.
- At the low field, the quality of the cavity increased by factor 2 at 2K and it increased approximately 10 times at 1.5K after Mid-T baking.

Thank you

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