Point contact tunneling spectroscopy for SRF cavities and Qubits

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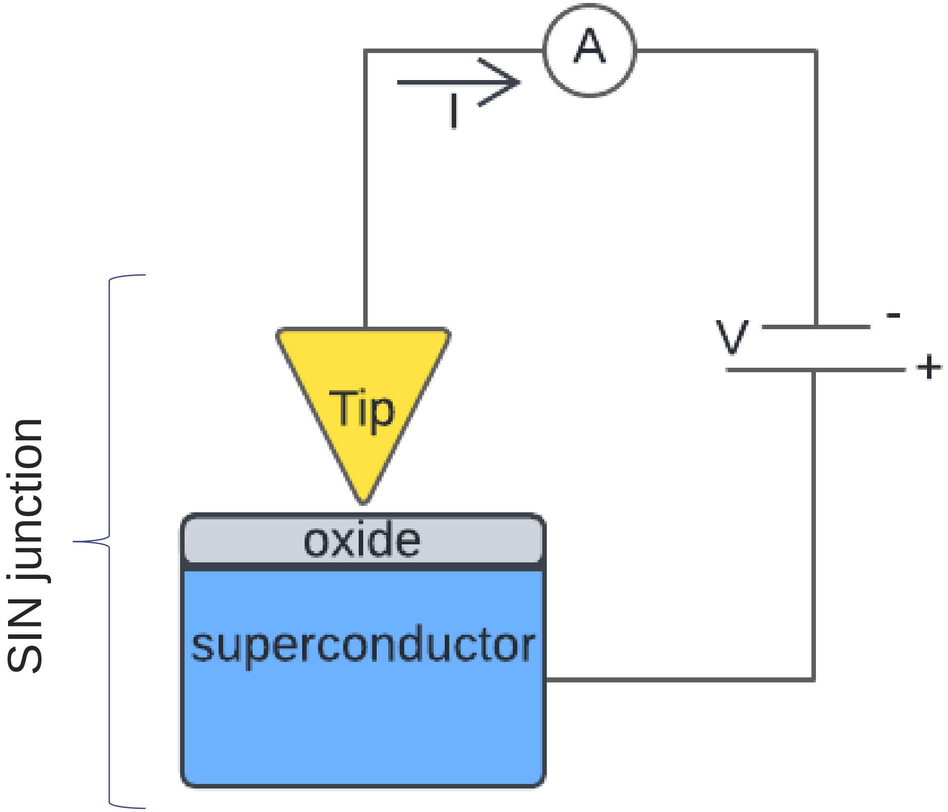
CEA/IRFU

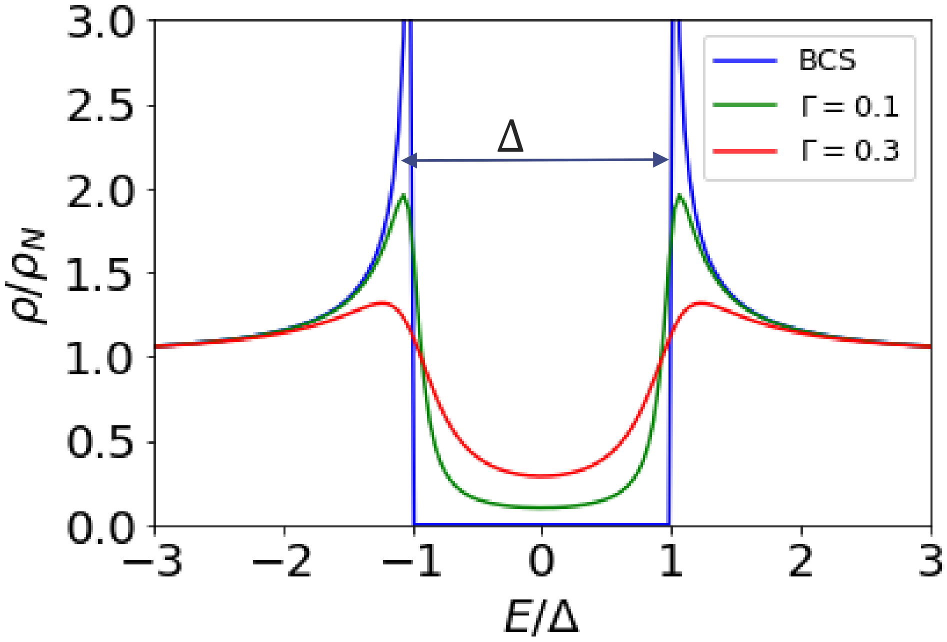
Principle of tunneling spectroscopy



$$\frac{dI}{dV} \sim \int \frac{\partial f(E+eV)}{\partial(eV)} \rho(E) dE$$

Fermi function

Superconducting DOS



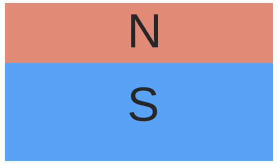
Dynes formula

$$\rho(E) \sim \mathrm{Re} \frac{\mathrm{E} - \mathrm{i}\Gamma}{\sqrt{(\mathrm{E} - \mathrm{i}\Gamma)^2 - \Delta^2}}$$

Other models:

- Shiba (magnetic impurities)
- Arnold
- McMillan

(Arnold, McMillan: proximity effect)



- Our PCT instrument has mapping capability with ~µm resolution → statistics of the superconducting parameters spatial distribution

Outline

1. ALD- coated Nb.
2. Nb-HPR-annealed.
3. Nb_3Sn-Cu.
4. Nb, Ta, Ta/Nb for 2D Qubits.

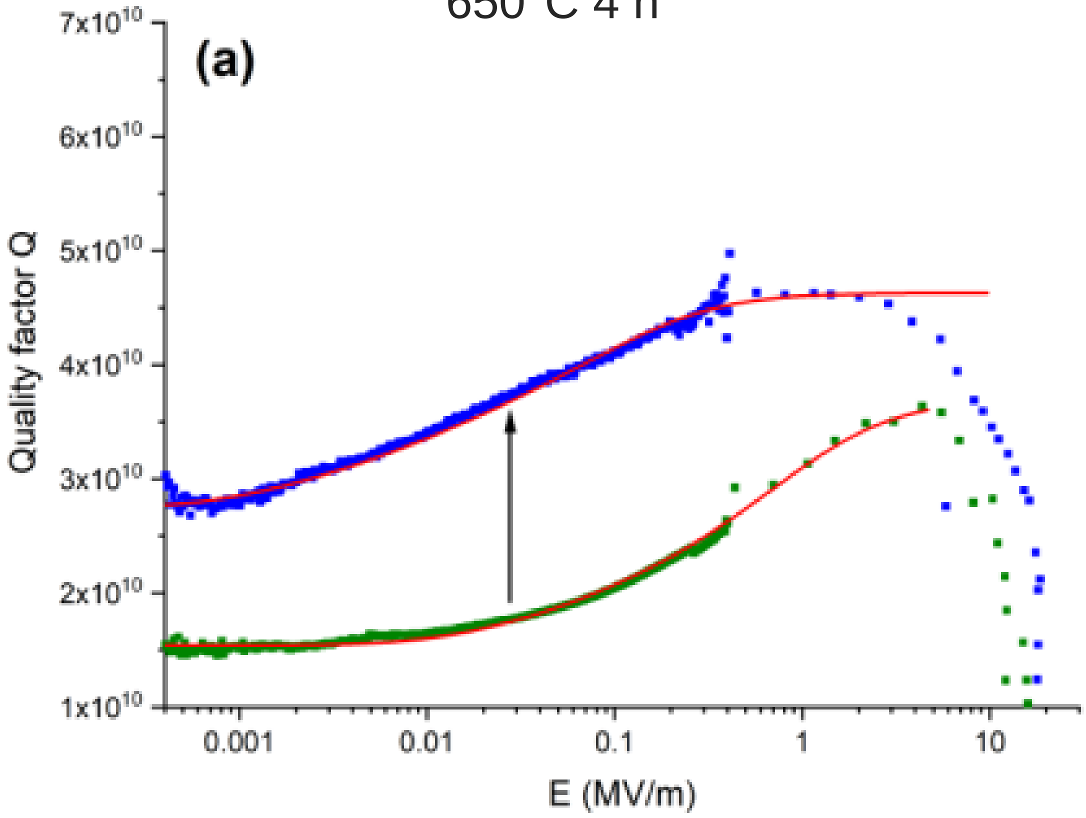
SRF cavities (items 1–3)

ALD Al_2O_3-Nb

- ALD + heat treatment decreases TLS losses and increases the quality factor at low fields.

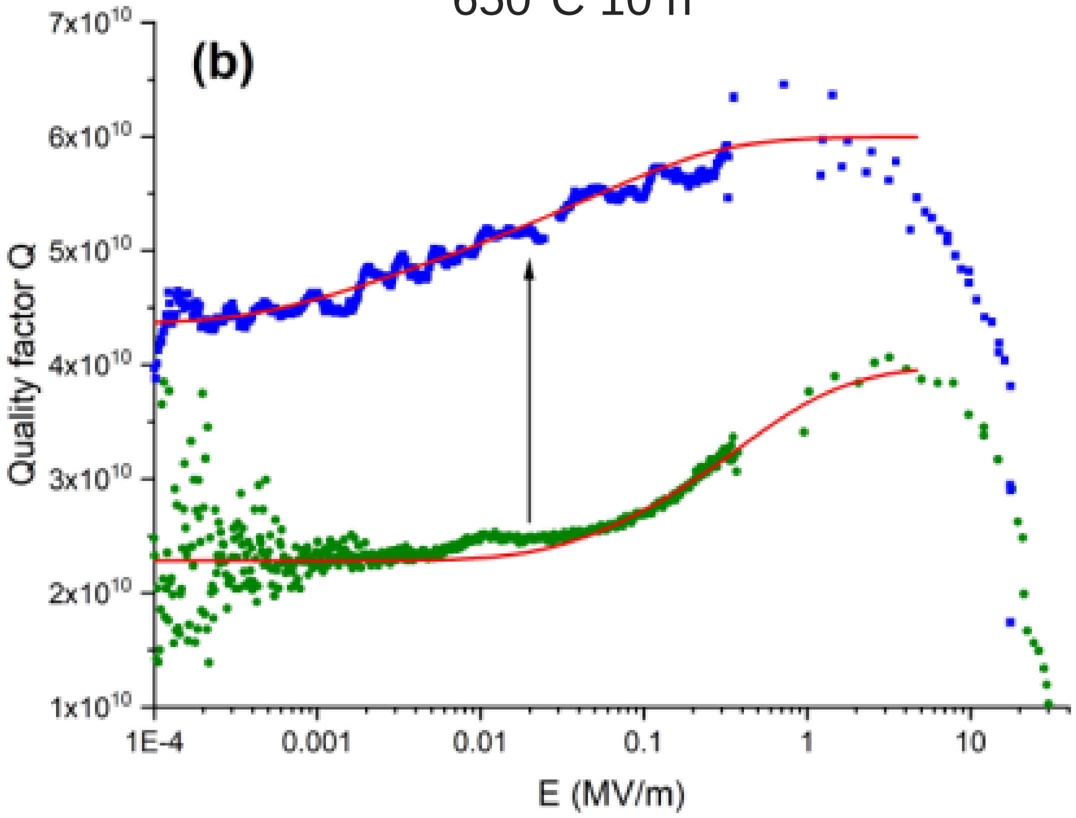
First experiment

650°C 4 h

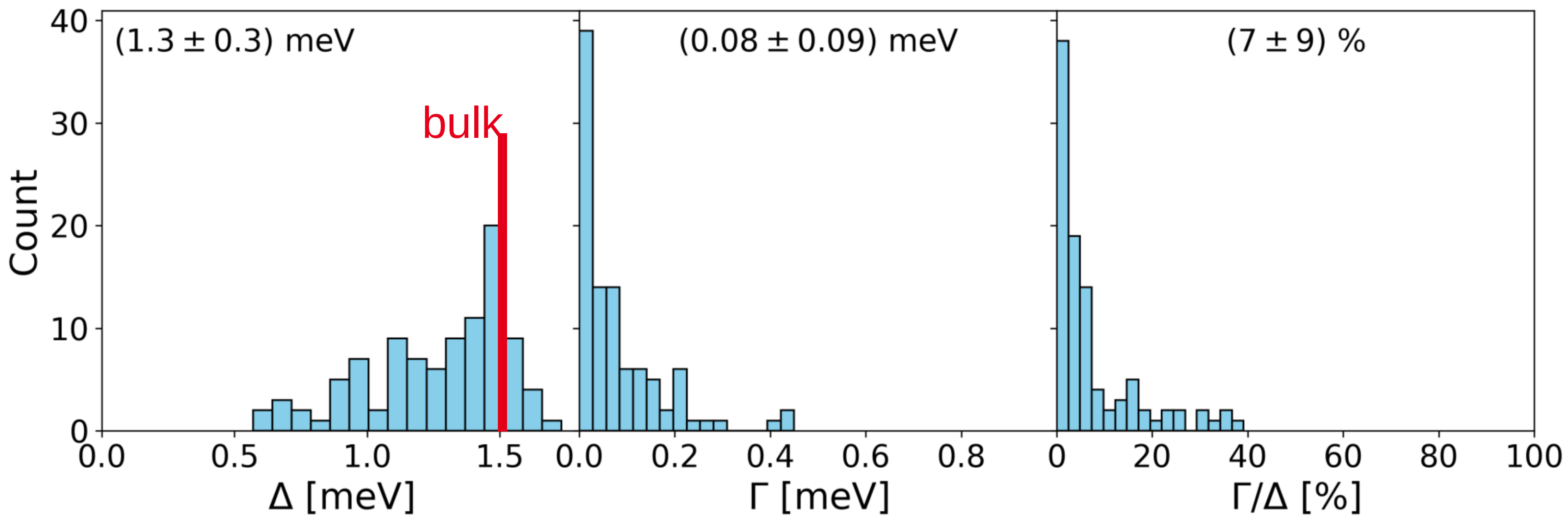


Second experiment

650°C 10 h



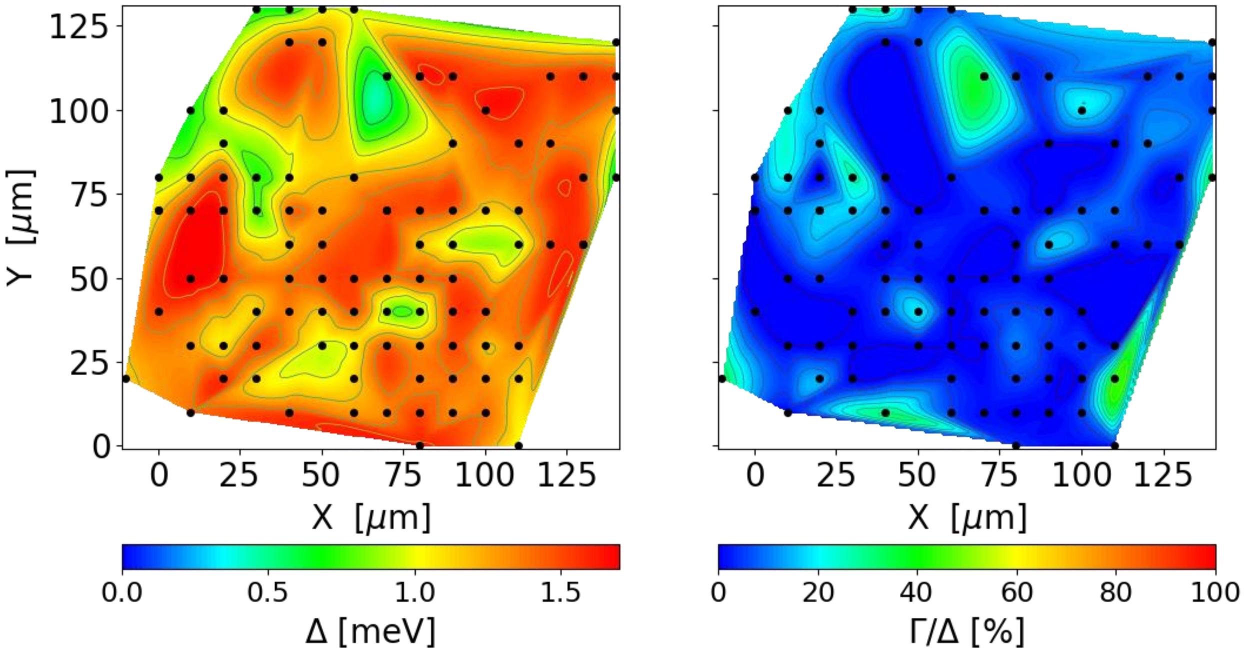
ALD Al_2O_3-Nb



Dynes formula

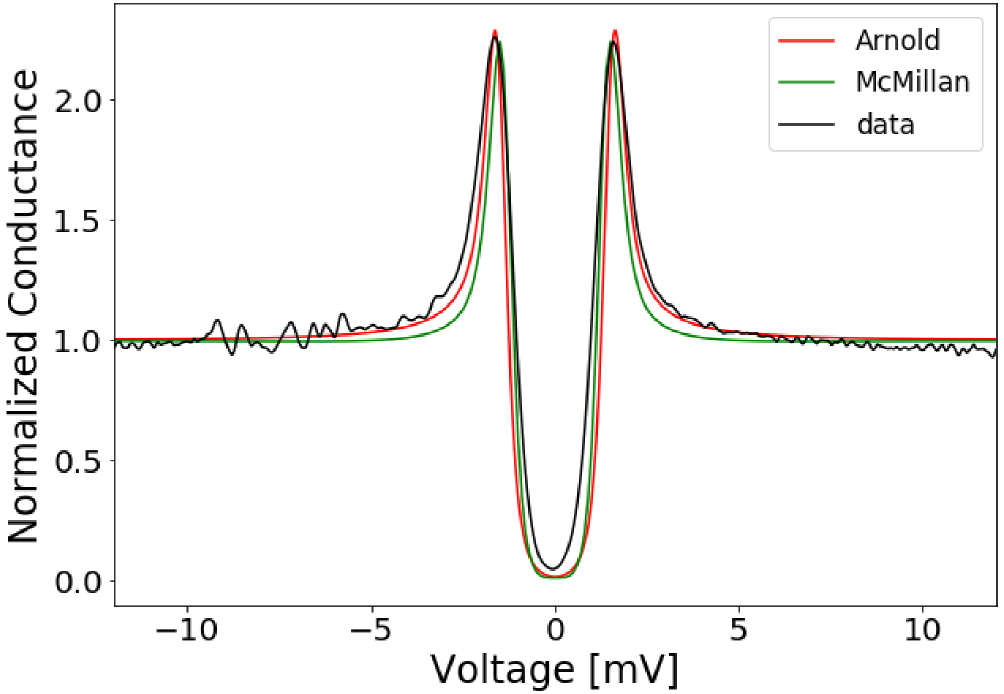
$$\rho(E) \sim \mathrm{Re}\frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}$$

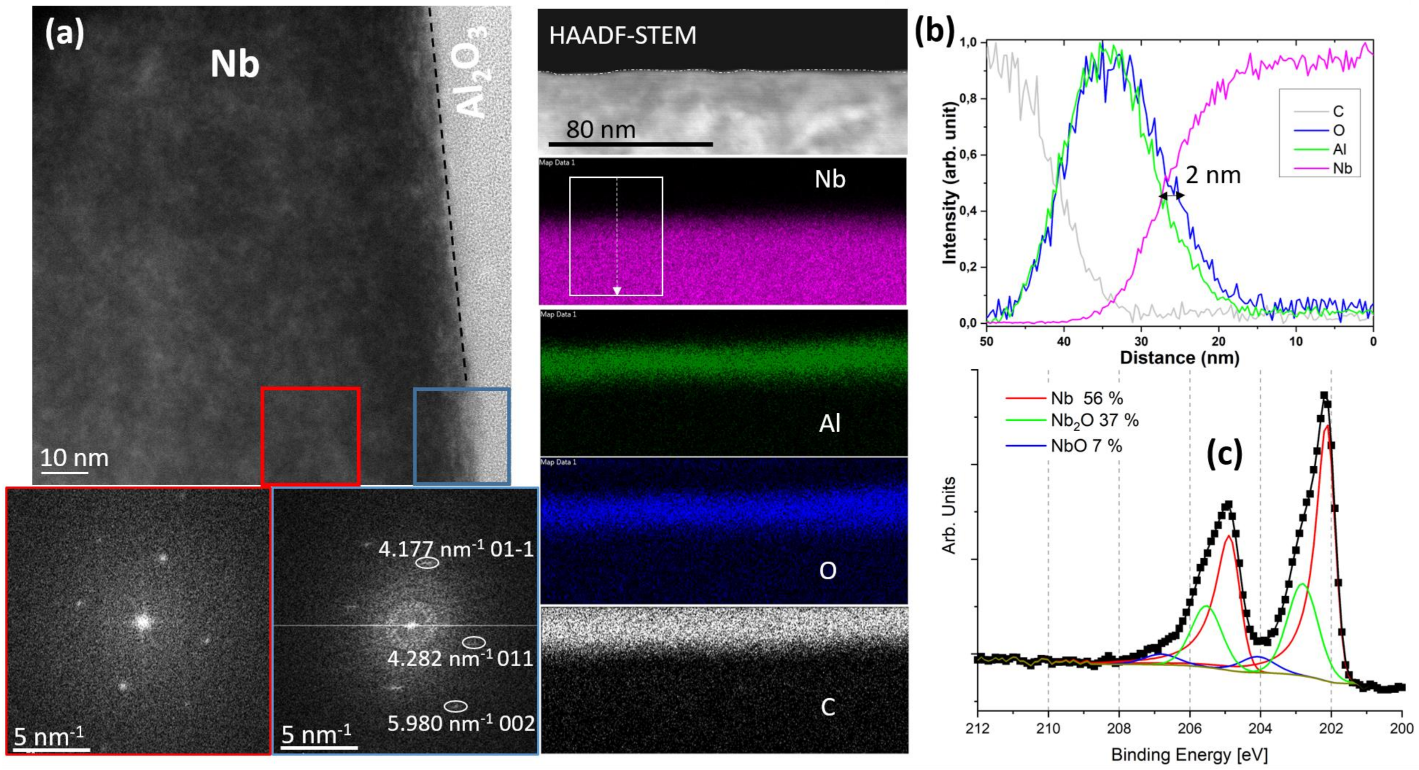
Reminder!!

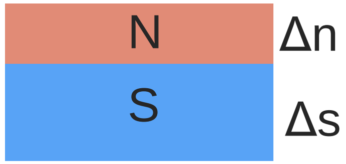


- Small Δ and Γ might reveal a proximity effect.
- Non- homogeneous spatial distribution of Δ and Γ.

Correlation between PCT, XPS and TEM







McMillan:
Δn=0, Δs=1.55, g1=5, g2=0.1, Γ =0.01

d ≤ 2.3 nm

See Y. Kalboussi talk…

- TEM and XPS reveal a 2 nm Nb oxide that might be responsible for the proximity effect.

Outline

1. ALD- coated Nb
2. Nb-HPR-annealed
3. Nb_3Sn-Cu
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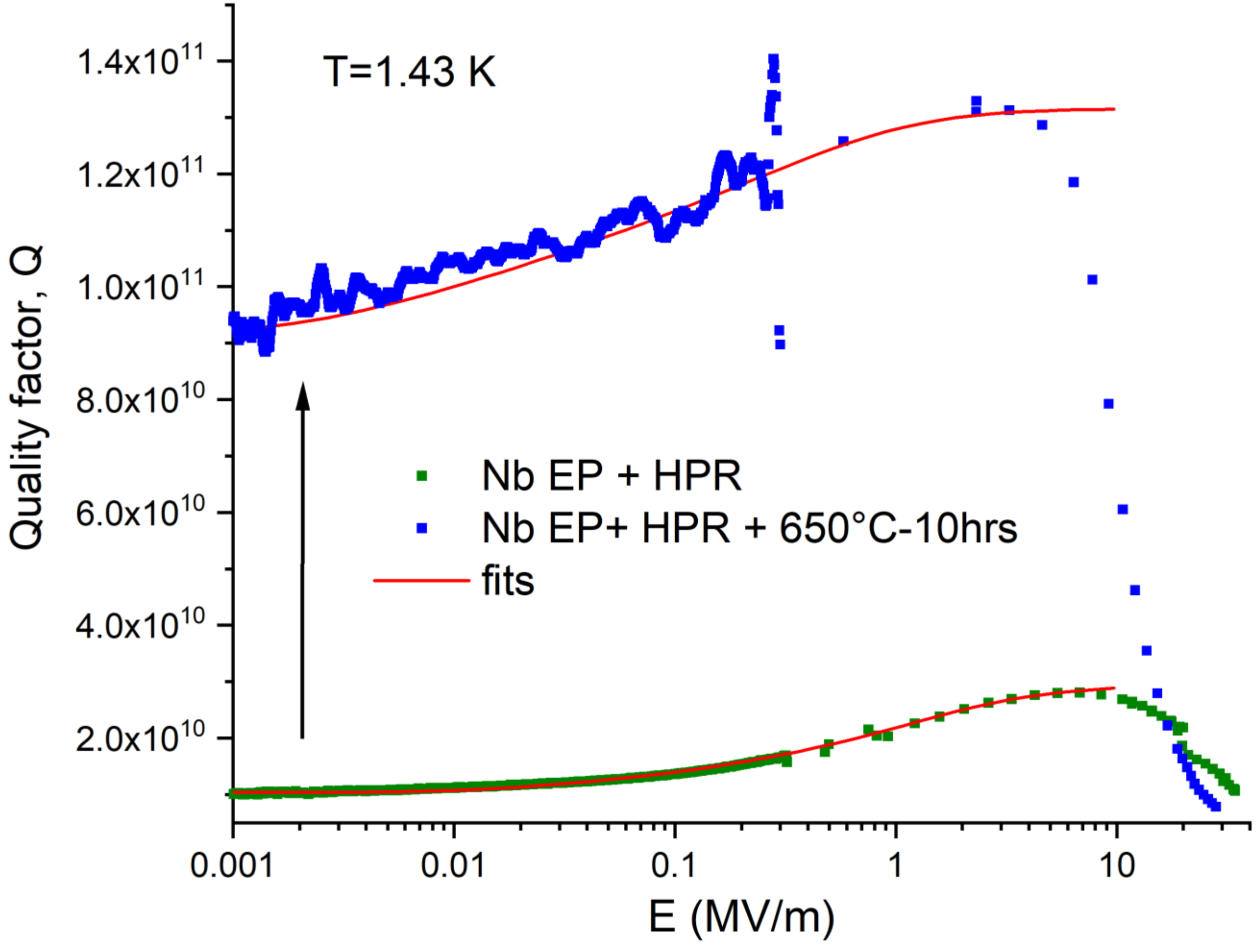
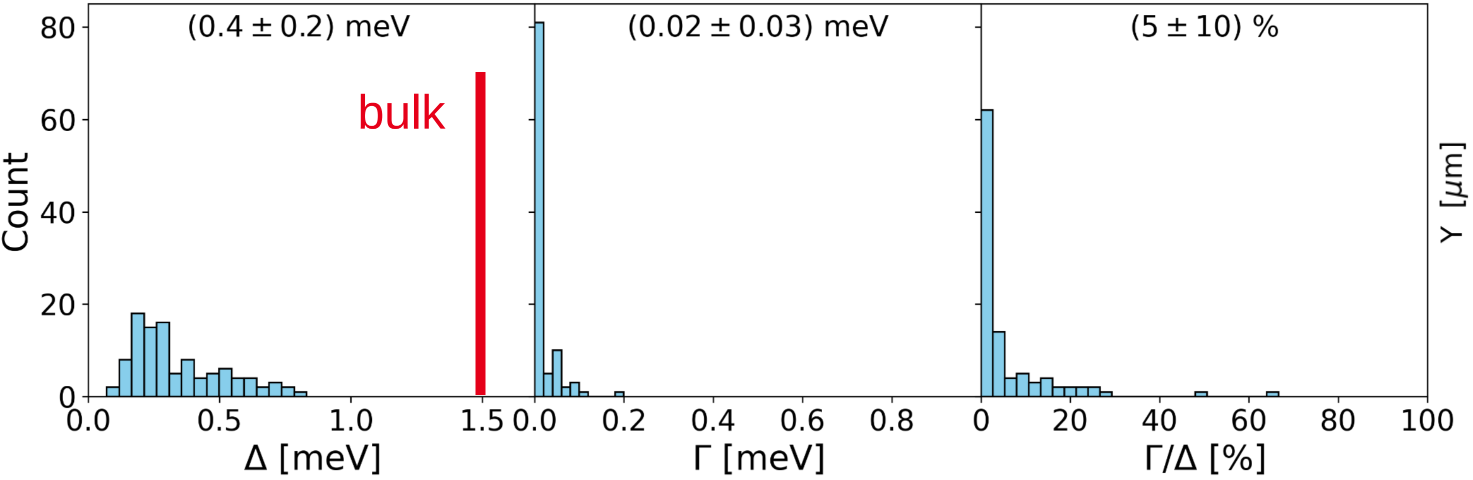
SRF cavities (items 1–3)

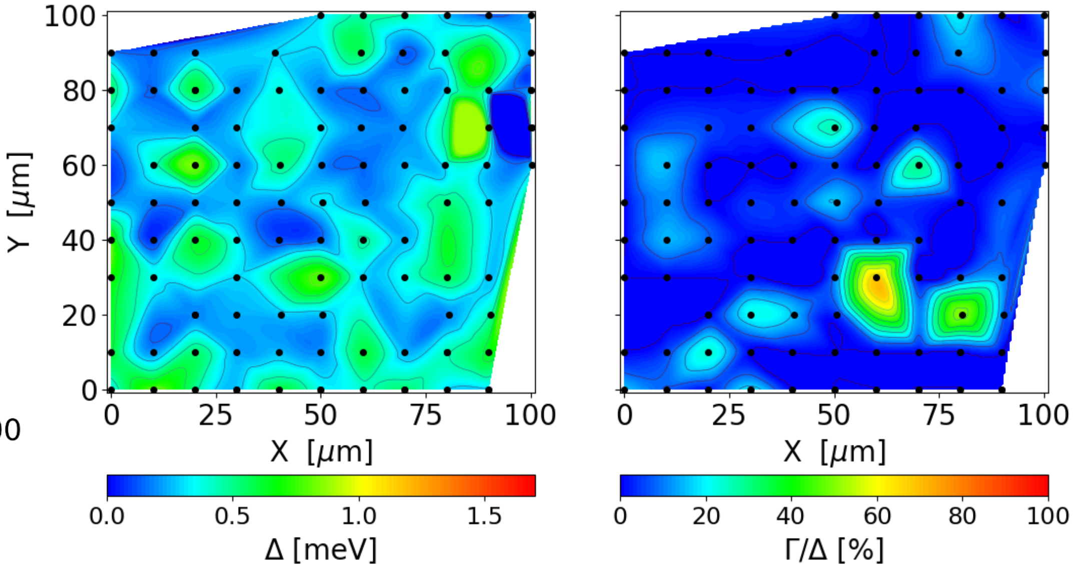
Nb-HPR-annealed
(Nb EP + HPR + 650°C-10hrs + HPR)

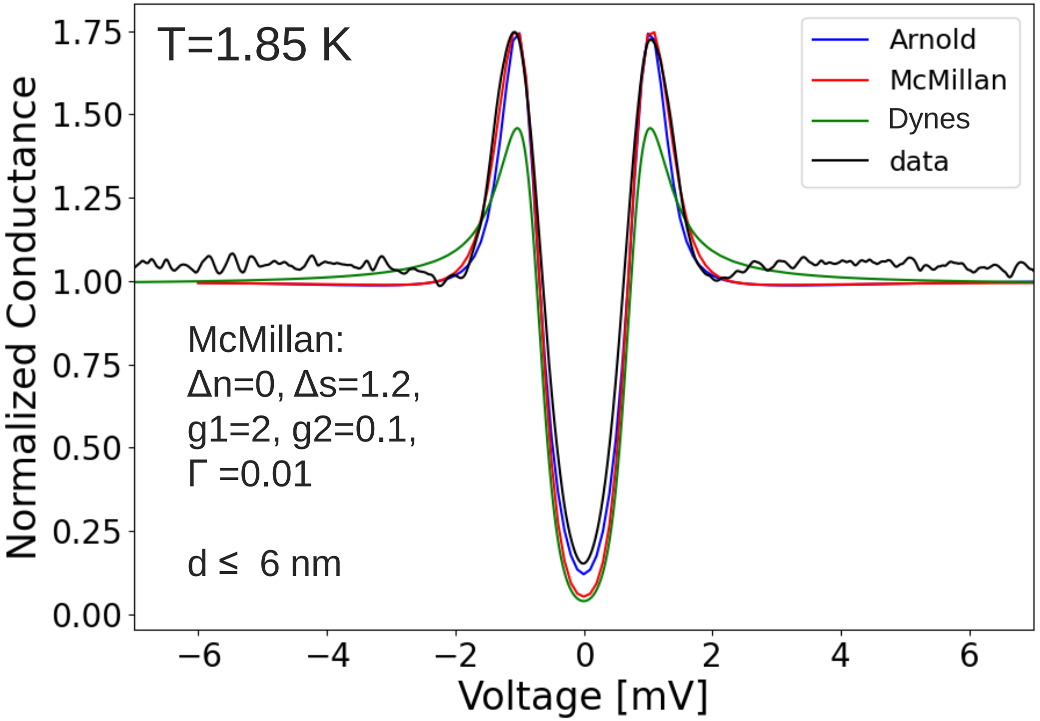
- SRF cavities show Q factors ~10 times higher than Nb EP + HPR
- σ_{TLS} and $\tan(\delta_{TLS})$ decreased by a factor 10.



Nb-HPR-annealed



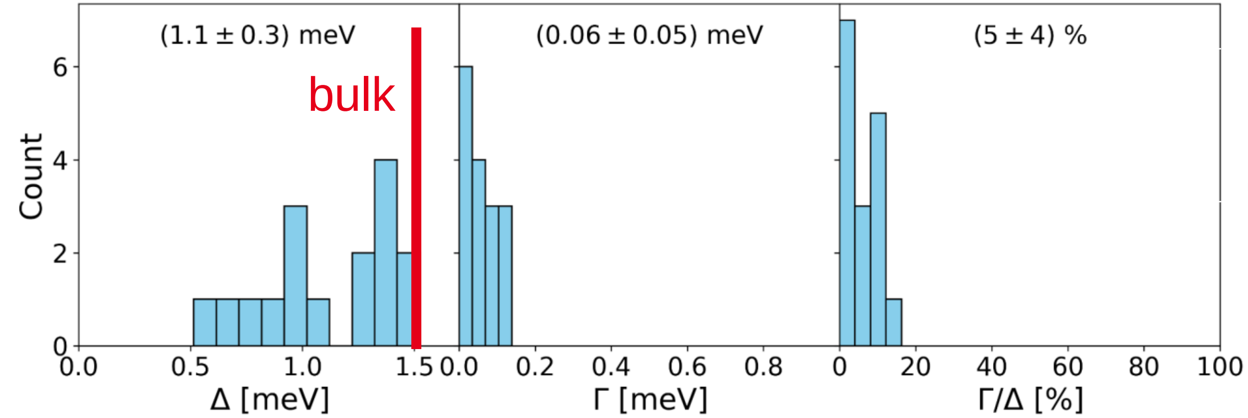


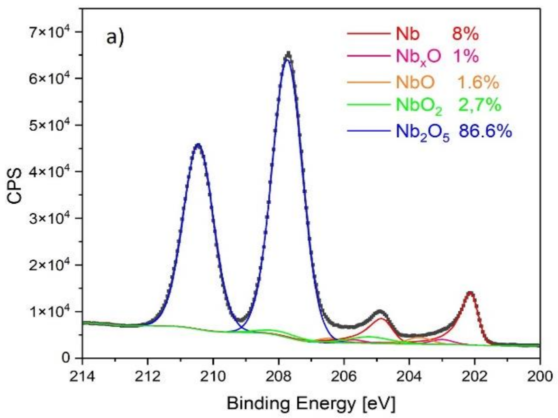


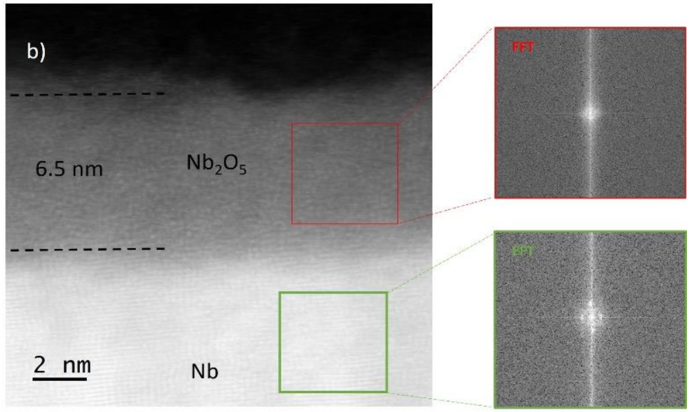
- Very small Δ and Γ reveal a proximity effect. Non-homogeneus spatial variation.
- McMillan predicts d ≤ 6 nm, consistent with TEM (~ 5 nm).
- However, for various junctions we did not obtain good fits with McMillan/Arnold.
- We want to test a new proximity effect model (Usadel).

Nb+HPR+annealed vs Nb+HPR

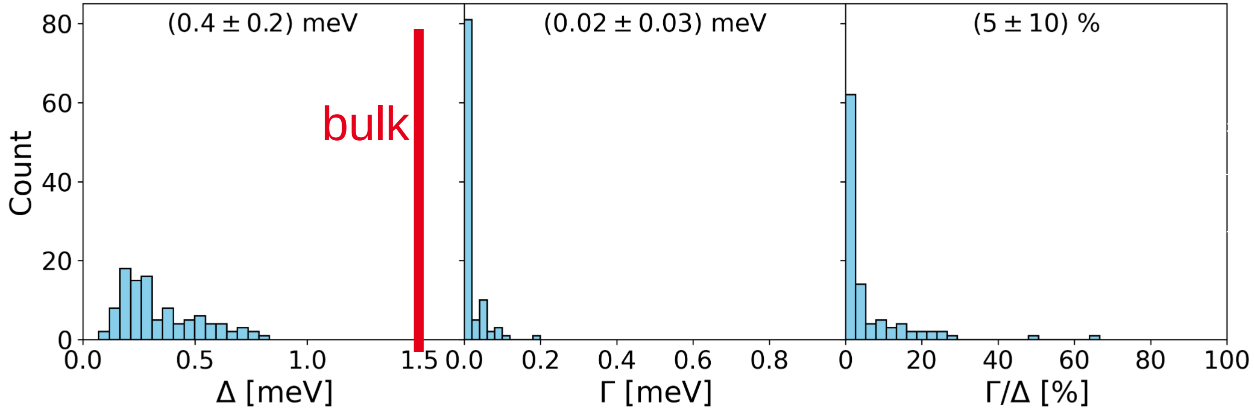
- Nb EP + HPR

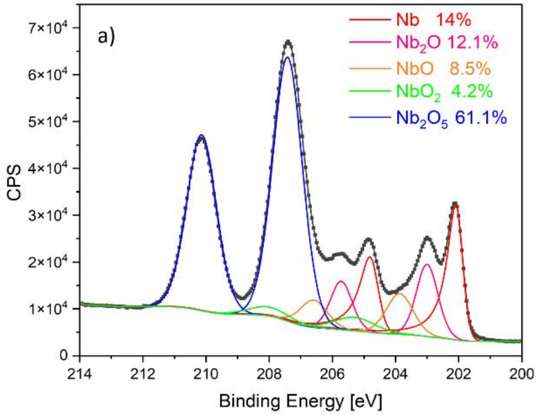


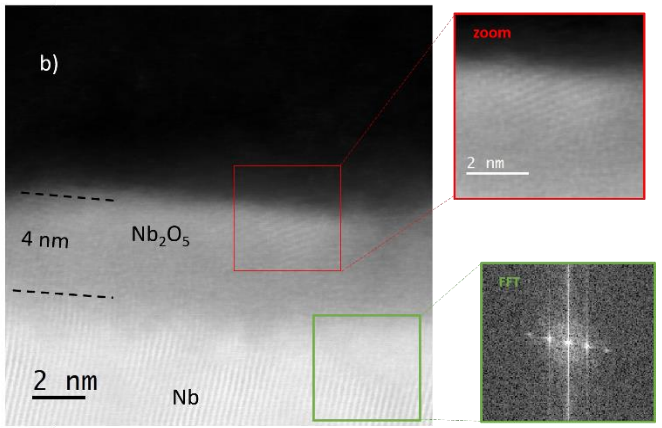




- Nb EP + HPR + 650°C-10hrs + HPR



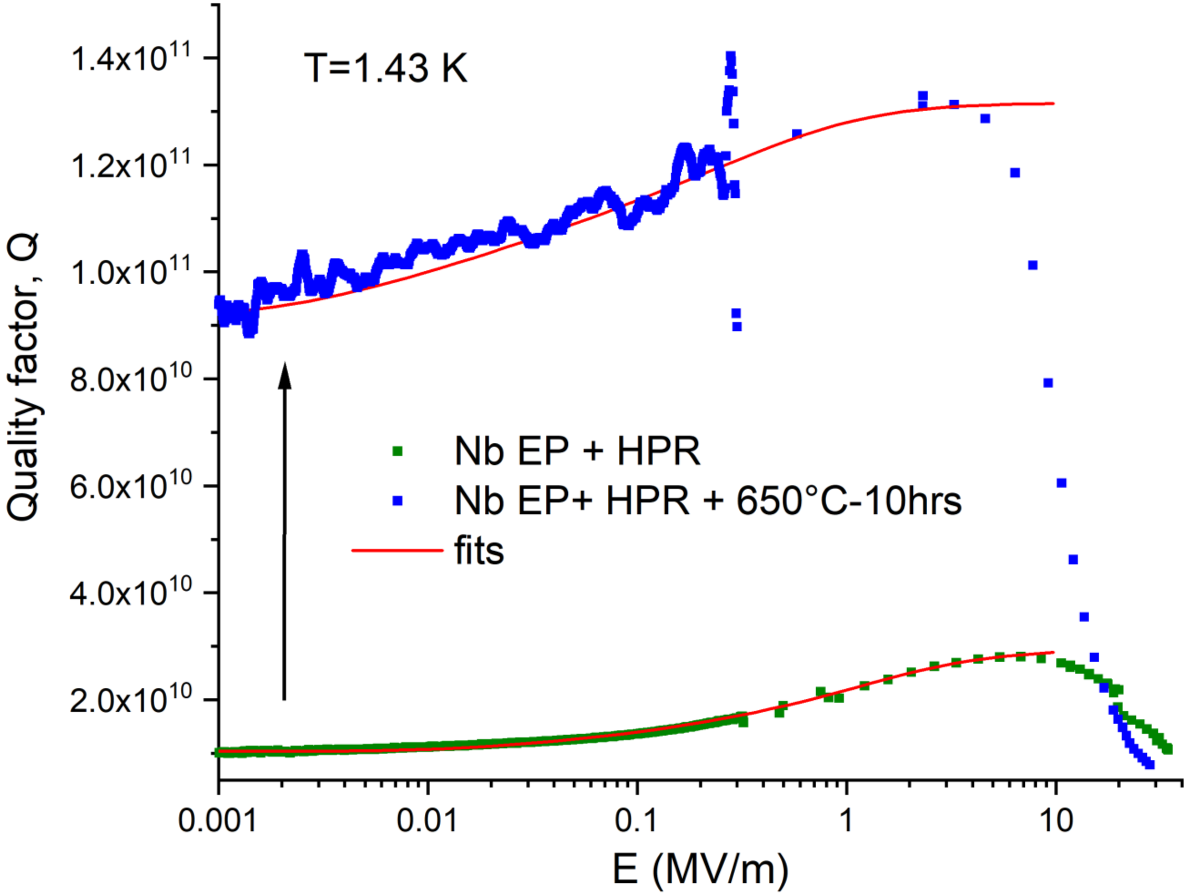


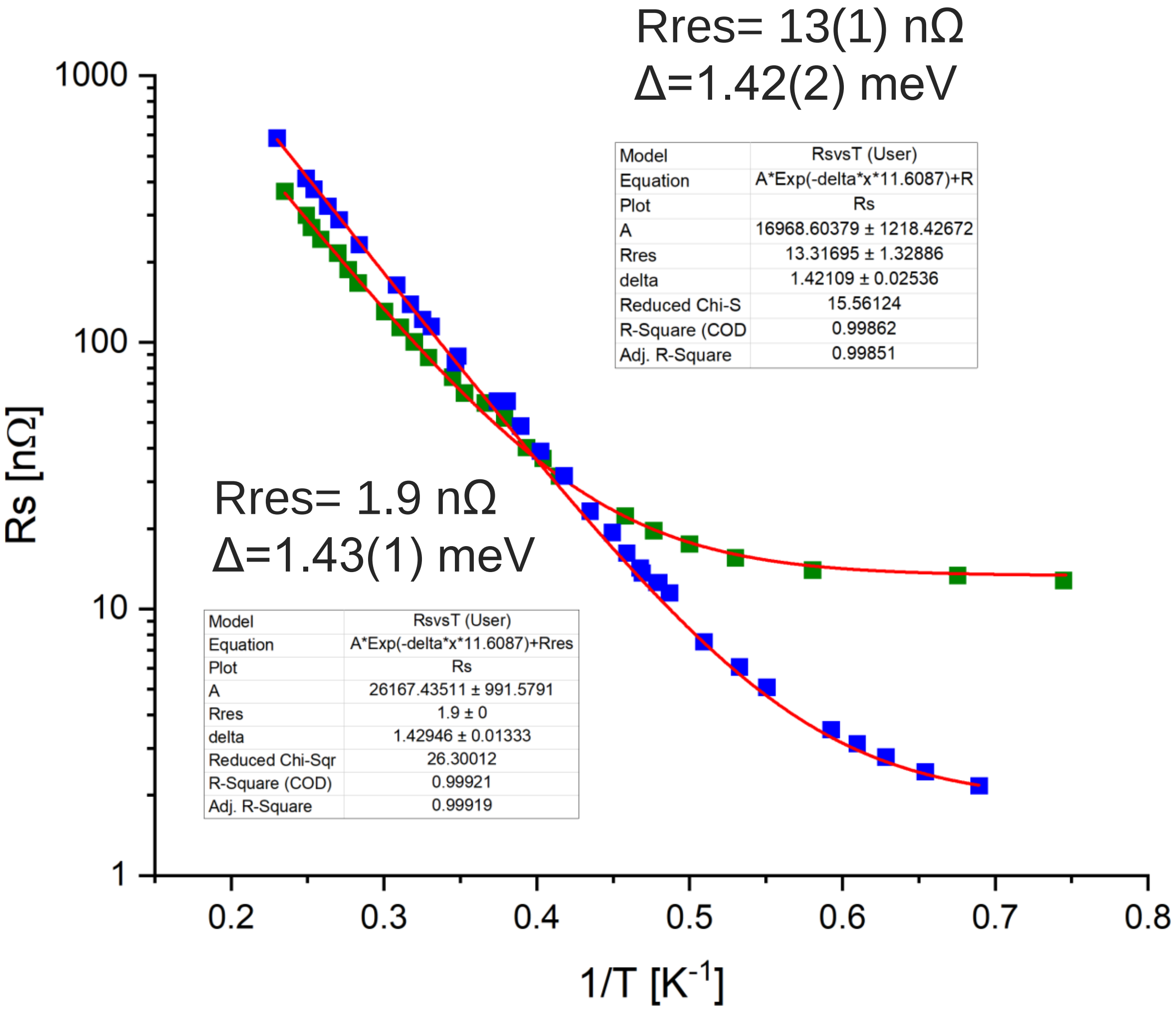


See Y. Kalboussi talk…

- Nb +HPR shows higher Δ and Γ than Nb+HPR+annealed.
- TEM and XPS show NbOx partially crystalline which explains the proximity effect in PCT.
- At low field, the increase in the Q factor can be explained by the thinner and more cristalline oxide (less defects, less TLS).
- And at higher field?

Nb+HPR+annealed vs Nb+HPR





Model	RsvsT (User)
Equation	A*Exp(-delta*x*11.6087)+R
Plot	Rs
A	16968.60379 ± 1218.42672
Rres	13.31695 ± 1.32886
delta	1.42109 ± 0.02536
Reduced Chi-S	15.56124
R-Square (COD	0.99862
Adj. R-Square	0.99851

Model	RsvsT (User)
Equation	A*Exp(-delta*x*11.6087)+Rres
Plot	Rs
A	26167.43511 ± 991.5791
Rres	1.9 ± 0
delta	1.42946 ± 0.01333
Reduced Chi-Sqr	26.30012
R-Square (COD)	0.99921
Adj. R-Square	0.99919

- Same Δ but $R_{Residual}$ is higher for the reference. $R_{Residual}$ ⟷ Γ ? Analysis on process
- PCT reveal a reduction in Δ due to a proximity effect. How can we explain the difference in Δ_{PCT} vs Δ_{Rs} ??

Outline

1. ALD- coated Nb
2. Nb-HPR-annealed
3. Nb_3Sn-Cu
4. Nb, Ta, Ta/Nb for 2D Qubits.

SRF cavities

Nb_3Sn-Cu for SRF cavities:

- There are current efforts aimed at obtaining cavities with high quality factors using Nb_3Sn on Cu.

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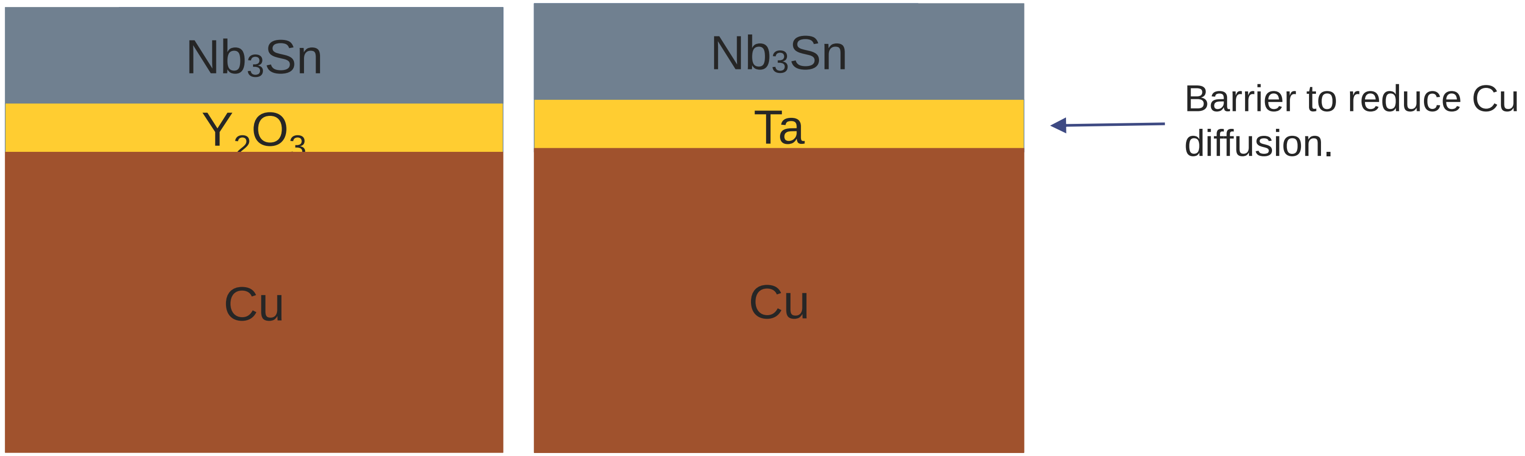
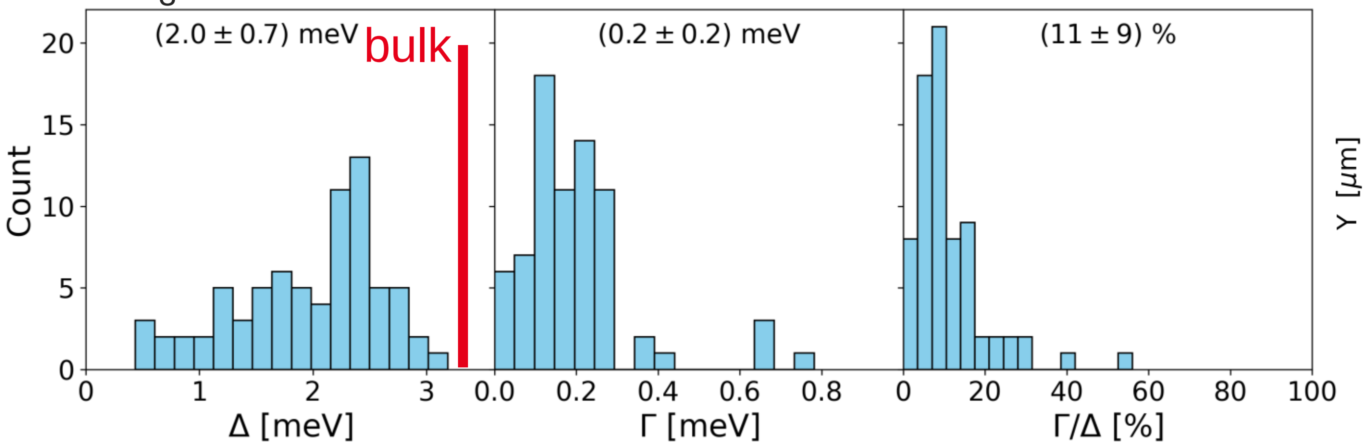


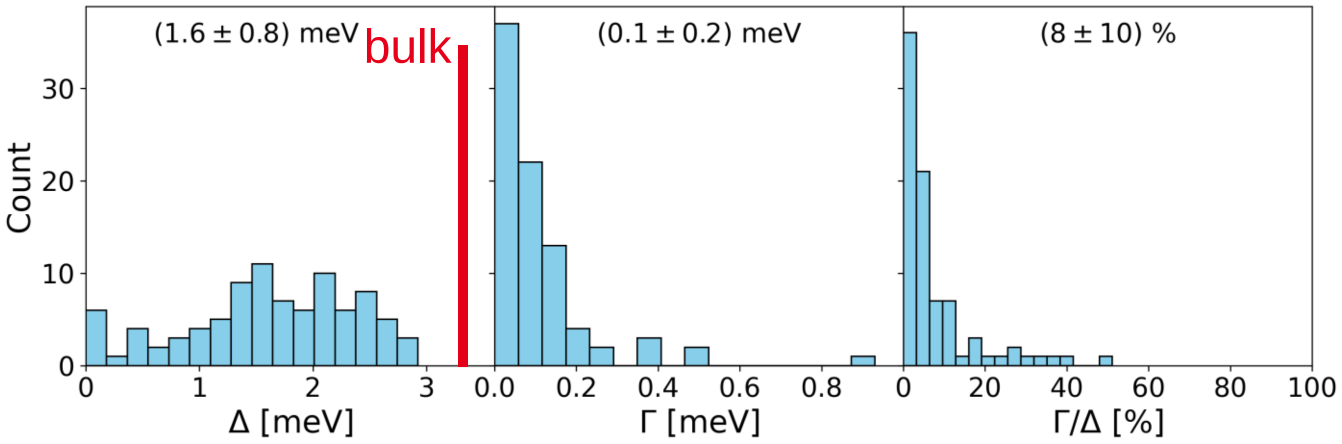
CERN samples

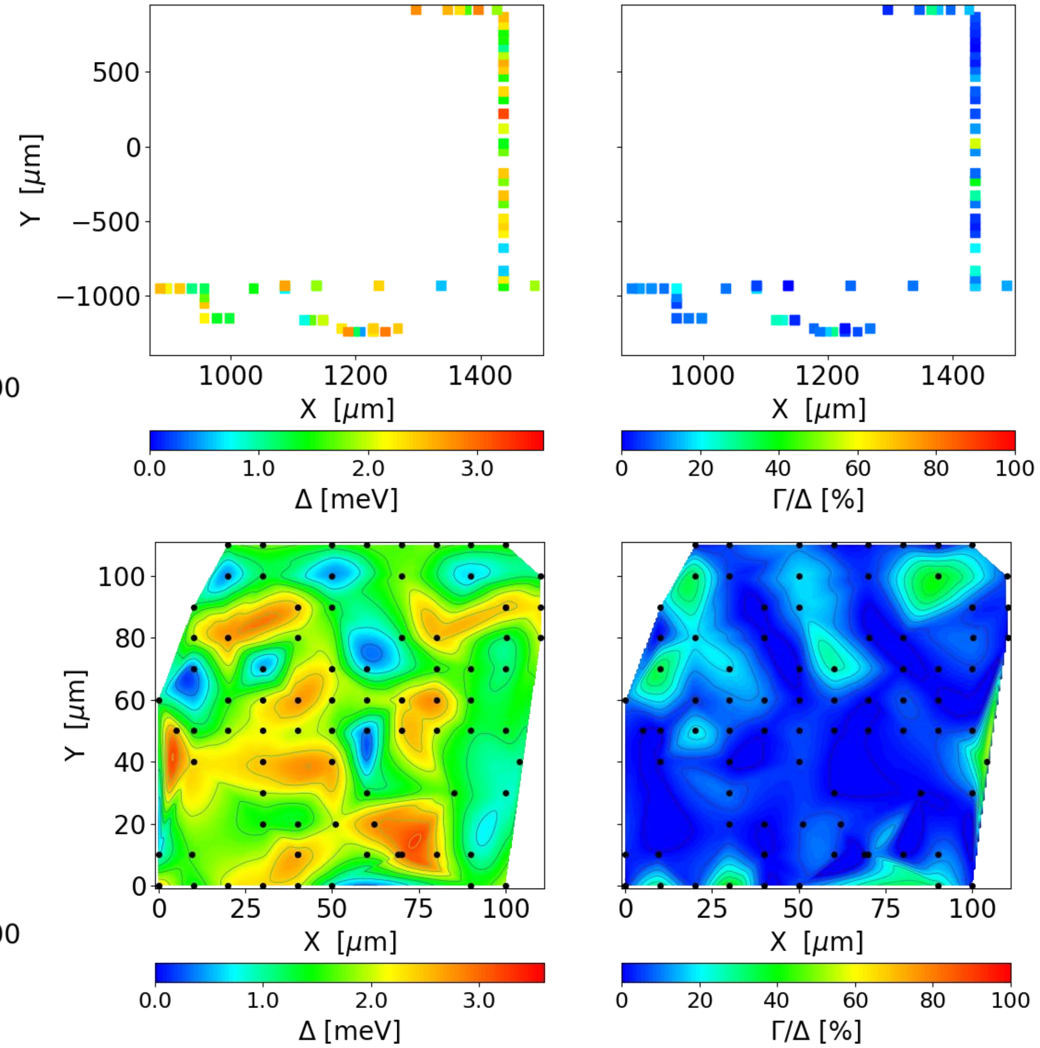
Nb_3Sn-Ta-Cu and Nb_3Sn-Y_2O_3-Cu

Nb_3Sn-Ta-Cu



Nb_3Sn-Y_2O_3-Cu

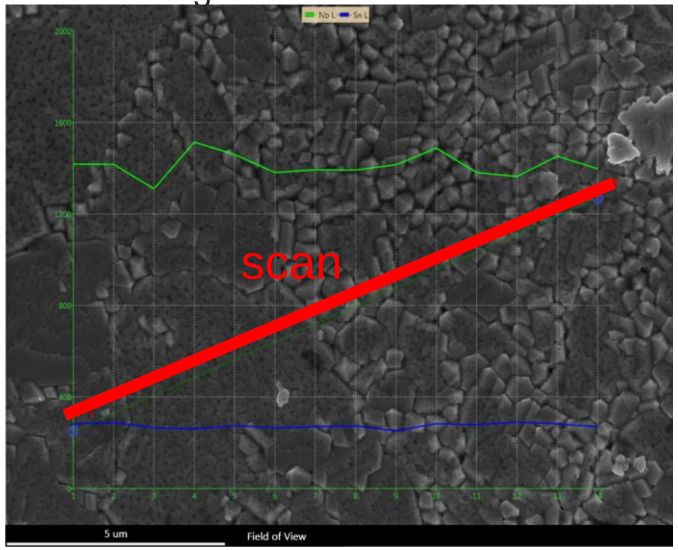


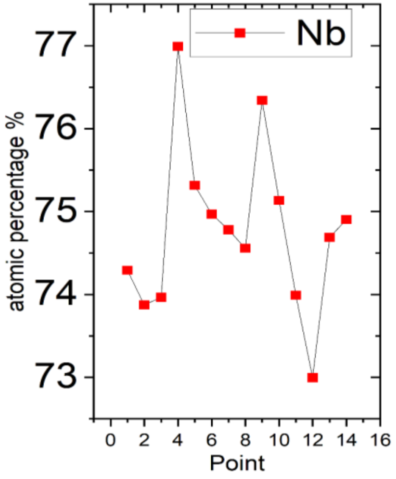


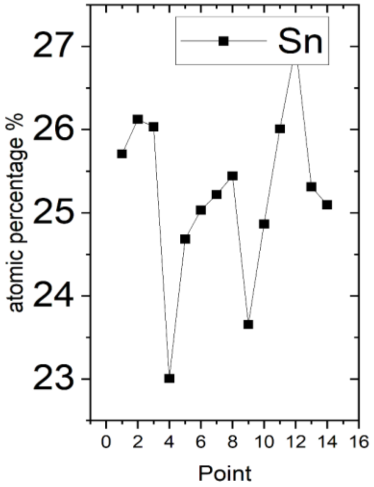
- Small Δ and Γ (smaller values for Nb_3Sn-Y_2O_3-Cu) Proximity effect? Nb? Cu?
- Non-homogeneous spatial distribution of Δ and Γ.

EDS/SEM for Nb_3Sn-Cu samples (CERN)

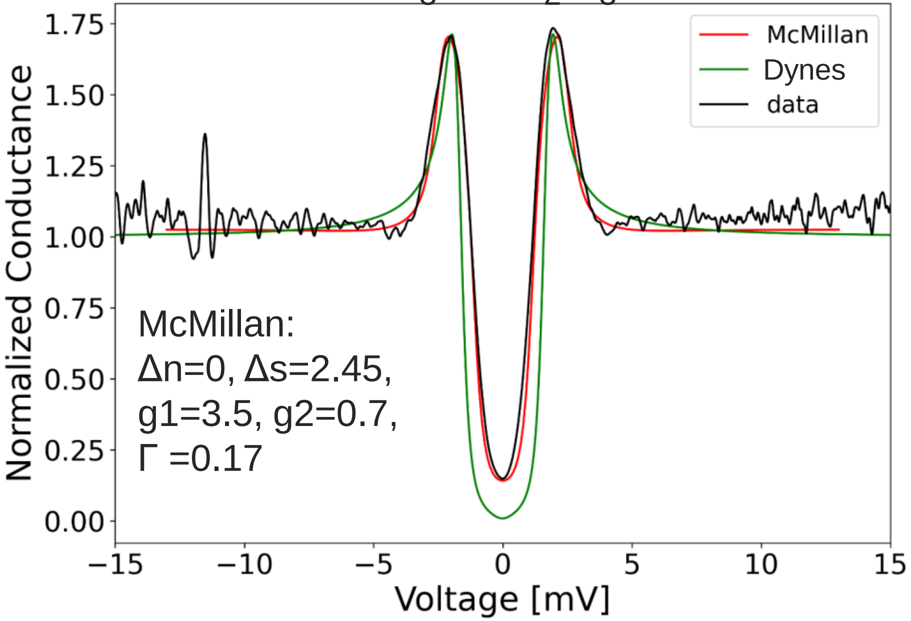
Nb_3Sn-Ta-Cu



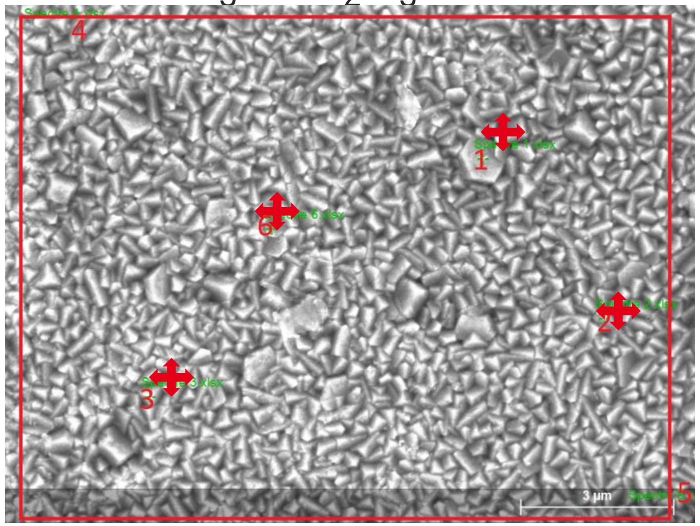


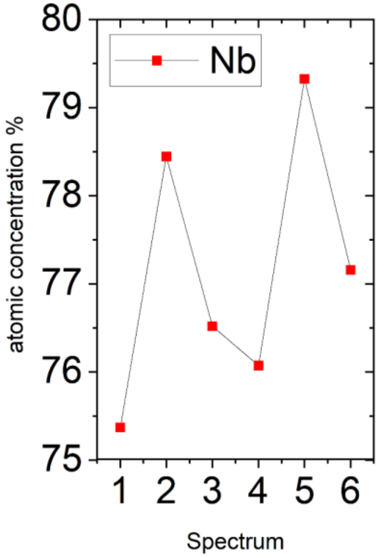


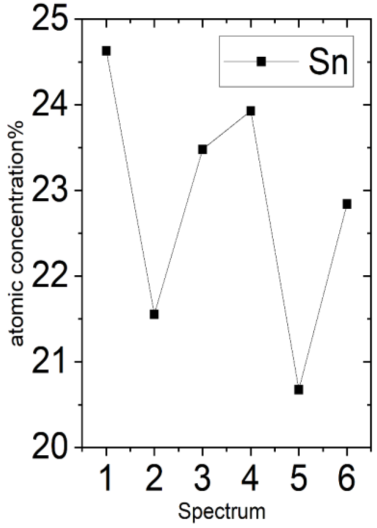
Nb_3Sn-Y_2O_3-Cu



Nb_3Sn-Y_2O_3-Cu







- EDS shows 73-77 %Nb variation for Nb_3-Sn-Ta-Cu sample and 75-79% for Nb_3Sn-Y_2O_3-Cu.
- For Nb_3Sn-Y_2O_3-Cu, some junctions fit with McMillan. It predicts d~3-7 nm.
- EDS does not show Cu on the surface.
- Not enough resolution?

XPS?

Tuesday's presentations!!

Outline

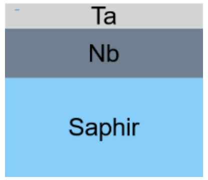
1. ALD- coated Nb.
2. Nb-HPR-annealed.
3. Nb_3Sn-Cu.
4. Nb, Ta, Ta/Nb for 2D Qubits.

} SRF cavities (items 1–3)

Qubits coherence time (literature):

T1~100 μs

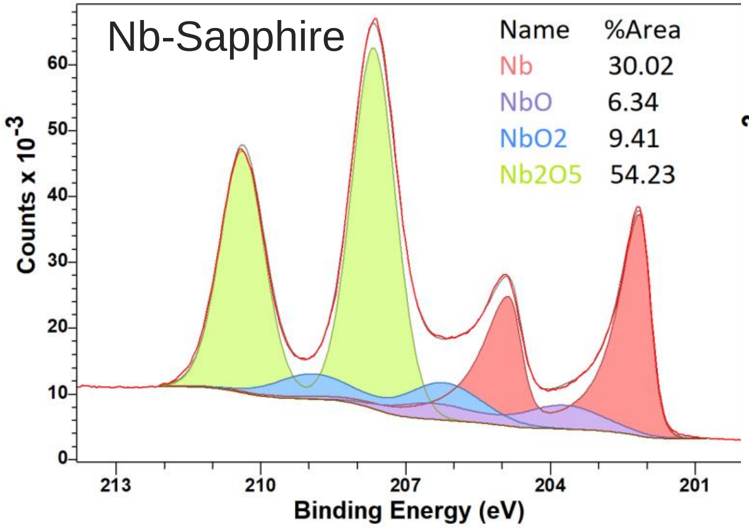
T1~200-300 μs



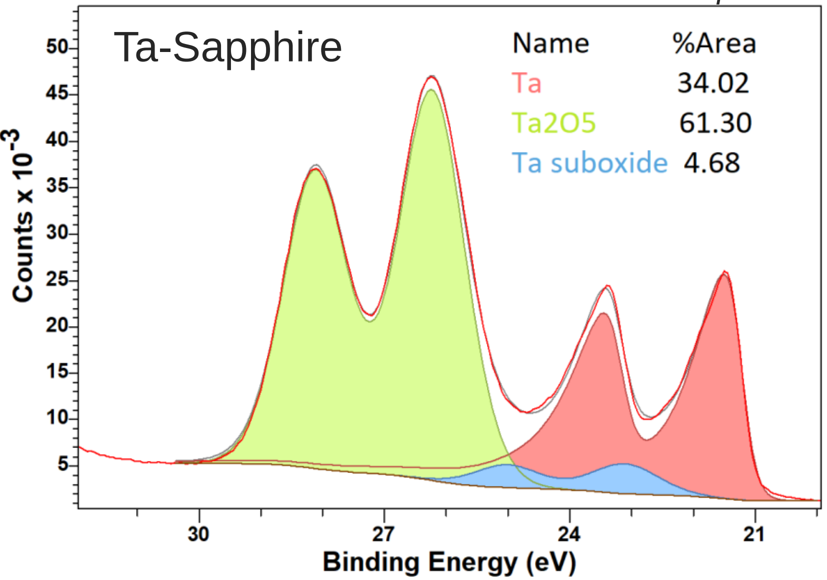
T1~ 400- 500 μs

$T1_{Ta-Nb} > T1_{Ta} > T1_{Nb}$ Why? Oxides?

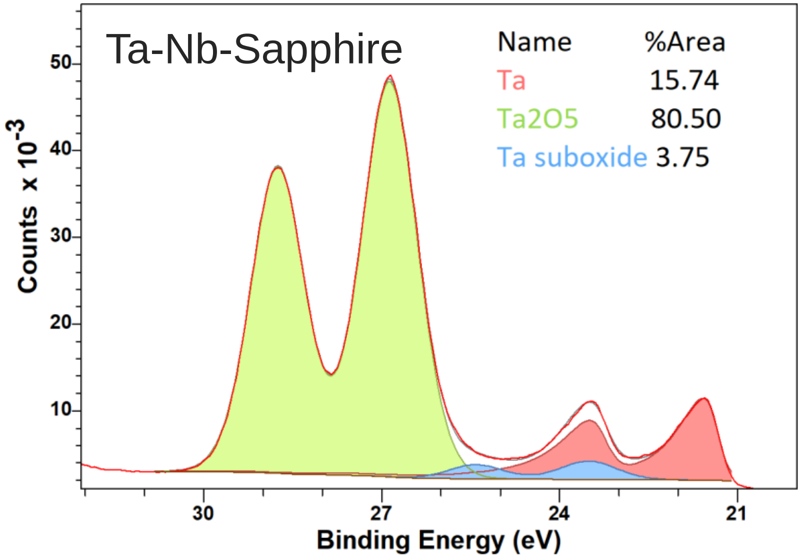
SPEC sample



SPEC sample

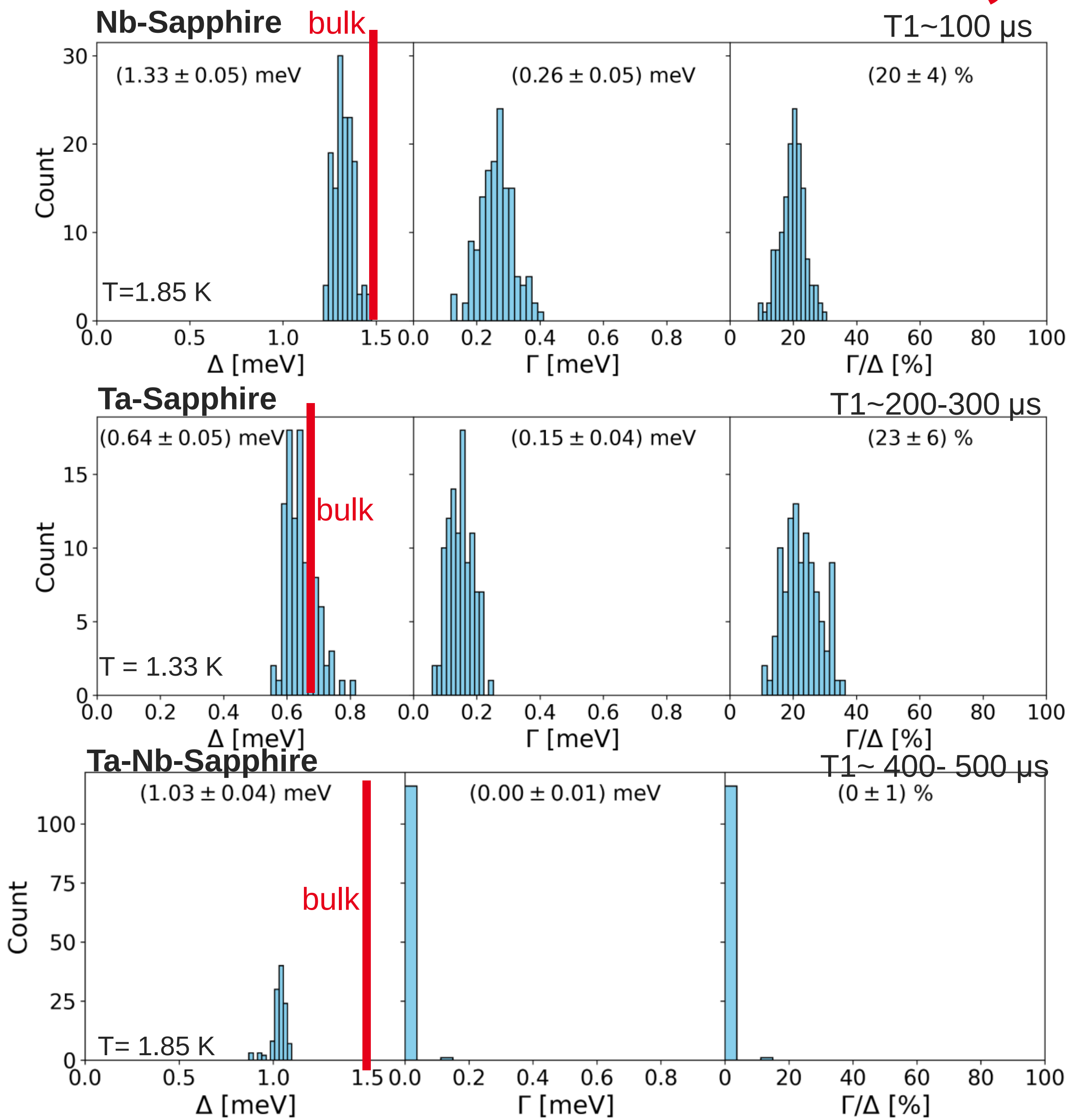


FNAL/SQMS sample



- What can PCT reveal to understand the difference between Ta and Nb Qubits?

PCT for Nb, Ta and Ta/Nb



- Losses are not dominated by Δ in Qubits.
- Γ ⟶ T1 ? How?

- $\Gamma_{Ta-Sapphire}$ = 0.15 < $\Gamma_{Nb-Sapphire}$=0.26.
  Correlation with $T1_{Ta}$ >$T1_{Nb}$?
- $T1_{Ta-Sapphire}$ for our sample vs literature?
- XRD reveal both α (wanted) and β (unwanted) phases.

- Small Δ and Γ on Ta/Nb ⟶ proximity effect between Ta and Nb.
- McMillan gives good fits for Ta/Nb. It predicts d ≤ 10 nm and Γ ~ 0.01.
- Γ_{Ta-Nb}=0.01 < Γ_{Ta} = 0.15.
  Correlation with $T1_{Ta-Nb}$ >$T1_{Ta}$?

- More PCT on Ta and Nb is needed!!

Conclusions

- PCT can uncover various phenomena on the surface of superconducting devices correlated to their performances.

- PCT on Al_2O_3-Nb reveals smaller gaps compared to the bulk. It can be attributed to the presence of Nb oxides.

- PCT on Nb-HPR-annealed samples reveals a proximity effect. **TEM** and **XPS** explain this by the presence of a partially crystalline/metallic Nb oxide. We want to correlate Γ values with R_{res}.

- PCT on Nb_3Sn-Cu shows regions with Δ closer to the bulk, but also with smaller Δ, which may indicate the presence of a normal layer (Nb,Cu) estimated to be around ~3-7 nm.

- We are trying to find a correlation between the Γ for Ta and Nb that might help in the understanding of Qubits T1. We need more samples to find a correlations.

References

1. Proslier, T., Zasadzinski, J., Moore, J., Pellin, M., Elam, J., Cooley, L., ... & Gray, K. E. (2008). Improvement and protection of niobium surface superconductivity by atomic layer deposition and heat treatment. *Applied Physics Letters*, *93*(19).

2. Kalboussi, Y., Delatte, B., Bira, S., Dembele, K., Li, X., Miserque, F., ... & Proslier, T. (2024). Reducing two-level system dissipations in 3D superconducting Niobium resonators by atomic layer deposition and high temperature heat treatment. *arXiv preprint arXiv:2402.04137*.

Thank you