DE LA RECHERCHE À L'INDUSTRIE

Correlation between tunneling spectroscopy and RF performances

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10/10/2018

8th workshop on thin films and new ideas for RF superconductivity - INFN

- ***Background***

- ***Bulk Nb : Hot and cold spots***
  N doped Nb

- ***Thin films: Nb_3Sn/Nb***
  Nb/Cu (HIPIMS, DCMS)

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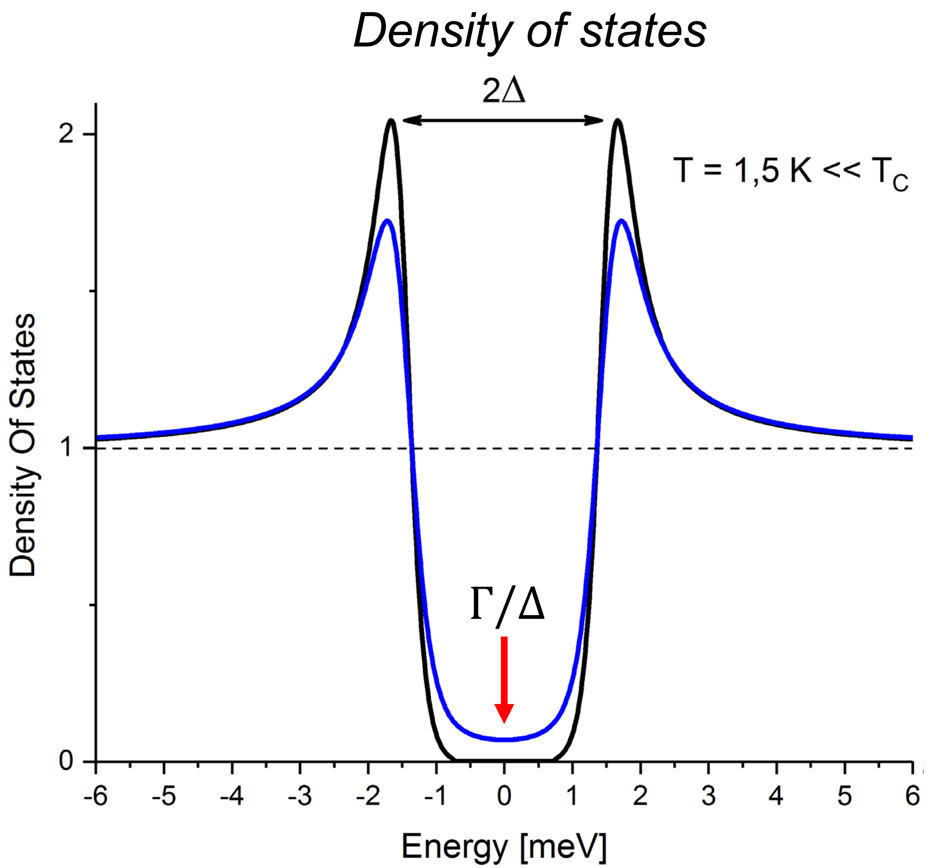
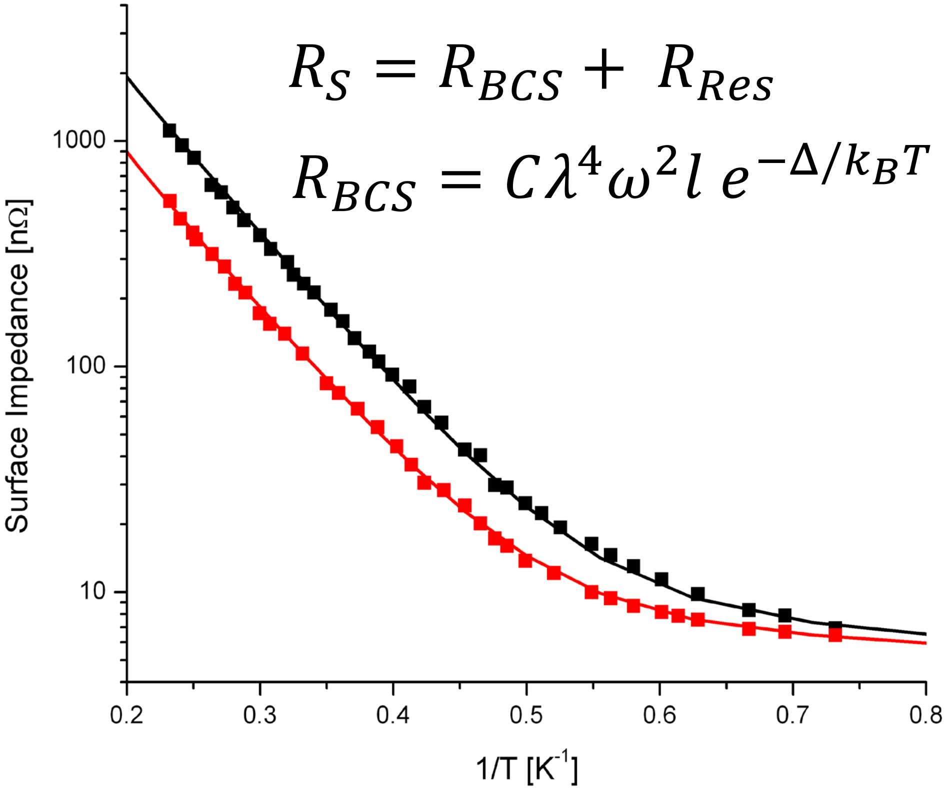
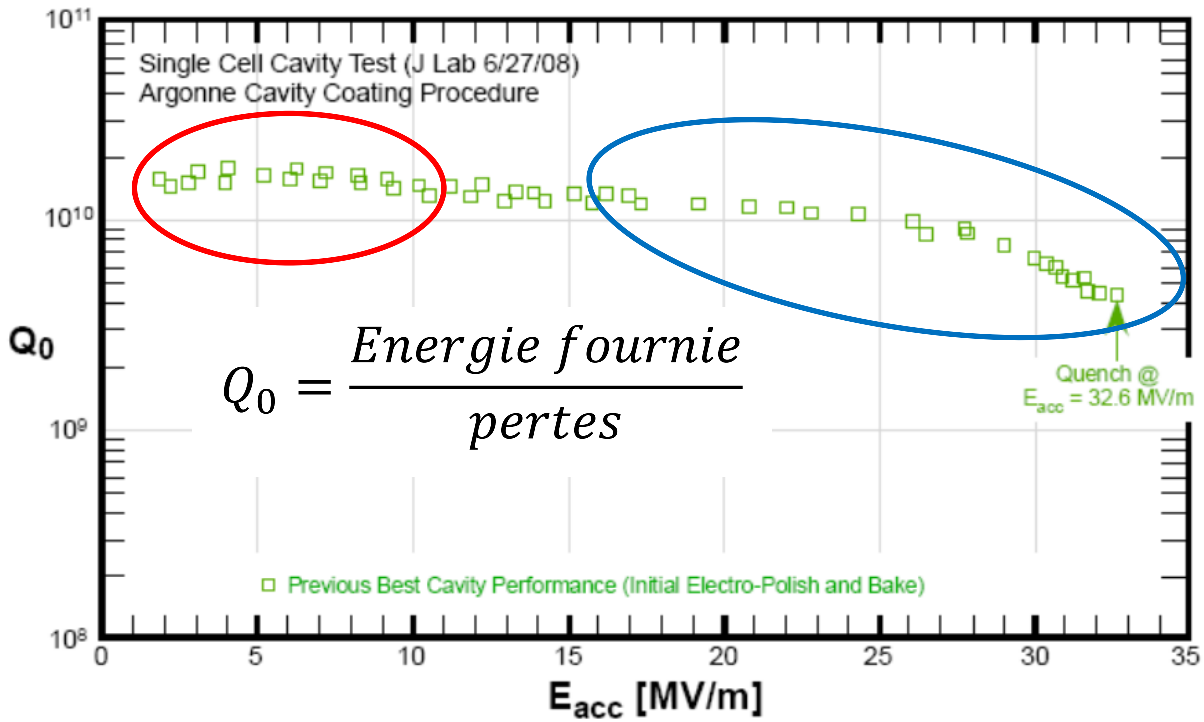
Background





- *Rs depends on DOS(E_F). DOS(E_F) (B, T, Δ, r)*
- *Higher Gap (Δ) -> Higher Q*
- *DOS (E_F) ≠ 0 -> dissipation @ T=0 K*
- *DOS(E_F) (B, T, Δ, r), R_S = <DOS(E_F) (B, T, Δ)>$_r$*
- *Saturation mechanisms of the DOS? -> Inelastic scattering (Γ)*

Background SRF cavities

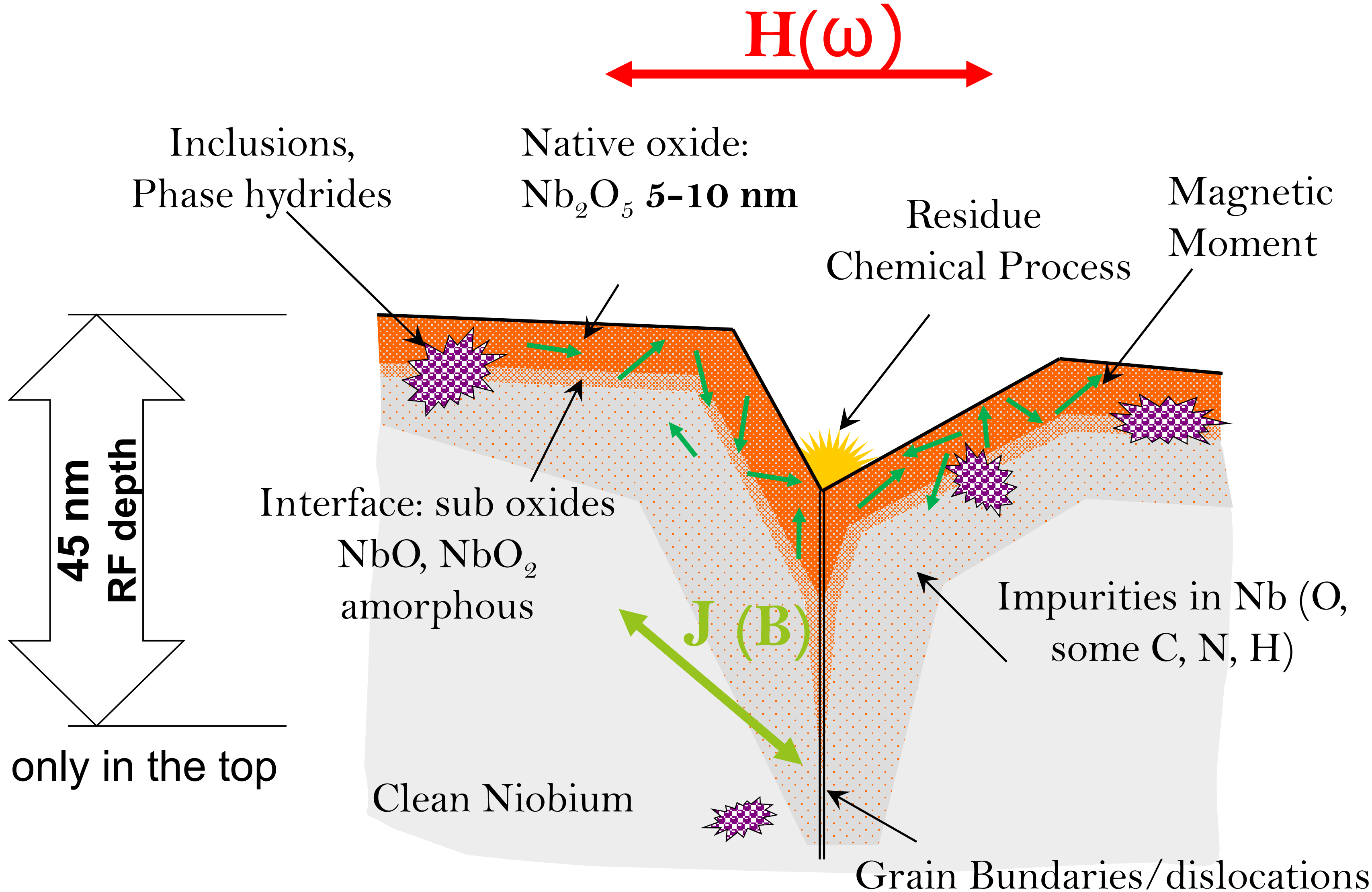


$$Q_0 = \frac{Energie\ fournie}{pertes}$$

At fixed temperature:

- **Low Acceleration Gradient: Q is dominated by Δ, Γ (Static)**
- **Higher Acceleration Gradient: vortex penetration/dissipation dominate (dynamic)**

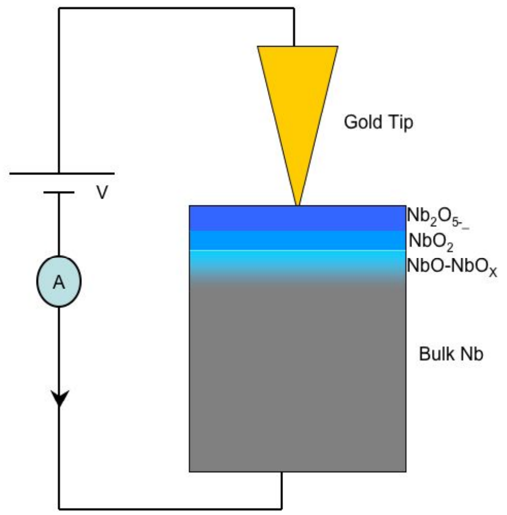
Background SRF cavities

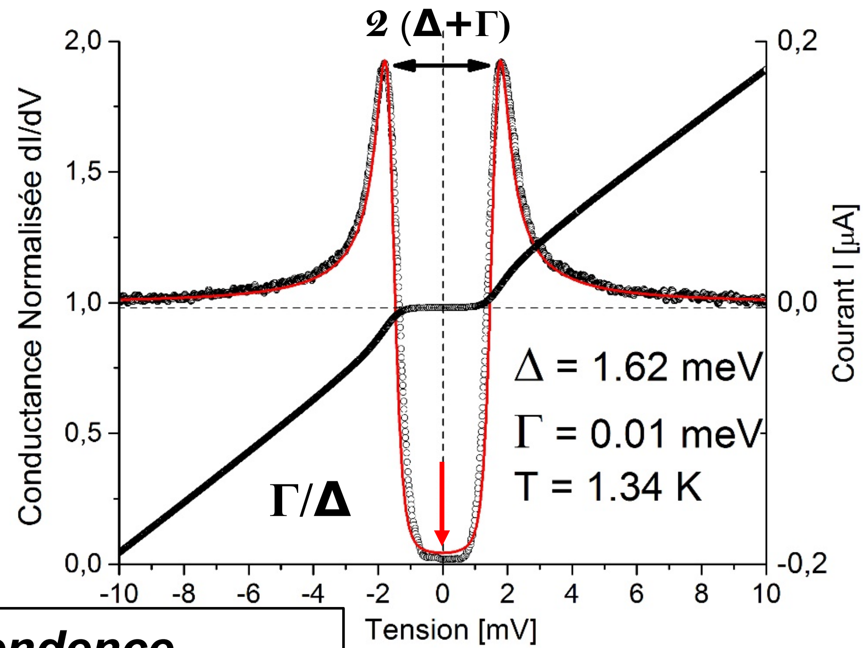


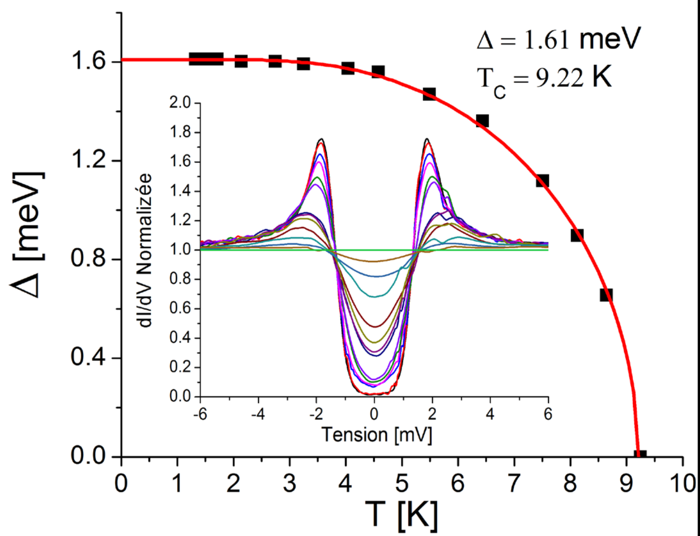
e⁻ flow only in the top 45 nm

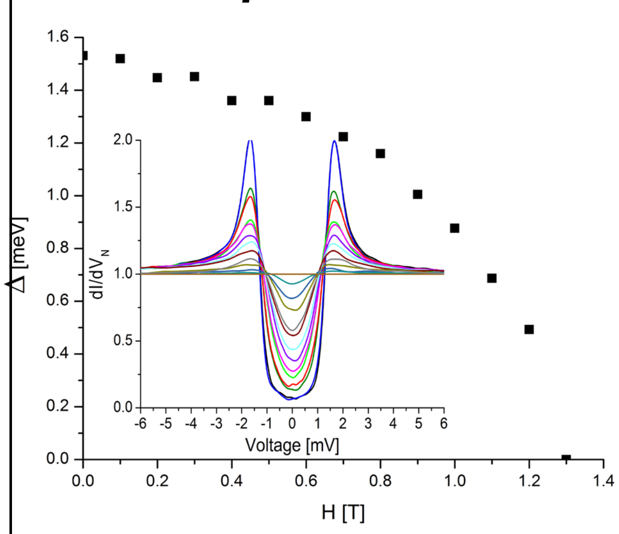
⇨ **Measure surface properties**

How to measure the DOS? Tunneling Spectroscopy



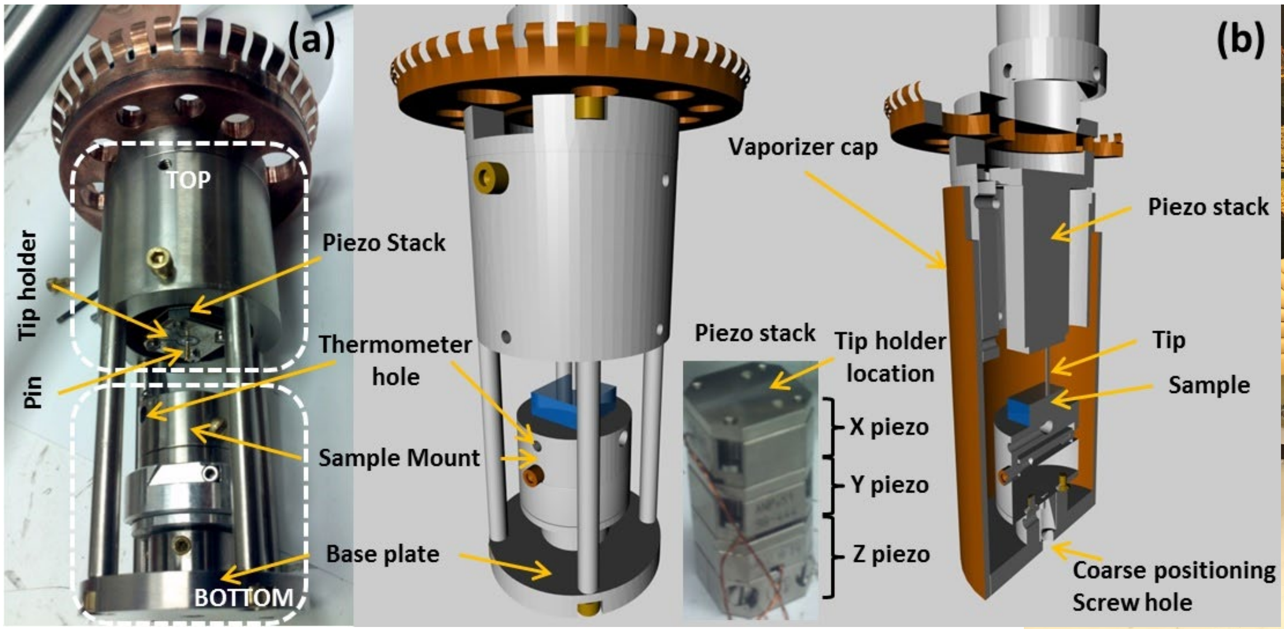






- Extract Δ, Γ, T_C, H_{C2}
- $DOS(0) = \Gamma / \Delta$ (%)
- Mapping ?

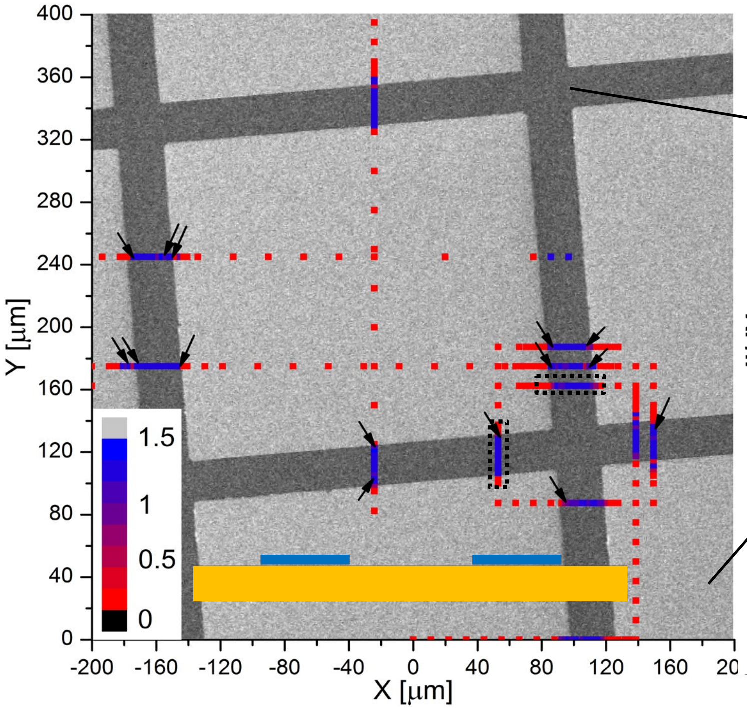
PCT apparatus

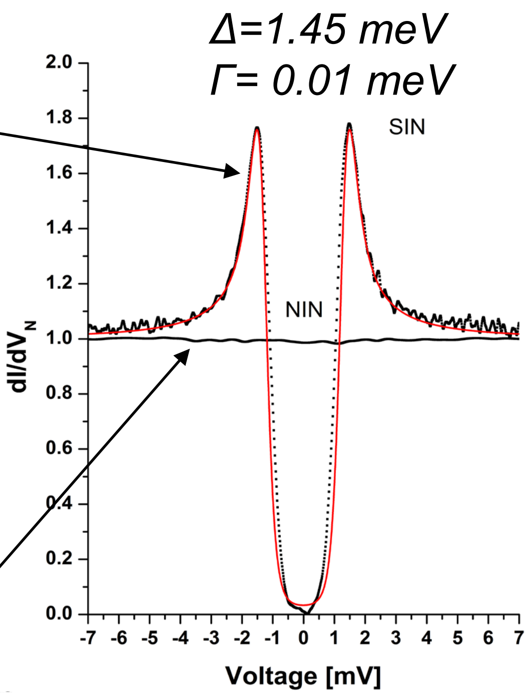


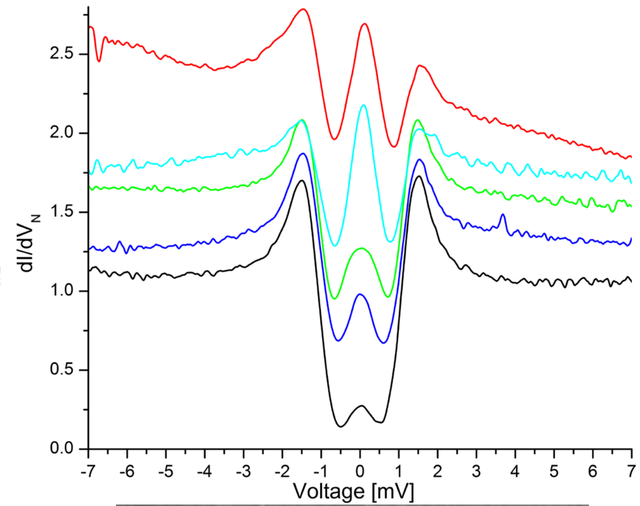
- Temp: 1,3 K – Magnetic field: 6,5 T
- Variable resistance: $2.10^2 – 2.10^9$ Ω.
- Cartography: 10 µm – 2 mm
- Fast measurements: 100-300 junctions/5hrs

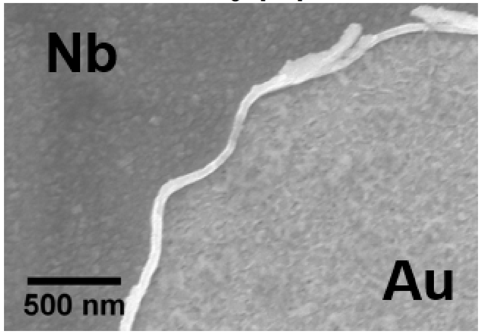
- Transport measurements.
- Cooling down:
  From 300 – 80K ~ 1.5 K/min
  From 80 – 4.2 K ~ 1 K/min

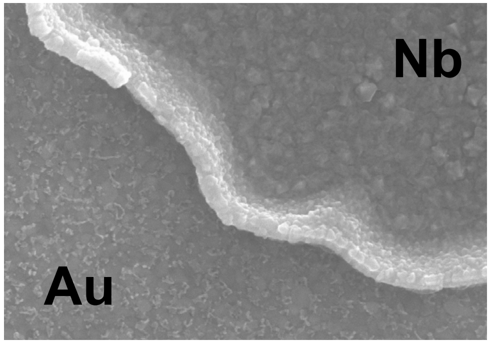
Calibration

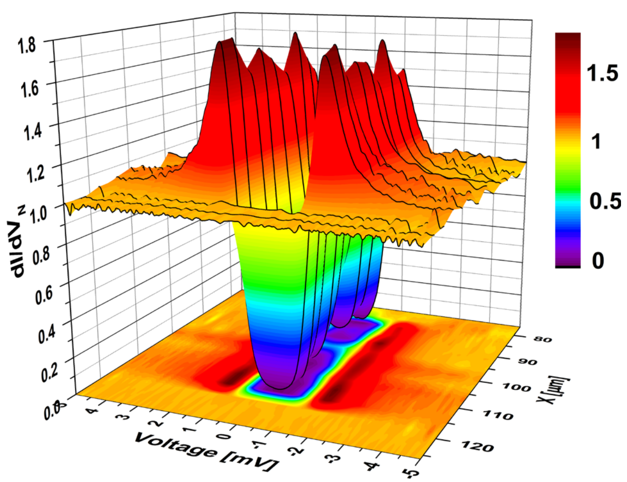












- Nb oxides -> ZBP
- Indication of magnetic impurities

- ***Background***

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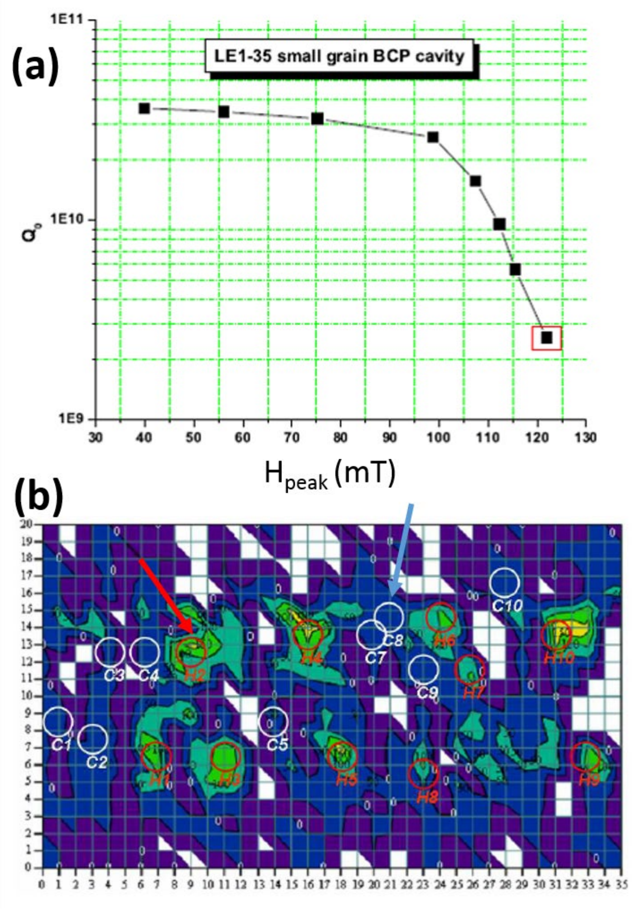
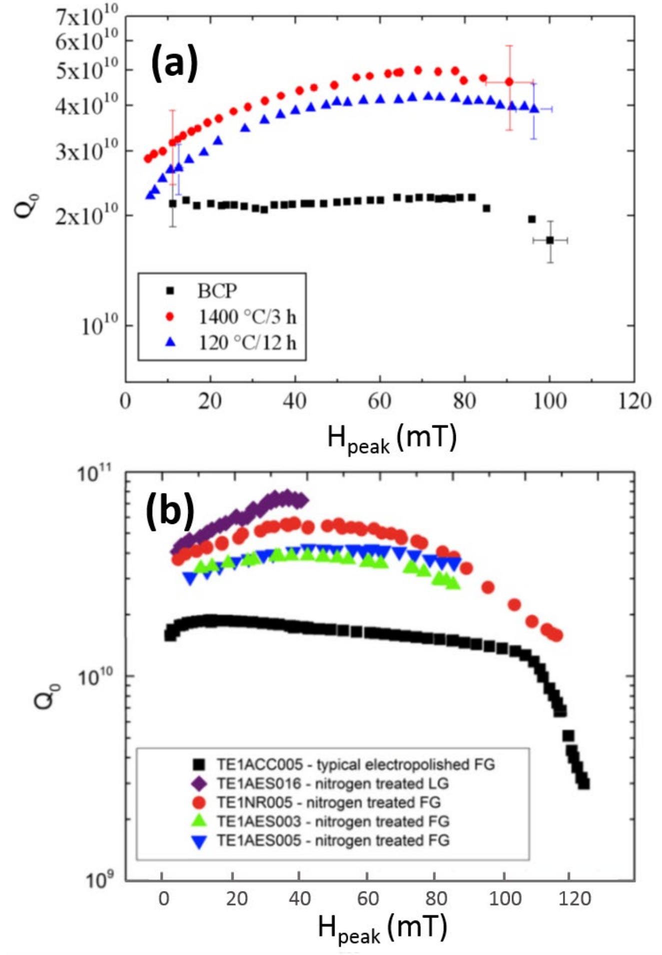
  Nb/Cu (HIPIMS, DCMS)

BULK NB HOT & COLD SPOTS – N DOPED NB

- Hot and Cold Spots from HFQS (FNAL)

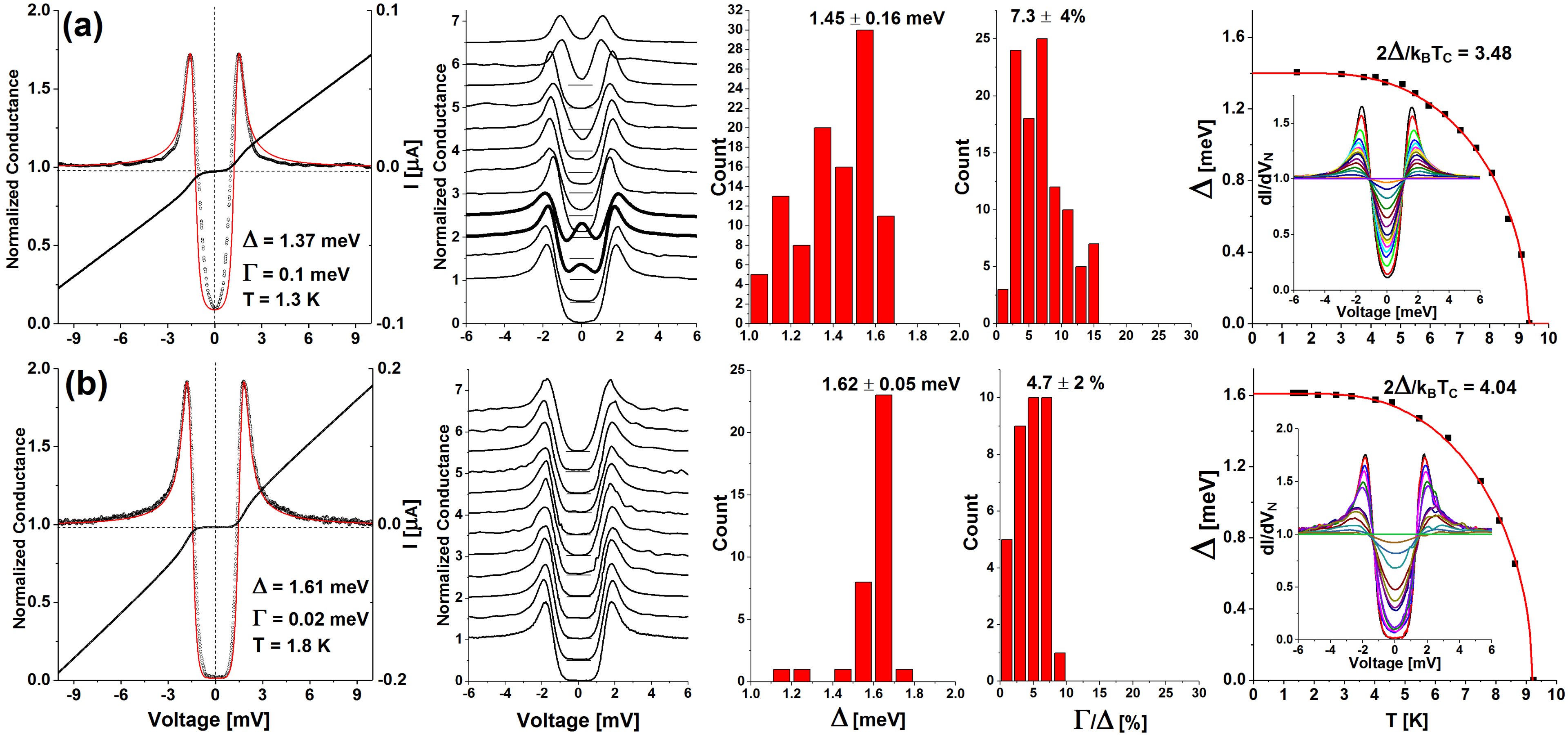


- N –Ti doped EP Nb (FNAL, JLAB)



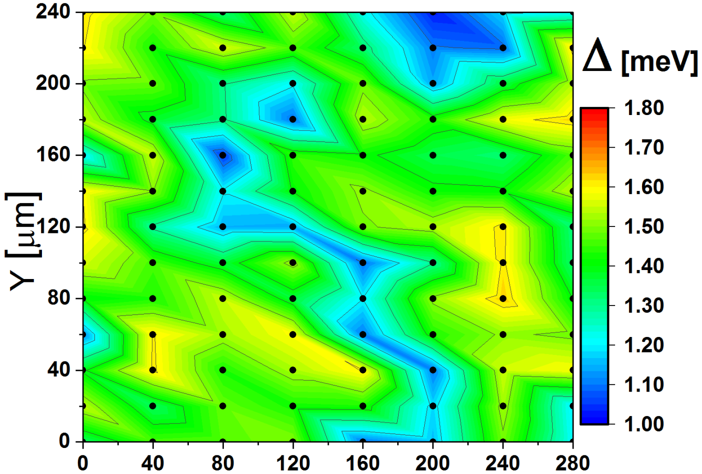
MEASUREMENTS

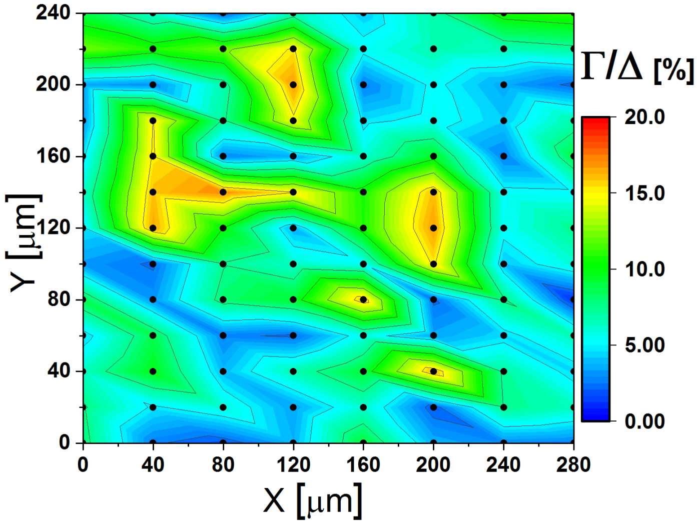
- Hot and cold spot Nb samples



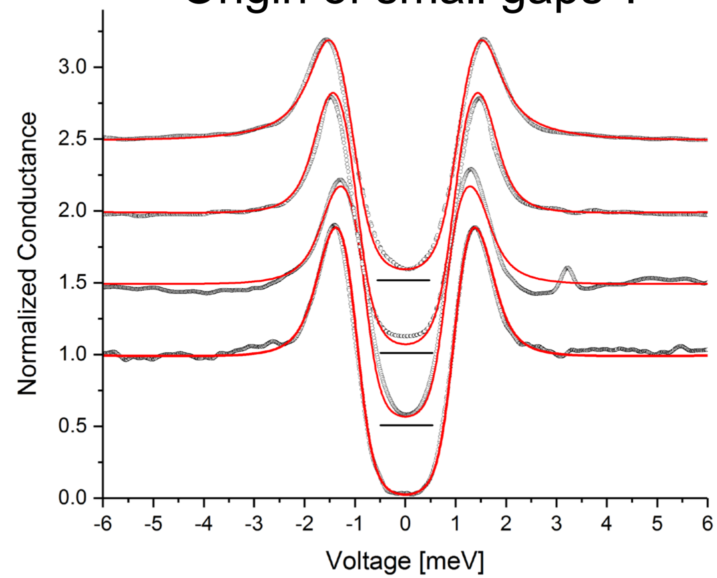
- Hot spot Nb: gap values < Δ_{Nb} (1.5 – 1.65 meV) + Zero bias peaks – High Γ
- Cold spot Nb: gap values = Δ_{Nb} + no ZBP – Low Γ values

MAPS





Origin of small gaps ?



$\Gamma_S \sim 0.2$, $\Gamma_N \sim 2$, , $\Gamma \sim 0.04$

McMillan Model:

- Any T
- Diffusive scattering
- Low transparency interface
- No spatial dependence

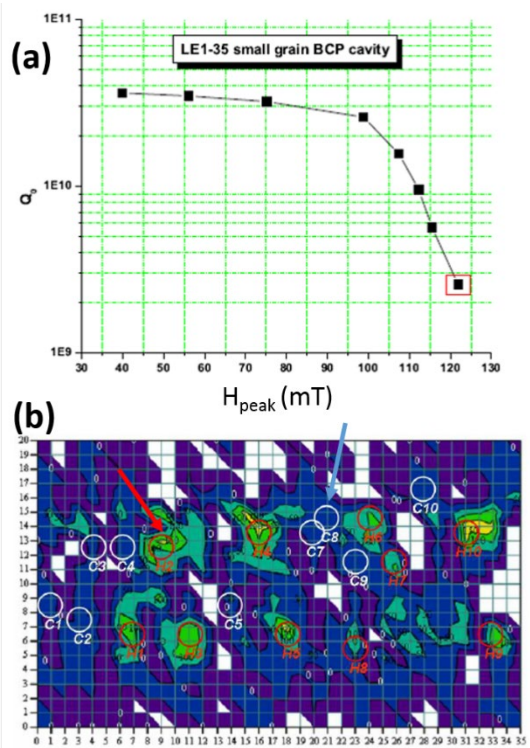
Γ_S, Γ_N, Δ_{Sph} (1.6 meV) , Δ_{Nph} (=0)

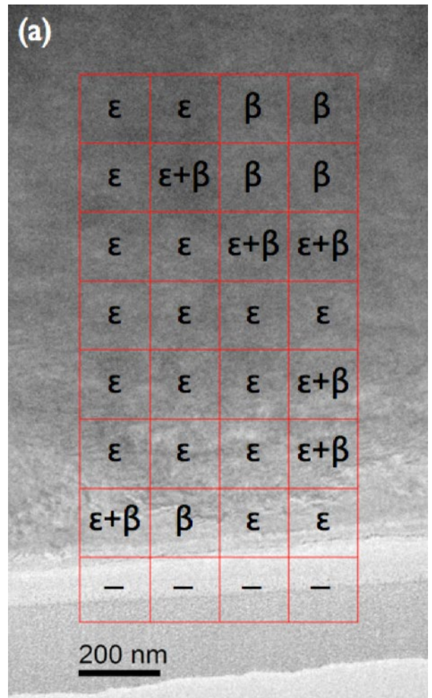
$\Gamma_N=\hbar.V_{FN}.\sigma/(2.B.d_N)$

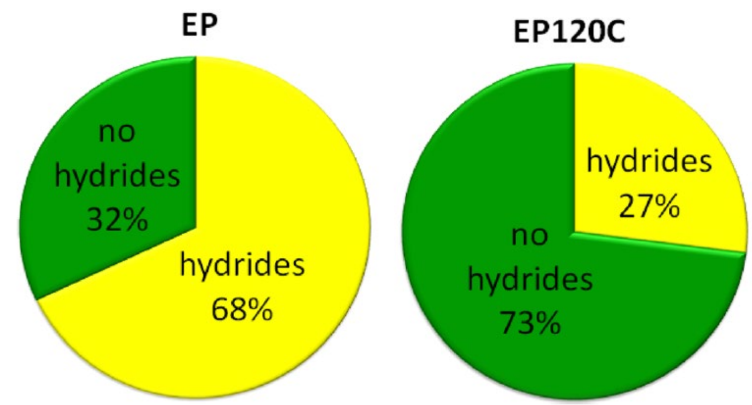
$d_N \sim 15$ nm

PROXIMITY EFFECT – ORIGIN?

- High field Q slope - Hydrides revealed by TEM







- Penetration field in proximity effect:

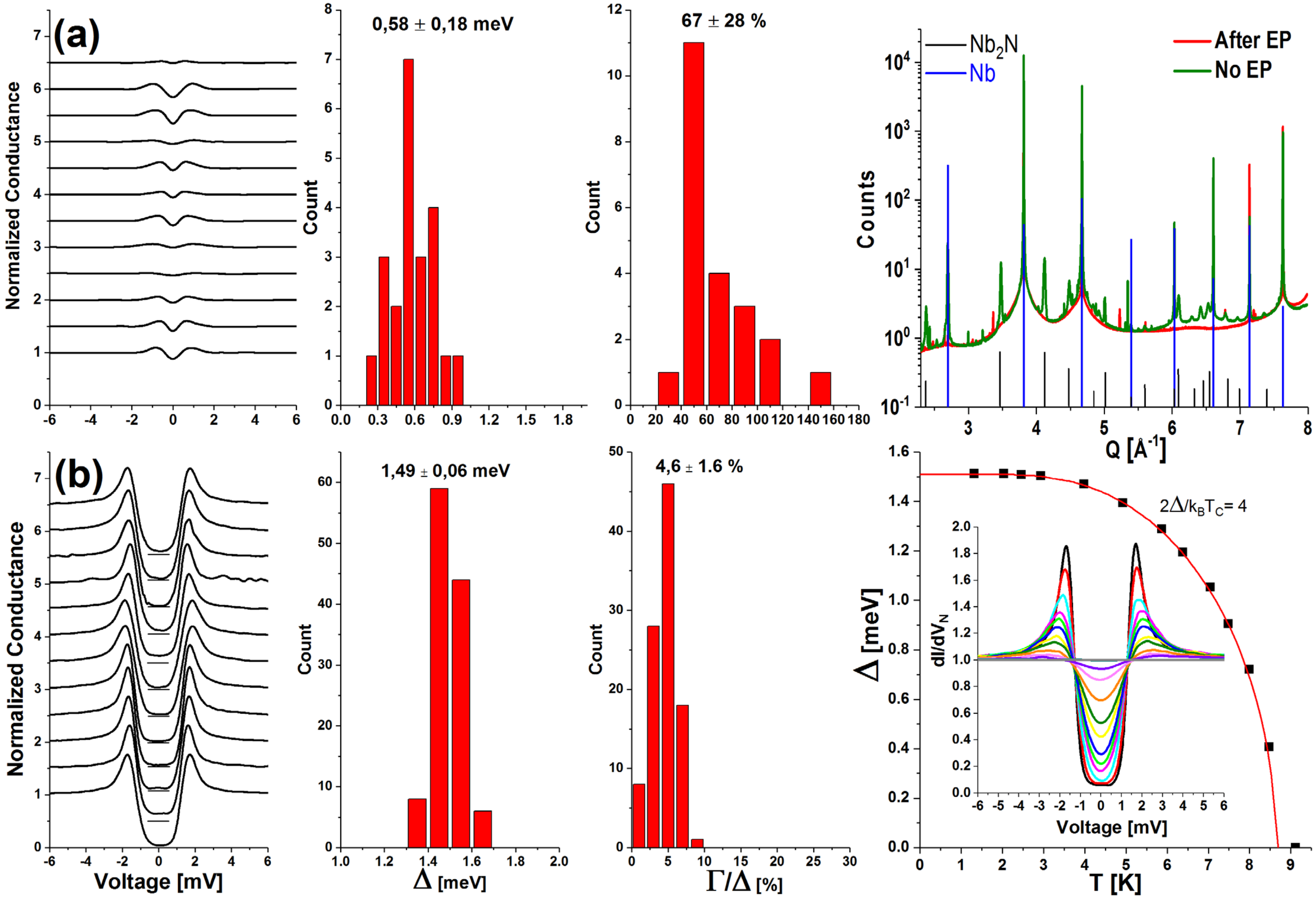
- Why hot and cold spots?
Correlation with Crystalline structure?

$T \sim 0$ K : $H_B \approx \Phi_0/(6.\lambda_N.d)$, $\lambda_N = \sqrt{(mc^2/4\pi ne^2)}$ -> $d \sim 20$ nm.

A. Fauchère et G. Blatter PRB 56, 14 102 (2017)

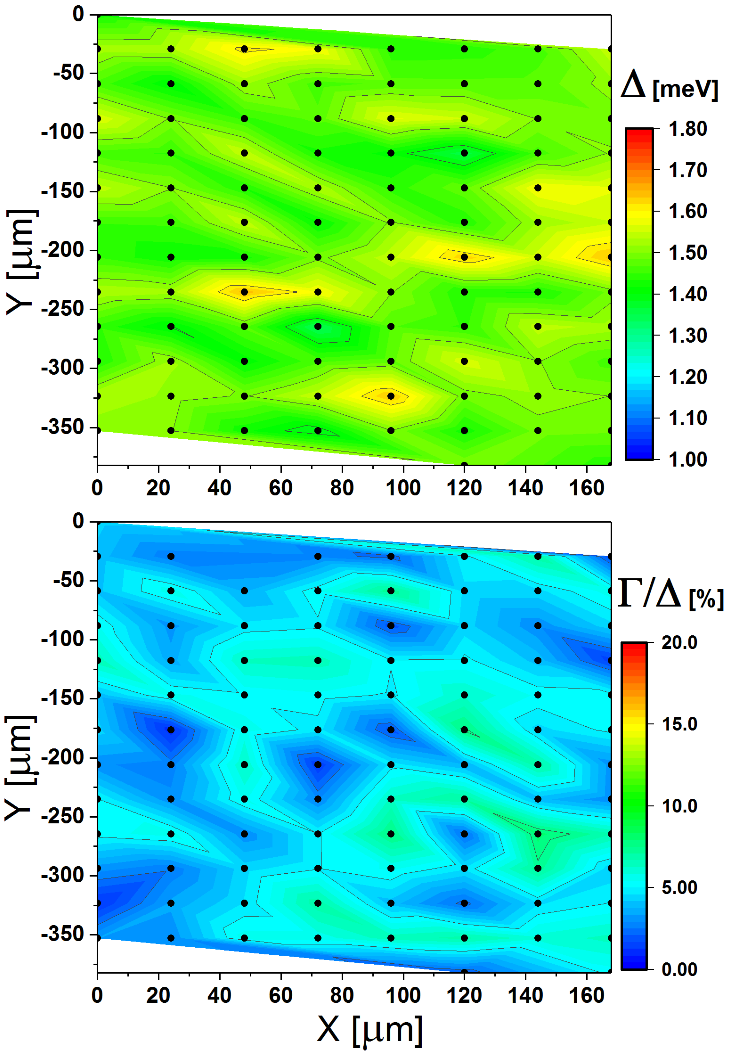
Y. Trenikhina et al. JAP 117, 154507 (2015)

N DOPED SAMPLES



- No EP: gap values << Δ_{Nb} + High Γ + Nb_2N phases ~ 30 nm
- After EP (5 µm): gap values ~ Δ_{Nb} + Tc < Tc_{Nb}+ Low Γ values, no ZBP

MAPS



- Homogeneous superconducting properties:
- Slightly decreased Tc and a ratio $2\Delta/K_BT_C = 4$
- Same $2\Delta/K_BT_C$ measured by R_{BCS} vs MFP
- Reproducibly found in Ti doped Cavity (Jlab)

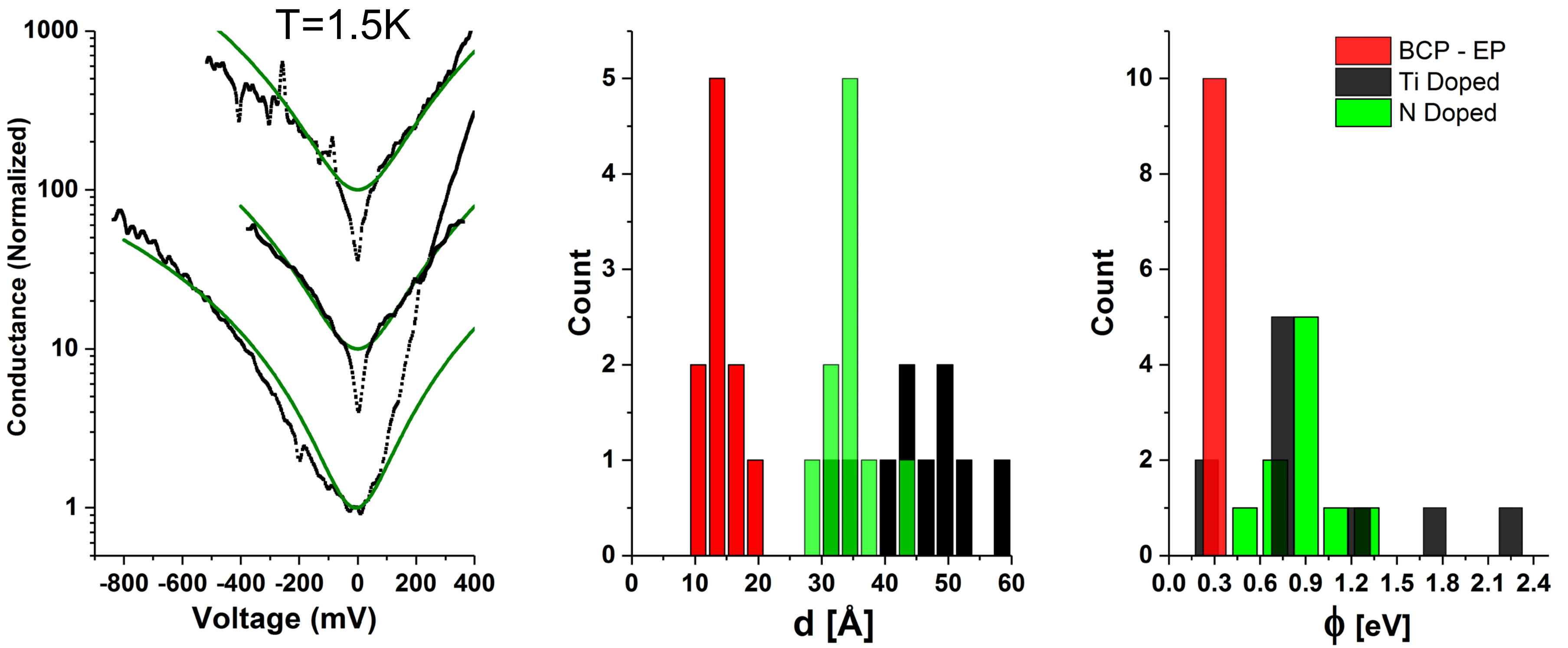
M. Martinello et al. APL109, 062601 (2016)

SUMMARY BULK NB

- Homogeneous superconducting Δ values (1.5-1.6 meV) close to bulk Nb and low Γ/Δ values (4-5%) correlate with the anti-Q slope effect.
  -> A. Gurevich non equilibrium theory.

- Homogeneous superconducting Δ values (1.5-1.6 meV) close to bulk Nb and larger Γ/Δ values (8-12%) measured on LTB Nb samples without HFQS correspond to RF performance with lower Q than the doped cavities, i.e. the absence of anti-Q slope, and an increased dissipation up to high accelerating fields.

- Inhomogeneous superconducting properties with values signicantly smaller than bulk Nb and large Γ/Δ values (8-15%) are measured in a hot spot sample responsible for the HFQS.



- Tunnel barrier height and thickness:

$$\frac{G(V)}{G(0)} = 1 - \left(\frac{A_0 \Delta\varphi}{16\bar{\varphi}^{3/2}}\right) eV + \left(\frac{9}{128}\frac{A_0^2}{\bar{\varphi}}\right)(eV)^2$$

d, thickness of the oxide
Φ, work function of the oxide
Φ_{TIP}, work function of the tip

W.F. Brinkman, R.C. Dynes et R. Rowell JAP, 41, 5 (1970)

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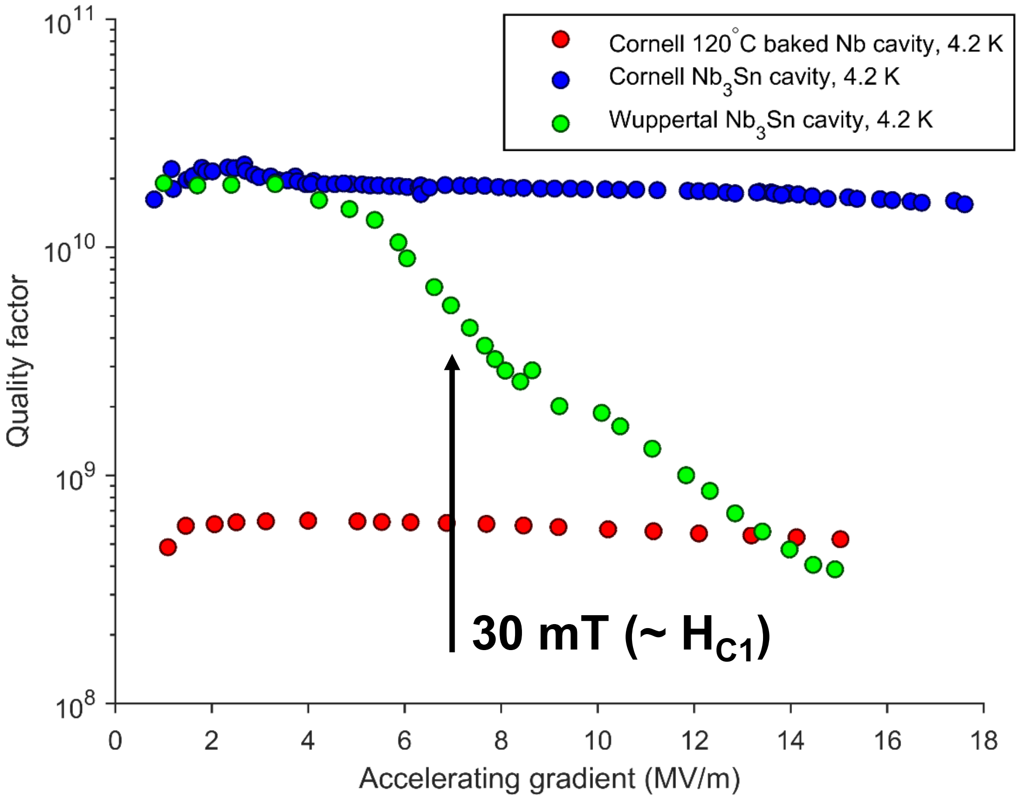
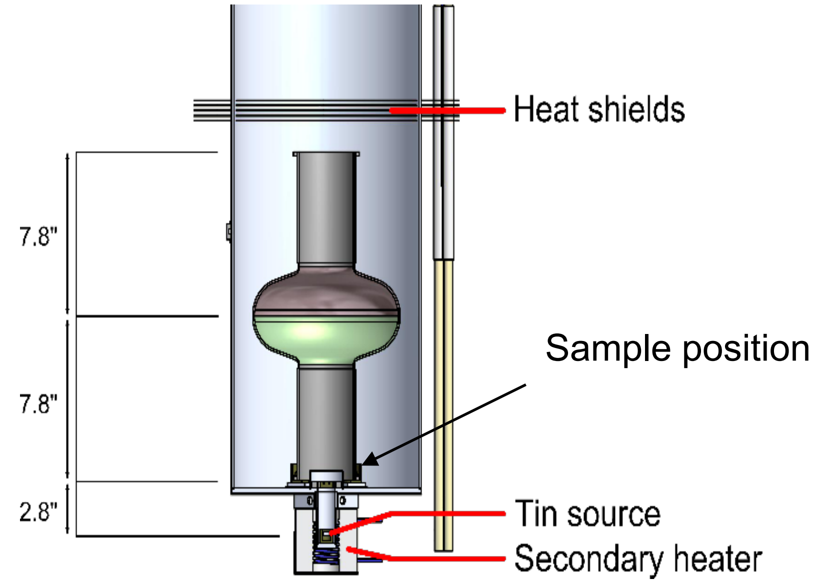
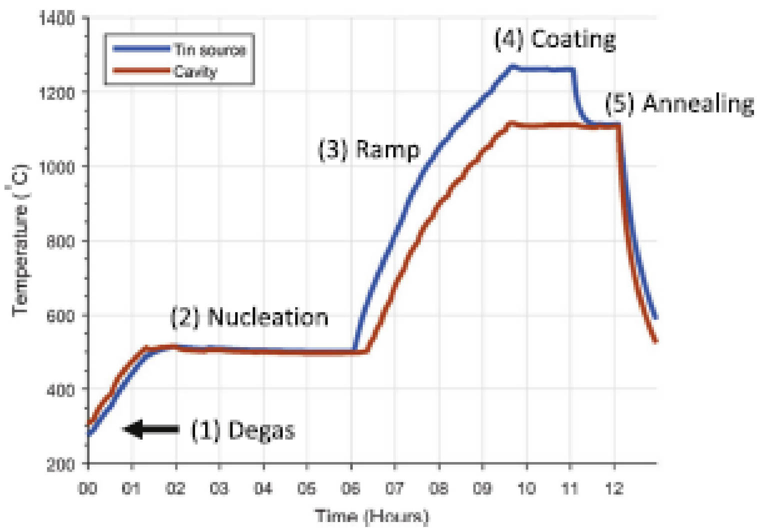
Nb_3Sn/Nb - Cornell



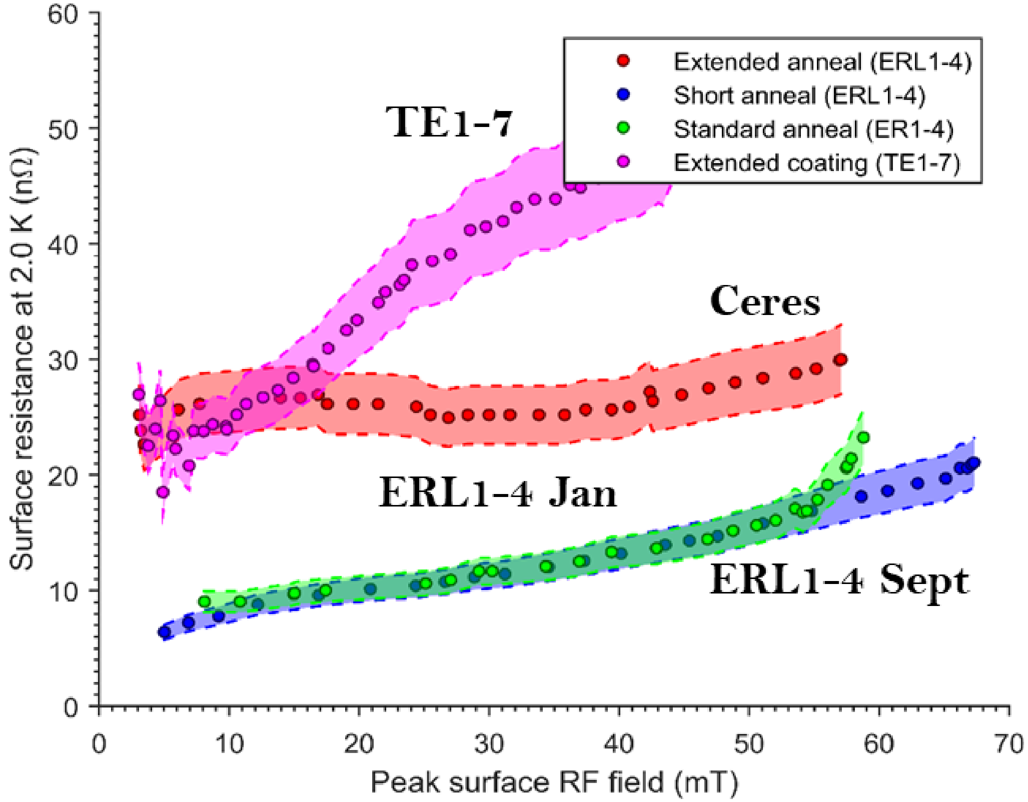




- Wupperthal method: diffusion of Sn in a Nb
- Nb_3Sn Q_0 at 4,2K ~ Nb Q_0 at 2K

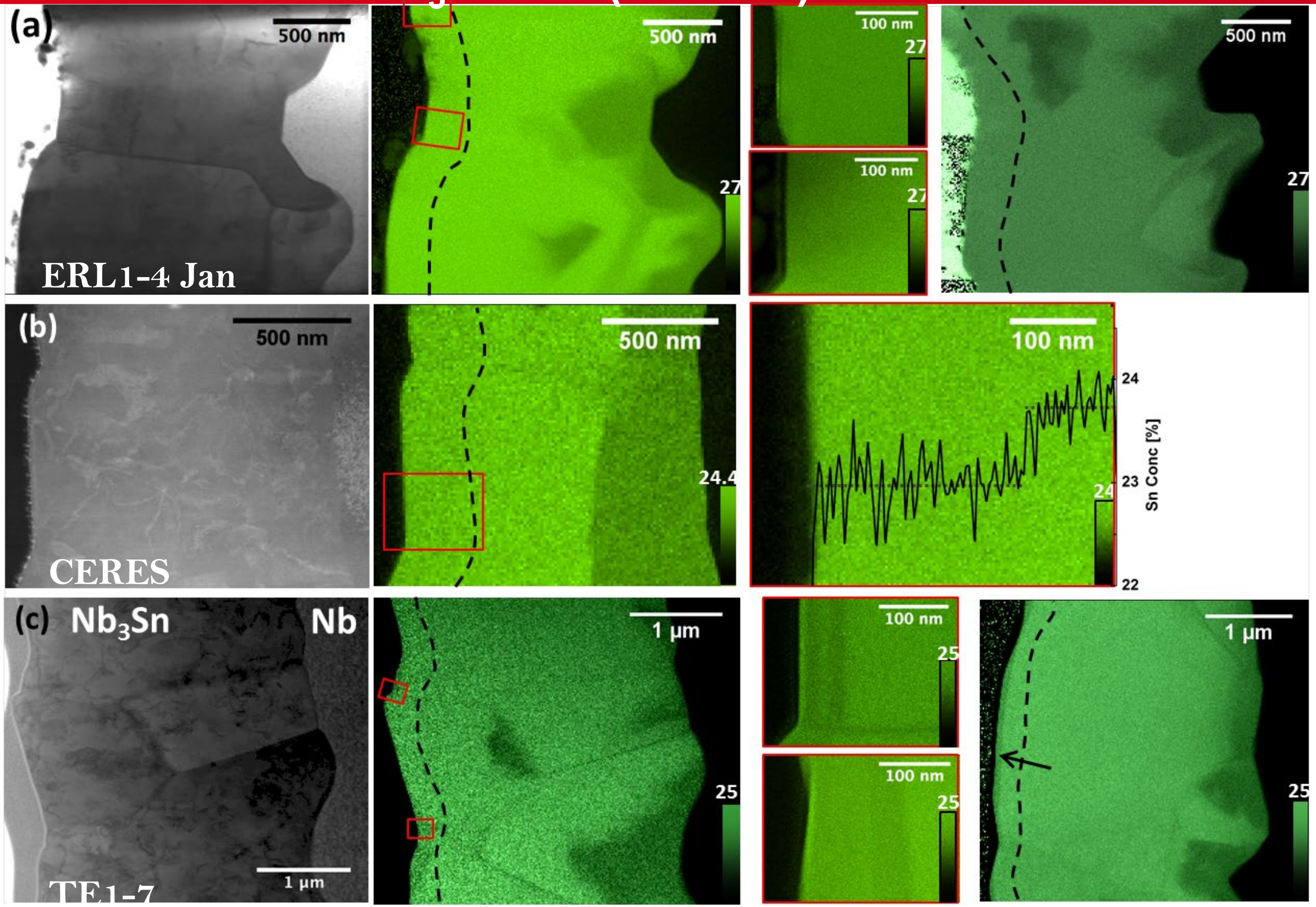
Have we reached the limits of Nb_3Sn ?

Nb_3Sn/Nb – varying deposition



Sample	Coating Temp (°C)	Coating Time (hr)	Annealing Temp (°C)	Annealing Time (hr)	Position	Nucleation agent ($SnCl_2$)	ΔT(°C)	Comments
ERL1-4 Sept	1200	3	1100	0.5	Low	YES	150	
ERL1-4 Jan	1200	3	1100	6.5	Low	YES	150	
Ceres	1200	3	1100	16	Low	YES	150	
TE1-7	1200	8	1100	6.5	Low	YES	150	

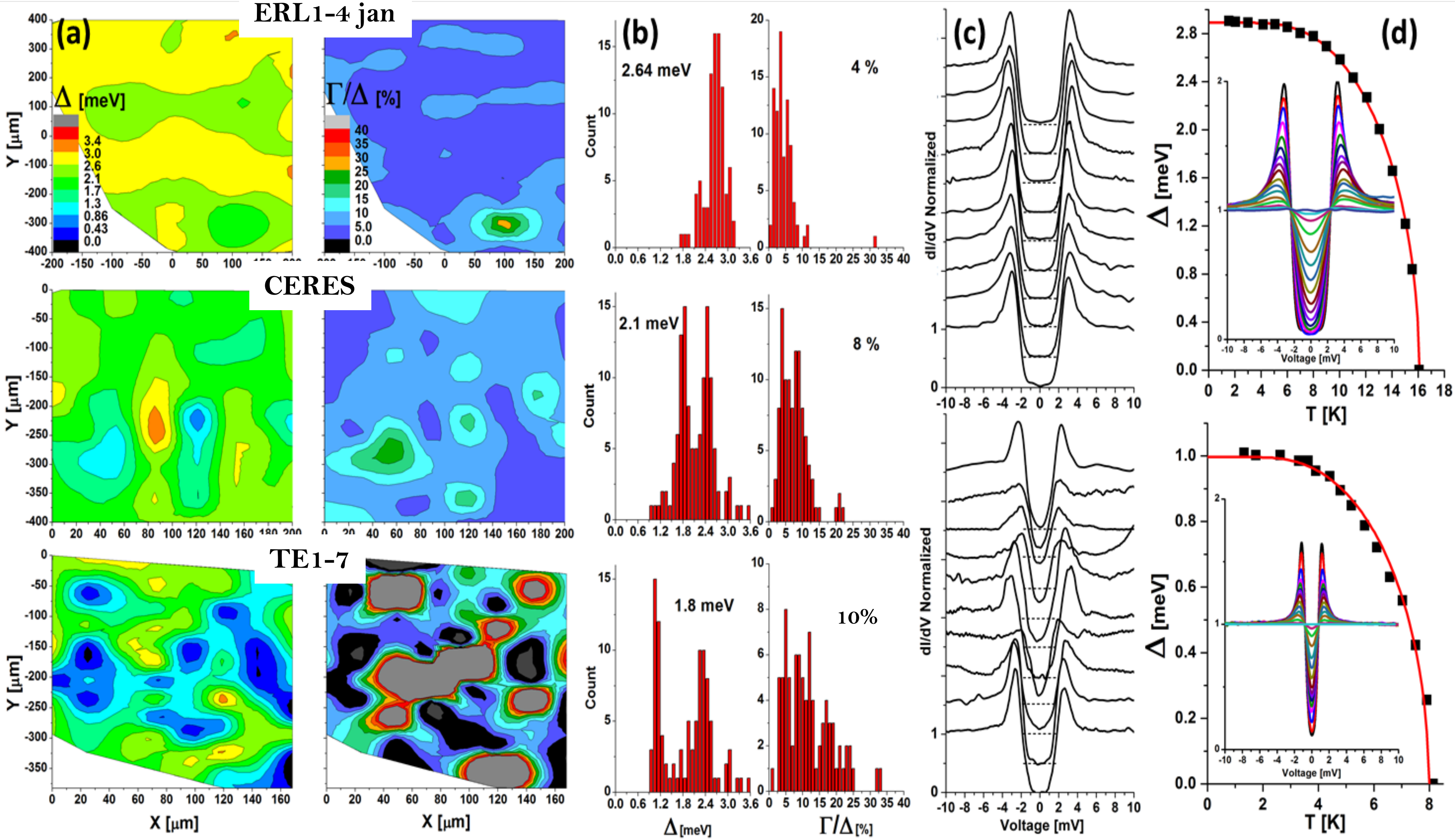
Nb_3Sn/Nb (Cornell) – TEM



- phase riche Nb ~ 17.5%
- Interface Nb-Nb_3Sn , grain boundaries
- Pockets near the surface

- Crystallite ~ 100 nm (XRD)
- 60% Nb_3Sn

Nb_3Sn/Nb (Cornell) - PCT



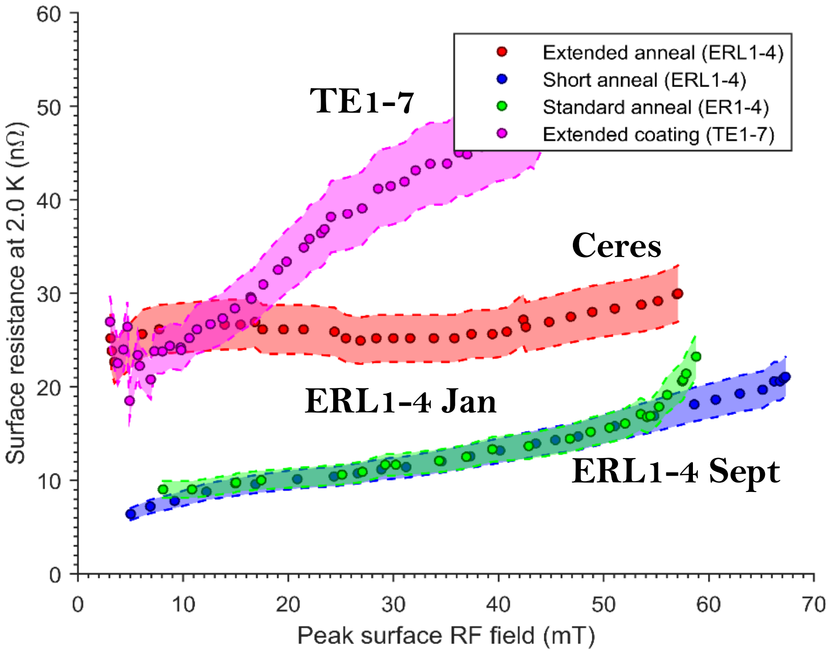
- Δ > Nb and Γ/ Δ is small

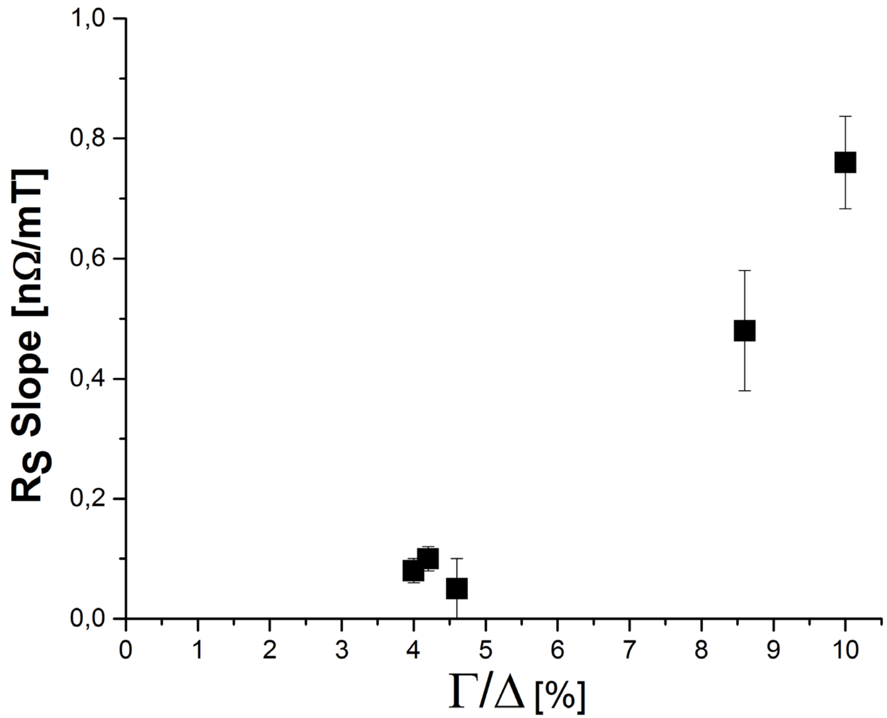
-> Quality factor @ 4K is ~ Nb @ 2K

- But pockets of Nb rich phases:

- Lower Tc and Δ

Nb_3Sn/Nb correlations RF test

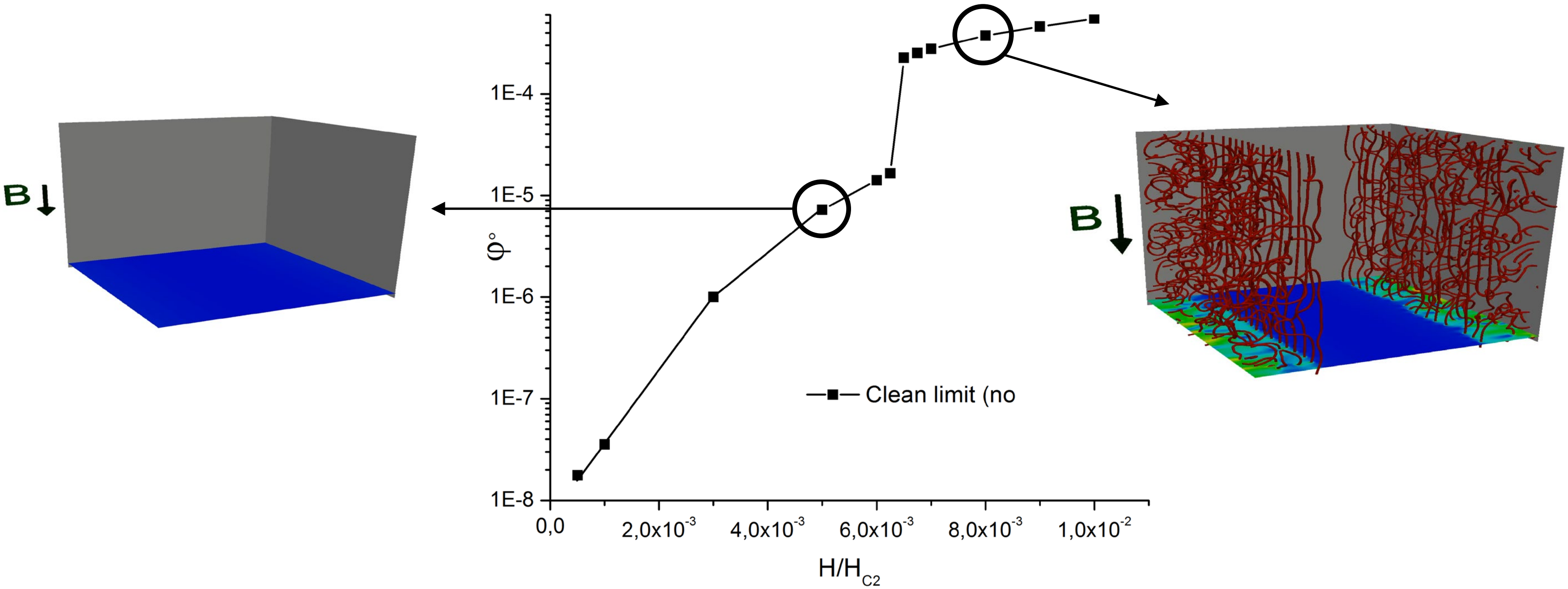




- Quench field (high field) increase linearly with the minimum of the PCT superconducting gap
- Surface impedance (low field) decreases linearly with the average PCT superconducting gap
- Q-slope increases with Γ/Δ ratio
- Optimized cooling procedure for ERL1-4 Sept: 69 mT -> 77 mT (18 MV/m)

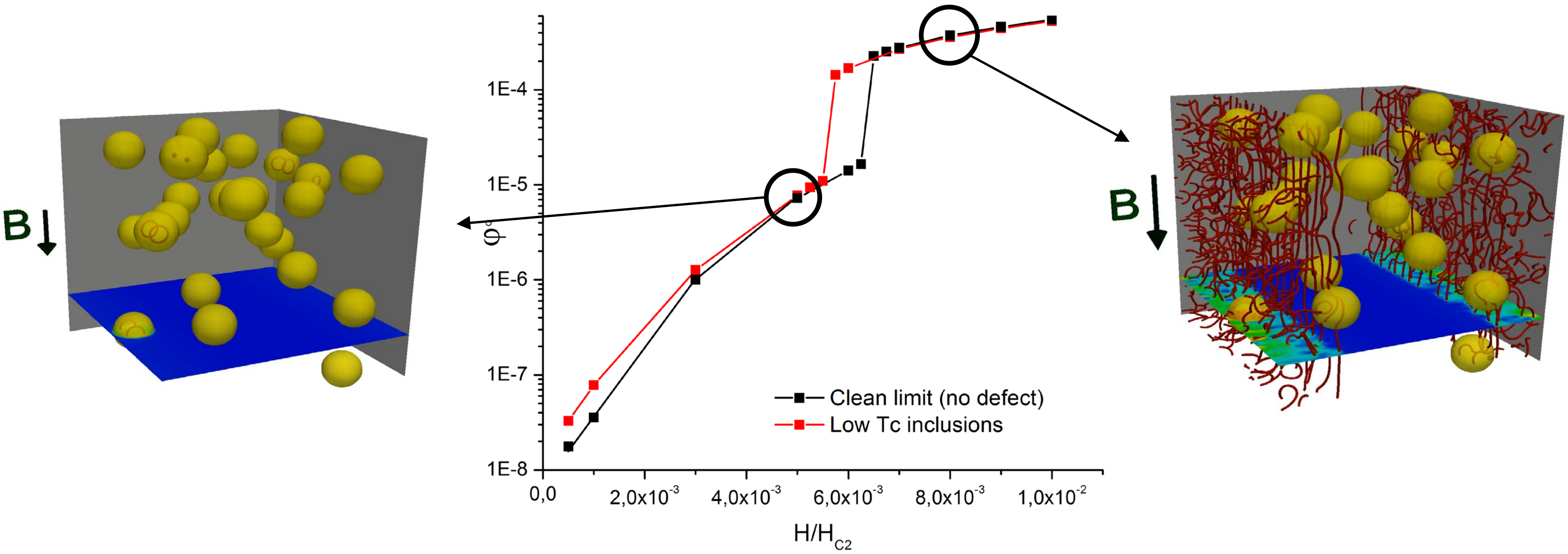
Nb_3Sn/Nb - simulation

Collaboration with A. Glatz (OSCon Project = Optimizing supercond. Transport properties Through large scale simulation).



- Nb3Sn film under AC field (1,3 Ghz) parallel to the surface, volume $(256\ \xi)^3 \sim (1{,}3\ \mu m)^3$
- Approximations: Time Dependent Ginzburg-Landau (TDGL) -> $\lambda = \infty$ and $T \sim T_C$
- Dissipation = time variation of the order parameter -> Quench = pénétration de vortex

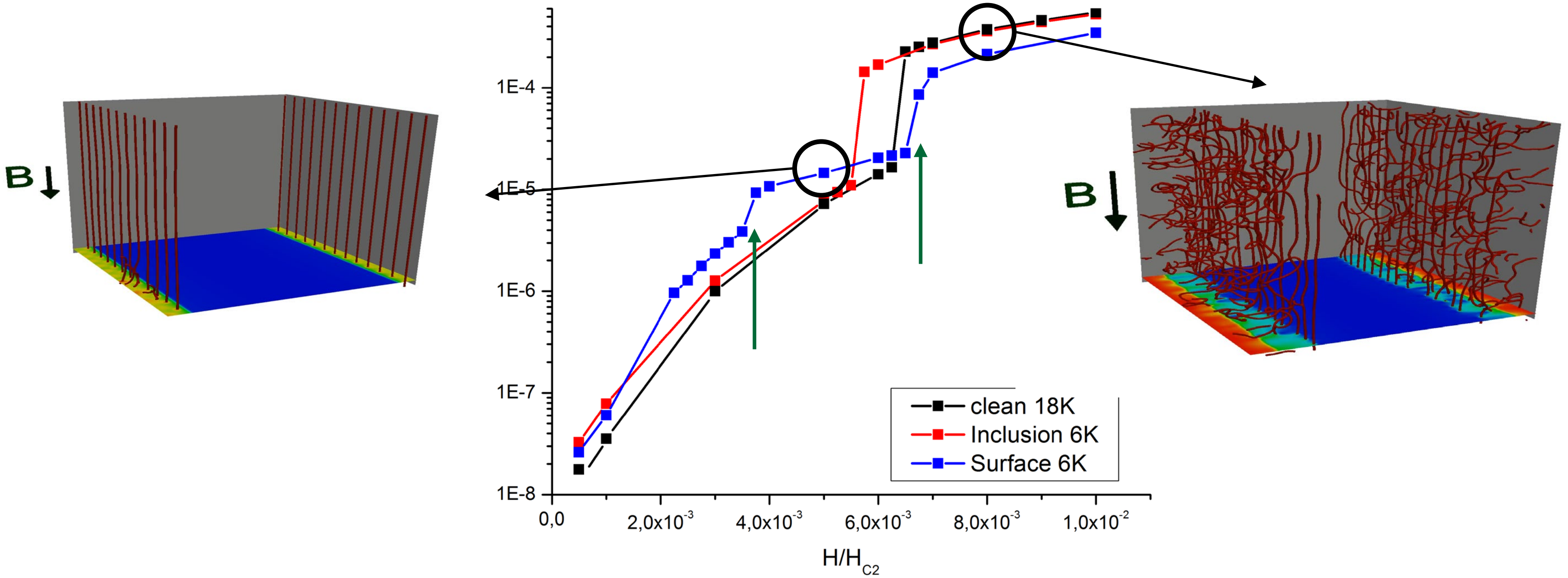
Variation of superconducting properties: Case of Low Tc inclusions 6K



- Vortex penetration at lower external field amplitude

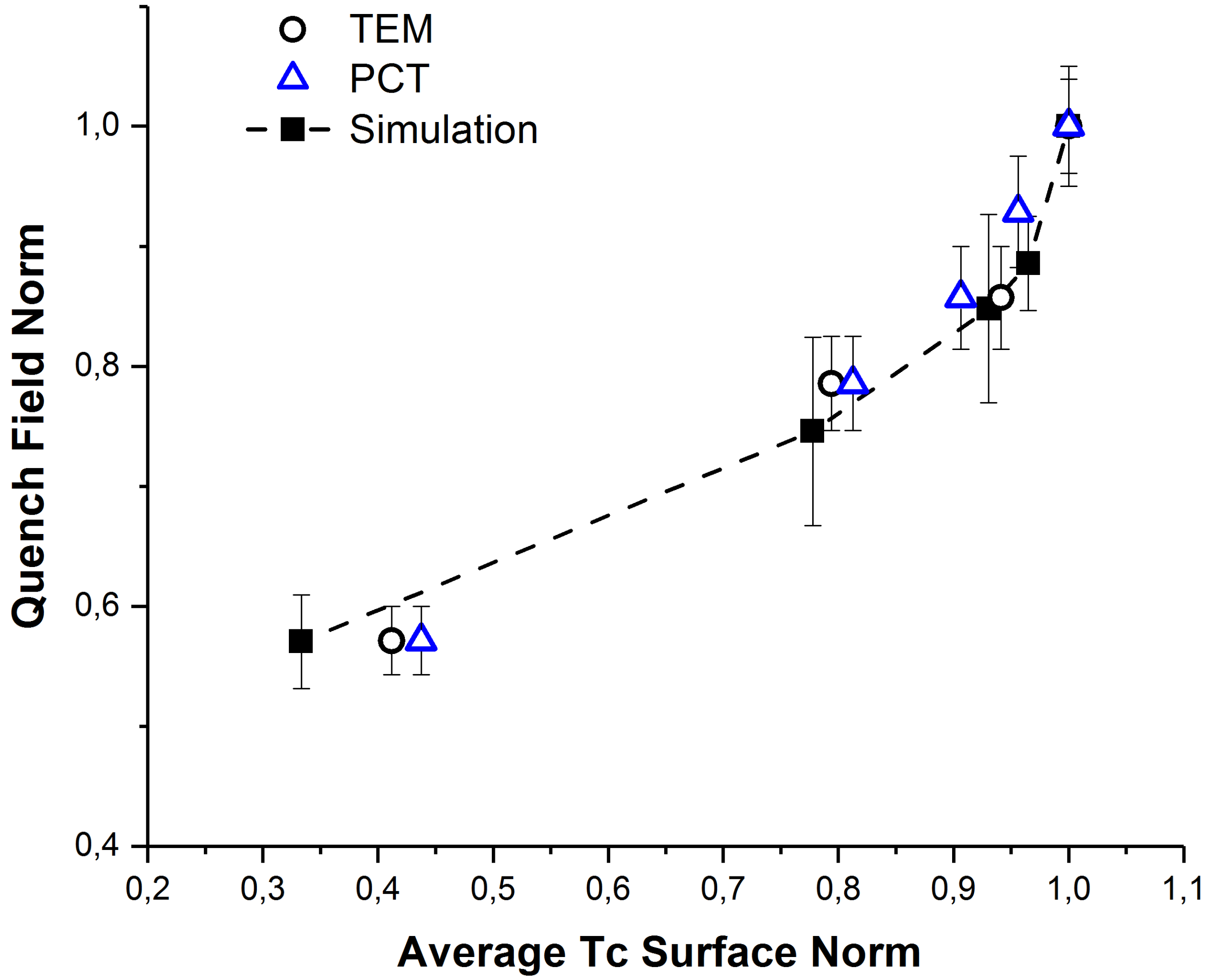
Nb_3Sn/Nb - simulation

Variation of superconducting properties: Surface layer Low Tc 6K



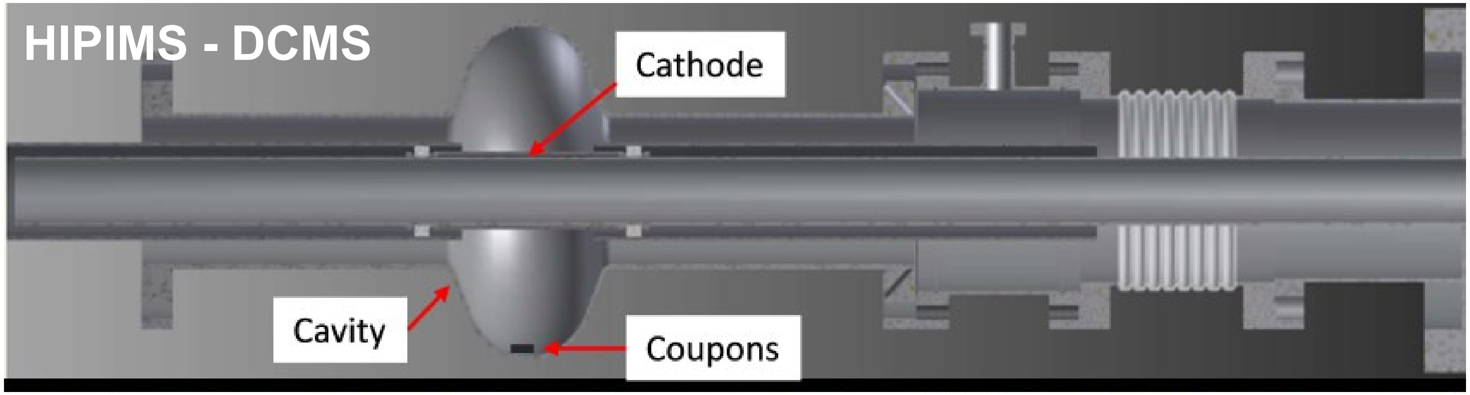
- Two Vortex penetration fields: Low Tc phase and High Tc phase.

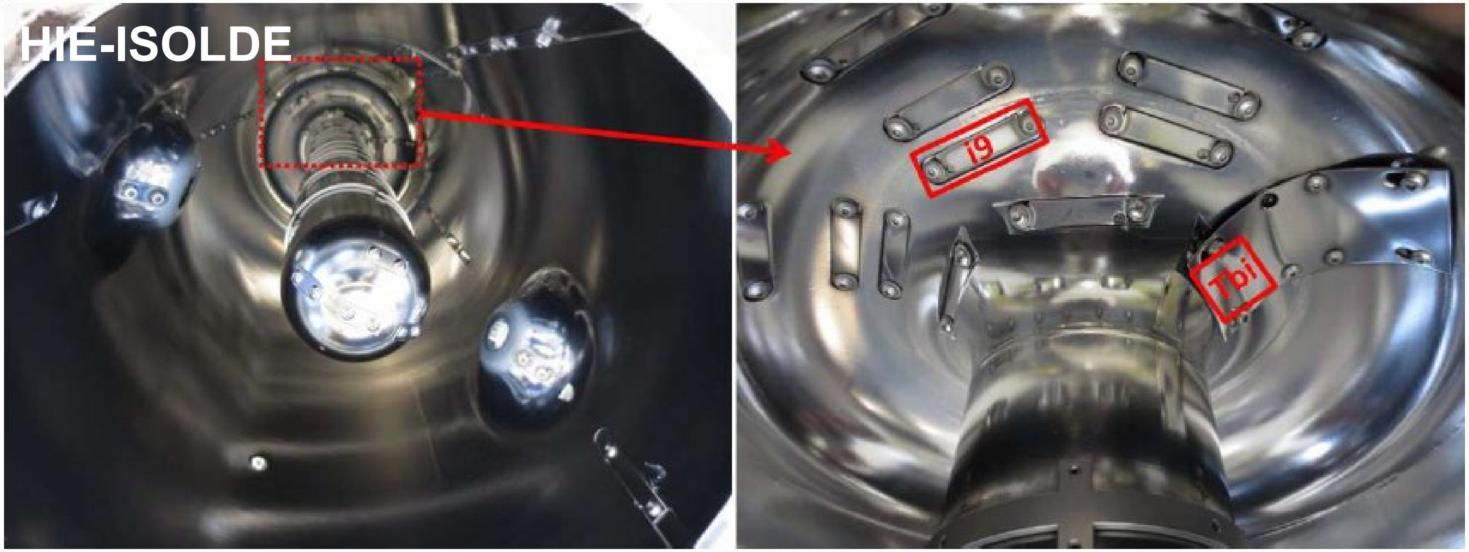
Nb_3Sn/Nb - Limit

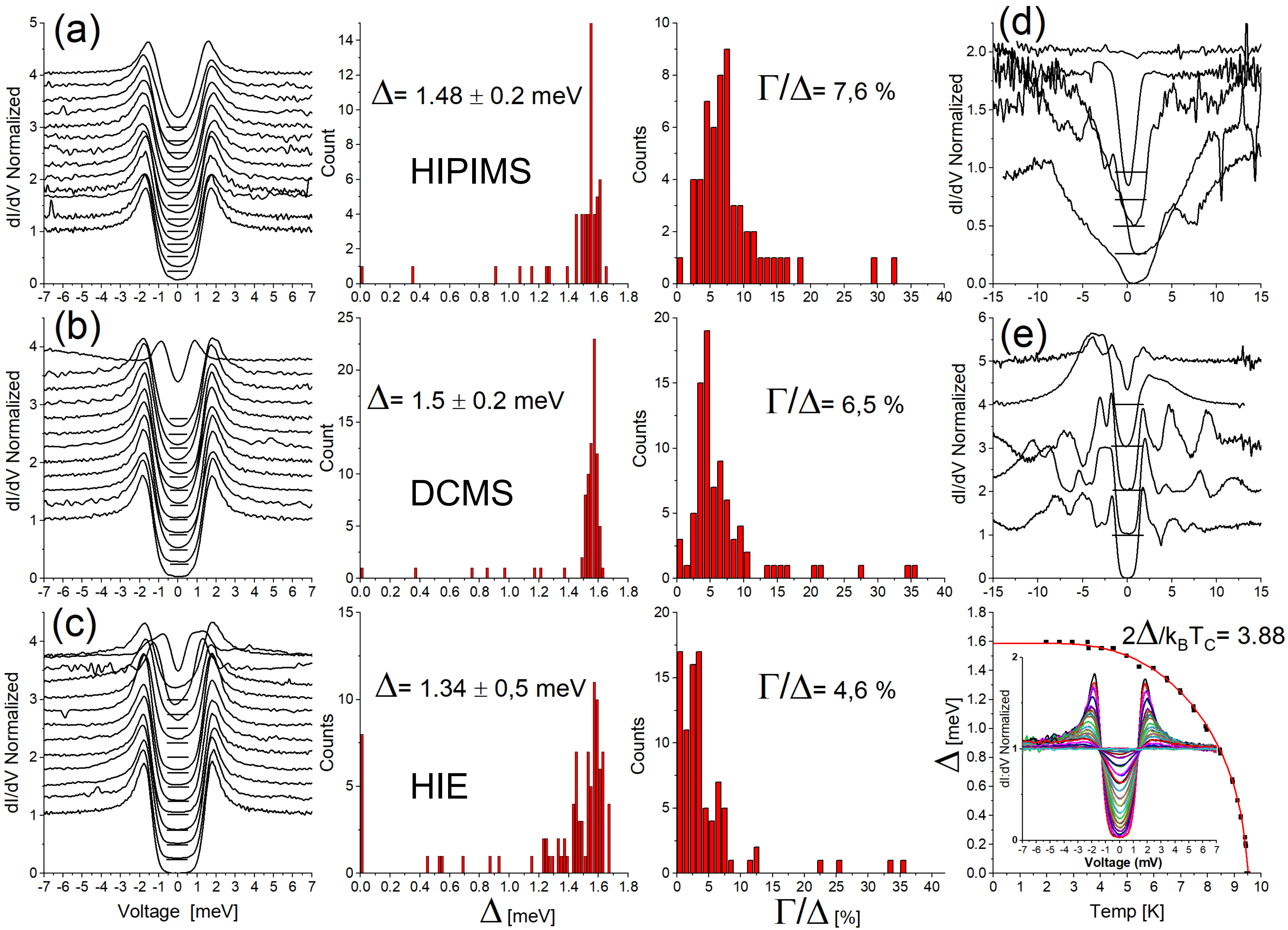


- Good Agreement between simulations and experiments
- Set a limit to the maximum accelerating field E_{MAX} to ~ 17-18 MV/m
- Nb_3Sn good for Q but what about E_{MAX} ?

Different deposition techniques:






(a)
(b)
(c)
(d)
(e)
dI/dV Normalized
Voltage [meV]
Δ= 1.48 ± 0.2 meV
HIPIMS
Δ= 1.5 ± 0.2 meV
DCMS
Δ= 1.34 ± 0,5 meV
HIE
Count
Counts
Δ [meV]
Γ/Δ= 7,6 %
Γ/Δ= 6,5 %
Γ/Δ= 4,6 %
Γ/Δ [%]
$2\Delta/k_BT_C$= 3.88
Δ [meV]
Temp [K]
dI:dV Normalized
Voltage (mV)

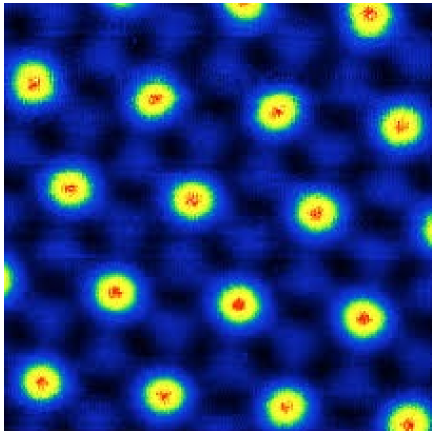
Future Tunneling spectroscopy

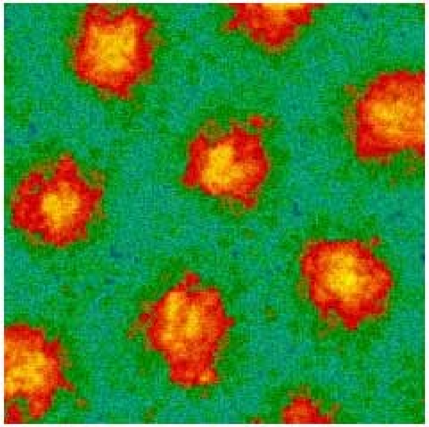
- Ideal technic to probe surface superconducting properties
- Tested on multiple SRF samples, bulk or films
- Limits: DC measurements -> How about field dependence? (Magnétometry, RF tests!)
- chemical, structural characterization?

Future directions:

- Mapping at smaller scale in continuous piezo mode ~ 800 nm, resolution ~ 0,1 nm

-> Gap and T_C near defects?
-> vortex lattice





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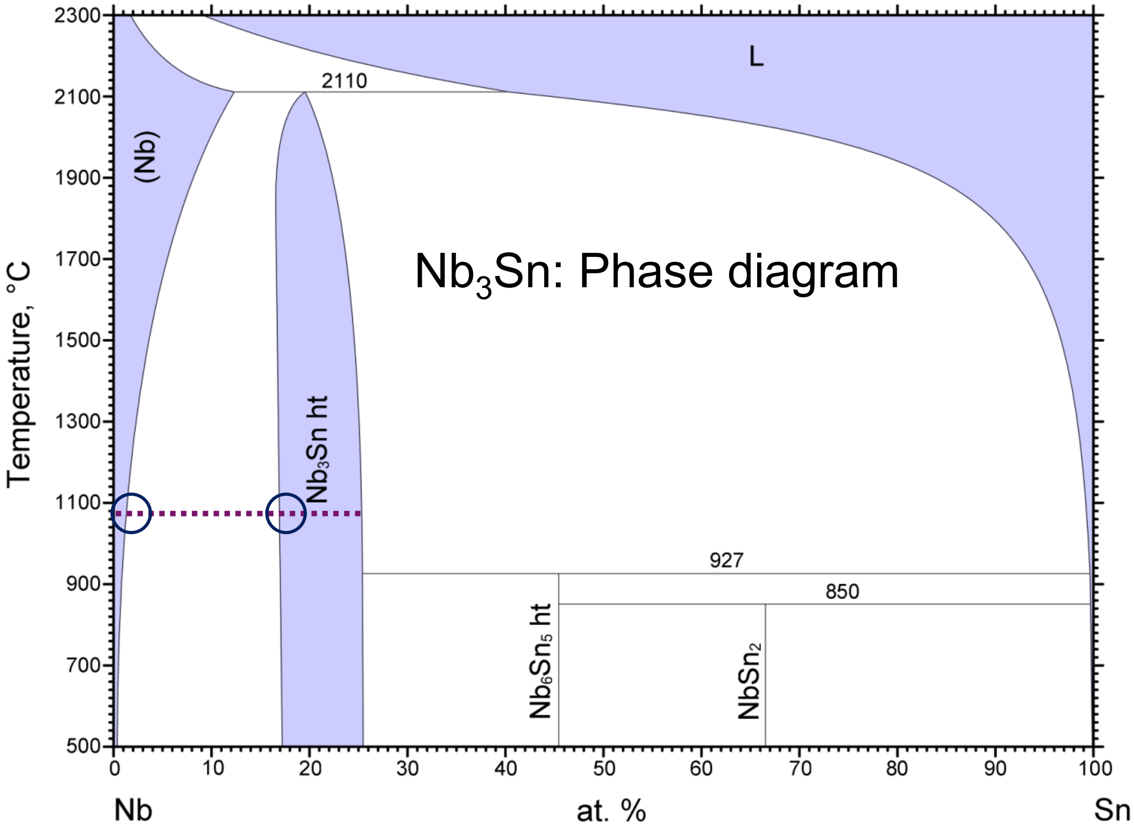
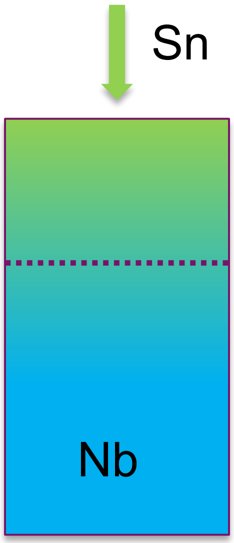
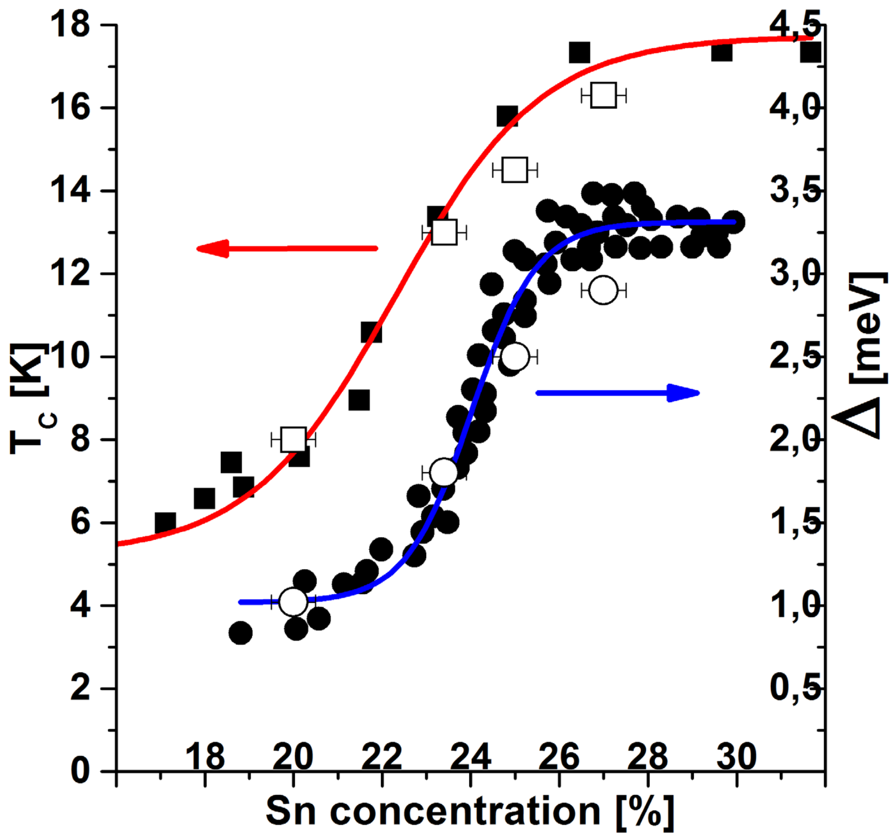
Nb_3Sn/Nb (Cornell) - Mechanism





- Processus de diffusion : 1000°C -> Segregation de phase 17% Sn and Pure Nb
- Accumulation de region à 17%
- Suggère plus haute concentration Sn



18
16
14
12
10
8
6
4
2
0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
18
20
22
24
26
28
30
T c [K]
Δ [meV]
Sn concentration [%]