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Updates of the SRF work at ANL: from fundamental dissipation mechanism to Atomic layer deposition

Th. Proslier, A. Glatz, W. Walkosz, P. Zapol and M. Pellin (ANL)

M. Kharitonov (Rutgers University)

J.F. Zasadzinski (IIT)

G. Ciovati, P. Kneisel (JLAB)

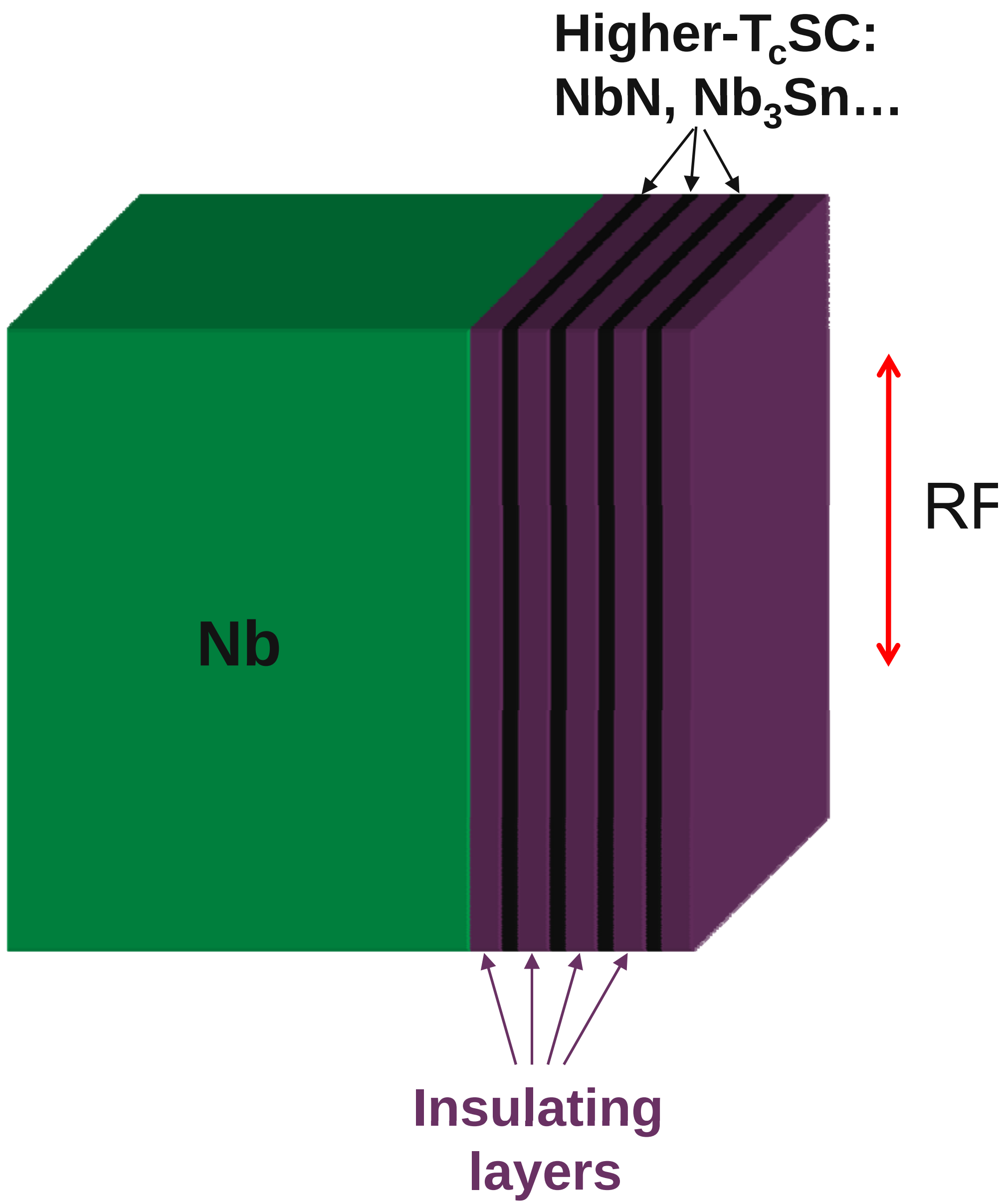
A. Romanenko (FNAL)

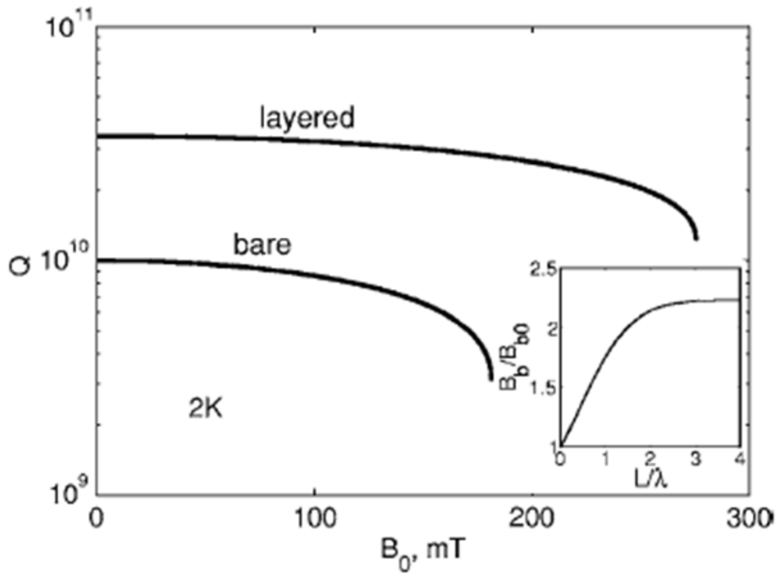
N. Groll, I. Chiorescu (NHMFL)

Funded by ARRA-DOE, Office of science, High Energy Physics.

Jefferson lab-seminar-2011

Purpose: An ideal world





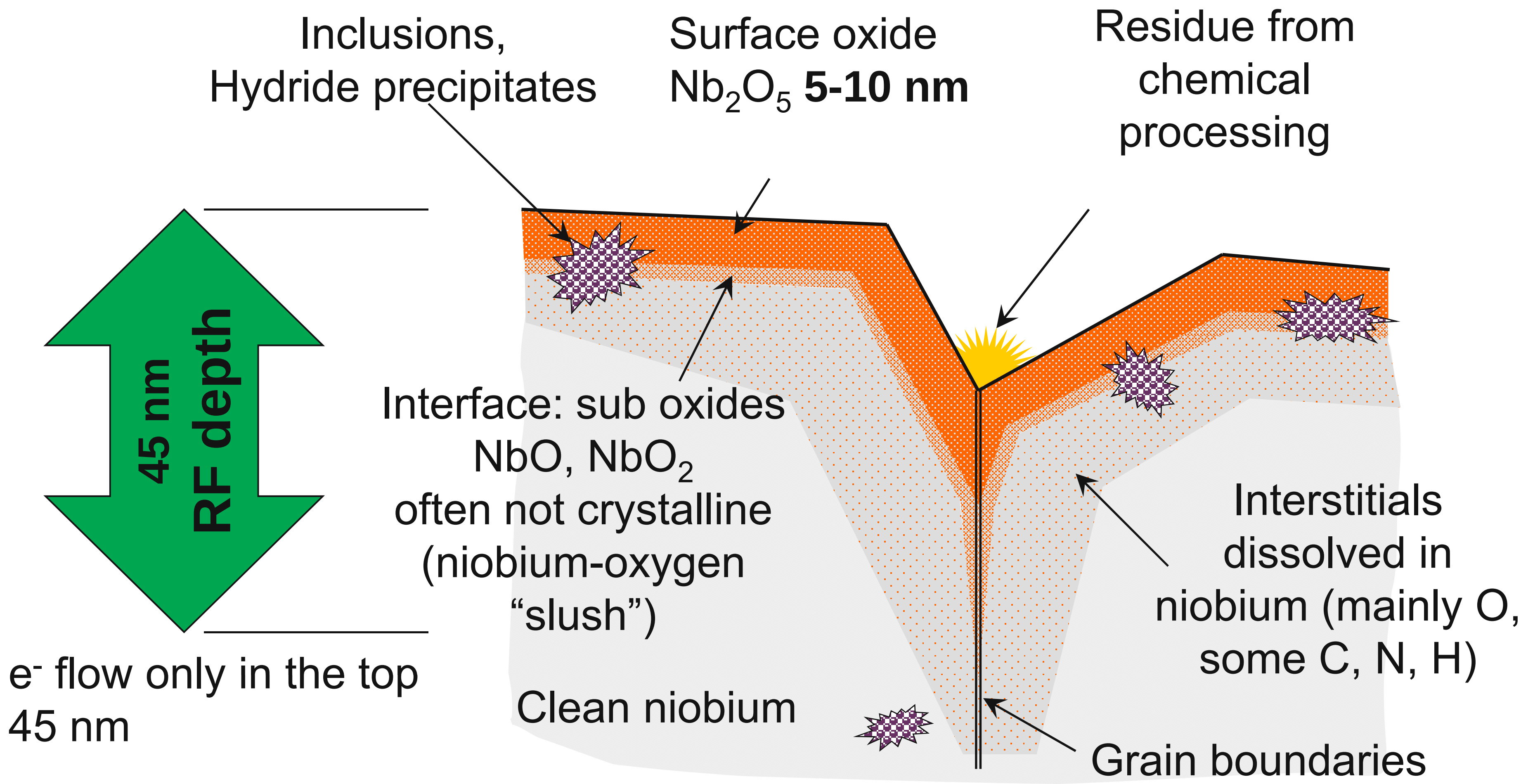
Part 1/ dissipation mechanisms

- **Experimental evidence: PCT, SQUID, EPR.**
- **Theory: surface impedance & residual resistance**
- **Conclusion**

Part 2/ Atomic layer deposition for SRF

- **Dielectric coatings**
- **Superconducting hetero-structures**

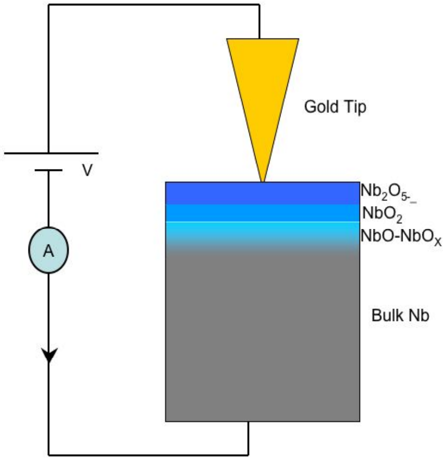
Niobium surfaces are complex, important, and currently poorly controlled at the nm level

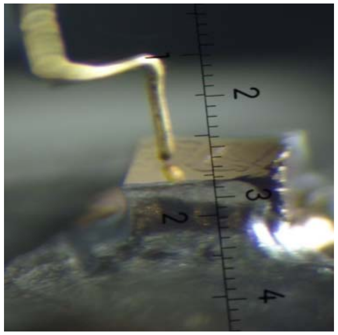


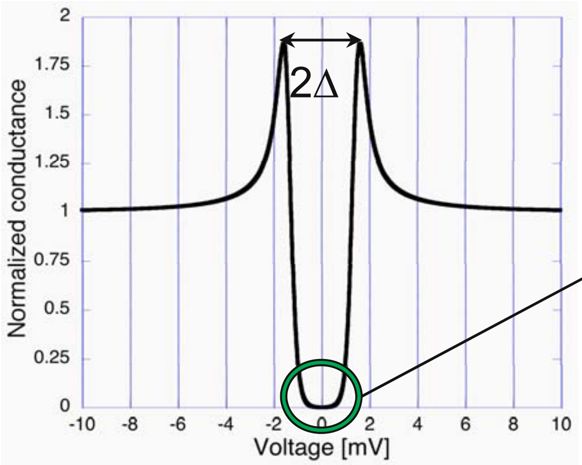
→ **Probe the surface superconductivity**

Experimental evidences of Magnetism: Point Contact

6 Tesla magnet 1.6-300 K





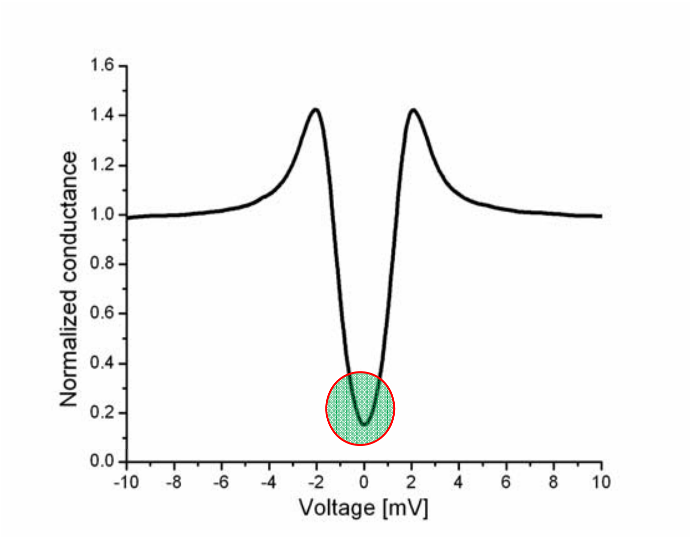


Ideal BCS superconductor

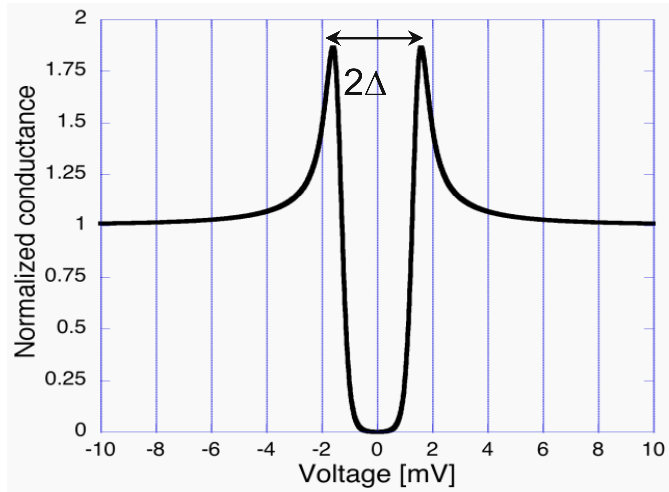
- Measure of the surface superconducting gap Δ
- The ZBC value -> Number of normal electron

Normal electrons in gap => dissipation and lower Q

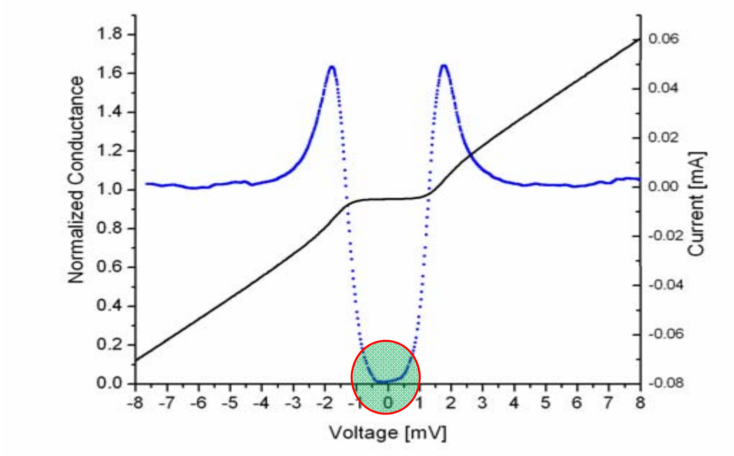
PCT Tunneling Data:
Correlation of the local DOS with the low field Q



Chem. etched Niobium



Ideal BCS, T~2 K

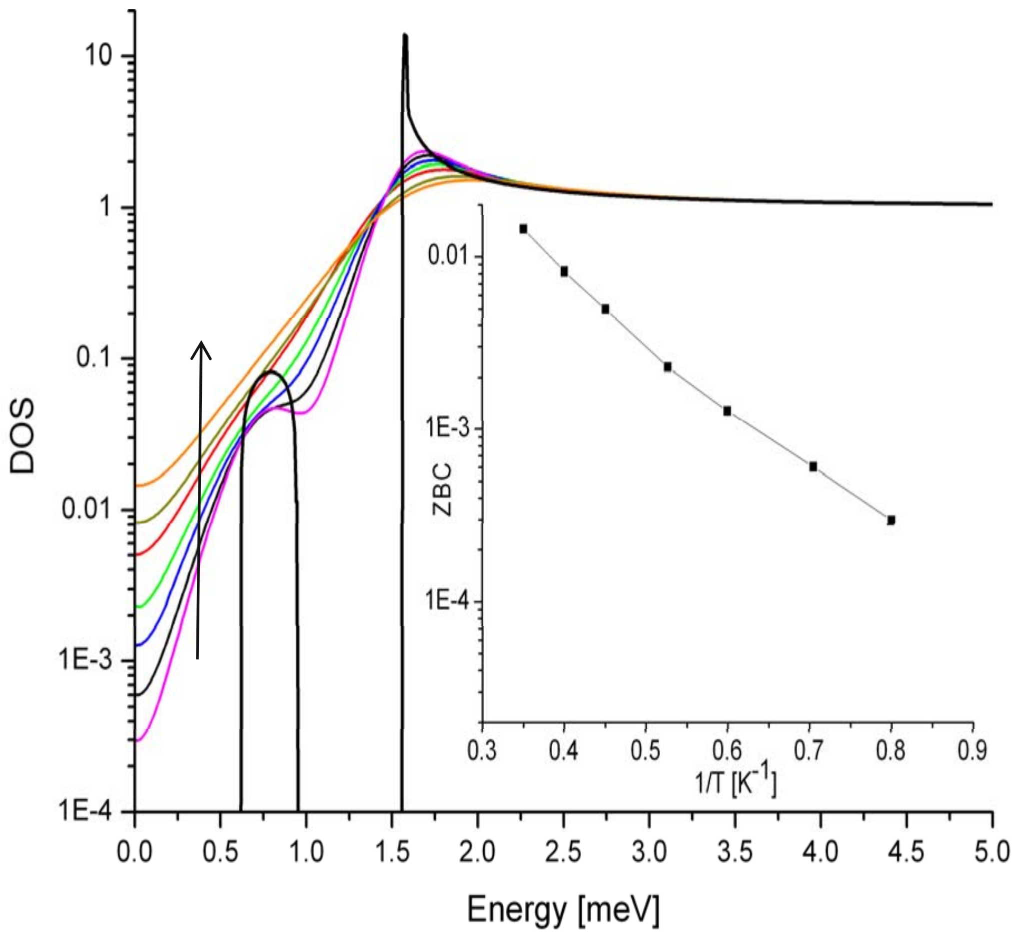


Oxide free Sputt. films

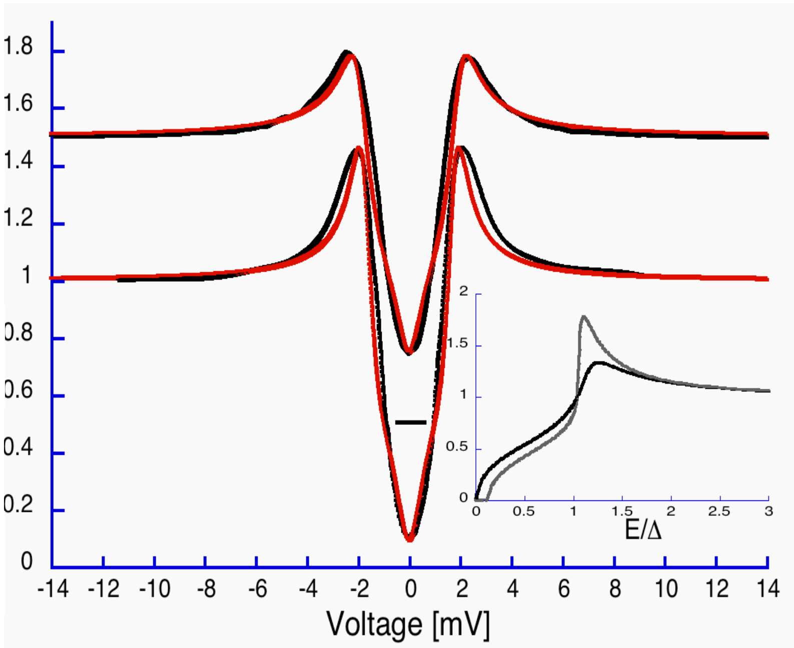
- Chemically etched ZBC ~ 0.3-0.2, Group II
- UHV annealed ZBC ~ 0.05-0.1, Group I
- Superconducting DOS depends:
  on oxide
  on surface treatement

T.Proslier, J.Zasadzinski, L.Cooley, M.Pellin et al. APL 92, 212505 (2008)

Experimental evidences of Magnetism: Point Contact



Fit using Shiba theory



Unbaked: Δ=1.55 meV, α=0.12, η=0.6
Baked: Δ=1.53 meV, α=0.25, η=0.6

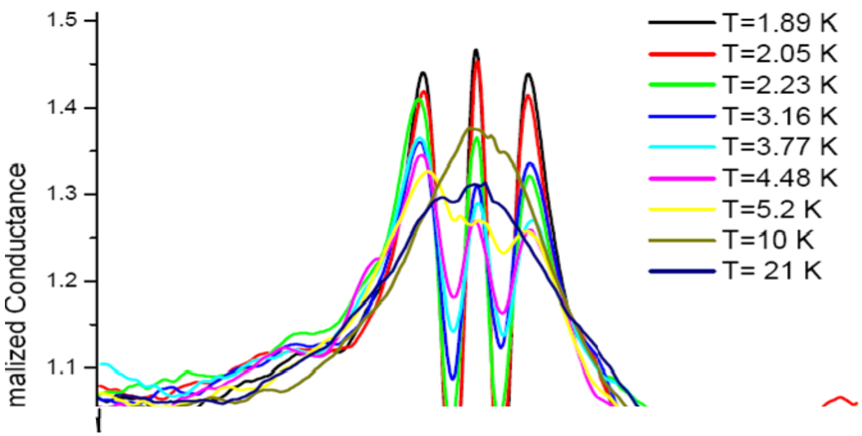
Conc= 0.1%

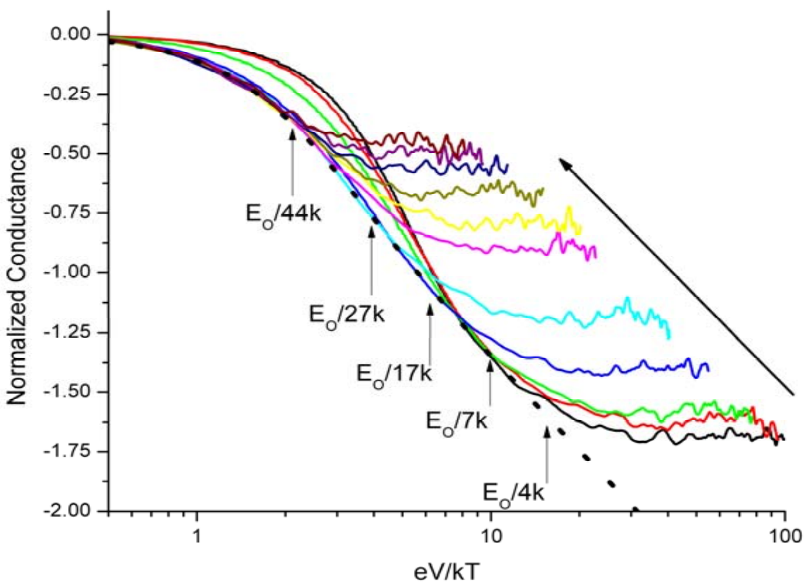
α is the pair-breaking
η is the delocalized band state

Th. Proslier, j. zasadzinski et al. APL 92, 212505 (2008)

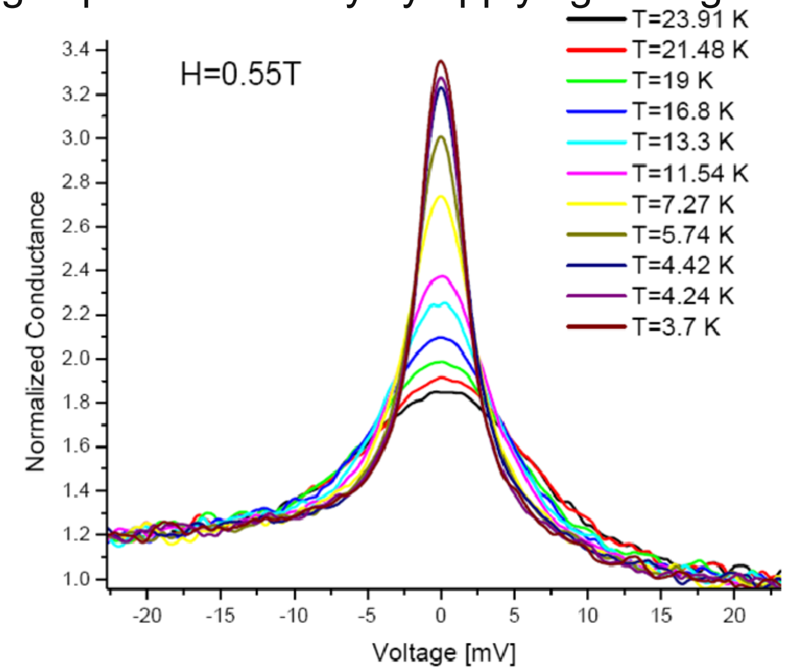
Hot and cold spots in Nb SRF cavity, Origin

Temp. dep: peak at 0 mV bias increases





Killing superconductivity by applying a mag. Field



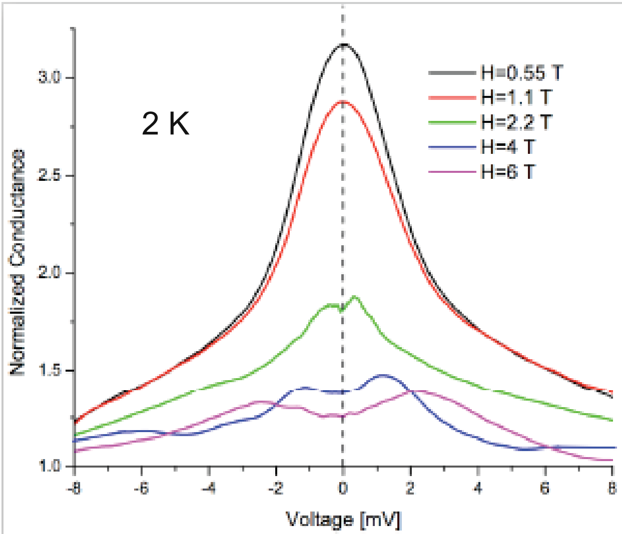
fits with Appelbaum theory

Magnetic impurities in the oxides
J>0 -> antiferromagnetic coupling

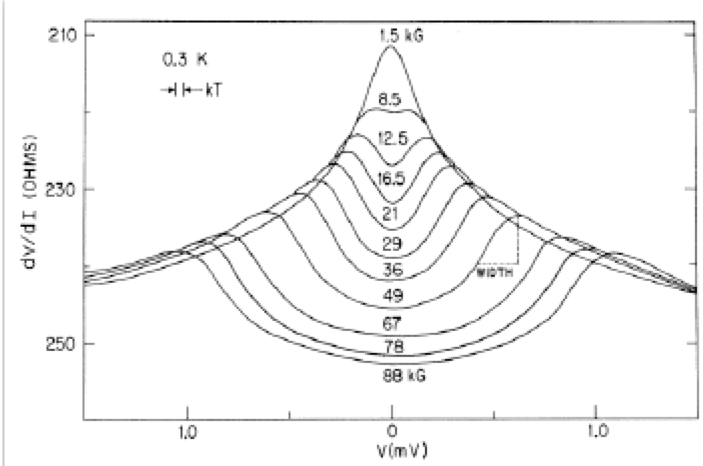
Th. Proslier, J. zasadzinski et al.PRB (2011)

Zero Bias Conductance (ZBC) peak: Spin Flip Tunneling

Nb-Nb_2O_5-Au (hot spots)

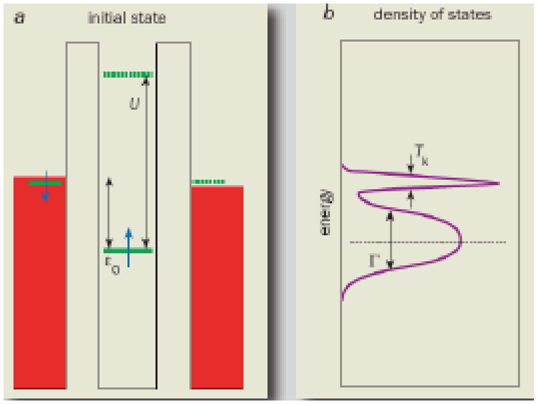


Ta-Ta_2O_5-Ta

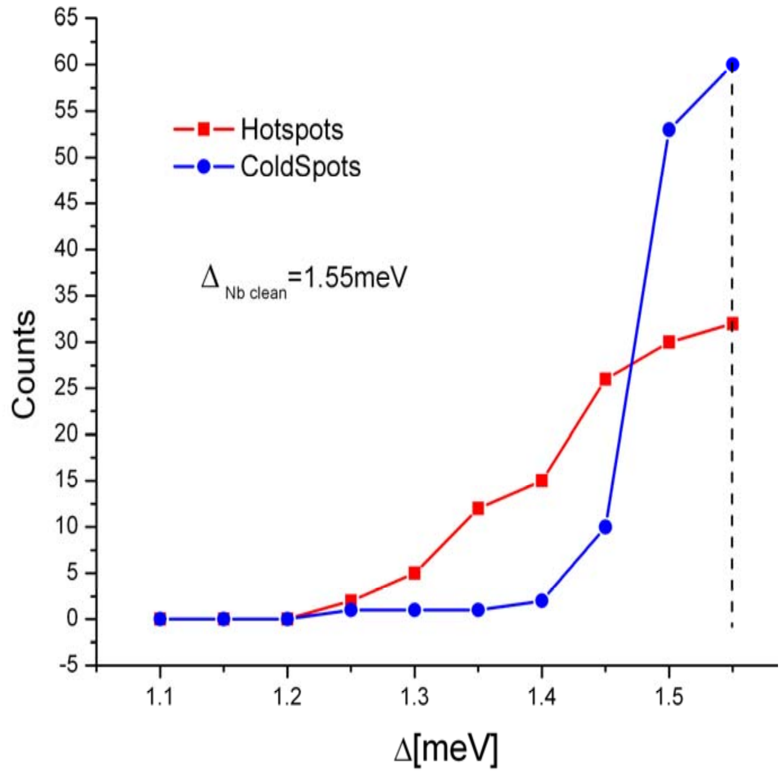


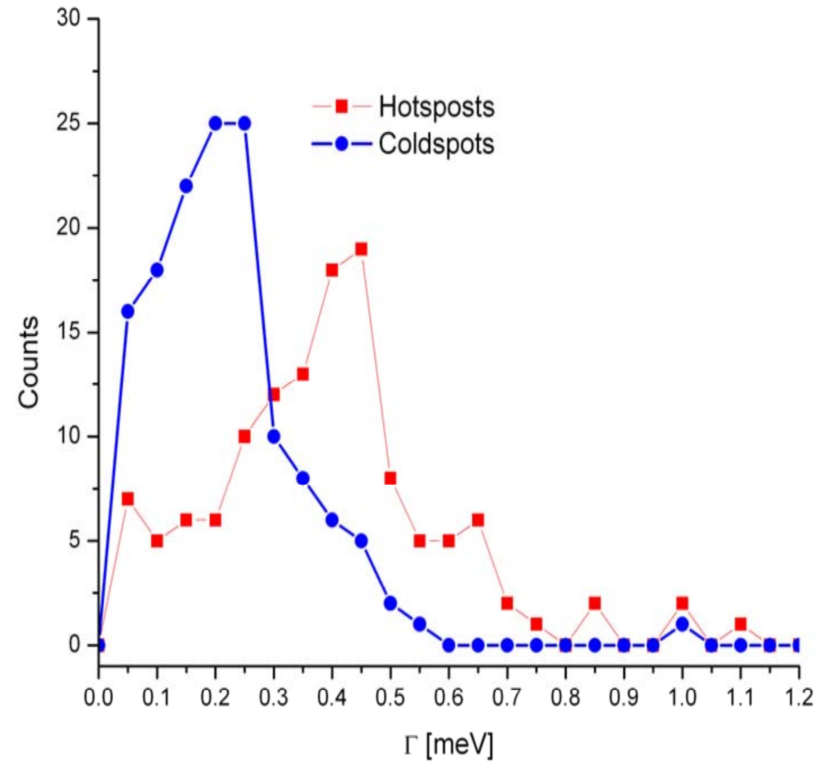
Kondo effect

Definite proof for localized paramagnetic moments
in the Niobium oxide



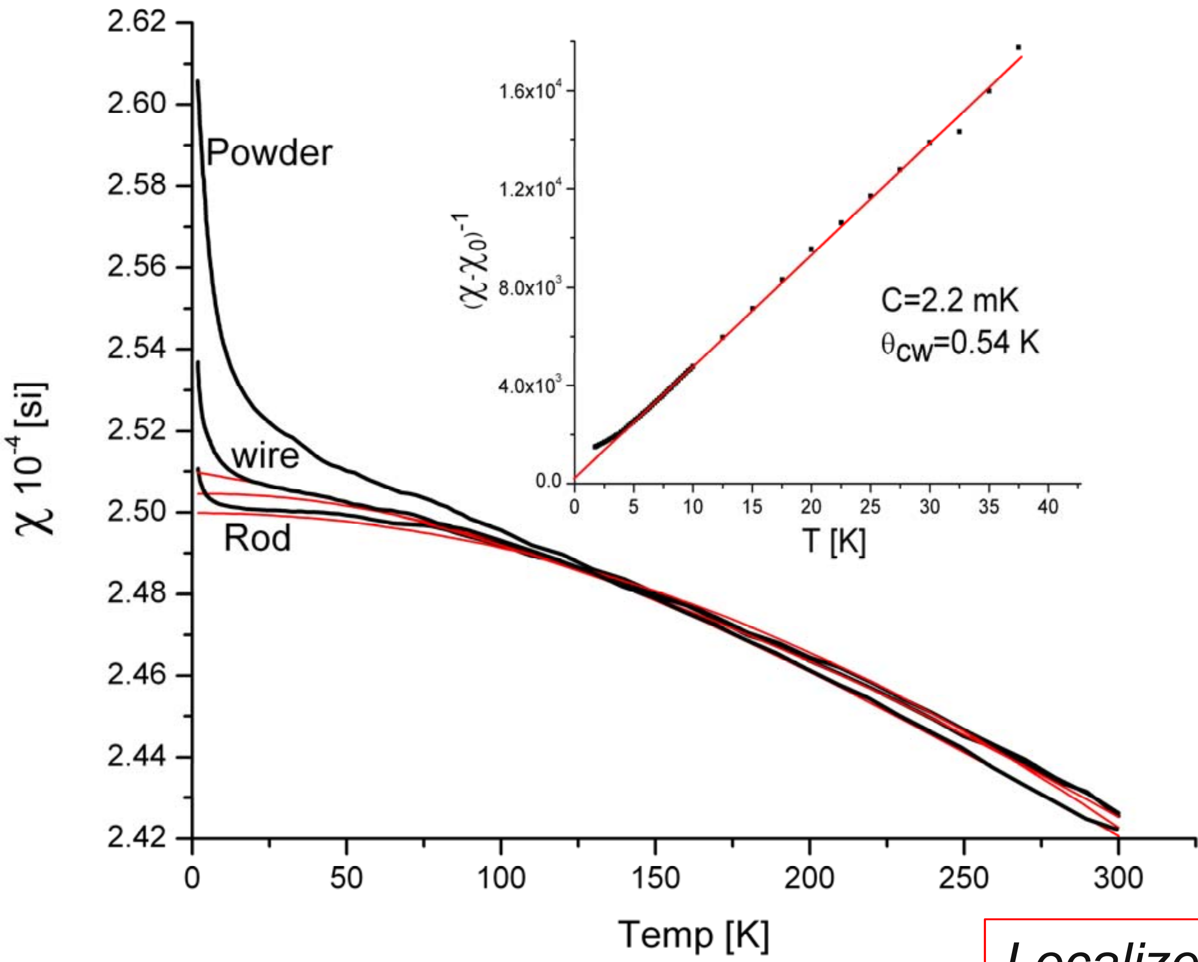
Hot and cold spots in SRF cavity, Origin





Enhanced dissipation -> lower gap + higher conc. mag. impurities

Experimental evidences of Magnetism: Superconducting Quantum Interference Device (SQUID)



$$\frac{M}{(B \times V)} = \chi$$

$$V = S \times d$$

$$\chi - \chi_0 = \frac{C}{T + \theta_{cw}}$$

$$(\chi - \chi_0)^{-1} = \frac{T}{C} + \frac{\theta_{cw}}{C}$$

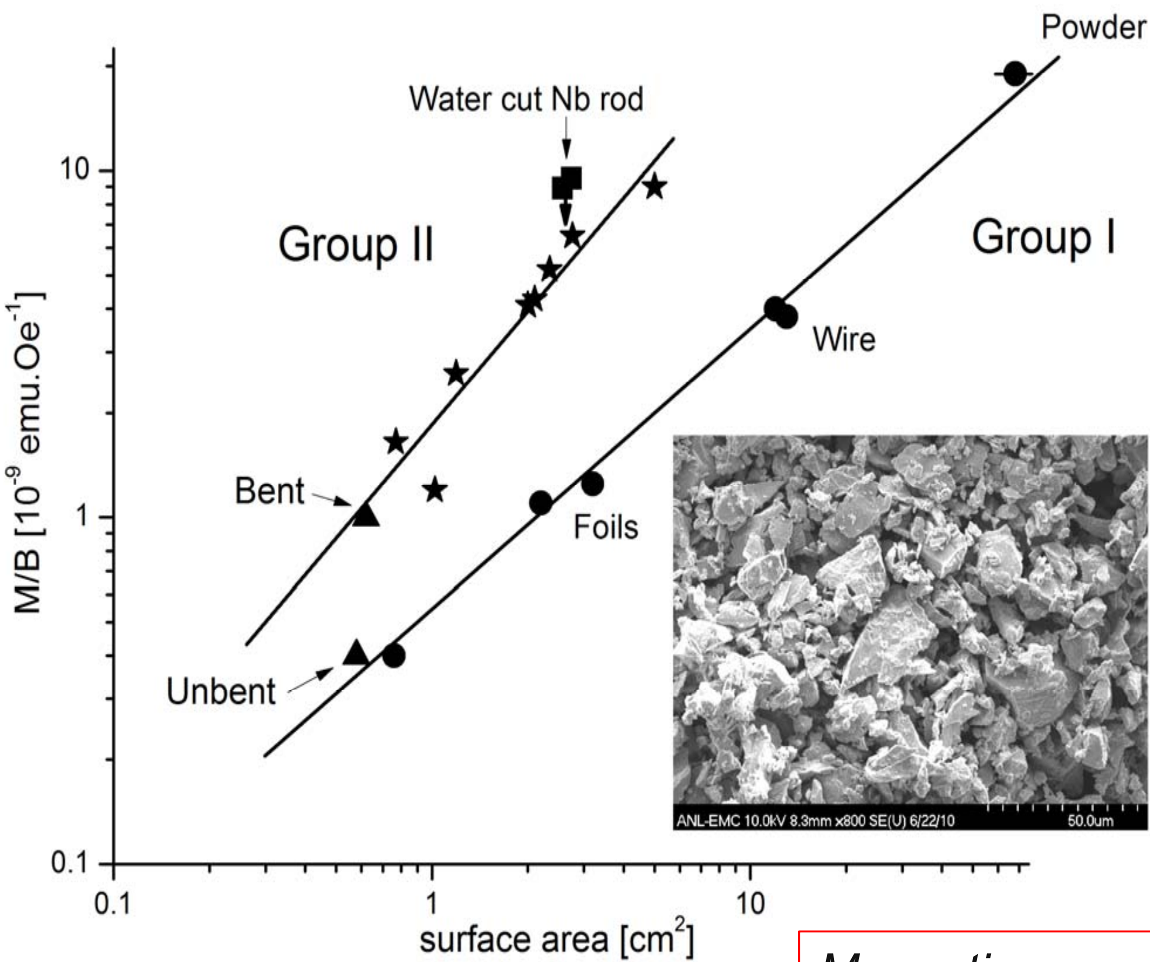
$$V \rightarrow V' > V$$

$$C \rightarrow C' < C$$

$$\theta_{cw} \rightarrow \theta_{cw}$$

Localized paramagnetic moments
With antiferromagnetic correlation

Experimental evidences of Magnetism: SQUID



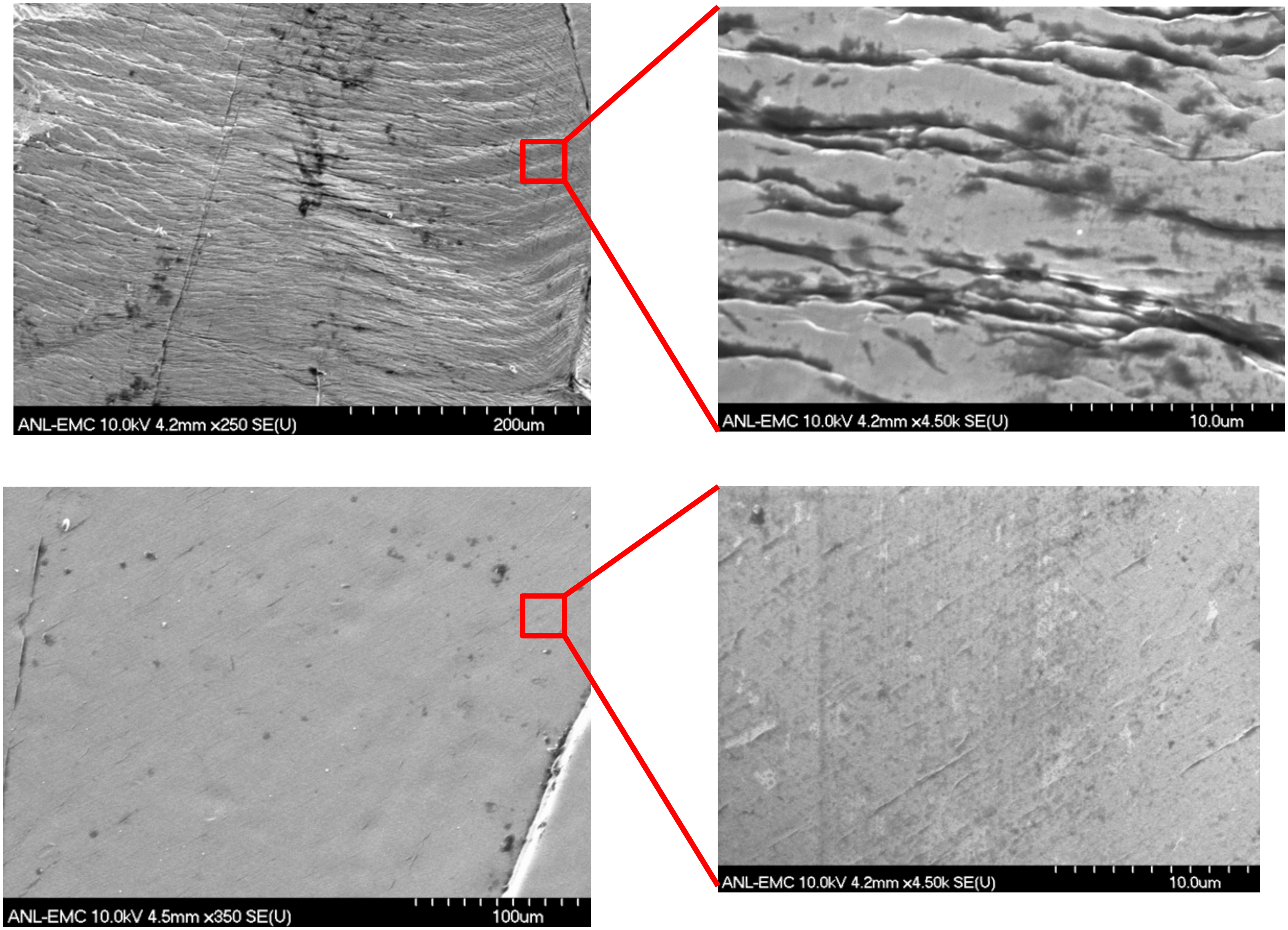
Group II: chemically etched
Wet oxides
ZBC ~ 0.2-0.3

Group I: UHV cleaned
Dry oxides
ZBC ~ 0.05-0.1

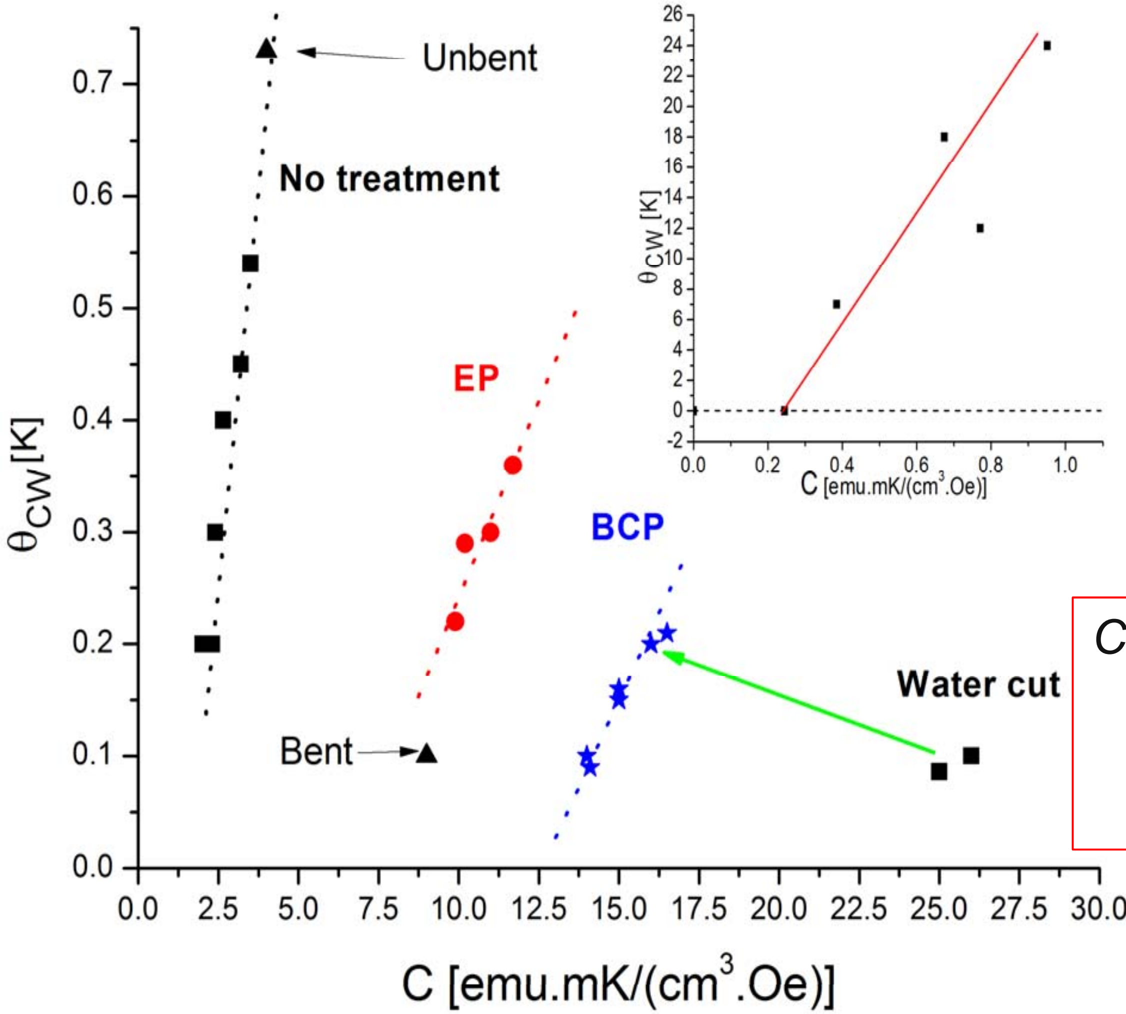
Role of dislocations?

Magnetic moments localized on the surface

Dislocations-role ?



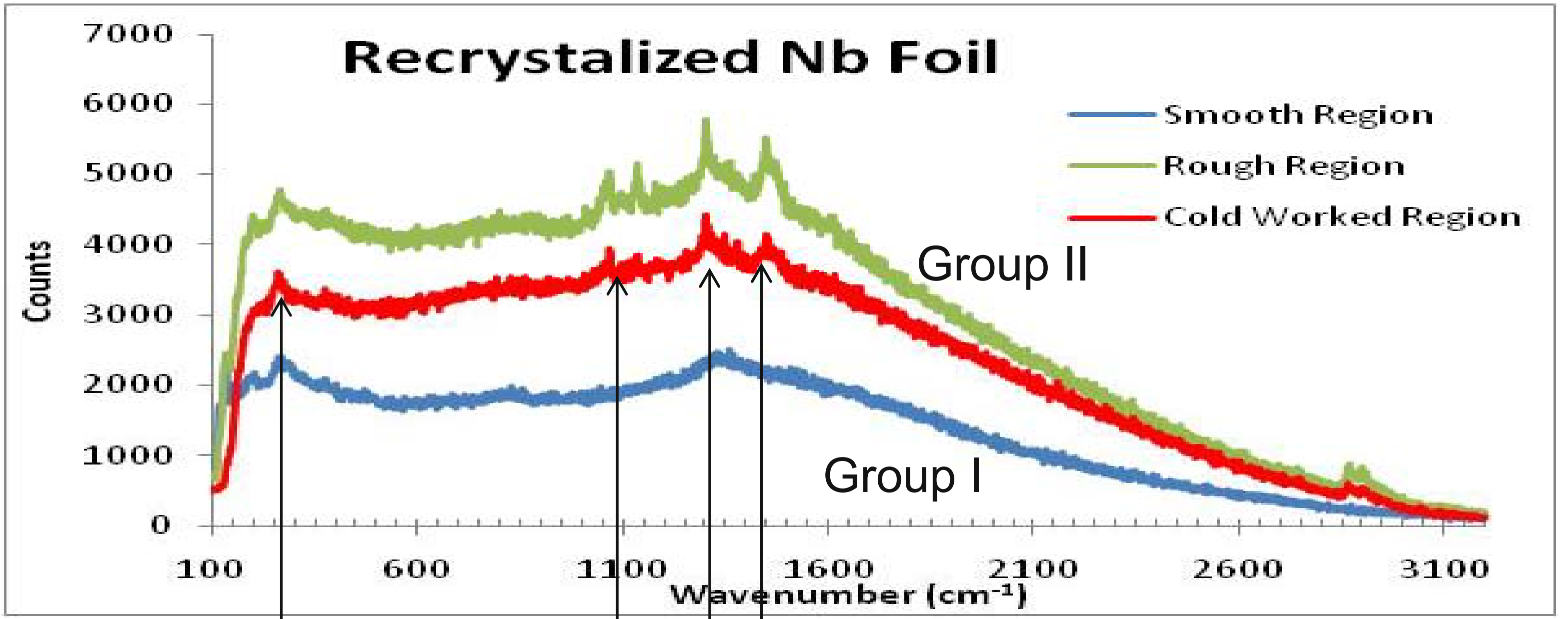
Experimental evidences of Magnetism: SQUID



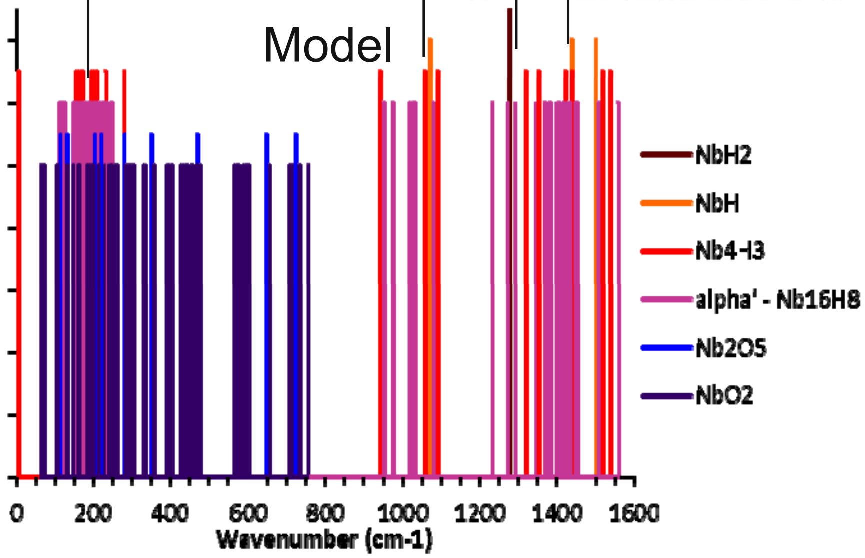
Assuming Mag. From oxides: d ~ 5 nm -> Volume.

Cannot come from oxides alone
- *-H in O vacancies*
- *-H+O diluted in Nb*
- *-dislocations segregation*

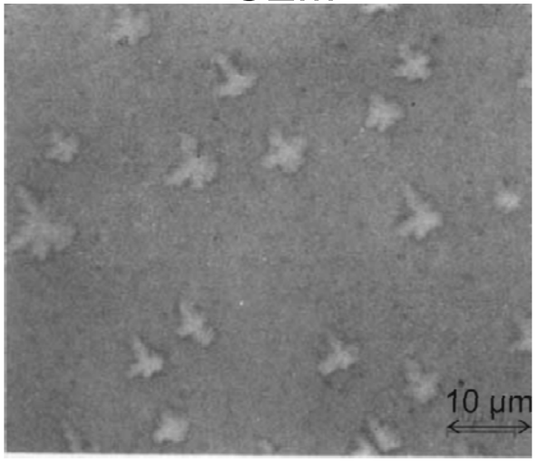
Raman spectroscopy



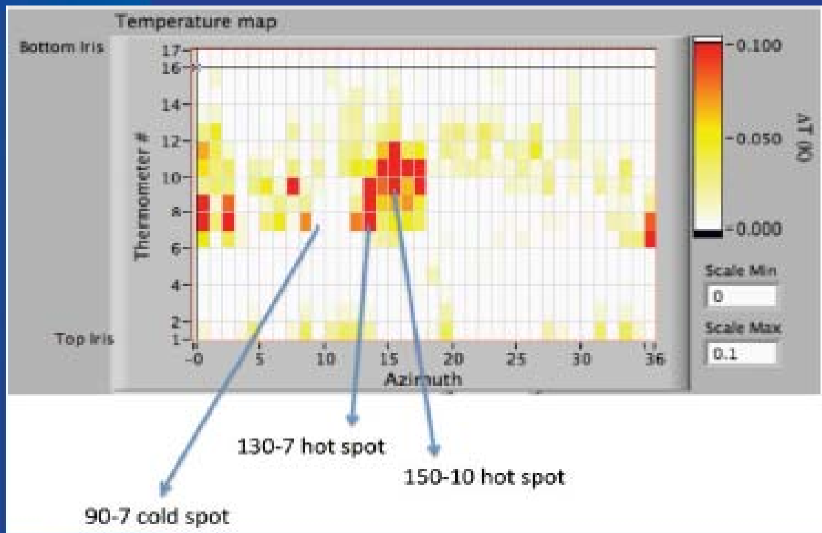
Model

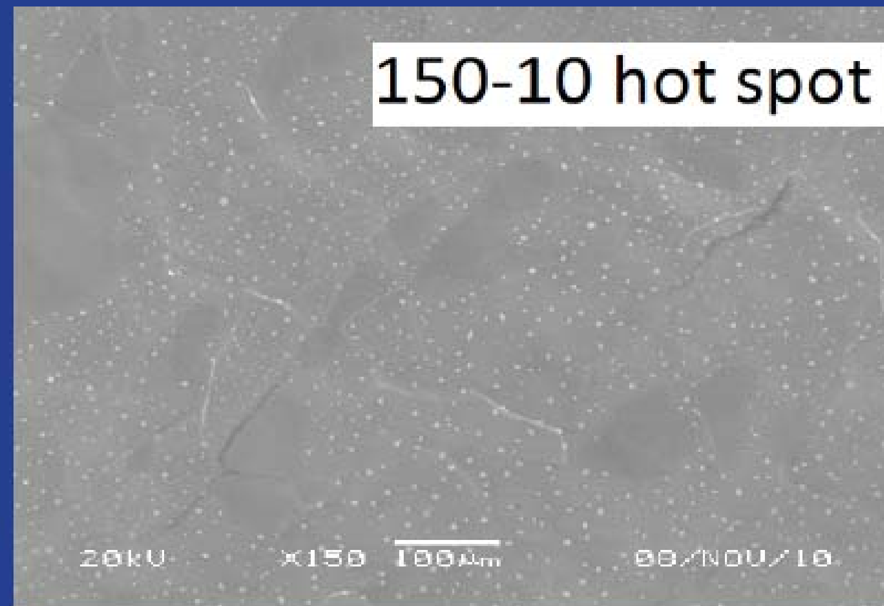


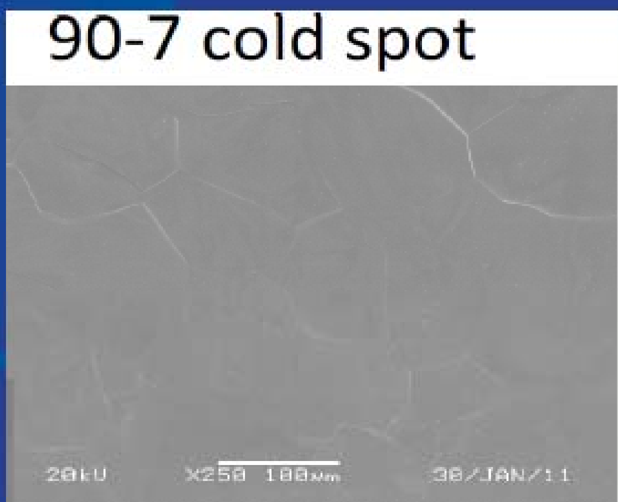
SEM



Connection between Q-slope (onset above 100 mT) and small near-surface hydride precipitates!





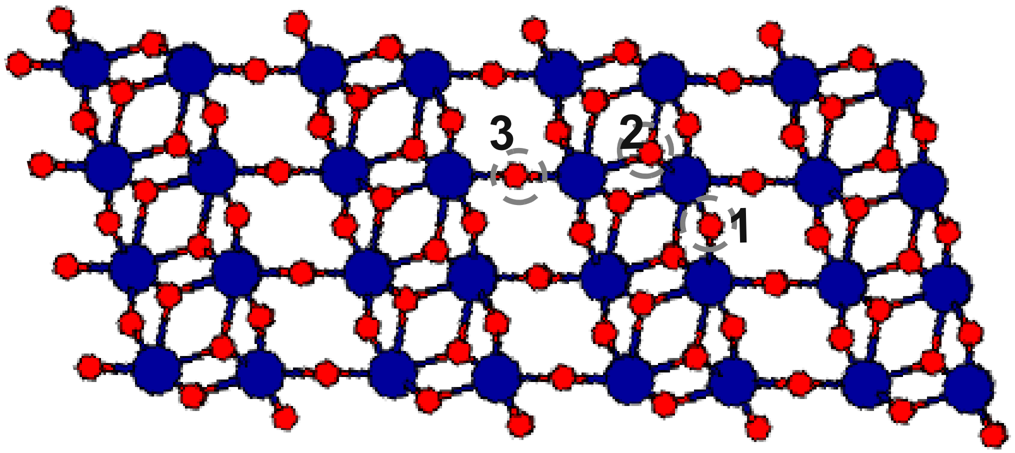


A. Romanenko, Fermilab, Unpublished work

These are hydrides: Vinnikov and Golubok, Phys. Stat. Sol. 69:631 (1982) and others

DFT-Simulation:

Nb_2O_5 : Monoclinic (B2/b symmetry)



SC	*vacany*	E_{vac} (eV)/vac	m (μ_B)
1x1x1	O1	5.86	0.00
	O2	5.42	1.82
	O3	5.89	0.00
1x1x2	O1	5.73	0.00
	O2	4.93	0.00
	O3	5.61	0.00

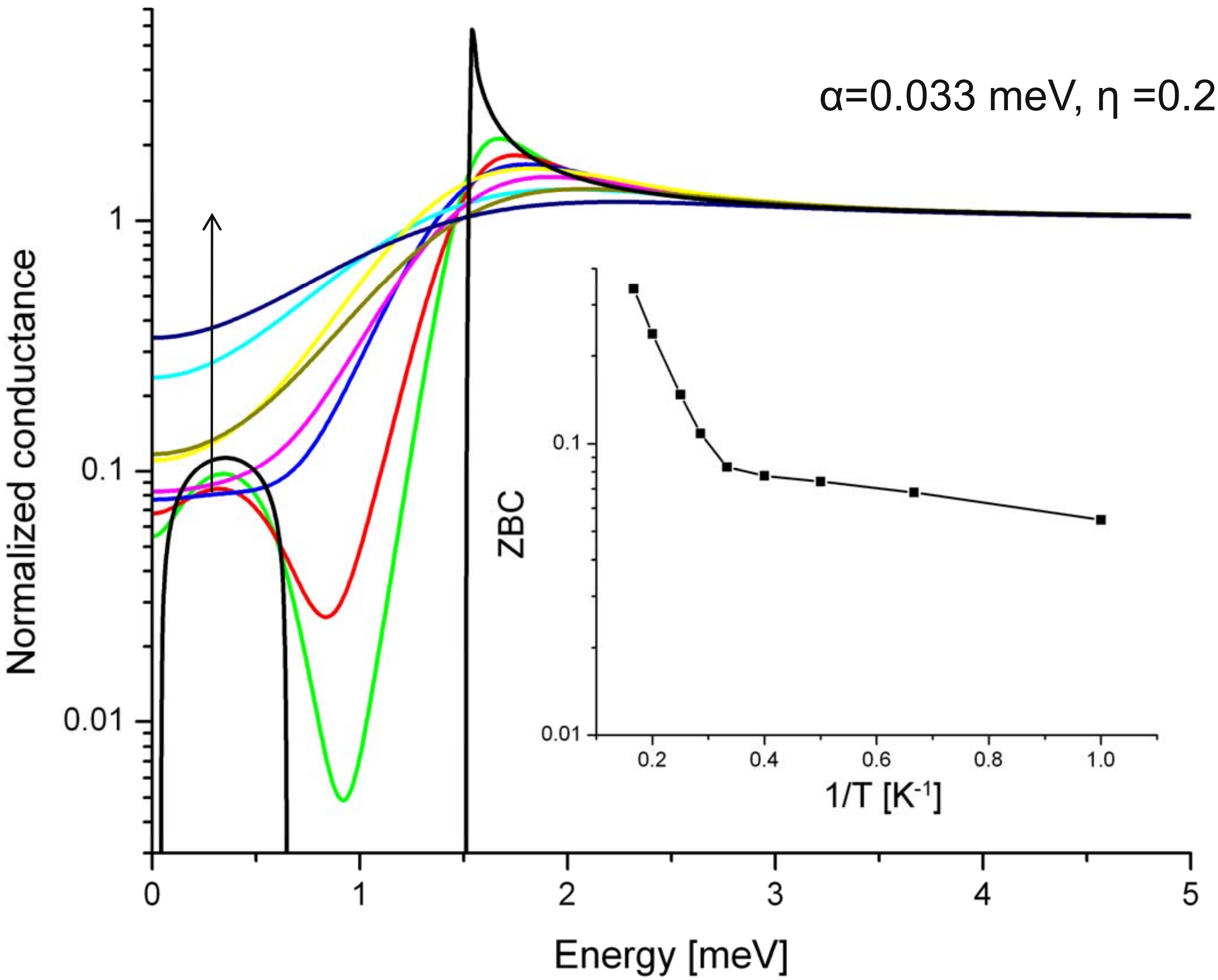
H_Interstit	Eform(eV)/vac	m (μ_B)
cose to O2	0.274101	0.6944671
cose to O1	0.572353	0

- For O2 vacancy magnetism was detected in (1x1) cell
- H interstitial close to O2 vacancy also shows magnetism

- In bulk metal: Nb vac / O / H interstitial -> no magnetism
- In bulk metal: Nb vac + O + H -> magnetism!

- Energetically favorable to have antiferromagnetic order.

Theory: The residual resistance



Theory: the residual resistance

Arbitrary mean free path, *l* and κ, homogeneous conc. in ξ

$$\zeta(\omega) = -\mathrm{i}\frac{\omega\,\delta(\omega)}{c},\ \ \delta(\omega) = \frac{2}{\pi}\int_0^{+\infty}\frac{\mathrm{d}k}{k^2 + 4\pi Q_\perp(\omega,k)/c}$$

$$Q_{\alpha\beta}(\omega,\mathbf{k}) = \frac{e^2 N_0}{mc}\bar{Q}_{\alpha\beta}(\omega,\mathbf{k}),\ \ \bar{Q}_{\alpha\beta}(\omega,\mathbf{k}) \approx [\bar{Q}^0_{\alpha\beta}(\mathbf{k}) - \mathrm{i}\bar{Q}^1_{\alpha\beta}(\omega,\mathbf{k})]\ \text{at}\ \omega \ll \Delta, 1/\tau$$

$$\bar{Q}^0_{\alpha\beta}(\omega,\mathbf{k}) = 3\cdot 2\cdot 2\pi T\sum_{\varepsilon>0} f_M^2(\varepsilon)\langle n_\alpha n_\beta D_0^M\rangle$$

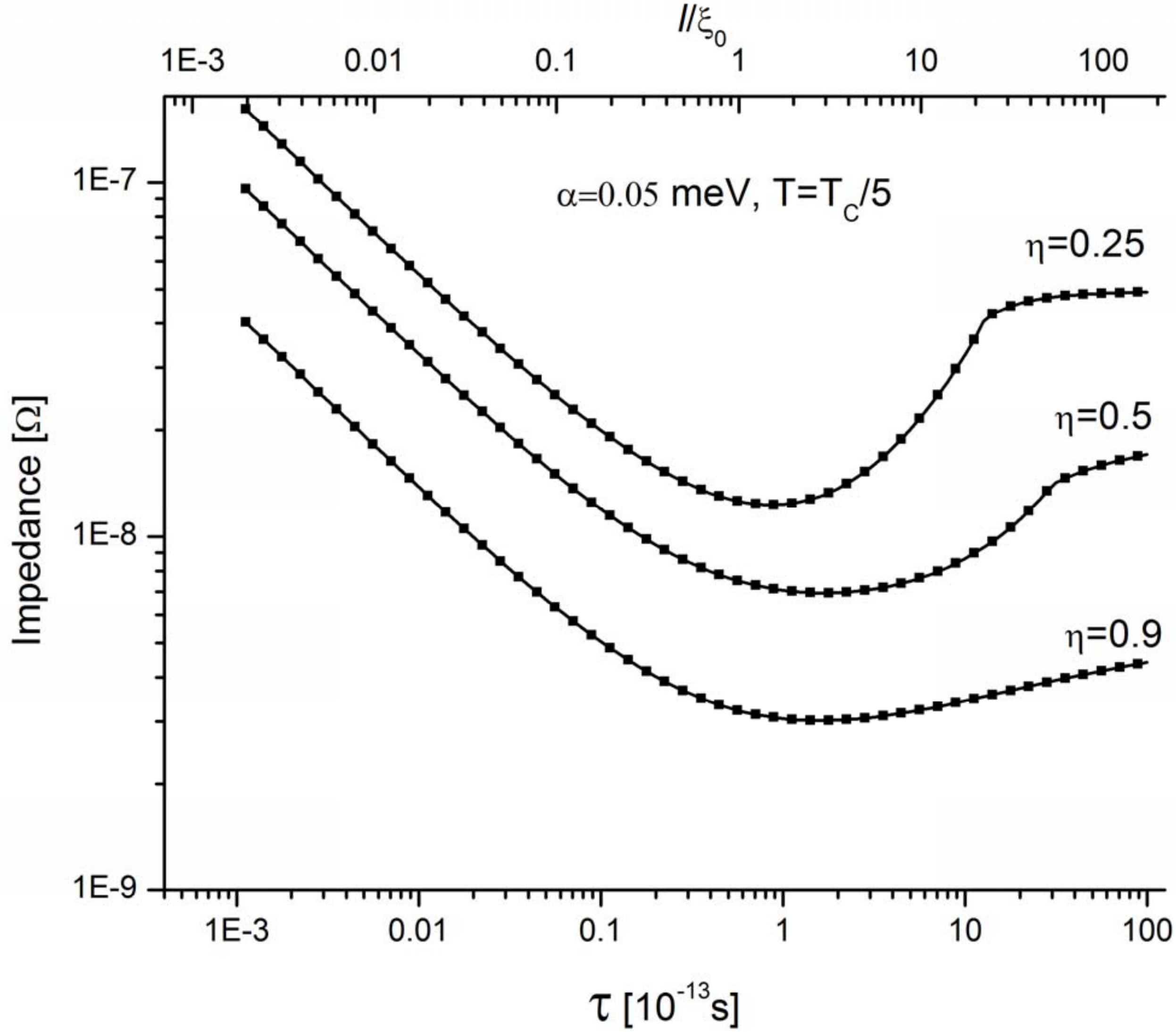
superfluid

$$\bar{Q}^1_{\alpha\beta}(\omega,\mathbf{k}) = 3\frac{\omega}{2}\int_{-\infty}^{+\infty}\mathrm{d}\epsilon\left(-\frac{\mathrm{d}n_0(\varepsilon)}{\mathrm{d}\epsilon}\right)\{[f(\epsilon)]^2\langle n_\alpha n_\beta D_0^{RR}\rangle + [f^*(\epsilon)]^2\langle n_\alpha n_\beta D_0^{AA}\rangle$$

$$+\langle n_\alpha n_\beta D_0^{RA}\rangle[1 + g(\epsilon)g^*(\epsilon) + f(\epsilon)f^*(\epsilon)]\}$$

Dissipative part

Theory: The surface impedance



Arbitrary MFP

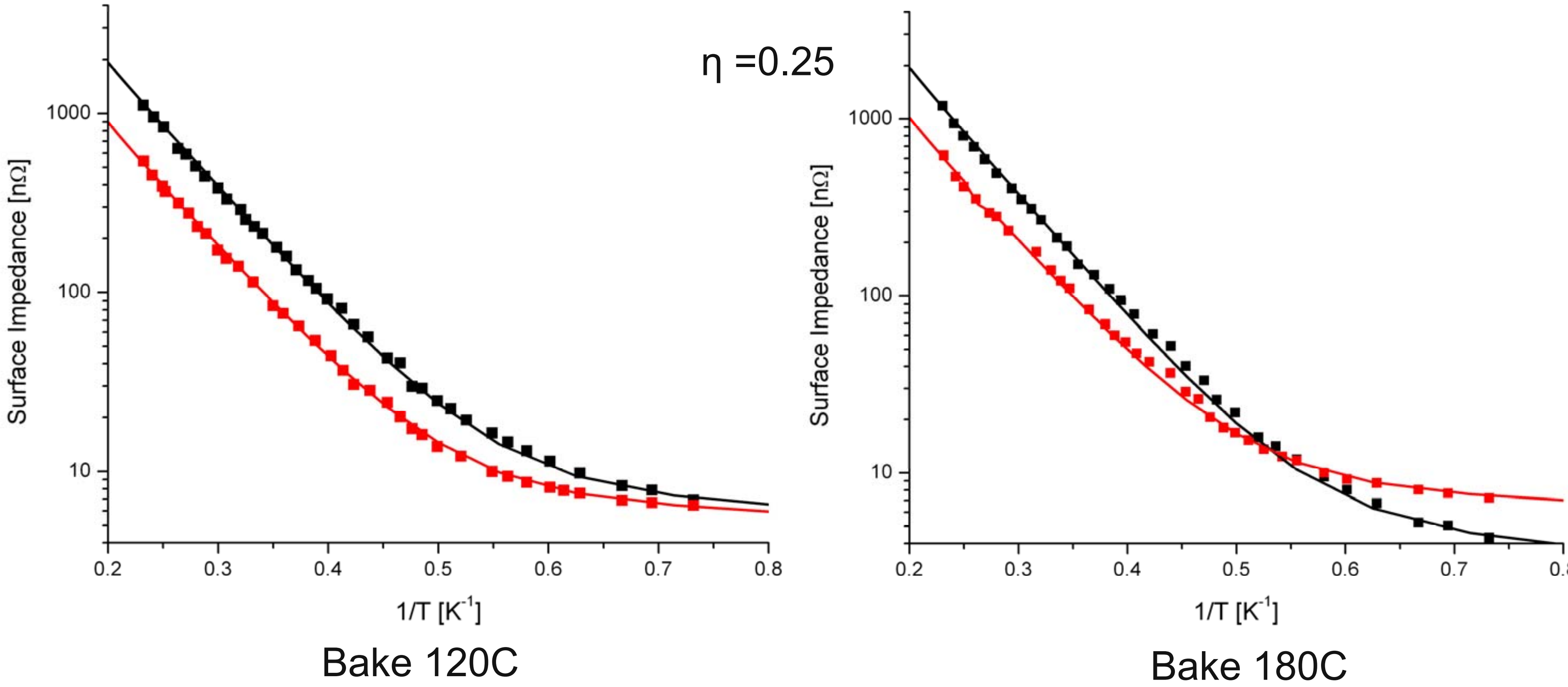
Arbitrary κ

3 parameters:

-*l* normal impurities

-*α, η* magnetic impurities

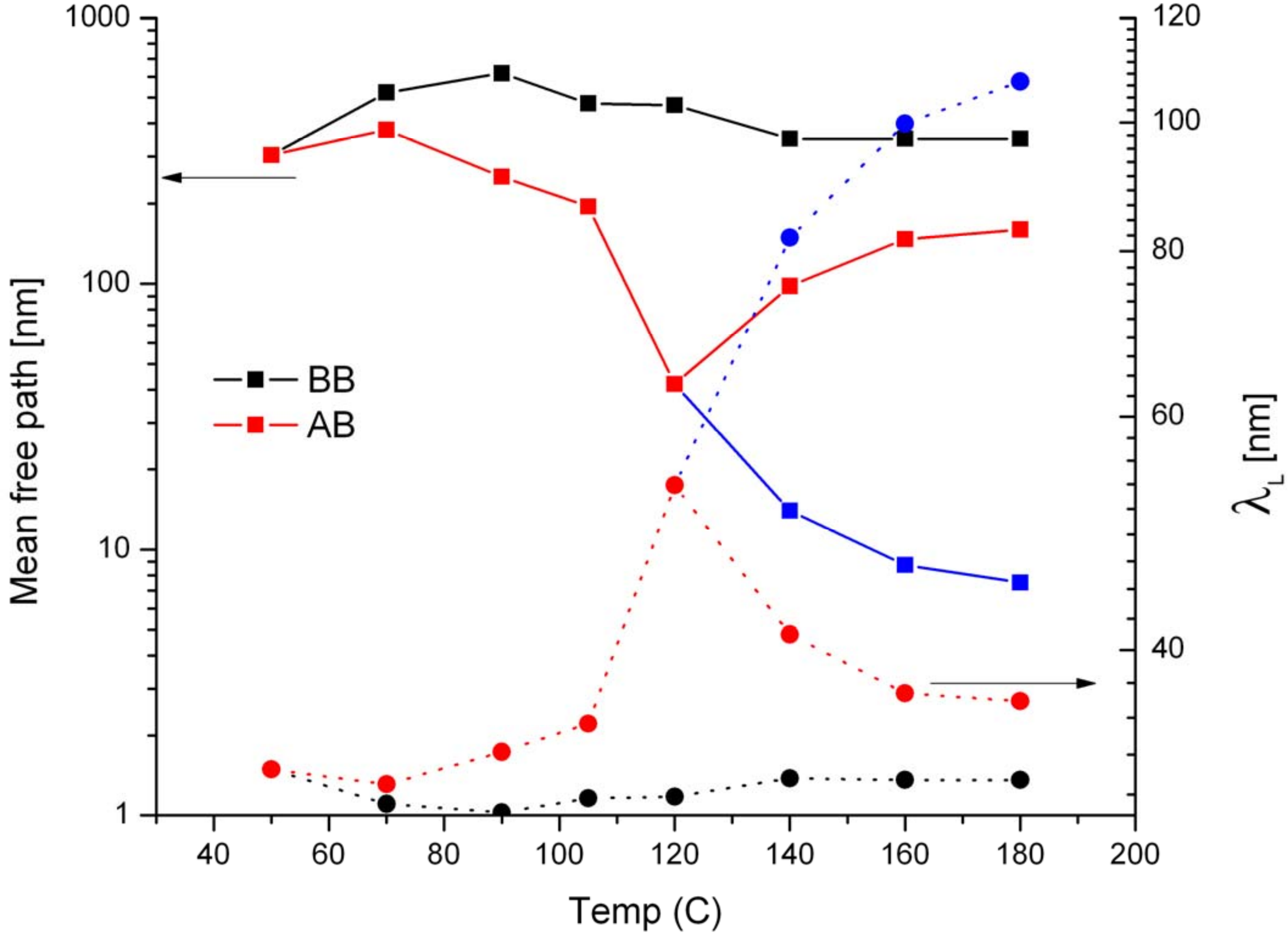
Theory: The residual resistance



α~4.10^{-2} meV & η=0.25 -> 800 ppm in Nb -> 6.10^{12} /cm^{2} in Nb oxides

Th. Proslier, M. Kharitonov submitted to PRL (2011)

Theory: residual resistivity



- Mean free path decreases after baking
- Concentration of mag. Impurities increase after baking

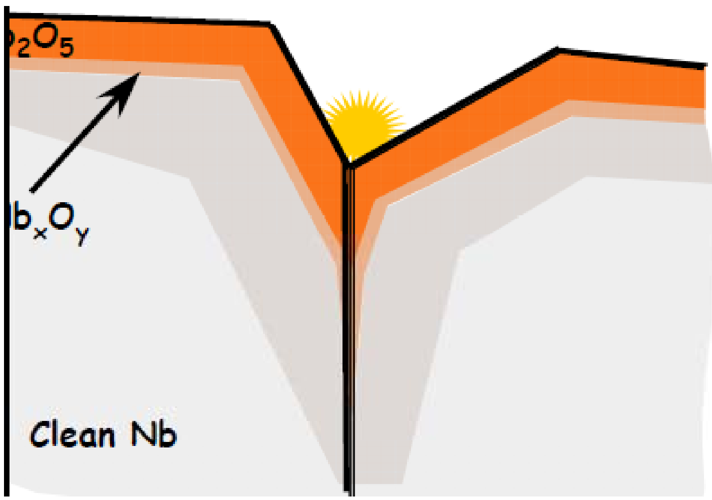
conclusion:

- Magnetic impurities present at the surface of Nb
  $Nb_2O_{5-\delta}$ is magnetic [1], H-O-dislocation complex
- Concentration is modified by surface treatment (mild, High T)
- Dissipation & higher concentration of Mag. Moments
- Theory: surface impedance [T] reproduce the R_{res}
- Paramagnetic Meissner effect + 1/f noise in Q-bits

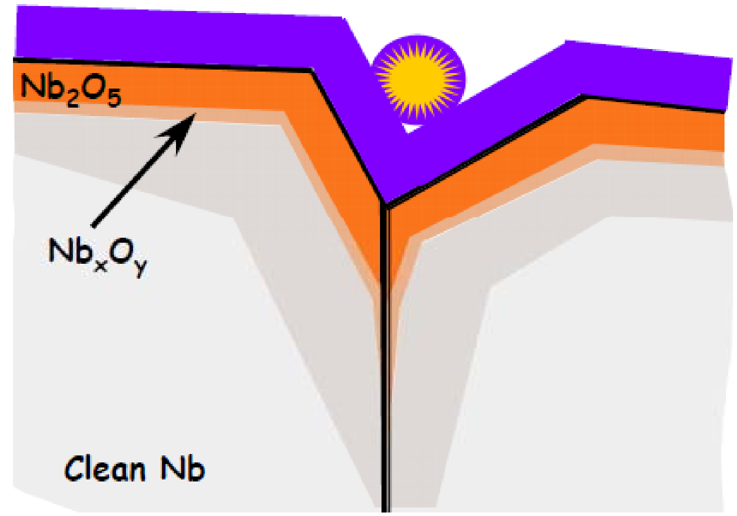
1: Cava et al. Nature 350, 598 (1991) & PRB 41, 13 (1991) & PRB 72, 033413 (2005)

Part 2: Atomic layer deposition - dielectric coatings

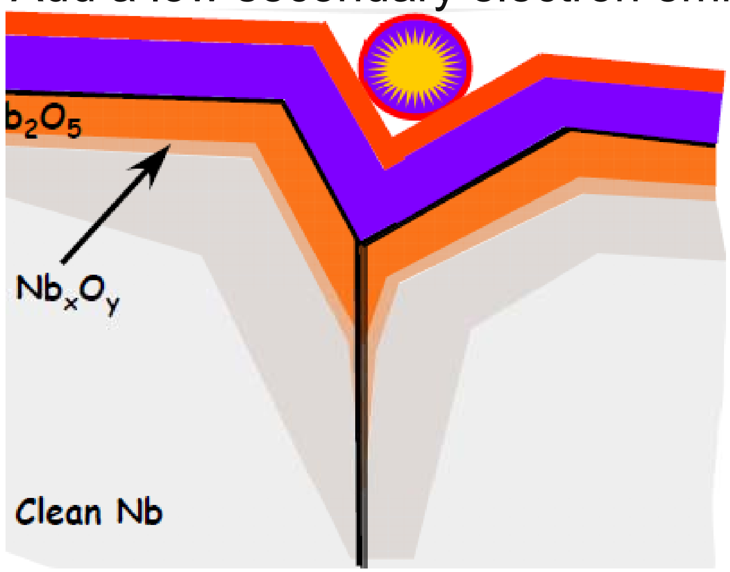
1. Begin with EP, Clean, Tested Cavity



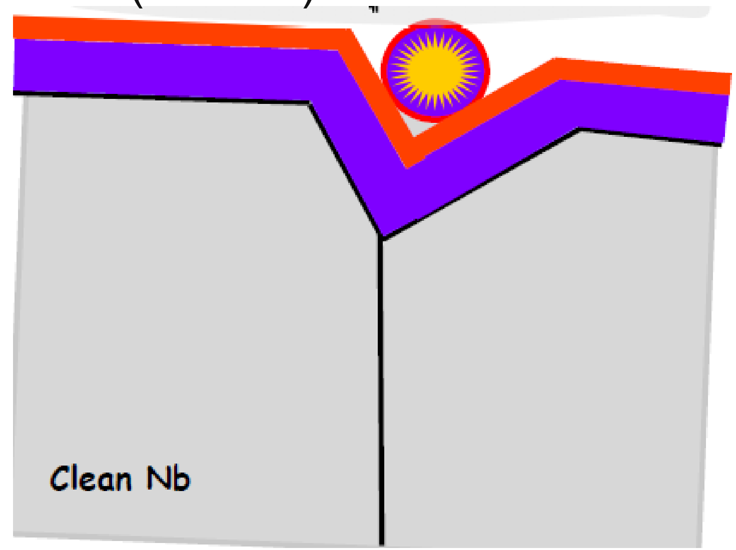
2. ALD with 10 nm of Al_2O_3



3. Add a low secondary electron emitter

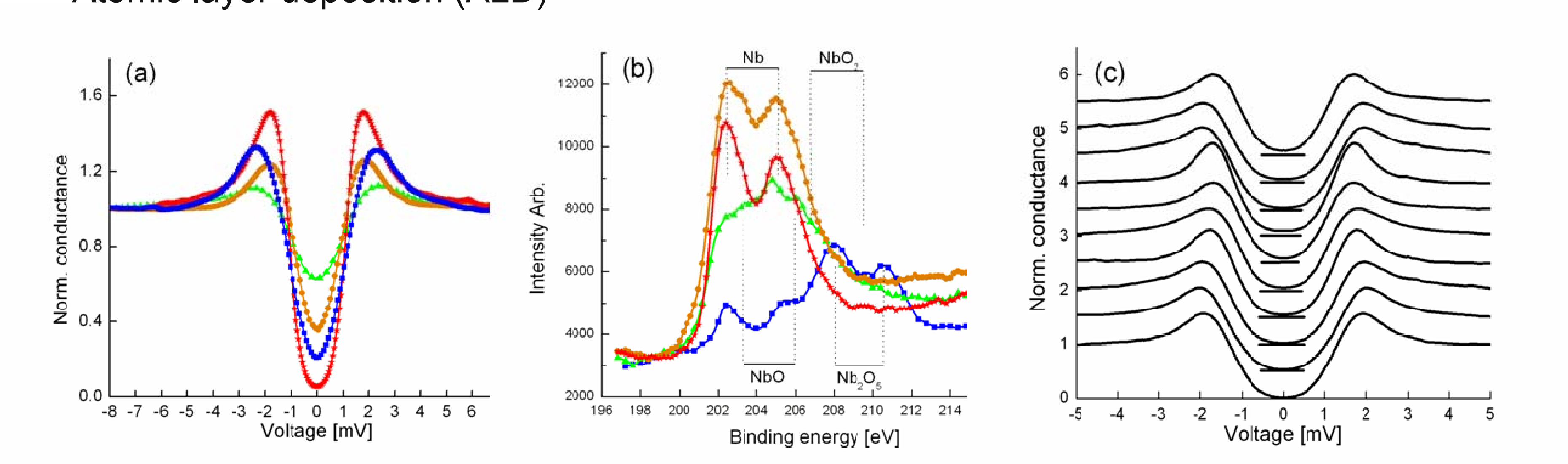


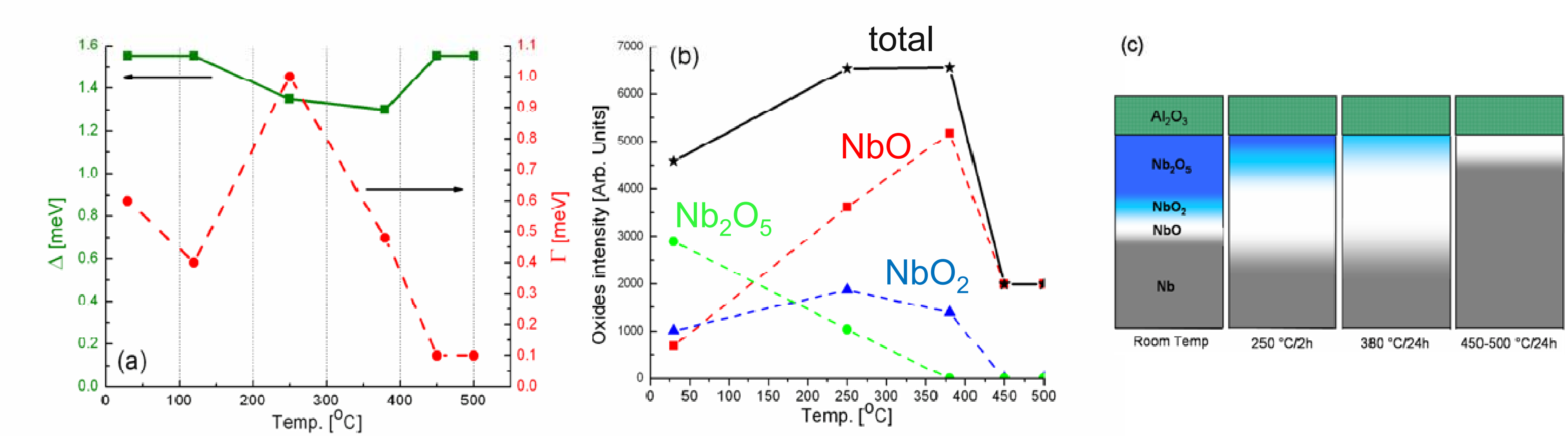
4. Bake (>400 C) to “dissolve O into bulk



coupons test

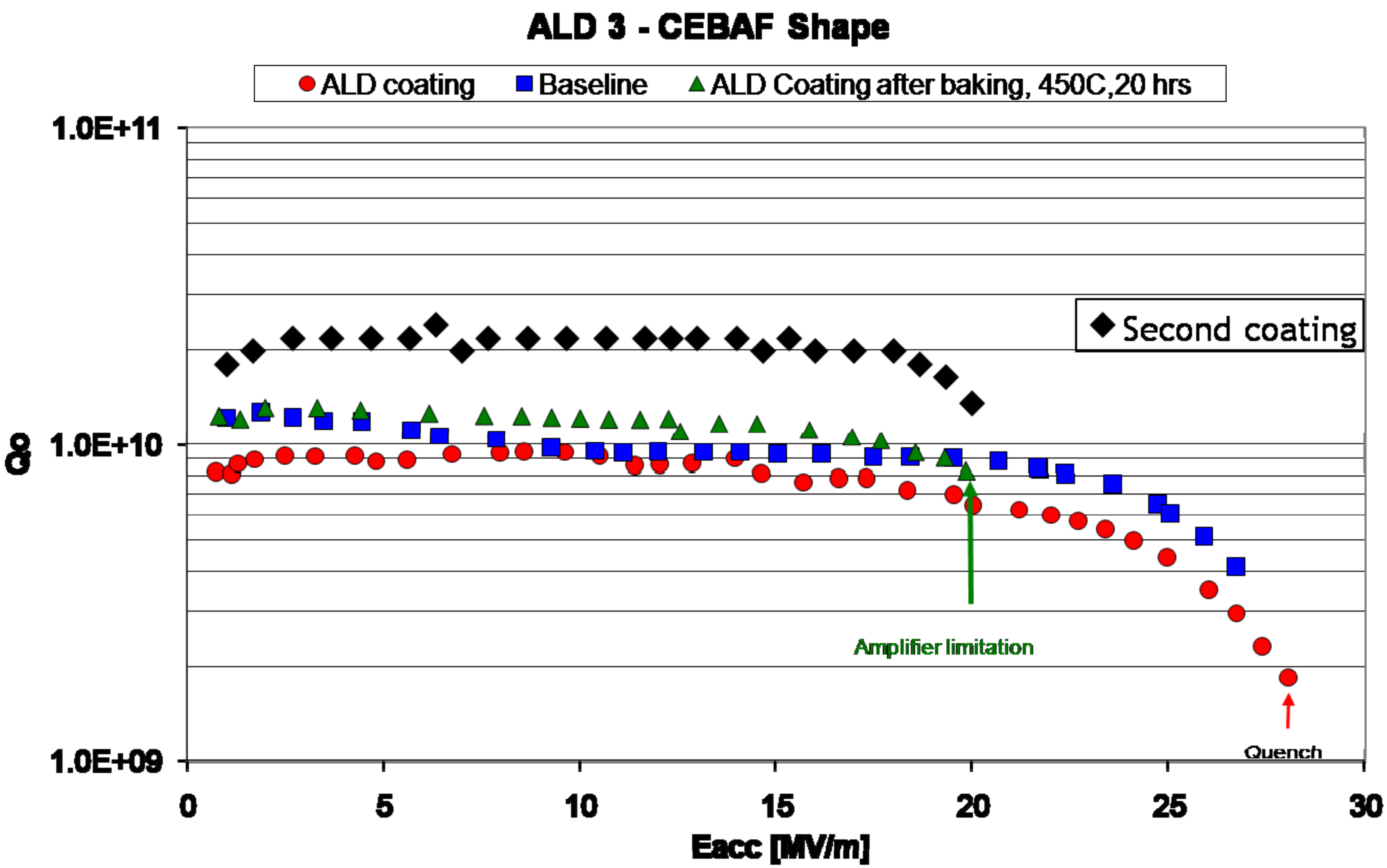
Atomic layer deposition (ALD)



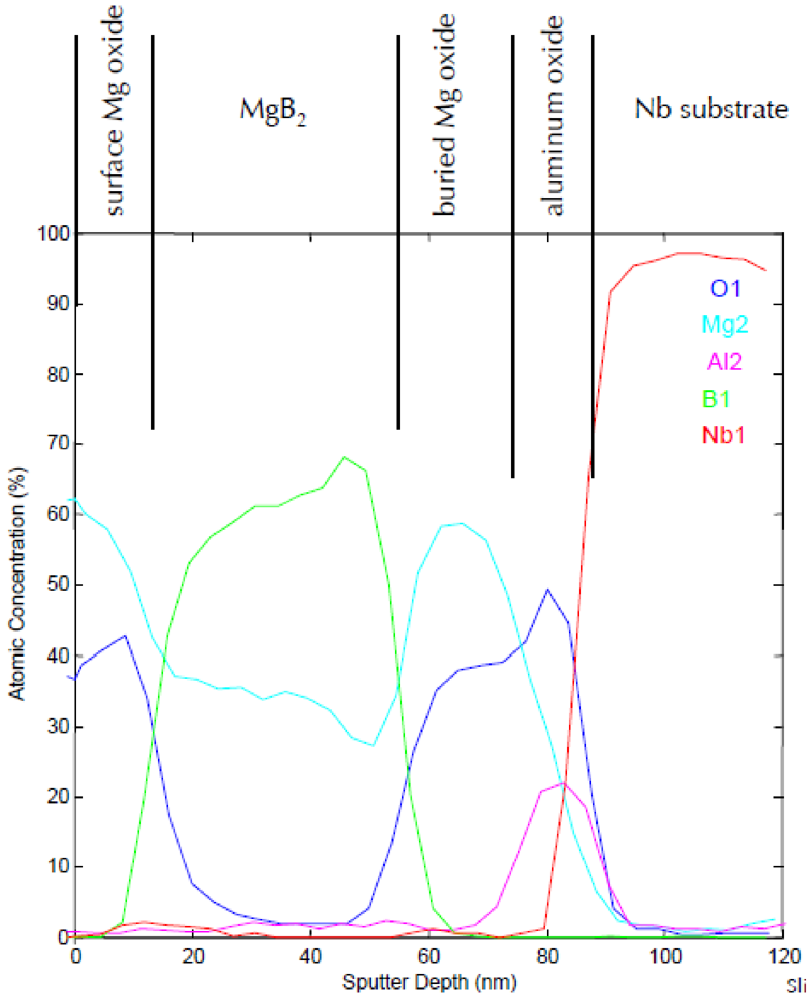


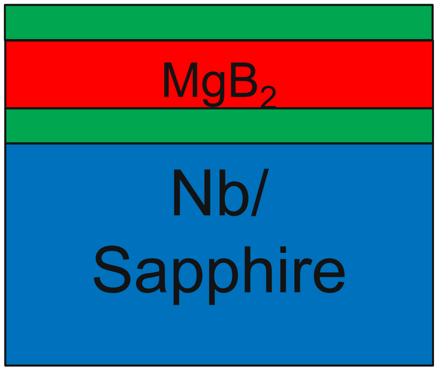
Th.Proslier, J. Zasadzinski, M.Pellin et al. APL 93, 120958 (2008)

J Lab Cavity 3: Annealing 450C/20hrs + Coating: 5nm Al_2O_3+15 nm Nb_2O_5



Dielectric coatings: multilayer (T. Tajima)





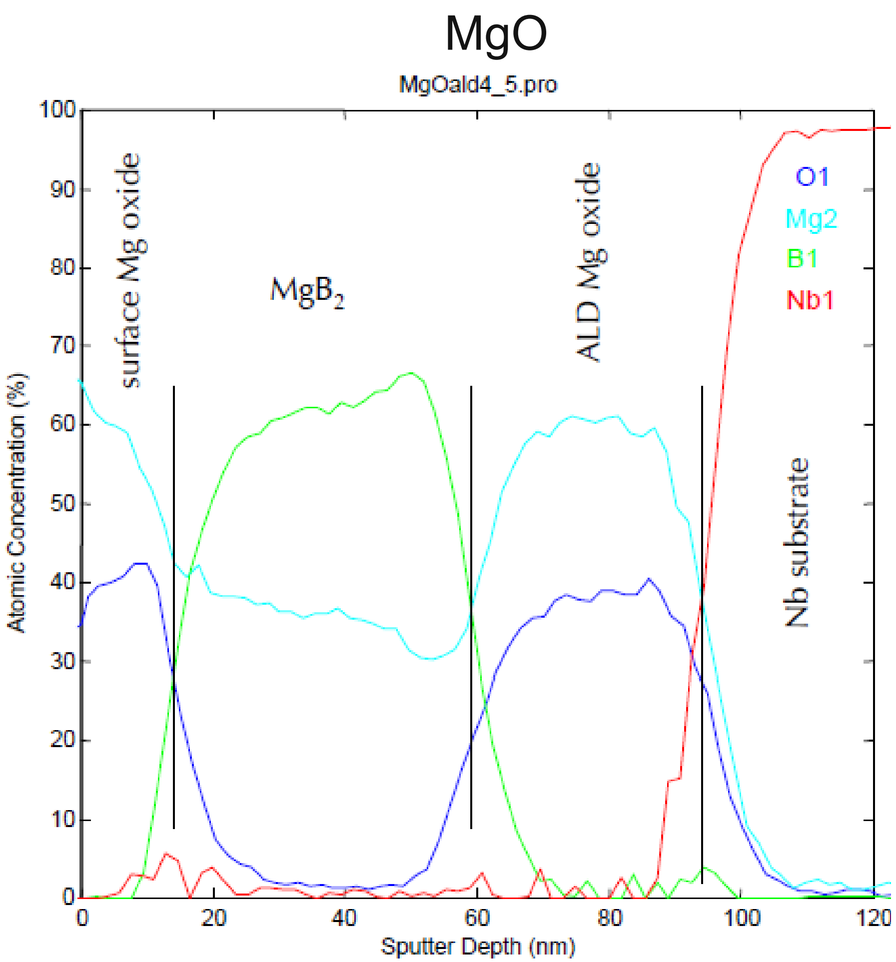
MgB_2 dep at 600 °C ~ 80 nm

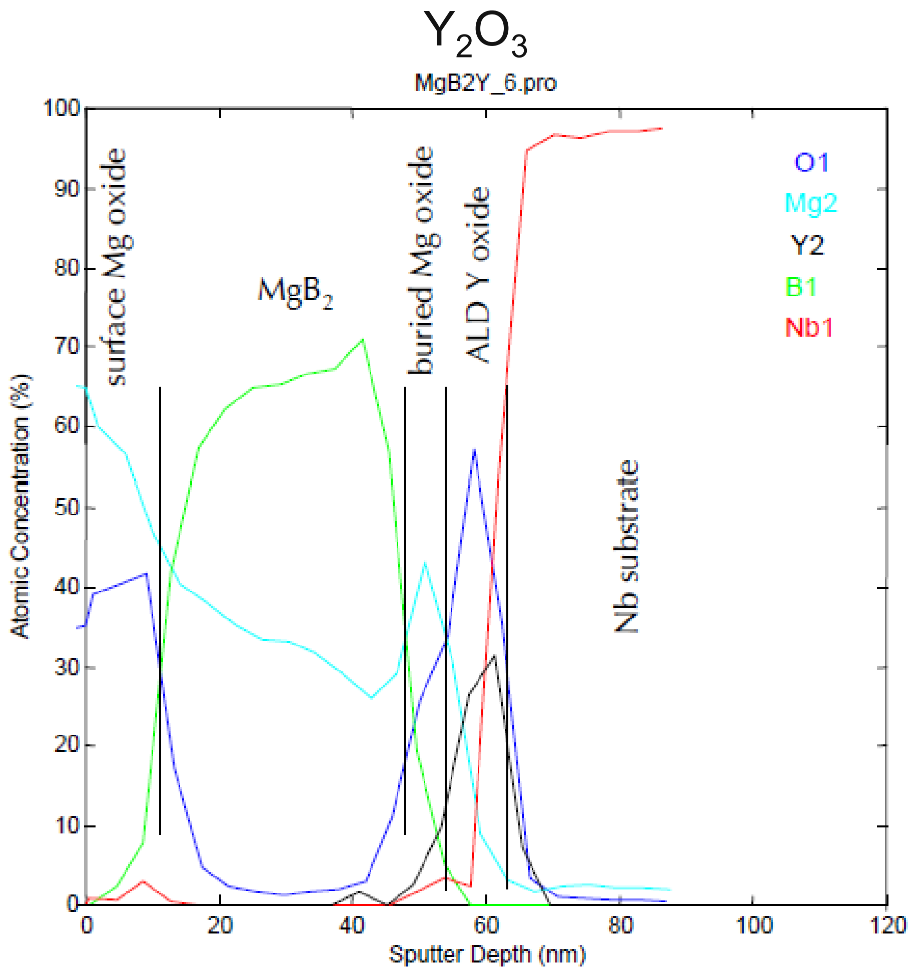
ALD insulator at 300 °C ~ 10 nm

Inter-diffusion !

Alumina coatings

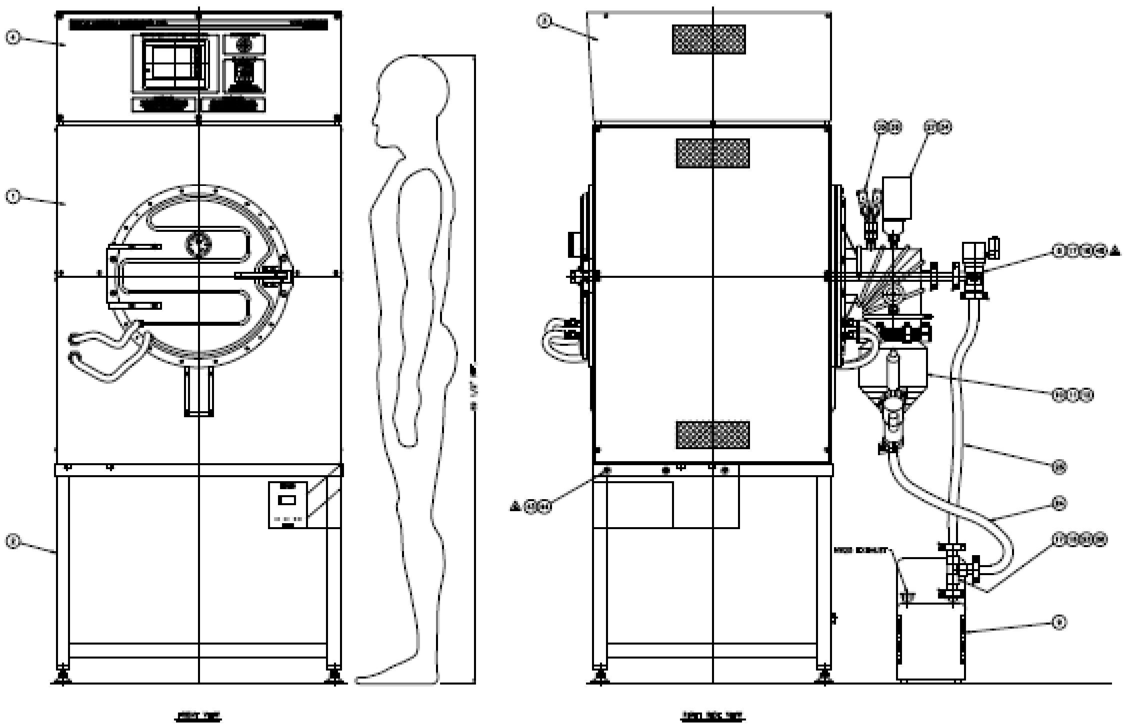
Dielectric coatings: multilayer (T. Tajima)





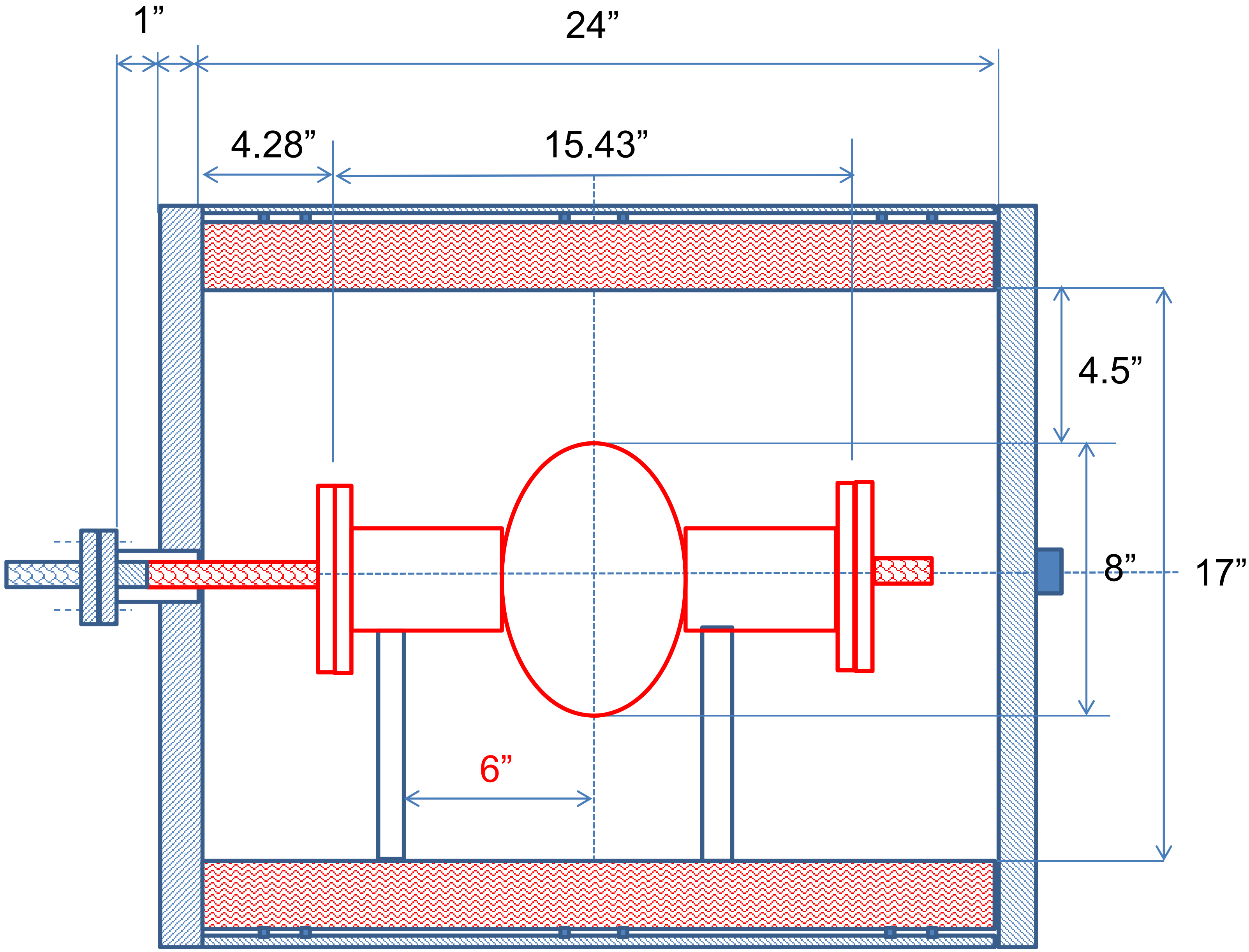
MgO and Al_2O_3 are amorphous
Y_2O_3 is crystalline and more stable

ALD coating cavities in UHV



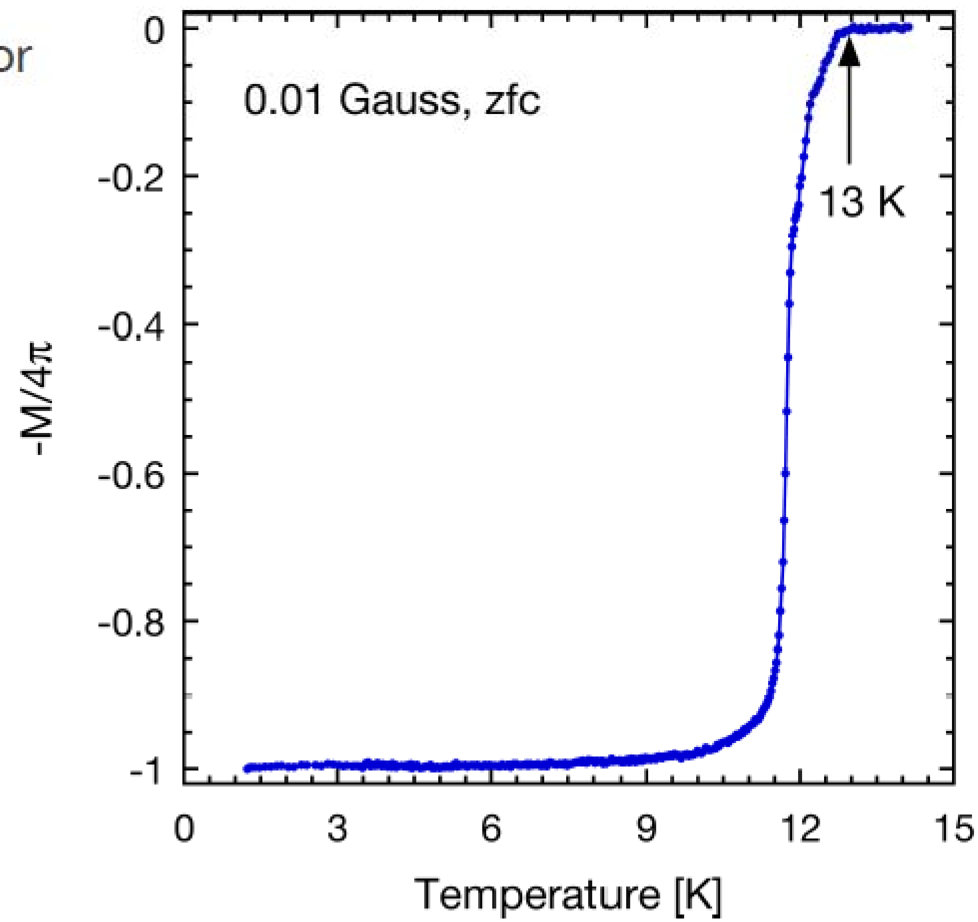
Characteristics:

650 C – UHV (10^{-9} T)
17”OD x 24” deep
Support for cavity
48 k$.


1”
24”
4.28”
15.43”
4.5”
8”
17”
6”

$Nb_{1-x}Ti_xN$: Superconducting T_c (SQUID)

- Yes, highest T_c to-date is 13 K for 80nm $Nb_{0.8}Ti_{0.2}N$ film (450°C)
- 30% higher than the highest reported T_c for an ALD film
- Now, time to try S-I multilayers



ALD of hetero-structures: superconductors-insulators

Aluminum nitride: AlN

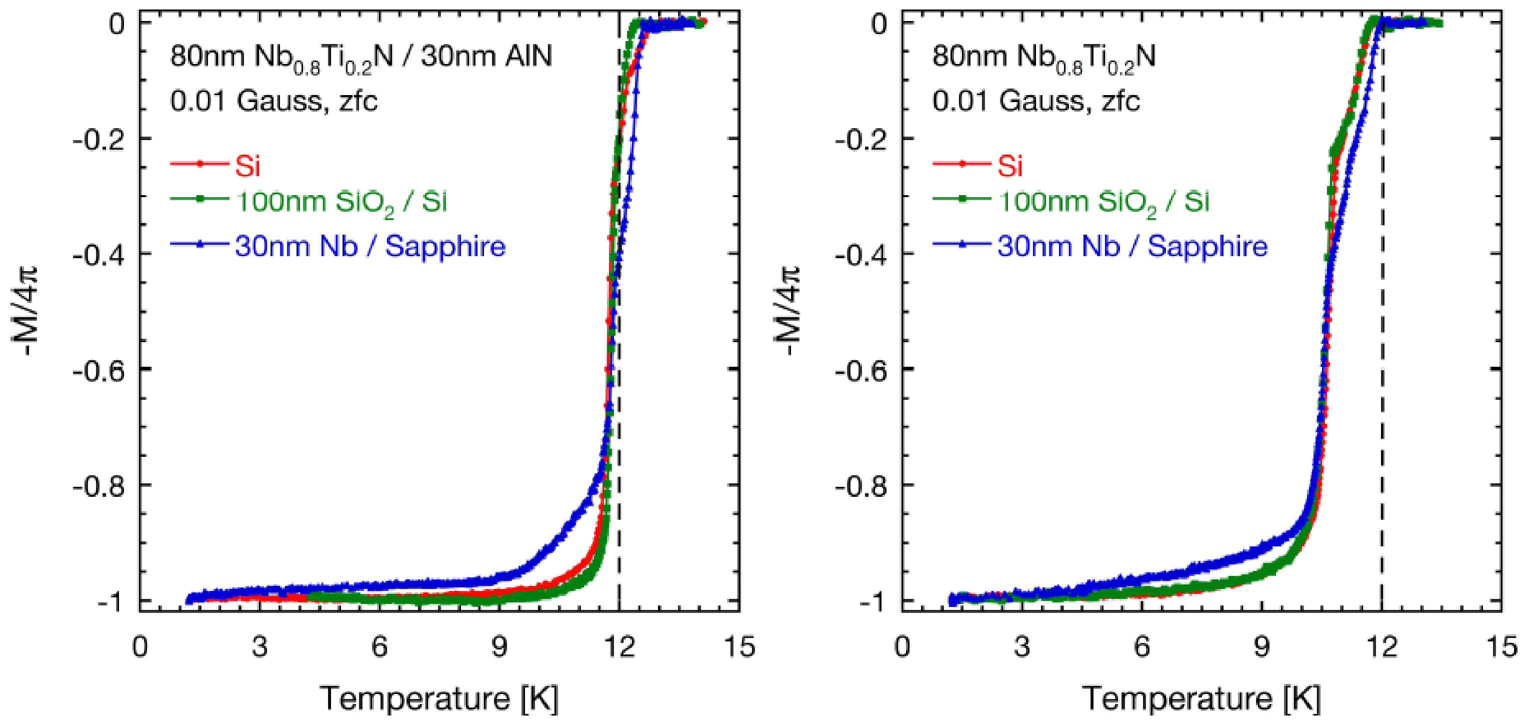
- Wide-gap (6 eV) semiconductor
- Oxygen-free, stable interface with Nb(Ti)N
- Similar structure to Nb(Ti)N
  - 0.27% mismatch between in-plane spacing of (0001)-oriented AlN and (111)-oriented NbN
- Can be grown with $AlCl_3$ and NH_3 at same temperature as Nb(Ti)N
  - No thermal cycling between deposition steps
  - ALD previously demostrated [K.-E. Elers, et al. *J. de Phys. IV* **5** (1995)]

- NbN/AlN multilayers grown previously by sputtering
  - Enhanced J_c at high fields [J.M. Murduck, et al. *Appl. Phys. Lett.* **62** (1988)]
  - Model system for vortex matter in HTS [E.S. Sadki, et al. *Phys. Rev. Lett.* **85** (2000)]

ALD of hetero-structures: superconductors-insulators

$Nb_{1-x}Ti_xN$ / AlN: Superconducting T_c

- Higher T_c with AlN layer



- Unclear why
- Strain? Crystallinity?

Conclusion and future work

- Dielectric coatings + in-situ baking
- Multilayer coatings on coupons and cavities
- New superconductor by atomic layer deposition: Pnictides.

Thanks!

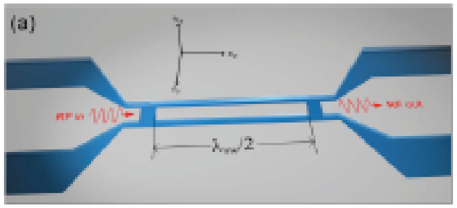
conclusion

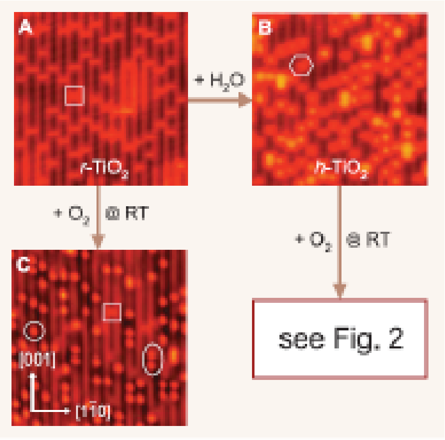
Summary

- PCT is revealing the bulk Nb gap ~1.55 meV
- Clear evidence of magnetic scattering
- EPR and ZBC peaks
- Explanation of residual RF resistance

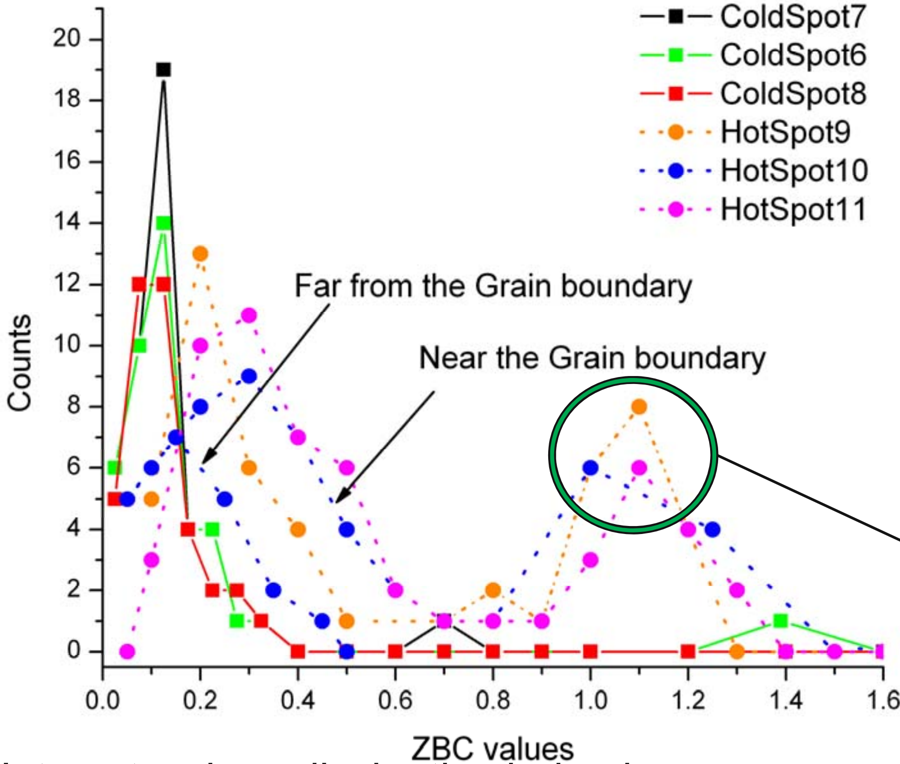
Future Work

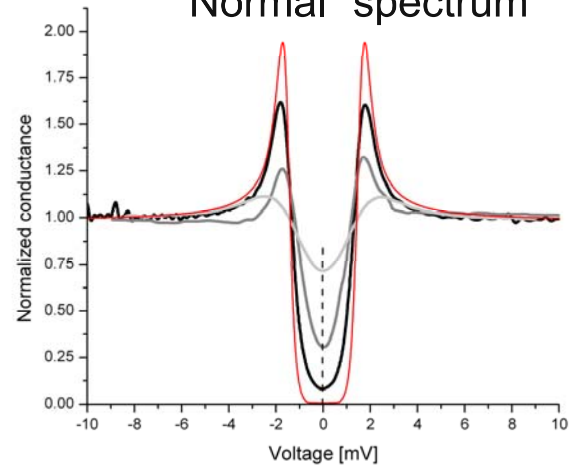
- Transport EPR of Nb films
- Planar junctions (low T, High H, weld pits)
- Co-planar waveguides (Zeeman splitting)
- STM of defects

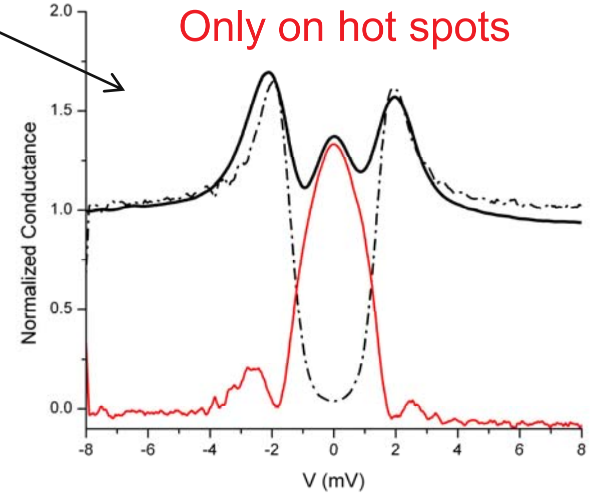




Hot and cold spots in SRF cavity (from J-lab)







Hot spots: show dissipative behavior

Higher ZBC and anomalous spec.

lower gap values (1.3<Δ<1.55)

Cold spots: “normal” dissipation

Low ZBC values

Normal gap values (1.5<Δ<1.55)

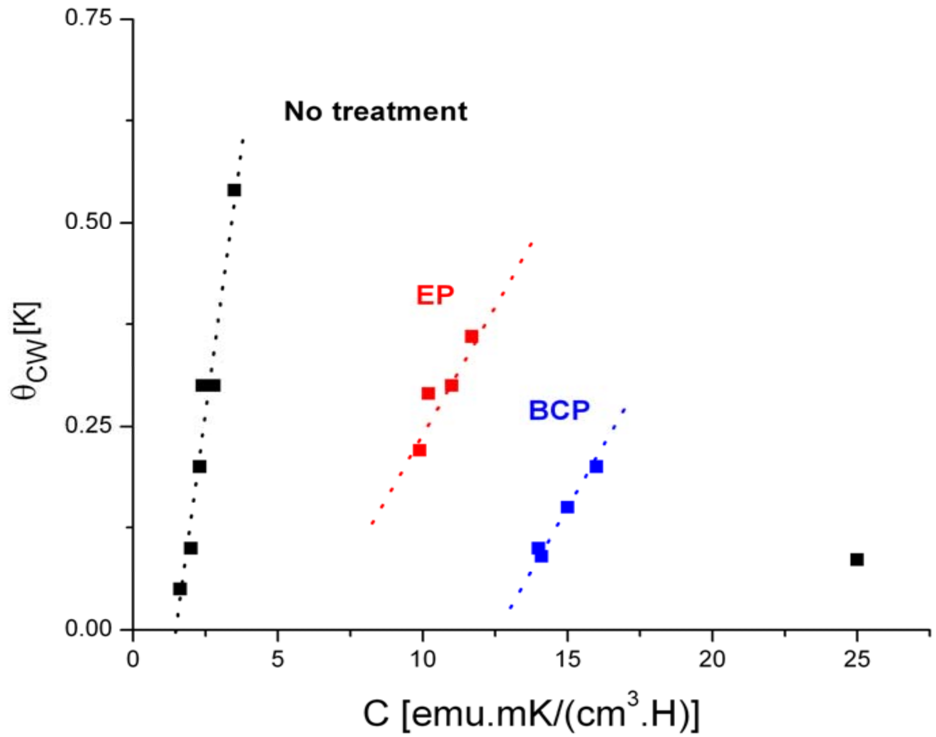
Correlates with cavities results! (once again)

Origin of peculiar spectrum and dissipation?

Th. Proslier, G. Ciovati to be submitted to PRST-AB (2010)

Experimental evidences of Magnetism: Mild and HT baking in UHV of EP samples

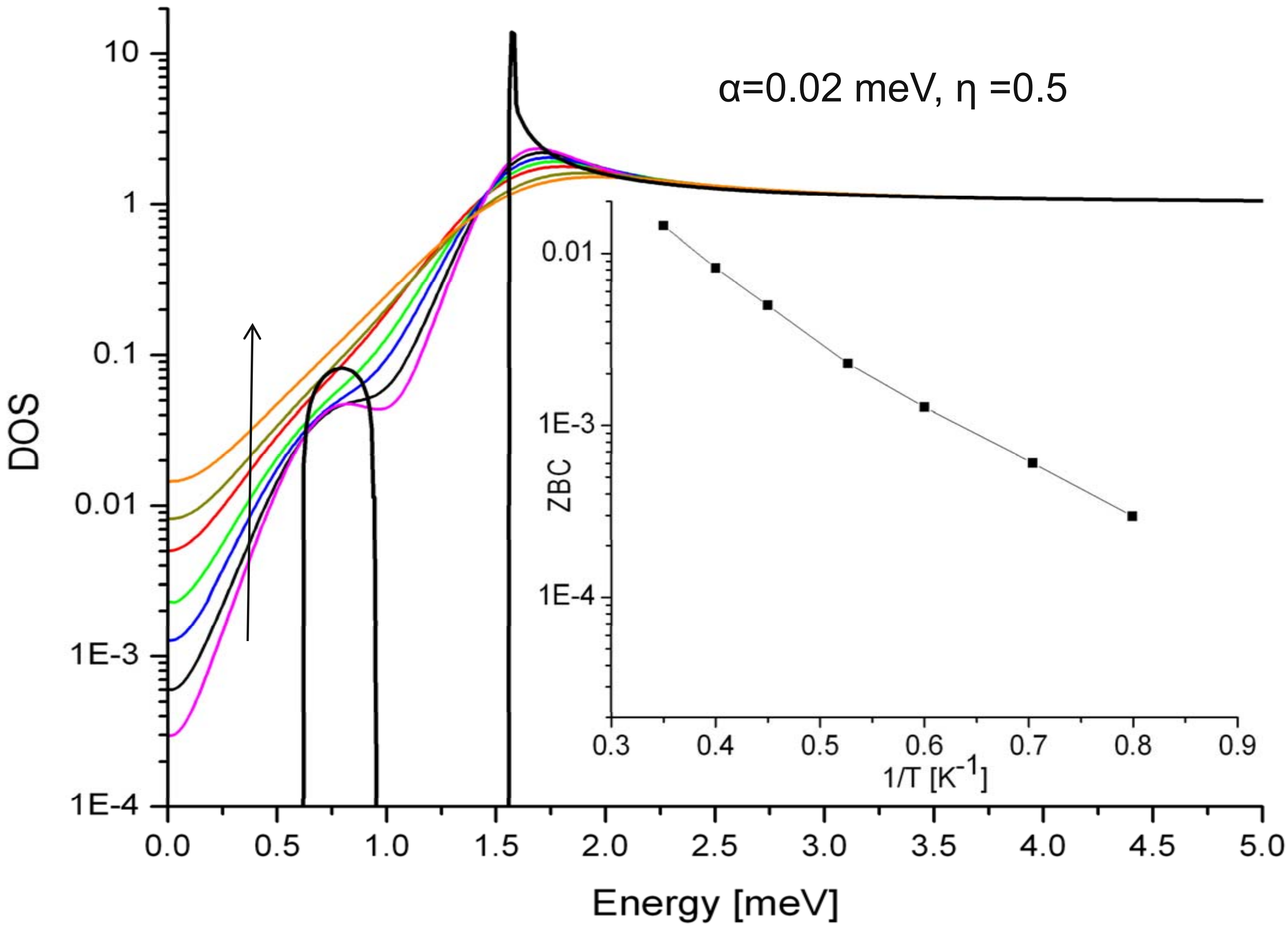
Sample treatment	C[mK]	θ_{CW} [K]
EP	10	0.3
EP UHV baked 120ºC	11.7	0.36
EP UHV 800ºC	8.9	0.22
EP UHV 800ºC + 120ºC	10	0.29



Samples:
-Mild baking Increase conc. of magnetic impurities (similar to Casalbuoni ArXiv:cond-mat /0310565v1)
-High Temp. baking decrease it.
Cavities:
-at 1.8 K higher Rres after mild baking
-High Temp. baking decrease Rres

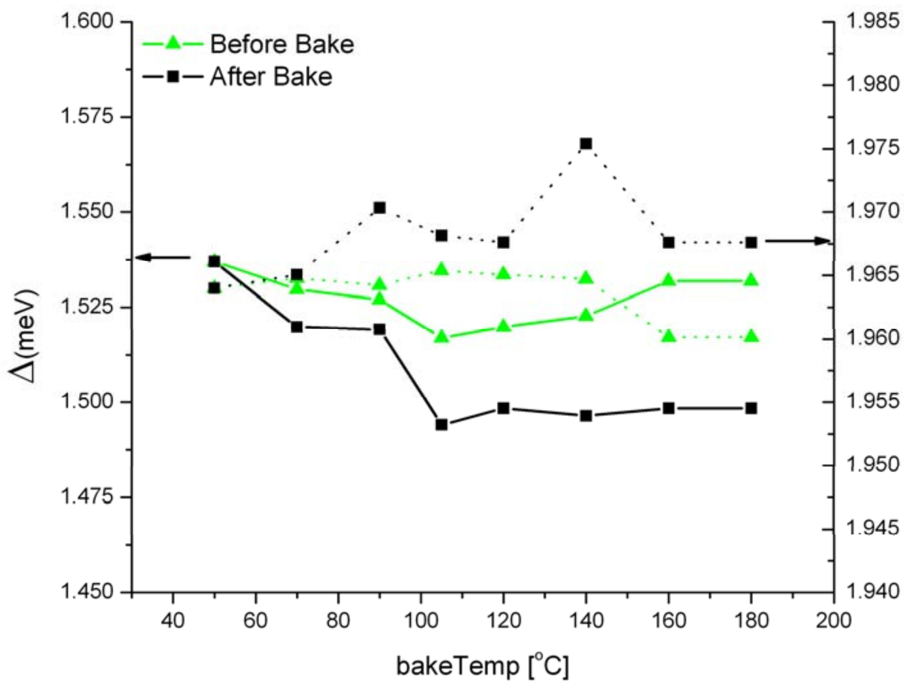
Increase conc. of Mag. moments
Increase correlations

Theory: The residual resistance

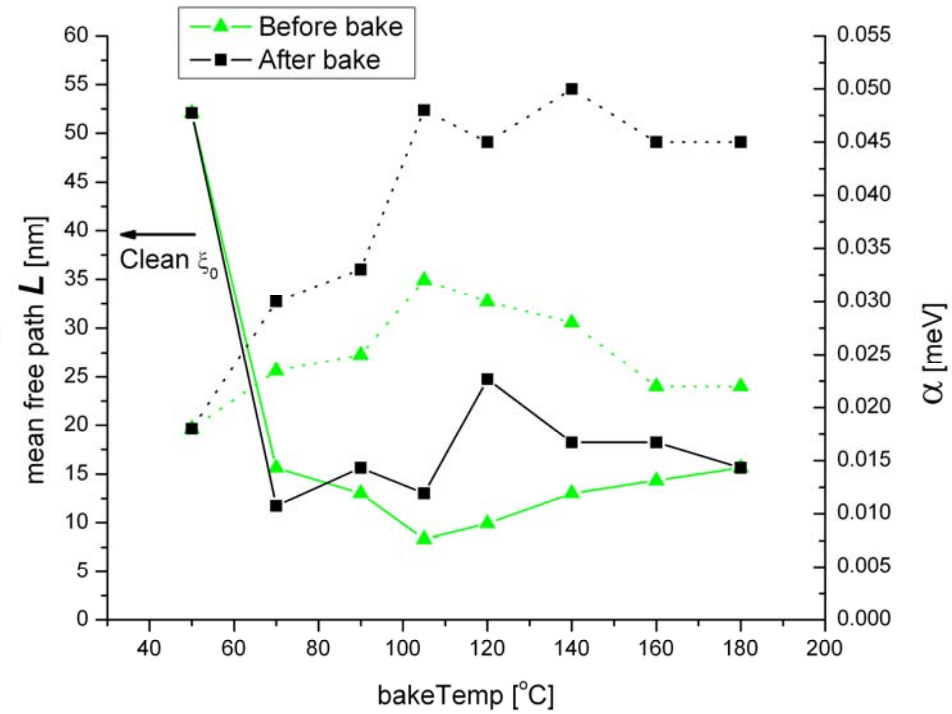


Theory: The residual resistance

Δ and Tc



Mean free path and α



Mean Free path, ℓ, increases after baking
consistent with BCS surface impedance fits

α~2.10^{-2} meV & η=0.2 -> 250 ppm in Nb -> 6.10^{12} /cm^2 in Nb oxides