Review of high field Q slope, cavity measurements

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13th SRF Workshop

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Tools

- Research on Q-drop and baking in Nb cavities is typically carried out on 1.3 GHz and 1.5 GHz single-cells

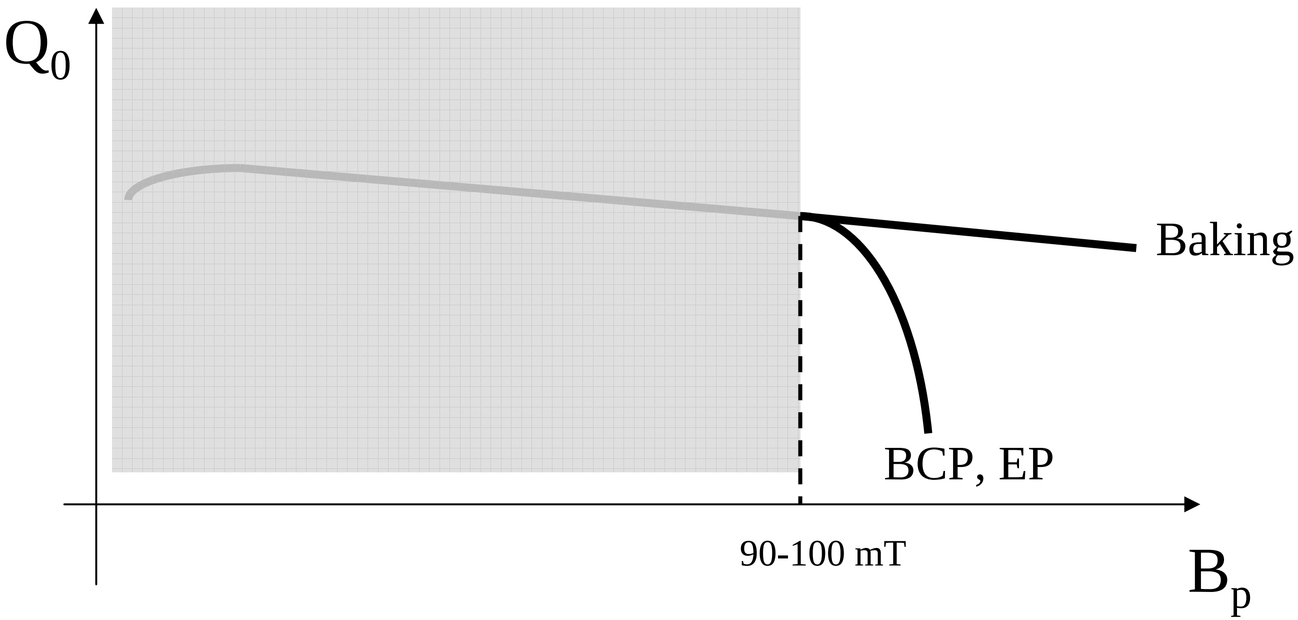
1.5 GHz
CEBAF Shape

1.3 GHz
Ichiro Shape

1.3 GHz
TESLA Shape

Introduction

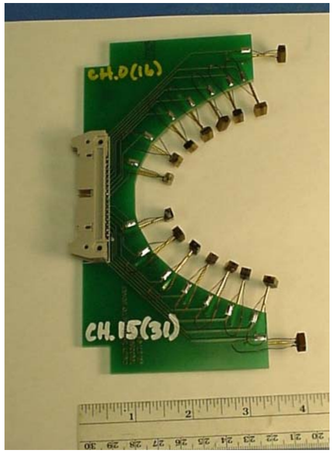
- Typical $Q_0(B_p)$ curve for high-purity bulk niobium L-band cavities

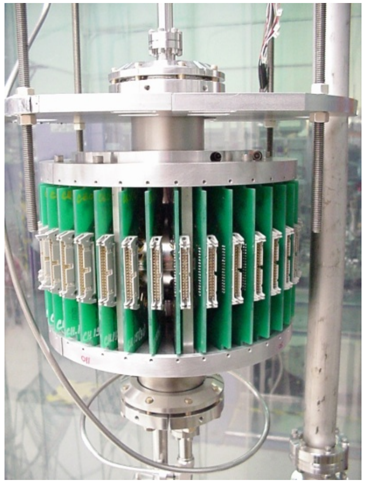


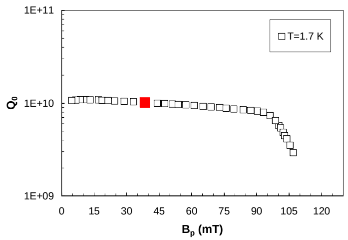
- High field Q-slope (or Q-drop): exponential increase of RF losses with no X-rays (field emission). First observed in 1997.
- In 1998 it was found that a low-temperature (100 – 140 °C, 48 h) bake strongly reduced the Q-drop

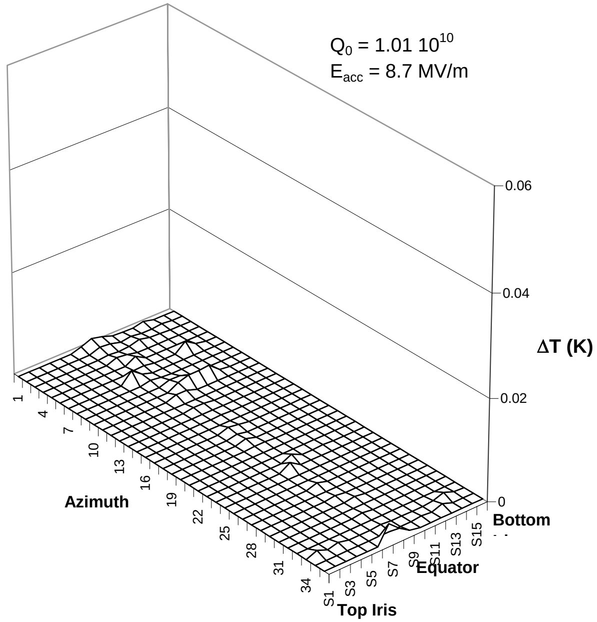
Temperature maps

• Temperature mapping show "hot-spots" in the equator region









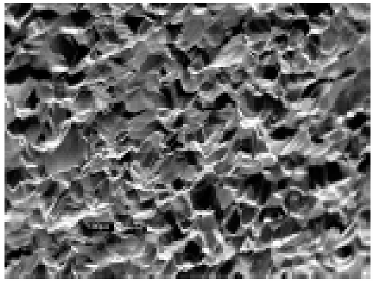
JLab system: 576 carbon resistors, based on Cornell design[1]

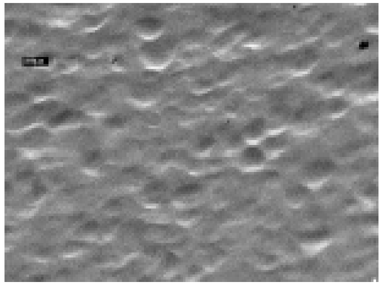
G. Ciovati, JLab

[1] J. Knobloch, Ph.D. Thesis, Cornell University, 1997

Role of surface roughness

- Polycrystalline Nb surfaces obtained by buffered chemical polishing (BCP) are in general rougher than obtained by electropolishing (EP)

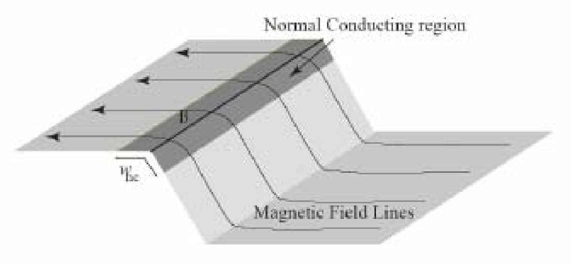


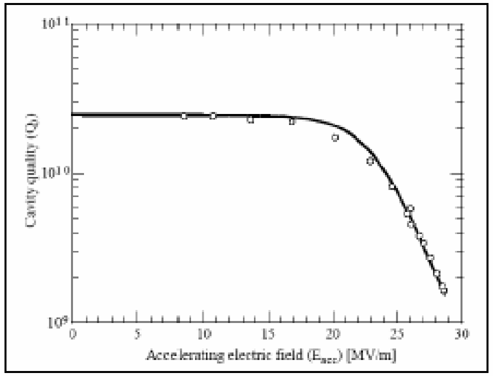


RMS step height: 5-10 μm with BCP 1-5 μm with EP R.L. Geng *et al*.-SRF 99-TUP021

- Magnetic field enhancement model:

Quenches of grain boundaries when $\beta_m H > H_c$

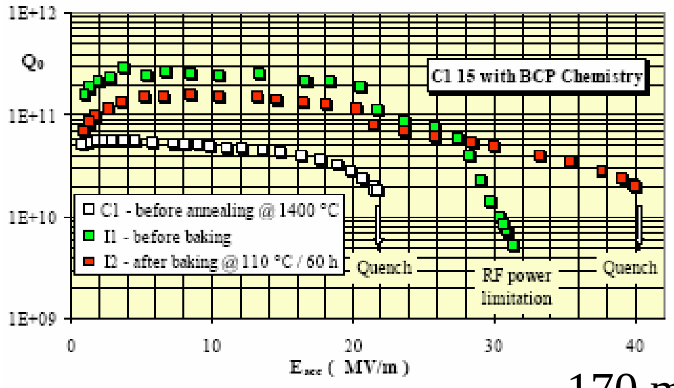




J. Knobloch *et al*.-SRF 99-TUA004

Exp. results against surface roughness (1)

Nevertheless:



B. Visentin *et al*.-EPAC 02-THPDO013

170 mT

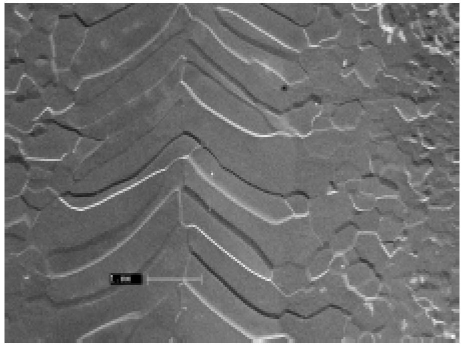
BCP treated cavity (4÷8 μm step height)

- Low temperature baking improves Q-drop without changing surface morphology

Exp. results against surface roughness (2)

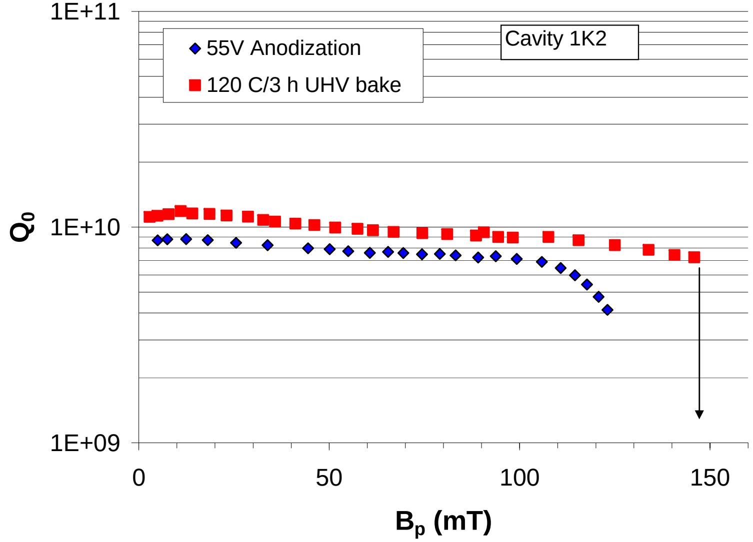
- The equator weld is typically the region of the cavity with more pronounced steps, yet the Q-drop occurs also in seamless cavities

SEM photo of typical EBW



R.L. Geng *et al*.-SRF 99-TUP021

Hydroformed, EP cavity



P. Kneisel, JLab

- The Q-drop occurs in cavities smoothened by barrel polishing and EP

Courtesy T. Saeki

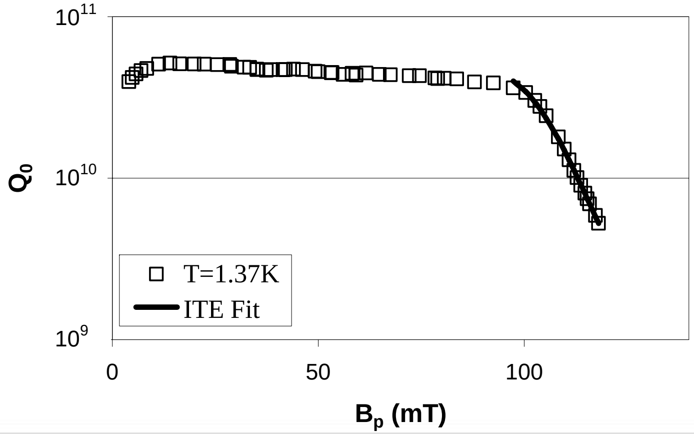
Role of the oxide layer

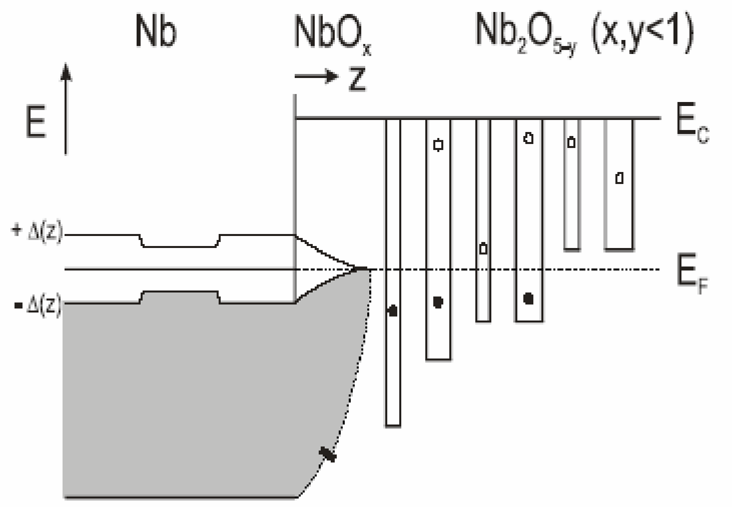
- Niobium is naturally covered by a dielectric amorphous Nb_2O_5 layer (3-5 nm thick) on top of a transition region (NbO_x x ~ 0.5 ÷ 2 suboxides) with metallic character

- Interface tunnel exchange model:

  ➢ Resonant energy absorption by quasiparticles in localized states in the oxide layer.

  ➢ Driven by electric field $E_{RF} > \frac{\varepsilon_r \Delta}{e\beta^* z^*}$



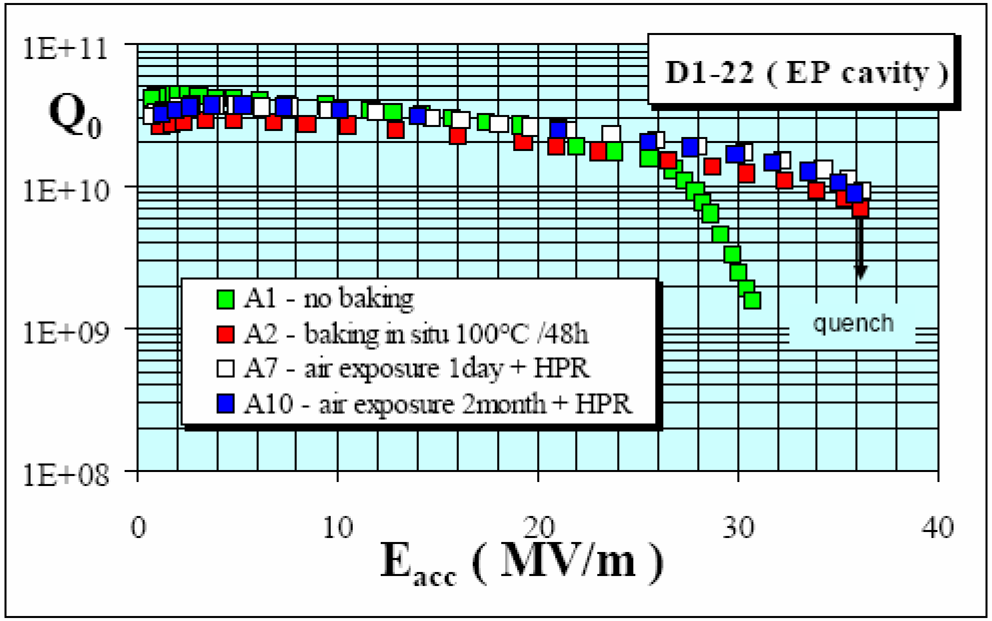


Band structure at Nb-NbO_x-Nb_2O_{5-y} interfaces

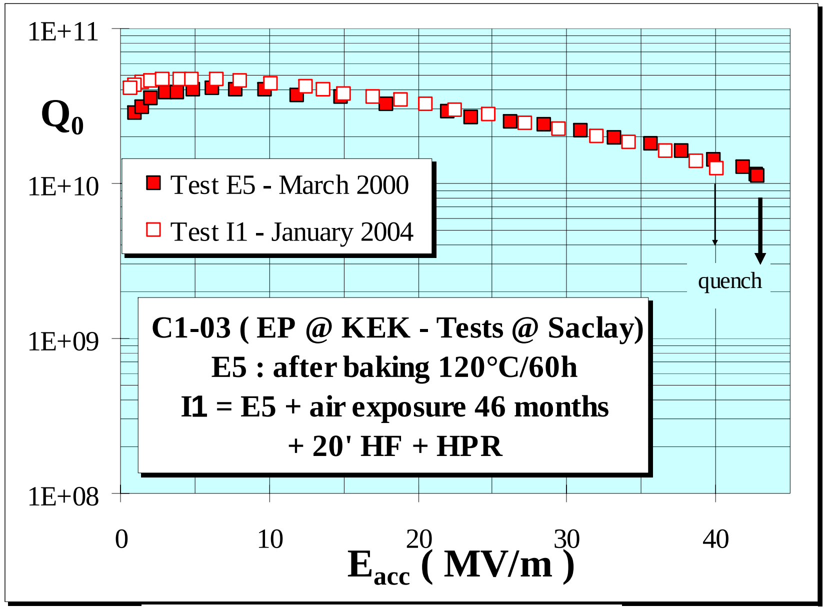
J. Halbritter - SRF 03 - MoP44

Exp. results against oxide layer (1)

- UHV baking effect stable after re-oxidation (air exposure for 2 months and HPR, HF rinse)



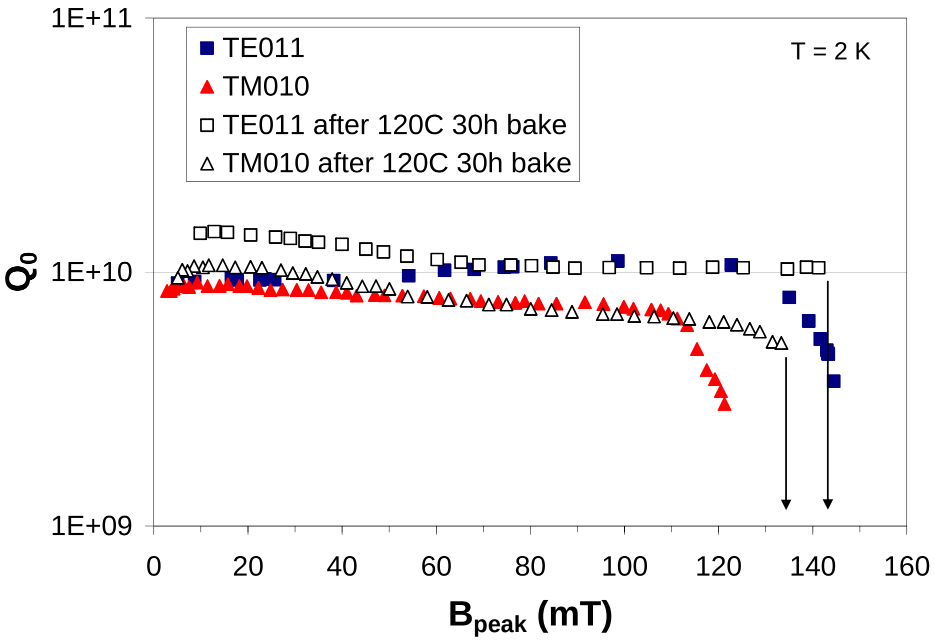
B. Visentin - SRF 03 – TuO01



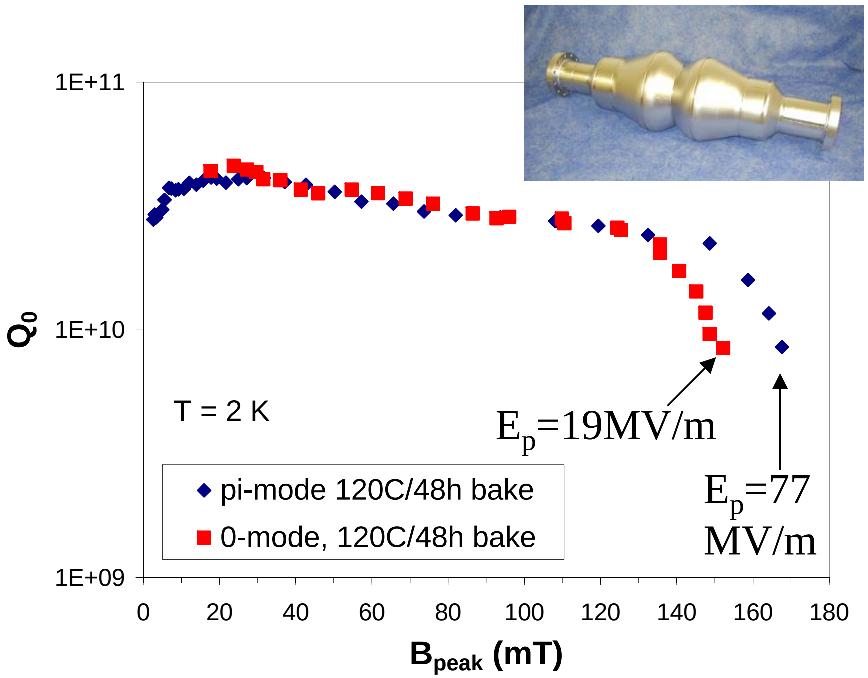
B. Visentin – Frontier Workshop – p. 94

Exp. results against oxide layer (2)

- Results show Q-drop driven by magnetic, rather than electric, field



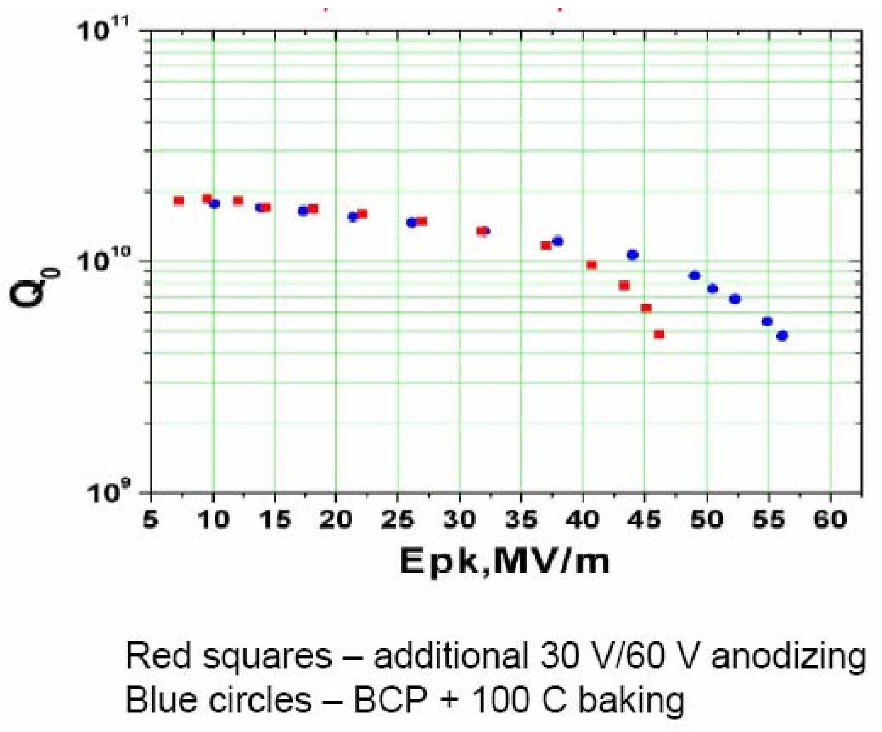
G. Ciovati and P. Kneisel, PRSTAB 9 (2006) 042001



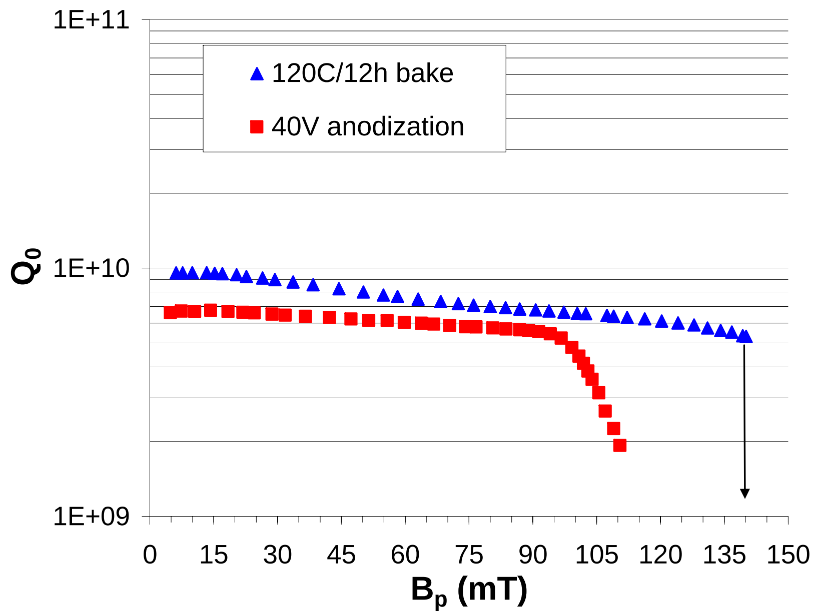
G. Ciovati, Ph.D. Thesis, Old Dominion Univ., 2005

Exp. results against oxide layer (3)

- Anodization experiments show that the baking effect occurs within a ~ 20 nm depth from the surface



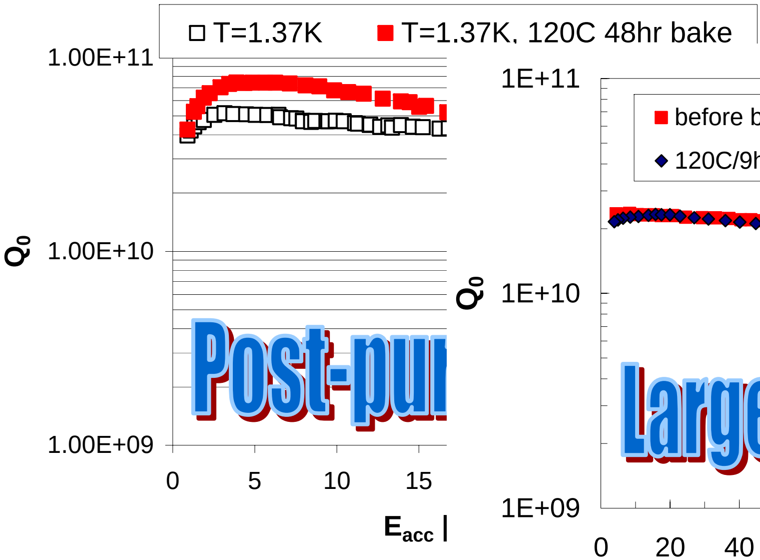
G. Eremeev and H. Padamsee, Physica C 441 No. 1-2 (2006) 62



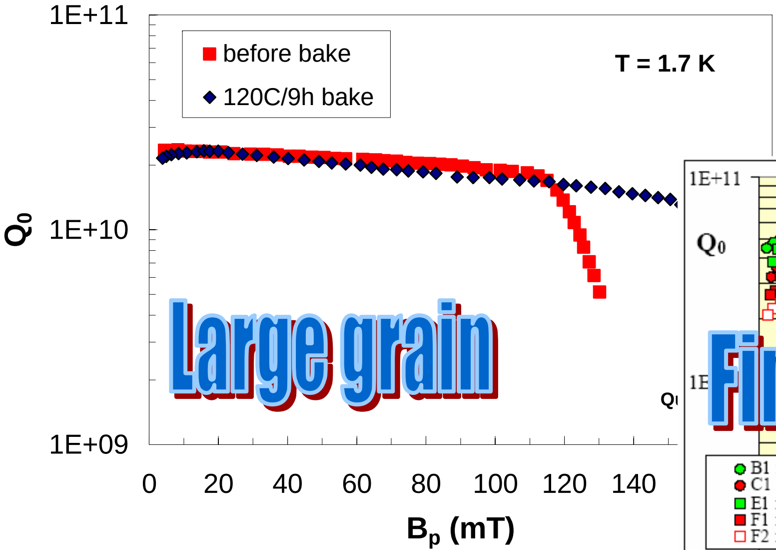
G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007) 062002

Role of grain size and chemical treat. (1)

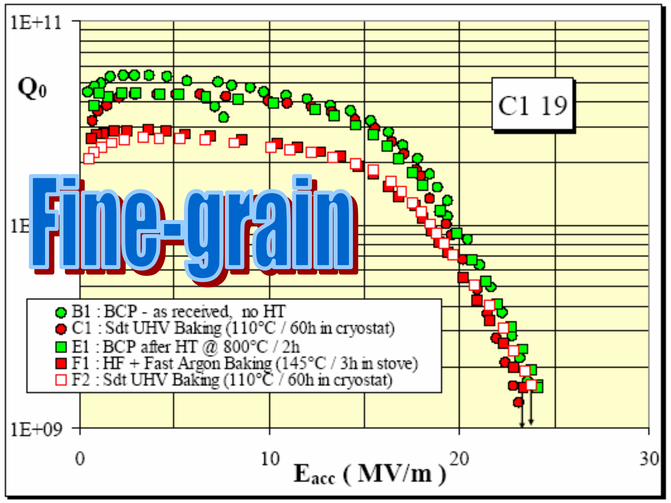
- On BCP treated surfaces, the baking improves Q-drop on:
  - Post-purified fine-grain Nb (final grain size ~ 1-2 mm)
  - Large grain Nb (cm-size)



G. Ciovati-J. Appl. Phy



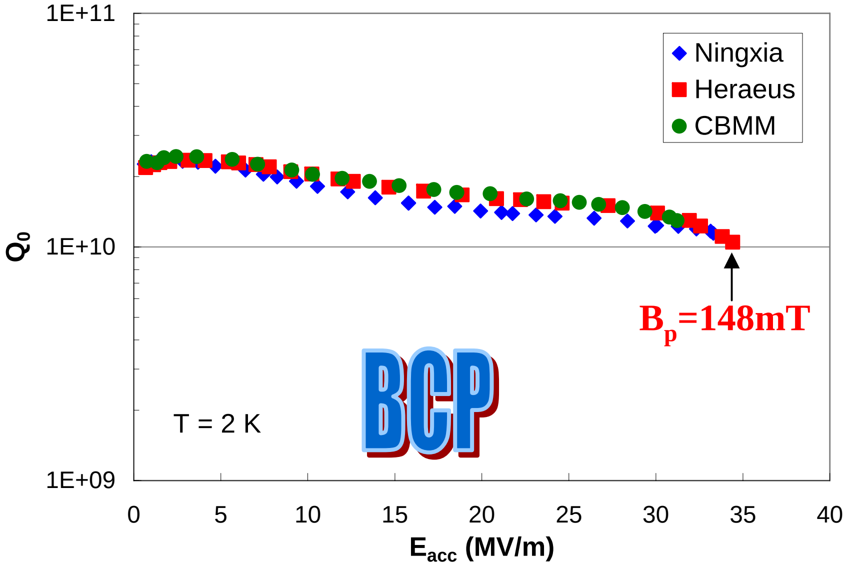
G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007)



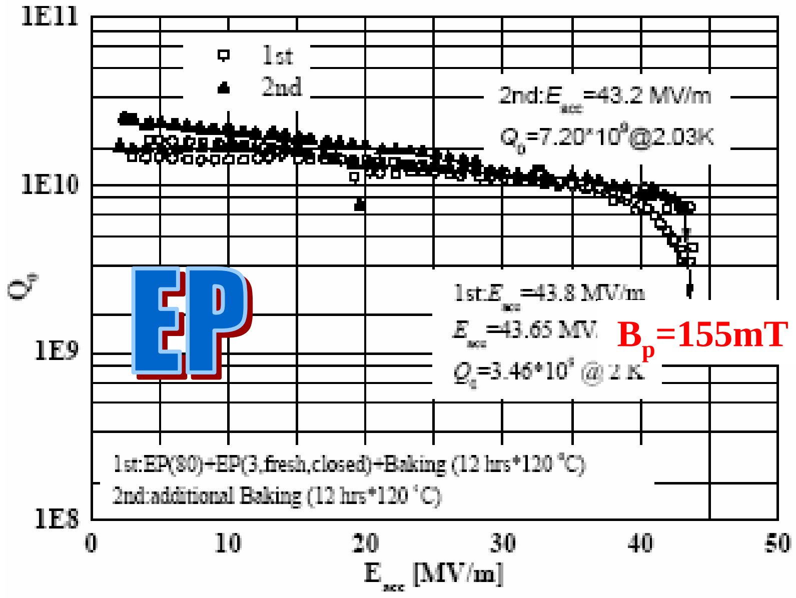
B. Visentin et al.- EPAC'06 – p.381.

Role of grain size and chemical treat. (2)

- Duration of 120° C baking on large-grain BCP cavities can be reduced to 12 h, while 48 h seems necessary for EP cavities



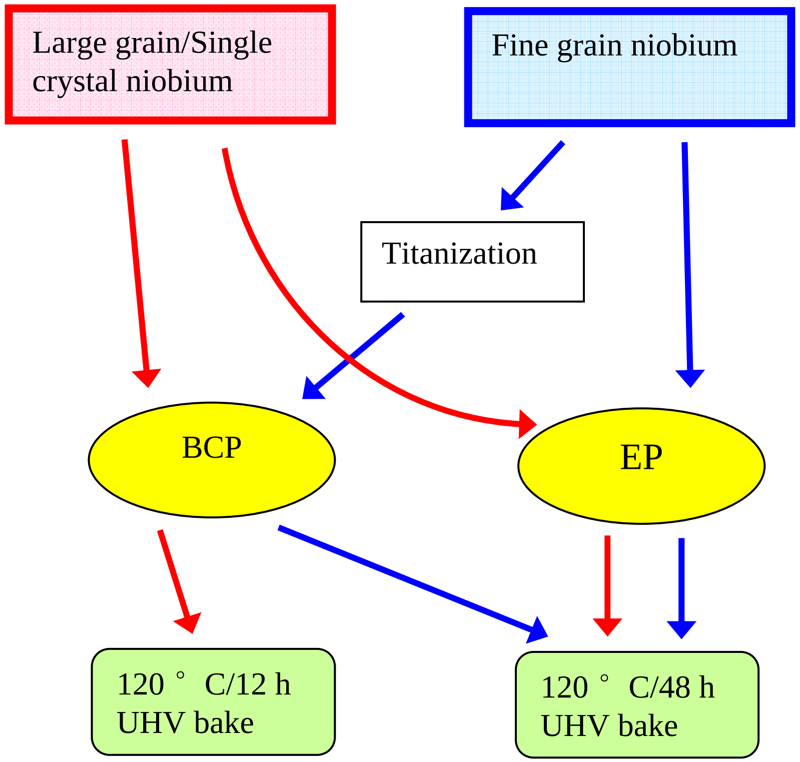
P. Kneisel, EPAC’06, WEXPA01



Z. G. Zong, PAC’07, p. 2143

Role of grain size and chemical treat. (3)

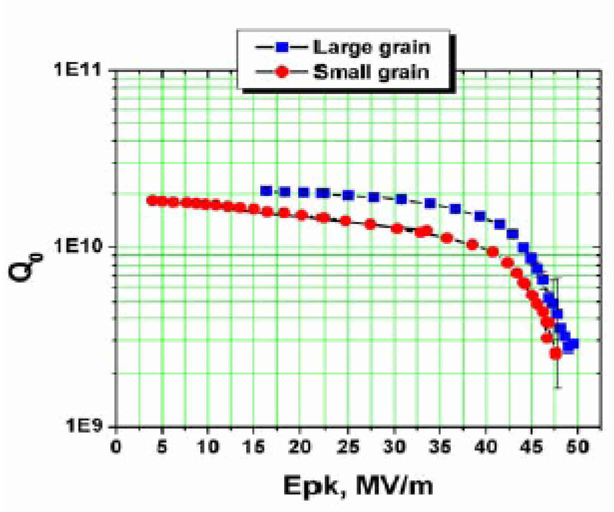
- Recipes necessary to overcome the Q-drop, depending on the starting material, based on current data:

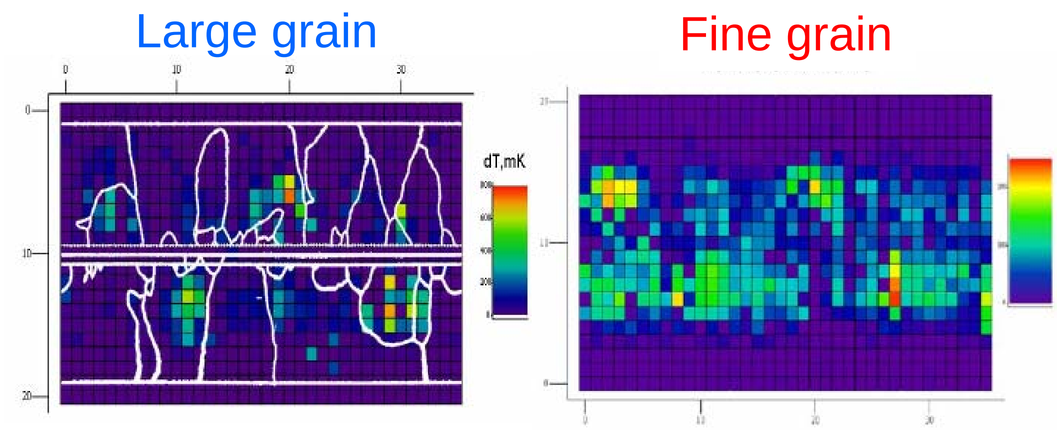


Role of grain boundaries

- Regions of degraded superconducting properties due to preferential segregation of impurities such as O, H, C.

Exp. results:





G. Eremeev and H. Padamsee, EPAC'06, p. 475

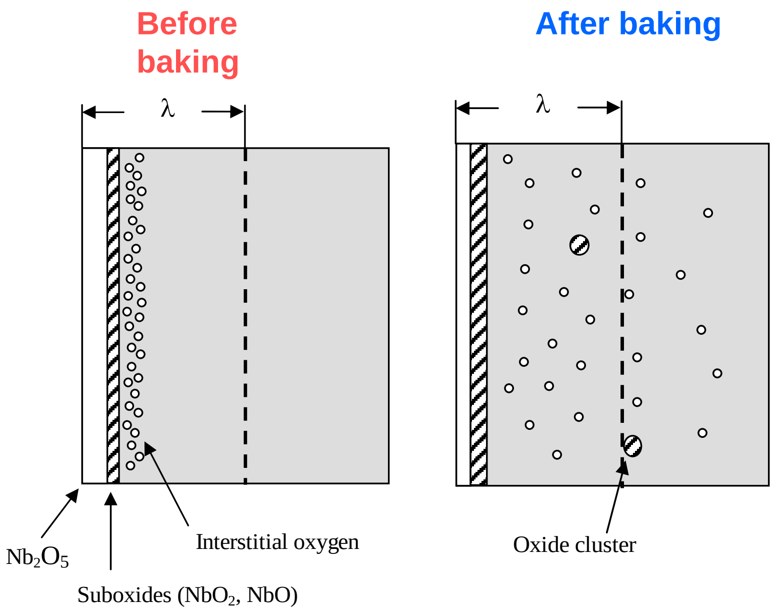
- Lower density of hot-spots has been observed in a large-grain cavity than fine grain
- In a recent study, the statistic of 33 RF tests on the same large grain cavity showed that ~ 30% of hot-spots occurred within 1 cm from a grain boundary*

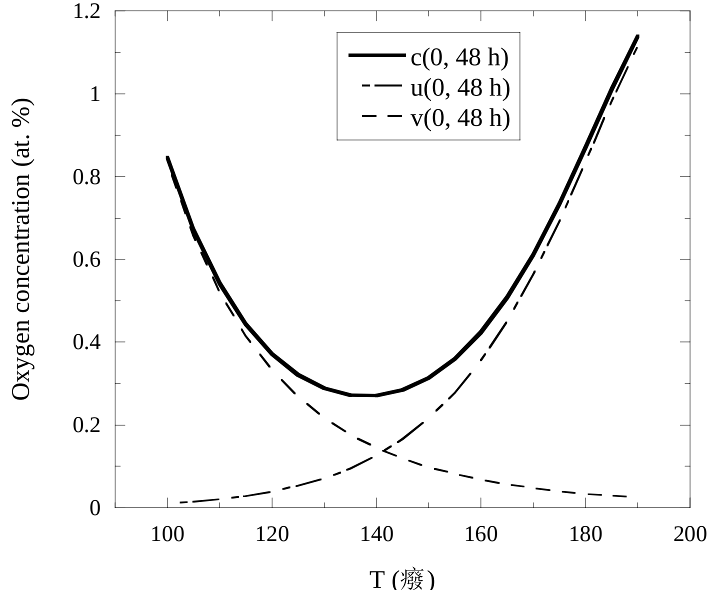
*G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007) 062002

Role of interstitial oxygen

- High concentrations of interstitial oxygen (~ 10 at. %) were found at the Nb/oxide interface

- Oxygen diffusion model:
  - Q-drop caused by local reduction of H_{c1} due to high O concentration

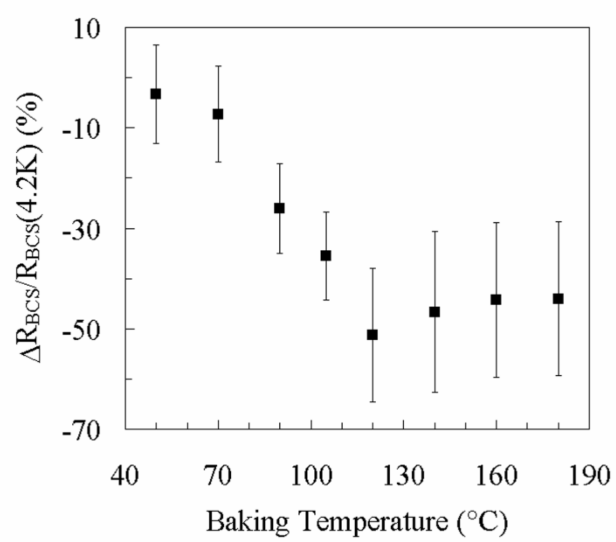




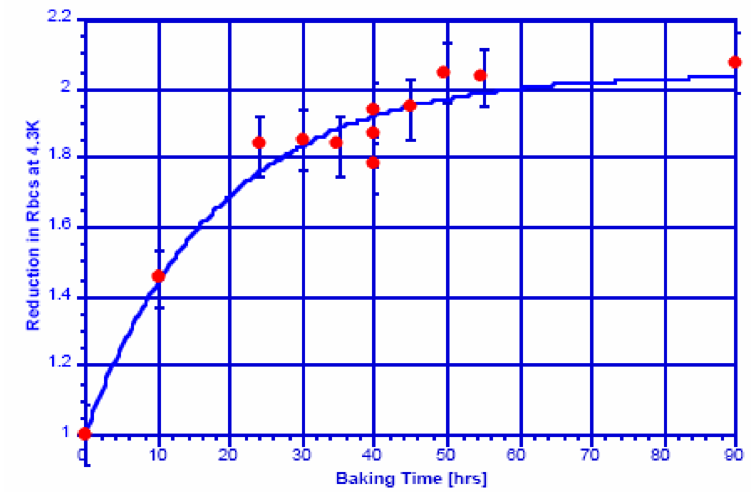
G. Ciovati, Appl. Phys. Lett. 89 (2006) 022507

Data supporting oxygen diffusion (1)

- Reduction of low-field R_{BCS} for increasing baking temperature and time (reduction of mean free path, increase of energy gap)



G. Ciovati, J. Appl. Phys. 96 (2004) p. 1591

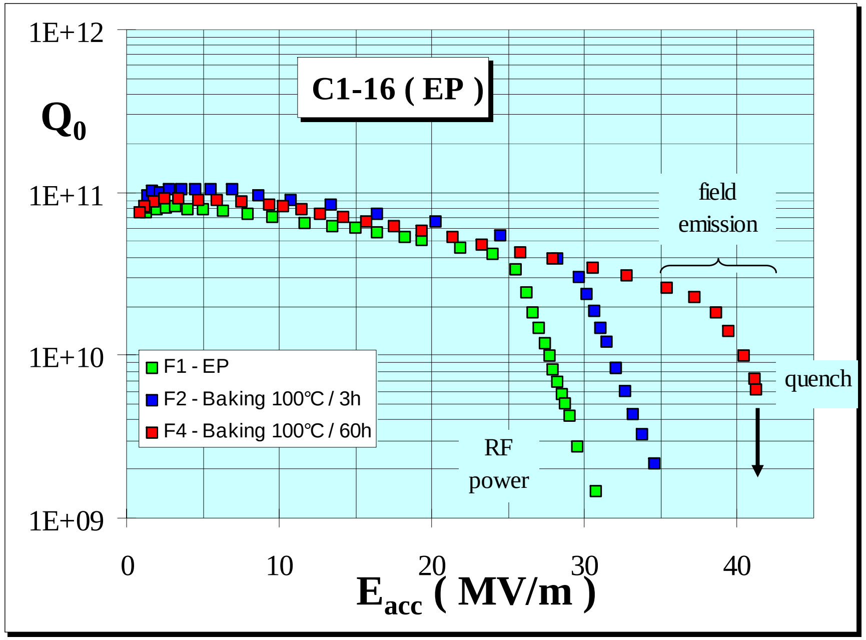


P. Kneisel, SRF'99, TuP044

Saturation of R_{BCS} reduction at ~ 140° C, ~ 48h measured on fine-grain Nb cavities

Data supporting oxygen diffusion (2)

- Q-drop onset increases for longer baking time

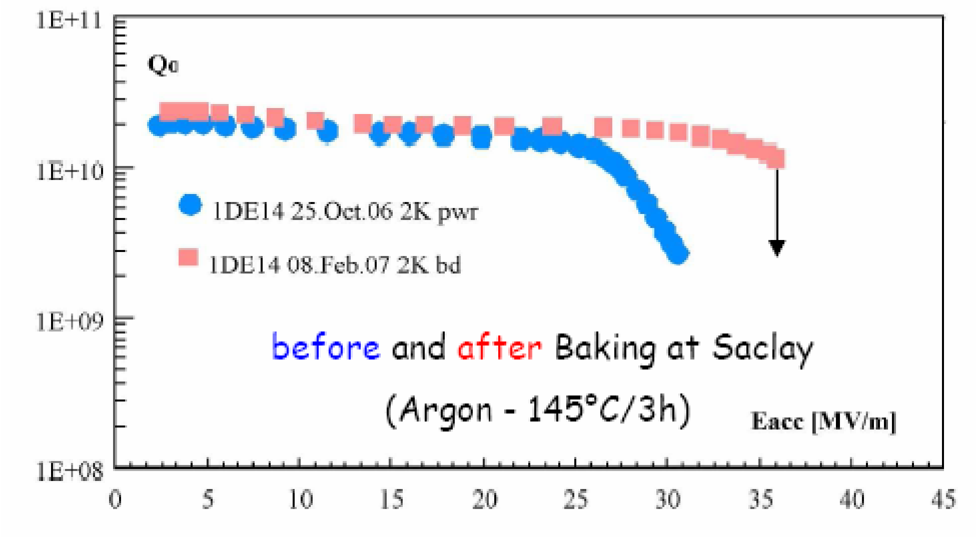


B. Visentin, Pushing the Limits of SRF Workshop, 2004, p. 94

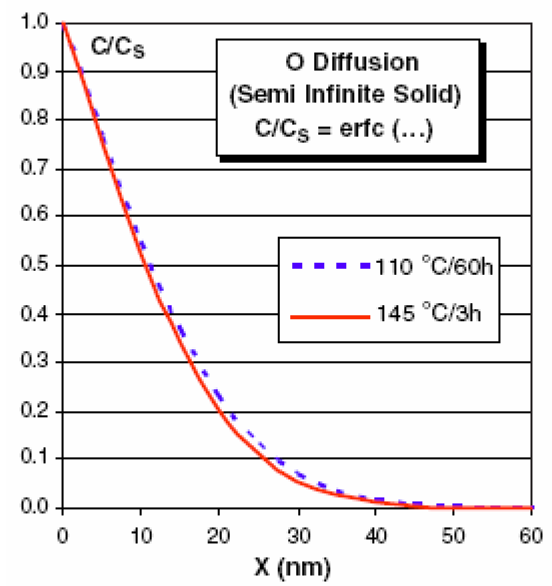
- Oxygen diffusion length at ~ 120 ° C/48 h compatible with RF penetration depth and anodization results

Data supporting oxygen diffusion (3)

- Baking in 1 atm Argon at 145° C/3h gives similar Q-drop improvement as 120° C/48h in UHV (similar oxygen diffusion depth)



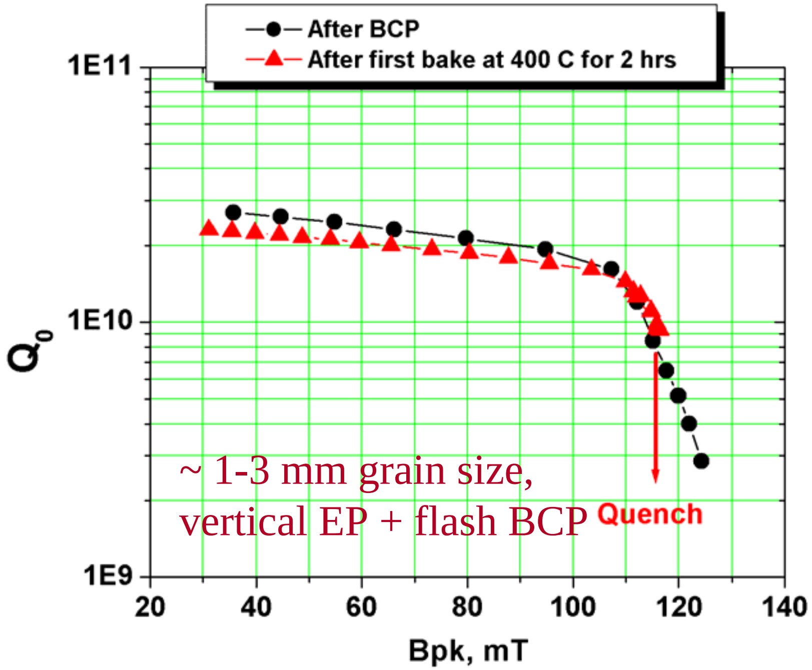
B. Visentin, TTC Meeting, FermiLab, April 2007.



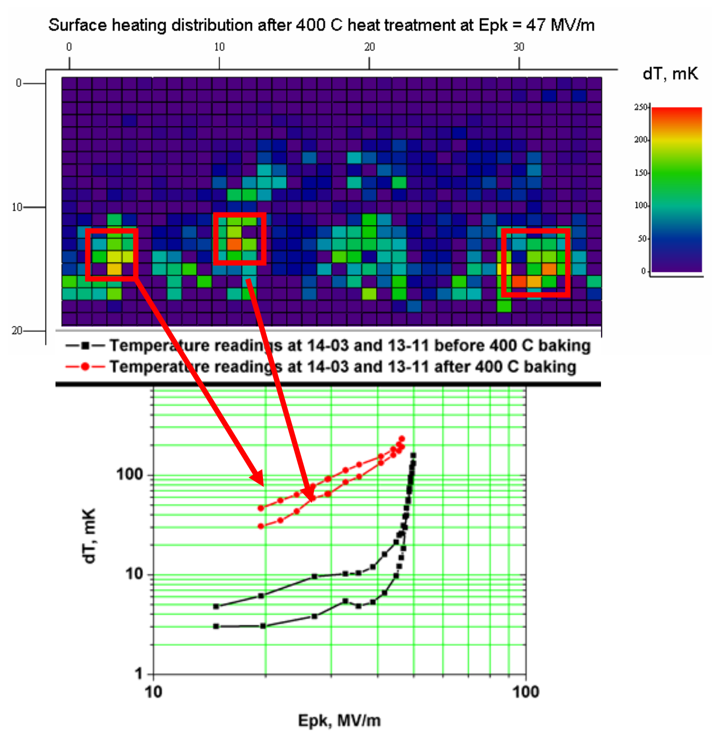
B. Visentin, Y. Gasser, J.P. Charrier, Physica C 441 (2006) p. 66

Data contradicting oxygen diffusion (1)

- By baking in UHV at 400° C/2h, oxygen diffuses to depths > λ and a thinner oxide layer (NbO) is left at the surface



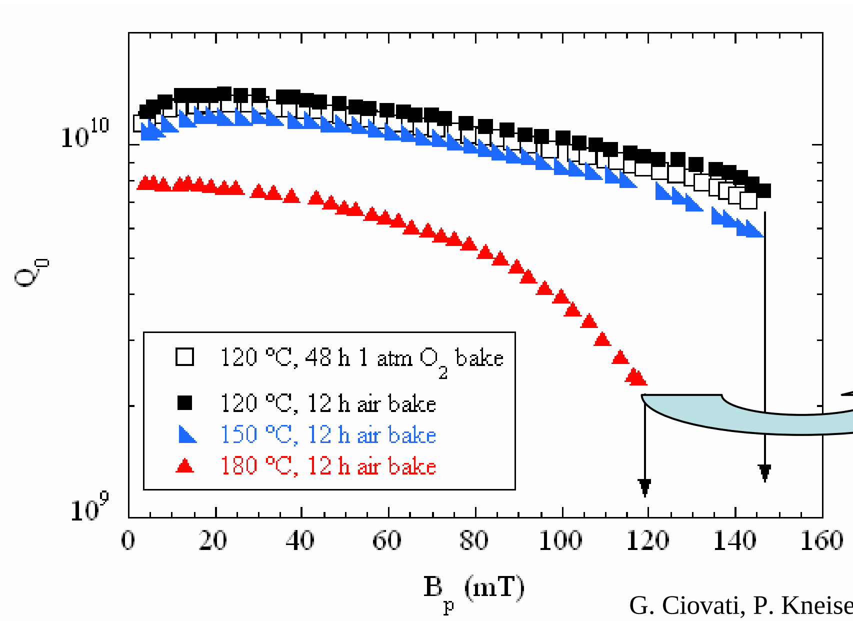
G. Eremeev and H. Padamsee, PAC'07, p. 2334

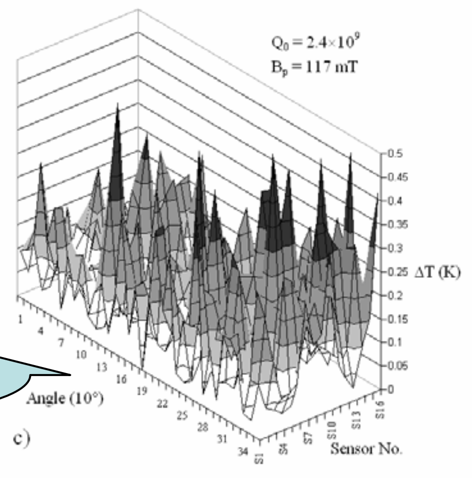


- Hot-spots with high R_{res} and quadratic losses after baking
- Hot-spots with Q-drop behavior still present

Data contradicting oxygen diffusion (2)

- Oxygen concentration near the surface and oxide layer thickness were increased by baking at 120° C/12h in 1 atm O_2 and in air up to 180° C a previously baked large grain cavity





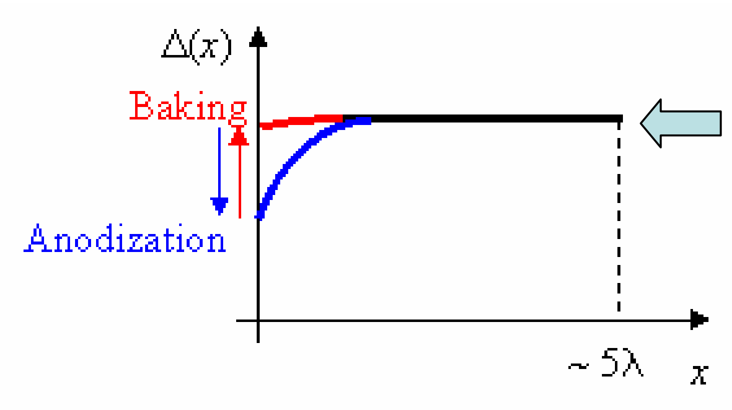
T-map after 180° C/12h air bake

G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007) 062002

- Q-drop not restored after baking in pure O_2 or air
- High R_{res} and quadratic losses after 180° C air bake

Role of the interface (1)

- In a systematic study* on the oxidation of a large grain cavity, it was found that baking and anodization affect the avg. value of the energy gap Δ over ~ λ [Obtained from BCS fit of R_s(T, 12mT)]
- Typical value of Δ/kT_c after chemical etching ~ 1.75



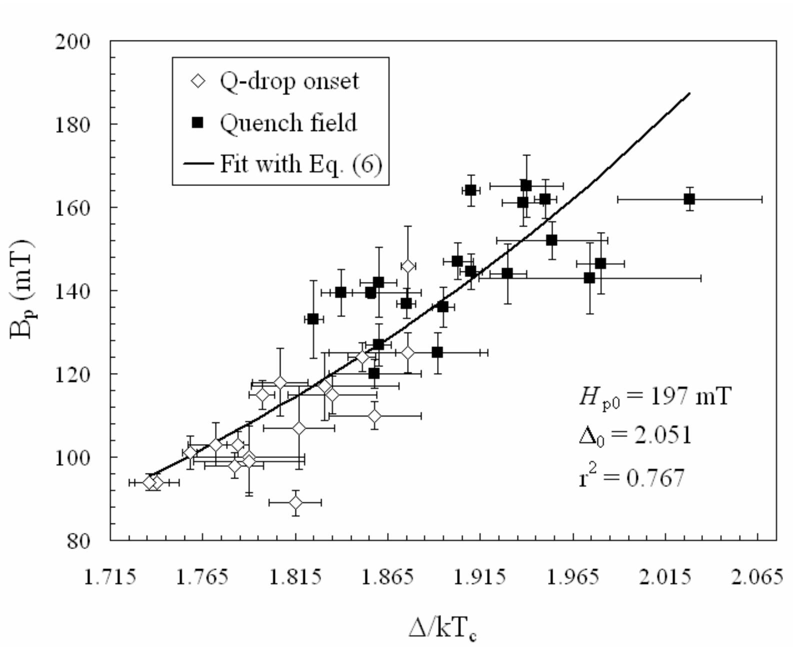
Δ/kT_c of pure Nb ~ 2.01

*G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007) 062002

- Baking for longer time increases Δ/kT_c up to ~ 1.95
- Anodization at higher voltages reduces Δ/kT_c down to ~ 1.75

Role of the interface (2)

- A correlation between Δ and Q-drop-onset/Quench-after-baking was found to be consistent with thermal feedback model*



G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007) 062002

Dependence of breakdown field# H_b on Δ:

$$H_b = H_{b0} e^{\frac{\Delta - \Delta_0}{2kT}}$$

H_{b0} ≅ critical field

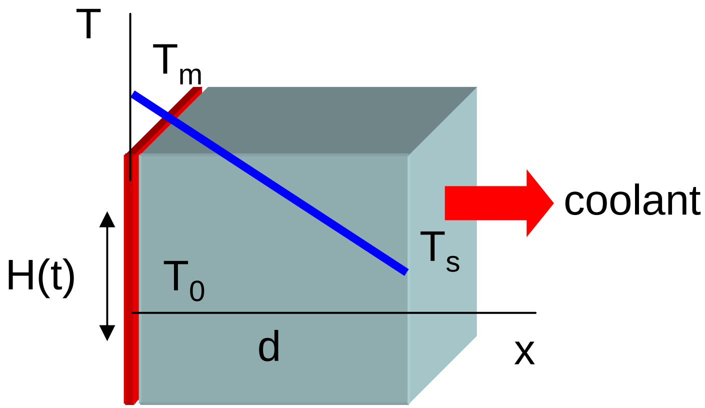
Δ_0 ≅ gap of pure niobium

H_b: breakdown of the Meissner state

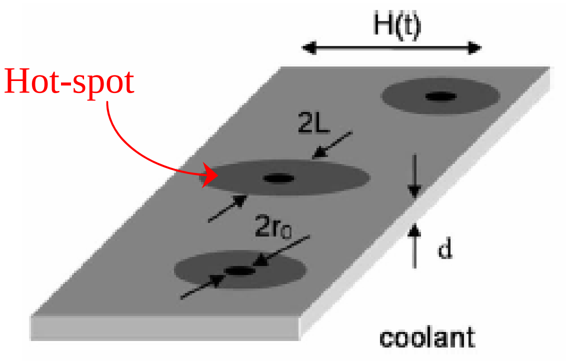
*A. Gurevich, Physica C 441 (2006) p. 38

#"Defect free" case

Hot-spots and thermal feedback



- Thermal feedback for uniform R_s does not reproduce the Q-drop
- Introducing "hot-spots" (regions of higher dissipation) makes it work



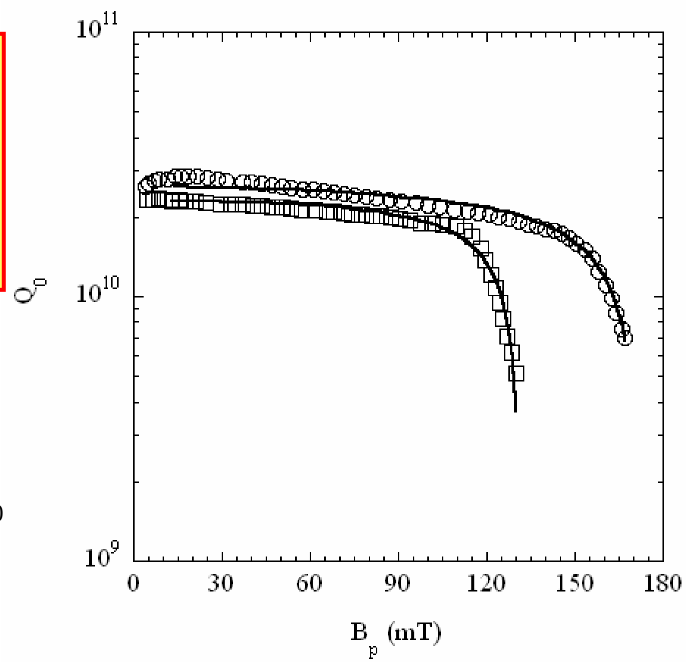
A. Gurevich, Physica C 441 (2006) p. 38

$$\frac{2B_p^2}{B_{b0}^2} = 1+g+u-\sqrt{(1+g+u)^2-4u}$$

$$Q_0 = \frac{Q_0(0)e^{-\theta}}{1+g\Big/\left[1-\left(B_p/B_{b0}\right)^2\right]}$$

3 fit parameters:

$g=\langle\eta\rangle\pi N_h L_h^2$ $\quad Q_0(0) \quad B_{b0}$



Conclusions (1)

Experimental results on Nb cavities show that:

- μm-scale surface roughness
- Nb_2O_5 oxide layer
- Grain boundaries

Do **NOT** play a dominant role in causing the Q-drop

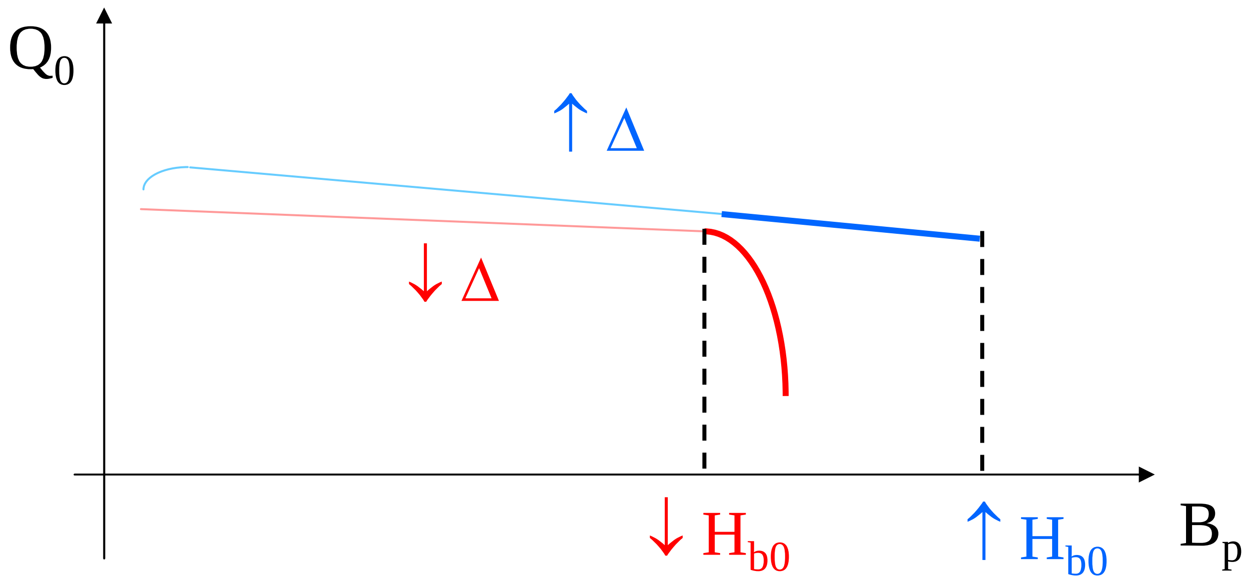
✓ The optimal baking procedure seems to depend on the metallurgical state (large-grain vs. fine-grain) and surface treatment (EP vs. BCP)

Conclusions (2)

- ✓ Q-drop and baking effect are related to changes up to a depth ~ 20 nm from the outer surface (interface?)
  - *A good amount of data indicates interstitial oxygen diffusion as the mechanism involved during baking but recent results are in contradiction*
  - *Oxygen is the impurity that has been looked at more systematically. The role of hydrogen (high concentration near the surface) is not quite clear*
- ✓ Q-drop is driven by high magnetic field
- ✓ Surface treatments which affect the energy gap also affect the Q-drop onset and the quench field after baking

Conclusions (3)

- ✓ The introduction of regions with higher dissipation ("hot-spots", observed experimentally) in a thermal feedback model gives a good description of $Q_0(B_p)$ curve. The same type of model explains the correlation between energy gap and "breakdown field" which leads to either Q-drop or quench depending on the thermal stability of the cavity



Conclusions (4)

- ✓ We have a good-working model which describes phenomenological aspects of Q-drop and baking effect

- ➢ It is not yet clear what physical entity is involved. In principle this should be easier to discover by surface analytical methods…

Let’s hear about it in the next talk!

Acknowledgements

G. Eremeev, A. Gurevich, P. Kneisel, G. Myneni, H. Padamsee, T. Saeki, B. Visentin

Thank you for your attention!

謝謝您的注意!