Review of high field Q slope, cavity measurements

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13th SRF Workshop
Oct. 15th-19th, 2007, Beijing, China
Tools

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

1J. 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
Nevertheless:

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

170 mT

BCP treated cavity (4÷8 μm step height)

Exp. results against surface roughness (1)

B. Visentin et al.-EPAC 02-THPDO013

- 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.

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

![SEM photo of typical EBW](image1)

![Graph showing experimental results against surface roughness](image2)

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

Courtesy T. Saeki
Role of the oxide layer

- Niobium is naturally covered by a dielectric amorphous Nb$_2$O$_5$ layer (3-5 nm thick) on top of a transition region (NbO$_x$ $\approx$ 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 $E_{RF} > \frac{\varepsilon_\Sigma}{\varepsilon F^* z}$

Band structure at Nb-NbO$_x$-Nb$_2$O$_{5y}$ 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)
Exp. results against oxide layer (2)

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


G. Ciovati, Ph.D. Thesis, Old Dominion Univ., 2005
Anodization experiments show that the baking effect occurs within a ~ 20 nm depth from the surface.


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)

![Graphs showing Q0 before and after bake](image)

G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007)
B. Visentin et al.- EPAC’06 – p.381.
• Duration of $120^\circ$ C baking on large-grain BCP cavities can be reduced to 12 h, while 48 h seems necessary for EP cavities
Role of grain size and chemical treat. (3)

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

- Large grain/Single crystal niobium
  - Titanization
  - BCP
  - 120 °C/12 h UHV bake

- Fine grain niobium
  - Titanization
  - EP
  - 120 °C/48 h UHV bake
Role of grain boundaries

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

Exp. results:

• 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

Data supporting oxygen diffusion (1)

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

Saturation of $R_{\text{BCS}}$ reduction at $\sim 140^\circ$ C, $\sim 48$h measured on fine-grain Nb cavities


P. Kneisel, SRF'99, TuP044
Data supporting oxygen diffusion (2)

- Q-drop onset increases for longer baking time

![Graph showing data for Q0 and Eacc (MV/m)]

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

- Oxygen diffusion length at \( \sim 120 \, ^\circ C/48 \, h \) 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.

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.

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

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

$\sim$ 1-3 mm grain size, vertical EP + flash BCP.

Thomas Jefferson National Accelerator Facility
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 O₂ and in air up to 180° C a previously baked large grain cavity.

- Q-drop not restored after baking in pure O₂ 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 $\Delta$ over $\sim \lambda$ [Obtained from BCS fit of $R_s(T, 12mT)$]
- Typical value of $\Delta/kT_c$ after chemical etching $\sim 1.75$
- Baking for longer time increases $\Delta/kT_c$ up to $\sim 1.95$
- Anodization at higher voltages reduces $\Delta/kT_c$ down to $\sim 1.75$

\(^*\)G. Ciovati, P. Kneisel and A. Gurevich, PRSTAB 10 (2007) 062002
Role of the interface (2)

- A correlation between $\Delta$ and Q-drop-onset/Quench-after-baking was found to be consistent with thermal feedback model.

\[ \Delta - \Delta_0 = kT \]

Dependence of breakdown field $H_b$ on $\Delta$:

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

$H_{b0} \approx$ critical field

$\Delta_0 \approx$ 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

\[ Q_b = \frac{Q_0(0)e^{-\gamma}}{1 + g\left[1 - \left(\frac{B_p}{B_{b0}}\right)^2\right]} \]

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
- $\text{Nb}_2\text{O}_5$ 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 \( \sim 20 \) 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.

![Diagram showing the relationship between $Q_0$, $B_p$, $H_{b0}$, and the energy gap $\Delta$. The diagram illustrates how changes in $H_{b0}$ affect $Q_0$ and $\Delta$.](image)
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


Thank you for your attention!

謝謝您的注意！