Q-Slope Studies at Fermilab: New Insight From Cavity and Cutouts Investigations

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• New experimental findings on Q slopes
  – Decomposition of the components of surface resistance ($R_{BCS}$ and $R_{res}$)
    • Shows which Q slope is due to what component
• New superconducting measurements
  – Low energy muon spin rotation
    • Baked/unbaked cutouts
    • N doped
• New proximity effect model of the high field Q slope
  – Evidence from cryogenic TEM investigations in cutouts
• New model of the 120C baking
  – Vacancy-based 120C baking mechanism and supporting evidence from cutouts
  – Suppression of the second phase of hydrides in direct observations
• Conclusions
• Using different temperature dependence to deconvolute the components of average surface resistance at ALL fields

\[ R_s(T) = R_{BCS}(T) + R_{res} \]

Due to thermally excited quasiparticles

Non-T-dependent, saturation value at \( T \rightarrow 0 \)
Measure $Q(E_{acc}, T)$ at many different $T<2.17K$ and $E_{acc}$

Can be fitted using both approximate formula $R_{BCS}(T)=A/T \exp(-\Theta/kT)$, and by more precise BCS calculation based on Halbritter’s program – virtually no difference in the results

A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)
Residual resistance

A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)

Contributes to the medium field Q slope

High field Q slope is clearly a residual resistance effect

For some treatments decreases at lower fields
Typically cited effect of 120C baking on the BCS surface resistance. A strong change in the field dependence due to 120C bake. More on the medium field Q slope – hot topic session on Thursday.
Field dependence of $R_{BCS}$ may be explained by the expected changes of pairing potential $\Delta=\Delta(H)$ in clean (unbaked) and dirty (120C baked) limits.
Instead of modeling the full temperature transfer with only $R_s = G/Q_0$ as an input use temperature mapping to measure the outside wall temperature.

Negligible effect on $R_{BCS}$ at $T \leq 2K$.

More – hot topic session on Thursday.
Correlation between medium and high field Q slopes in unbaked cavities

T-map data shows that local surface resistance in HFQS regime is highly correlated to Rs at lower fields (MFQS)

More info – please see [A. Romanenko et al, TUP101]
New cavity data allows to “filter” models

• High field Q slope is due to residual
  – Not SC gap closing, thermal feedback etc.
• Medium field Q slope is a combination of $R_{\text{BCS}}$ and $R_{\text{res}}$
  – Not due to the difference in Trf and Tbath
  – Correlation between high and medium fields in unbaked cavities
• Low field Q slope is likely due to residual
• Bulk muon spectroscopy
  – A. Grassellino et al, TUP031
• Low energy muon spectroscopy
  – A. Romanenko et al, TUP038
• Bitter decoration
  – F. Barkov et al, TUP016
Muon spin rotation

\[ N(t) = N_0 \exp\left(-t/\tau_{\mu}\right) \left[1 + a G(t)\right] + \text{Bkg} \]

Contains physics

\[ \omega_{\mu}(\tilde{z}) = \gamma_{\mu} B_{\text{loc}}(\tilde{z}) \]

Frequency – field amplitude
Damping – field non-uniformity
Muon spin rotation – measure $B(z)$

Superconductor in the Meissner State

$B(z)$

$B_{\text{ext}}$

$\omega_\mu(z) = \gamma_\mu B_{\text{loc}}(z)$
Use variable energy muons, which stop in the first ~100nm

![Graph showing normalized stopping distribution vs depth](image)

BCP and EP unbaked -> strong screening, excellent fit provided by the clean limit Pippard/BCS model

EP+120C bake-> strongly suppressed m.f.p., gradient of the m.f.p. from the surface, dirty limit

N-doped -> intermediate m.f.p., no gradient

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~15 nm - no screening

$mfp \sim 2$ nm at the surface, increasing deeper

$mfp > 400$ nm

Fit by Gaussian model for the field at the muon site – approximate, qualitative comparison
New model of the HFQS

• Main element: presence of small proximity effect coupled nanohydrides within the penetration depth
  – Q disease “in miniature”

• Consistent with all experiments, provides quantitative description

• Falsifiable
  – Testable predictions

Neither standard 800°C degassing nor “fast” cooldown help facilitate the removal of surface hydrogen.

Near-surface H-rich layer is still present after standard H degassing treatments.

C. Antoine et al, SRF’01

T. Tajima et al, SRF’03

Integrate the H diffusion over the time spent in the precipitation temperature range $T < 160K$ => $L > 1 \text{ um}$.

All free near-surface H will precipitate into hydrides.

TB9RI029 Cooldown

Typical fast cooldown of a cavity (FNAL)

Integrate the H diffusion over the time spent in the precipitation temperature range $T < 160K$ => $L > 1 \text{ um}$.

All free near-surface H will precipitate into hydrides.
Not 120°C baked sample

Nanohydrides upon cooldown

T = 300K

Interstitial hydrogen

Oxide

~50 nm

“fast” cooldown

T = 2K

Niobium hydrides

Note drastic change in the hydrogen-related m.f.p.
Proximity effect model

- Normal conducting hydrides of size $d$ are superconducting by proximity effect up to the field $H_b \sim 1/d$

- Excellent fits

\[ R_s \sim R_0 + R_n \times F_H(H_a) \]

Shape is determined by the distribution of hydride critical fields $H_b$

• So what happens with 120C bake?
• Positron annihilation spectroscopy: 120°C baking results in “doping” of the first ~50 nm from the surface with defects, most likely vacancies
  – EP itself introduces some vacancies in ~1 um – may be the reason for more efficient 120°C baking in EP cavities
Effect of 120°C baking

Free interstitial hydrogen

T = 300K

Oxide

Hydrogen is trapped by vacancies

T = 300K

Oxide

~50 nm

120°C baking

Effect of 120°C baking

Cooling down of 120°C baked niobium

Oxide

T= 300K

“fast” cooldown

Oxide

T= 2K

No/smaller hydrides are formed due to significant portion of hydrogen trapped

Note no change in the hydrogen-related m.f.p. – remains low
TEM evidence for nanohydrides

- Direct imaging of the cross-sections of cavity cutouts in cryo-TEM [see Y. Trenikhina et al, TUP043]

**Cold:** 120°C in situ bake for 48 hours
**Hot:** no such bake

Look at this area with subnanometer resolution in TEM at room AND T<100K temperatures

See also R. Tao et al, J. Appl. Phys. 114, 044306 (2013) and TUP042 for cryoimaging of H-reach Nb samples
Direct evidence for nanohydrides

Y. Trenikhina et al, TUP043

NED at room T Hot and Cold spot: NO additional reflections, just Nb

Hot spot NED at 94K: low T phase(s) along with Nb

“Statistics” of the second phase appearance: 44%-68% of the probed spots
Growing of hydrides at T=160K in a mechanically polished sample
Further evidence: 100K and 120C baking effect

• Second phase (lower concentration, lower temperature) forms at 100K
  – NOT observed on 120C baked samples
Summary

- Both residual and BCS surface resistances carry a field dependence
  - Analysis of Q slopes should only be done on components
- Mean free path/ Meissner screening is lowest, depth-dependent in 120C baked material, highest in unbaked, N-doping leads to the “intermediate” situation
- Nanohydrides may be an omnipresent entity not appreciated before
  - May be THE cause of the high field Q slope
    - Proximity-induced superconductivity breaks down at lower fields than host (Nb)
  - May be related to the residual resistance field dependence
    - Dominant source of the medium field Q slope in unbaked cavities
  - Absence of nanohydrides may be behind the effect of doping
  - Plausible mechanism of 120C baking -> trapping of hydrogen by vacancies -> preventing/decreasing size of nanohydrides
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