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ANALYSIS OF THE MEDIUM FIELD Q-SLOPE IN SUPERCONDUCTING CAVITIES MADE OF BULK NIOBIUM*

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Abstract

The quality factor of superconducting radio-frequency cavities made of high purity niobium is observed to decrease for increasing rf field in the medium field range (peak surface magnetic field between 20 and 80 mT). The causes for this effect are not clear yet. The dependence of the surface resistance from the peak surface magnetic field is often observed to be linear and quadratic. This paper will present an analysis of the medium field Q-slope data measured on cavities treated with buffered chemical polishing (BCP) at Jefferson Lab, as function of different treatments such as post-purification and low temperature baking. The data have been compared with a model involving a combination of the thermal feedback effect and of hysteresis losses due to "strong-links" formed on the niobium surface during oxidation.

Models for the medium field Q-slope

• Heating of the rf surface due to the niobium helium thermal resistance (global heating) [1]

$$R_s(T,B_p) = R_{s0}(T)\left[1+\gamma^*(T)\left(\frac{B_p}{B_c}\right)^2 + O(B_p^4)\right]$$ **Quadratic dependence**

$R_{s0}(T)=R_{BCS0}(T)+R_{res}$ is the surface resistance at 15 mT

$B_c(0K)=200$ mT is the critical field of niobium

$$\gamma^*(T) = \frac{\partial R_{s0}}{\partial T}\frac{B_c^2}{2}\left(\frac{d}{\kappa}+R_K\right) \approx R_{BCS}(T)\frac{B_c^2\Delta}{2kT^2}\left(\frac{d}{\kappa}+R_K\right)$$

• Global heating including an intrinsic nonlinear dependence of the BCS surface resistance due to pairbreaking effect [2]

$$R_s(T,B_p) = R_{s0}(T)\left[1+\gamma(T)\left(\frac{B_p}{B_c}\right)^2\right]$$ **Quadratic dependence**

$$\gamma(T) = \frac{R_{BCS0}(T)}{R_{s0}(T)}C\left(\frac{\Delta}{kT}\right)^2 + \gamma^*(T)$$

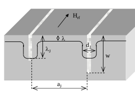
C=0.028 at 1.5 GHz, depends on material parameters. C is weakly dependent on frequency

• Hysteresis losses due to Josephson fluxons penetrating in the niobium, particularly at grain boundaries, above about $B_{c1J} \cong 30$ mT [3]

$$R_{hys}(B_p) \approx \frac{4}{3\pi}\frac{\omega}{J_{cJ}\left[1+(\omega/\omega_0)^2\right]^{3/2}}\frac{\lambda}{a_J}B_c\left(\frac{B_p}{B_c}\right) = R^1_{res}\left(\frac{B_p}{B_c}\right)$$ **Linear dependence**

ω_0 ($\cong$ 5 GHz) is a characteristic creation frequency. $J_{cJ} \cong 10^{11}$ A/m^2 is the Josephson critical current density. R_{hys} is predicted to be temperature independent for $T<T_c/2$

Schematic representation of "strong-links" in niobium



λ_J = 0.18 μm, Josephson penetration depth

a_J = 10-100 μm, "island" size

w = 0.001-0.1 μm, depth of oxide "cracks"

d_J = 2λ+oxide thickness = 0.082 μm

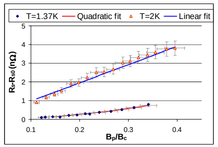
[1] J. Halbritter, Proc. of the 38th Eloisatron Workshop, Erice, Italy (1999), p. 9.

[2] A. Gurevich, Proc of the Pushing the Limits of SRF Workshop, Argonne, USA (2004) p. 17

[3] J. Halbritter, J. Appl. Phys **97**, 083904 (2005).

Data analysis

The plot of the experimental data of the surface resistance as function of B_p in the medium field range often shows a linear or quadratic dependence.



Average correlation factors (from 7 rf tests) for the linear and quadratic models at three different temperatures

Model	Avg. r^2 (2.2 K)	Avg. r^2 (2 K)	Avg. r^2 (1.37 K)
Quadratic	**0.958**	0.900	**0.973**
Linear	0.931	**0.966**	0.964

Data have been fitted including both linear and quadratic term

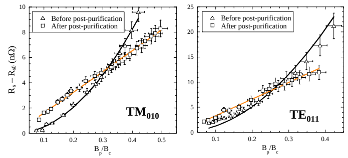
$$R_s(T,B_p) = R_{s0}(T) + R^1_{res}\left(\frac{B_p}{B_c}\right) + R_{s0}(T)\gamma^*(T)\left(\frac{B_p}{B_c}\right)^2$$

The fit parameters are R_{s0} and the slopes γ^* and R^1_{res}, with the constraint that the values have to be positive

TM_{010}/TE_{011} CEBAF single cell

Average values of the fit parameters at **2K** before and after baking for the TM_{010} mode (1.47 GHz) and TE_{011} mode (2.82 GHz)

	Before post-purification			
	Before baking		After 100-120 °C baking	
	TM_{010}	TE_{011}	TM_{010}	TE_{011}
R_{s0} (nΩ)	26.9 ± 0.2	51.5 ± 0.4	16.7 ± 0.2	36.3 ± 0.2
R_{res}^1 (nΩ)	7.46 ± 1.46	0.003 ± 3.7	27.1 ± 1.3	5.32 ± 2.40
γ^*	1.55 ± 0.11	2.76 ± 0.14	0.97 ± 0.13	3.34 ± 0.14
r^2	0.995	0.994	0.998	0.997
	After post-purification			
	Before baking		After 100-120 °C baking	
	TM_{010}	TE_{011}	TM_{010}	TE_{011}
R_{s0} (nΩ)	28.7 ± 0.1	79.3 ± 0.3	23.3 ± 0.3	52.7 ± 0.3
R_{res}^1 (nΩ)	16.4 ± 1.1	24.1 ± 2.8	34.1 ± 2.0	71.9 ± 1.5
γ^*	0.01 ± 0.07	0.00 ± 0.06	0.00 ± 0.13	0.25 ± 0.03
r^2	0.987	0.988	0.993	0.989



Theoretical estimates:

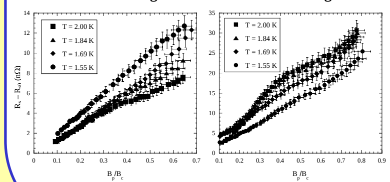
	Before post-purification		After post-purification	
	TM_{010}	TE_{011}	TM_{010}	TE_{011}
R_{res}^1 (nΩ)	198	284	20.0	28.4
γ^*	0.67	1.47	0.19	0.78
γ	2.33	3.40	1.72	2.59

2.2 GHz Single crystal CEBAF HG single cell

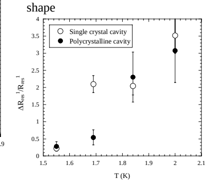
Average values of the fit parameters before and after baking at 120°C for 48 h at different temperatures

T (K)	R_{s0} (nΩ)	R_{res}^1 (nΩ)	γ^*	r^2
Post-purified single crystal cavity, before bake				
2	29.1 ± 0.2	12.3 ± 1.3	0.00 ± 0.06	0.983
1.84	18.3 ± 0.2	14.3 ± 1.1	0.00 ± 0.08	0.994
1.69	8.7 ± 0.2	11.8 ± 1.0	0.95 ± 0.14	0.997
1.55	4.2 ± 0.1	20.0 ± 0.6	0.00 ± 0.2	0.999
Post-purified single crystal cavity, after bake				
T (K)	R_{s0} (nΩ)	R_{res}^1 (nΩ)	γ^*	r^2
2	24.3 ± 1.1	55.4 ± 2.1	1.03 ± 0.05	0.980
1.84	15.0 ± 1.0	43.5 ± 1.5	1.77 ± 0.13	0.978
1.69	11.8 ± 0.2	36.7 ± 0.6	2.52 ± 0.08	0.995
1.55	10.1 ± 0.2	24.5 ± 0.8	2.81 ± 0.07	0.975

Before baking **After baking**



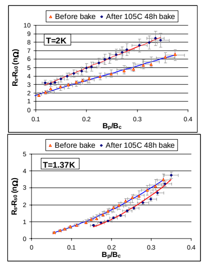
Change of the linear slope coefficient before and after baking for the single crystal cavity and a polycrystalline cavity of the same shape



Post-purified CEBAF single cell 1.47 GHz

Average values of the fit parameters before and after baking for 48h between 70°C and 180 °C

	Before baking	After baking
T = 2 K		
R_{s0} (nΩ)	21.6 ± 0.1	15.2 ± 0.2
R_{res}^1 (nΩ)	11.6 ± 1.1	20.2 ± 1.9
γ^*	0.04 ± 0.10	0.10 ± 0.24
r^2	0.952	0.950
T = 1.37 K		
R_{s0} (nΩ)	4.81 ± 0.03	4.82 ± 0.06
R_{res}^1 (nΩ)	2.27 ± 0.31	4.39 ± 0.47
γ^*	1.36 ± 0.14	1.46 ± 0.17
r^2	0.982	0.988



Theoretical estimates:

Temperature	R_{BCS} (nΩ)	R_K (m^2K/W)	κ (W/m K)	γ^*	γ
2 K	14	$1.06 \cdot 10^{-4}$	30	0.16	1.63
1.37 K	0.4	$4.67 \cdot 10^{-4}$	8	0.04	0.26

$R^1_{res} \cong 20$ nΩ (T-independent)

Summary

- The medium field Q-slope data are well described by the sum of a linear and quadratic dependence of R_s vs B_p
- The quadratic slope coefficient γ^* is related to overheating of the cavity rf surface
  - The addition of a term due to BCS pairbreaking effect overestimates the values obtained from the data fit: $C(\Delta/kT_c)^2 < 0.06$ for niobium#.
  - γ^* is reduced by post-purification due to the higher thermal conductivity and Kapitza conductance
  - The quadratic term dominates at frequencies > 2.2 GHz due to higher R_{BCS}
- The linear slope coefficient R^1_{res} could be explained by hysteresis losses
  - R^1_{res} is enhanced by baking, possibly due to a reduction of J_{cJ}
  - R^1_{res} seems to increase at higher frequencies, as predicted by the model
  - Under the assumption that the "island" size a_J is of the order of the grain size, an estimate of R^1_{res} gives good agreement with the fit result for post-purified cavities, but not for the "fine" grain and single crystal cavities
  - The linear slope seems to be smaller at lower temperatures, in the range 1.4-2K, but this dependence seems to be reversed by baking. The model predicts T-independent hysteresis losses.

#See Ref. [1].

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