CAVITY BAKING :
A CURE FOR THE HIGH ACCELERATOR FIELD Q_0 DROP

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Abstract

As we have reported before [1-2], the chemically polished Niobium cavities performances get improved by baking: the BCS resistance is decreased and the Q_o drop for high field is smoothed off.

We have recently achieved identical results in heating electropolished cavities, and these improvements have not been altered after the cavity air exposure, followed by a high-pressure water rinsing.

In addition, magnetic penetration depth measurements initially showed a bad RRR value on the surface and the increase of the electron mean free path after baking.

These results prove that, whatever the cavity polishing technique, even after a baking at low temperature, the intrinsic superconducting parameters are involved in the cavity performances improvement, rather than water or gases removed from the surface.

In this paper we also investigate the "global thermal instability" as a model to explain the Q_o drop.

1. INTRODUCTION

In 1998, we first discovered a new method [1-2] to improve the quality factor Q_0 at high gradients for an unloaded cavity by using a moderate heat treatment (100°C < T < 170°C for 48 hours). In this experiment, the surface treatment of the 1.3 GHz Niobium cavity was a buffer chemical polishing (BCP) using the classical "FNP" acid mixture ($HF/HNO_3/H_3PO_4$:1/1/2 in volume). After initial RF measurements, the cavity was baked in-situ, i.e. on the test bench and under vacuum pumping, and it was re-tested. New measurements then showed both the Q_0 slope and the R_s decrease at 4.2K. We also verified successful effect of baking on a Niobium coated Copper cavity [3], but the phenomenon origin seems different from a Nb cavity.

In the same period, the KEK group proved the superiority of electropolishing (EP with HF/H_2SO_4:1/10 acid mixture) over the chemical polishing for suppression of the steep Q_0 drop [4-5].

2. BAKING EFFECT ON Nb CAVITIES

2.1 Q_0 drop improvement and polishing methods

To determine if a surface pollution by specific chemical waste was possible, several cavities have been chemically polished with different mixtures [6]:

- $HF/HNO_3/H_2SO_4$:1/1/1 or 1/0.5/9 (FNS), and
- HF/HNO_3:1/9 (FN)

All these cavities show roughly the same Q_o drop (Fig.1), and the slope is improved after baking as for the FNP polishing (Fig.2).

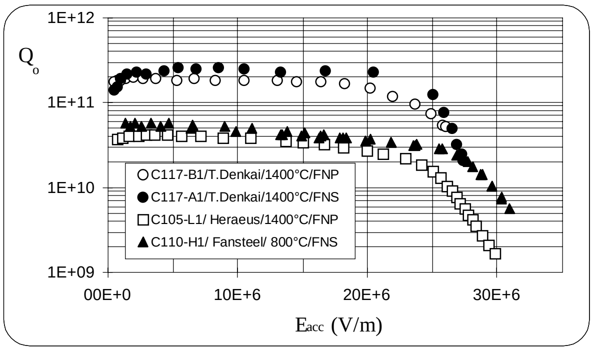

Figure 1: Comparison of different BCP acid mixtures (FNP and FNS).

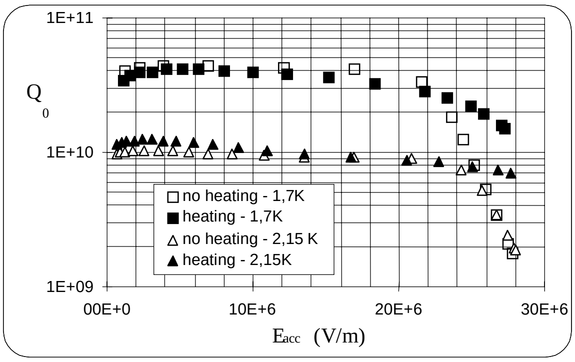

Figure 2: $Q_0(E_{acc})$ @1.7K and 2.15K for a BCP cavity (C1-05) before and after baking (105°C for 50hrs). All curves are limited by a thermal quench.

In the mainframe of the DESY/CERN/Saclay collaboration [7], it has been possible to test in our laboratory an electropolished cavity built at DESY and

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electropolished (100 µm) at CERN (D1-22 or 1S2 according to the DESY denomination). This cavity shows, as BCP cavities, a steep Q_o drop with a 31 MV/m power supply limitation. After baking (105 °C for 50 hours) we observe the slope improvement and the quench limitation at 35 MV/m (Fig.3). The beneficial effect seems greater: the same improvement on Q_o slope is obtained with less heating time.

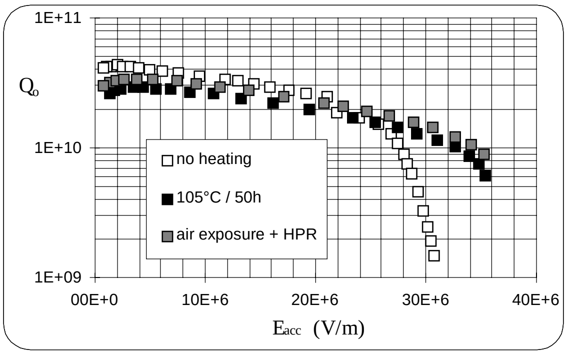

Figure 3: $Q_0(E_{acc})$ @1.7K for the EP cavity (D1-22) before (power limitation) and after heating (quench).

So, whatever the polishing method, we observe the same phenomenon. We can then put forward the idea that in KEK experiments, where the wet cavity is heated during the pumping (80°C for 20 hours), the baking is also responsible for the slope vanishing rather than the different polishing method.

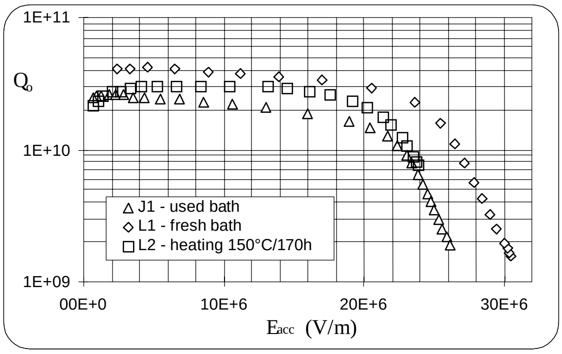

Figure 4 : Quench limitation on a BCP cavity (C1-05) can be shifted by using of a fresh acid bath, or after baking on a long time. All curves are limited by a quench.

At the present time, the advantage of electropolishing on the BCP is to push away the quench limitation to higher accelerator field values. Nevertheless, a defect free cavity has been got yet with chemical polishing [8], and as for us we have several times observed the quench limit improvement on a BCP cavity by using a fresh acid bath, or its degradation after baking for a long period (Fig.4). These observations show that the quench limitation can be shifted on a BCP cavity and we think that it will possible to find a way to reach values higher than 30 MV/m.

The Q_o improvement after heating is conserved, even after the cavity opening in a class 100 clean room, a high pressure rinsing (HPR) and the dust-free air drying for three hours before the vacuum pumping (Fig.3). This gives a clear indication that adsorbed water and gases on the surface are not involved in the Q_o drop.

2.2 Surface resistance

The other identified effects on a heated cavity [1-2] are the decrease of the surface resistance R_s at 4.2K up to a factor of two (Fig.5-9), and the slight increase of Rs at 1.5K

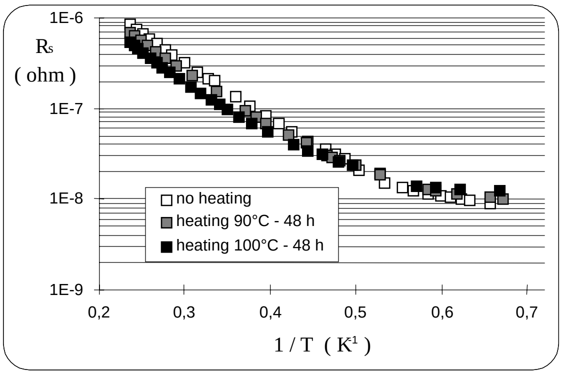

Figure 5: Surface resistance evolution after successive cavity heatings.

R_s is the sum of a residual resistance R_{res} (temperature-independent) and the BCS resistance. In the Bardeen-Cooper-Schrieffer theory R_{BCS} can be expressed by :

$$R_{BCS} = \frac{A\omega^2}{T} e^{-\Delta/kT}$$

where A depends on the superconducting material, especially on its magnetic penetration depth λ. So to explain R_{BCS} behaviour, λ measurement appears crucial to see its possible change after baking.

3. MAGNETIC PENETRATION DEPTH

The penetration depth of the magnetic field gives us information about the superconducting surface layer, because λ is related to the electron mean free path through the formula :

$$\lambda = \lambda_L \sqrt{1+\xi_F/l} \quad \text{where} \quad \xi_F = \pi\xi_0/2$$

λ_L is the London penetration depth and ξ_F is the coherent length of the Cooper electrons pair [9] (λ_L=32 nm, ξ_F=62 nm for Nb when T=0 and $l \to \infty$).

Furthermore, the penetration depth changes with the temperature :

$$\lambda(T,l)=\frac{\lambda(0,l)}{\sqrt{1-(T/T_C)^4}}$$

At temperatures close to T_c, this change is large enough to affect the resonant frequency by the size variation of the cavity. The frequency perturbation is given by

$$\frac{\Delta f}{f}=\frac{X_S}{2R_SQ_0} \quad \text{with} \quad X_S=\omega\mu_0\lambda$$

where X_s is the imaginary component of the surface impedance. The penetration depth change can be directly related to the frequency change [10] by the formula:

$$\Delta\lambda(T,l)=\frac{G}{\mu_0\pi f^2}\Delta f \quad \text{with} \quad G=R_SQ_0$$

where G is the geometry constant of the cavity.

So to determine the λ parameter, we have measured the cavity eigenfrequency change versus the temperature, between 7K and the critical temperature T_c = 9.2K, where the λ(T) variation is the most important.

3.1 Experimental setup

The frequency of the RF source (250W linear amplifier) is kept at the peak of the cavity resonance by a phase lock feedback in using a voltage-controlled oscillator (VCO).

A frequency counter measures the cavity frequency (±10Hz). The temperature is measured with a calibrated Germanium resistor set near the upper cavity iris. Carbon sensors control the temperature homogeneity on the cavity surface.

The cavity temperature increases from 4.2K up to T_c (for 2 hours) by means of a resistive heater that slowly warms up the He gas, surrounding the cavity, above the liquid helium bath. The cryostat is open to the atmospheric pressure to avoid a frequency shift due to the pressure variation.

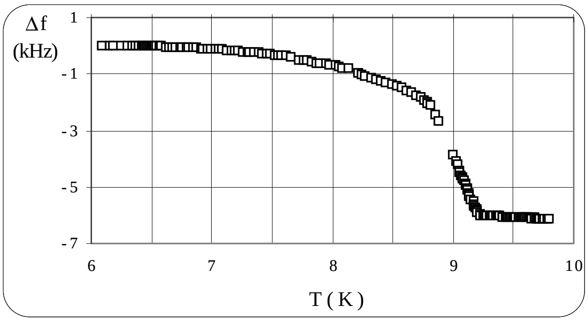

Figure 6 : The cavity frequency changes when the surface temperature increases up to T_c.

The acquisition of parameters (f,T) is performed in using a Labview program. We can set the time between two data records from 20s down to 1s: that is necessary for the fast frequency change when the temperature is near T_c (Fig.6).

3.2 Experimental results

The critical temperature value is determined experimentally from the f(T) curve (Fig. 7).

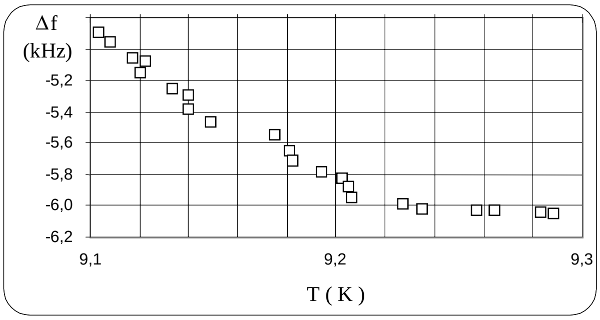

Figure 7 : Critical temperature determination.

According the BCS theory the Δλ variation versus $[1-(T/T_c)^4]^{-1/2}$ is linear with a slope λ(0,*l*) (Fig. 8). The measurements are performed on six cavities (chemically and electropolished).

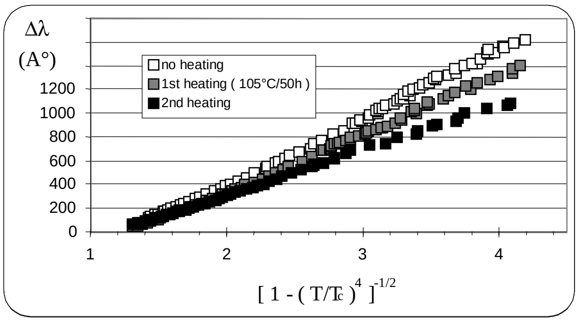

Figure 8 : Penetration depth change after successive baking (D1-21).

- before heating, penetration depth measurements (Fig.9), corresponding to cavities submitted to a high temperature treatment for purification with Ti getter, give high λ(0,*l*) value (>60nm). These values agree with a very short surface mean free path (*l*<25nm) and with a very low residual-resistivity-ratio on the surface (RRR_{surf} < 10) compare to the bulk value [11] (RRR_{bulk} > 200). Similar results have been observed before. The explanation proposed by authors for this unexpected behaviour is either the thermal faceting and the surface roughness [12] developed during the Nb heat treatment to high temperature or inhomogeneities [10-13] induced by the Nb oxydation, O and H dissolution during the cooling down.
- among the six cavities, three of them have been heated (C1-05, C1-18, D1-21/1S1). In each case, T_c is unaltered. We observe (Fig.8-9) the λ(0,*l*) decrease after cavity

baking, likely due to the less stress induced by the Nb_2O_5 on the superconducting layer: the oxide thickness reduction is observed by surface analysis on heated Nb samples [14].

3.3 Correlation between R_{BCS} and $\lambda(0,l)$

To verify the good agreement between the different experiments, we have plot on Fig.9 the R_S measurements at 4.2K versus the $\lambda(0,l)$ values achieved from the f(T) analysis. The curve behaviour seems consistent with the theory [9] and show a minimum predicted around $\lambda(0) \approx$ 45nm ($l \approx \xi_F$).

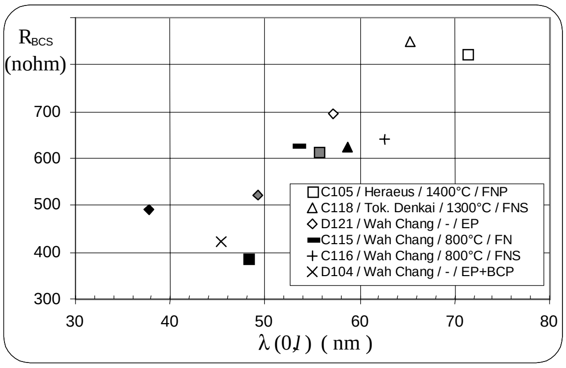

Figure 9 : Dependence of the Nb surface resistance @T=4.2K on the mean free path through $\lambda(0,l)$. White, grey or black colouring are related with successive heating on the cavities.

4. GLOBAL THERMAL INSTABILITY

The unchanged value of T_c and the penetration depth decrease after heating can not involve the O diffusion inside the bulk material and the NbO layer in the slope origin as alleged before [2]. To attempt an other explanation, we have investigated the "thermal feedback" possibility [15].

In this model the temperature dependence of the surface resistance is taken in account through:

$$R_S = R_0 + \frac{\delta R_S}{\delta T}\Delta T \ ,$$

R_0 is the surface resistance at low accelerator field, and ΔT is the temperature variation on the cavity inner wall due to the increase of the RF power inside the cavity.

We can express ΔT by:

$$R_{therm}\Delta P = \left(\frac{l_b}{\kappa_b} + \frac{1}{h_K}\right)\frac{R_S H_S^2}{2} ,$$

where R_{therm}, l_b, κ_b and h_k are respectively the thermal resistance, the thickness, the thermal conductivity and the Kapitza conductance of the Niobium.

After development the surface resistance get:

$$R_S = \frac{R_0}{1 - CE_{acc}^2} ,$$

$$\text{with} \qquad C \approx \frac{1}{2}\left(\frac{4.10^{-9}}{\mu_0}\right)^2 \frac{\delta R_S}{\delta T}\left(\frac{l_b}{\kappa_b} + \frac{1}{h_K}\right) \qquad (1)$$

On figures 10 and 11 we can see the good agreement between the experimental data and the theoretical equation where C is the adjustable term. After baking the $R_s(E_{acc})$ slope is smoothed off and of course the C parameter (proportional to $\delta R_s/\delta T$) decreases. That is consistent with the observation of A parameter decrease in the R_{BCS} ($\delta R_s/\delta T \propto A$).

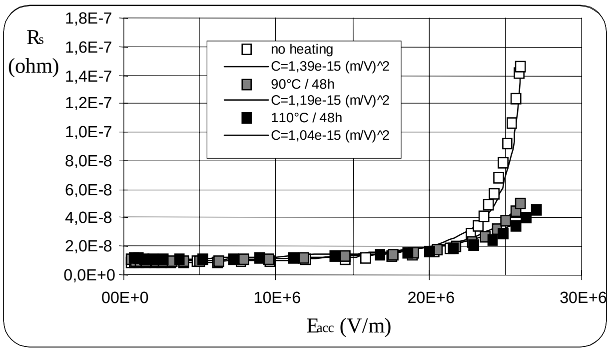

Figure 10 : Experimental data of the C1-05 BCP cavity fitted by $R_s=R_0/(1-CE_{acc}^2)$, before and after baking.

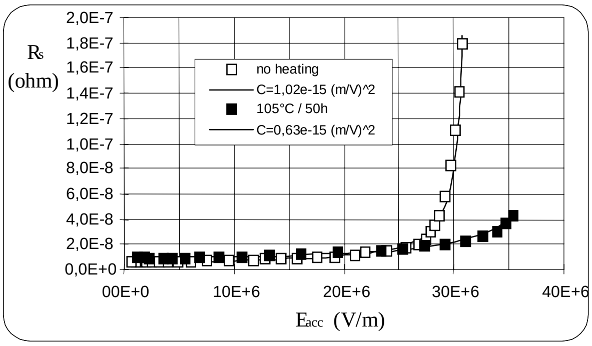

Figure 11 : Experimental data of the D1-22 EP cavity fitted by $R_s=R_0/(1-CE_{acc}^2)$, before and after baking.

So after baking the change in $\lambda(0,l)$ value could be imply not only the R_{BCS} decrease, but also the Q_o slope vanishing.

The theoretical fit and the C determination have been achieved, before and after heating, for different cavities in term of Nb thickness and high temperature treatment. On Fig.12 these results are plotted versus the $\delta R_s/\delta T$ values, determined from the $R_s(T)$ data. We found indeed proportionality between the C parameter and $\delta R_s/\delta T$.

Unfortunately, this proportionality factor ($\approx 2.10^{-8}$) is higher than the calculated factor around 2.10^{-9} (Eq.1) by using estimated values for κ_b = 15 (5) W/m.K and

h_k=7.10^3 (5.10^3) W/m^2.K according the heat temperature treatment of the cavity.

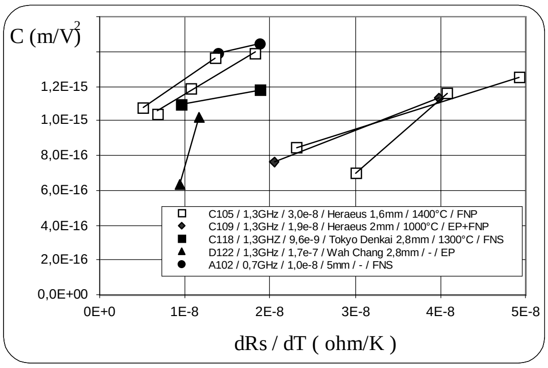

Figure 12 : Experimental correlation between C and $\delta R_s/\delta T$, before and after cavity baking.

5. CONCLUSION

The new prospective result on the baking effect, discussed in this paper, allow the following statement:

- the baking is also effective on the electropolished cavities that initially show the same Q_o drop as the BCP cavities,
- the water and adsorbates on the cavity surface are not the cause of the Q_o slope,
- the λ superconducting parameter is modified after baking. The decrease of the surface penetration depth is consistent with the experimental observation of the R_{BCS} decrease, and could also explain the high fields Qo drop by a global thermal instability.

Baking appears as the necessary ultimate step in the surface treatment of Nb cavities, and has to become part of the usual process.

6. ACKNOWLEDGEMENT

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