IMPROVEMENTS OF SUPERCONDUCTING CAVITY PERFORMANCES AT HIGH ACCELERATING GRADIENTS

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Abstract

A moderate heating (170°C - 70 hours), under vacuum, modifies the Niobium cavity features:

- at 4.2 K the BCS resistance is reduced by 46%,
- at 1.5 K the high field $Q_O(E_{acc})$ slope is smoothed off with an unchanged residual resistance value. This is a very attractive effect for the high gradient quest.

These modifications are induced by the electron mean free path shortening, due to an oxygen diffusion into the superconducting material.

In agreement with these results we develop a hypothesis about the $Q_O(E_{acc})$ slope that take into account the NbO_X superconducting layer and the magnetic field dependence on the energy gap.

1 INTRODUCTION

In a superconducting cavity, the accelerating electric field E_{acc} is theoretically limited around 50 MV/m. Experimentally, with a few exceptions [1-2], the quality factor Q_O decreases when the accelerating field increases, what limits the usable high accelerating gradient, as required for TESLA. So far, the gradient limit was mainly due to the cavity electron loading by Field Emission. Now the High Pressure Rinsing avoids the FE and, as a general rule, no more electrons, or X-ray emissions associated, are detected in our cavities [3]. The main problem now, is a slope for fields higher than 20 MV/m. Recently, we have succeeded in reducing this slope by means of a cavity heating [4].

2 EXPERIMENTAL DESCRIPTION

2.1 The Niobium Cavity

The C1-05 single cell cavity is made of 2 mm Niobium sheets (RRR 200) supplied by Heraeus. The working RF frequency is 1.3 GHz on the TM_{010} mode. The cavity features are L = 0.112 m for the gap length, R/Q = 104 Ω and G = 283 Ω for the geometric factors.

The cavity has been baked at 1400°C with Titanium vaporisation to improve the RRR by impurities bulk elimination. Before each RF test, we have subjected the cavity to a standard cleaning process [5].

2.2 Experimental method

To characterise the RF cavity performance we determine the quality factor of the unloaded cavity $Q_O = (1+\beta)\, Q_L$,

- the measurements of the incident, reflected and transmitted RF powers, allow to calculate the coupling coefficient β and the dissipated power on the cavity surface P_{cav},
- Q_L , the loaded cavity quality factor , is measured in using the transient method [6]: $Q_L = \omega\, \tau$ where τ is the P_{cav} decay time.

From these values we determine:

- the surface resistance ($R_S = G / Q_O$),
- the accelerating field E_{acc}, using the relationship $E^2_{acc} = Q_O P_{cav}\, (R/Q) / L^2$.

2.3 Measurements

To avoid dust contamination by several valve apertures the heating is carried out with the cavity in its RF test position inside the magnetically shielded cryostat. Two kinds of measurements have been performed for each heating cycle:

- $R_S(1/T)$, at low accelerator field (1 MV/m), during the fast cavity cool down from 4.2 K to 1.5 K, as shown on Fig.1,
- $Q_O(E_{acc})$, at low temperature (~ 1.5 K), as shown on Fig.2.

3 EXPERIMENTAL RESULTS

3.1 Results

As we see on Fig.1 and Table 1, at 4.2 K R_S decreases all the time after the heating process. At 1.5 K the residual resistance R_{res} deteriorates about few nΩ during intermediate warm-up, but the initial value is roughly unchanged after a 170°C / 70 hours heating.

Heating	**$R_{4.2K}$**	**R_{res}**	**A**	**Δ_0/k**	**B'_c**
(°C) / hours	(nΩ)	(nΩ)	(10^{-4} Ω.K)	(K)	(mT)
no	860	8.2	2.8	18.5	182
90 / 48	710	9.7	2.2	18.5	192
110 / 48	540	12.0	1.7	18.5	195
no	850	10.3	2.8	18.5	179
170 / 70	460	10.8	1.45	18.5	190

Table 1: Modification of cavity parameters before and after two heating cycles.

On Fig.2, we can see that the heating improves the Q_O slope. For high field values the limitation, on all curves, is due to a thermal quench around 27 MV/m.

Furthermore, several points have to be specified:

- these results are the same after a voluntary oxidation of the external C1-05 cavity surface,

- same results have been achieved with a second cavity (C1-13) manufactured with Tokyo-Denkai Nb sheets and that did not undergo the initial 1400°C/Ti heat treatment,
- the improvements by heating are preserved during several weeks if the cavity is kept under vacuum,
- the initial situation is recovered after a new chemical polishing (20 µm) and cleaning process.

From these facts we conclude that the thermal conductivity part (RRR or Kapitza resistance) is not concerned in the observed phenomenon, and that only the inner cavity surface is involved.

3.2 Comments on BCS and Residual Resistance

By the simple formula $R_S = R_{res} + A/T \exp[-\Delta_O/kT]$, we can determine R_{res}, A and Δ_O from the $R_S(1/T)$ curve (Table1). The results after heating (R_{res} increase, A decrease, no change for Δ_O) are similar to an experiment performed by Palmer [7] on the Nb oxide layers. In his case, the cavity was warmed up to temperatures between 250 and 300°C after a clean Nb surface oxygen exposure (0.1 Torr /2 hours). According to this paper and Halbritter [8], the BCS decrease is due to the electron mean free path reduction resulting from oxygen diffusion in Nb bulk (the dielectric oxide Nb_2O_5 is unstable at 300°C).

In the same way, in our case, interstitial impurities like oxygen dissolved into the different surface layers [9], could cause the R_{BCS} decrease. At 100°C the oxygen diffusion in Nb is not negligible (0.3 nm/h).

As for the R_{res} , the cause is more speculative and could be due, according to Palmer [10], to a surface roughening, instead of a formation of a NbO conducting layer, or of losses induced by a non stoechiometry in the Nb_2O_5 dielectric layer. We don't express a view about that, although the NbO layer does seem to take part in the residual resistance.

3.3 Magnetic Field Dependence of Energy Gap

We have, for the first time, obtained a controlled change of the Q_O slope. Before any attempt to explain that, it is necessary to analyse the slope origin.

The Q_O dependence on the accelerating field is exponential. As it happens, R_S depends on the magnetic field through the energy gap Δ [11]. In fact, if $T << T_c$, $\Delta = \Delta_O[1 - \alpha(H/H_{cb})^2]$ where H_{cb} is the critical magnetic field for the SC bulk, α is a function depending on the ratio of the SC thickness to the magnetic penetration depth (d/λ) with a maximum value of 0.213 for $d/\lambda=3.3$. The α expression is simplified for the extreme limits: $d>>\lambda$ (bulk), $\alpha = \lambda/d$, so $\Delta \approx \Delta_O$, and $d<<\lambda$ (thin film) where $\alpha \propto d^2/\lambda^2$, that has been experimentally verified [12]. When $d<5^{1/2}\lambda$, the magnetic field dependence on Δ is a second order transition.

On Fig.3 we compare the experimental values with the calculated Q_O (E_{acc}) curve by using the relationship $R_S = R_{res} + A/T \exp [- \Delta_O/kT (1- B^2 / B'^2_c)]$ where $B'_c = B_{cb} / \alpha^{1/2}$. B'_c is the only fitting parameter since $B = 4.10^{-9}E_{acc}$ and T are the experimental data , R_{res}, A and Δ_O being determined by the fit of the Rs(1/T) data at low field. The experimental curves are well fitted by this formula with around 180 mT for the B'_c value of the unheated cavity, and higher values after heating (Table1).

3.4 Implied Superconducting Layer

The heating consequences (B'_c increase and R_{BCS} decrease) involve a simultaneous decrease for α and d/λ . So, two conditions should be satisfied $\alpha<0.213$ and $d/\lambda<3.3$, and the superconducting medium features should be: $T_C >> 1.5$ K, $B_{cb}< 83$ mT and $d < 3.3 \lambda$ (that is to say lower than about a 100 nm). Such a superconducting medium is not different from the NbO_X ($x < 0.01$) layer, built up by the oxygen injected into the Nb surface during the dielectric Nb_2O_5 growth [9].

4 CONCLUSION

A Nb subsurface layer NbO_X ($x < 0.01$) seems to be involved in the $Q_O(E_{acc})$ slope observed for high accelerating fields, through the energy gap dependence with the magnetic field generated at the surface.

The different results achieved by the superconducting cavity heating have shown an electron mean free path increase resulting from an oxygen diffusion into the superconducting material. As a consequence we observe an R_{BCS} decrease and high field Q_O slope smoothing. In the next future we plan to increase the heating time and to change the polishing chemicals to verify if only oxygen is involved in the impurities diffusion.

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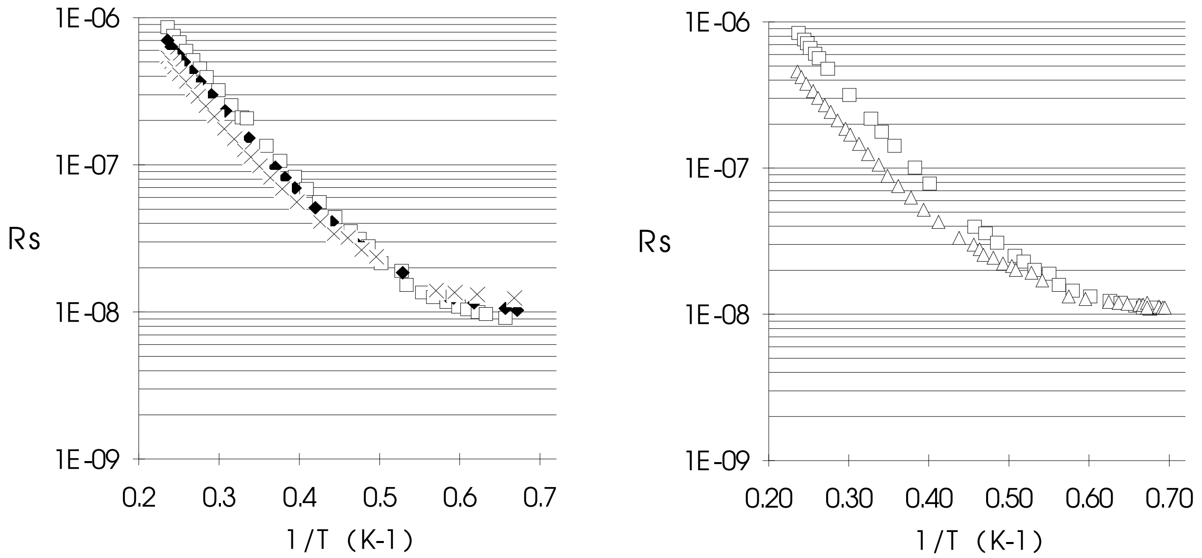
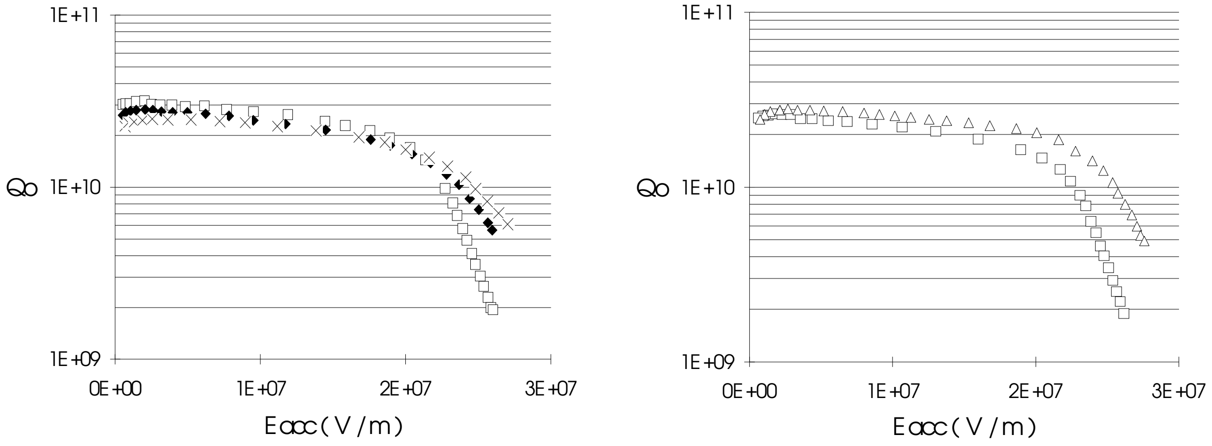
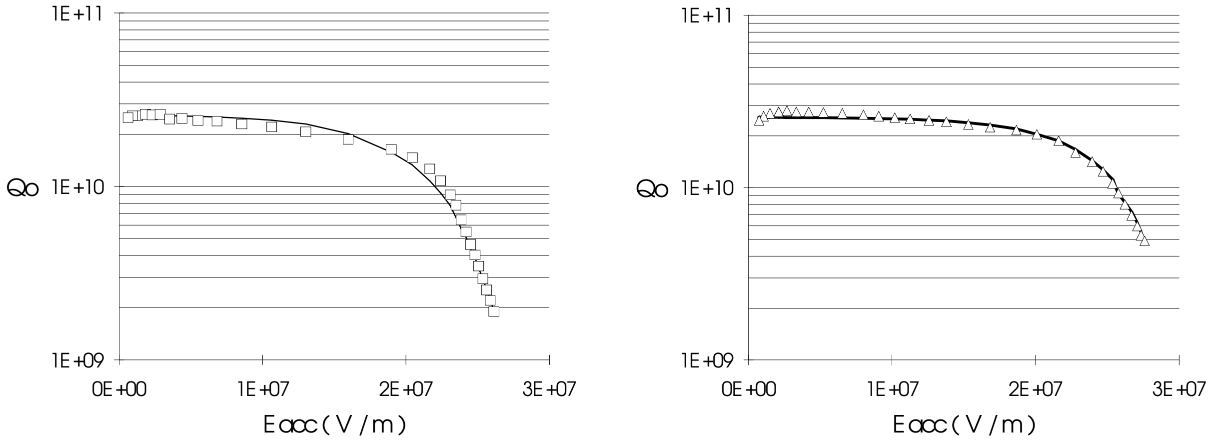


Figures 1: Temperature dependence of the surface resistance before ( ) and after heating (♦, x, Δ) for the two heating cycles.



Figures 2: Quality factor versus the accelerating field before ( ) and after heating (♦, x, Δ) for the two heating cycles.



Figures 3: Experimental points approximation, for the second heating cycle before ( ) and after heating (Δ), by using the relationship $Q_O=G/R_S$ where $R_S = R_{res} + A/T \exp[-\Delta_o/kT (1-B^2/B'_c{}^2)]$ with B'_c as the only fitting parameter.