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2014 J. Phys.: Conf. Ser. 507 032053

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## New evidence for thermal boundary resistance effects in superconducting 6 GHz cavities

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**Abstract.** Thermal boundary resistance and, more specifically, Kapitza resistance effects have been often considered as a possible source of “non ideal” superconducting accelerating cavity behavior, through the formation of a temperature difference between the inner cavity superconducting surface and the helium bath. However, in the present literature the general reported assessment is that such effects could be neglected, at least at low or moderate input power. In this communication we present new data on small test bulk Nb 6GHz cavities, showing that when the cavity surface resistance (or the Q) is plotted as a function of the temperature at constant input power, a clear anomaly occurs at the Helium superfluid transition point  $T_\lambda$  reflecting the abrupt change of the thermal boundary resistance at that temperature. The data analysis shows that this anomaly is consistent with the typically measured values of the thermal boundary (Kapitza) resistance. Implications on the cavity optimization strategy are finally discussed.

### 1. Introduction

The performance improvement of superconducting rf cavities is a relevant issue for future particle accelerators development. The parameters to be optimized are the absolute value of the cavity quality factor Q, the maximum value of the accelerating electric field (breakdown field) and the “Q-slope” i.e. the level of degradation of the Q for increasing values of the accelerating field.

The quality factor Q is directly related to the superconductor surface resistance  $R_s$  by the relation  $Q = \Gamma/R_s$ , where  $\Gamma$  is a constant (temperature and field independent) related to the cavity geometry.

The surface resistance is usually written as a sum of two terms [1]:

$$R_s(T) = R_{BCS}(T) + R_0 \quad (1)$$

At  $T \ll T_c$  and in the dirty-local limit we can assume  $R_{BCS}(T) = \frac{A(\omega)}{T} \exp\left(-\frac{\Delta_0}{K_B T}\right)$ .

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$R_0$  is a temperature independent residual term that accounts for a large set of possible “spurious” effects.  $R_{BCS}$  has also a weak dependence on the rf field  $H_{rf}$  (through the gap energy  $\Delta_0$  field



dependence), directly proportional to the amplitude of the accelerating field  $E_{acc}$ . The field dependence of  $R_o$  depends on the specific mechanism that is supposed being active.

Independent of the possible intrinsic field dependence of the surface resistance, another effect has to be considered when analyzing the Q vs  $E_{acc}$  cavity data. In fact the heat dissipated by the rf field per unit area,  $P_d = \frac{1}{2} R_s(T) H_{rf}^2$ , can produce a temperature increase of the inner cavity superconducting

layer in respect to the liquid helium bath temperature. Using a simple “one-dimensional” model, the temperature difference  $\Delta T$  between the inner cavity surface  $T$  and the bath temperature  $T_0$  can be written as :

$$\Delta T = T - T_0 = \left( \frac{d}{k_m} + R_B \right) P_d \quad (2)$$

Here  $d$  is the thickness of the cavity wall,  $k_m$  is the thermal conductivity of the superconducting cavity material and  $R_B$  represents the thermal resistance present at the interface between the cavity outer surface and the He bath. The thermal boundary resistance  $R_B$  has a fully different nature above and below the superfluid He transition temperature  $T_\lambda$ . Above  $T_\lambda$  the heat transfer from a metal surface to a pool boiling liquid (HeI) occurs via a strong and complex convective process involving the formation of bubbles [2]. In the superfluid regime, below  $T_\lambda$  (He II), boiling is suppressed and the thermal boundary resistance can be identified with the Kapitza resistance  $R_k$  [3], much lower than the value of  $R_B$  above the transition.

In the presence of a thermal gradient between the inner cavity surface and the He bath, the BCS surface resistance can be rewritten as :

$$R_{BCS}(T_0) = \frac{A(\omega)}{T_0 + \Delta T} \exp \left[ - \frac{\Delta_0}{K_B (T_0 + \Delta T)} \right] \cong R_{BCSO}(T_0) \left( 1 + \frac{\Delta_0 \cdot \Delta T}{K_B T_0^2} \right) \quad (3)$$

where  $R_{BCSO}$  is the BCS surface resistance in the absence of a thermal gradient and  $\Delta T \propto P_d \propto H_{rf}^2$ ; the linear approximation is valid for  $\Delta T \ll T$ , that always holds in our experiments. Eqs. 2-3 imply a dependence of the surface resistance on the rf power and therefore on the rf field, and a corresponding Q-slope effect.

The relevance of thermal effects on the accelerating cavity behavior has been often discussed in the literature [4],[5], however, the current assessment is that thermal effects can be essentially neglected at low or medium input power, and that the main mechanism causing the Q-slope is the intrinsic dependence of the surface resistance on the rf field.

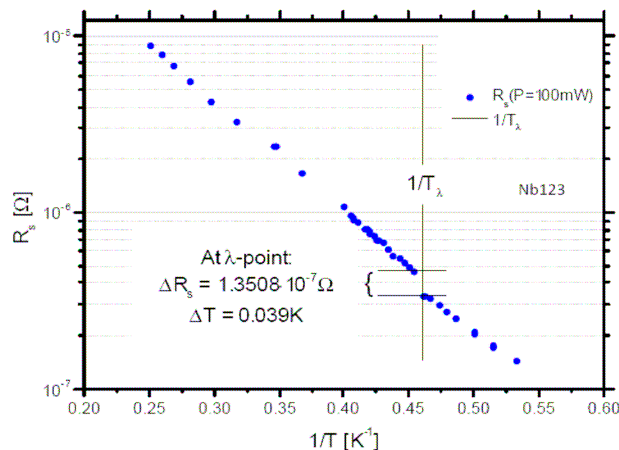
In the present communication we present new surface resistance data on small test bulk Nb 6Ghz cavities, in a wide range of temperatures and input power. The body of our data suggest that thermal effects are indeed one of the main limiting factor on our accelerating cavity performances.

## 2.Experimental Techniques, Results and Discussion

Our monocell 6GHz cavities were realized by the spinning process developed at INFN-LNL. [6].

6GHz cavities can be produced in large number at low cost from a relatively small amount of Niobium and allow to make a large experimental statistics [7]. The Q-factor of the cavity is determined by measuring the decay time, while the accelerating field value is extracted by the measurement of the corresponding power injected into the resonator at the critical coupling. The rf coupler adjustment is made by a stepping motor that is remote controlled. Temperature, vacuum and cryogenic parameters are visualized and automatically acquired and stored in a database [8].

In Fig. 1 the temperature dependence ( $1/T_0$ ) of the residual resistance  $R_s$  as extracted by Q measurements on one of our 6GHz cavities is reported, keeping constant the input power  $P_d$ .



**Fig. 1.** Surface resistance as a function of the inverse bath temperature at constant input power.

The data clearly show an abrupt “jump” at the He<sub>I</sub>-He<sub>II</sub> transition ( $T_\lambda = 2.18\text{K}$ ,  $1/T_\lambda = 0.46\text{K}^{-1}$ ). This behavior is always found, with the same general characteristics, in all our measured samples. We also found that the amplitude of the jump  $\Delta R_s$  is a linear function of the input power  $P_d$ . This jump has to be attributed to the change of  $\Delta T$  across the  $\lambda$  transition, in turn determined by the abrupt change in the thermal boundary resistance  $R_B$ . The linear  $P_d$  dependence of  $\Delta R_s$  is a natural consequence of Eqs. 2-3. It is worth observing that in many similar experiments reported in the literature, the Q measurements are performed at constant rf field, and not at constant rf power. In that case the anomaly at  $T_\lambda$  is still seen, but appears as a smooth “bump” and has never been considered as a relevant effect (as an example, see ref. [9]). Inverting Eqs. 1,3 we can extract the overall thermal resistance :

$$\frac{d}{k_m} + R_B = \frac{K_B T_0^2}{\Delta_0 P_d} \left[ \frac{R_s(T_0) - R_0}{R_{sBCS0}(T_0)} - 1 \right] \quad (4)$$

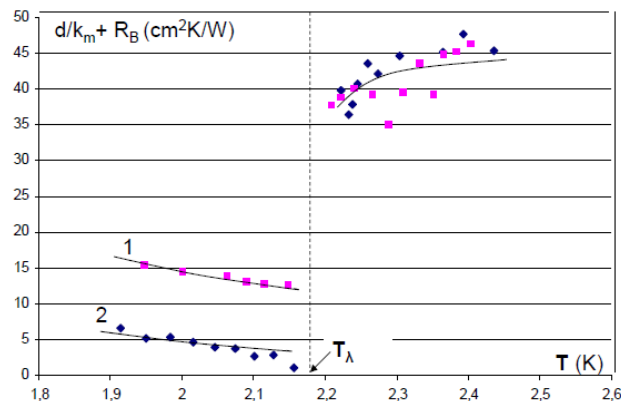
In Fig. 2, curve 1, the temperature dependence of the overall thermal resistance deduced by Eq. (4) is reported, using for  $R_s(T_0)$  the experimental data reported in Fig. 1. The values of the parameters set to invert the data are reported in Tab. I.

| <b>Tab. 1. Parameters set to invert the data</b> |  |       |
|--|--|-------|
| $\Delta_0$                                       | $A(\omega)$                                | $R_0$ |
| 1.40meV  | $2.18 \cdot 10^{-3} \Omega \cdot \text{K}$ | 20 nΩ |

$\Delta_0$  depends only by the slope of the  $\ln R_s$  vs  $1/T$  curve at high temperatures and is independently determined. The reported value implies  $\Delta_0/K_B T_c = 1.76$ , very close to the theoretical BCS value.

The  $A\omega^2$  value has been chosen to guarantee that all the reported values of the overall thermal resistance (including those of curve 2 that will be discussed later) were positive and within the limits of the typically literature reported values. Finally the value of the residual resistance has been determined to ensure that the low temperature data (below  $T_\lambda$ ) were following a  $T^{-3}$  dependence as theoretically predicted for the Kapitza resistance (continuous fitting curve in the figure). In fact, due to the already discussed small value of  $d/k_m$  for our 6GHz cavities and the nature of the external surface our cavities, the Kapitza resistance should be the dominant term in the overall thermal resistance, as discussed in ref. [4]. It is worth underlining that, though the described fitting procedure has some degree of arbitrariness, the deduced temperature dependence of the thermal resistance is relatively sensitive to the parameters choice (as an example the assumption of a  $T^{-4.5}$  temperature dependence of the Kapitza resistance, as assumed, as an example, in ref. [5], would not change much the choice of  $R_0$  nor the overall shape and values of the deduced thermal resistance curve.

It is important to observe that the absolute values of the thermal resistance both above and below the



**Fig. 2.** Thermal boundary resistance for a 6GHz Nb cavity before (1) and after (2) external surface anodization treatment

lambda point are compatible with the data reported in the literature for heat transfer to pool boiling He<sub>I</sub> [2] and for the Kapitza interface resistance between polished Nb and superfluid He<sub>II</sub> [4].

Literature data clearly indicate that it is possible to reduce the Kapitza boundary resistance through appropriate external surface treatments that could optimise the acoustic phonon transmission to the He bath. To achieve this goal we used an Electrolytic Pad Anodization process to grow, externally to the cavity surface, a blue-violet porous Nb oxide a few tenths of nm thick. The process did not influence in any way the inner cavity surface.

The data points reported in Fig. 2, curve 2, refer to the same 6GHz cavity whose behavior was described above (Fig.1), and have been obtained by Eq. 4 using the surface resistance data measured after the external surface anodization process and the same set of parameters reported in Tab.1 .

Fig. 2 clearly shows that the thermal boundary resistance is not affected by our external surface anodization above  $T_\lambda$ , but it is reduced below  $T_\lambda$  (Kapitza regime), determining a reduction of the surface resistance and, in turn, an increase of the Q and an improvement of the cavity performances.

### 3. Conclusions

Our data on 6GHz Nb accelerating cavities clearly indicate the relevance of Nb-He thermal boundary resistance and allowed to deduce both its magnitude and temperature dependence both above and below the He superfluid transition (Kapitza resistance). External surface treatments (anodization) have been proven to reduce the Kapitza resistance, improving the overall cavity performances.

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