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THERMAL BOUNDARY RESISTANCE MODEL AND DEFECT STATISTICAL DISTRIBUTION IN Nb/Cu CAVITIES*

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Abstract

The 'Q-slope' problem has so far strongly limited the application of niobium thin film sputtered copper cavities in high field accelerators.

In our work, we consider the hypothesis that the Q-slope is related to local enhancement of the thermal boundary resistance at the Nb/Cu interface, due to poor thermal contact between film and substrate. We introduce a simple model that directly connects the Q versus E_{acc} curves to the distribution function $f(R_{Nb/Cu})$ of the $R_{Nb/Cu}$ thermal contact values at the Nb/Cu interface over the cavity surface. Starting from the experimental curves, using inverse problem methods, we deduce the distribution functions generating those curves.

The technique has been applied to different cavity typologies, and by different groups, including LNL-INFN and CERN (ISOLDE and TQR cavities). In all the examined cases to fit the data it is sufficient to assume that only a small fraction of the film over the cavity surface is in poor thermal contact with the substrate. The distribution functions typically follow a simple power-law statistical distribution, and are temperature and frequency independent.

The whole body of information and data reported seems to be consistent with the hypothesis that the main origin of the Q-slope in thin film cavities is indeed related to bad adhesion at the Nb/Cu interface.

INTRODUCTION

As well known to the SRF community, the 'Q-slope' problem has so far strongly limited the application of niobium thin film Nb/Cu sputtered copper cavities [1]. Indeed, though in principle, sputtered Nb/Cu RF superconducting cavities should present many relevant advantages over bulk Nb cavities, in practice, the large Q-solpe, typically observed in these cavities, limits their use in high field accelerators**.** A comparison of the accelerating field dependence of bulk and film cavities is schematically reported in Fig.1.

Since the early nineties researchers tried to understand and fight the Q-slope problem in thin films. Among others, the following effects were considered [2-6]:
-hydrogen or oxygen diffusion from the bulk Cu substrate
-grain-boundary losses due to film polycristallinity
-enhanced field dependence of the gap or of the fluxon dissipation mechanisms

Though all these mechanism can indeed be active, no convincing experimental proof of their relevance has been given and all attempts to fight the problem where not fully successful.

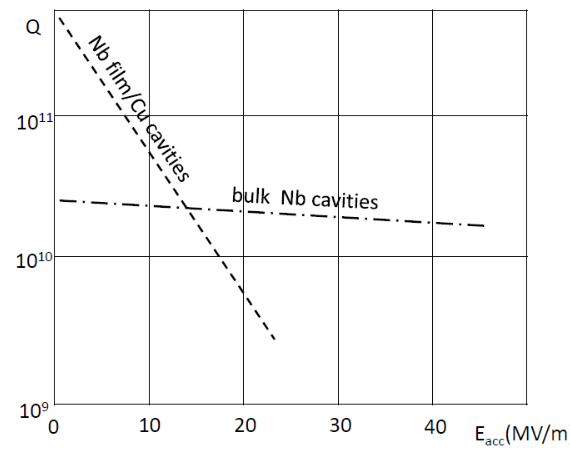

Figure 1 : Q-factor versus the accelerating field for Nb film sputtered cavities compared to bulk niobium cavities. Typical behavior is schematically reported for 1.3 – 1.5 GHz CERN cavities at low temperatures (1.7-1.8K).

In our recent works [7,8], we considered the hypothesis that the Q-slope is related to local enhancement of the thermal boundary resistance at the Nb/Cu interface, due to poor thermal contact between film and substrate. We introduced a simple model that directly connects the Q versus E_{acc} curves to the distribution function $f(R_{Nb/Cu})$ of the $R_{Nb/Cu}$ thermal contact values at the Nb/Cu interface over the cavity surface. Starting from the experimental curves, using inverse problem methods, we deduce the distribution functions generating those curves.

Here we will show and discuss new data taken in our laboratory and we will show how the extracted statistical distributions does not depend, for thin film cavities, on temperature, proving the robustness of the model. Similar results obtained at CERN will be finally discussed

THE THERMAL FEEDBACK MODEL

The thermal feedback model assumes that, in the presence of rf power P_{rf} at the cavity inner surface, the surface resistance R_s can be calculated by iteration through the following equations:

$$R_S(T) = \frac{A\omega^2}{T}\exp\left[-\frac{\Delta(T)}{K_B T}\right] + R_{so}\ ;\ T = T_o + \Delta T$$
$$\Delta T = R_B P_{rf} = \frac{1}{2} R_B R_s(T) H_{rf}^2 = \frac{1}{2} R_B R_s(T)\left(\frac{k}{\mu_o}\right)^2 E_{acc}^2 \quad (1)$$

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where T_o is the helium bath temperature, R_B is the overall thermal boundary resistance form the cavity inner surface to the He-bath and k represents the ratio between the maximum RF magnetic field at the inner cavity surface and the maximum accelerating field, and is a known constant depending on the specific cavity geometry.

It can be easily shown that the thermal feedback model gives a negligible Q-slope and very high quench fields for typical R_B values of bulk Nb cavities (finite *Nb* thermal conduttivity+ *Nb/He* Kapitza interface thermal resistance; $R_B = 2 \div 10 cm^2 K/W$). Of course even lower Q-slope effects should be expected in Nb/Cu cavities, due to the higher Cu thermal conductivity. Moreover careful temperature measurements in thin film cavities presenting severe Q-slope, performed at CERN, showed no relevant surface temperature increase of the inner cavity surface, proving that the thermal feedback mechanism was not relevant in that case [9].

THE MODEL OF THERMAL DEFECTS AT THE Nb/Cu INTERFACE

In a recent paper [7] we have extensively discussed how bad Nb/Cu adhesion (or other mechanisms as powder inclusions) can create thermal defects, locally increasing up to high values the interface thermal boundary resistance $R_{Nb/Cu}$, so that we can assume $R_B = R_{Nb/Cu}$. A possible model for such defects is illustrated in Fig. 2.

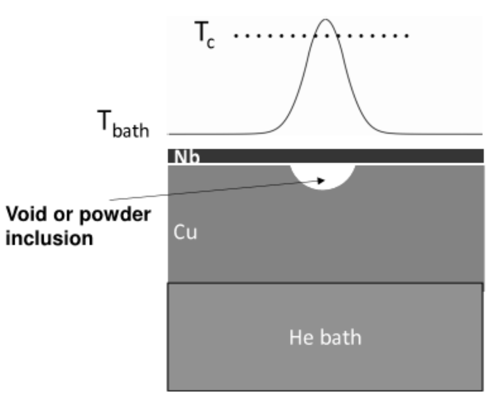

Figure 2 : Model for an isolated thermal defect at the Nb/Cu interface, and relative local temperature profile.

Due to the small film thickness the heath is not efficiently dissipated at the defect location, producing locally a temperature increase (at high incident power, the local temperature can overcome the critical temperature T$_c$). A finite elements calculation performed at CERN using this simple model, showed that the temperature increase is confined to the defect area, so that the presence of the defect can be simply modeled as a local increase of $R_{Nb/Cu}$.

Assuming that local thermal defects at the Nb/Cu interface are the main source of the Q-slope, from the measured Q vs RF field amplitude, through "inverse problem" techniques one can determine the statistical distribution function $f(R_{Nb/Cu})$ of thermal boundary resistances. $f(R_{Nb/Cu})$ represents in fact the fractional surface area with a given value of the thermal boundary resistance $R_{Nb/Cu}$.
Summarizing, the presence of a large interface thermal resistance $R_{Nb/Cu}$ locally affects the value of the surface resistance R_s through the thermal feedback mechanism so that we can obtained the function $R_s=R_s(T_o, E_{acc}, R_{Nb/Cu})$ using Eqs. (1) with $R_B= R_{Nb/Cu}$ The measured cavity quality factor Q will be related to the average value of R_s. The following relations hold:

$$\overline{R_s(T_o,E_{acc})} = \int_0^\infty R_s(T_o,E_{acc},R_{Nb/Cu}) f(R_{Nb/Cu}) dR_{Nb/Cu}$$

$$Q = \frac{\Gamma}{\overline{R_s(T_o,E_{acc})}}$$

$$\overline{R_{Nb/Cu}} = \int_0^\infty R_{Nb/Cu} f(R_{Nb/Cu}) dR_{Nb/Cu} \qquad (2)$$

$$\int_0^\infty f(R_{Nb/Cu}) dR_{Nb/Cu} = 1$$

($\overline{R_{Nb/Cu}}$ represents the average value of the thermal boundary resistance).

The first of Eqs. (2) represents a classical first type Fredholm integral equation, and, by well known inverse problem methods, can be "inverted" to extract $f(R_{Nb/Cu})$ as was discussed in [7]. The results showed that f is well described by a power law dependence of the form $f(R_{Nb/Cu}) = \alpha R_{Nb/Cu}^{-\beta}$. A power law (or log-normal) behavior is compatible with different thermal defects formation mechanisms, including void formation at the interface [10] or ambient powder size distributions.

The fractional area of the detached surface, can be defined as :

$$I_d = \int_{R_{Nb/Cu}^{min}}^\infty f(R_{Nb/Cu}) dR_{Nb/Cu} \qquad (3)$$

where $R_{Nb/Cu}^{min}$ is the minimum "measured" value of $R_{Nb/Cu}$, corresponding to the maximum measured value of the accelerating field E_{acc}. The values of $f(R_{Nb/Cu})$ below that value are unknown and do not influence the results. One can imagine, for simplicity, that the value of the integral ($1-I_d$) of the distribution below $R_{Nb/Cu}^{min}$ comes from a delta-function centred at zero, i.e. that the film is perfectly adherent to the substrate everywhere but in the detached areas, where $R_{Nb/Cu} > R_{Nb/Cu}^{min}$.

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The values of I_d reported in ref [7] were of the order of 10^{-3} -10^{-4}. This showed how it is sufficient to assume that a very small fraction of the overall cavity surface presents adherence problems (or other problems determining a significant increase of the thermal boundary resistance) to explain the quite large Q slope observed in thin film cavities.

The estimated average value of the interface thermal-boundary resistance $\overline{R_{Nb/Cu}}$ was always very low, so no average temperature increase of the inner cavity surface is expected, in agreement with the experimental results [9].

SIMPLIFIED INVERSION PROCEDURE

As discussed in [8], the inversion procedure can be simplified assuming for $R_s=R_s(T_o, E_{acc}, R_{Nb/Cu})$ a step-like behavior, in place of the full dependence that can be extracted by Eqs. (1) (See Fig. 3). Below the "quench field" E_q, R_s is assumed to be field independent keeping its zero-field value. Above E_q the temperature increases fast and overcomes the critical temperature, so the superconductor surface resistance reaches its normal state value R_n , assumed to be temperature independent.

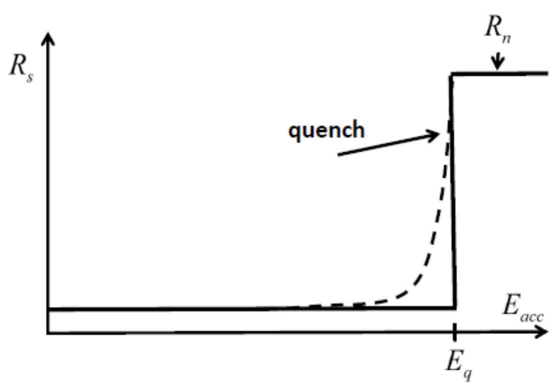

Figure 3 : Simplified behavior for $R_s=R_s(T_o, E_{acc}, R_{Nb/Cu})$ (full line) compared to the "real" behavior calculated from Eqs. (1) (dashed line).

E_q scales as the inverse of the square root of $R_{Nb/Cu}$, as easily seen by Eqs. (1) (remember that we are assuming $R_B=R_{Nb/Cu}$) i.e:

$$E_q = \sqrt{\frac{K}{R_{Nb/Cu}}} \quad (4)$$

(to calculate the constant K, it is sufficient to calculate the quench field E_q from Eqs. (1) for a single value of $R_{Nb/Cu}$).

Using the simplified R_s *vs* E_{acc} dependence reported in Fig. 3, we can easily deduce behaviour of the function f, as discussed in [8] (the number of determined values for f is equal to the measured Q_i *vs* $E_{acc,i}$ data points) using the following relations :

$$f_N = \frac{1}{\Delta R_{Nb/Cu,N}} \frac{\overline{R_s(T_o, E_{acc,2})} - \overline{R_s(T_o, E_{acc,1})}}{R_n - R_{so}}$$

....

$$f_2 = \frac{1}{\Delta R_{Nb/Cu,2}} \frac{\overline{R_s(T_o, E_{acc,N})} - \overline{R_s(T_o, E_{acc,(N-1)})}}{R_n - R_{so}}$$

$$f_1 = 1 - \sum_{2}^{N} f_i \Delta R_{Nb/Cu,i} \quad (5)$$

$$with: \ \overline{R_s(T_o, E_{acc,i})} = \frac{\Gamma}{Q_i},$$

$$and: \Delta R_{Nb/Cu,i} = R_{Nb/Cu,i} - R_{Nb/Cu,(1-i)} ,$$

$$R_{Nb/Cu,i} = K / E^2_{acc,(N+1-i)}$$

DATA ANALYSIS AND DISCUSSION

The use of the simplified procedure outlined in the previous section, has allowed the analysis of large sets of data. In particular a systematic study has been carried out in [8] on the HIE-ISOLDE SRF cavities.

The data confirmed that the extracted defects distribution functions follow a power-law behaviour, with a fractional area of the detached surface I_d = 10^{-4} -10^{-5} (even lower in respect to the data discussed in ref. [7]). I_d scales linearly with the first order term in the $R_s=R_s(E_{acc})$ series development, that quantifies the Q-slope.

An interesting result reported in [8], is that for a single ISOLDE cavity, a "bilinear" behaviour of f (when reported in a ln-ln scale) and a large value I_d were observed. Indeed, only in this case, cross-sectional analysis showed the presence extended delaminations of the film, that could justify the observed anomalous behaviour.

To further investigate the overall consistency of the thermal boundary resistance model, in this work we report on new measurements performed on INFN-LNL 6GHz thin film Nb/Cu cavities at different temperatures. The results of the measurements are reported in Fig. 4.

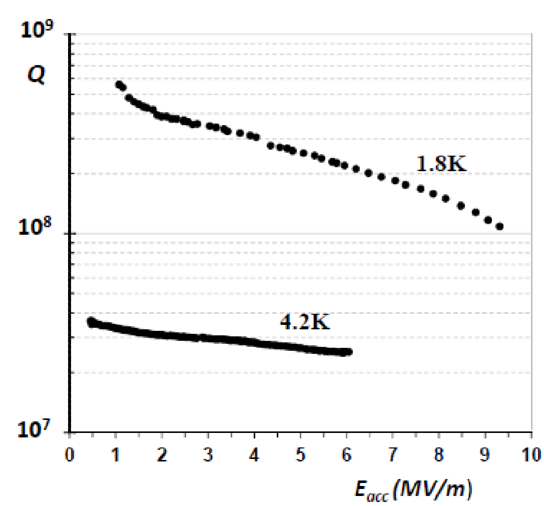

Figure 4 : INFN-LNL 6GHz thin film Nb/Cu cavity measured at 1.8K and 4.2K.

The data reported in Tab. 1 are deduced by standard procedures from the measured low-field temperature dependence.

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By the use of Eqs. (1) (with k= 4.5mT/(MV/m) it is possible to determine the costant K appearing in Eq. (4).

Table 1: List of Parameters Used for the Inversion Procedure

$A\omega^2$	$\Delta(0)$	R_{so}	T_c
$2.1\cdot10^{-3}\Omega\cdot K$	1.38meV	$0.3\cdot10^{-6}\Omega$	9.20K

The procedure gives K(1.8)=1232 and K(4.2)=117.8 (measuring $R_{Nb/Cu}$ in cm^{2}K/W and E_{acc} in MV/m).

Inserting these calculated K values and assuming R_n =0.005Ω, we obtained the distribution function f at the considered temperatures, as reported in Fig. 5. In the absence of a specific model for the thermal defect and its parameters, $R_{Nb/Cu}$ is assumed to be temperature independent (a moderate change with temperature in any case would not affect the results reported here).

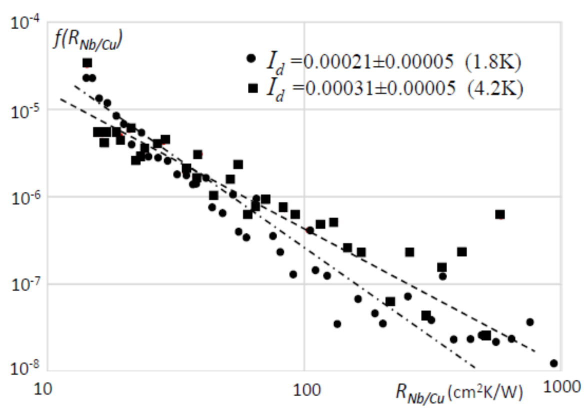

Figure 5 : Thermal defects distribution function $f(R_{Nb/Cu})$ for a INFN-LNL 6GHz thin film Nb/Cu cavity measured at 1.8K and 4.2K. The dashed lines represent the linear best fits of the two series.

From the figure and the values of the detached surface area I_d it is clear how the function f results to be substantially temperature independent, as it should be obviously expected. This represents indeed a further test of the model conherence.

Data inversion procedures at different temperatures were also performed on CERN ISOLDE cavities, confirming with better resolution the temperature independence of the thermal defects statistical distribution [11]. Recent measurements performed on a Test Quadrupole Resonator (TQR) at CERN, reconfirmed the temperature and frequency (400-800MHz) independence of f. The same inversion procedure at different temperatures and frequency, when applied to a Nb bulk cavity, gave fully inconsistent results, giving further elements of the overall consistency of the model [12].

CONCLUSIONS

In our opinion, he following conclusion can be safely drawn:

- Thermal effects can be relevant in Nb/Cu cavities due to enhanced thermal boundary resistance R_B at the interface due bad film adhesion (voids or powder inclusions).
- The use of a simplified procedure allows a straightforward procedure to determine of the statistical distribution of thermal defects from the Q *vs.* E_{acc} measurements.
- For all the measured cavities (LNL, CERN-ISOLDE-TQR) the distribution follows a simple power-law dependence.
- The fractional area of the detached surface is always of the order of 10^{-3} - 10^{-5}.
- The distribution is essentially temperature and frequency independent for thin film cavities, the results is instead fully inconsistent if the «inversion» method is applied to bulk cavities.

Finally, we are aware that the validity of the model can be only reconfirmed by independent measurement techniques of the defect statistics, or showing that improving the film adhesion systematically lowers the Q-slope.

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