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ON THE LOW-FIELD Q-SLOPE OF RF SUPERCONDUCTING NIOBIUM CAVITIES COOLED BY HELIUM-I*

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Abstract

Experimental measurements have consistently shown that RF superconducting Niobium cavities cooled by He-I exhibit a mild Q-slope starting at very low gradients. This Q-slope has been attributed to a BCS resistance increase resulted from the Kapitza impedance across the interface between the exterior surface of Niobium cavities and liquid Helium. Thermal modeling of Niobium cavities is performed in this paper, detailing the role of Kapitza impedance. Our results show that Kapitza impedance plays an insignificant role in this low-field Q-slope. Experimental results are also presented, showing the surface treatment has a strong effect on the low-field Q-slope. We conclude that this low-field Q-slope is intrinsic to the material properties of the RF surface of Niobium.

1 INTRODUCTION

Vertical tests of 500 MHz and 508 MHz Niobium cavities at 4.2 K cooled by He-I at Cornell and KEK have consistently shown that these cavities exhibit a mild Q-slope (Q is referred to as the unloaded quality factor), starting at very low gradients. An example of such a Q-slope is shown in Fig. 1 which depicts the vertical test results of four Niobium cavities manufactured for KEK-B factory [1].

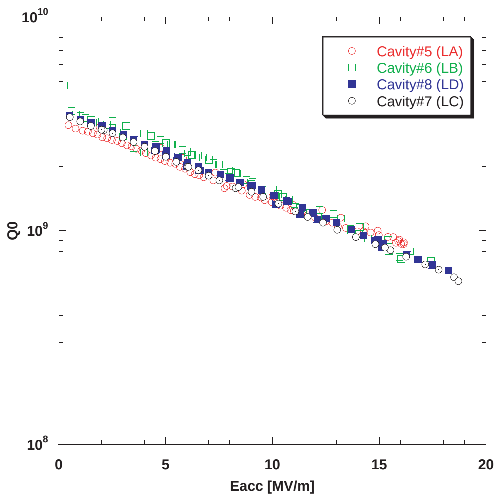

Figure 1: Test results of KEK-B 508 MHz Niobium cavities at 4.2 K in a vertical cryostat. Q_0 starts dropping at very low gradients, where x-ray is not detected.

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Apparently, this mild Q-slope is not attributable to loading by field emission electrons, which arise only above a threshold gradient and usually result in a much steeper Q-drop. The field emission onset gradient for Cornell cavities was in the range of 6 - 10 MV/m. Above this threshold gradient, significant x-rays are detected and Q_0 quickly deviates from the low-field Q-slope.

In case the loading by field emission electrons is not a concern, the unloaded quality factor Q_0 is directly related to the surface resistance R_s through

$$Q_0 = \frac{G}{R_s}, \qquad (1)$$

where G, the geometry factor of the cavity, is dependent only on the geometry of the resonator. It has been well established that RF surface resistance is composed of two parts, namely the BCS resistance R_{BCS} and residual resistance R_{res} [2].

$$R_s = R_{BCS} + R_{res}. \qquad (2)$$

As will be seen in Section 2, the surface surface resistance of Niobium at 4.2 K and 500 MHz is dominated by the BCS component. From Eq. 1 and 2, it is evident that any Q drop is readily to be interpreted as an increase in R_{BCS}.

However, our current understanding indicates that the BCS resistance of Niobium is not explicitly dependent on the strength of the RF field. Therefore it has long been believed [3] that the observed Q-slope in Niobium cavities is a secondary thermal effect due to RF heating of the Niobium surface. One hypothesis correlates the Q-slope to the Kapitza impedance across the Niobium and liquid Helium interface: When the field gradient is increased, the increased heat flux across the Niobium-Helium interface results in an elevated temperature on the RF surface of Niobium and lead to a decreasing Q. This hypothesis seems to be reasonable but has not been seriously checked in the past.

In Section 4 and 5, a 500 MHz Cornell type Niobium cavity is numerically modeled with special attention paid on the role of the Kapitza impedance. Our results do not support the above hypothesis and show that the effect of the Kapitza impedance alone can not account for the low field Q-slope of 500 MHz range Niobium cavities.

In Section 6, experimental results are presented for cavities with different surface treatment. These results show that the low-field Q-slope of Niobium cavities is intrinsically coupled to the material properties of the RF surface of Niobium.

In conclusion, we demonstrate that a field-dependent BCS resistance seems to be unavoidable to fully account the low-field Q-slope of 500MHz range Niobium cavities cooled by He-I.

2 SURFACE RESISTANCE

In the frame work of the BCS theory, the BCS resistance of RF superconductors depends on material properties, temperature and frequency of RF fields. For the temperature range of $<$ 4.6 K and frequency range of $<$ 1000 GHz, BCS resistance of Niobium can be formulated as

$$R_{BCS} = A\frac{f^2}{T}e^{-\frac{\Delta}{kT}}, \quad (3)$$

where Δ is the energy gap, k is Boltzmann constant, T is temperature, and f is RF frequency. The constant A depends on material properties, such as the Fermi velocity, the London penetration depth, the coherence length, and the mean free path of electrons. Computer programs, such as SRIMP [4], are available for computing the BCS resistance of materials at known temperatures and RF frequencies.

Common sources of the residual resistance R_{res}, which is temperature independent, include trapped magnetic flux, material impurities, and surface contaminants. Measurements of 500 MHz cavities at lower temperatures have placed the residual resistance of RRR250 Niobium in the neighborhood of 10 nΩ for a residual earth magnetic field level of about 5 μTesla (50 mGauss).

Measurements at 4.2 K show that the unloaded quality factor ranges from 2 - 4 $\times 10^9$ at low gradients, which translates into a BCS resistance in the range of 60 - 120 nΩ. As a result, the surface resistance of Niobium at 500 MHz is dominated by the BCS component at 4.2 K. Hence the observed mild Q-slope for 500 MHz range Niobium cavities at 4.2 K is relevant to the BCS resistance only. This is further justified by the fact that Q_0 virtually does not drop when the same cavity is tested at lower temperatures, where the residual resistance dominates over the BCS resistance.

3 KAPITZA IMPEDANCE FOR HE-I

Because of the f^2 dependence of the BCS resistance, 500 MHz range Niobium cavities have been chosen to operate at 4.2 K. At this temperature, liquid Helium is in a state called He-I at saturated vapor pressure.

For a heat flux of 50 - 10^4 W/m^2 across the solid and He-I interface, cooling process is characterized as the so called nucleate boiling regime [5]. Across the interface between the Niobium and liquid Helium, there exists a temperature jump, which correlates to the heat flux q through the Kapitza conductance H_k,

$$q = H_k(T - T_b). \quad (4)$$

The inverse of the Kapitza conductance is called Kapitza impedance. A conservative empirical fit for Kapitza conductance of He-I exists [6],

$$H_k = 10^4(T - T_B)^{1.5}. \quad (5)$$

4 THERMAL MODELING

In this paper, the thermal behavior of a 500MHz Cornell type cavity is modeled with the aid of the commercial code ANSYS [7] and home developed code HEAT [9].

In the ANSYS model, the full cavity is accounted in a two dimensional cylindrical coordinate system as depicted in Fig. 2.

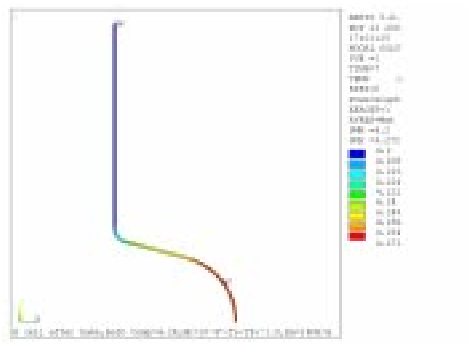

Figure 2: The two dimensional ANSYS model of the 500MHz Niobium cavity.

The heating effect on the RF surface of the cavity is realized through a convective boundary condition, which takes into account the temperature dependence of the BCS resistance. A detailed description of this scheme can be found in Ref. [8]. The cooling provided by He-I is also modeled as a convective boundary condition, with the Kapitza conductance directly plugged into the code.

In the HEAT model, only the most critical section of the cavity, namely the equator region, is considered. This results in a slab of Niobium with circular geometry. For thermal calculations of Niobium free of defects, lateral heat transpotation is disabled. Detailed description of the HEAT model can be found in Ref. [9].

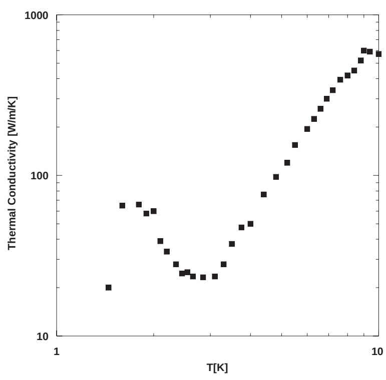

Figure 3: Thermal conductivity used in modeling for RRR250 Niobium [10].

The thermal conductivity of Niobium as a function of temperature is formulated in Eq. 6 after curve fitting the experiment data obtained from [10] for RRR250 material (see Fig. 3).

$$k_{Nb}(T) = 261.92 - 183.72T + 39.9T^2 - 1.794T^3. \quad (6)$$

5 EFFECT OF KAPITZA IMPEDANCE

Modeling results are shown in Fig. 4, together with the experiment results of the corresponding Niobium cavity.

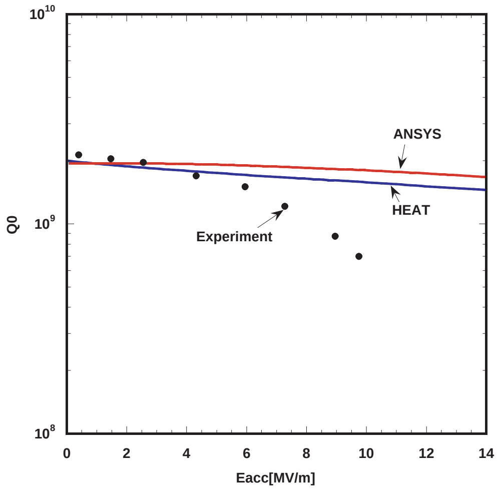

Figure 4: The quality factor of a 500 MHz Niobium cavity as calculated by ANSYS and HEAT models, together with the measurement results. There exists a large discrepancy between calculation and measurement results .

Both the ANSYS and HEAT results show that the quality factor of the cavity drops with increasing field gradients. But the amount of Q-drop is much less than the experimentally observed one. The HEAT model somehow gives a more pronounced Q-drop compared to the ANSYS results. This is attributable to the fact that lateral heat transfer in disabled in the HEAT model.

It is well known that the Kapitza conductance may vary by a factor of as much as 10 depending on factors like, among others, surface roughness and surface orientation with respect to the gravitational force. Further ANSYS modeling is therefore conducted to check the modeling tolerance to the Kapitza conductance.

Fig. 5 shows modeling results with various Kapitza conductance, from which one can see that the observed Q-slope is reproduced only when modeling with a Kapitza conductance 50-100 times lower than the canonical values (which is already a conservative fitting of the low end of experimental data).

It is evident that even with the factors such as surface roughness or orientation is taken into account, the low-field Q-slope can not be solely explained by the effect of the Kapitza impedance.

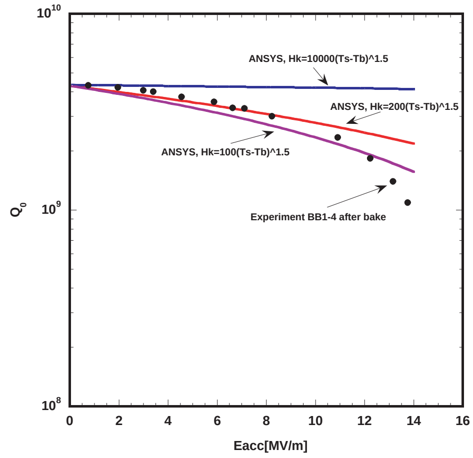

Figure 5: Modeling results with various Kapitza impedance. The measured mild Q-slope is reproduced only when modeling with a Kapitza conductance 50-100 times lower than the canonical values.

6 EFFECT OF SURFACE TREATMENT

As shown in Section 5, the effect of the Kapitza impedance attributes only a part to the low-field Q-slope. We will show in this section that the major contribution to the Q-slope arises from the material property of the RF layer of Niobium.

Fig. 6 depicts experimental results of Cornell and KEK type cavities, which are subjected to different surface treatments. Here the unloaded quality factor is drawn against the peak magnetic field for comparison purposes for the following reasons: 1) The definition of the peak RF field is unique (as is not for the definition of the accelerating gradient); 2) The magnetic field is more relevant than the electric field when discussing losses of the RF surface. It is evident

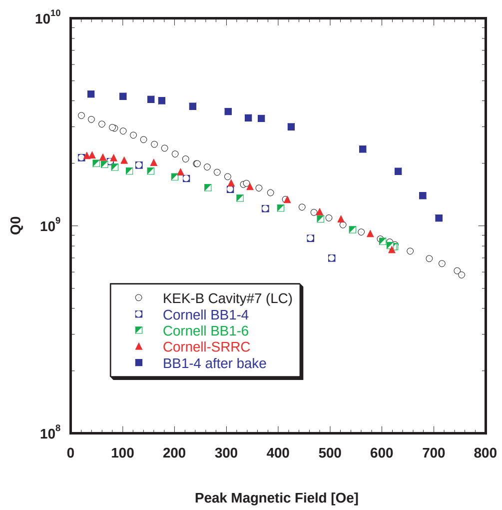

Figure 6: The measurement results for cavities with different surface treatment. There is a strong effect of surface treatment on the low-field Q-slope.

that the low-field Q-slope is different for the two class of cavities. Cornell type cavities exhibit a milder Q-slope as compared to the KEK type cavities. It is also shown that baking at 140 °C has some effect on the Q-slope for Cornell cavities.

The material used for manufacturing Cornell cavities is RRR250 sheet Niobium with a thickness of 3 mm, and RRR200 with a thickness of 2.5 mm for KEK-B cavities. The thermal impedance due to the wall thickness for these cavities is estimated to be just about the same (note the proportionality between Niobium thermal conductivity and RRR). For this reason, the difference in the low-field Q-slope for these two class of cavities lies in nowhere but the difference in the material property of the Niobium RF surface due to different surface treatment.

Cornell Cavities are etched with BCP1:1:2 for a surface removal of 120 μm followed by high pressure water rinsing (HPR) for about 100 minutes. KEK cavities are prepared in a more involved manner [11] [12] [13]: Electropolishing for a surface removal of 80 μm; Degassing at 700 °C for 1.5 hours; Electropolishing for another 15 μm of surface removal followed by rinsing with 3 ppm ozonized water (OWR); Baking at a temperature of 80 - 140 °C prior to test. It is believed that the Niobium RF surface of KEK cavities is covered with a dense and uniform layer of Nb_2O_5 due to ozonized water rinsing [14].

For the convenience of comparison, we adopt an exponent-law formalism $e^{\alpha \cdot Hpk}$ to quantify the field dependent of Q_0. Hpk, in Oe, is the peak magnetic field. The increase of $\frac{1}{Q_0}$, or the modified surface resistance R_s/G, as a function of the field amplitude is then proportional to $e^{\alpha \cdot Hpk}$. A steeper Q-slope is characterized by a larger field dependent factor α, which has a dimension of Oe^{-1}.

Table 1 lists the field dependent factors for cavities with different treatment. The cavity labeled as KEK-B #7 LC is one out of the latest batch of Niobium cavities for the KEK B Factory. All the four cavities of this batch show the same field dependent characteristics as can be seen from Fig. 1. The cavity labeled as Cornell BB1-4 is a Niobium cavity for the upgrade of Cornell Electron-positron Storage Ring (CESR). This cavity was manufactured by the industry and the surface treatment was finished at Cornell. In addition to the standard surface treatment, this cavity was baked at 140 °C for about 60 hours. The cavity labeled as Cornell BB1-6 and Cornell-SRRC are Niobium cavities manufactured by the same company as for BB1-4. The surface treatment of these two cavities were finished at the company with their own facilities, following the Cornell procedure. Totally, nine Cornell type Niobium cavities have been tested, all showing the same field dependent characteristcs after a standard Cornell surface treatment. Also listed in Table 1 are the field dependent factors due to the effect of the Kapitza impedance as calculated by the ANSYS and HEAT model presented in Section 5.

From Table 1, the following findings are made. 1) The effect of the Kapitza impedance contributes only a small fraction to the overall low-field Q-slope of Niobium cavities; 2) The major effect on the low-field Q-slope is attributable to the material property of the RF surface; 3) The low-field Q-slope is reduced by baking at 140 °C [1].

Table 1: Comparison of field dependent factors

Identity	α $\times 10^{-3}\mathrm{Oe}^{-1}$	Note
KEK-B #7 LC	2.41	EP+700°C+OWR +EP+Baking
Cornell-SRRC	1.38	BCP+HPR
Cornell BB1-6	1.38	BCP+HPR
Cornell BB1-4	1.38	BCP+HPR
Cornell BB1-4	1.20	BCP+HPR+Baking
Kapitza effect	0.23	ANSYS result
Kapitza effect	0.40	HEAT result

7 DISCUSSION

According to BCS theory, the surface resistance of superconductors is independent of the amplitude of the external RF field. This renders a constant quality factor up to the onset gradient of field emission. However, experiment results are at odd with this prediction.

The effect of the Kapitza impedance across the interface between the Niobium and He-I has been blamed to be responsible for this Q-slope. This were the case, a field independent BCS resistance can still be preserved. However, our calculation results show that the effect of Kapitza impedance contributes only a small part to this Q-slope.

The surface treatment has a strong effect on the low-field Q-slope at 4.2 K. However, Q_0 virtually does not drop at lower temperatures, where the residual resistance dominates over the BCS resistance. This indicates that the Q-slope arises from the BCS resistance, rather than some additional loss mechanism. As shown in Section 6 the material property contributes to the major part of the Q-slope. We believe a field dependent term is somehow intrinsically coupled to the BCS resistance, through factors such as the mean free path of electrons.

It should be mentioned that film Niobium cavities [15] exhibit similar low-field Q-slope but at a rather pronounced degree - field dependent factors being in the range of 3.8 - 5.0 $\times 10^{-3}$ Oe^{-1}. It has been also argued that the BCS resistance depends on the amplitude of the RF field for these film Niobium cavities [16].

8 CONCLUSIONS

The effect of Kapitza impedance contributes only a small fraction to the low-field Q-slope of superconducting Niobium cavities cooled with He-I. The major contribution to

[1] This appears to be an added bonus to the 140 °C baking, which is proved to be effective in reducing the BCS resistance by a factor of as much as 2.

this Q-slope arises from the material property of the Niobium RF surface. To fully account this Q-slope, the BCS resistance has to be dependent on the amplitude of the RF field resonating in the cavity.

9 ACKNOWLEDGMENT

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