THERMAL ANALYSIS OF A 200MHZ NB-CU CAVITY

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Abstract

The expected Q(Eacc) curves are calculated for a 200 MHz Nb-Cu cavity. An exponent-law formalism for BCS resistance is introduced to account for the Q-drop as a function of Eacc. Pipe-cooling of the cavity is explored. At a 15 MV/m gradient, a Q_0 of 2×10^9 and 7×10^9 is expected at a bath temperature of 4.5 K and 2.5 K, respectively. A 200 MHz cavity cooled by 17 pipes can reach a Q_0 comparable to that of a bath-cooled cavity at 15 MV/m.

1 INTRODUCTION

Superconducting RF cavities with elliptical geometry are envisaged to find applications in the acceleration sections of a muon collider [1]. 200 MHz Niobium sputtered Copper cavities are currently under investigation at LNS, Cornell University. It is desired to have some Q_0(Eacc) numbers extrapolated from today's technology for producing Nb-Cu cavities. The fact that these cavities are to be operated in a pulsed mode underscores the importance of the Lorentz force detuning effect. From this point of view, a pipe cooling scheme is more attractive than the conventional bath cooling scheme , as pipes provide extra enforcement to the cell of the cavity. Another advantage to pipe cooling is its cost effectiveness.

In this paper, calculations with ANSYS modeling are carried out to address the following questions: (1) Based on today's technology, what Q_0 numbers can we expect when 200MHz Nb-Cu cavities are operated at the desired gradients? (2) For a pipe-cooled cavity, can we achieve reasonably high Q comparable to that of a bath-cooled cavity?

2 MATERIAL PROPERTIES

2.1 Surface Resistance

Our calculations are based on the measurement results for LEP 350 MHz[2] and LHC 400 MHz Nb-Cu[3] cavities. From measurements, a noticeable Q-drop as a function of accelerating gradient is evidenced starting from very low gradients, indicating that the surface resistance of Niobium films on Copper is field dependent. Due to the fact that a coherent formula describing the field dependent surface resistance is still lack, in our thermal calculations we introduced an *ad hoc* exponent-law formalism accounting the field dependent effect. In this formalism, the regular field independent BCS resistance is multiplied with an exponent of the form $e^{\alpha \cdot Eacc}$.

$$R_s(T, f, Eacc) = R_{res} + (\frac{f}{f_0})^2 \cdot R_{BCS}(T)|_{f_0} \cdot e^{\alpha \cdot Eacc}, \tag{1}$$

where R_s is the surface resistance in Ω, T is surface temperature in K, f is the frequency of the cavity in MHz, Eacc is the field gradient in MV/m, R_{res} is the residual resistance in Ω, f_0 in MHz is the reference frequency at which experimental data are available, R_{BCS} in Ω is the regular BCS resistance at the reference frequency f_0, α is the field dependent factor in $(MV/m)^{-1}$. Here we assume the residual resistance is independent of T, f, or Eacc. The measurements show R_{res} is normally in the range of 10 - 30 nΩ. The BCS resistance is calculated with the computer code SRIMP developed by Halbritter [4].

Material properties and the field dependent factor α are obtained by fitting experimental data of LEP 350 MHz and LHC 400 MHz cavities operating at 4.5 K and 2.5K. Depending on material property of Niobium and bath temperature, the field dependent factor α is found to vary in the range from 0.15 to 0.2 $(MV/m)^{-1}$. Q(Eacc) curves for a 200 MHz Nb-Cu cavity is then calculated, scaling the BCS resistance according to a f^2 law, as indicated in Eq.1.

2.2 Cooling at Copper-LHe Interface

Thanks to the f^2 dependence of the BCS resistance, today's low frequency SRF cavities are normally cooled by LHe-I working at a bath temperature of 4.2 - 4.5 K [5] [6] [7]. Across the interface between a solid and LHe-I, there exists a temperature jump $\Delta T = T_s - T_B$, where T_s is the solid surface temperature in K, T_B is the bath temperature in K. ΔT is related to the heat flux q in W/m^2 across the interface through Eq.2[8],

$$q = h \times (T_s - T_B). \tag{2}$$

The convective film coefficient h in $W/(m^2 \cdot K)$ represents the cooling capability of LHe-I,

$$h = 10^4 (T_s - T_B)^{1.5}. \tag{3}$$

Eq.3 is valid up to a heat flux of $10^4 W/m^2$, above which film boiling starts and the cooling capability of LHe dramatically decreases.

2.3 Thermal Conductivity of Copper

The thermal conductivity of Copper we used in calculations is shown in Fig.1.

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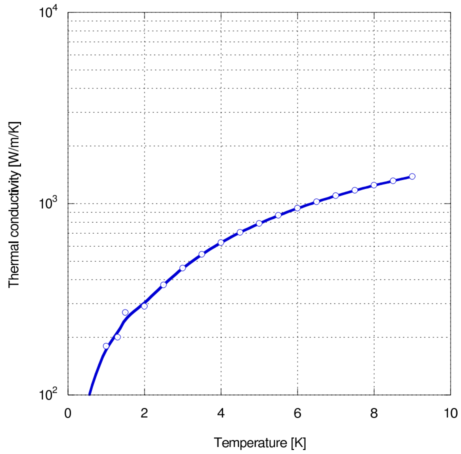

Figure 1: Temperature dependent thermal conductivity of Copper used in calculations.

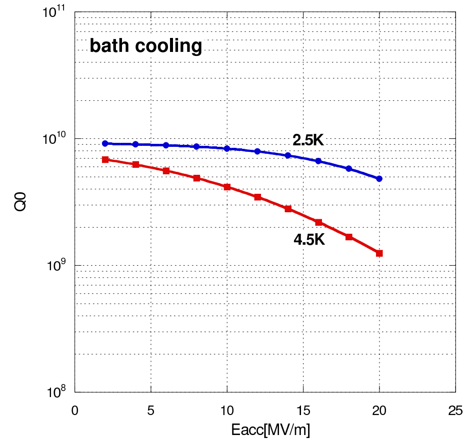

Figure 3: Calculated Q(Eacc) curves of the 200MHz Nb-Cu cavity at a bath temperature of 4.5K and 2.5K.

3 MODEL

Instead of considering a full scale cavity, only a narrow belt zone along the equator is treated in our model. Because there is no heat transfer in azimuthal direction, the model is further simplified to a Niobium slab in a Cartesian coordinate system as illustrated in Fig. 2. The slab has a unit length in z direction. This model is validated as far as the Q_0-Eacc dependence is concerned. A comparison was made for results obtained with the slab model and with a full scale cavity model. We found the difference in calculated Q(Eacc) curves is negligible. This is to say that Q(Eacc) can be solely calculated by the following equation

$$Q_0 = \frac{G}{R_s(T, f, Eacc)}, \qquad (4)$$

where G in Ω is the geometry factor bearing the usual definition, $R_s(T, f, Eacc)$ in Ω is the surface resistance of Niobium in the equator region (Eq.1).

The slab has a thickness of 3mm (the wall thickness of the cavity) in y direction and a length of 3cm in x direction. Insulation boundary conditions are applied to the left and right surfaces of the slab. The cooling effect by LHe-I is represented by a convective boundary condition on the top surface. The "bulk temperature" is the bath temperature and the film coefficient is described in Eq. 3. The RF heating effect is also represented by a convective boundary condition, following Knobloch's methodology [9]. The idea is to set the "bulk temperature", T_V, well above the bath temperature, so that the film coefficient in $W/(m^2 \cdot K)$ can be approximated by the following equation

$$h_{RF} \approx \frac{R_s(T, f, Eacc){H_s}^2}{2T_V}, \qquad (5)$$

where $R_s(T, f, Eacc)$ is the surface resistance of Niobium (Eq.1) and H_s in A/m is the magnetic field strength in the equator region at a given accelerating gradient.

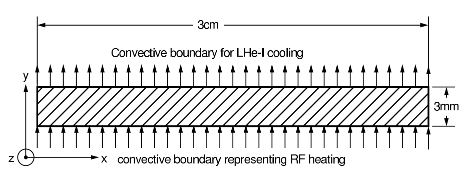

Figure 2: The slab model for thermal analysis of Nb-Cu cavities.

4 RESULTS

4.1 Expected Q_0 at 200 MHz

Fig.3 shows the calculated Q(Eacc) curve of the 200MHz cavity based on experiment results measured with 400MHz Nb-Cu cavities for LHC. At a bath temperature of 4.5K, a Q_0 value of 3×10^9 and 1×10^9 can be expected at an accelerating gradient of 15 MV/m and 20 MV/m, respectively.

4.2 Pipe cooling

Because of its low frequency, a 200 MHz cavity will have a radial dimension larger than 1m. When such cavities are bath-cooled, the inventory of LHe will be tremendous. To improve cost effectiveness, pipe cooling is more attractive.

Pipe cooling is made possible for a Nb-Cu cavity due to the following reasons: (1) Thermal conductivity of Copper is 10 times higher than that of Niobium at a temperature near 4.5 K; and (2) Copper cooling pipes can be easily brazed onto the Copper body of the cavity.

Another advantage of pipe cooling is that cooling pipes provide extra stiffening to the cell. This is very desirable for a cavity susceptible to Lorentz force detuning, which is the case for muon collider SRF cavities.

Fig. 4 shows the calculated Q(Eacc) curve for a 200 MHz Nb-Cu cavity cooled by pipes filled with 4.5K LHe[1].

[1] Convective film coefficient of LHe in pipes is taken as the same as that in bath pool

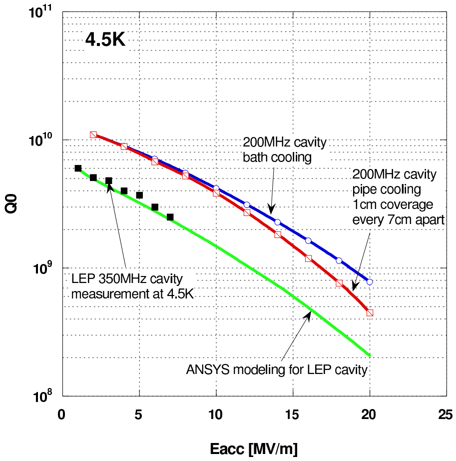

Figure 4: Q(Eacc) of the pipe-cooled 200MHz Nb-Cu cavity at 4.5K, together with that of the same cavity with bath cooling at 4.5K. Calculations are based on LEP 350MHz cavities. Experiment data and ANSYS fitting for LEP cavities are also given.

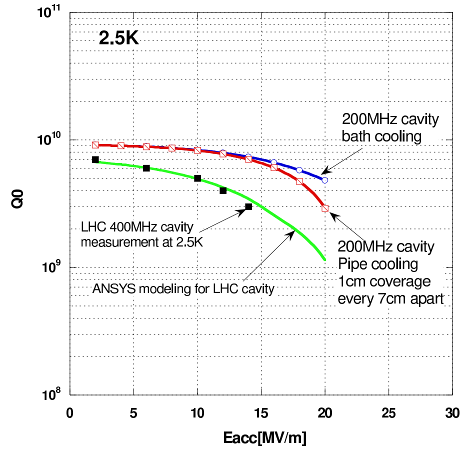

Figure 5: Q(Eacc) of the pipe-cooled 200MHz Nb-Cu cavity at 2.5K, together with that of the same cavity with bath cooling at 2.5K. Calculations are based on LHC 400MHz cavities. Experiment data and ANSYS fitting for LHC cavities are also given.

The pipes provide a surface cooling coverage of 1 cm every 7 cm apart. For comparison, the calculated Q(Eacc) for bath cooling at 4.5K is also given. These calculation curves are based on experiment results measured with 350 MHz Nb-Cu cavities for LEP. The measurement results and ANSYS fitting for LEP cavities are shown also in Fig. 4.

As can be seen from Fig. 4 that the Q_0 of a pipe-cooled cavity is very close to that of a bath cooled cavity up to an accelerting gradient of 15 MV/m. However, Q_0 values differ by a factor of 4 at 20 MV/m.

In Fig. 5, Q(Eacc) curves for pipe cooling and bath cooling at 2.5 K are illustrated. Again, the cooling pipes are arranged in such a way that there is a 1 cm surface cooling coverage every 7 cm apart. These curves are based on experiment results measured with 400 MHz Nb-Cu cavities for LHC. The experiment results and ANSYS fitting curve for LHC cavities are also given in Fig. 5.

At 2.5K, the difference between bath cooling and pipe cooling is reduced compared to the case at 4.5K. Even at a gradient of 20 MV/m, the Q_0 values for pipe and bath cooling differs only by 40%.

A pipe-cooled 200 MHz cavity with a pipe arrangement discussed above is illustrated in Fig. 6. The whole cell can be covered by 17 cooling pipes.

5 CONCLUSION

Extrapolating from today's technology in manufacturing Nb-Cu cavities, we expected a Q_0 of 2×10^9 and 7×10^9 when a 200MHz Nb-Cu is operated at a gradient of 15MV/m at a bath temperature of 4.5K and 2.5K, respectively.

Pipe-cooled Nb-Cu cavities at a moderate surface cooling coverage can reach Q_0 values comparable to that of bath cooled cavities, given the cooling effectiveness of LHe-I flowing in cooling pipes is comparable to that of LHe-I in a bath pool.

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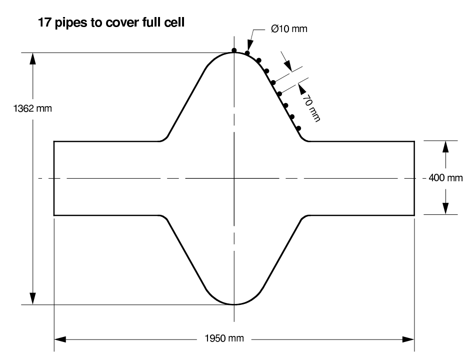

Figure 6: Sketch of cooling pipe arrangement of the 200MHz Nb-Cu cavity.