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OPERATIONS OF COPPER CAVITIES AT CRYOGENIC TEMPERATURES*

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Abstract

How the anomalous skin effect in copper affects the efficiency of copper-cavities will be studied in the experiment, especially at lower temperatures. The accurate quality factor Q and resonant frequency of three coaxial cavities will be measured over the temperature range from 300 to 22 K. The three coaxial cavities have the same structure, but different lengths, which correspond to resonant frequencies: around 100 MHz, 220 MHz and 340 MHz. The motivation is to check the feasibility of an efficient pulsed, liquid nitrogen cooled ion linac.

INTRODUCTION

There are plenty of studies in copper conductivity at liquid nitrogen temperatures and below and this had inspired cavity designers since long - see for example [1]. The RF loss in copper is given by

$$P = \frac{1}{2}\int R_s \cdot H_0^2 \cdot dA \qquad (1)$$

where H_0 is the magnetic field amplitude and R_s is the surface resistance and is given by

$$R_s = \sqrt{\pi f \mu_0 \mu_r \rho} \qquad (2)$$

where f is the resonant frequency, μ_0 is the magnetic permeability in vacuum, μ_r is the relative magnetic permeability of copper and ρ is the electrical resistivity.

From Eq. (2) we can see that R_s is proportional to $\sqrt{\rho}$ which depends on the temperature. It is decreasing with temperature, see Fig. 1 [2].

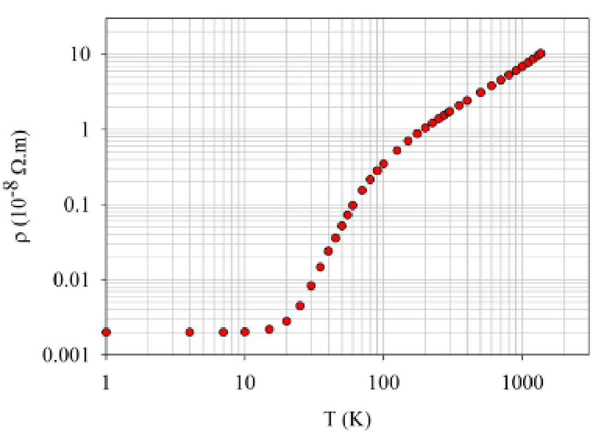

Figure 1: The electrical resistivity dependence on the temperature of very pure copper.

This means that the RF losses decrease when the copper is cooled down to lower temperature. This is true when the temperature drops to a certain value for a specific frequency. Below this temperature the electron free path becomes comparable to or even greater than the skin depth $\delta = \sqrt{2\rho/\omega\mu_0\mu_r}$, where ω is the angular frequency, the anomalous skin effect starts to play an increasing role and will reduce the advantage of rising conductivity. Below this temperature the RF losses don not follow $\sqrt{\rho}$ any more. Even so there might be still a potential for the cryogenic cavities at relatively low rf frequencies and very low duty factor such like in case of heavy ion structures and up to about 350 MHz. The goal of this work is to find out in which cases the potential is.

STRUCTURE OF CAVITIES

For this work three simple $\lambda/4$ coaxial cavities have been designed and was fabricated at the workshop in IAP. They have the same structure, see in Fig. 2, but different lengths, which correspond to the resonant frequencies: around 100 MHz, 220 MHz and 340 MHz. The designed parameters for the cavities are listed in Table 1.

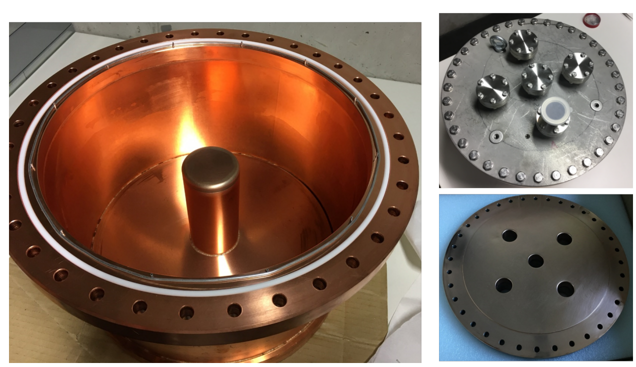

Figure 2: Structure of the shortest $\lambda/4$ coaxial cavity and the cover.

Table 1: Design Parameters of the Cavities

***f*(design) (MHz)**	***Q*(simulated)**	**length (mm)**	**Gap (mm)**
100	13166	735	54
220	17072	324	54
340	19449	201	54

The main parts of the cavities were made of copper and the top cover is made of stainless steel. Later the inner side of the cover was copper plated with the thickness of 100 µm. A teflon ring and an aluminum ring were used for the sealing. The aluminum ring was also used as RF contact between the main part of the cavity and the cover. The gap width of 54 mm between the top of the inner cylinder and the inner side of the top cover is identical for all three cavities.

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CAVITY MEASUREMENTS

The first measurements were done with the 340 MHz cavity early this year. The Q factors over the temperature range from 8 K to 300 K with the weak coupling were measured after the conditioning to 50 W.

Weak Coupling

The coupling strength is defined by [3]

$$\beta = \frac{Q_0}{Q_{ex}} \tag{3}$$

where Q_0 is the unloaded quality factor and Q_{ex} is the external quality factor.

In the measurement a very small input coupler about 1 cm^2 was used, whose coupling strength β_{in} is equal to $4.24x10^{-4}$. An even smaller loop was used for the output coupler. This means the cavity and the two couplers are very weakly coupled. The loaded Q_L and the unloaded Q_0 are related by

$$Q_0 = Q_L(1 + \beta_{in} + \beta_{out}). \tag{4}$$

In the experiment the Q_L was measured. Because β_{in} and β_{out} are very small, so by weak coupling Q_0 is approximately equal to Q_L.

Conditioning

The conditioning for the cavity is up to 50 W and the conditioning process lasted about one day. After the conditioning the output signal was split to be measured simultaneously with an oscilloscope. Figure 3 shows the measured voltage signal from the oscilloscope versus the power from the amplifier.

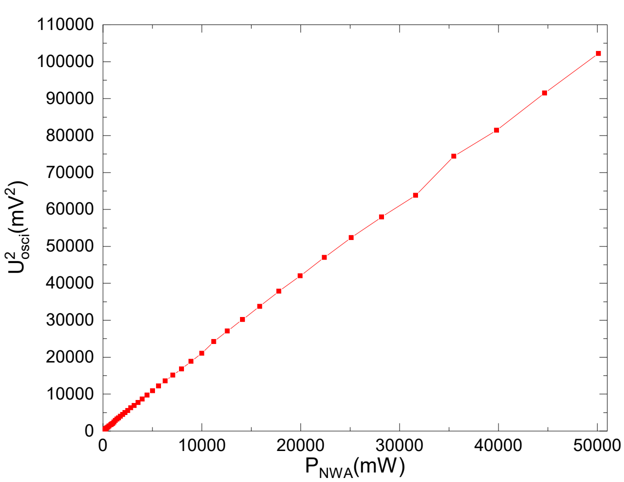

Figure 3: Measured voltage versus the power from the amplifier.

Clearly we can see from the figure that the curve is linear without peaks, which means the cavity is free from multipacting and ready for precise Q-measurements.

Measurement of Q Factor

After all the preparations the cavity was cooled down to about 8 K by liquid helium. The Q factor was measured over the temperature range from 8 K to 293 K. Figure 4 shows the ratio of the measured Q factor over the temperature range from 40 K to 293 K of the measured Q factor at 293 K in comparison with $\sqrt{\rho(293)}/\sqrt{\rho}$, where the best literature values of ρ for bulk pure copper are used.

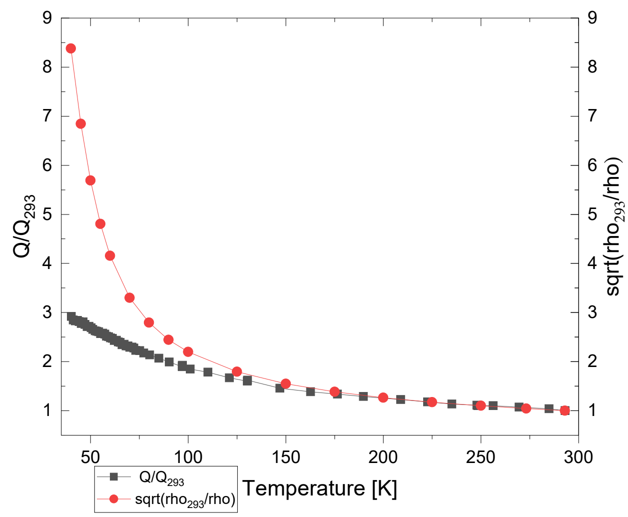

Figure 4: Measurements of the Q factor for the temperature range from 40 K to 293 K.

One can see that from 100 k down to lower temperatures the difference between these two curves is growing, which means in this case from 100 K the anomalous skin effect, the real $\rho(T)$, or both together have already play an increasing role. At 40 K the ratio of between theory and measurement is already about a factor 2.87.

ELECTRICAL RESISTIVITY

A copper coil was made from the same material of the cavity, see Fig. 5. Later the dc electrical resistivity ρ of the coil with the temperatures will be measured, which will be screwed on the cover of the cavity. These measurements can rule out the influence of the impurity of copper on the measurements of Q factor.

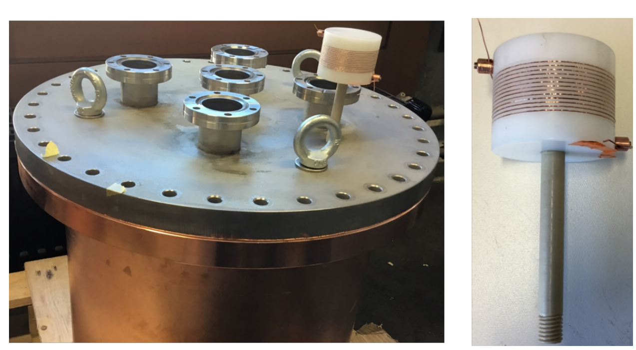

Figure 5: Coil for the measurements of ρ from cryogenic temperature to room temperature.

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The length of the copper wire is about 2.1 m and the diameter is about 0.5 mm. The theoretically calculated resistance of the coil is 186 mΩ at T=300 K and 2.16 mΩ at T=10 K.

THERMODYNAMIC CALCULATION

The temperature response that results from a short, instantaneous pulse of energy Pdt at the surface is given by [4]

$$\Delta T = [Q_0 / A\rho c(\pi\alpha\tau)^{1/2}] exp(-x^2/4\alpha\tau) \quad (5)$$

where ΔT is the temperature change, A is the Area of the inner surface, ρ is the density of the solid, c is the heat capacity, α is the thermal diffusivity and k is the thermal conductivity.

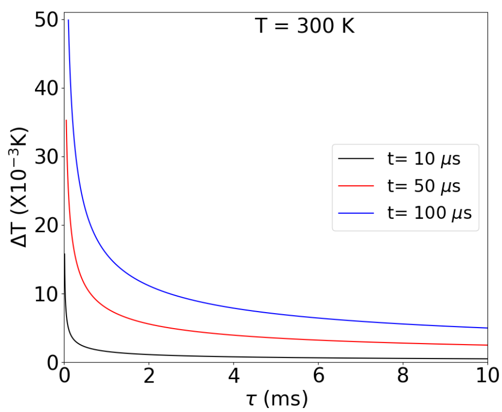

Figure 6: Surface temperature response with time at T_{start}=300 K. Pulse length t, power P/A=317 kW/m^2.

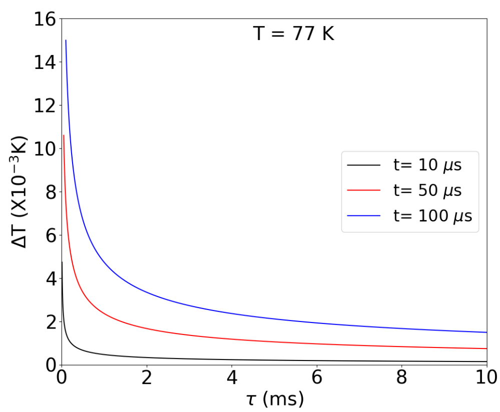

Figure 7: Surface temperature response with time at T_{start}=77 K. Pulse length: t, power P/A=106 kW/m^2.

All the results (see Figs. 6, 7, 8 and 9) are calculated with the 340 MHz cavity with the simulated power loss of 109.5 kW at 300 K and 36.8 kW at 77 K. The area A is 0.3457m^2. Figures 6 and 7 shows that ΔT depends on the copper starting temperature. Figures 8 and 9 shows that ΔT goes to zero faster in the wall in case T=300 K than T=77 K. The difference between these two cases is due to the temperature dependence of the heat conductivity and the specific heat.

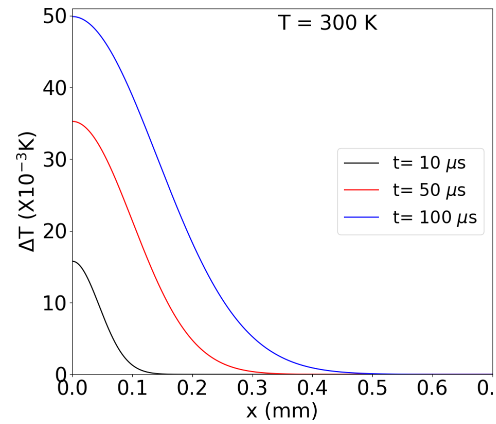

Figure 8: Temperature distribution along the heat flux immediately at the end of the pulse. Same conditions as shown in Fig. 6.

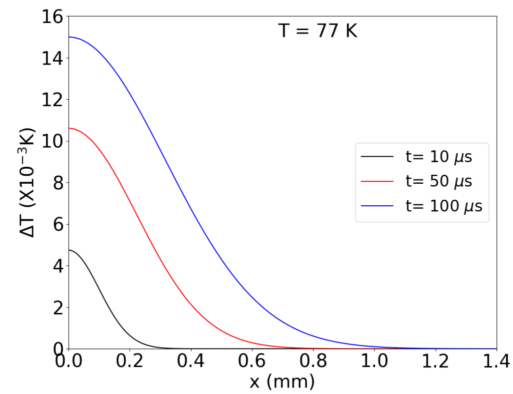

Figure 9: Temperature distribution along the heat flux immediately at the end of the pulse. Same conditions as shown in Fig. 7.

CONCLUSION

The measurements with the 340 MHz cavity are already finished. The preparations for the 100 MHz cavity have been started, followed by the 220 MHz cavity. At the same time the dc measurements of ρ will be done. The results should finally allow to judge, in which cases nitrogen cooled, pulsed linacs might be superior to room temperature linacs.

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