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OPERATIONS OF COPPER CAVITIES AT CRYOGENIC TEMPERATURES*

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Abstract

This work is focused on the anomalous skin effect in copper and how it affects the efficiency of copper-cavities in the temperature range 40-50 K. The quality factor Q of three coaxial cavities was measured over the temperature range from 10 K to room temperature in the experiment. The three coaxial cavities have the same structure, but different lengths, which correspond to resonant frequencies: around 100 MHz, 220 MHz and 340 MHz. Furthermore, the effects of copper-plating and additional baking in the vacuum oven on the quality factor Q are studied in the experiment. The motivation is to check the feasibility of an efficient, pulsed, ion linac, operated at cryogenic temperatures.

INTRODUCTION

The RF loss in copper is given by

$$P = \frac{1}{2}\int R_s \cdot H_0^2 \cdot dA \tag{1}$$

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

$$R_s = \sqrt{\pi f \mu_0 \mu_r \rho} \tag{2}$$

where ρ is the specific electrical resistivity.

From Eq. (2) we can see that R_s is proportional to $\sqrt{\rho}$. ρ decreases as the temperature decreases, see Fig. 1 [1].

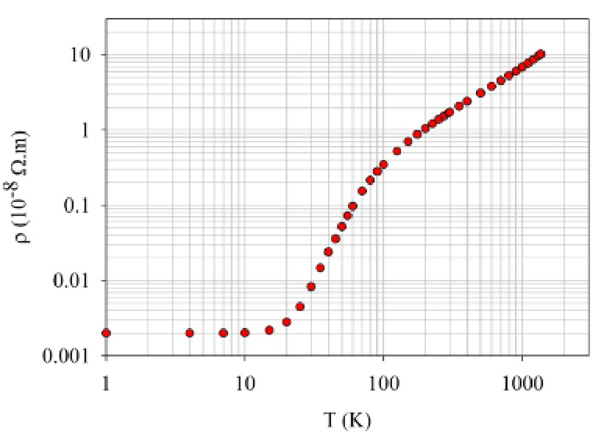

Figure 1: The electrical resistivity dependence on the temperature of very pure copper (RRR $\simeq$ 550).

Figure 1 shows how the electrical resistivity changes with temperature in the case of direct current (DC) with a high RRR value. This curve is still applicable for the RF case when the temperature drops to a certain value for a specific frequency. Below this temperature the mean free path of electrons becomes comparable to or even greater than the skin depth $\delta = \sqrt{2\rho/\omega\mu_0\mu_r}$, the anomalous skin effect starts to play an increasing role and will reduce the advantage of rising conductivity. Below this temperature the RF resistivity will not changes like the DC resistivity shown in Fig. 1. It still decreases with the temperature but more slowly.

The definition of the quality factor Q_0 of a cavity is

$$Q_0 = \frac{\omega W}{P} \tag{3}$$

where W is the stored energy. According to Eqs. (1), (2) and (3), $Q_0 \propto 1/P \propto 1/R_s \propto 1/\sqrt{\rho}$, which means, Q_0 increases with decreasing temperature. However, it increases slower in the cryogenic temperature region due to the anomalous skin effect. Even so, there might be still a potential for the cryogenic cavities at modest rf frequencies and at low duty factor such like in case of heavy ion synchrotron injectors. The goal of this work is to find out in which this approach might be attractive.

TEST CAVITY GEOMETRY

For this work three simple $\lambda/4$ coaxial cavities have been designed and were 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)	Length (mm)	Gap (mm)
100	735	54
220	324	54
340	201	54

The main parts of the cavities were made of copper and the top cover was made of stainless steel. The inner side of

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the cover was copper plated with the thickness of 100 µm in the company Galvano-T. A teflon ring and an aluminum ring were used for the sealing. The size of the gap between the top of the inner cylinder and the inner side of the top cover is the same for all three cavities, which is 54 mm.

CAVITY MEASUREMENTS

In the experiment the quality factor Q over the temperature from about 10 K up to 300 K was measured after a conditioning procedure to 50 W cw mode. The measurements of the quality factor were performed in transmission mode at very weak coupling.

Weak Coupling

Two small loops with effective coupling areas of a few mm^2 each were used for the input and output couplers for the inductive coupling. β_e and β_t are the coupling strengths of the input and output couplers. The loaded quality factor Q_L and Q_0 are related by

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

The qualtity factor measured directly from the experiment is Q_L, what we need is Q_0. But if β_e and β_t are both very small, according to Eq. (4), Q_0 is approximately equal to Q_L. The measured coupling strengths of the couplers were about 4.2×10^{-4} at room temperature, which satisfies the condition of weak coupling even at cryogenic temperatures.

Measurement of Q factor

After all the preparations the cavities were cooled down to about 10 K with liquid helium. The Q factor was measured then over the temperature from about 10 K to room temperature during the warming up process. To study how the copper plating affects the quality factor, the shortest cavity (340 MHz) was matt copper plated with the thickness about 50 µm in the company Galvano-T. Additionally, the vacuum annealing can further improve the conductivity of the copper plated layer [2]. So the shortest cavity was sent to GSI for the vacuum annealing at 400°C during one hour. All the measured results are plotted in Fig. 3.

In order to better compare the results, the curves show the ratio of the quality factor at different temperatures against the room temperature value. If the RRR value of the copper is smaller than 15, the anomalous skin effect does not occur [3]. Therefore, this effect doesn't occur at 100 MHz, 220 MHz and the original 340 MHz cavity measurements on bulk copper[1].

After the copper plating and the vacuum annealing, the RRR of the copper is improved significantly. The ratio of the quality factor at the cryogenic temperatures is smaller

[1] As the ratio $Q(T)/Q_{room}$ is less pronounced at lower frequencies, we assume a massively RF acting alloy in this copper-like ion with μ_r' and μ_r'' increasing at lower frequencies. At room temperature the Q factor for the 100 MHz cavity is 11803, the 220 MHz cavity 15812 and the 340 MHz cavity 17569. That means, the bulk copper shows reasonable RF conductivity at room temperature operation.

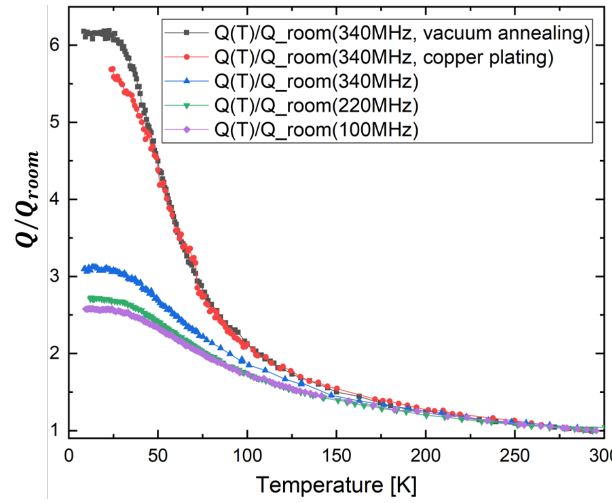

Figure 3: Measurements of the Q factor for the temperature range from about 10 K to room temperature.

than the ratio of the DC resistivity due to the anomalous skin effect for these two cases. The RRR of copper after the copper plating and the vacuum annealing can not be directly measured to compare it with the results of the quality factor measurements. However, one can calculate the RRR from theory.

The vacuum annealing process can improve the RRR of the copper additionally, but only slightly in our case.

Theoretical Calculation of RRR

The ratio of the surface resistance R with and without the anomalous skin effect is given by [4]

$$\frac{R(T)}{R_a(T)} = \frac{Q_a}{Q} = \sqrt{\frac{\rho}{\rho_a}} = \frac{1.93 \cdot p_0^{1/3}}{1 + 1.157\alpha^{-0.276}} \tag{5}$$

where the index a denotes quantities including the anomalous skin effect. The parameter α is equal to $1.5/p_0^2$ and P_0 is defined as

$$p_0 = \frac{\delta}{l} = \frac{1.7 \cdot 10^6}{f^{1/2}} \cdot (\frac{\rho}{\rho_n})^{3/2} \tag{6}$$

where ρ_n is the electrical resistivity at room temperature and l is the mean free path of electrons. According to Eq. (5) and (6), the ratio $\sqrt{\rho_n/\rho}$ can be calculated and is plotted in Fig. 4.

Eq. (5) holds with high accuracy only by $\alpha > 3$. Therefore, the calculated curves are just plotted to $\alpha = 3$. The calculated $\sqrt{\rho_n/\rho}$ at 10 K is 9.48 after the vacuum annealing, while the Q factor ratio Q/Q_n is only 6.18 at 10 K due to the anomalous skin effect. Nevertheless, the ratio of the quality factor at 40 K is still 5.37 and at 50 K is 4.5. Accelerators operated around these temperatures still have a lot of potential: the RF power losses are reduced by these factors. Additionally, measurements at cryogenic temperature operation of copper cavities showed a higher electric surface field limit [5–7]. This should allow for an optimum accelerator

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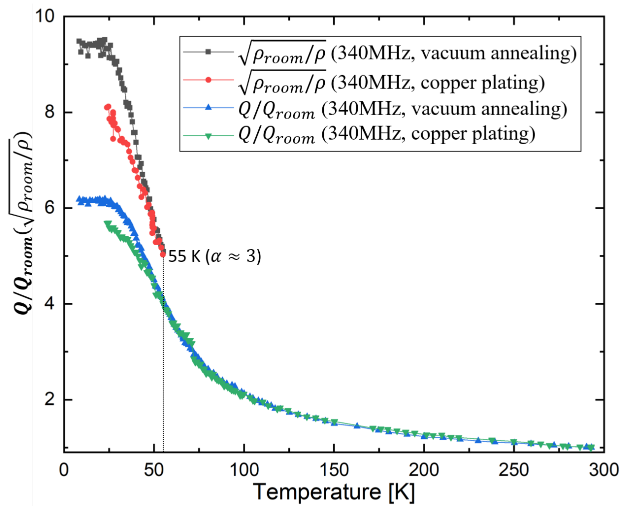

Figure 4: Calculated ratios of the electrical resistivity compared with the ratios of the quality factor.

layout with respect to RF power amplifiers and compactness of the linac.

THERMODYNAMIC CALCULATION

The temperature response that results from a short, instantaneous pulse of energy $Q_0 = Pdt$ at the surface is given by [8]

$$\Delta T = [Q_0/A\rho c(\pi\alpha\tau)^{1/2}]exp(-x^2/4\alpha\tau) \qquad (7)$$

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

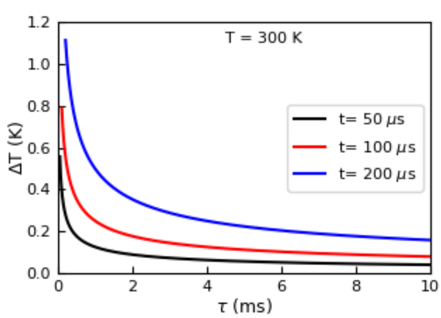

Figure 5: Surface temperature response with time at T_{start} = 300K. Pulse length t, power P/A=5 MW/m^2.

All the results (see Fig. 5, 6, 7 and 8) are calculated for copper parameters as reached after the vacuum annealing. Figures 5 and 6 show that ΔT depends on the copper starting temperature. Figures 7 and 8 show that the heat expansion into the wall is faster in case T=40 K than at T=300 K. The difference between these two cases is mainly due to the temperature dependence of the heat conductivity and the specific heat.

In a technical application, it is suggested to use helium gas as a coolant, efficiently precooled by liquid nitrogen.

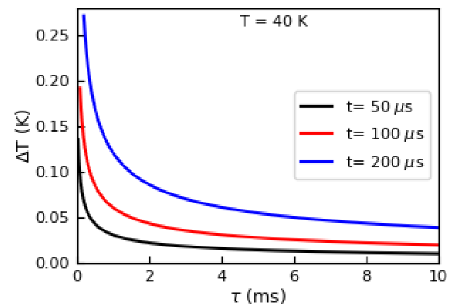

Figure 6: Surface temperature response with time at T_{start} = 40K. Pulse length: t, power P/A=0.816 MW/m^2.

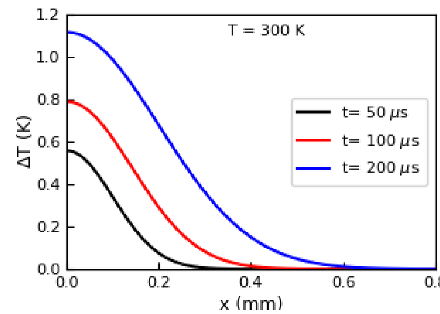

Figure 7: Temperature distribution along the heat flux immediately at the end of the pulse. Same conditions as shown in Fig.5.

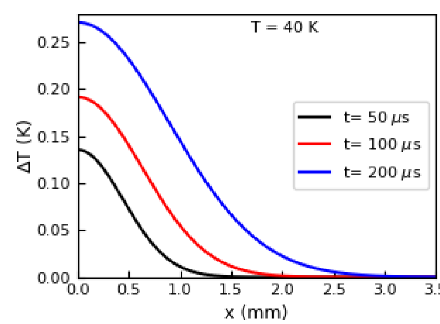

Figure 8: Temperature distribution along the heat flux immediately at the end of the pulse. Same conditions as shown in Fig.6.

CONCLUSION

This work shows us that the RRR of copper can be greatly improved by the copper plating and the vacuum annealing, thereby improving the efficiency of the accelerators. Although the quality factor has declined due to the anomalous skin effect at the cryogenic temperatures, there is still quite a potential of the pulsed ion linac, operated at cryogenic temperatures between 40-50 K.

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