Operations of Copper Cavities at Cryogenic Temperatures

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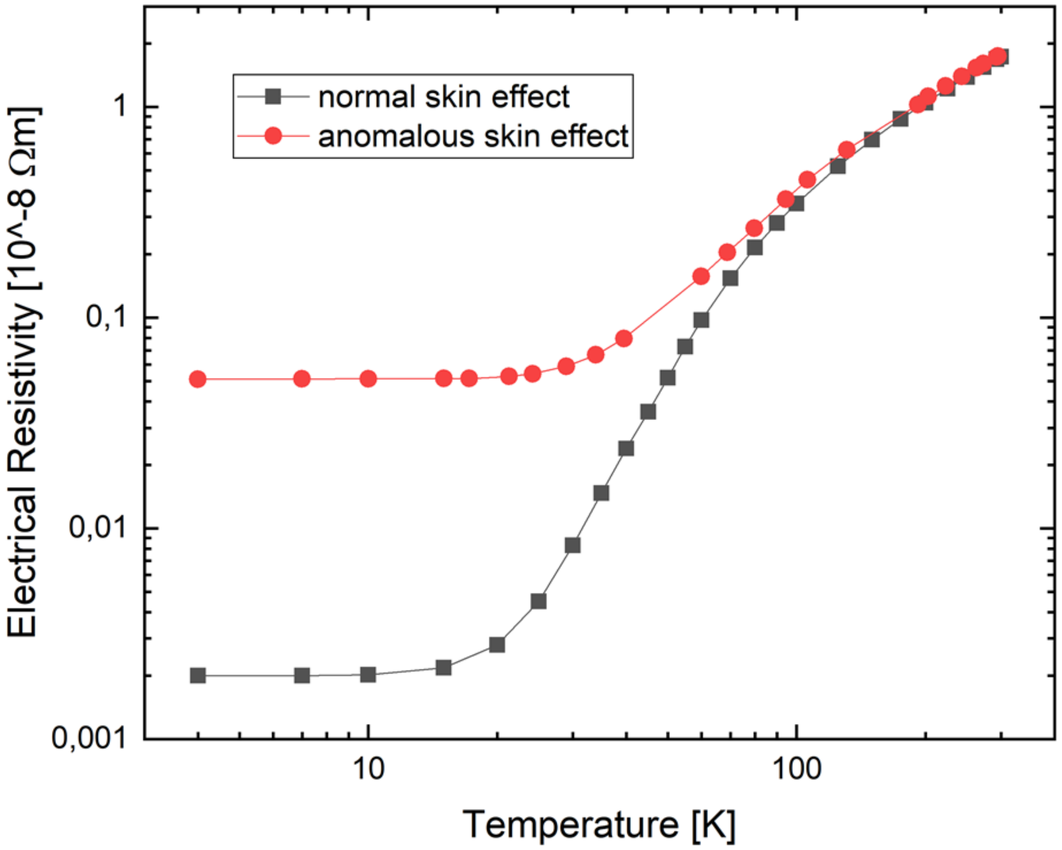
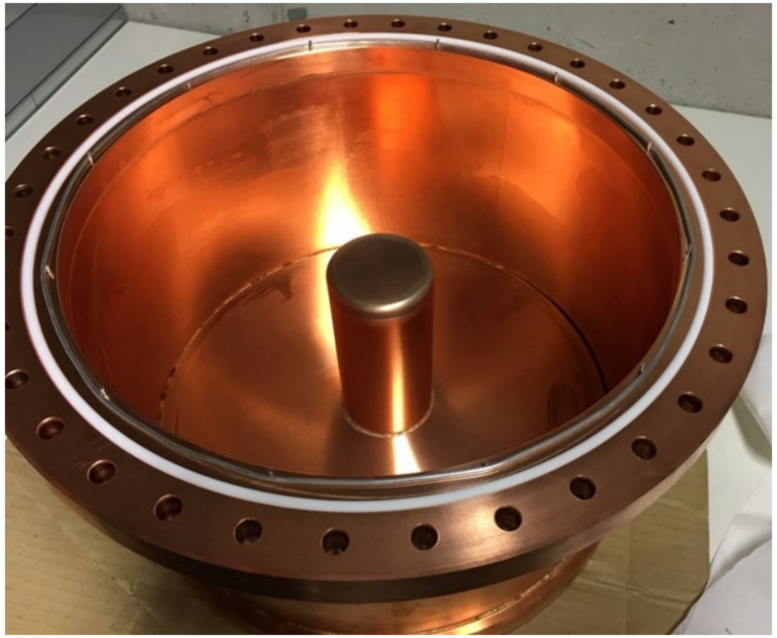
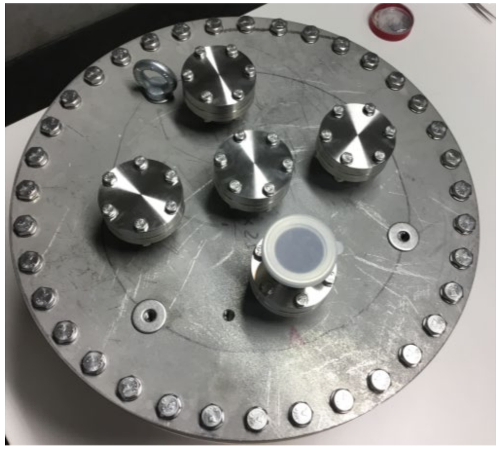
Anomalous skin effect

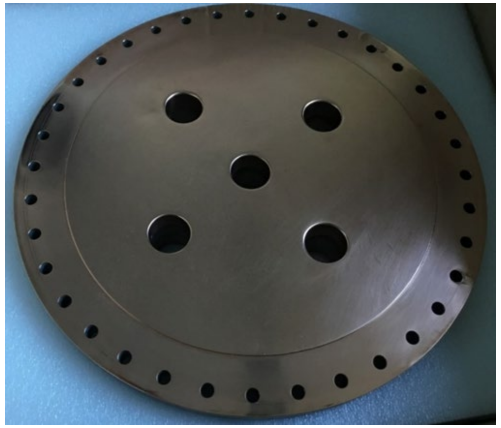


If the mean free path of electrons l is comparable to or greater than the skin depth $\delta = \sqrt{2\rho/\mu\omega}$, the conductive electrons in the skin depth will get out of this area, leading to a decrease in conductivity.

Test cavity geometry and experiment setup







f (Design, MHz)	Length(mm)	Gap(mm)
100	735	54
220	324	54
340	201	54

Measurement method

Loaded quality factor Q_L will be measured in the Experiment over the temperature range from about 20 K to 300 K with a network analyser.

$$Q_0 = Q_L(1 + \beta_e + \beta_t)$$

β is the coupling strength. When $\beta_e, \beta_t \ll 1,\ Q_0 \cong Q_L$.

β_e(100MHz)	3.21e-4
β_e(220MHz)	6.15e-4
β_e(340MHz)	4.24e-4

Presentation of results

Definiton of Quality factor Q_0:

$$Q_0 = \frac{\omega W}{P_c}$$

$$Q_0 \propto \frac{1}{P_c} \propto \frac{1}{R_s} \propto \frac{1}{\sqrt{\rho}}$$

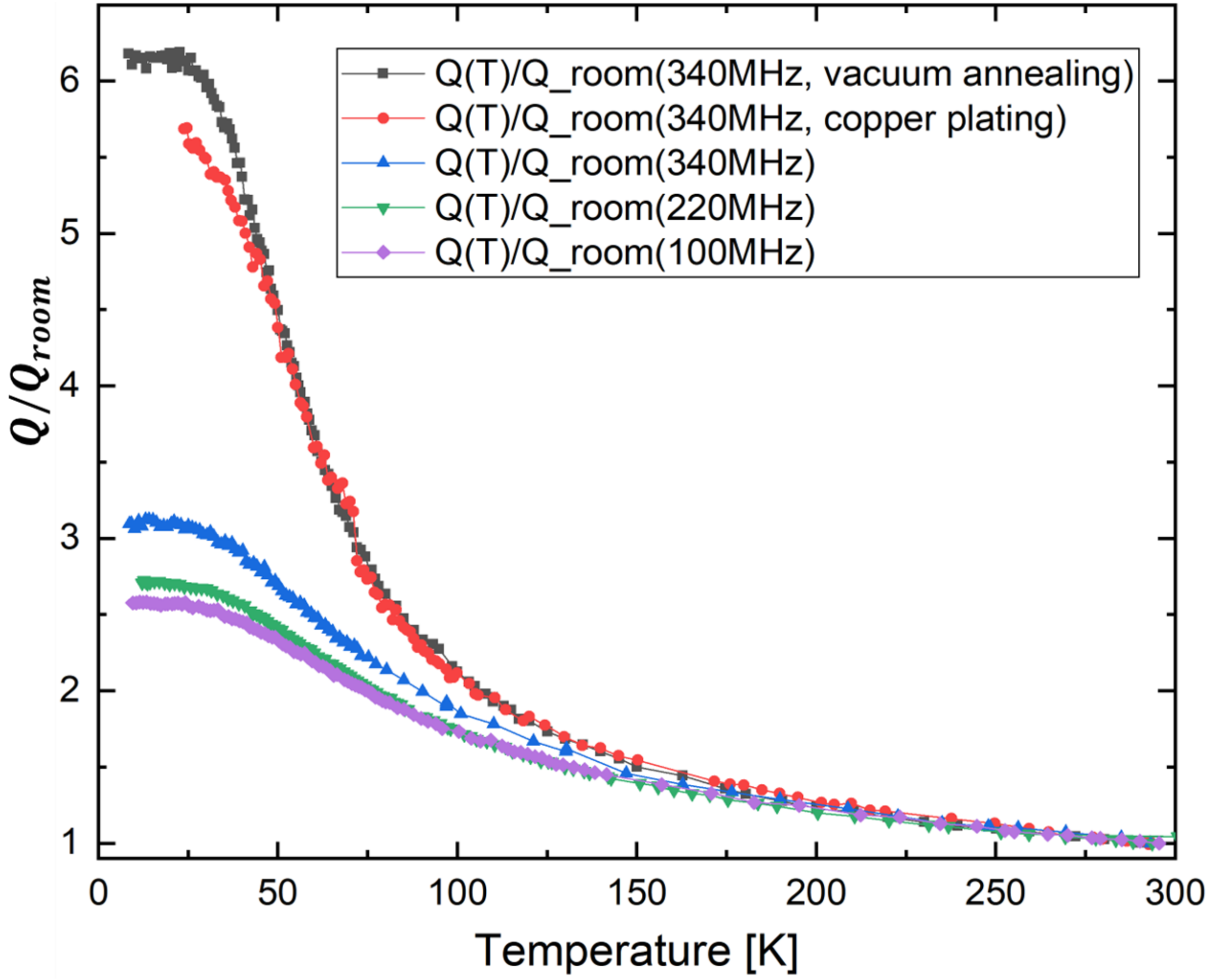
$$\frac{Q}{Q_{room}} = \sqrt{\frac{\rho_{room}}{\rho}}$$

At room temperature:

Bulk copper: $Q_{exp} \cong 0.9(\pm 0.01) \cdot Q_{sim}$

Copper plated cavity: $Q_{exp} \cong 0.96 \cdot Q_{sim}$

Copper plated and vacuum annealed: $Q_{exp} \cong 0.92 \cdot Q_{sim}$



Theoretical calculation of the electrical resistivity

Surface resistance without the anomalous skin effect:

$$R(T) = \sqrt{\pi f \mu_0 \rho(T)}$$

Surface resistance with the anomalous skin effect:

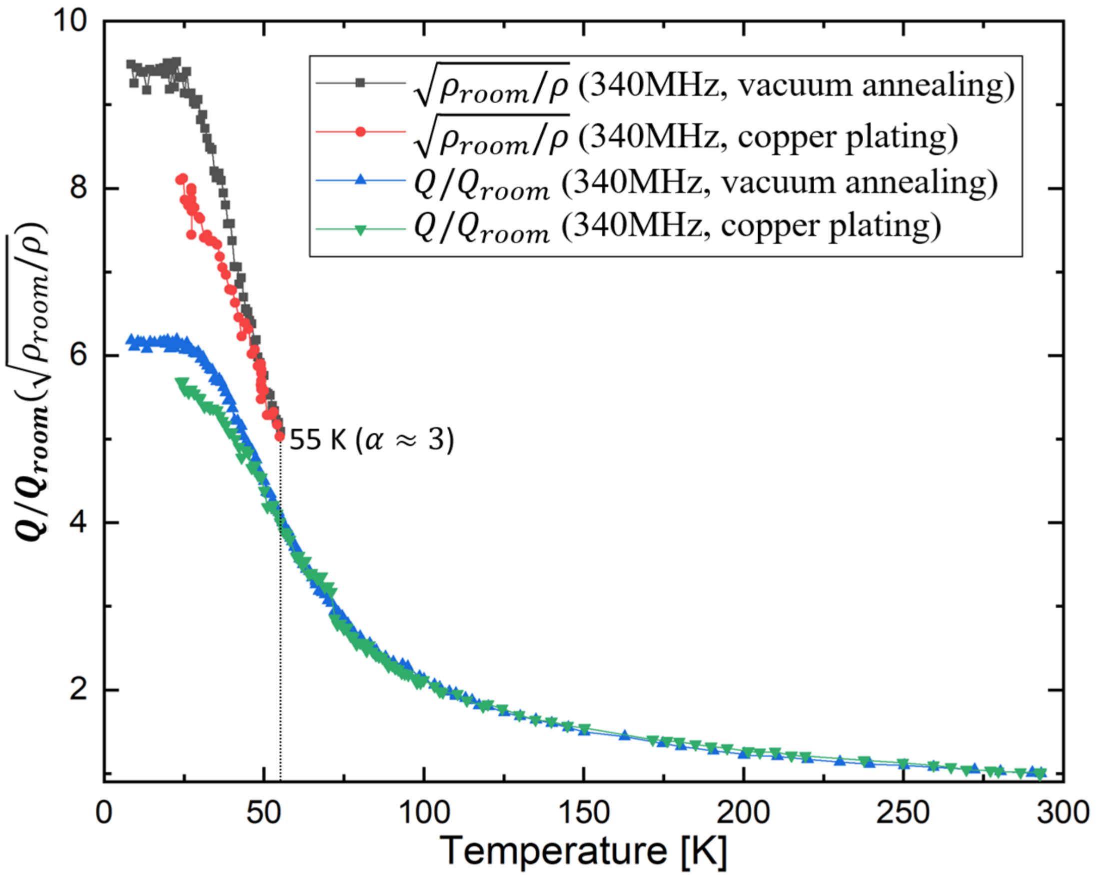
$$R_a = 1.123 \cdot 10^{-9} \cdot f^{2/3}[1 + 1.157 \cdot (\alpha)^{-0.276}]$$

[R. G. Chambers, *The anomalous skin effect,* 1952.]

$$\frac{R(T)}{R_a(T)} = \frac{Q_a}{Q} = \sqrt{\frac{\rho}{\rho_a}} = 1.93 \cdot \frac{(1.5/\alpha)^{1/6}}{[1 + 1.57 \cdot (\alpha)^{-0.276}]}$$

$$\alpha = \frac{1.5 \cdot l^2}{\delta^2} > 3;$$

$$f = 340\ MHz$$



Conclusion

This work shows, that the RRR of standard bulk copper can be significantly improved by copper plating and followed by vacuum annealing.

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 - about a factor 5 reduction in RF power losses at 340 MHz.

Groups at CERN[M. Jacewicz et al.] and SLAC[M. Nasr et al.] experimentally demonstrated higher field limits and more stable cavity operation at low temperatures. This gives motivation for a compact design of future short, pulsed ion linacs - like synchrotron injectors.

Thank you for your attention