MICROWAVE RESIDUAL SURFACE RESISTANCE OF SUPERCONDUCTORS*

Mario Rabinowitz

Stanford Linear Accelerator Center
Stanford University, Stanford, California   94305

Abstract

Two distinct models account for the microwave residual sur-
face resistance of superconducting cavities with equally good
agreement with the measured temperature and frequency depend-
ence. In presenting his phonon generation model, Passow claimed
that Rabinowitz's fluxoid power loss model of residual resistance
does not fit the experimental data, whereas his does. In fact, the
two models have essentially the same temperature and frequency
dependence.

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An analysis presented by Passow[1] showed that phonons generated in a super-conductor by incident electromagnetic radiation result in a residual power loss with an equivalent surface resistance which agrees well with experimental measurements of temperature and frequency dependence. His expression for surface resistance is

$$R = \frac{4\pi}{c^2}\, \omega^2 \Lambda \left[\rho + \frac{\beta v_s \Lambda^3}{\left(1 + \omega^2 \Lambda^2 / v_s^2\right)^2} \right] \quad .$$ (1)

The first term represents the superconducting surface resistance derived from the BCS theory.[2,3] The second term is related to the power loss as electromagnetic energy is transformed into acoustical energy. He claims that this latter term becomes dominant in superconductors at low temperatures, and that it "can account for the whole of the low-temperature surface resistance measured in the purest currently available materials." He goes on further to say, "Rabinowitz has tried to explain the residual surface rf resistance in terms of frozen-in magnetic flux.[4] However, experiments with cavities in high magnetic fields are reported to show a different frequency dependence from that predicted by his treatment." Passow acted on a remark made by Kneisel et al.,[7] who evaluated their experiments to investigate the influence of frozen flux on the surface resistance.

The oscillating fluxoid power loss occurs in addition to the well-known BCS superconducting loss[2,3] and dominates over it at low temperature. The super-conducting loss decreases rapidly with decreasing temperature at low temperature, whereas the fluxoid loss has a negligible temperature dependence at low temperature in agreement with experimental observations. The effective resistivity of an oscillating fluxoid is[4,5]:

$$\rho = \left\{ \omega^2 \phi^2 H H_0 \mu^2 / \left[\rho_n^2 (\omega^2 M - p)^2 + \omega^2 \phi^2 H_0^2 \mu^2 \right] \right\} \rho_n \quad ,$$ (2)

and the equivalent surface resistance is $R_f = \rho/2\lambda$.

ρ has a different meaning here than in Eq. (1), but since we are only interested in comparing the frequency dependence of Eq. (2) with that of the second term in Eq. (1), it is sufficient to retain only the common symbol ω for the angular frequency. Hence we may write the second term of Eq. (1) as

$$R_a = \frac{a\,\omega^2}{\left(1 + b\,\omega^2\right)^2} = \frac{a\,\omega^2}{b^2\omega^4 + 2b\,\omega^2 + 1} \tag{3}$$

for the frequency dependence of the phonon contribution, where $a = 4\pi\Lambda^4 v_s \beta/c^2$, and $b = (\Lambda/v_s)^2$. The frequency dependence of the fluxoid contribution to the surface resistance may similarly be written from Eq. (2) as

$$R_f = \frac{a_2\,\omega^2}{b_2^2\omega^4 + d\,\omega^2 + 1} = \frac{a_2\,\omega^2}{\left(1 + b_2\,\omega^2\right)^2} , \tag{4}$$

when $d = 2b_2$; where $a_2 = \phi^2 H H_0 \mu^2/2\lambda p^2 \rho_n$,

$$b_2 = M/p,$$

and

$$d = \left(\phi^2 H_0^2 \mu^2 - 2M p\rho_n^2\right)/\left(p\rho_n\right)^2 .$$

Thus we see that the two surface resistances R_a and R_f have virtually the same form of frequency dependence, which become identically the same form when $\left(\phi^2 H_0^2 \mu^2 - 2Mp\rho_n^2\right)/p\rho_n^2 = 2M$. The frequency dependence of the oscillating fluxoid, R_f, is a little more general and includes that of R_a as a special case. Hence, if R_a fits the experimental data extremely well,[1] the same thing may be said for R_f.

Although the residual loss due to acoustic coupling certainly represents a fundamental limitation and fits the temperature and frequency dependence of the

experimental data quite well, one may question the magnitude of this effect. Since the fluxoid loss (and possibly other losses) fit the data equally well, the good fit itself does not point to the correctness of the one model over the other in explaining the present limits on residual resistance, R_r. There are, however, some experimental observations which raise some doubt as to whether the acoustic loss presently represents the dominant contribution to R_r.

Two cavities made of the same high purity material, having the same processing history, and, as far as could be ascertained, the same bulk and surface properties, can differ by over an order of magnitude in their residual resistance. It is hard to believe that their acoustic properties differ by this much. Exposure of a high Q cavity to CO and/or CO_2 (as was first done at the Stanford Linear Accelerator Center) can increase R_r by more than two orders of magnitude. Again it is unlikely that this would change the acoustic coupling to the electromagnetic radiation by this amount. In many cavities, R_r first decreases with increasing field level, before it starts to increase. This seems counter to the expected increase in acoustic loss. The surface resistance can differ substantially, depending on the method of cavity cool-down and on the ambient magnetic field. Again, this would not be expected from the acoustic loss theory. On the other hand, many, if not all, of these observations are consistent with the fluxoid power loss model. Perhaps equally important is the fact that the fluxoid model also predicts the frequency dependence of the magnetic breakdown field, H'_p, in agreement with experiment,[6] whereas the phonon model makes no prediction. Though the observed R_r and H'_p are amenable to explanation by this model, it is important to bear in mind the complexity of the phenomena and that other alternative explanations may also fit the data.

References

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