CHARACTERIZATION OF RESIDUAL RF LOSSES IN SUPERCONDUCTORS

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In the design and use of superconducting resonant structures, whether for use in accelerator applications, frequency control, or otherwise, it is desirable to minimize losses and obtain as high a Q as possible. It is theoretically possible to obtain unlimited Q, if temperature limitations are disregarded and if the superconducting surface resistance is the only factor contributing to losses. However, it is always found in practice that some extraneous mechanism limits the Q to finite values. It is seldom easy to determine the sources of such residual loss. The purpose of a portion of the work at the University of Texas has been to characterize the residual losses and, insofar as possible, determine their source. This research was initiated by the author and W.H. Hartwig,[1] but the bulk of the work reported here was performed by Hartwig and J.M. Victor.[2]

On the basis of our previous experience and that of the Stanford group,[3] it seems that trapped magnetic flux can be a very strong source of residual loss. Thus, it is now possible to remove one type of rf loss from the group of undefined losses:

$$\text{Total loss} = \begin{matrix}\text{Loss in surface}\\ \text{resistance}\end{matrix} + \begin{matrix}\text{Loss due to}\\ \text{trapped flux}\end{matrix} + \text{Other losses} \quad .$$

The "other" group of losses may possibly include dielectric loss, radiation loss, etc., depending on the arrangement of the structure or other unknown factors. The flux-trapping loss can effectively be eliminated by proper design of the circuit and magnetic shielding. However, the Texas group believes it is important to study the flux-trapping effect so that it could be subtracted from the experimental data entirely, thereby leaving the "other" losses for inspection and analysis. Also, it is felt that understanding of the flux-trapping phenomenon might lead to the development of materials such that it can be minimized when magnetic shielding is not feasible.

The experiments were carried out in the frequency range from 30 MHz to 500 MHz on circuits made of foil strips wrapped on Teflon forms and enclosed in superconducting shield cans. The Teflon has been demonstrated to have a very low dielectric loss[4] and was not in a high electric field region. Full details of the experiment are reported in an article published in the Journal of Applied Physics[2] and data reported here are taken from that article with permission of the authors.

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1. C.R. Haden and W.H. Hartwig, Phys. Rev. 148, 313 (1966).
2. J.M. Victor and W.H. Hartwig, J. Appl. Phys. 39, 2539 (1968).
3. M. Pierce, H.A. Schwettman, W.M. Fairbank, and P.B. Wilson, Low Temperature Physics, LT 9 (Plenum Press, New York, 1964), p. 396.
4. D. Grissom and W.H. Hartwig, J. Appl. Phys. 37, 4784 (1966).

Flux trapping occurs when the test sample is cooled in an ambient magnetic field. When the sample becomes superconducting, the magnetic field is driven out except for isolated groups of flux tubes which become trapped at sites throughout the material. Due to the collapse of the field, the cores of these tubes may be considered normal, thereby creating a resistive rf loss. This is indicated in Fig. 1. The effective surface resistance is then dependent upon the area of the normal regions, which is proportional to the critical field, and upon the depth of rf field penetration. It thus seems logical to assume a solution for the temperature dependence of the flux-trapping loss which is the product of the temperature dependences of the critical field and the superconducting penetration depth. Using the empirical forms which are widely utilized in the literature, one obtains for the temperature dependence:

$$V(t) = \left[(1 - t^2)\ (1 - t^4)^{\frac{1}{2}} \right]^{-1} \quad . \tag{1}$$

and

$$r = A(\nu)\ f(t) + r_h(0)\ V(t) + r_o \quad . \tag{2}$$

In Eq. (2), r is the measured surface resistance normalized to the normal value, $A(\nu)$ is a frequency-dependent part of the true surface resistance, $r_h(0)$ is the field-dependent part of the flux-trapping loss, r_o is the constant residual loss, and $f(t)$ is the Pippard function for the true surface resistance[5]:

$$f(t) = \frac{t^4\ (1 - t^2)}{(1 - t^4)^2} \quad . \tag{3}$$

Other temperature dependences for flux-trapping losses are available in the literature.[1,3] In particular, use has been made of the two functions:

$$\lambda(t) = (1 - t^4)^{-\frac{1}{2}} \tag{4}$$

and

$$\varphi(t) = (1 - t^2)^{-1} \quad . \tag{5}$$

In deciding which is the correct function, one need realize that, for any given function, $q(t)$, elimination of r_o and surface resistance would yield a curve given by:

$$r = q\,\frac{dr}{dq} \quad . \tag{6}$$

Thus, if the dependence is correct, a "theoretical" curve obtained from (6) should only differ from the experimental data by a negative constant. Inspection of Fig. 2 for $\lambda(t)$ and Fig. 3 for $\varphi(t)$ shows that r_o is not constant and, in fact, changes sign. On the other hand, Fig. 4 gives a constant r_o. It is thus concluded that $V(t)$ is the correct temperature dependence.

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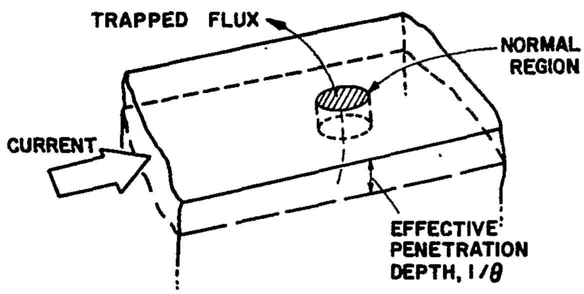
5. A.B. Pippard, Proc. Roy. Soc. (London) A203, 98 (1950).

Experiments were run with magnetic field and frequency as variables. The field data are summarized in Fig. 5. It is evident that the loss is proportional to the field intensity as expected. The frequency data for the surface resistance only are summarized in Fig. 6. Agreement with theory seems quite good. The normal material lies somewhere between the classical and anomalous limits. For the flux-trapping loss, the resistance ratio showed little or no frequency dependence, corresponding to normal flux core regions.

Annealing tests were run on a number of samples. This is demonstrated for a 4%In-96%Sn circuit cooled in the earth's field in Fig. 7 and for pure tin at two fields in Figs. 8 and 9. These data indicate that $A(\nu)$, $f(t)$ and r_o are readily reduced by annealing, but that $r_h(0)$ may not easily be changed. The intercept change in Fig. 7 is due to a change in r_o. The slope remains constant since the order parameters are controlled by impurities in this sample. In Fig. 8, both the intercept and slope change, indicating that structure now dominates the order parameters. In the higher ambient field of Fig. 9, the normal regions at the flux cores dominate so that the slopes are approximately the same for all annealing times.

In conclusion, the flux-trapping effect definitely exists and may be explained by losses in resistive regions at the flux cores. Also, the remaining residual losses are apparently independent of temperature and magnetic field.



$$\theta = \sqrt{\frac{1}{2\lambda^2} + \sqrt{\frac{1}{4\lambda^4} + \frac{1}{\delta^4}}}$$

$$r = \frac{R_s}{R_n} = A(\nu)f(t) + r_h(0)V(t) + r_o$$

where $$r_h = r_h(0)V(t) = \beta(H/H_c)\left[(1 - t^2)(1 - t^4)^{1/2}\right]^{-1}$$

Fig. 1. Flux-trapping model with an effective depth of penetration.

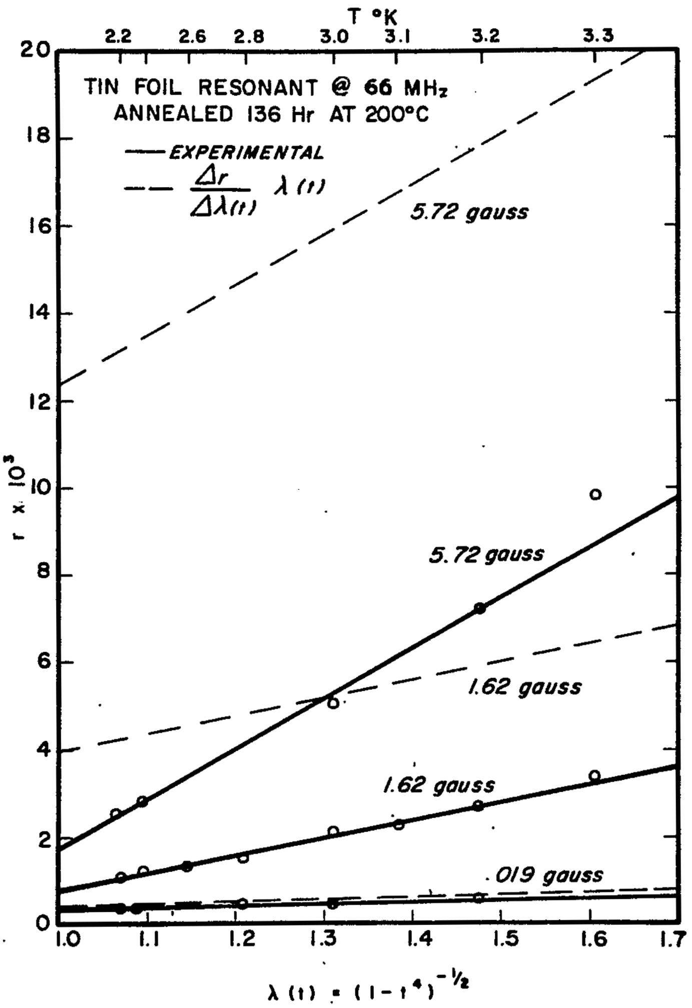


Fig. 2. Relative resistance ratio vs λ(t) (solid lines) and theoretical curves for flux-trapping loss only (dashed). Since the difference is not constant nor positive, as a field- and temperature-independent residual resistance would be, λ(t) is not applicable for the model.

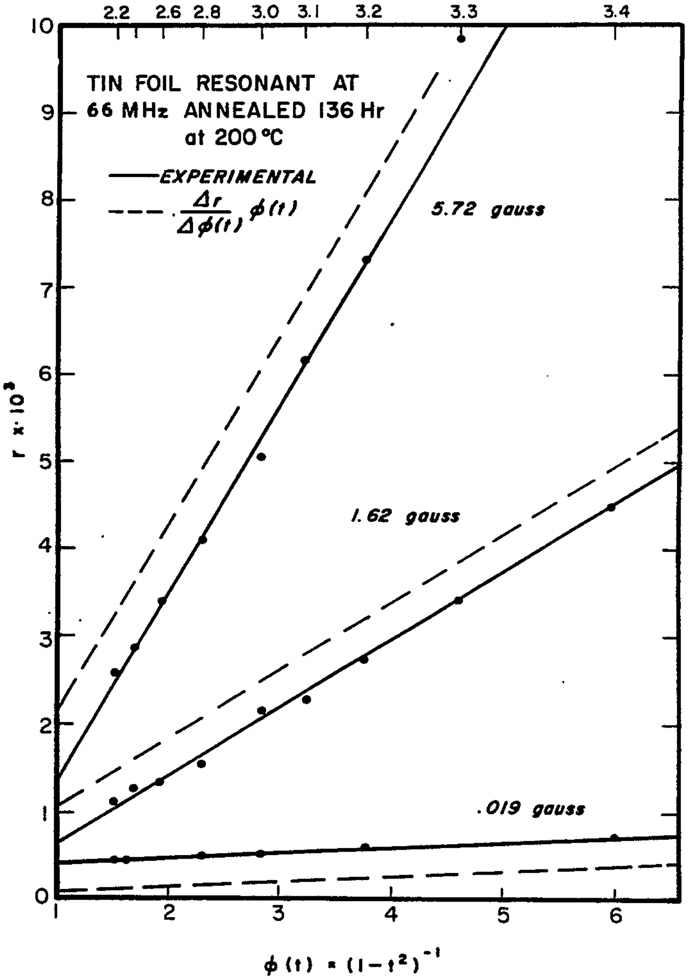


Fig. 3. Relative resistance ratio vs φ(t) showing the same disagreement with the model as in Fig. 2.

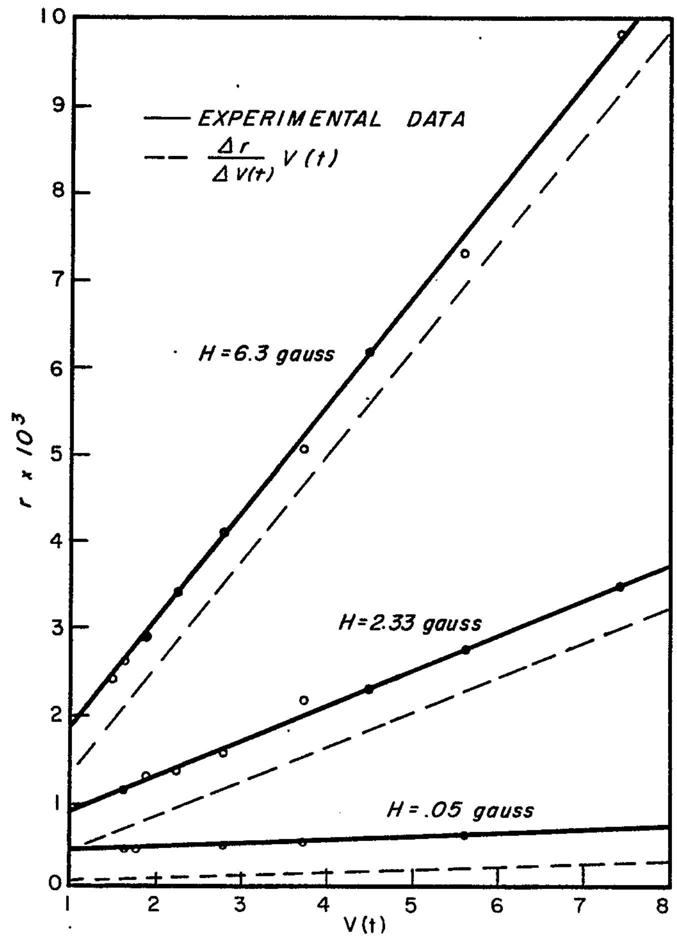


Fig. 4. Relative resistance ratio vs V(t) showing existence of a constant residual resistance that is independent of T or H.

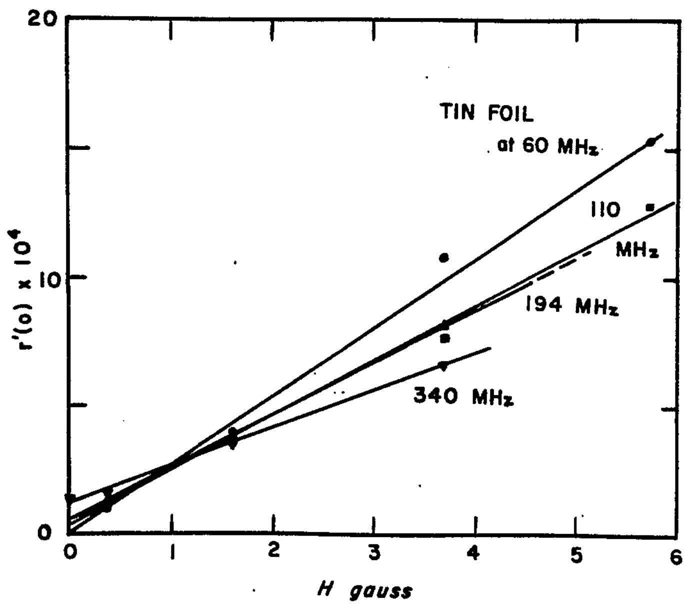


Fig. 5. Magnetic field dependence of $r_h'(0)$ taken from the slopes of $r_h'(0) + r_o'$ to eliminate r_o'. Intercept at H = 0 shows KA(ν) term can be resolved.

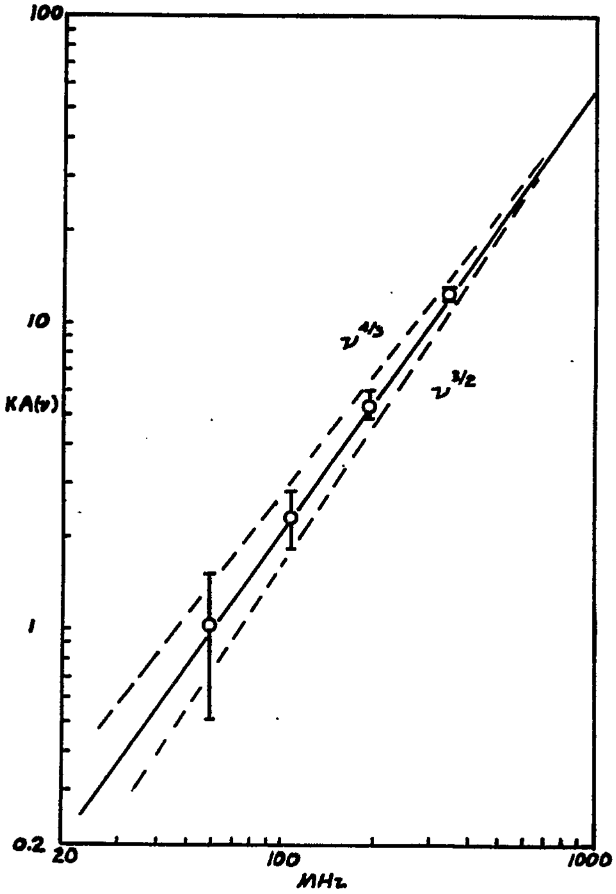


Fig. 6. KA(ν) data from Fig. 5 vs frequency shows tin foil is between the classical skin depth limit and the anomalous limit.

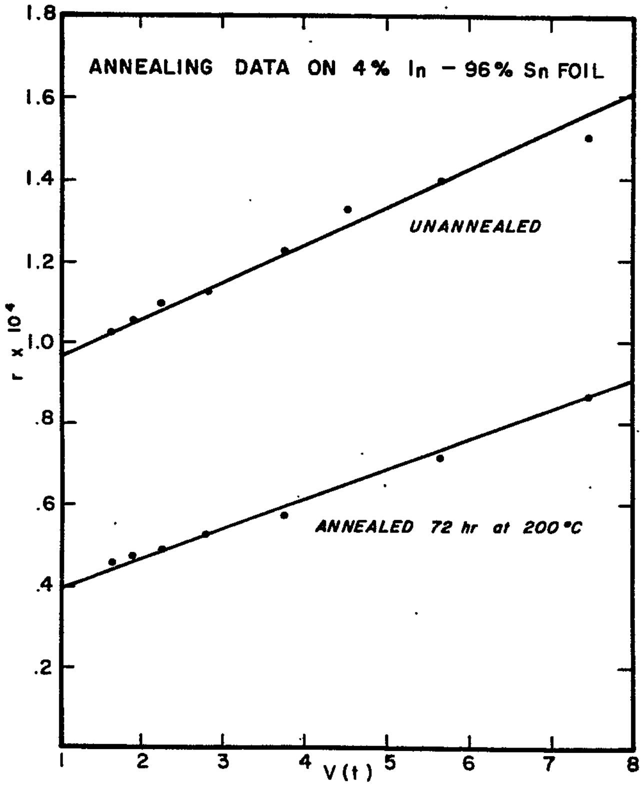


Fig. 7. Annealing 4%In-96%Sn foil shows a large reduction in temperature-independent loss. Data are for earth's field.

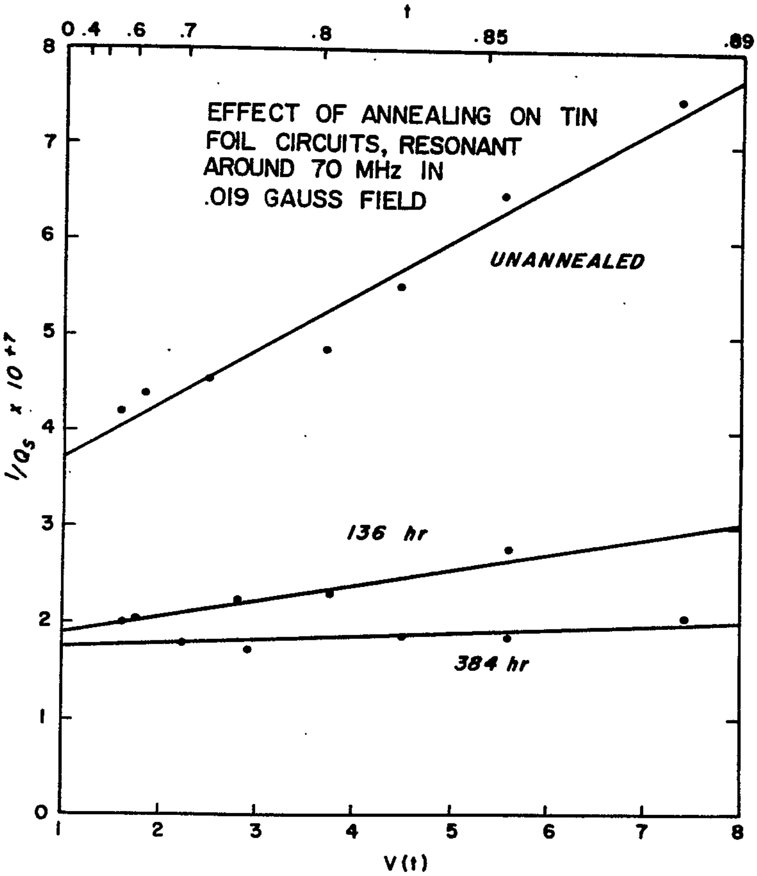


Fig. 8. Annealed pure tin cooled in a magnetic field of 0.019 G shows large change in superconducting resistance in the absence of trapped flux. Annealed loss in attributable to Pippard surface resistance and residual resistance. Straight lines refleot similar shapes of f(t) and V(t).

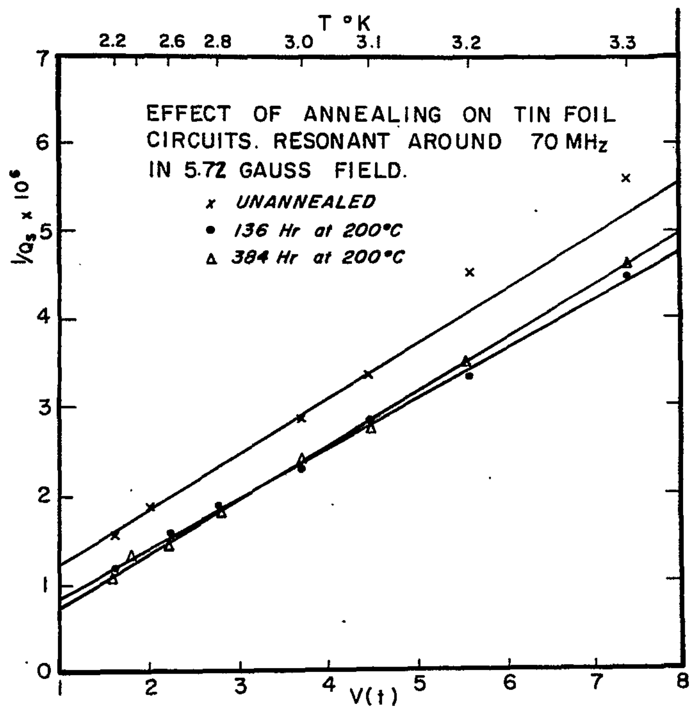


Fig. 9. Annealed tin circuit cooled in a magnetic field of 5.72 G shows small drop in temperature-dependent loss, indicating flux-trapping loss is not readily annealed. Residual resistance annealed out to a minimum.