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Measurements of the low-temperature rf surface resistance of lead at frequencies from 136 to 472 MHz*

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A helically loaded lead-plated cavity has been used to measure the superconducting rf surface resistance of lead at low field levels at frequencies from 136 to 472 MHz and temperatures from 1.5 to 4.2 K. Fits with the BCS theory were found to be consistent with a normal electron mean free path between 350 and 6000 Å. The residual resistance at 136.7 MHz was found to be 4.7×10^{-9} Ω, to vary as $f^{1.23 \pm 0.05}$ over the frequency range 136–472 MHz, and to be independent of temperature. Measurements of magnetic field trapping by a lead-plated cavity were also made. The results indicated that the cavity, rather than exhibiting a macroscopic Meissner effect, trapped even weak magnetic fields without significant modification of their magnitude or spatial distribution when the cavity surface was cooled below the critical temperature. Further observations above the critical temperature of lead indicated the presence of transient magnetic fields within the cavity when the cavity was subjected to rapid temperature changes. These magnetic fields are attributed to thermoelectric effects. The magnitude and frequency dependence of the observed residual resistance is compared to that expected from trapped flux, phonon generation, and dielectric losses according to several appropriate theories. No theoretical model predicts the observed frequency dependence. The measured magnitude is in agreement with that expected according to a phonon generation theory due to Passow, and is also in agreement with that expected from a trapped magnetic flux of about 12 mG according to a model due to Pierce. Trapped flux is considered to be the most likely source of the residual resistance measured in this experiment.

I. INTRODUCTION

Theoretical treatments of rf surface resistance[1,2] based on the BCS microscopic theory of superconductivity predict a surface resistance which, for $T \lesssim \frac{1}{2}T_c$, decreases exponentially with temperature and varies approximately as ω^2 for frequencies below the energy gap. For this reason superconducting rf structures have great practical interest since they should be able to support large rf fields while consuming power many orders of magnitude less than that required for similar structures fabricated of normal metal. Many recent experimental investigations[3-7] of superconducting resonators in the GHz region have shown that, as temperature is reduced, theoretical predictions are at first fulfilled but that ultimately surface resistance does not continue to decrease with temperature. Instead, it approaches a limiting value. It is generally agreed that, at low fields, measured resistance R_{obs} can be expressed as the sum of two components; R_{th}, the superconducting surface resistance predicted by exact theory, and a weakly temperature-dependent component R_{res} called residual resistance. Aside from limiting the practical quality of rf superconducting structures at low fields, R_{res} poses problems of theoretical interest since its source is not yet properly understood. In fact, R_{res} may be caused by many sources acting simultaneously, complicating attempts to predict its magnitude or understand its behavior.

In an effort aimed at contributing to the understanding of the superconducting rf surface resistance of lead and, in particular, its residual resistance, we have measured the surface resistance of an evacuated superconducting lead-plated copper cavity at low field levels at five frequencies from 136 to 472 MHz at temperatures from 1.5 to 4.2 K. These measurements are of interest for several reasons. First, the frequency range of the present measurements is lower than that used in most previous measurements on lead. Since the theoretical rf surface resistance decreases as a strong function of decreasing frequency, lower-frequency measurements have the advantage of clearly illuminating differences between theory and experiment. Second, the present experimental results constitute a new lower limit for the surface resistance of lead. Finally, our measurements shed some light on the problem of residual resistance. In this regard we have tried to clarify the role played by trapped flux in the residual resistance of lead by making measurements of magnetic field along the axis of a similar but somewhat modified cavity under varying conditions. These magnetic field measurements were made at room temperature, liquid-nitrogen temperature, and liquid-helium temperature with the cavity in a region shielded from undesired external magnetic fields. Some of these measurements were made during rapid temperature changes above the critical temperature of lead to search for the existence and effects of thermoelectrically produced currents. The extent to which our lead-plated cavity would display the Meissner effect by rejecting flux or, instead, trap flux was investigated by cooling the cavity below the critical temperature of lead in the presence of an applied external magnetic field and comparing the flux distribution along the axis before and after the cavity surface became superconducting.

In this paper we describe our apparatus and measurement techniques, present the results of our investigations, and compare these results with predictions of several theories.

II. APPARATUS USED IN SURFACE-RESISTANCE MEASUREMENTS

To obtain the low frequencies used in our studies of the surface resistance of lead, we constructed a helically loaded cavity. An assembly drawing showing some of its features and its connection with the external measuring system is shown in Fig. 1. Some aspects of the cavity geometry were motivated by the desire to construct an apparatus suitable not only for measurements of superconducting surface resistance but also for investigation of the characteristics of a prototype structural element for a heavy ion accelerator.

Three 50-Ω coaxial transmission lines, only one of which is shown in full, lead down to the top of the cavity and were coupled to the cavity fields. The axial positions of the ends of the center conductors were independently adjustable to provide each line with a wide range of coupling strengths and also to allow determination of coupling loss with coupling strength. Only two of the three lines were used in the present experiment. The third was incorporated into the structure to permit future investigation of frequency tuning of the cavity.

The four parts of the cavity body were machined from solid billets of oxygen-free high-conductivity copper. The helix, of the same material, was wound from 6.35-mm-diam tubing and then oven brazed into the cylindrical section in a hydrogen atmosphere. The tubing ends extended through the body surface to the outside, allowing cooling fluid to enter the tubing when the assembled system was immersed in liquid helium. Vacuum pumping on the cavity was provided through an axial cylindrical hole in the top cavity section. It was joined to the high-vacuum manifold at the top of the assembly by means of a connecting tube. Prior to final assembly with indium gaskets and aluminum screws, the four units making up the cavity were lead plated. The high-vacuum manifold, transmission line inner and outer conductors, pumping tube, and most other components with surfaces normally under high vacuum, were fabricated from stainless steel. The inner conductors of the transmission lines were copper plated and a solid copper stub was screwed into each of their bottom ends. For operation at cryogenic temperatures, the assembly was lowered into a cryostat whose top flange mated with the top plate of the high-vacuum manifold. The principal dimensions of the cavity were cylinder length, 216 mm; cylinder inside diameter, 140 mm; helix diameter (center to center), 51 mm; helix length, 152 mm; and helix turns, 11. A cylindrical trimmer coil and two tubes of high-permeability ferromagnetic material, not shown in Fig. 1, surrounded the outside of the cryostat. They functioned to cancel, and shield against, ambient magnetic fields.

The materials of construction of both cavity and cryostat were completely nonmagnetic. The choice of construction materials was based, in part, on the wish to minimize the effect of ambient magnetic fields on the surface resistance of the cavity. For instance, as previously mentioned, most parts of the apparatus other than the cavity were fabricated from No. 304 stainless steel, which is nonmagnetic at room temperature. Field measurements, made at room temperature with a fluxgate magnetometer, indicated that the magnetic field within the shielded cryostat in the region enclosing the resonator was less than 1 mG.

Contamination of the lead-plated cavity surfaces was guarded against by taking special care to achieve a clean high-vacuum system. Ethyl alcohol was used as the lubricant when machining the copper cavity pieces. Surfaces to be exposed to high vacuum were degreased and, whenever possible, electropolished before final assembly. Metal gaskets were used everywhere except in valves separating vacuum pumps from the manifold. In these valves the gaskets were of polyimide, a low-vapor-pressure synthetic material. A cryogenic molecular sieve pump was used in the first stage of pumpdown to bring pressure from atmospheric to a few microns. An electrostatic getter-ion pump reduced pressure further and then kept it at a low value by continual pumping. Before the cavity subassembly was installed, the remainder of the system was baked at temperatures up to 270 °C while under high vacuum. The cavity alone was not baked. In the final step of the plating process the four cavity pieces were separately rinsed in acetone, then dried in a moisture-free argon atmosphere. The four pieces were also assembled in a dry argon atmosphere and then the unit was temporarily stored with one atmosphere of the same gas sealed within it. Joining of the cavity to the transmission lines took place with normally evacuated regions of the system temporarily flooded with flowing dry argon. Contamination of cavity surfaces by cryopumping when they were cooled was reduced by a copper baffle at the bottom of the pumping tube. Also, near the bottom of each transmission line, a ceramic disk served both as an electrical insulating spacer and a vacuum baffle. With the entire system assembled, the pressure at room temperature, measured at the manifold, was about 2×10^{-8} Torr. With the cavity immersed in liquid helium, pressure decreased further by a factor of 10. The pressure difference between cavity and manifold is dependent on at least three effects: outgassing rates, cryopumping by the cooled elements, and thermal transpiration. Since the first two are difficult to estimate, we did not attempt to calculate this pressure difference. As indicated above, our primary concern was cleanliness of the cavity surfaces.

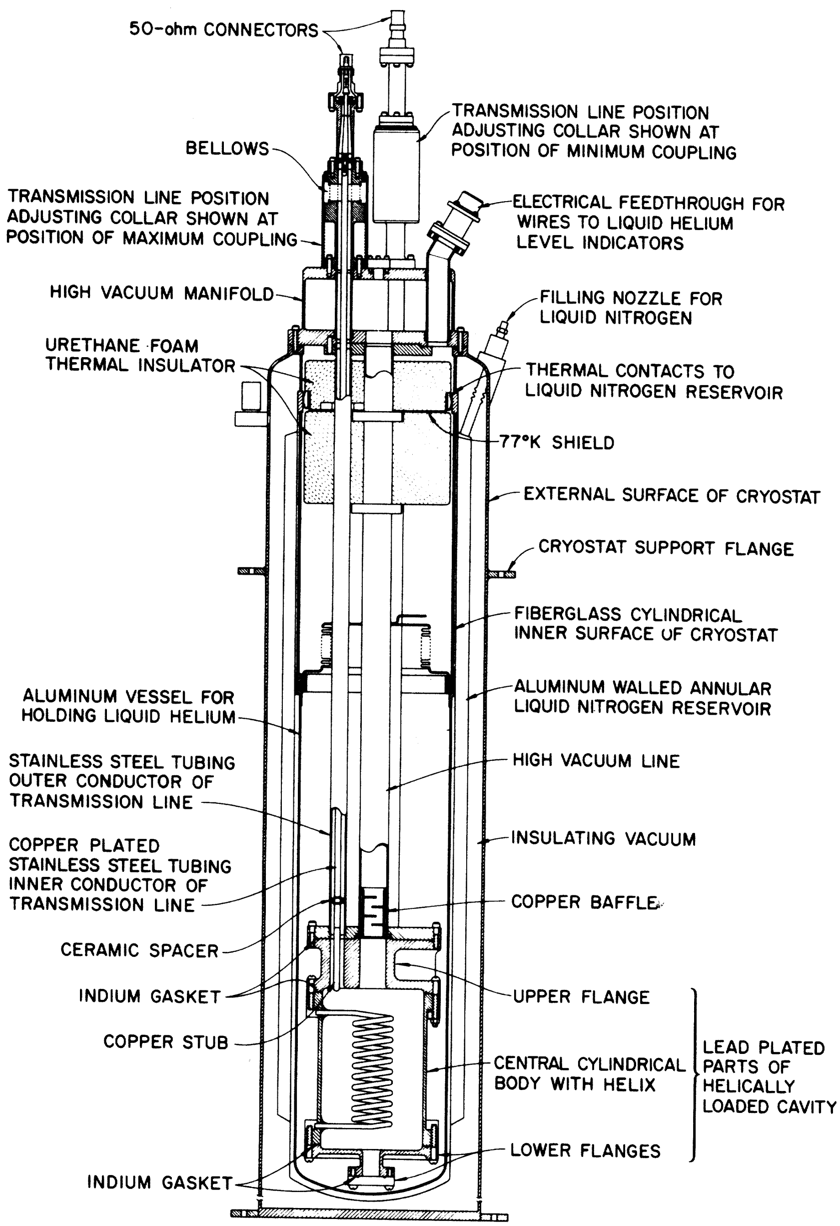

FIG. 1. Assembly drawing of the cryostat and cavity-transmission line system used in making the measurements of low-temperature surface resistance of lead.

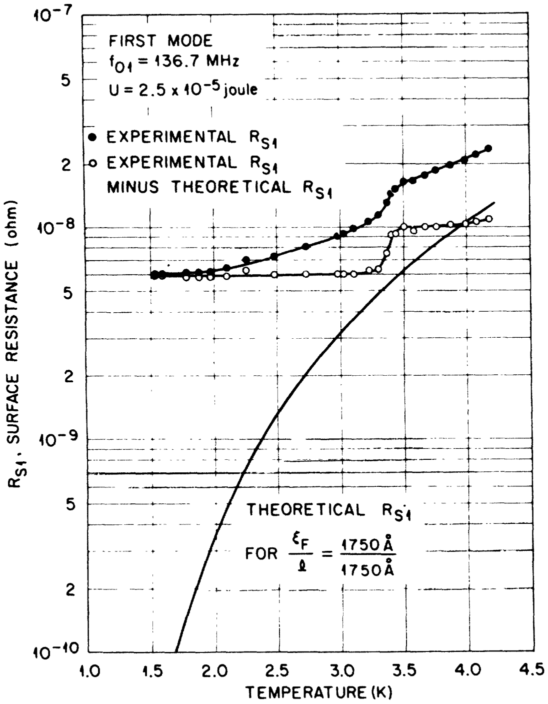

FIG. 2. Measured surface resistance of lead, the theoretical surface resistance of lead, and the difference between the measured and theoretical results, as a function of temperature from 1.5 to 4.2 K at a frequency of 136.7 MHz and a stored energy of 2.5×10^{-5} J. The pronounced drop in resistance as the temperature decreases from 3.5 to 3.3 K is attributed to the transition of the indium gaskets from the normal to the superconducting state.

The helium-bath temperature was controlled by pumping on it with a mechanical vacuum pump through an adjustable regulator valve which kept the helium pressure fixed at a chosen value. Pressure above the liquid helium was monitored with precision Bourdon gauges and converted to temperature readings using the 1958 ^{4}He Temperature Scale.[8]

The four pieces comprising the cavity were plated with lead by electrodeposition from a lead fluoborate solution. The procedure has been given in the description of the plating of a previous cavity[9] and some further details of the process are described elsewhere.[10] The average lead thickness, determined by integrating the plating current and assuming a 100% deposition efficiency was 9.1 μm. The plating thickness was also checked[10] by measuring the room-temperature surface resistance of the plated cavity at its first five eigenfrequencies. This method indicated a thickness of 13 to 16 μm.

III. RESULTS OF MEASUREMENTS OF SURFACE RESISTANCE

The surface resistance R_{sm} of the lead-plated cavity was obtained for the first five modes m of the cavity from a measurement of the loaded quality factor Q_{lm} by the decay time method. The electronics and other details are discussed elsewhere.[10] A measurement of the coupling factor of each transmission line to the cavity permits calculation of Q_{0m}, the unloaded quality factor, provided the coupling losses are known. Coupling losses were determined by measuring Q_{lm} as a function of transmission-line position.

R_{sm} is related to Q_{0m} by the expression $R_{sm} = \Gamma_m / Q_{0m}$, where Γ_m is the geometry factor for the mth mode. The Γ_m were previously determined from a room-temperature measurement of the Q_{0m} of the electropolished copper cavity before it was lead plated, with the assumption that its surface resistance was given by the classical relation $R_{sm} = (\omega_{0m}\mu/2\sigma)^{1/2}$. A value of 5.8×10^7 $(\Omega\ \mathrm{m})^{-1}$ was used for the conductivity of copper at 296 K.

Figures 2–6 show the measured surface resist-

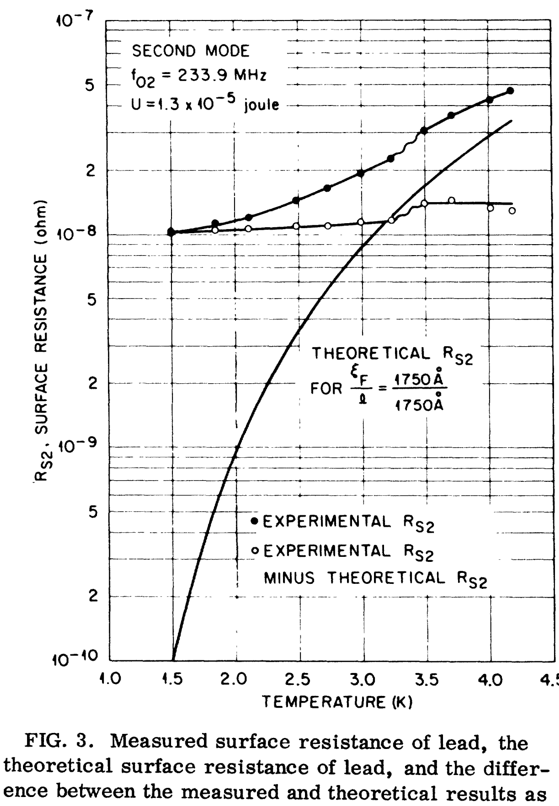

FIG. 3. Measured surface resistance of lead, the theoretical surface resistance of lead, and the difference between the measured and theoretical results as a function of temperature from 1.5 to 4.2 K at a frequency of 233.9 MHz and a stored energy of 1.3×10^{-5} J. An effect attributed to indium gaskets is visible near 3.4 K.

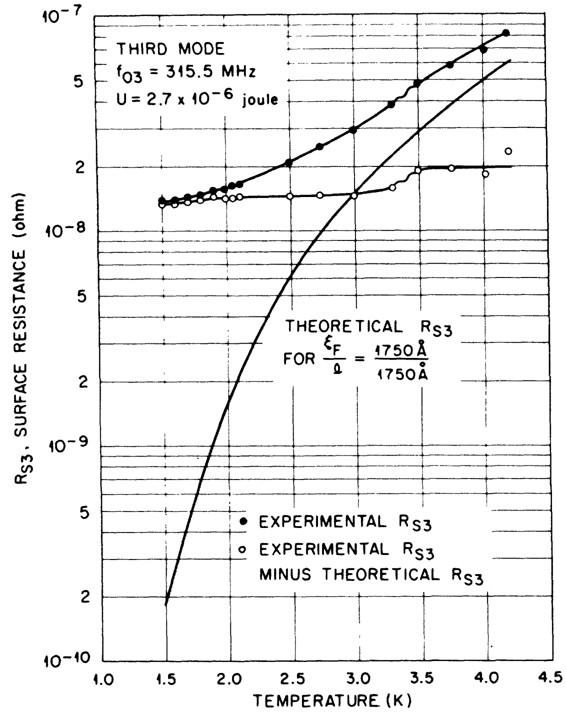

FIG. 4. Measured surface resistance of lead, the theoretical surface resistance of lead, and the difference between the measured and theoretical results as a function of temperature from 1.5 to 4.2 K at a frequency of 315.5 MHz and a stored energy of 2.7×10^{-6} J. An effect attributed to indium gaskets is visible near 3.4 K.

ance of lead as a function of temperature for the first five modes of the cavity at indicated values of stored energy U. In the measurements, cavity excitation was deliberately kept low in order to obtain a true measurement of low-temperature surface resistance uncomplicated by extraneous phenomena such as multipactoring[11] (resonant multiplication of electrons within a cavity). The measured values of surface resistance are estimated to be accurate to within ±10%.

Figures 2–6 also show the theoretical surface resistance calculated with a computer code[12] based on a development by Halbritter,[13] as well as the difference between measured and theoretical values. The computer code calculates exact values of surface resistance from the BCS theory in the weak-coupling limit. It should be noted that lead is a strong-coupling superconductor. For lack of a detailed theory of surface resistance of strong-coupling superconductors, the theory developed for weak-coupling superconductors has been applied by many workers to make theoretical calculations to compare with measurements on lead surfaces at high frequencies. In general, until the residual-resistance region has been reached, the agreement has been quite good. Following Ref. 13, we used the following parameters for calculating the theoretical curves shown in Figs. 2–6: critical temperature, $T_c = 7.20$ K; gap parameter, $\Delta(0)/kT_c = 2.05$; $\xi_F = 1750$ Å [ξ_F is related to the intrinsic coherence length, ξ_0, by $\xi_0 = (2/\pi)\xi_F$]. The normal electron mean free path l was considered a free parameter. Although it is possible that lead plated on copper may become strained at low temperature and then exhibit a critical temperature different from that of bulk lead, we, and others who have measured the superconducting surface resistance of lead, have found that a use of $T_c = 7.20$ K gives a good fit of measured results to predictions of the theory. In addition, in a measurement[14] (on the same cavity) subsequent to the present work, an abrupt change in the character of the surface resistance took place as the cavity temperature passed through 7.21 ± 0.01 K. Use of $T_c = 7.21$ K would have made the calculated surface resistance 0.65% smaller at 4.2 K and 1.50% smaller at 1.5 K. These differences produce a negligible effect on our results and conclusions. As shown in Fig. 3 of Ref. 13, R_s at lower frequencies is a sensitive function of the

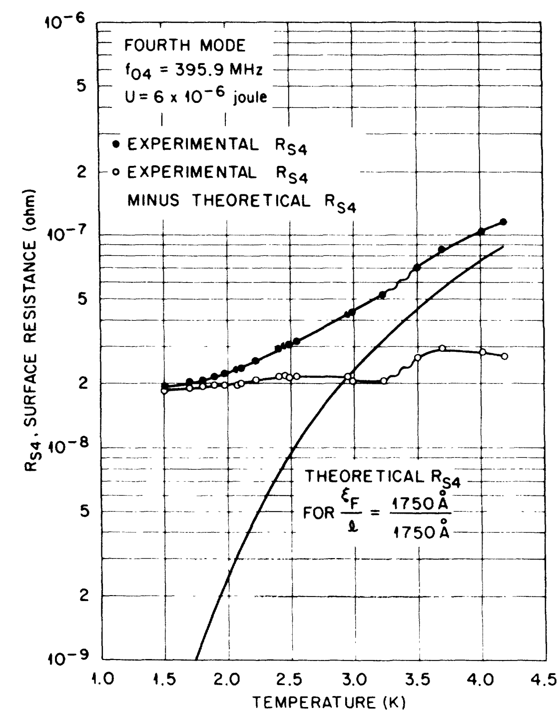

FIG. 5. Measured surface resistance of lead, the theoretical surface resistance of lead, and the difference between the measured and theoretical results as a function of temperature from 1.5 to 4.2 K at a frequency of 395.9 MHz and a stored energy of 6×10^{-6} J. An effect attributed to indium gaskets is visible near 3.4K.

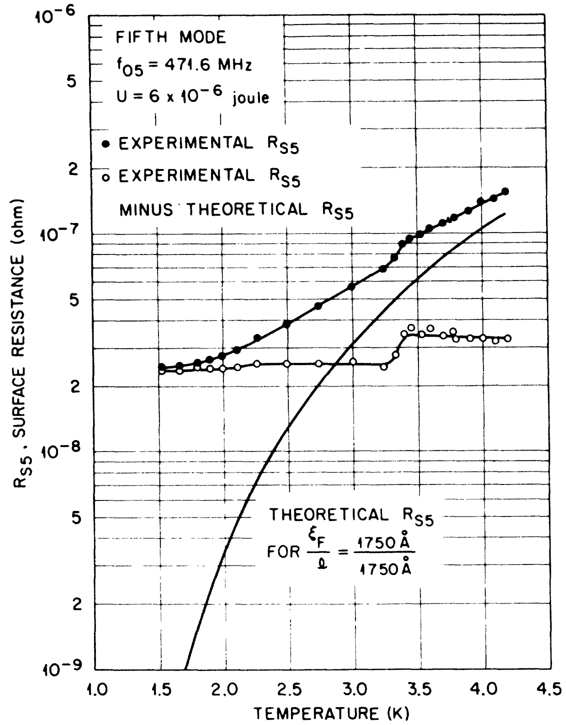

FIG. 6. Measured surface resistance of lead, the theoretical surface resistance of lead, and the difference between the measured and theoretical results as a function of temperature from 1.5 to 4.2 K at a frequency of 471.6 MHz and a stored energy of 6×10^{-6} J. The pronounced drop in resistance as the temperature decreases from 3.5 to 3.3 K is attributed to the transition of the indium gaskets from the normal to the superconducting state.

ratio ξ_F/l and for the frequency range of our experiment reaches a minimum at values of ξ_F/l between 1 and 2. The interesting result of the calculations is that when we use values of ξ_F/l near this minimum, the residual resistance R_{res} is, with the exception of the indium transition at 3.4 K, essentially independent of temperature. If one assumes that residual resistance is independent of temperature, this procedure serves as a determination of ξ_F/l. Unfortunately, our best "fits" in this sense come at the minimum of the R_{sm}-vs-ξ_F/l function where the sensitivity is the least. Nevertheless, if we use this criterion we can limit ξ_F/l to a range of about 0.3–5.0. This corresponds to a range of l between 350 and 6000 Å. The curves shown in Figs. 2–6 were calculated with the value $l = 1750$ Å.

We have interpreted our results in the following way. Above 3.4 K, the measured value of surface resistance R_{obs} is assumed to be the sum of three components: R_{th}, the theoretical superconducting surface resistance of lead calculated as described above; R_{in}, the surface resistance component from indium, which was used as the gasket material between the four lead-plated cavity sections; and R_{res}, the temperature-independent residual resistance of lead. From 4.2 to 3.4 K, indium is in the normal state and exhibits anomalous surface resistance, i.e., a surface resistance independent of temperature. In our measurements above 3.4 K, indium contributes various amounts to the observed values of surface resistance at the different frequencies. These contributions range from 7% to 17%. Below 3.4 K, indium is superconducting and its contribution to our observed values of surface resistance rapidly becomes negligible as temperature decreases. Somewhat below 3.4 K and, in particular at 1.5 K, we have taken $R_{obs} = R_{th} + R_{res}$.

Measurements of Q_{0m} were made at all five frequencies at 1.5 and 4.2 K as a function of stored energy U. Figure 7 shows the results for the second mode. These results, which are typical of those observed, but not shown here for the other four modes, demonstrate a slight dependence of R_{res} on stored energy. This dependence, which occurs well below the first multipactor levels, is possibly associated with nonresonant multiplication of electrons in the cavity. Pierce,[4] however, has also suggested thermal runaway in whisker-like surface protrusions to explain a power dependence observed in some of his measurements. Each of our measurements of surface resistance at 1.5 K was extrapolated to a stored energy of 10^{-6} J. The extrapolated value was taken as R_{res}, which was found to vary as $f^{1.23\pm0.05}$, as shown in Fig. 8.

To see if changes in surface resistance would occur with the cavity kept under ideal conditions of low pressure and low temperature for extended periods, two sequences of measurements were made. They were separated by a seven-month interval. During this time the cavity was kept under high vacuum and at temperatures no higher than that of liquid nitrogen. The observed residual resistance, when normalized to the same stored energy, was very nearly the same at the beginning and end of the seven-month interval. This is in contrast to reports of others,[4,7] who observed degradation even with short-time scale thermal cycling.

IV. POSSIBLE SOURCES OF RESIDUAL RESISTANCE

Since R_{res} is weakly dependent on temperature, it may be investigated by comparing the frequency dependence predicted by a particular theoretical model to the measured frequency dependence of losses in an rf structure. We expect such a com-

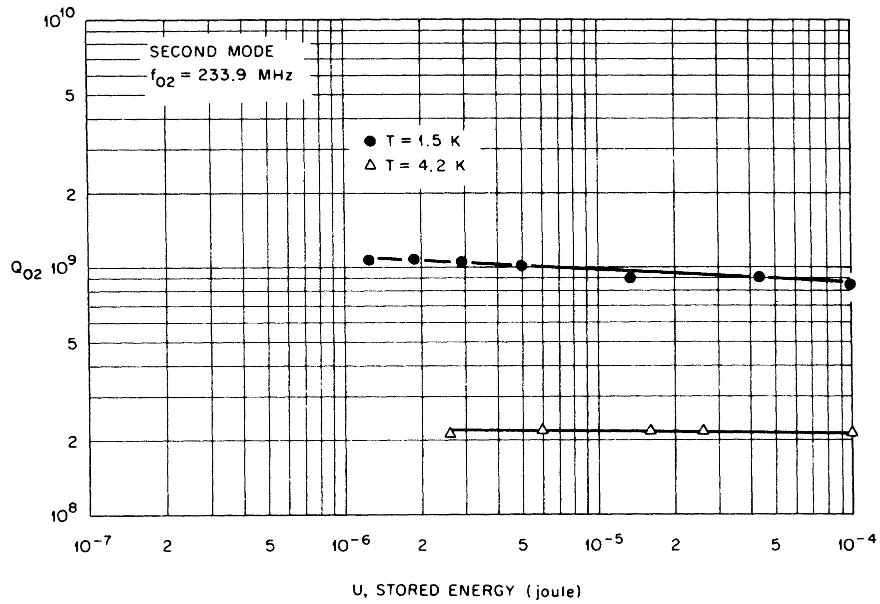

FIG. 7. Measured unloaded quality factor at 4.2 and at 1.5 K as a function of the electrical energy stored in the cavity at a frequency of 233.9 MHz. The surface resistance varies as the reciprocal of the unloaded quality factor. These results at 233.9 MHz are typical of those observed at the other four frequencies of our measurements.

parison to be valid provided the mechanism under investigation dominates other existing losses. In addition, the distribution over the surface of the loss mechanism must be known since surface distribution of the rf fields will vary with the mode. (For an example of some rf electrical field distributions along the axis of a helically loaded cavity, see Ref. 9.) In an extreme case, a small lossy region may be situated at a node of the field at one frequency and remain unexcited. At another frequency it may be at an antinode and receive maximum excitation. In the simplest case, a single dominant loss mechanism will be distributed evenly over the surface. In the interpretation of our results we assume the latter is approximately the case for our cavity, particularly for the surface of the helix where the rf field magnitudes are the greatest.

Dielectric or magnetic contaminants, small particles of foreign normal metals, exposed spots of normal base metal from imperfections in the plating, areas of normal superconductor caused by trapped magnetic flux embedded in the otherwise superconducting surface, and phonon generation by interaction of the electromagnetic fields with the lattice are some possible sources of R_{res} in a cavity fabricated by plating a superconductor such as lead onto a normal metal such as copper.

Several investigations[4,7,15] have shown that the residual resistance of a superconducting surface increases if it is cooled below the transition temperature in the presence of an applied magnetic field. Pierce[4] has suggested that when a cavity in

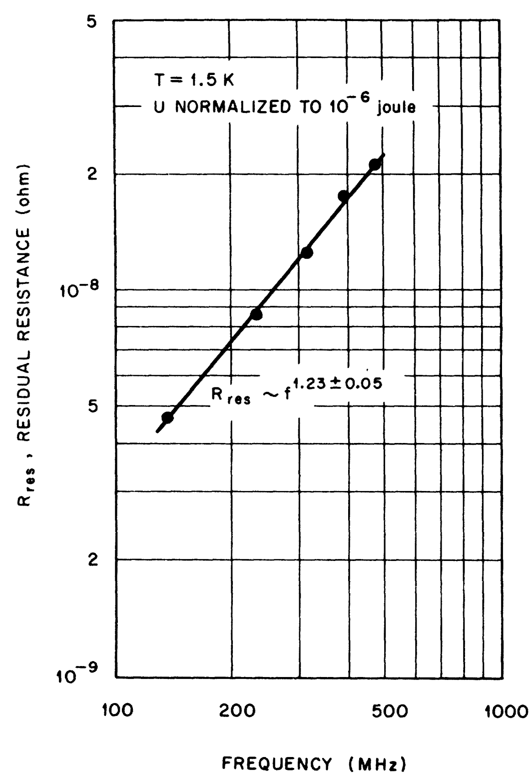

FIG. 8. Measured surface resistance at 1.5 K as a function of frequency. The measured values are normalized to a stored electrical energy of 1×10^{-6} J. For the same stored energy, the peak electric and magnetic fields are approximately equal at the different frequencies.

a field-free region is cooled, thermoelectric currents may flow and generate magnetic fields which will become trapped and contribute to R_{res}. Below the critical magnetic field H_c, The Meissner effect expels magnetic fields from the interior of a very pure single crystal of superconductor when it becomes superconducting. However, the smallest impurity or inhomogeneity of the material can be sufficient to prevent the appearance of the Meissner effect.[16] Under such nonideal conditions "frozen in" magnetic flux may be found and the superconductor surface has flux-free superconducting areas alternating with normal areas through which the flux passes.

V. APPARATUS USED IN MAGNETIC-FIELD MEASUREMENTS

A lead-plated cavity cannot be expected to have the properties of a pure single crystal of superconductor. To examine some of its magnetic properties, we modified a cavity to allow measurements of the magnitude and direction of the magnetic field along its axis. We believe examination of the magnetic properties of the modified cavity is important since the magnetic behavior of the cavity used in making surface resistance measurements is expected to be similar. This apparatus is shown in Fig. 9. It consisted of a second lead-plated cavity system in which the cavity was supported by a single stainless-steel tube located on the major axis of the apparatus. Within this tube, which also served as a pumping connection for the cavity, was situated a cylindrical copper chamber, nominally at room temperature. The copper chamber was open at the top but closed off at the bottom so that its interior could be maintained at atmospheric pressure while its outer surface was in contact with the high-vacuum system of the apparatus. The copper chamber, whose emissivity was reduced by electropolishing its outer surface, was prevented from thermally radiating directly into the lead surfaces of the cavity by the addition of a copper shield thermally anchored at the neck of the cavity.

The magnetic field along the axis of the system was measured by means of a flux gate magnetometer (Hewlett-Packard Model 3529A) mounted at the end of a long probe situated within the copper chamber described above. The magnetometer's axis was inclined to the axis of the helix. During measurements, the probe remained at room temperature. It could slide freely along the axis of the copper chamber and rotate about the chamber's axis. The magnetometer is a device which measures the magnetic field component directed along its axis. By rotating the probe, observing the magnitude of the maximum and minimum magnetic field at a given axial point, and by noting the azimuthal direction of the magnetometer's axis at the maximum and minimum, the vector components of the magnetic field $\vec{B}$ at the point could be determined. The homogeneity of the field at an axial point could also be tested from an interpretation of the variation in magnetometer reading with changes in azimuthal direction of its axis. After the apparatus shown in Fig. 9 was lowered into the magnetically shielded cryostat, measurements indicated the magnetic field within the cavity was less than 1 mG at room temperature and at liquid-nitrogen temperature.

To allow testing for a macroscopic Meissner effect, a coil with its axis perpendicular to the cavity's axis was attached to the outside of the cavity. The coil had an average diameter of 3.25 cm and its center was located about 14 cm above the bottom of the cavity.

VI. MAGNETIC FIELD MEASUREMENTS

In the first of a sequence of three runs, the cavity was immersed in liquid nitrogen and the coil attached to the cavity was excited with a dc current. The resulting magnitude of the field measured along the axis of the cavity is shown by the lower curve in Fig. 10. In this figure, the position index Y is related to the distance of the magnetometer above the bottom of the cavity. In a succeeding run, while the coil remained excited with a dc current of the same value as in the first run, the cavity was cooled from liquid-nitrogen temperature to the temperature of liquid helium. The coil excitation was then switched off. The resulting measured flux is shown by the upper curve of Fig. 10. Figure 11 shows the flux measured along the axis in a third run after the cavity was cooled from 77 to 4.2 K with no externally applied field.

We interpret Fig. 10 to be a demonstration that the lead-plated cavity exhibits no macroscopic Meissner effect for an applied field well below H_c. With a measured maximum field of 350 mG produced by the coil at the helix axis, the calculated maximum field produced by the coil at the cavity cylindrical surface is less than 40 G. Instead of being expelled to the outside when the cavity's surface becomes superconducting, flux appears to be trapped and frozen with about the same magnitude and distribution as exhibited by the externally applied field from the coil when the cavity was not superconducting. In addition to showing a trapping of the applied flux, the upper curve of Fig. 10 shows a flux that appears to have increased further by an amount that can be accounted for by adding values about equal to those

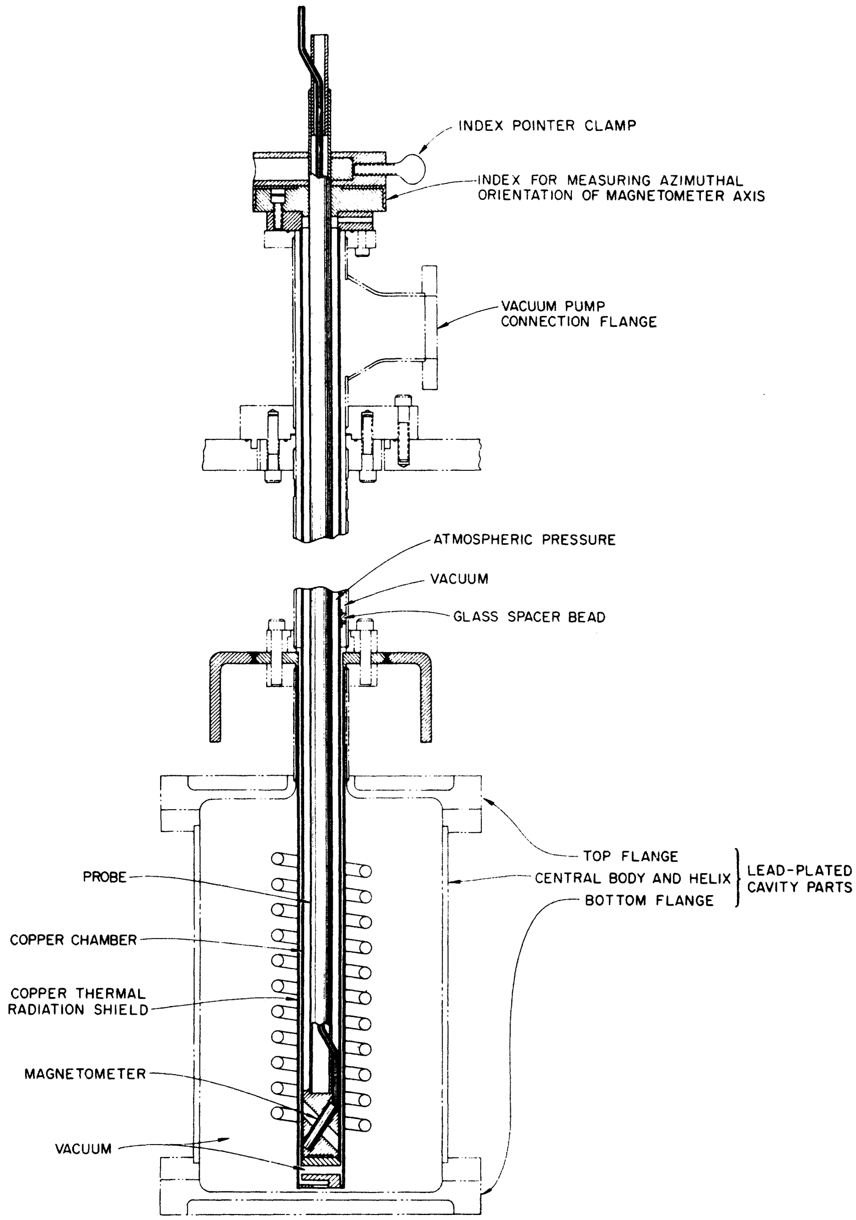

FIG. 9. Assembly drawing of a helically loaded lead-plated cavity modified to permit measurements of the magnetic field $\vec{B}$ along its axis. Measurements were made with this apparatus at temperatures from 300 to 4.2 K. A 3.25-cm-diam coil, not shown in the figure, was attached to the outside of the cavity to permit the application of a magnetic field to allow testing for a macroscopic Meissner effect.

of the curve of Fig. 11.

We believe Fig. 10 demonstrates convincingly that a lead-plated cavity will trap even weak externally applied magnetic fields without significant modification due to the Meissner effect. On the other hand, we hesitate to claim Fig. 11 is a measurement of trapped flux that was spontaneously or thermoelectrically generated for we have not investigated to what extent the magnetometer generates and interacts with its mirror image in the surrounding superconducting surface. However, many observations made during our magnetic flux measurements when the surface was not superconducting indicated the presence of transient magnetic fields associated with transient thermal phenomena. For instance, during a cooling of the cavity from room temperature to liquid nitrogen temperature, the magnetometer was placed at a fixed position at an axial point within the helix. At room temperature the measured field was about 0.3 mG. During the rapid temperature decrease, the magnetic field oscillated in an agitated manner, reaching values as high as 45 mG. When the entire system was finally stabilized at liquid-nitrogen temperature, the magnetic field magnitude had returned to its initial value of 0.3 mG. Similar

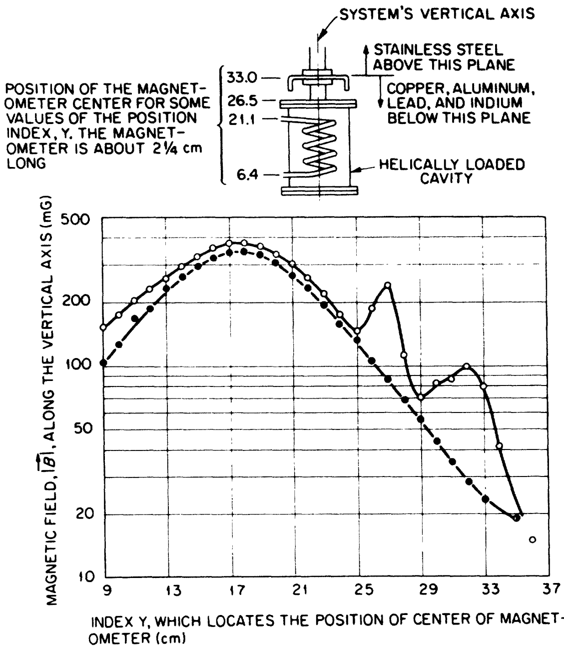

FIG. 10. Lower curve shows the measured magnitude of the magnetic field along the axis of the cavity at 77 K when a fixed excitation current flowed in the coil attached to the outside of the cavity. The upper curve shows the measured magnitude of magnetic field along the axis of the cavity at 4.2 K after it was cooled from 77 K while the same excitation current flowed through the coil. When the temperature reached 4.2 K, the current through the coil was switched off.

effects were observed when cooling the cavity from liquid-nitrogen to liquid-helium temperature. In all cases, after the cavity had been cooled below the critical temperature of lead, the measured flux within the cavity became extremely quiescent. Measurements repeated several hours after the cavity surface had become superconducting indicated the trapped flux had not changed appreciably. The measurement in which the cavity temperature was lowered from 77 to 4.2 K with no externally applied field was repeated several times. Usually the flux measured within the helix was 10–20 mG.

VII. DISCUSSION

In our experience with fabrication of a lead-plated cavity, we found that, even when exercising great precaution, complete exclusion of contaminating materials from solutions used in plating was not possible. As an example, several solvents were tested for cleanness to see which should be used as a final rinse after plating. Each tested solvent was allowed to evaporate slowly from a clean covered watch glass. Electronic grade acetone proved to be best, but even it left an easily visible residue of unidentified material. The presence of such material on a superconducting surface may give rise to dielectric losses.

Daniels[17] states that most dielectrics are found to exhibit a frequency dependence more complicated than that of simple Debye behavior and can only be described by assuming the presence of a number of relaxation times. We consider, however, a hypothetical material with a single relaxation time. (In fact, Victor and Hartwig[15] report observation of a single relaxation time in some commonly used dielectric materials.) In such a case, dielectric loss is proportional to $\omega^2\tau/(1+\omega^2\tau^2)$. It can be seen that for $\omega\tau \ll 1$, loss is proportional to ω^2, while for $\omega\tau \gg 1$, it is proportional to ω^0. Thus, over some frequency interval, the loss is approximately proportional to $\omega^{1.23}$, which is the frequency dependence of R_{res} in the results reported here. For a τ of about 0.49 nsec, a Debye-type loss curve can be fitted

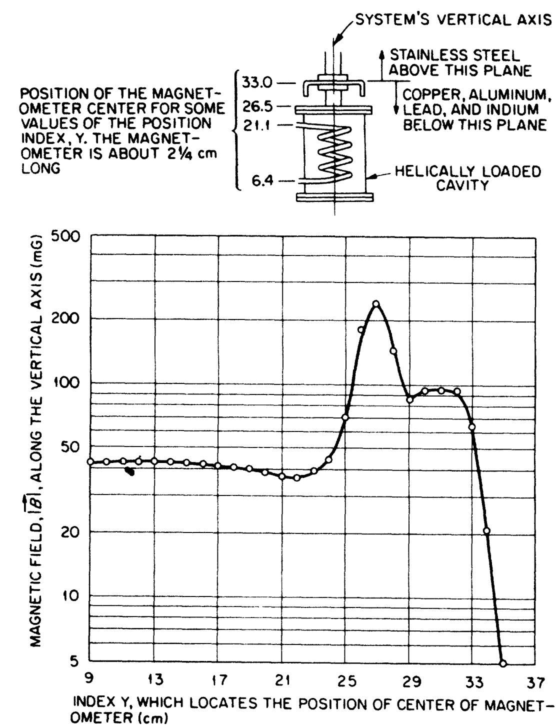

FIG. 11. Measured value of the magnitude of the magnetic field along the axis of the cavity at 4.2 K after it was cooled from 77 K. During the cooling no current was permitted to flow through the coil attached to the outside of the cavity. We have not investigated to what extent this measured magnetic field is due to the magnetometer's generation of and interaction with its mirror image.

to within 10% of the magnitude of our measured data over the frequency range 137 to 472 MHz. The Debye curve, however, varies approximately as $f^{1.5}$ at the beginning of this frequency interval and as $f^{0.8}$ near the end of this interval. The best fit through the experimental points of Fig. 8 is a straight line, as shown. A Debye curve gives a much less likely fit.

A similar argument applies in the case of a magnetic contaminant with a single relaxation time since, in this case, magnetic loss is again proportional to $\omega^2\tau/(1+\omega^2\tau^2)$.

Turneaure and Weissman[7] argue that increased residual losses which occur in a lead-plated cavity when electric fields are normal to the surface can be interpreted as being due to dielectric loss. However, from comparisons of reported values of surface resistance in superconducting cavities which could be excited in both the TE and TM modes, Halbritter[18] concludes dielectrics cannot account for R_{res}. Although our observed frequency dependence does not exclude the possibility of loss from some unknown dielectric or magnetic material, we believe, because of Halbritter's[18] argument that our observed R_{res} is due to other causes.

It is clear that, if the entire cavity surface were normal rather than superconducting, its low temperature surface resistance would show the $\omega^{2/3}$ frequency dependence of anomalous surface resistance. Pierce[4] measured such a frequency dependence for a cavity cooled in the presence of applied fields H that were larger than those that might arise from thermoelectric currents. He suggests that, if H_c is the critical field, a fraction (H/H_c) of the cavity surface becomes normal and contributes a surface resistance component $R_H = R_N(H/H_c)$, where R_N is the anomalous surface resistance in the normal state. Although Pierce's measured results follow the frequency dependence expected from anomalous surface resistance, his measured magnitudes are about a factor of 3 less than expected from an estimate of the fraction of the surface which has become normal because of trapped flux. However, Rabinowitz[19] derives relations which show that small normal regions within a superconducting surface will contribute a resistance whose frequency dependence is proportional to ω^2. Assuming the correctness of this theory for small normal regions, we would expect a more complete theory to show a smooth transition from an ω^2 frequency dependence when the normal regions are small and few in number to an $\omega^{2/3}$ dependence when the number and size of normal regions has increased to the extent that the entire surface has become normal.

For an assumption of still another mechanism, namely, that trapped flux interacts with rf fields in the cavity, Rabinowitz[19-21] derives another relation which shows a resistance contribution, due to oscillating fluxoids, which changes smoothly with frequency. At low frequencies it varies as ω^2, while at high frequencies it varies as $1/\omega^2$. At some intermediate frequency there is again a range where residual resistance due to oscillating fluxoids is proportional to $\omega^{1.23}$, which is the dependence we have measured. Thus we see there are several theories of expected frequency dependence due to normal regions embedded in a superconducting surface, and the validity of any particular theory still needs to be resolved.

Halbritter[18] points out that, for an ideal uncontaminated superconducting surface, the surface resistance will have a lower limit. The electric field will interact with the charged lattice points and generate phonons. The process will extract energy from the fields and produce a surface resistance component. Halbritter suggests that phonon generation losses can be enhanced by the presence of microscopic surface irregularities, or fissures, and that through this mechanism normal components of electric field can produce a surface resistance of 10^{-7} Ω, independent of frequency. On the other hand, components of electric field parallel to the surface can cause phonon generation losses which vary as ω^2. In the latter case Halbritter estimates such losses produce a surface resistance of only 5×10^{-10} Ω at 1 GHz. Neither of these magnitudes or frequency dependencies fit our measured results.

Passow[22] has also derived an expression which attempts an explanation of residual resistance in ideal cavities by phonon generation. Passow's expression for surface resistance has two terms. The first term is the superconducting surface resistance; the second accounts for losses from phonon generation. In Fig. 12 we have again plotted our experimental values for R_{res} along with the residual resistance expected according to the expression of Passow for two different values of Λ, a parameter directly related to coherence length and London penetration depth. One curve uses $\Lambda = 1683$ Å, the value suggested by Passow. In the second curve we have adjusted Λ to get better agreement in magnitude between Passow's theory and our measured results. In addition we have plotted a curve for losses from a trapped flux of 12 mG calculated using the assumptions of Pierce discussed above. A reasonable estimate of thermally generated flux trapped by our cavity is 12 mG.

Both Pierce and Passow's expressions predict magnitudes in fair agreement with that observed, but the frequency dependence predicted by both differs from our measured $f^{1.23}$. We find a further

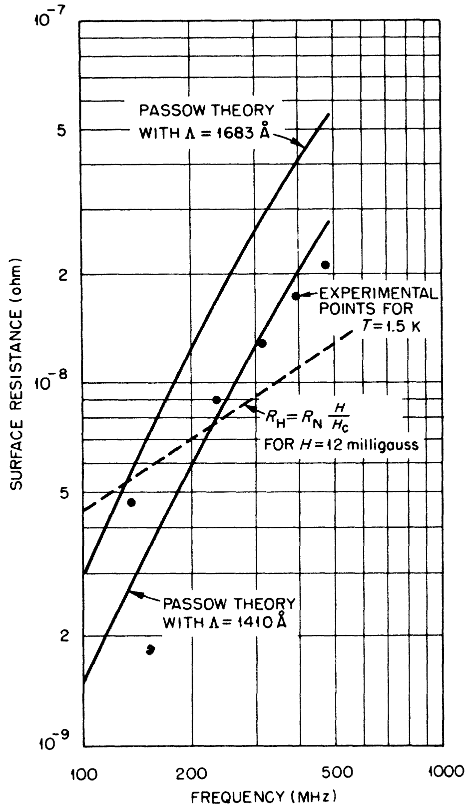

FIG. 12. Frequency dependence of the surface resistance of lead at 1.5 K normalized to a stored electrical energy of 10^{-6} J. The closed circles are values measured in the present experiment. The dashed line is the theoretical surface resistance expected from a trapped magnetic field of 12 mG according to an expression of Pierce. The solid lines are the theoretical surface resistance due to phonon generation for two values of Λ according to a theory of Passow.

problem with Passow's expression since calculations of superconducting resistance using his first term gives results 10 times higher than exact results for lead at the temperatures and frequencies we compared. This disagreement casts doubt on the validity of Passow's entire expression and hence on the second term which gives values for resistance due to generation of phonons. A severe criticism of Passow's work has also been made on theoretical grounds by Alig.[23]

Kartheuser and Rodriguez[24] have also developed an expression for R_{res} due to phonon generation. They compare their predictions with results reported for lead and niobium and show good agreement in the case of niobium above 1 GHz, but poor agreement in the case of lead, for which measured values are much higher than predicted by the phonon generation model. For our frequencies of 136.7 and 471.6 MHz their expression predicts an rf surface resistance of 1.7×10^{-14} and 2.3×10^{-12} Ω, respectively. These results are several orders of magnitude less than those which we measured. We feel that phonon generation may present an ultimate lower limit for R_{res} but that these predicted losses are too small to account for the residual resistance currently measured in lead cavities, and particularly in our lead-plated cavity. In view of our observations of flux generation during rapid temperature changes and of flux trapping by our cavity, trapped flux is a strong candidate for the source of our measured residual resistance. We also note that cavity geometries different from ours may be less susceptible to flux trapping.

VIII. SUMMARY OF RESULTS AND CONCLUSIONS

The chief results of the present measurements are tabulated.

(i) The data are consistent with the following: (a) The BCS theory in the weak-coupling limit; (b) R_{res} independent of temperature; and (c) $350 < l < 6000$ Å.

(ii) With a stored energy of 10^{-6} J, the observed surface resistance at 136.7 MHz and 1.5 K was 4.7×10^{-9} Ω. This corresponds to a cavity Q of 1.77×10^{9}. The lowest previously reported surface resistance for lead was 1.66×10^{-8} Ω.[9] The present measurements serve as an upper limit for surface resistance in the frequency range 137–472 MHz.

(iii) A frequency dependence of $\omega^{1.23\pm0.05}$ was observed for R_{res}. The magnitude and frequency dependence are not exactly consistent with simple explanations. However, the magnitude is in fairly good agreement with a simple model based on a trapped magnetic field whose magnitude is consistent with values measured within a similar but not identical cavity. The magnitude of R_{res} is also consistent with a phonon generation model due to Passow. Less significance is attached to this result because the first term of Passow's expression overestimates superconducting surface resistance by an order of magnitude. The present measured results are also several orders of magnitude higher than predicted by Kartheuser and Rodriguez for losses due to phonon generation. In measurements made up to now in lead-plated cavities, we do not believe phonon generation is responsible for R_{res}. Instead, trapped flux is a more likely source of the observed loss.

(iv) R_{res} has a slight dependence on stored energy, possibly associated with nonresonant multiplication of electrons in the cavity.

(v) For a lead surface kept in a cold clean evacuated cavity, R_{res} showed no appreciable change over short time intervals as well as after a seven-month time interval despite being cycled a large number of times from 77 to 1.5 K. This result is in contrast to other reported observations.

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