Particle Accelerators, 1972, Vol. 3, pp. 103–113

PRELIMINARY MEASUREMENTS ON A LOW PHASE VELOCITY SUPERCONDUCTING RESONANT CAVITY†

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Preliminary measurements are described on a low phase velocity, superconducting, helically loaded, lead plated resonant cavity operated in its fundamental mode at 136 MHz. The following approximate fields were obtained at a power consumption of 320 mW/m:

maximum magnetic field	187 G
maximum electric field	4.75 MV/m
axial accelerating field	0.7 MV/m

Axial electric field distributions in the fundamental and first two harmonic modes were measured.

1. INTRODUCTION

The measurements reported here are part of a general study at the Oak Ridge Laboratory of the feasibility of accelerating heavy ions with a superconducting linear accelerator, i.e., an accelerator employing superconducting resonant cavities.[1] From the viewpoint of nuclear physics, the energy range of particular interest has as its upper limit something in the order of 10 MeV/nucleon, and it is this problem that we are considering. An important problem in the design of an accelerator of this type is the low velocity of the ions being accelerated. For example, an energy of 7.5 MeV/nucleon corresponds to $\beta = v/c = 0.126$. This low ion velocity requires the use of cavities with corresponding low phase velocities. In our opinion, the optimum form for such cavities has not been established. However, it does seem clear that these cavities must be geometrically complex and operate at relatively low frequencies, i.e., in the order of 50 to 400 MHz. Very little is known about superconducting cavities of this type. Thus, we have begun a series of measurements on geometrically complex, low frequency cavities. For our first measurements, we have chosen to build a lead plated, helically loaded cavity. We chose lead rather than niobium because lead plating is a relatively simple and cheap technology. The helically loaded geometry was chosen because of fabrication simplicity, small size, and because this geometry is reasonably well understood.[2]

The measurements presented here are our first and are quite obviously incomplete. We have chosen to publish this preliminary account because of the paucity of published measurements on rf superconductors at low frequencies and the importance of such measurements to the feasibility and design of superconducting heavy ion accelerators.

† Research sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

2. APPARATUS

A layout drawing showing the principal features of the resonant cavity and dewar is shown in Fig. 1. The cavity is supported by a single stainless steel tube which serves as a vacuum connection and housing for two 50 Ω transmission lines which couple electrically to the cavity. This tube is connected to a vacuum manifold and ion pump which allows the cavity to be evacuated before cooling. The construction of this vacuum system followed standard ‘ultra high vacuum’ practice, and pressures of 1×10^{-7} torr near the throat of the pump before cooling the resonant cavity were typical. The transmission lines are fabricated with a solid copper inner conductor and stainless steel

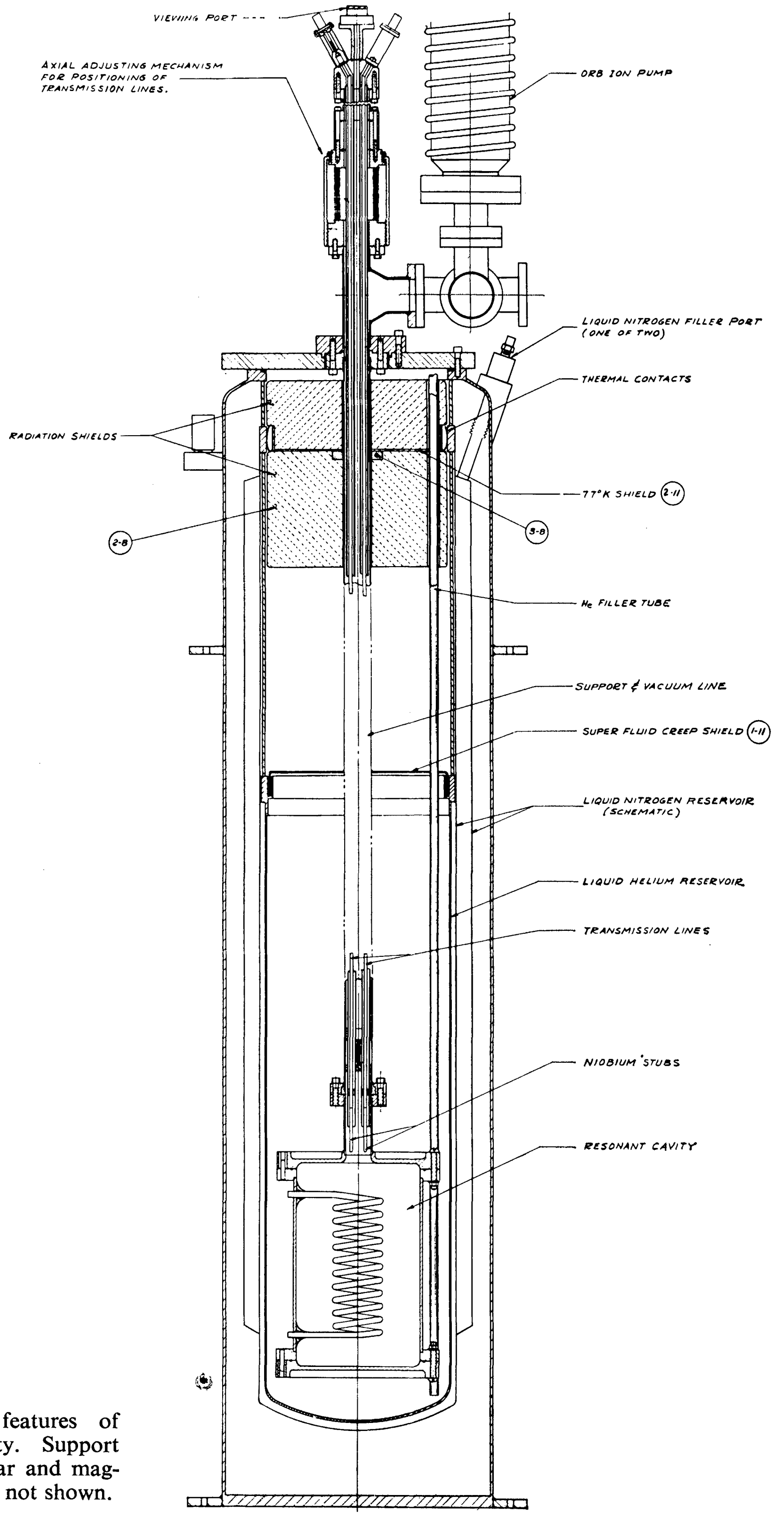

FIG. 1. General features of cryostat and cavity. Support structure for dewar and magnetic shielding are not shown.

outer conductor separated by cylindrical quartz spacers. The terminating stubs are fabricated of solid niobium. The position of the lines with respect to the cavity may be varied, thus changing the electrical coupling between the lines and cavity. The transmission lines are physically connected together so that it is not possible to change their relative coupling strength. In the present measurements, the coupling between the lines was much less than the coupling to the cavity.

In order to minimize the ambient magnetic field in the region of the cavity, and thus 'frozen flux' in the cavity, two steps were taken. First, the dewar was fabricated[3] of the nonmagnetic materials, aluminum and fiberglass. Second, the dewar was surrounded by two concentric Moly-Permaloy[4] cans (not shown in Fig. 1). The inner can was wrapped with a coil which was used for 'degaussing' and trimming. For the present measurements, the average field in the region of the cavity was approximately zero and the maximum field at any point was less than 0.5 milligauss.

The temperature of the cavity was controlled in the usual way by controlling the pressure of the He gas within the dewar. A minimal amount of vibration isolation was provided by mounting the dewar on elastic pads[5] normally used for the support of machine tools.

3. CAVITY

Only one lead plated cavity was used in the present measurements. As shown in Fig. 1, it consists of three parts: a bottom plate, center piece, and top plate. Each was constructed of OFHC copper. The bottom plate was machined from solid stock. The center piece was fabricated in the following sequence. A tube was formed by rolling and heliarc welding. After rough machining, flanges were heliarc welded on each end and the piece was machined to size. Finally, the prewound helix was attached by furnace brazing in a hydrogen atmosphere. This operation not only joins the helix to the tube, but also produces an extremely clean surface. The top plate was formed by machining and heliarc welding. Ethyl alcohol was used as a lubricant for the final machining operations, and the parts were not touched after machining.

The lead surface was obtained by electrodeposition of Pb on the surface of the copper cavity. The lead fluoborate solution, prepared from hydrofluoric acid, boric acid, and PbO, contained 120 g/liter of Pb and 0.2 g/liter of animal bone glue. The anode structure was 0.015 in. 'chemical' lead foil (99.9 per cent Pb). The crystal grain size of the copper surface and the electrodeposited Pb surface ranged from 50 to 400 μm. The lead surface had an average thickness of 5 μm (5.5 mg/cm^2). The following steps were used in the electrodeposition process:

(1) Electropolished for 3 minutes in a 60 per cent solution of H_3PO_4 at a current density of 80 to 100 mA/cm^2.
(2) Dipped and rinsed in distilled H_2O.
(3) Electrocleaned (cathodic cleaning) for 3 minutes in a 6 per cent solution of trisodium phosphate ($Na_3PO_4 12H_2O$) at a current density of 15 mA/cm^2 and at room temperature.
(4) Dipped and rinsed in distilled H_2O.
(5) Copper strike ($\sim$ 0.5 mg/cm^2) from a low efficiency copper cyanide bath for 3 minutes at a current density of 10 mA/cm^2 and at room temperature.
(6) Dipped and rinsed in distilled H_2O.
(7) Pb plated for 8 minutes at a current density of 10 mA/cm^2 at room temperature.
(8) Dipped and rinsed in distilled H_2O.
(9) Dipped and rinsed in 200-proof ethyl alcohol.
(10) Dried in a He or Ar atmosphere.

The cavity parts were attached with aluminum bolts, and indium 'O' rings were used as a vacuum seal. A knife edge was machined on the top and bottom plates to insure good electrical contact between the three pieces. However, when the cavity was disassembled after the measurements to be described, it was discovered that the indium 'O' rings had not sufficiently compressed for these knife edges to seat and that electrical contact between the pieces was made via the indium 'O' rings.

The interior dimensions of the cavity are as follows:

length: 8.8 in.
diameter: 5.5 in.
helix diameter (center to center): 2.0 in.

helix tube outer diameter: 0.25 in.
helix tube to tube spacing: 0.5 in.
number of turns: 11

For the measurements to be described, the cavity was operated in its fundamental ($\lambda/2$) mode at 136.5 MHz. This gives a phase velocity of 0.107 c which is typical of a heavy ion accelerator.

4. ROOM TEMPERATURE MEASUREMENTS

A fundamental assumption in these measurements is that the cavity behaves as a homogeneous cavity, i.e., that the surface impedance of the cavity is independent of position. There are two important consequences of this assumption. First, the unloaded quality factor, Q_0, and the surface resistivity, R_s, are related by a constant, Γ, which depends only on the excitation mode, i.e., $Q_0 = \Gamma/R_s$. Second, relative field strengths depend only on excitation mode but not on R_s or power level.

These ideas were exploited in the following way. A copper cavity was fabricated with essentially the same dimensions as the lead plated cavity used for the low temperature measurements. The Q for this cavity in its fundamental mode (134.9 MHz) was measured to be 2740. When combined with an assumed surface resistivity for copper of $3.03 \times 10^{-3}\ \Omega$, this gives a geometry factor $\Gamma = 8.3\ \Omega$. Using this geometry factor, we were then able to calculate surface resistivities for lead from observed values of Q_0 for the lead plated cavity.

In order to estimate the fields within the cavity, we used the fact that if U is the total rf energy within the cavity and E the electric field at a given point the ratio E^2/U for a homogeneous cavity is constant, independent of R_s or U. E^2/U may be measured by the usual frequency perturbation technique in which the resonant frequency of the cavity is perturbed by an object and the perturbation is proportional to (field strength)$^2/U$. In the

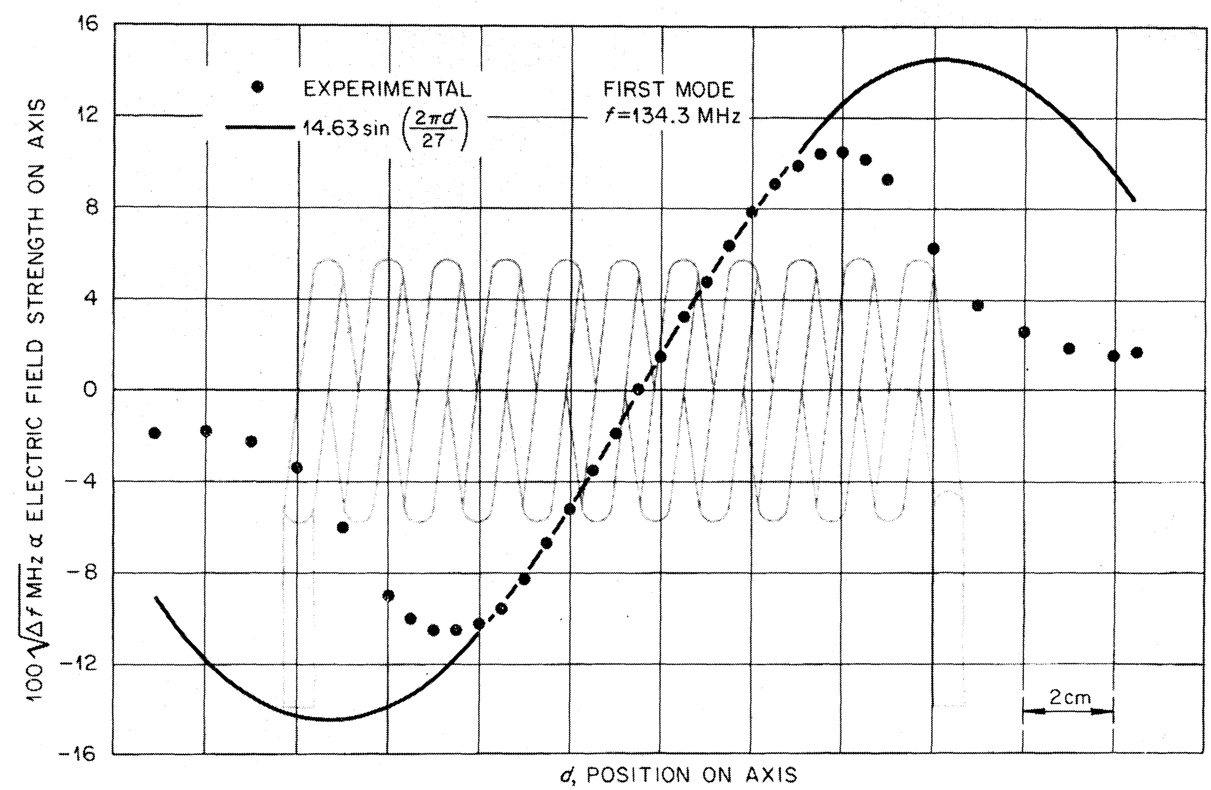

FIG. 2. Axial electric field in fundamental mode. The closed circles are the observed frequency shift as a function of position of the perturbing element along the axis of cavity. The solid line is a least mean square fit using the central points. The helical element is shown in the same scale for perspective.

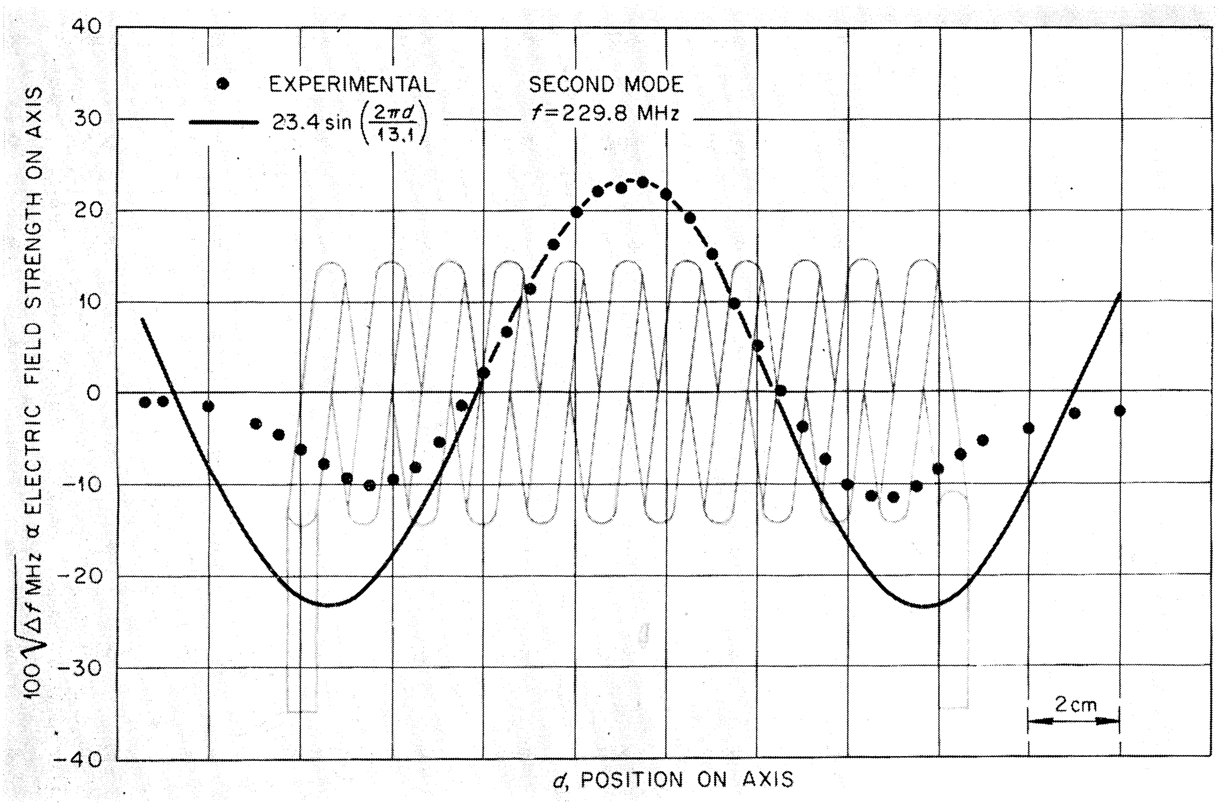

FIG. 3. Axial electric field in first harmonic mode. See Fig. 2.

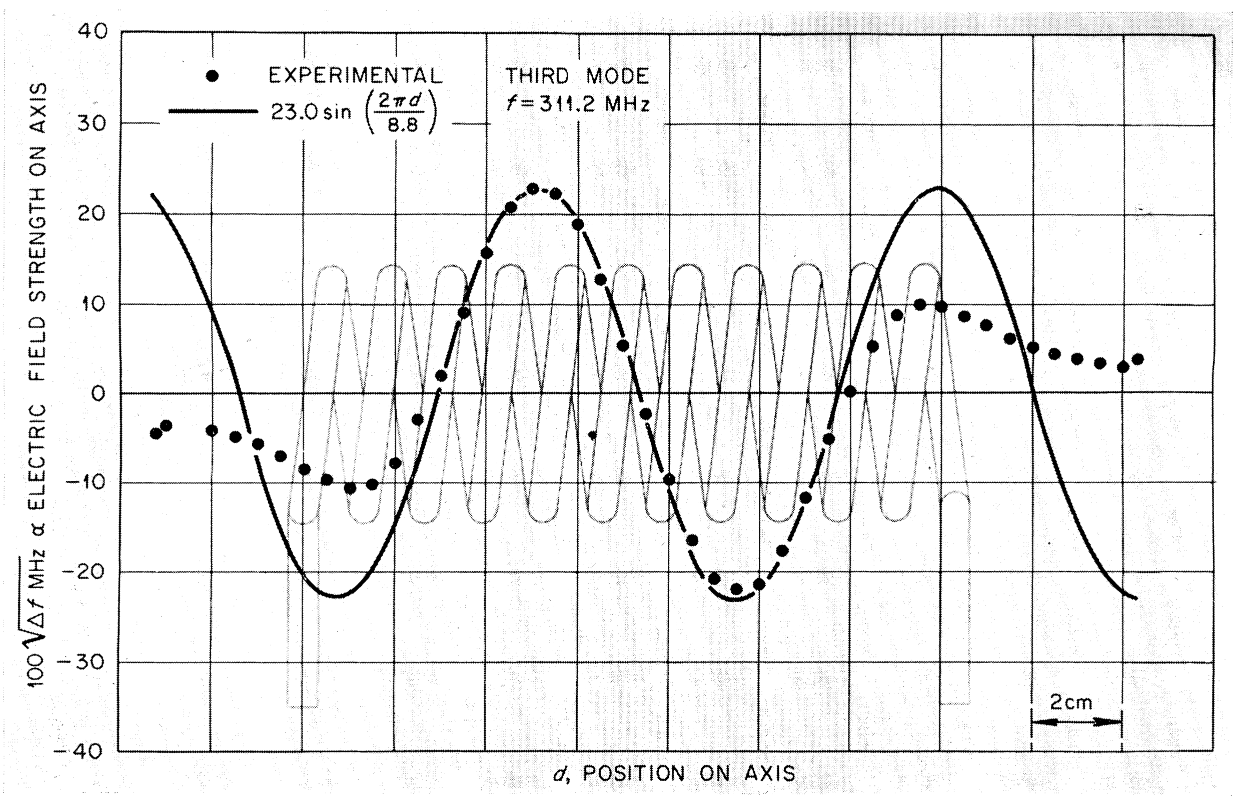

FIG. 4. Axial electric field in second harmonic mode. See Fig. 2.

present experiment, we measured the axial electric field in the copper cavity for the first three excitation modes using as our perturbing object a dielectric ball of volume V and relative dielectric constant ε. In this case,[6]

$$\frac{\delta f}{f} = -\tfrac{3}{4}V\frac{\varepsilon-1}{\varepsilon+2}\varepsilon_0\frac{E^2}{U},$$

or

$$\frac{E^2}{U} = \frac{\delta f}{f} \times (1.13 \pm 0.06 \times 10^{18}\left(\frac{\text{volts/meter}}{\text{joule}}\right)^2$$

using the measured constants for our ball.[7] The results of these measurements are shown in Figs. 2, 3, and 4. In these figures, the measured points are shown as closed circles. The solid lines are the least mean square fit of sine functions of the wavelength which would be expected if the helix were long. It is clear that the axial electric field is strongly perturbed by the physical end of the helix.

5. LOW TEMPERATURE MEASUREMENTS

The general theory of cavity measurements is well documented.[8] However, in order to simplify the subsequent discussion, we will describe very briefly our nomenclature and measurement technique. We assume in the following that the cavity is being excited exactly at its resonant frequency. Our system consists of a cavity and two coupled transmission lines, labeled 1 and 2. We define P_{wall} as the power dissipated in the walls of the cavity and transmission line terminations. $P_{\text{rad }1}$ and $P_{\text{rad }2}$ are defined as the power radiated into transmission lines 1 and 2. The coupling constants, β_i, are then defined by $\beta_i = (P_{\text{rad }i}/P_{\text{wall}})$; $i = 1, 2$. We define the loaded quality factor, Q_L, as the Q of the cavity plus transmission line system and the unloaded factor, Q_0, as the Q which would be present if no power were radiated into the transmission lines. Q_L is the Q that we measure. That is, $Q_L = \omega_0\tau$ where ω_0 is the angular frequency and τ is the observed characteristic time constant. Q_0 is ideally related to power lost in the walls of the cavity. In practice, it also includes nontrivial effects due to losses associated with the transmission line terminations. Q_L and Q_0 are related by $Q_0 = (1+\beta_1+\beta_2)Q_L$. If we excite the cavity by one transmission line, for example No. 1, we can measure, at equilibrium, the voltage ratio, R_1, of reflected to forward power (with the convention $R_1 > 0$ if $\beta_1 < 1+\beta_2$, $R_1 < 0$ if $\beta_1 > 1+\beta_2$). Similarly, we may excite the cavity to the same field level by transmission line No. 2 and measure R_2. After some algebraic manipulation, it can be shown that

$$Q_0 = 2Q_L/(R_1+R_2),$$

and

$$U = 2Q_L(1-R_i)\, P_{\text{inc }i}/\omega_0,$$

where U is the rf energy within the cavity and the cavity is being excited by transmission line i with incident power $P_{\text{inc }i}$.

The low temperature electrical measurements proceeded in a straightforward way. For a given excitation level, the cavity was excited in the steady state mode using first one transmission line and then the other while V_{fwd} and V_{ref}, the forward and reflected voltages respectively, were measured using a directional coupler and sampling oscilloscope. With suitable calibrations, it was then possible to calculate R_1, R_2, P_1 and P_2. In practice, the coupling for line No. 2 was slightly stronger, so that the data presented for high power are those in which the cavity was excited by this line. The characteristic time constant was measured using the decrement method. In the present experiment, we pulsed the input power on and off repetitively and observed the cavity decay time. This pulsing operation was done with an electronic switching network which maintained proper impedance matches. The decay time was then used to calculate Q_L. Q_0 and $\sqrt{U}$ were then calculated using the expressions given above.

There is one feature of our experimental arrangement which probably deserves some additional discussion. It is evident that, mechanically, the helix in a helically loaded cavity behaves like a flexible coil spring. This has two important consequences. The first is that the cavity shows a marked sensitivity to ambient vibration. The frequency modulation introduced by vibration is typically much larger than the bandwidth of the cavity which, in the present experiment, is in the order of 1 Hz. Thus, it is necessary to provide a servo loop which maintains the external driving frequency equal to the instantaneous frequency of the cavity. The second consequence is that coupling between the rf and mechanical energy in the cavity[9] can excite mechanical vibrations of the helix. One solution to these problems has been proposed by Schulze *et al.*[10] In this technique, the cavity is excited by an oscillator whose instantaneous frequency is controlled by a servo amplifier whose input signal is a voltage proportional to the phase difference between the signals at input and output ports of the cavity. Mechanical oscillations may be damped by proper choice of parameters in the servo amplifier feedback loop. We constructed such a system and made our first measurements with it.

Later, we discovered the simple technique of exciting the cavity as a self-excited oscillator also solved these problems. The general technique is well known and has also been suggested for high frequency superconducting cavities.[11] We preferred it because it requires fewer components and, for us, was simpler to operate. The essential physical idea is that when the cavity is operating at the 'top of the resonance curve' the rf and mechanical systems are effectively decoupled.

6. EXPERIMENTAL RESULTS

The first measurements that we wish to describe were made at very low power levels with the cavity evacuated. The first of these is shown in Fig. 5 where we have measured Q_0 as a function of transmission line position for temperatures of 1.4 and 4.2 °K. Two features are apparent. First, Q_0 is a function of transmission line position. We interpret this as being due to resistive losses in the transmission line terminations. Since the stubs are niobium (hopefully at a temperature below their transition temperature) and the cavity neck is lead plated, these losses are presumably associated with the stainless steel transmission line outer conductors. Two mechanisms seem likely. The first is resistive losses in the ends of the outer conductors close to the cavity. The second is propagation of energy up the transmission line which is formed by the outer surface of the outer conductors and the inner surface of the outer support tube.

The second important feature of Fig. 5 is the fact that at 4.2 °K the dependence of Q_0 on position levels off, while at 1.4 °K it does not. 'Four inches' was the position of maximum possible withdrawal in these measurements and corresponds to a distance of 0.375 inches from the stubs to the plane defined by the inner surface of the top plate of the cavity. Thus our Q measurements at lower temperatures are not representative of the cavity itself but are degraded by losses associated with the lines. All measurements described below were made with the transmission lines in the '4 inch' position.

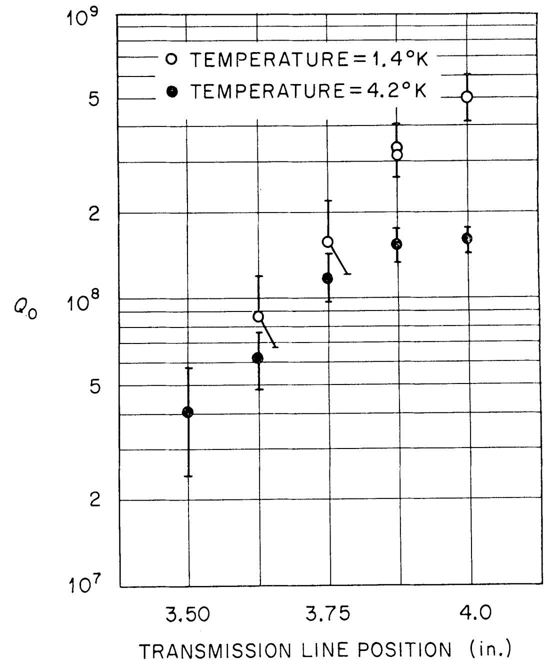

FIG. 5. Unloaded Q, Q_0, as a function of transmission line position. The horizontal scale is an arbitrary measurement at the top of the dewar. Increasing values of this dimension correspond to withdrawal of the transmission lines.

The second measurement at low power is shown in Fig. 6. This is a measurement of Q_0 as a function of temperature. As can be seen, Q_0 rises rapidly when the temperature is lowered until a distinct shoulder is reached at a temperature of about 3.0 °K. Two factors contribute to this rise. One is the change in surface resistivity with temperature. This will be discussed below, but it should be mentioned at this point that the theoretical surface resistivity[12] decreases rapidly with decreasing temperature and, thus, the theoretical Q rises rapidly with decreasing temperature, about a factor of 100 in the range 4.2° to 1.8 °K. The second factor is the fact that in the present experiment,

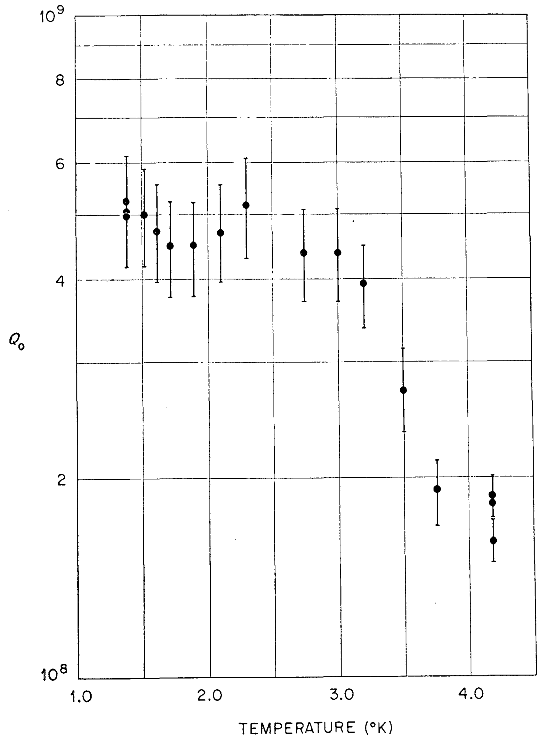

FIG. 6. Unloaded Q, Q_0, measured as a function of temperature for transmission line position of '4 inch'.

currents flowed through the indium 'O' rings which sealed the cavity. The transition temperature for indium is 3.3 °K and we would expect a rapid change in Q_0 near this temperature if the losses due to these currents were a significant fraction of the losses within the cavity. We believe two factors contribute to the markedly reduced slope observed at temperatures below 3.0 °K. One is the transmission line loading effect described above. The other is the so-called residual resistance.[13] This is the component of surface resistivity (generally thought to be a weak function of temperature) which arises from extraneous causes such as impurities, surface layers, and topological irregularities. Because of our limited information on transmission line loading, it is difficult to reliably separate these two effects.

Of greater interest to potential accelerator applications is the behavior of the cavity at higher power levels, and it is this problem to which we devoted most of our attention. Before discussing these in detail, it will be helpful to digress slightly and discuss the determination of field strengths. As discussed above, in a well behaved cavity, the ratio, (field strength)/$U^{1/2}$, is a constant dependent only on excitation mode. Furthermore, we may calculate $U^{1/2}$ from the quantities we measure. However, we have measured (field strength)/$U^{1/2}$ for only a particular case, namely, the axial electric field. These measurements show that end effects are very important. Unfortunately, currently available treatments of helically loaded cavities do not include applicable treatments of end effects. In order to estimate the fields within our cavity, we used the calculations of Sierk *et al.*[2] normalized to the sine wave fit in Fig. 2. Thus, our field strengths take into account the finite size of the helix but not end effects. They should be considered as an estimate only. The more reliable quantity is that which we measure,

$$U^{1/2}(\mathrm{mJ})^{1/2} = \sqrt{2Q_L(1-R_2)\,P_{\mathrm{inc}\ 2}\,(\mathrm{mW})/\omega_0}.$$

For simplicity, we will suppress the constant factors and subsequently use

$$U'^{1/2} = \sqrt{Q_L(1-R_2)\,P_{\mathrm{inc}\ 2}\,(\mathrm{mW})}.$$

Applying the results of Sierk *et al.*[2] to our cavity, we find the axial electric field to be

$$E_z(\mathrm{MV/m}) = 17.4 \times 10^{-6} \times U'^{1/2}.$$

The maximum electric field is the radial field outside the helix

$$E_r^{\,0}(\mathrm{MV/m}) = 59.1 \times 10^{-6} \times U'^{1/2},$$

while the maximum magnetic field is the longitudinal field inside the helix,

$$B_z^{\,i}(\mathrm{G}) = 2.33 \times 10^{-3} \times U'^{1/2}.$$

The first effect observed when the field levels were increased was multipactoring. We know of two practical ways to overcome multipactoring: processing;[14] and multiple mode excitation.[15] Processing consists of exciting the cavity with relatively high incident power levels (substantially above the multipactoring threshold). The resulting electron bombardment then alters the surface and in particular, reduces the secondary electron emission coefficient. We were reluctant to try this technique in the present experiment due to the possibility of surface degradation.[14] We did not try multiple mode excitation because we had not thought of it. The first multipactoring level occurred at $U'^{1/2} = 0.19 \times 10^4$. After very mild processing, we were occasionally able to pass through this level and observe a second level at $U'^{1/2} = 0.58 \times 10^4$.

To prevent multipactoring at high power levels, we filled the cavity with helium in the form of gas at 4.2 °K and liquid at 1.85 °K. The helium gas pressure in the 4.2 °K measurements was slightly below 1 atmosphere. Since helium has a negligibly small loss tangent,[16] the only effect on the cavity is a slight reduction in the resonant frequency. There are, however, two serious disadvantages to this method. The first is that helium (at the pressures available to us) has a lower dielectric strength than vacuum and sparks occur at lower field levels than would be present in an evacuated cavity. The second is that one cannot study field emission effects.

High power measurements were made at 4.2 °K and 1.85 °K. These are shown in Figs. 7 and 8 where we have plotted $U'^{1/2} = \sqrt{Q_L(1-R_2)\, P_{\mathrm{inc}\ 2}}$ and Q_0 *vs* $\sqrt{P_{\mathrm{inc}\ 2}}$. Both measurements show rather similar features. As the power is increased, there is a slight degradation in Q_0 followed by an abrupt discontinuity or 'break' where in both cases, Q_0 drops to about 1×10^8. After this break, the field levels rise to the point of spark discharge. In both figures, the highest field points are the highest that may be sustained without sparks. As an aside,

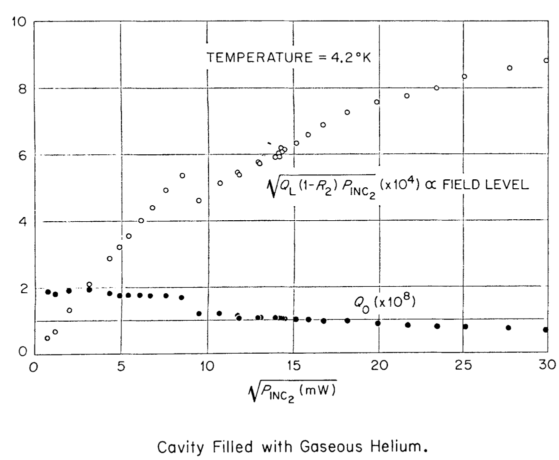

FIG. 7. Unloaded Q, Q_0, and

$U'^{1/2} = \sqrt{Q_L(1-R_2)\, P_{\mathrm{inc}\ 2}}$ in units of $(\mathrm{mW})^{1/2}$

measured as a function of $\sqrt{P_{\mathrm{inc}\ 2}}$. Experimental uncertainties of a few per cent are not shown.

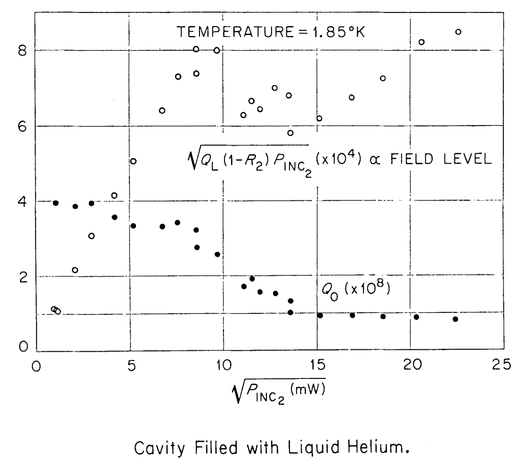

FIG. 8. Unloaded Q, Q_0, and

$U'^{1/2} = \sqrt{Q_L(1-R_2)\, P_{\mathrm{inc}\ 2}}$ in units of $(\mathrm{mW})^{1/2}$

measured as a function of $\sqrt{P_{\mathrm{inc}\ 2}}$. Experimental uncertainties of a few per cent are not shown.

these sparks may be easily heard outside the dewar.

Two observations point to an explanation of the break observed in these measurements. When the cavity output is observed in pulsed power operation at levels above the break point, it is clear that a sudden transition occurs (within at least a few milliseconds) after which the cavity comes to a new stable level. In addition, there is recovery during the power off part of the pulsing cycle (typically 0.5 sec). This suggests magnetic breakdown.[17] The absence of complete breakdown strongly suggests a spatial limitation to the region of breakdown. The only superconducting elements which satisfy this condition are the transmission line stubs. Thus, we believe the break we observe is probably due to magnetic breakdown in the transmission line stubs and not in the cavity. No effort was made to optimize these stubs, either with respect to shape, temperature, or surface preparation. For this reason, we believe the points of particular interest in these figures are those occurring before the breaks.

7. DISCUSSION

It is of some interest to compare our results with the predictions of the BCS theory. To do this, we calculated theoretical surface resistivities at low fields with a program[18] based on a development by Halbritter.[12] As mentioned above, the theoretical surface resistivity drops rapidly by a factor of about 100 in the temperature range 4.2 °K to 1.8 °K. Our measured values ($4.5 \times 10^{-8}\Omega$ at 4.2 °K) are a factor of 2 to 3 higher than the theory in the temperature range 4.2 to 3.0 °K and then diverge completely. However, in view of the experimental problems described above, this comparison should not be taken too seriously.

Again, based on developments by Halbritter,[19] the dependence of R_s on field strength suggests the presence of effects associated with residual resistance rather than fundamental effects. However, our experimental problems again make a meaningful comparison difficult.

It is also of interest to compare our results with other published measurements on low frequency cavities. Early measurements in lead plated cavities were reported by Grissom and Hartwig.[20] However, these measurements were directed primarily towards the study of dielectric materials at low temperature, and high cavity Q's and fields were not emphasized. Q's obtained in these measurements were in the order of 2×10^7. Recently, Dick *et al.* have reported two measurements on lead plated cavities.[15,21] In the latter they report peak fields greater than 300 G and Q's greater than 10^8 observed at a frequency of 54 MHz. Vetter *et al.* have reported[22] measurements at low power on a lead plated cavity loaded with a niobium helix. At 136 MHz, they observe Q's of 3×10^8 at 4.2 °K and 6×10^8 at 1.9 °K. These measurements and those of Dick *et al.* appear to be consistent with ours.

Finally, we wish to discuss aspects of our work which bear on the technical feasibility of a low phase velocity superconducting accelerator. We consider first the question of field strength. We have described above the procedure used for estimating field strengths. Applying these estimates to our most favorable point at 1.85 °K (last point before the break where $U'^{1/2} = 8.0 \times 10^4$), we have the following fields:

$$E_z\text{(standing wave)} = 1.4 \text{ MV/m}$$
$$E_x\text{(accelerating)} = 0.7 \text{ MV/m}$$
$$E_r^{\,0} = 4.75 \text{ MV/m}$$
$$B_z^{\,i} = 187 \text{ G}$$

The power lost in the cavity walls at this point was 40 mW or about 320 mW/m.

In spite of the strong coupling between rf and mechanical energy in the cavity, we found that stable operation of the cavity was possible and in fact easy with the self-excited oscillator method. We do not think this will be a significant problem in future designs. The frequency modulation observed in our cavity was 10 to 30 Hz at a principal frequency of about 250 Hz. The observed frequency modulation was not a function of field level.

It should be noted that stable operation of a single helically loaded cavity is a much simpler problem than phase synchronous operation of a number of cavities. Several solutions to the latter problem are conceptually possible, but to our knowledge, none has been successfully demonstrated.

During the course of these measurements, the cavity was cycled in temperature (300 °K → 2 °K → 300 °K) several times and exposed to gaseous and liquid helium. We observed only a slight degradation in the properties of the cavity, and we strongly suspect that this was associated with spark discharges. Upon disassembly after the measurements, we could, however, observe no macroscopic damage due to sparks.

The present measurements have given no information about field emission and very little about multipactoring. These are, of course, very important considerations for a real accelerator.

In summary, we have been encouraged by these measurements. We have discovered no insurmountable obstacles to the use of helically loaded structures in an accelerator, and we think that the relatively low fields and high surface resistivities which we observed are a result of defects in our experimental apparatus and not limitations of the cavity.

ACKNOWLEDGEMENTS

We wish to express our appreciation to C. E. Cox, W. F. Bunch, W. H. Hamley, J. M. Loftus, and J. E. Weidley who designed and fabricated the experimental apparatus and cavity. The preparation of this paper took place while one of the authors (CMJ) was a guest at the Institut für Experimentelle Kernphysik, Kernforschungszentrum, Karlsruhe. We wish to thank Professor A. Citron for his hospitality and members of the Institut, especially J. Halbritter, for helpful discussions.

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Received 24 November 1971