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SUPERCONDUCTING NIOBIUM CAVITY MEASUREMENTS AT SLAC*

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Summary

The program of measurements at SLAC on superconducting niobium cavities is described. Results for TE and TM mode X-band cavities are presented. An RF magnetic breakdown field of 960 gauss and Q values greater than 10^{11} were measured for an electron beam welded TE_{011} mode cavity at 10.5 GHz. The best result for a TM mode cavity was a Q of 1.4×10^9 and a breakdown field of 360 gauss, limited probably by the quality of the electron beam weld. Data on the effect of exposure to air and to nitrogen are presented.

Introduction

The superconducting accelerator research program was established at SLAC in 1968 to study the feasibility of the eventual conversion of the SLAC accelerator to a two-mile-long superconducting machine. Since its inception, the superconducting accelerator project has proceeded in two parallel directions: a program of basic studies to measure and understand the RF properties of superconducting materials, and the construction of an operational superconducting prototype accelerator. The second objective is embodied in a two-foot-long traveling wave resonant accelerator, project Leapfrog, which is currently under construction at SLAC and which has been described elsewhere.[1] The present paper reports on recent progress in the area of materials studies by means of measurements on superconducting niobium X-band cavities.

During the past year, a substantial fraction of the effort at SLAC on superconducting accelerator research has gone into the construction of in-house facilities for the fabrication and processing of niobium cavities and structures. A 25 kW electron beam welder with a 5 ft × 5 ft × 9 ft vacuum chamber is now operational. Welding can be done in a vacuum of 10^{-7} torr, with cryopanels surrounding the work for added cleanliness. The construction of a high temperature, ultra high vacuum furnace having a working hot zone 5 inches in diameter by 9 inches long has also been completed. Temperatures in excess of 2000°C at pressures on the order of 10^{-8} torr have been achieved in initial operation. The first S-band cavities and structures are now being fabricated and processed using these facilities. Only preliminary measurements have so far been made at S-band, and the results reported in this paper are limited therefore to those obtained for TE and TM mode X-band cavities. In most cases these cavities were vacuum fired at high temperature by induction heating. The advantage of this technique is that only the cavity itself is heated; there are no other hot metallic surfaces in the same vacuum system. It is not yet clear whether equivalent standards of cleanliness can be achieved in the large furnaces needed for processing S- and L-band accelerating structures.

A superconducting SLAC could be a much more useful high-energy physics tool than the present accelerator if a higher energy gradient, as well as a much greater duty cycle were obtained. A major goal of the cavity measurement program is to obtain peak RF fields which are high enough to give an effective accelerating gradient of 10 MV/ft. To achieve this in a traveling wave structure peak fields on the order of 1000 G and 5×10^7 V/m are required. It must be possible to build such structures on a large scale using practical fabrication and processing techniques, and furthermore, the Q's and peak fields must remain stable in the environment of an operating accelerator. Some of the results reported here indicate that meeting this latter objective will not be easy.

TE_{011} Mode X-Band Measurements

The TE_{011} mode X-band cavities used at SLAC are cylindrical cavities, in which the internal length and diameter are both equal to 1-1/2 inches. Earlier cavities comprised three separate parts: a top plate (with coupling hole), a cylinder and a bottom plate. These were joined together by indium gaskets. Measured residual Q's ran from 5×10^8 to 5×10^9, while the magnetic breakdown fields were typically several hundred gauss. Changes in Q during a given run, and from one run to the next with the cavity remaining in place in the dewar, were not unusual. It was concluded that these changes were due at least in part to contamination being cryopumped by the cavity from the room temperature portion of the vacuum system, and that the addition of a low temperature vacuum window close to the cavity would be desirable. All measurements reported here were made with such a window in place. The cavity properties have, in fact, generally proven to be better and more stable with time since the window was added.

Table I summarizes measurements made on a particular TE_{011} mode cavity. The cavity cylinder and bottom plate were machined as an integral unit from a solid piece of reactor grade niobium (obtained from Wah Chang Albany Corporation). A flange at the top of the cylinder gave this assembly the appearance of a top hat, and hence the name. The top hat portion of the cavity was joined to the top coupling plate by an indium gasket in the initial tests. A typical measurement result for this cavity configuration is given in Table I (test #23). After these early tests, the indium joint was eliminated by machining off the flange and electron beam welding the cylinder to a new top coupling plate. Tests #26 and #28 show the results obtained after this change. For the first time at SLAC really satisfactory Q's and fields were obtained in a superconducting cavity.

TABLE I

Summary of Measurements on "Top Hat" TE_{011} Mode X-Band Cavity

Test Number	Cavity Status and Treatment	Unloaded Q at Low Power	Breakdown Field (Gauss)	Remarks
23	Cavity has indium joint. Test preceded by double etch-fire (2200°C)	3×10^9 (1.6°K)	385	
26	Cavity electron beam welded. Cleaned and refired (2200°C)	5×10^{10} (1.4°K) $Q_{res} > 10^{11}$	760	Q decreased to 1.5×10^{10} at breakdown (see figure)
28	Retest of #26	1×10^{11} (1.3°K)	780	
29	Exposed to N_2 for one hour	2×10^{11} (1.3°K) $Q_{res} > 5 \times 10^{11}$	780	
33	Exposed to air for 8 hours	1.5×10^9 (1.5°K)	405	Q increased with field (see figure)
34	Fired at 1000°C	1.5×10^9 (1.5°K)	245	Q nearly constant vs. field (see figure)
35	Fired at 2000°C. No etch	5×10^{10} (1.5°K) $Q_{res} > 10^{11}$	960	
36	Retest of #35	2×10^{10} (1.4°K)	835	Q nearly constant vs. field (see figure)
38	Fired in large furnace at 1950°C	2×10^8 (1.9°K)	10	Pathological behavior. Not typical magnetic field breakdown
39	Etched and refired (2000°C) in induction furnace	1.5×10^{10} (1.45°K)	340	Q decreased to 5×10^9 at breakdown
40	Etched only - no high temperature firing	3×10^9 (1.4°K)	160	Q decreased to 3×10^8 at breakdown (see figure)
41	Fired at 2000°C after test #40	5×10^9 (1.45°K)	270	Q increased slightly with field (see figure)

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The Q as a function of temperature for test #26 is shown in Fig. 1. The solid curve gives the theoretical Q, calculated using a computer program for the surface resistance written by J. Halbritter,[2] in the limit of diffuse reflection at the surface. The material parameters used in the calculation were: transition temperature T_c, 9.25°K; energy gap, 3.72 kT_c; coherence length, 385 Å; London penetration depth, 330 Å; mean free path, 10,000 Å. Error bars (± 10%) show roughly the magnitude of the random errors involved in the measurements. It is also apparent that systematic errors are present in the measured data. In particular, sufficient filling time was not allowed in making the measurements for some of the points shown, and the Q's for these points should be adjusted slightly upward. Taking this factor into account, the measured Q's are estimated to be 15% higher than the theoretical curve shown. By lowering the mean free path to 2000 Å, good agreement is obtained between the computed and measured Q's.

Figure 2 (bottom curve) shows the variation in surface resistance as a function of the peak RF magnetic field present around the middle of the cylindrical side wall for the cavity of test #26. The surface resistance in this and the following figures is an effective resistance which assumes that losses are distributed uniformly over the cavity surface. The dashed curve shows the variation in surface resistance to be expected on the basis of heating alone. The deviation of the experimental points from the calculated curve at lower field levels may or may not be significant, but at higher field levels the measured points indicate that there is a probable degradation due to surface heating. The problem of the effective thermal impedance for a niobium cavity wall composed of large crystals is discussed in a later section.

Test #29 in Table I shows the result obtained after exposing the cavity to room temperature nitrogen gas for one hour. It is seen that there has been no degradation in breakdown field, and that if anything, the residual Q has increased. This apparent improvement in residual Q must not be given too much weight. For residual Q's exceeding 10^{11}, factors such as the residual magnetic field and thermoelectric currents generated during cooldown may explain the observed variation. In any event, it can be concluded that exposure to pure nitrogen gas for a reasonable length of time does not degrade a previously good niobium surface.

Test #33 shows the result obtained after exposing the cavity to Stanford air for eight hours. The breakdown field has been degraded by a factor of two, while the residual Q has dropped by two orders of magnitude. In most of our measurements a similar coupling between residual loss and breakdown field has been observed, although by no means is this correlation precisely defined. The behavior of surface resistance as a function of field level is quite interesting for this test, as is seen in Fig. 2 and in more detail in Fig. 3. The surface resistance drops rather dramatically with increasing field, and there is a suggestion of a peak at about 15 gauss. A peak at B (gauss) ≈ 4 f (GHz) has been predicted by Halbritter,[3] as the result of surface states. At 10 GHz this peak should occur at about 40 gauss. However, Halbritter's calculation assumes the theoretical behavior for the superconducting surface; that is, the cavity is not in the residual Q region. For test #33 at 1.5°K, the surface resistance is clearly dominated by residual loss.

An attempt was next made to restore the cavity properties by firing at 1000°C. It was thought that this temperature would be sufficient to remove most surface contaminants, although it was known (e.g., see Dickey et al.[4]), that oxides are not removed from a niobium surface below a temperature of about 1800°C. The RF measurements (test #34) show that the cavity properties had, in fact, been further degraded. Changes in surface resistance with field level (top curve, Fig. 2) are not as pronounced as in the preceding test, although there is still a suggestion of a peak at about 50 gauss.

Our best TE cavity results, as far as breakdown field is concerned, were obtained after again firing the cavity at 2000°C (test #35 and #36). The surface resistance as a function of RF magnetic field is also plotted in Fig. 2 for test #36. Discounting the wiggles in the curve, which are comparable in amplitude to the accuracy of the measurement, the Q is nearly constant up to the breakdown field level (835 G). A leak developed during the latter stages of the test, and the cavity was disassembled and fired in the newly constructed all-metal furnace. The results after firing were extremely poor (test #38), and a later examination of the cavity showed a small metallic protuberance (an eruption from the niobium surface?) projecting into the coupling iris. The cavity was then etched and refired in the induction furnace with the result shown (test #39).

The next two tests (#40 and #41) give results after etching only (without firing), and then after subsequent firing, for this cavity. The improvement in Q and breakdown field was not dramatic, but the behavior as a function of field level was quite distinctive for the two cases. As seen from Fig. 4, the Q's are nearly the same at a field level of 5 gauss. The surface resistance of the etched-only cavity, however, increased rapidly with increasing field, while the surface resistance of the fired cavity remained nearly constant. Again, the suggestion of a resonant peak at about 20 gauss is present in the data for test #41.

At the conclusion of test #41 it was felt that the cavity properties had reached a limit imposed by unknown factors, and that further etching and firing was not likely to restore the former high Q's and breakdown fields. It was decided to perform an autopsy to see if there might be visual evidence of these limiting factors. The micrographs in Figs. 5 through 8 show the results. Figure 5, taken with strong side lighting on a piece of the cylindrical side wall, shows what appears to be several small pits scattered along a crystal boundary. Note also the textured appearance of the surface. Figures 6 and 7 show the cleft along the grain boundary at successively higher magnifications. It is evident that this fissure is considerably deeper than the pits. In Fig. 7 sharp whiskers can be seen projecting across the fissure, sometimes nearly touching one another. Figure 8 is a section normal to the surface, showing the subsurface erosion at one of the pits. All in all, the micrographs are suggestive of a rather unhealthy situation. Repeated cycles of etching and firing can apparently lead to the formation of pits, fissures and sharp projections in the fissures. Recent calculations[5] indicate that, in addition to the enhancement of the RF magnetic field at such surface perturbations, a strong electric field (displacement current) is induced by the gradient in the magnetic field near a perturbation. This induced field can act on any lossy contaminating dielectric layer near the projection to produce breakdown and residual loss.

TM_{010} Mode X-Band Measurements

Measurements have been made on two TM mode X-band (8.6 GHz) cavities to date at SLAC. The cavities are 1.06 inches in diameter by 0.37 inches in height, with 0.31 inch diameter cutoff tubes on each end. They were machined from solid material and electron beam welded from the outside.

Measurement results are given in Table II. The variation in surface resistance with field level for two of the tests is shown in Fig. 9. A distinctive feature of test #1 is a linear increase in resistance (or decrease in Q) with field. Such a linear variation in Q has been predicted by Rabinowitz,[6] based on a model in which this decrease in Q is due to highly localized heating near trapped flux quanta or other small normal state imperfections in the superconducting surface.

After test #3 it was felt that, because of the relatively poor results obtained with this cavity, an autopsy was in order. The outcome is shown in Fig. 10. It was found that

TABLE II

Summary of TM Mode X-Band Cavity Results

Test Number	Treatment	Unloaded Q at Low Power	Breakdown Field (Gauss)	Remarks
1 (Cavity #1)	Double etch-fire	8×10^7 at 1.5°K	105	Q decreased to 3×10^7 at breakdown (see figure)
3 (Retest of Cavity #1)	Re-etched and refired	1×10^9 at 1.44°K	205	Q decreased to 3×10^8 at breakdown (see figure).
4 (Cavity #2)	Double etch-fire	1.4×10^9 at 1.44°K	360	Pathological behavior at higher fields (multipactor ?)

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during welding the electron beam had pierced through into the cavity interior and that numerous small globules of niobium were spattered about over the inner cavity surface. Such a situation must obviously be avoided if good Q's and breakdown fields are to be obtained. Further measurements are in progress on a TM mode cavity with a redesigned weld joint.

Thermal Degradation

An increase in surface resistance at high field levels can result from both the inherent nonlinear properties of the surface and a temperature rise due to the total thermal impedance between the surface and the helium bath. A calculation using an expression due to Turneaure[7] gives an increase in resistance at breakdown by a factor of 1.4, as the result of the nonlinear component of the surface resistance, for the lowest curve in Fig. 2. The major part of the measured increase can be attributed to surface heating.

The total thermal impedance is the sum of three factors: the Kapitza resistance at the metal to liquid helium interface, the thermal impedance of the material in the cavity wall, and a possible thermal barrier for heat transfer away from the superconducting surface as described by Harrington.[8] This latter effect can be important when the mean free path for the carriers of thermal energy becomes comparable to the cavity wall thickness. Reflection of the thermal carriers at the surface reduces the efficiency of heat transfer within a distance from the surface on the order of a mean free path length. According to Harrington,[8] the effective thermal conductivity at a distance x from the surface for the case of diffuse reflection is

$$K(x) = K_0 \left[1 - \exp(-1.33\,x/\ell)\right] ,$$

where ℓ is the mean free path of the thermal carriers and K_0 is the bulk thermal conductivity. This relation is strictly valid only in the limit of zero heat flow, but the approximation should be reasonable for the small temperature differences encountered in a superconducting cavity wall. By integrating $dT = P(x)\,dx/K(x)$ from $x=0$ to $x=t$, where t is the cavity wall thickness, we can obtain an approximate expression for the temperature rise at the cavity surface (see Ref. 5 for a more detailed derivation)

$$\Delta T = (\Delta T)_0 \left[1 + 0.75\,(\ell/t)\,\ln(1.5\,\ell/\lambda_s)\right] .$$

Here λ_s is the superconducting penetration depth and (ΔT_0) is the temperature rise that would be expected in the absence of this effect. It is seen that considerable enhancement can take place when $\ell \approx t \gg \lambda_s$. As an example consider the case of niobium cavity at 1.5°K. At this temperature the thermal carriers are largely phonons. Assuming that the phonon mean free path is comparable to the crystal dimensions, which are in turn comparable to the cavity wall thickness, the preceding relation given an enhancement factor of 10 for $\ell = t = 5$ mm and $\lambda_s = 500$ Å. For $\ell = 1$ mm the enhancement factor is 2.5.

The data of Fig. 2 (test #26) indicates that the total thermal impedance is about 20°K/watt/cm^2. This number is too large to be explained by the bulk thermal conductivity for unstrained, large crystal niobium. One or more of the following factors might contribute to this increase in the thermal impedance: 1) the Kapitza resistance is considerably larger than expected,[9] 2) the nonlinear contribution to the surface resistance is larger than calculated, 3) the bulk thermal conductivity is decreased by strains, or 4) a surface enhancement in the thermal impedance as discussed here is taking place.

Conclusions

It has been shown, both at SLAC and HEPL,[10] that RF magnetic breakdown fields on the order of 1000 gauss and residual Q's on the order of 10^{11} can be obtained in properly processed X-band niobium cavities. At HEPL peak electric fields on the order of 70 MV/m have also been obtained[10] in TM mode X-band cavities. Thus it has been demonstrated that, under ideal conditions at least, high fields and extremely low losses can be realized in small test cavities. Experience so far at SLAC, however, indicates that niobium surfaces which have been etched and fired to give the best Q's and breakdown fields are also highly reactive. Exposure to air for even a short period of time seems to be detrimental. Further, the cavities cannot tolerate exposure to vacuum conditions considered good by conventional accelerator standards. It would be highly desirable to find a method for stabilizing the niobium surface against the deleterious effects of air and the contaminants typically present in conventional high vacuum systems.

In discussions at SLAC and with workers at BNL,[11] it has been suggested that a layer of niobium nitride (itself a superconductor) might provide the necessary protection against contaminants without significantly degrading the superconducting properties of the surface. Calculations indicate[12] that exposure to nitrogen gas at a pressure of 5×10^{-6} torr and a temperature of 400°C for 15 minutes should produce a nitride layer about 100 Å thick. Experiments are currently in progress to nitride a TE_{011} mode cavity using this procedure. If measurements show that this technique, or some modification of it, is not successful, then high priority will be given at SLAC to the search for alternative methods of surface stabilization.

Acknowledgements

The contributions of Mr. Hank Deruyter in all phases of processing, assembling, and measuring the niobium cavities are gratefully acknowledged. Dr. Mario Rabinowitz has added to our understanding of the basic physic of superconducting materials through many discussions. We want also to thank Mr. Gerald Fritzke for the fine micrographs in Figs. 5-8. Mr. Howard Martin and Mr. Bob Silvers have made substantial contributions to the microwave and cryogenic systems used for the cavity measurements. Mr. John Mohun has done an excellent job in machining the X-band niobium cavities.

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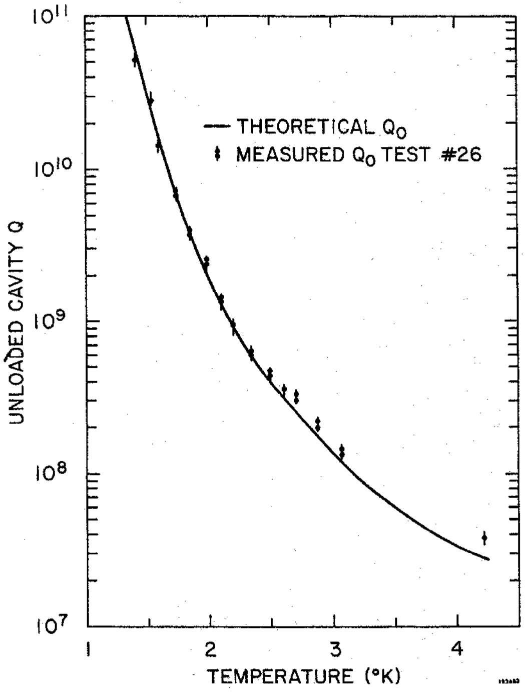

FIG. 1--Experimental and theoretical Q as a function of temperature for a TE_{011} mode X-band cavity at 10.48 GHz.

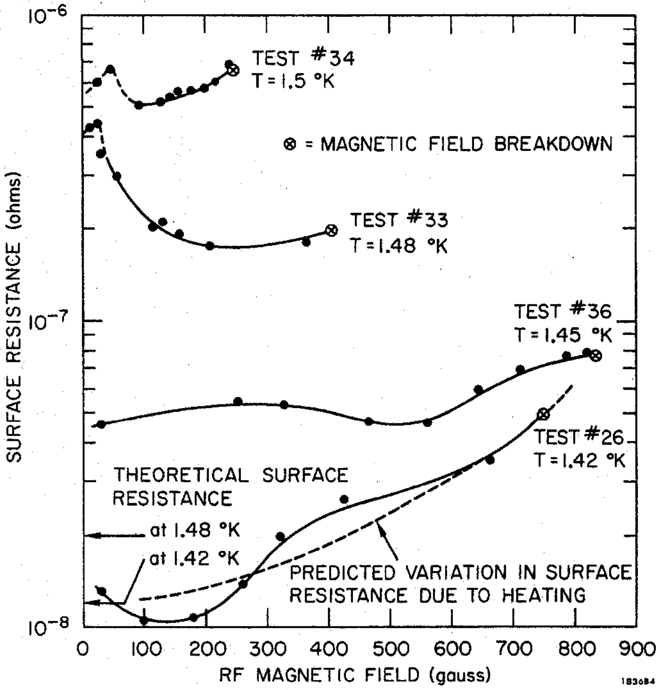

FIG. 2--Surface resistance as a function of RF magnetic field for TE_{011} tests #26, #33, #34 and #36.

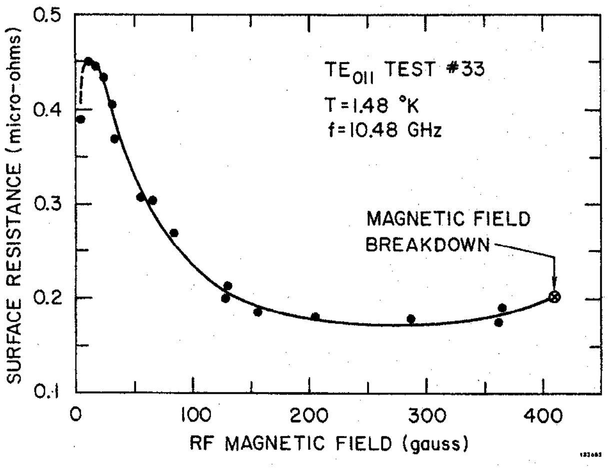

FIG. 3--More detailed plot of surface resistance as a function of RF magnetic field for TE_{011} test #33.

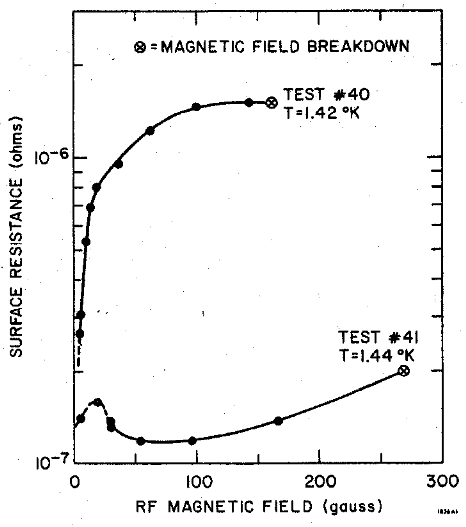

FIG. 4--Surface resistance as a function of RF magnetic field for TE_{011} tests #40 and #41.

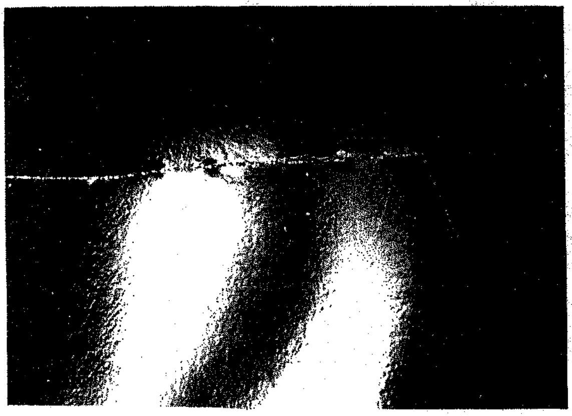

FIG. 5--Micrograph of grain boundary with pits from a section of the side cylinder of the TE_{011} top hat cavity. Magnification on original 35 mm negative is 3 X.

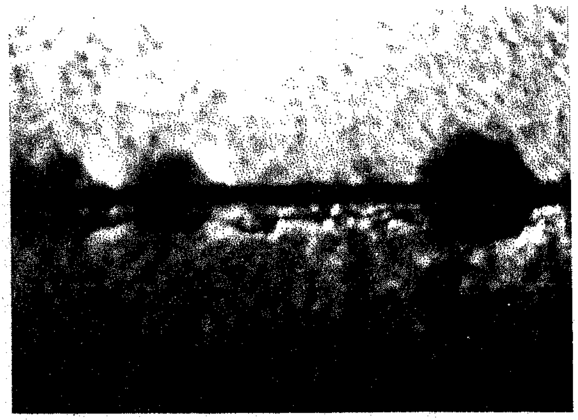

FIG. 6--Grain boundary with pits at higher magnification (17 X on original 35 mm negative).

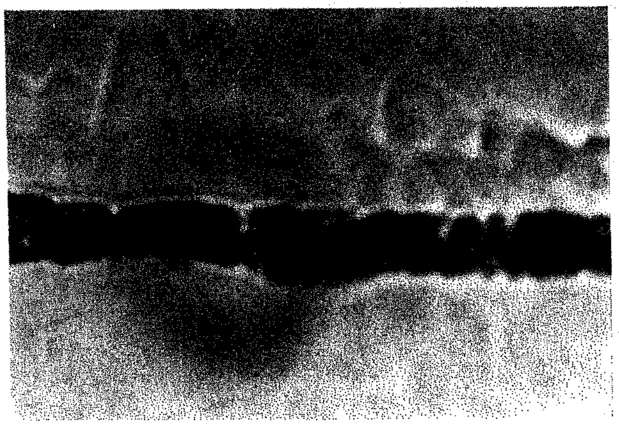

FIG. 7--Grain boundary at 68 X original magnification. Area covered by micrograph is about 0.3×0.5 mm. Outline of a pit is barely visible.

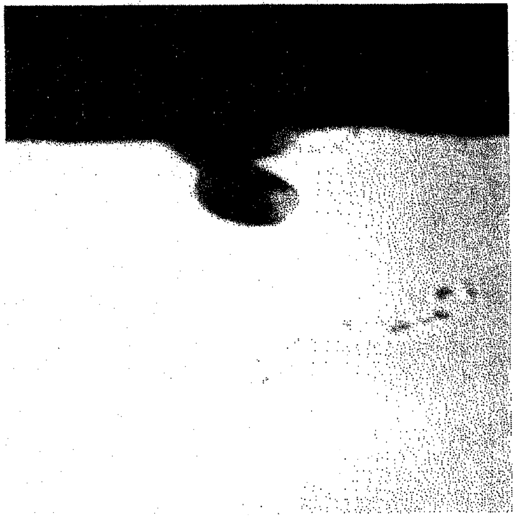

FIG. 8--Cross section showing erosion along grain boundary (168 X original magnification.

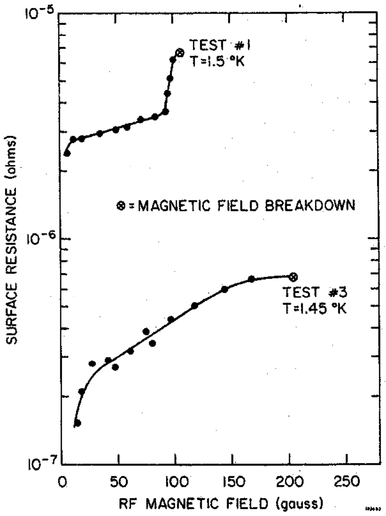

FIG. 9--Surface resistance as a function of RF magnetic field for two TM_{010} tests.

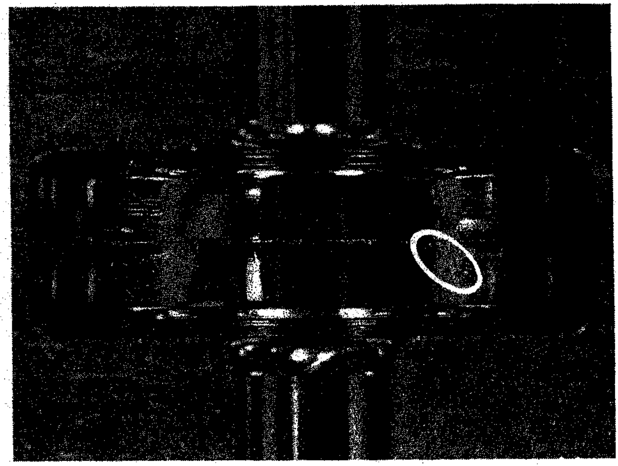

FIG. 10--Cross section of TM mode X-band cavity showing electron beam weld. Outlined area indicates niobium globules spattered on cavity wall.