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MEASUREMENTS AT SLAC ON SUPERCONDUCTING NIOBIUM CAVITIES AND STRUCTURES*

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Abstract

Tests are continuing at SLAC on superconducting niobium cavities and structures at S- and X-band frequencies. Peak electric and magnetic fields on the order of 20 MV/m and 400 G have been obtained in a TM mode cavity at 2.85 GHz with unloaded Q's at high fields on the order of 10^{10}. These fields and Q's are adequate for superconducting RF systems for high energy storage rings and recirculating linear accelerators.

A. Introduction

Long range plans at SLAC include the possibility of converting the present accelerator to a 100 GeV superconducting linac. The proposed energy gradient (33 MV/m) would require a traveling-wave resonant superconducting structure capable of sustaining peak RF electric and magnetic fields on the order of 55 MV/m and 1000 G. While fields of this order have been demonstrated in single cavities at X-band, formidable technological difficulties still remain to be overcome before the construction of a high-gradient accelerator on this large a scale can be realized. Recently, other SLAC improvement projects that might lead to applications of RF superconductivity in the more immediate future have been suggested. For example, it has been proposed[1)] that the energy and duty cycle of the SLAC accelerator be increased by storing the beam and then recirculating it a second time through the existing linac. This machine, termed a recirculating linear accelerator (RLA), would initially be constructed to store and recirculate the beam at 17.5 GeV. At present it is planned to use a conventional RF system, consisting of a 200 m length of disk-loaded accelerating structure, to provide an energy gain of 150 MeV per turn for the proposed RLA. Because of the rapid increase in synchrotron radiation loss with increasing recirculation energy, it is not practical to upgrade the RLA to the final design energy of 25 GeV using a conventional RF system. However, a superconducting RF system only 30 m in length would provide the required additional energy gain of 450 MeV per turn. The accelerating gradient would be 7.5 MV/m, assuming two passes per turn in opposite directions through a standing wave structure. The peak fields in the structure would be on the order of 340 G and 19 MV/m.

High energy storage rings are also under consideration at SLAC[2)] and elsewhere. In such an application an energy gradient on the order of 4 MV/m, requiring peak fields of about 180 G and 10 MV/m, would be satisfactory. The superconducting accelerator development effort at SLAC is now directed toward the development of superconducting structures which can meet the relatively modest energy gradients required by the RLA and high energy storage rings.

Until recently most of the superconducting cavity measurements at SLAC have been made at X-band. A summary of experimental results obtained to February of this year was recently published.[3)] Residual Q's exceeding 10^{11} and peak RF magnetic fields on the order of 1000 G were attained in a TE_{011} mode cavity operating at 10.5 GHz. Since this date measurements on X-band cavities have continued, but the principal measurement results have been obtained on S-band cavities and structures.

B. X-Band Tests

Although any superconducting accelerator or RF system constructed at SLAC will operate at S-band frequency (or lower), it remains convenient to test new ideas concerning materials or fabrication and processing techniques using small X-band cavities. A second electron-beam welded TE_{011} mode cavity, similar to the one which gave the good results reported previously,[3)] has been made. The initial test results were not outstanding (a residual Q of 5×10^9 and magnetic breakdown field of 240 G were obtained), but the behavior of the surface resistance as a function of field level was quite interesting (see Fig. 1).

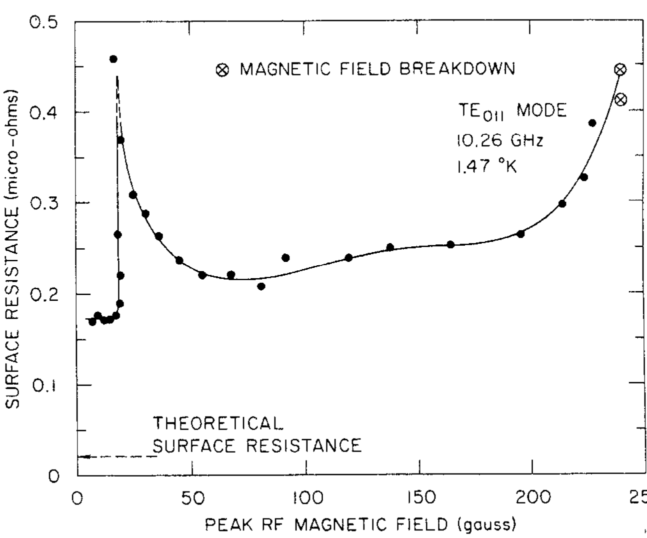

FIG. 1--Surface resistance as a function of RF magnetic field level for TE-mode X-band cavity (test no. 44).

As has been the case for most previous tests on X-band cavities operating in the residual loss region, a rather sharp increase in surface resistance by about a factor of two is observed at an RF magnetic field of about 20 G. In the case of the test shown in Fig. 1, the low field edge of the absorbtion peak is very sharp, while the high field edge is less so. Halbritter[4)] has suggested that increased absorbtion can be expected as the result of surface states at an RF magnetic field level given by H(G) = 4f(GHz), or at about 40 G for a frequency of 10 GHz. The shape of the peak in Fig. 1 can be explained by the fact that no increase in absorbtion takes place until the field reaches some critical level at the location of the maximum field within the cavity. If the resonance is sharp, the increase in loss will be sharp. As the field is increased further, however, other portions of the cavity gradually experience

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the loss enhancement but with decreasing effect on the total loss, which could lead to an asymmetric absorbtion peak having the form shown by the data in Fig. 1.

Two TM X-band cavities were fabricated and tested, but with very poor results ($Q_0 \approx 10^7$). It is felt that the low Q's are a result of either the technique used to electron-beam weld the cavity halves together, or the impurity content of the niobium. Tests are in progress to distinguish between the two possibilities.

C. S-Band Tests

An extensive series of tests was made at 2.85 GHz on the cavity shown in Fig. 2. The cavity was machined

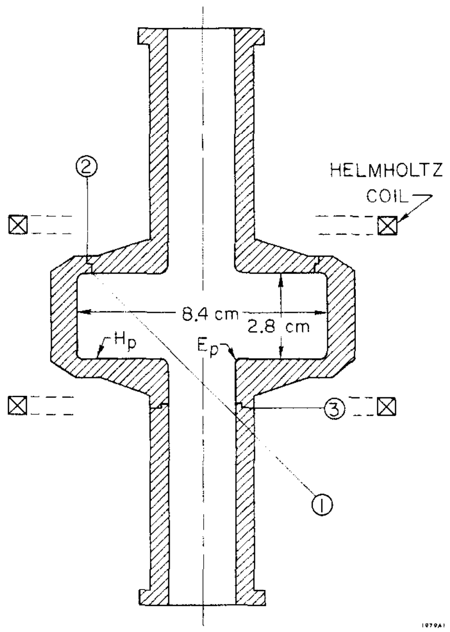

FIG. 2--TM-mode S-band niobium cavity. Numbers indicate location and order of electron-beam welds.

in three separate pieces from a solid bar of niobium. The pieces were then joined together by electron-beam welding using the welding sequence shown in Fig. 2. The locations of the peak electric and magnetic fields (E_p and H_p) are also shown. The fields were determined in terms of the unloaded cavity Q and power dissipation, using the LALA program[5)] adapted for the SLAC 360/91 computer, to be $H_p(G) = 1.08 \times 10^{-2} (Q_0 P)^{1/2}$, and $H_p/E_p = 18.4$ G/MV/m.

The experimental results obtained for this cavity are given in Table I (see next page). The results of all tests made on this cavity to date, successful or otherwise, are listed. Several tests can be singled out for more detailed discussion. Figure 3 shows the variation of surface resistance as a function of field level for the test in which the highest magnetic breakdown field was reached. In Table II the values of the Q and the peak fields are given. By processing at a peak electric field of about 20 MV/m, the Q was increased by about a factor of two. Peak magnetic and electric fields of 420 G and 23 MV/m were attained at magnetic field breakdown after processing. Radiation indicated the presence of field emission, however, and after some minutes of operation at field levels

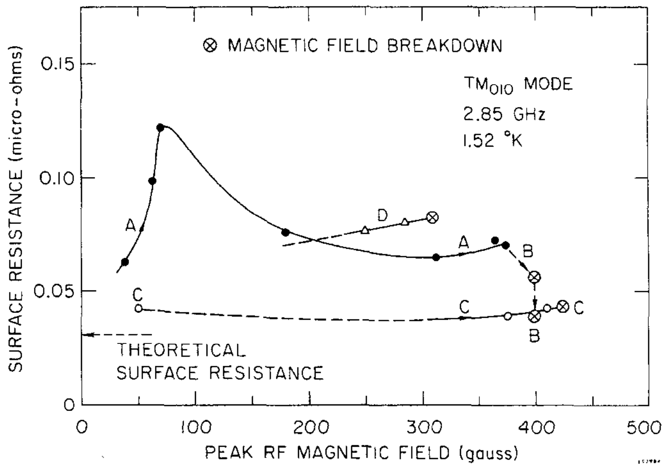

FIG. 3--Surface resistance as a function of RF magnetic field level for TM-mode S-band cavity (test no. 2). Curve A: initial application of high power. Curve B: decrease in surface resistance during processing. Curve C: behavior after processing. Curve D: behavior after Q degradation.

TABLE II

Measurement Results for TM Mode S-Band Cavity (Test #2)

	Q_0	H_p (G)	E_p (MV/m)	Remarks
Initial results at low power	3.2×10^9	40	2.2	
Results at high power before processing	2.9	374	20.3	Some radiation observed
Results after processing:				
Low power	4.8	50	2.6	
High power	4.6	424	23.1	Magnetic field breakdown
Results after Q degradation	2.4	311	16.9	Magnetic field breakdown

close to breakdown, the cavity suddenly experienced a degradation both in Q and in the breakdown field level. Subsequent cavity behavior was then stable at the new field level (310 G and 17 MV/m). Note also the peak in Curve A at about 70 G. The peak seems to be too far from the predicted field level to be explained by magnetic surface states.

Tests 11 through 14 give results obtained by cooling the cavity down in an external dc magnetic field applied using the Helmholtz coil mounted as shown in Fig. 2. The currents in the two coils were in opposition so that the applied field was radial and maximum at the surface of the cavity in the plane of symmetry normal to the cavity axis. Figure 4 shows the surface resistance as a function of the maximum applied d.c. magnetic field at the cavity surface, assuming that the field distribution does not change as the cavity goes superconducting. There is no simple way to measure the amount of flux which is actually trapped, or the distribution of the trapped flux over the cavity surface in the superconducting state. With this uncertainty understood Fig. 4 shows an attempt to determine the enhancement of the surface resistance due to the applied field. The total surface resistance (R_{tot}) can be considered to be the sum of a theoretical surface resistance,

TABLE I

Measurement Results for TM Mode S-Band Cavity (2848 MHz)

Tests	Q_0 at Low Power	Q_0 at H_p	H_p (gauss)	E_p (MV/m)	Remarks
1--After initial etch and high temperature firing.	6×10^8 (1.56° K)	2×10^8 (1.56° K)	140*	7.6	Cavity surface looks poor (dust and roughness). Some radiation.
2--Cavity re-etched and re-fired. See also Table II.	4.8×10^9 (1.54° K)	4.6×10^9 (1.54° K)	424*	23.1	Cavity underwent degradation during operation at E_p.
3--Cavity re-etched and re-fired.	----	4.7×10^9 (1.60° K)	45	2.4	Apparent helium leak limited field.
4--Cavity etched lightly and refired.	9.7×10^9 (1.52° K)	5.7×10^9 (1.52° K)	255*	13.9	
5--Repeat of previous test. Lower ambient dc magnetic field.	2.9×10^9 (1.52° K)	5.6×10^9 (1.52° K)	245*	13.3	
6--Cavity re-etched and re-fired.	$\approx 10^{10}$	----	---	---	Erratic behavior. Either poor rf connection or helium leak.
7--Cavity refired without etch.	1.8×10^{10} (1.49° K)	1.9×10^{10}	380*	20.7	
8--Repeat of previous test.	1.9×10^{10} (1.63° K)	2.3×10^{10} (1.63° K)	383*	20.8	Life test: cavity operated several hours at $H_p \approx 350$ G
9--Repeat of previous test.	----	1.7×10^{10} (1.79° K)	388*	21.1	Life test: ≈ 5 hours at H_p = 300-380 G
10--Helmholtz coil installed. H_{dc} = 1.5 mG	----	1.2×10^{10} (1.85° K)	388*	21.1	Life test: several hours at $H_p \approx 350$ G.
11--Cooled down in H_{dc} = 1G.	----	$1.6\text{-}2.7 \times 10^9$ (1.46° K)	170 - 280	9.2 - 15.2	Unable to reach breakdown field due to strong variation of frequency with rf field level.
12--Cooled down in H_{dc} = 300 mG.	1.1×10^{10} (1.57° K)	$1.1\text{-}1.7 \times 10^{10}$ (1.57° K)	390*-409*	21.2 - 22.2	
13--Cooled down in H_{dc} = 100 mG	1.5×10^{10} (1.49° K)	2.1×10^{10} (1.50° K)	386*	21.0	
14--Cooled down in H_{dc} = 30 mG	1.8×10^{10} (1.52° K)	$2.1\text{-}1.4 \times 10^{10}$ (1.51° K)	315 - 386*	21.0	
15--Attempt at nitriding. Exposed to N_2 for 24 minutes at 340° C and 8×10^{-5} torr.	5×10^8 (1.57° K)	6×10^8 (1.60° K)	205*	11.8	Nitriding done with poor base pressure (5×10^{-6} torr).
16--Repeat previous test.	----	5×10^8 (1.60° K)	186*	10.1	
17--Cavity exposed to air for 60 minutes	1.3×10^8 (1.50° K)	2×10^8 (1.50° K)	166*	9.0	
18--Cavity etched only, not fired.	1.8×10^9 (1.60° K)	1.1×10^9 (1.65° K)	208*	11.3	

* Indicates magnetic field breakdown.

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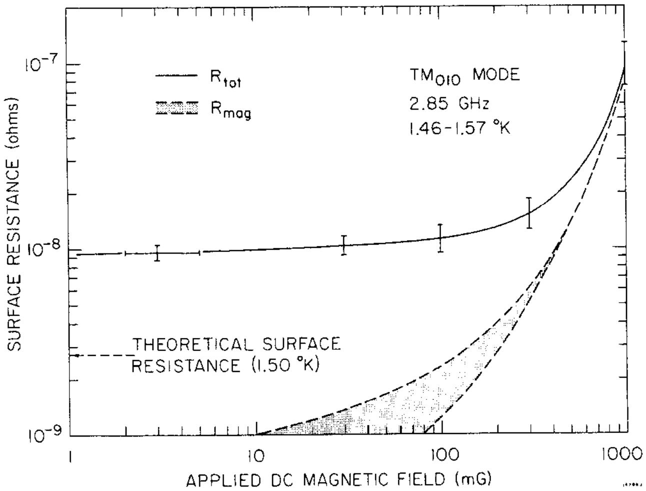

FIG. 4--Surface resistance as a function of applied d.c. magnetic field. Shaded area between dashed curves gives range for the additional residual loss due to the d.c. magnetic field.

plus a residual resistance due to nonmagnetic losses, plus a component (R_{mag}) due to the loss introduced by trapped magnetic flux. The result of subtracting the theoretical and nonmagnetic residual loss from the total loss is shown in Fig. 4. The total loss is shown by the solid line. Each experimental point is given as a range in surface resistance, since in addition to experimental uncertainties the surface resistance varies considerably with RF field level. The shaded area gives the range in R_{mag} obtained by subtracting total nonmagnetic surface resistances of 0.9×10^{-8} and 1.0×10^{-9} ohms. At high d.c. magnetic field levels, R_{mag} appears to vary approximately as $H^2_{d.c.}$. At low d.c. field levels, using the limits given by the shaded area in Fig. 4, the functional dependence of R_{mag} on $H_{d.c.}$ seems to lie between $H^{0.5}_{d.c.}$ and $H^{1.0}_{d.c.}$. Accurate and extensive measurements would be needed to pin this dependence down more precisely. However, from a practical standpoint, if a superconducting accelerator operating at 1.85° K is shielded against d.c. magnetic fields to a level of less than 10 mG, the loss enhancement by trapped magnetic flux should be negligible.

From Table II it is also seen that the presence of trapped d.c. magnetic flux did not result in a decrease in the RF magnetic breakdown field, at least up to $H_{d.c.}$= 300 mG. It was not possible to reach magnetic breakdown at $H_{d.c.}$ = 1 G because the cavity resonance became highly nonlinear; that is, the resonant frequency was strongly dependent on RF field level. The shift in resonant frequency was about $\Delta f = -40$ Hz at H_{RF} = 100 G, and appeared to be proportional to H^2_{RF}. At this field level the frequency shift was much greater than that produced by radiation pressure. This result can perhaps be explained if the effective volume of an oscillating fluxoid[6] increases with the amplitude of the oscillation.

A two cell disk-loaded niobium cavity (Tadpole II) is being tested. A drawing of the cavity is given in Fig. 5. As in the case of the TM mode S-band cavity, the structure was machined from solid material and electron-beam welded together as shown in the diagram. Two modes can be excited in the structure, a symmetric and an antisymmetric mode. In the symmetric mode the

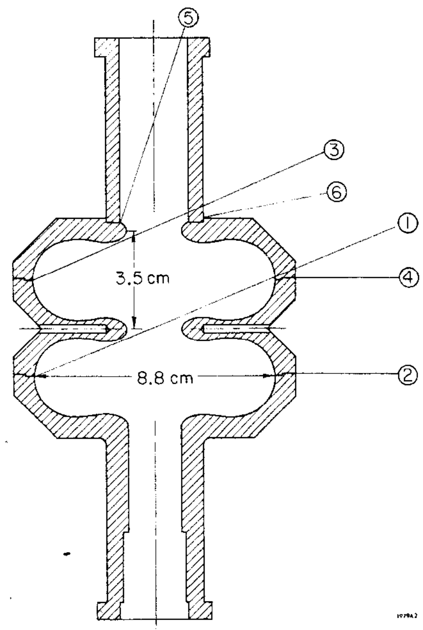

FIG. 5--Two cell niobium S-band test structure (Tadpole II). Numbers indicate location and order of electron-beam welds.

fields are in phase in the two cells (0-like mode), and the peak electric field at the surface is maximum at the shoulder of the cut-off holes. It is nearly as high on the bulgy part of the central disk, but very low at the very tip of the disk. In the antisymmetric mode the fields have opposite phases in the two cells (π-like mode), and the peak electric field at the surface occurs just off the tip of the central disk, although it is nearly as high at the shoulders of the cut-off tubes.

The general inability to reach 1000 G RF magnetic breakdown field at frequencies below X-band has not yet been satisfactorily explained. One possibility being explored at SLAC is that larger cavity structures are not cooled sufficiently uniformly through the transition temperature region. Thermoelectric voltages generated by the Thomson effect and the Seebeck effect (between adjacent crystals and across the boundaries between superconducting and normal regions) could give rise to large currents on the cavity surfaces with the concomitant trapping of magnetic flux. Pierce[7] has considered the problem in lead-plated copper cavities. Attempts are being made to cool S-band cavities very slowly, minimizing temperature gradients as the transition is made to the superconducting state.

D. Conclusion

The tests made at SLAC so far on a superconducting niobium S-band cavity are encouraging in that Q's and fields have been obtained which would be adequate for superconducting RF systems applicable to high energy storage rings and recirculating linear accelerators. However, many problems concerning the stability and reproducibility of cavity properties under the fabrication, installation and operating conditions required for a full scale superconducting linac remain to be solved. In particular, it would be highly desirable to find some method for stablizing the niobium surface against the degradation produced by oxygen and other potential contaminants, either by coating the surface or by reacting the surface with some material to form an inert surface layer. Such a layer, of course, must not result in an appreciable degradation in the cavity Q or breakdown field. Toward this end, work is in progress at SLAC to investigate the formation and properties of surface layers of niobium nitride and niobium carbide. The search will continue to find still other materials or techniques which might contribute to the production of a more stable surface under the conditions to be expected for an operational accelerator.

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