RECENT MEASUREMENTS OF S-BAND AND L-BAND CAVITIES AT STANFORD*

C. Lyneis, M. McAshan and Nguyen Tuong Viet

Department of Physics and High Energy Physics Laboratory

Stanford University
Stanford, California

Summary

Studies of S-band and L-band TM_{010} mode niobium superconducting cavities have been carried out to determine the mechanisms limiting microwave field levels in cavities and to test techniques for overcoming these limits. Electron loading is more prevalent in tests made at S-band and L-band than was found in earlier experiments at X-band. Peak surface electric fields as high as 35 MV/m in S-band niobium cavities and 22 MV/m in L-band niobium cavities have been achieved. Unloaded Q's greater than 10^{10} have been measured in both S-band and L-band cavities. In a 7-cell S-band structure, an effective accelerating voltage gradient of 6.5 MV/m and an unloaded Q of greater than 10^{10} were attained.

Introduction

S-band (2.85 GHz) and L-band (1.3 GHZ) TM_{010} mode superconducting niobium cavities are being studied in order to understand the mechanisms which limit electric and magnetic fields achieved in superconducting accelerators. Large differences between the performance of TM_{010} mode cavities at 8.5 GHz and the performance of TM_{010} mode cavities at 1.3 GHz have been reported earlier.[1,2,3,4] While peak surface electric fields of 70 MV/m were obtained at 8.5 GHz the highest surface electric field, E_p, reached at 1.3 GHz was 16 MV/m. Improvements made in niobium cavity processing have led to an increased E_p of 22 MV/m in a single-cell L-band cavity. In a single-cell S-band niobium cavity field levels as high as 35 MV/m have been attained. We have also tested a 7-cell S-band structure which attained $E_p = 23$ MV/m. While both thermal magnetic breakdown and electron loading contribute to the problems of attaining higher fields, experiments on cavities L-band - G and L-band - H indicate that the ultimate problem in TM_{010} mode L-band cavities is electron loading. In S-band TM_{010} mode cavities higher fields can be reached before electron loading becomes severe. In these S-band cavities sometimes electron loading and other times thermal magnetic breakdown limits the field level. An experimental technique for locating the position of thermal magnetic breakdown in S-band cavities is discussed later in the paper.

The test cavities have been fabricated by the same methods used to construct the superconducting accelerator at Stanford. This fabrication involves hydroforming niobium plates into cups, machining the cups, electron-beam welding the cups together, and ultra-high-vacuum firing.[4] A number of surface preparation techniques have been investigated including chemical polishing, electropolishing, mechanical polishing, anodizing, and ultra-high-vacuum firing.

Discussion of Results

A brief summary of some of the measurements made on S-band cavities at 2.85 GHz and L-band cavities at 1.3 GHz is shown in Table I. The highest surface magnetic field (H_p) achieved in an S-band cavity was 650 Oe which corresponds to $E_p = 35$ MV/m. This field level would give an effective accelerating voltage gradient of 12 MV/m. X-radiation of 2 R/hr was observed on an ionization gauge located outside the helium dewar 30 cm from the cavity. S-band - 7 had the lowest field emission at high fields of any of the cavities. In Test 3 of this cavity, surface fields of 500 Oe and 27 MV/m were achieved with a Q_o of 1.7×10^{10} and only 4 mR/hr radiation 30 cm from the cavity. For the L-band single-cell cavity measurements, the highest magnetic field at the surface achieved was 350 Oe and the highest surface electric field was 22 MV/m. The cavity produced more than 6 R/hr radiation 30 cm from the cavity.

Included in Table I are the results of tests on a 7-cell S-band structure which is basically an S-band version of the L-band capture section of the superconducting linear electron accelerator at Stanford. Recently the 7-cell S-band structure was operated at $H_p = 355$ Oe and at a Q_o of more than 10^{10}. The effective accelerating voltage gradient at this field level is 6.5 MV/m which is much higher than the 3.8 MV/m achieved at Stanford in a multi-cell L-band structure. The 7-cell S-band structure exhibited only 7 mR/hr radiation at a distance of 60 cm. It is significant that the first S-band structure achieved a considerably larger effective voltage gradient than that of any of the L-band structures.

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Electron Loading

The greatest difference between the performance of L-band cavities and that of S-band cavities was in the electron loading which occurred at high fields. While L-band cavities were limited to $E_p = 22.2$ MV/m by electron loading, $E_p = 35$ MV/m was attained in a S-band cavity. The electron loading and radiation observed appears to be caused by cold electron field emission taking place in areas of high electric field on the cavity walls. These electrons are then accelerated by the fields in the cavity and collide with the wall producing bremsstrahlung.[4] The onset of observable radiation, about 0.5 mR/hr, usually occurred at E_p of 10 to 12 MV/m. From Table I it is clear that in all the L-band cavities which reached an E_p of approximately 22 MV/m intense radiation, > 6 R/hr at a distance of 30 cm was produced, while in S-band - 7 $E_p = 30$ MV/m was reached with only 20 mR/hr radiation 30 cm from the cavity. S-band - 5 exhibited 2 R/hr radiation at 30 cm during Test 5 but only when the field level reached $E_p = 35$ MV/m. In Test 3 of the 7-cell S-band structure a field level of $E_p = 23$ MV/m was achieved with only 7 mR/hr radiation at 60 cm. It should be noted that the S-band 7-cell structure's surface area is 1.4 times that of L-band - G which produced 6 R/hr 30 cm from the cavity when the field level reached $E_p = 22$ MV/m. These experiments indicate that electron loading from field emission is not simply dependent on field level or surface area but also depends on frequency.

During Test 5 of L-band - G excitation of a higher frequency mode by electrons accelerated by field of the TM_{010} mode was observed. The frequency of the excited mode, thought to be TM_{020} mode, was 2.937 GHz, while the frequency of the TM_{010} mode was 1.326 GHz. The excitation of this mode occurred only when the field level in the TM_{010} mode reached $E_p = 20.6$ MV/m. At this field level there was strong electron loading and 7 R/hr radiation was measured 30 cm from the cavity. The time required to excite the second mode decreased as the field level in the main mode increased. The most probable explanation of this phenomenon is that an interaction develops between the electrons which are being accelerated by the TM_{010} mode and the electromagnetic fields of the TM_{020} mode.

Multipactoring levels were frequently observed in S-band and L-band measurements. The single-cell S-band cavities typically exhibited two multipactoring levels, one at E_p between 13.5 and 16.3 MV/m and another between 20 and 22 MV/m. In L-band - H similar multipactoring levels were observed at E_p of 7.8 MV/m and 11.2 MV/m. Generally when the coupling factor, β , was greater than 1 , those barriers could be overcome by increasing the power incident on the cavity for a few minutes. With fixed coupling probes and $\beta < 1$, it is difficult to couple in enough power to overcome these barriers. Comparison with calculations done by R. M. Laszewski[5] at the University of Illinois, indicated that the multipactoring levels which occurred at 7.8 and 11.2 MV/m were 3rd and 2nd order respectively.

Effect of Vacuum on Q_o Degradation

Degradation of Q_o for Nb cavities due to operation at field levels producing radiation has been reported earlier.[4] Experiments done on both S-band and L-band cavities now indicate that the Q_o degradation is related to the vacuum in the cavity at the time it is cooled to liquid helium temperatures. Two microwave coupling methods which affect the vacuum in the cavities have been used. Some of the tests have been done using an adjustable coaxial probe which was pumped by a 2 ℓ/s sputter-ion pump attached to the top of the dewar. In this system the cavity vacuum was in common with that of the probe, and before cool down the pressure was typically about 10^{-7} torr. The other coupling system which provided fixed coupling was a microwave coaxial probe with a ceramic window for vacuum. The cavity, after it was assembled to the fixed coupling probe, was pumped out with a sputter-ion pump while being baked at 100°C. After baking for 24 hours at 100°C, the system was cooled to room temperature and sealed by pinching off a copper tubulation. The vacuum at the time the cavity was sealed was typically 10^{-9} torr.

Tests 2 and 3 of L-band - G illustrate the effect that the two coupling methods had on cavity performance. In Test 2 L-band - G was mounted on an adjustable probe. The initial low power Q_o of 1.25×10^{10} degraded to 2.9×10^9 after 2 hours of measurements during which the radiation level varied from a few mR/hr to more than 2R/hr . In Test 3 L-band - G was assembled with a fixed probe and after it had been tested at similar radiation levels for comparable times, there was no degradation of its low power Q_o which was 2.4×10^{10} . Similarly in Test 5, S-band - 5 was run continuously for an hour with radiation of 50 to 100 mR/hr at 60 cm being emitted by the cavity, after which the low power Q_o was still equal to its initial value of 8.5×10^9.

Thermal Magnetic Breakdown

Considerable work has been done studying thermal magnetic breakdown in the S-band cavities at Stanford. This breakdown is typified by a sudden decrease in the cavity Q_o by a factor of 10^2 to 10^3 with the energy in the cavity being converted into heat in 1 to 10 μs . Since an S-band cavity at $H_p = 500$ Oe contains 0.2 joules, this means that a very strong heat pulse is sent into the helium. A method has been developed for locating where the thermal magnetic breakdown occurs. The heat pulses were detected by fifteen 56 Ω , 1/8 watt carbon resistors mounted on a device which held the resistors a few millimeters away from the cavity wall. The device could be rotated azimuthally around the cavity axis so that the location, size and shape of the hot spot could be measured. Figures 1 and 2 show the location of a typical hot spot and also the type of heat pulse detected by a resistor near the point of breakdown. Using this device we have located the point of breakdown in seven S-band tests, and in each test the breakdown was on the bottom disk as indicated in Fig. 1. The field level at breakdown was as low as $H_p = 150$ Oe in one test and as high as $H_p = 550$ Oe in another, but it always was on the bottom disk. There are two conclusions which can be drawn from these experiments. First, the electron-beam weld was not the cause of the thermal magnetic breakdown. Second, factors other than the type of surface preparation are involved in the determination of the breakdown location. The simplest explanation is that loose particles, which are on the bottom of the cavity, trigger the magnetic breakdown. It is also possible that during the transfer of liquid helium residual gas in the cavity condenses on the bottom disk.

Surface Preparation

Several surface preparation techniques have been tested. A combination of electropolishing, anodizing and ultra-high-vacuum firing has given the best results at S-band both in Q_o and fields. Anodizing and firing cavities was suggested by P. B. Wilson.[6] Typically the cavities were anodized with 100 V in a solution of NH_3, cleaned in hot distilled water and methanol, and then fired at 1800°C for 10 hours at 10^{-8} to 10^{-9} torr. Some work on electropolishing, anodizing and firing has been done on an L-band cavity but the results are comparable to those achieved by chemical polishing, anodizing and firing. The most successful chemical polishing solution used was 60% HNO_3 with 40% of 40% HF at - 10°C . The results given in Table I for Test 3 on L-band - G and Tests 2 and 3 on the 7-cell S-band structure were achieved using this polishing solution followed by anodizing and firing. Mechanical polishing by tumbling particles made of epoxy impregnated with line abrasive material has been used on 2 S-band cavities. It appears to be useful for removing spatter left by electron-beam-welding, but unncessary for cavities which are properly welded.

Conclusion

While at S-band both thermal magnetic breakdown and electron loading appear to be problems, the dominant problem in L-band cavities appears to be electron loading. S-band cavities have been operated at considerably higher fields than L-band cavities and with much lower radiation levels for comparable field levels. Electron loading is not only a function of the peak fields and the area of the cavities but seems to depend on frequency as well. Q_o degradation by radiation can be reduced by improving the vacuum in the cavities before they are cooled to liquid helium temperatures.

Acknowledgements

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TABLE I

SUMMARY OF S-BAND AND L-BAND NIOBIUM CAVITY TESTS

Cavity Test	T	Q_o max R	H_p E_p	Q_o at max field	Radiation	Treatment	Remarks
L-band - G f = 1.326 GHz Test 1	1.27°K	2.3×10^9 $5.9 \times 10^{-8}\Omega$	254 Oe 15.9 MV/m			Chem. Polished Fired	Adjustable Probe
Test 2	1.27°K	1.25×10^{10} $1.1 \times 10^{-8}\Omega$	272 Oe 17 MV/m	1.4×10^9	> 2 R/hr	Chem. Polished Fired with O_2 Introduced into furnace	Adjustable Probe Magnetic Breakdown
Test 3	1.27°K	2.4×10^{10} $5.7 \times 10^{-9}\Omega$	350 Oe 21.9 MV/m	1.2×10^9	> 6 R/hr	Chem. Polished Anodized Fired	Fixed Probe. Initially limited by electron loading, then limited by magnetic breakdown. Saw excitation of higher frequency mode

Cavity Test	T	Q_o max R	E_p H_p	Q_o at max field	Radiation	Treatment	Remarks
Test 5	1.27°K	3.2×10^{10} $4.25 \times 10^{-9} \Omega$	344 Oe 21.5 MV/m	1.2×10^{9}	7.3 R/hr	Chem. Polished Anodized Fired	Fixed Probe. Field limitation was electron loading. Excitation by electrons of a mode at 2.937 GHz
L-band - H f = 1.304 GHz Test 1	1.27°K	3.7×10^{10} $7.4 \times 10^{-9} \Omega$	326 Oe 22.2 MV/m	7.9×10^{8}	> 10 R/hr	Electropolished Anodized Fired	Fixed Probe. Electron loading Multipactoring at E_p = 7.8 MV/m and E_p = 10.6-11.4MV/m
Test 2	1.27°K	4.3×10^{9} $6.4 \times 10^{-8} \Omega$	245 Oe 16.7 MV/m	3.6×10^{8}	> 2 R/hr	Electropolished Anodized Fired	Fixed Probe. Electron loading Multipactoring at E_p = 7.9 MV/m and E_p = 11.2 MV/m . Saw excitation of higher frequency mode.
S-band - 5 f = 2.85 GHz Test 1	1.5°K	4.2×10^{8} 5×10^{-7}	308 Oe 16.7 MV/m	2.1×10^{8}	2 R/hr	Mechanically polished, fired mechanically polished electropolished	Adjustable probe Magnetic breakdown
Test 2	1.5°K	3.5×10^{9}	200 Oe 10.9 MV/m	1.7×10^{9}	None	Fired	Adjustable probe Magnetic breakdown
Test 3	1.5°K	5.15×10^{9} $4.1 \times 10^{-8} \Omega$	395 Oe 21 MV/m	2.75×10^{9}	150 mR/hr	Electropolished Anodized Fired	Fixed Probe Multipactoring at E_p = 12.7 MV/m and E_p = 17.6 MV/m Magnetic breakdown
Test 4	1.5°K	2.1×10^{8} $9.9 \times 10^{-7} \Omega$	130 Oe 6.9 MV/m	1.2×10^{8}	None	Anodized, Stripped Anodized	Adjustable probe Thermal Heating
Test 5	1.5°K	1.1×10^{10} $1.9 \times 10^{-8} \Omega$	650 Oe 35.3 MV/m	1×10^{9}	2 R/hr	Electropolished Anodized Fired	Fixed Probe. Initially limited by electron loading later by magnetic breakdown. Multipactoring at E_p = 15 MV/m and E_p = 20.5 MV/m
S-band - 7 f = 2.85 GHz Test 1	1.5°K	1.8×10^{9} $1.15 \times 10^{-7} \Omega$	265 Oe 14 MV/m	1.67×10^{9}	None	Fired, electropolished anodized and stripped	Adjustable probe Magnetic breakdown
Test 2	1.5°K	2.8×10^{9} $7.4 \times 10^{-8} \Omega$	310 Oe 16.6 MV/m	4.7×10^{8}	40 mR/hr	Anodized and stripped several times, anodized and fired	Fixed Probe. Magnetic breakdown with much electron loading
Test 3	1.5°K	2.3×10^{10} $9.1 \times 10^{-9} \Omega$	550 Oe 30 MV/m	7.4×10^{9}	20 mR/hr	Electropolished Anodized Fired	Fixed Probe Magnetic breakdown $Q_o = 1.7 \times 10^{10}$ at H_{max} = 500 Oe Multipactoring at E_p = 15.2 MV/m and E_p = 22 MV/m

Cavity Test	T	Q_o max R	E_p H_p	Q_o at max field	Radiation	Treatment	Remarks
Test 4	1.5°K	2.3×10^{10} $9.1 \times 10^{-9}\Omega$	425 Oe 23 MV/m	1.8×10^{10}	3 mR/hr	Cavity left at room temperature for 1 month under vacuum	Fixed Probe Magnetic breakdown Multipactoring at E_p = 15.2 MV/m
7-Cell S-band Structure f = 2.851 GHz Test 1	1.5°K	4.3×10^{8} $4.3 \times 10^{-7}\Omega$	113 Oe 7.3 MV/m	1.2×10^{8}	None	Fired, chemically polished, fired	Adjustable probe Magnetic breakdown
Test 2	1.5°K	8.16×10^{9} $2.25 \times 10^{-8}\Omega$	243 Oe 15.7 MV/m	3×10^{9}	None	Chemically polished, anodized, fired	Fixed Probe Magnetic breakdown
Test 3	1.5°K	1.6×10^{10} $1.15 \times 10^{-8}\Omega$	356 Oe 23 MV/m	-	7 mR/hr	Chemically polished anodized, fired	Fixed Probe Magnetic breakdown

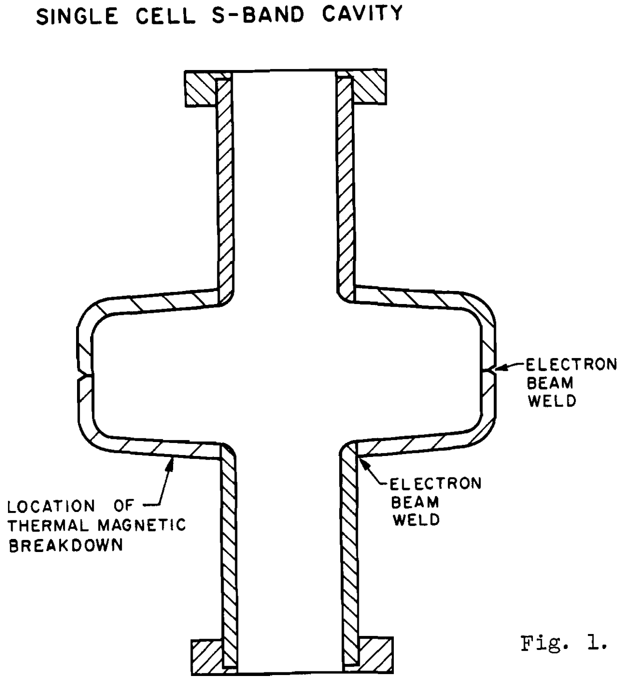

Fig. 1. Schematic drawing of an S-band cavity showing the typical location of thermal magnetic breakdown.

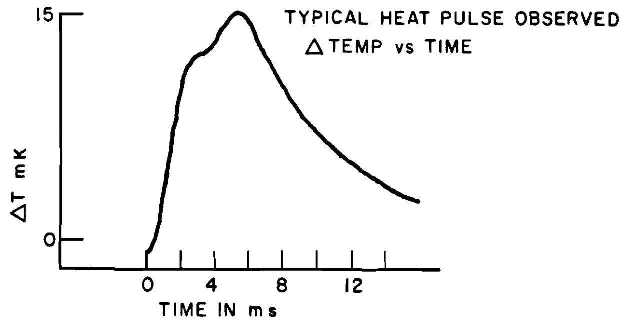

Fig. 2. Typical heat pulse observed by a carbon resistor located a few millimeters from point of thermal magnetic breakdown.

DISCUSSION

Citron, Karlsruhe: Are the Q's in the table measured at low field, or at the peak fields given?

Lyneis: All except the third were the low-field value.

Klein, Frankfurt: You measured the x-ray spectrum from your cavity. The peak energy is higher than expected. Can you comment?

Schwettman, Stanford: Experiments were done by John Turneaure. They showed that the x ray spectrum had components as high as three times the voltage applied across a single cavity. We thought the only possible solution was that electrons had a high back-scattering cross section. However, recently an alternative explanation is that there may be orbits where the electron can pick up more than the maximum cavity voltage.

Leiss, NBS: Of course, I don't know that such orbits exist, but what exists is an oscillating magnetic bottle and this is a reasonable possibility.

Bollinger, ANL; Do you have positive evidence that you are limited by field emission in all cases?

Lyneis: Yes. One starts to see a decrease in Q at the same time the x-ray level increases. These can be plotted and seem to follow.

Blewett, BNL: Can you turn the test cavity over and see if it still breaks down on the same side?

Lyneis: Yes, but we have not yet done that particular experiment.