SLAC-PUB-3074
March 1983
(A)

TRANSIENT HIGH-FIELD BEHAVIOR OF NIOBIUM SUPERCONDUCTING CAVITIES*

I. E. CAMPISI, Z. D. FARKAS, H. DERUYTER, AND H. A. HOGG
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Summary

Tests have been performed on the breakdown behavior of a TM_{010} mode, S-band niobium cavity at low temperatures. Unloaded Q's of 9×10^7 at 4.2 K and of 7×10^9 at 1.35 K were measured during several tests performed using pulses long enough for the cavity to reach steady state. The breakdown field at 1.35 K was increased from 15 to 20 MV/m by processing the cavity at room temperature using 1 MW, 2.5 μs pulses. The response of the cavity at 4.2 K to 1 MW, 2.5μs pulses was also tested in several cool-downs. In these tests the cavity was heavily overcoupled to lower its time constant to a value of 0.80 times the RF pulse length of 2.5 μs. This condition maximizes the energy transfer from the klystron source to the cavity. Measurements made during these experiments clearly indicated that fields of about 50 MV/m were being reached in the cavity without breakdown.

Introduction

The application of superconducting cavities in accelerator technology has been limited so far, mainly because their use in CW accelerating structures encounters difficulties in carrying away average power dissipated on the cavities inner surfaces. This problem limits the achievable powers to levels below what the critical fields would allow. In order to decrease the average power effects and to approach the theoretical critical field limits, operation in the pulsed mode is required. This method could be used in high-gradient superconducting accelerator structures operating with very short beam pulses.[1]

Preliminary high-power pulsed tests on a Nb TM_{010} cavity operating at 2856 MHz have been performed over the past several months. The apparatus included a coaxial coupling probe which was not designed for operation at high power and which, we believe, might have limited the peak fields reached in the cavity. This cavity was built and previously tested in 1971: quality factors of up to 2.6×10^{10} and peak surface electric fields up to 23 MV/m were then reported. The recent measurements were performed with a short RF pulse length. The expressions for the cavity fields normalized to the incident field, stored energy, peak surface electric field and power dissipation as a function of cavity parameters when operating in the pulsed mode are given in Ref. 2.

Experimental Apparatus

The apparatus used in the high power testing of the niobium TM_{010} cavity is illustrated schematically in Fig. 1.

The vacuum system included a Residual Gas Analyzer (RGA) which was used to monitor the composition of ions outgassed from the cavity surface during the application of high-power RF pulses.

The average power dissipated by the superconducting cavity, P_{ad} was determined by measuring the helium boiloff rate with a laminar flow element and a U-tube manometer. This system had a resolution of 0.02 l/hr, which corresponds to a difference in the power deposited into the bath of approximately 15 mW. P_{ad} is inversely proportional to Q_0 for high Q_0 and can be used to determine it. To obtain an expression for P_{ad}, we integrate the instantaneous dissipated power and obtain U_d, the energy dissipated during a period. If Q_0 is much greater than $Q_e = 2.5 f T_p$, (which is the value of Q_e for maximum pulse energy transfer into the cavity), then

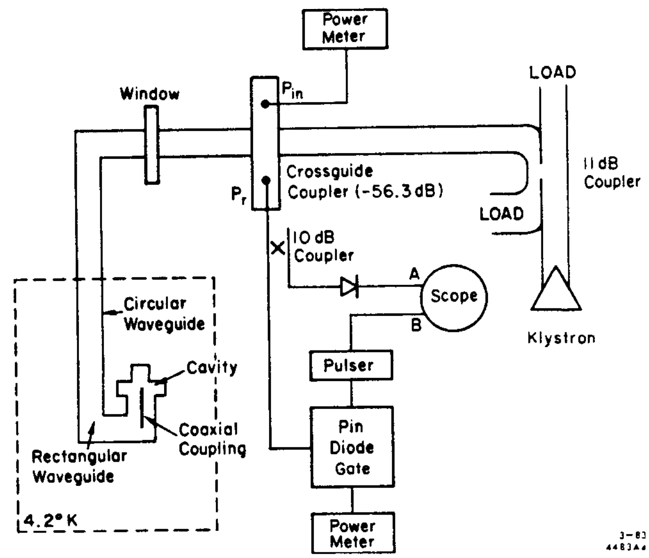

Fig. 1. Microwave network for the gated measurements.

$$\frac{U_d}{U_i} = \frac{7.46 \times 10^4}{Q_0} \tag{1}$$

U_i, the incident pulse energy, is the product of peak power P_i and pulse length T_p. This energy ratio is also the ratio of the average dissipated power to the average incident power, P_{ai}, so that we can express Q_0 as

$$Q_0 = 7.5 \times 10^4 \frac{P_{ai}}{P_{ad}} \tag{2}$$

The average incident power can be measured with a power meter.

A standard SLAC klystron was used to generate a 2.5 μs long, 24 MW maximum peak power pulse. The power from the klystron was divided using a high-power coupler which provided 11 dB of decoupling (see Fig. 1). The power was finally transmitted through the UHV cryogenic transmission line to the cavity.

The cavity was operated at variable pulse repetition frequencies (PRF) between 20 and 360 pps in order to discern between average heating effects and peak field effects. A variable-frequency, variable-PRF source was used to excite the cavity both at room temperature and at 4.2 K.

Part of the reflected power (10 dB down) was detected with either a crystal diode, or with a receivers, (linear or logarithmic), and the pulse observed on a scope (Figs. 2 and 3). Theoretical curves of reflected power and log of reflected field versus time are shown in Figs. 4 and 5. The rest of the reflected power was sent through a PIN diode modulator to a power meter.

The PIN diode modulator was used to gate the power pulse so as to allow various portions of it into the power meter. In particular, we could separate and measure the power emitted from the cavity after the end of the klystron pulse. From the measurement of this average power, the peak surface electric field in the cavity is obtained as follows.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Contributed to the Particle Accelerator Conference
March 21-23, 1983, Santa Fe, New Mexico

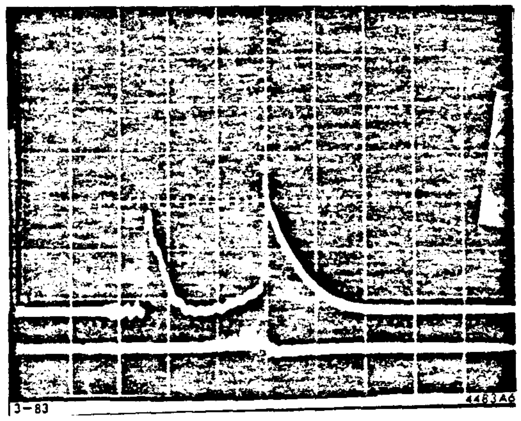

Fig. 2. Reflected power pulse with correlated X-ray output.

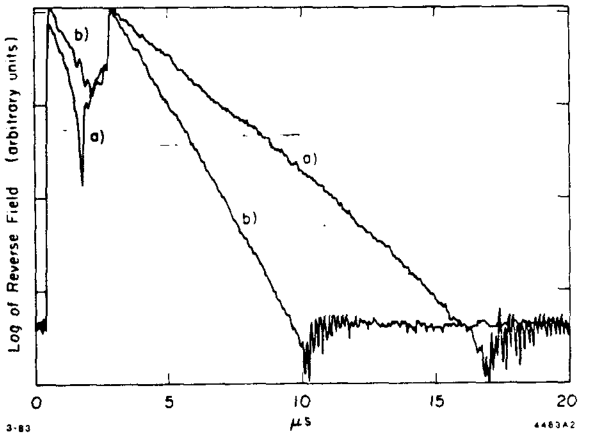

Fig. 3. Reflected power detected with logarithmic amplifier. a) Before breakdown, b) At breakdown.

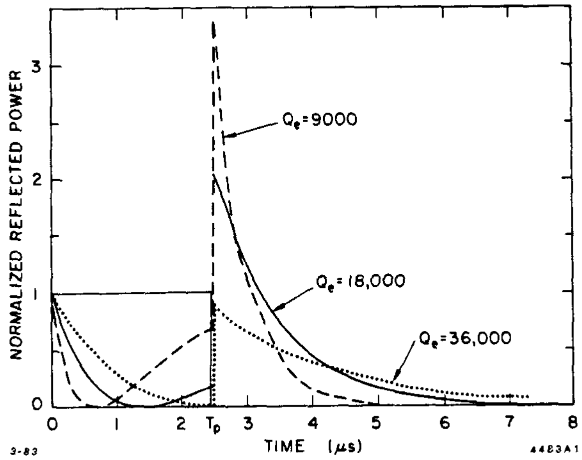

Fig. 4. Reflected power versus time at high Q_0.

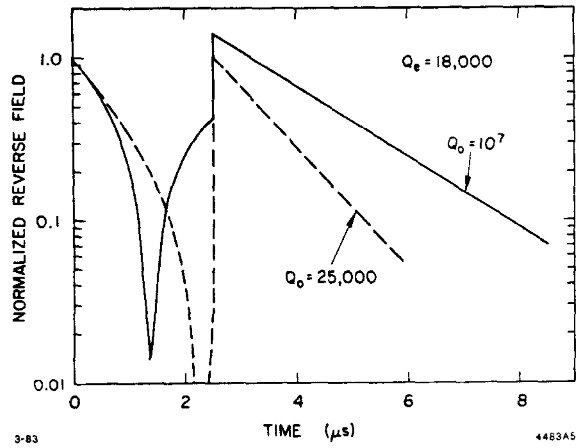

Fig. 5. Log of reflected field versus time at optimum Q_e.

The emitted energy during discharge is $U_e = P_{em}/(PRF)$, from which we obtain the energy stored in the cavity at the inception of discharge

$$U_s = U_e + U_e\frac{Q_e}{Q_0} = U_e\frac{Q_e}{Q_L} = \left(\frac{P_{em}}{(PRF)}\right)\frac{Q_e}{Q_L} \quad (3)$$

The peak surface electric field E_s is proportional to the square root of the stored energy. The proportionality constant was obtained from SUPERFISH[3]: $E_s = 76\sqrt{U_s}$ MV/m.

Results of the Measurements

Preliminary measurements were performed at low power both at 4.2 K and at 1.35 K with a pulse length much longer than the cavity filling time. During those runs Q_0 at 4.2 K was 9×10^7, while at 1.35 K it varied between 4 and 7×10^9. The data indicated that Q_0 slightly but systematically increased with the surface field in the cavity, up to the point where thermo-magnetic breakdown took over. This breakdown occurred at power levels corresponding to a CW surface electric field of 15 MV/m.

After these measurements the cavity was subjected to a series of high-power, room-temperature runs (RF processing) with pulses of up to 800 kW peak power and repetition rates adjusted in such a way that the indium vacuum seals at the ends of the cavity cutoff tubes would never exceed a temperature of 100°C. Intense outgassing was observed, together with strong X-ray emission. The cavity was then tested again at low power: the CW breakdown field had increased from 15 to 20 MV/m.

A short high-power test was then performed to determine the breakdown fields in the pulsed mode at 4.2 K. The breakdown field was determined by measuring the emitted average power at the threshold of the sudden increase in the helium boiloff rate. The maximum peak surface field was 50 MV/m but with an unknown error. After this preliminary set of measurements the experiment had to be interrupted for several months due to the unavailability of the high power klystron.

A more complete series of measurements was performed recently on the same cavity, with a sensitive helium-flow measuring apparatus installed. The breakdown was determined as the sudden decrease of the average emitted power as a function of the incident power (quantities which are independent of the model adopted for the losses). We separated two different regimes of operation. The low repetition rate regime is one for which the emitted power deviates from the linear dependence at "breakdown" but the deviation is such that the P_e versus P_i curve remains reversible. Beyond a certain power level an irreversible hysteretic behavior of the curve is observed. This constitutes a second, final breakdown in which the losses are too large for the system to recover into the low-loss regime from pulse to pulse. Instead, an intermediate loss condition is observed. The high repetition rate regime is one for which the emitted power suddenly drops when the incident power reaches a critical value: this point is taken as the breakdown level and it can be determined quite accurately (see Fig. 6).

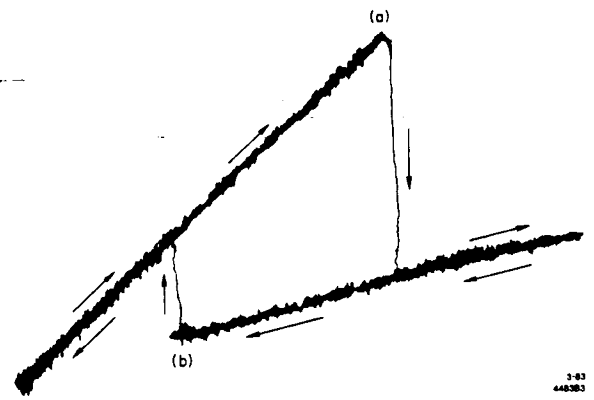

Fig. 6. Experimental curve of P_e versus P_i for high PRF.

The $P_e - P_i$ curve has in this case a very strong hysteretic behavior and the interpulse time is shorter than the thermal relaxation time of the loss phenomenon, so that the cavity is still in the high loss state when the next pulse is delivered. The crossover repetition rate, at which one regime turns into the other, is at about 80-90 pps for our system, which indicates that the relaxation time of the thermal process is of the order of 10-12 ms.

The breakdown field level was determined through several measurements of P_e at the point (a) of Fig. 6. From these measurements we determined the peak surface field to be about 48-50 MV/m in the high repetition rate regime, and 49-52 MV/m in the low PRF regime. This peak surface electric field corresponds to a peak surface magnetic field of approximately 950 G, as determined using SUPERFISH.

The helium boiloff was measured right before breakdown in both regimes and it was equal to or less than the resolution available with the laminar flow element manometer. We determined that the unloaded Q was $\geq 5 \times 10^7$.

Since the variable-coupling system was not designed for high power performance (it includes a sliding contact in the coaxial transmission line), the possibility was not ruled out that the breakdown could have been caused or initiated by some phenomenon occurring at the transmission line cavity interface. This hypothesis is also supported by the observation of the behavior of thermometers and the X-ray detector monitoring the system.

Resistor thermometers were placed on a constant-azimuth plane, so that very little sensitivity to "bad spots" was possible. On the other hand, true maximum field breakdowns could be detected, since they should exhibit an axial symmetry. Resistors were placed also on the cutoff tubes and at the locations of the welds, as well as at the brazed joints of the crossbar which supports the coaxial line's center conductor. Since the last two inches of this center conductor are made of niobium, the surface of which is subjected to the coaxial-line fields as well as to the cavity fields (the cavity is strongly overcoupled), it is possible that parts of this niobium tip could break down thermally and not recover due to the long thermal path to the helium bath.

In order to monitor the emission of X-rays in phase with the microwave pulse, a fast scintillator-phototube detector was employed. Fig. 3 shows the output of the X-ray detector which correlates the onset of the X-ray emission not with the time of maximum fields in the cavity (which happens at the end of the klystron pulse), but with the point of zero reflected power during the pulse (which corresponds to a completely forward travelling wave, and therefore to maximum travelling fields in the transmission line). As a function of input power, thermal breakdown was always preceded by X-ray emission which, at least at the beginning of breakdown, was confined to the "on" part of the pulse.

Conclusions

The measurements performed on a single S-band TM_{010} niobium cavity prove that by operating in the pulsed mode, peak surface fields can be reached which exceed the typical CW fields by a factor of three. That is, the surface fields can be increased from 15-20 MV/m up to 50 MV/m. The presence of strong X-ray emission seems to point to indirect electron heating as the cause of the breakdown rather than to peak surface magnetic field effects. It should be noted also that the cavity was not designed for good heat transfer across the thick walls. On the basis of these observations we believe that it should be possible to reach even higher peak surface fields on niobium with a properly modified coupling to the cavity. Steps being taken in this direction should allow us to give, within a few months, an answer to the question of whether the theoretical peak surface fields on superconductors can be approached without significant losses. If indeed the breakdown was not directly related to the peak magnetic field, it is possible that higher peak fields may be reached in niobium cavities.

Acknowledgements

The Authors would like to thank Mr. Jerry Zamzow, who painstakingly assembled and maintained in perfect working order the complicated measurement system, and the personnel of the SLAC Klystron Department for the support given during the high-power measurements.

References

1. Z.D. Farkas, IEEE Trans. Nucl. Sci. 1983 Applied Superconductivity Conference, to be published.
2. Z.D. Farkas, IEEE Trans. Nucl. Sci. NS – 28, 3242, 1981.
3. K. Halbach and R.F. Holsinger, Particle Accelerators, 1976, Vol 7, pp 213-222.