VOLTAGE BREAKDOWN AT X-BAND AND C-BAND FREQUENCIES

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Summary

Economy of length and electric power in the design of future linear accelerators requires a knowledge of the electric field breakdown limits in RF structures as a function of frequency. The limits predicted by the Kilpatrick breakdown criterion, which gives a law of maximum surface electric field increasing with frequency, have already been exceeded at frequencies under 1 GHz and S-band (3 GHz). The work described here explores these limits at 5 and 9 GHz in single cavities. Experimental setups, procedures and results are presented.

Introduction

In the design of high gradient accelerator structures (accelerating gradients over 100 MV/m) for high energy physics linear colliders, or for medical and industrial applications where space is limited, voltage breakdown becomes a major constraint. Recently, the authors of this paper have separately conducted a series of breakdown experiments at S-band frequencies and have obtained maximum surface electric fields in excess of 300 MV/m for a few μsec pulsed operation.[1,2] These results indicate that the maximum surface electric field for well prepared OFHC copper in a clean environment can exceed six times the "Kilpatrick breakdown criterion."[3] It is of interest to investigate the breakdown threshold level at even higher frequencies since the criterion states that the maximum field increases with the operating frequency. Moreover, there are other advantages of using higher frequencies for accelerators, i.e., higher shunt impedance per unit length, smaller diameter, and shorter filling time.

Figure 1 shows the Kilpatrick criterion with several recent experimental results obtained by various investigators, shown in Table 1.[4,5,6] These experimental studies also indicate that the breakdown threshold level increases with the frequency.

In order to study the breakdown threshold further, new C-band (5000 MHz) and X-band (9300 MHz) cavity breakdown test setups have been developed. The RF cavities for these experiments are similar to that of the S-band setup reported on two years ago. In this paper, the new experimental setups, procedures and some results are presented.

Experimental Setup and Procedure

Figure 2 shows a cross-sectional view of a demountable, single cavity, C-band breakdown system. The test cavity was made from OFHC copper. In order to obtain good RF contact as well as to eliminate any gap between the cavity and copper plated stainless steel end plate, a knife-edge was introduced at the inner diameter of the cavity. The test cavity was clamped with six bolts torqued to 100 inch-pounds. The indium gasket placed at the outer diameter of the cavity was used for maintaining vacuum. This new technique of separating the RF and contact vacuum seal worked fairly well. A 2 liter/sec vacuum ion pump was

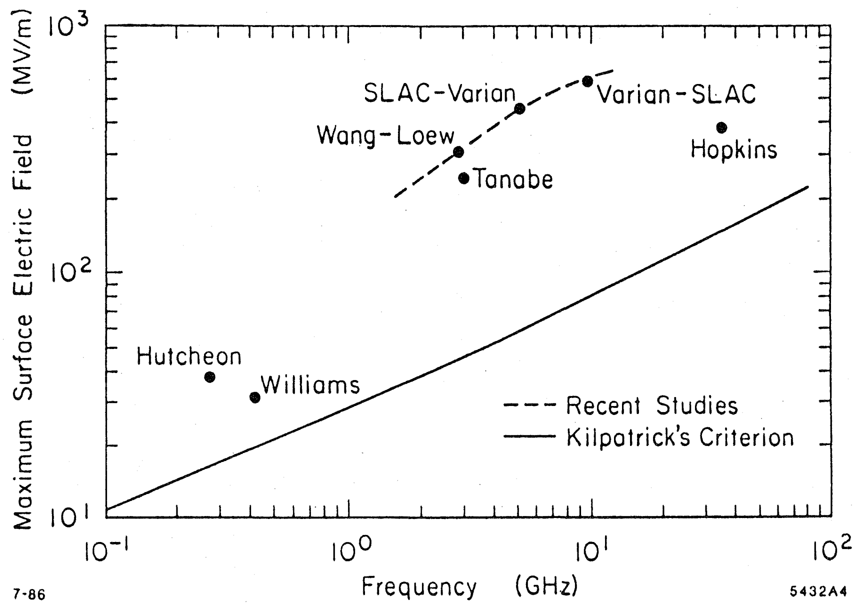

Fig. 1. Kilpatrick breakdown criterion and some experimental results.

Table 1. Summary of experimental study of breakdown on copper electrodes.

Investigators	Frequency (MHz)	Pulse Width (μsec)	Breakdown Threshold (MV/m)	Ratio to Kilpatrick Criterion
Nikolaev (USSR)	23.6	750	80	11.3
Hutcheon (AECL)	270	CW	38.2	2.3
Williams (LASL)	425	100	32.2	1.6
Wang-Loew (SLAC)	2856	2.5	312	6.7
Tanabe (Varian)	2997	4.5	240	5.1
Hopkins (LBL)	35000	0.01	380	2.6

installed at the cavity to increase the vacuum conductance. Table 2 shows the half-cavity parameters computed by the SUPERFISH program for the X-band and C-band frequencies.

After careful machining, inspection of surface and cold test, the test cavity was chemically cleaned (vapor degrease, alkali soak, cyanide bath, and water and methanol rinse) and assembled in a clean room. After the system was pumped down to 10^{-7} Torr, the RF processing started. The test cavity was first excited to a very low peak power level (0.4 MW) at a relatively high repetition rate for a few hours. By keeping the cavity pressure level below 10^{-6} Torr, RF processing was slowly carried out by gradually increasing the peak power level and repetition rate. C-band and X-band coaxial magnetrons, VMC-1288 (4998 MHz) and SFD-303B (9300 MHz), were used as RF sources. The peak power was varied from 0.2 MW to full power by varying the anode current for both magnetrons. Forward and reflected powers were monitored through 50 dB calibrated directional

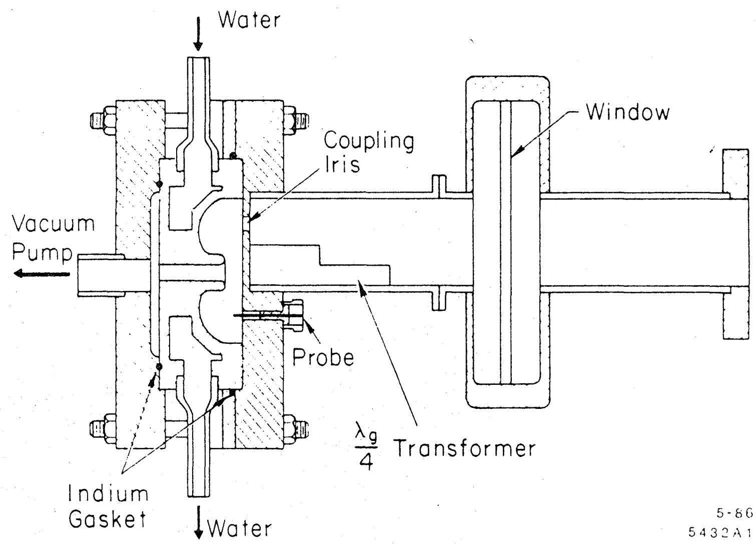

Fig. 2. A cross-sectional view of the C-band demountable, single-cavity tester.

Table 2. Field Calculated for Normalizing Conditions
$| \int_0^L E_z(z) \exp^{j(\omega z/c)} dz | / L = 1$ MV/m

	C-Band	X-Band
Resonant frequency, f	4998	9303
Q (half single cavity, including end plate)	7018	5595
r/Q per unit length	113.3 Ω/cm	158.8 Ω/cm
Energy stored, W	3.915×10^{-5} J	7.205×10^{-6} J
Power dissipated, $P_D = \omega W/Q$	176.8 W	76.26 W
Maximum surface field, E_{max}	7.542 MV/m	4.876 MV/m
Average accelerating field, $\bar{E}_{acc}$	0.966 MV/m	0.908 MV/m
$E_{max}/\bar{E}_{acc}$	7.81	5.37

couplers. The transmitted RF power into the test cavity is monitored through a probe in the end plate. This probe was also used to monitor the field emission current. The breakdown level was determined by monitoring the forward, reflected and transmitted power as well as the ion pump current.

Experimental Results

Using the notations given in Table 2, the maximum measured surface electric field, E_m, can be determined by the expression

$$E_m = \left[\frac{E_{max}^2}{P_D} \frac{Q_m}{Q} P_m \right]^{1/2}$$

where P_m is the measured breakdown level input power, Q_m and Q are the measured Q and theoretical Q factors respectively, and E_{max} is the theoretical maximum surface electric field, corresponding to the dissipated power P_D. Table 3 summarizes the results of breakdown threshold levels for the C- and X-band cavities. The results indicate that the maximum surface electric field was as high as seven times the Kilpatrick criterion.

Table 3. Experimental Results

Frequency (MHz)	4998	9303
Q_m	5400	4820
P_m (MW)	0.80	1.22
E_m (MV/m)	445	572

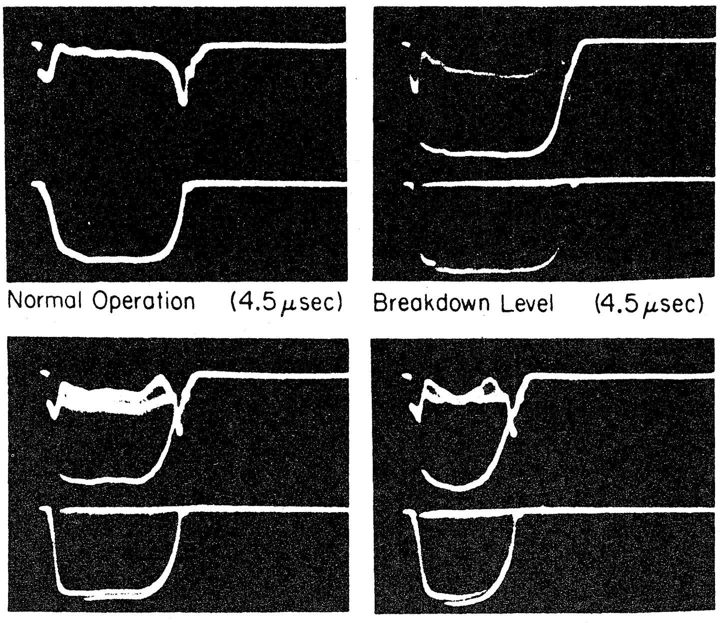

Fig. 3. Reflected and transmitted RF pulses for C-band cavity.

Figure 3 shows the reflected and transmitted RF pulses for the C-band cavity under normal and breakdown operation for various pulse widths. The results indicate that the breakdown limit does not appreciably depend on pulse width between 2.7 to 4.5 μsec. Figure 4 shows a modified Fowler-Nordheim plot of field emission current measured at the probe of the C-band cavity. The slope of $\log_{10} I/E_P^{2.5}$ versus $1/E_P$ has the following form:[7]

$$\frac{d\left(\log_{10} \bar{I}/E_P^{2.5}\right)}{d(1/E_P)} = -\frac{5.8 \times 10^9\, \phi^{1.5}}{\beta} \tag{1}$$

where $\bar{I}$ is the average field emission current under the influence of an external macroscopic surface field E_P enhanced by a factor β. $\bar{I}$ is measured in amperes, E_P in volts/m and ϕ is the work function in electron volts. The value of β obtained from this plot is about 75.

Conclusions

Multiple-use, demountable, single-cavity, breakdown test setups were successfully used for breakdown studies at C-band and X-band frequencies. The maximum surface electric fields obtained were as high as 445 MV/m at 5000 MHz and 572 MV/m at 9300 MHz. These breakdown thresholds did not appreciably depend on pulse width (between 2.7 to 4.5 μsec) and repetition rate (between 70 to 350 pps).

The field enhancement factor, β, which was calculated from the measurements of the average field emission current and RF field level, was 75 for the C-band cavity. The field emission enhancement factor is a measurable quantity for a certain accelerator structure and it is a very important parameter related to the RF breakdown limits.

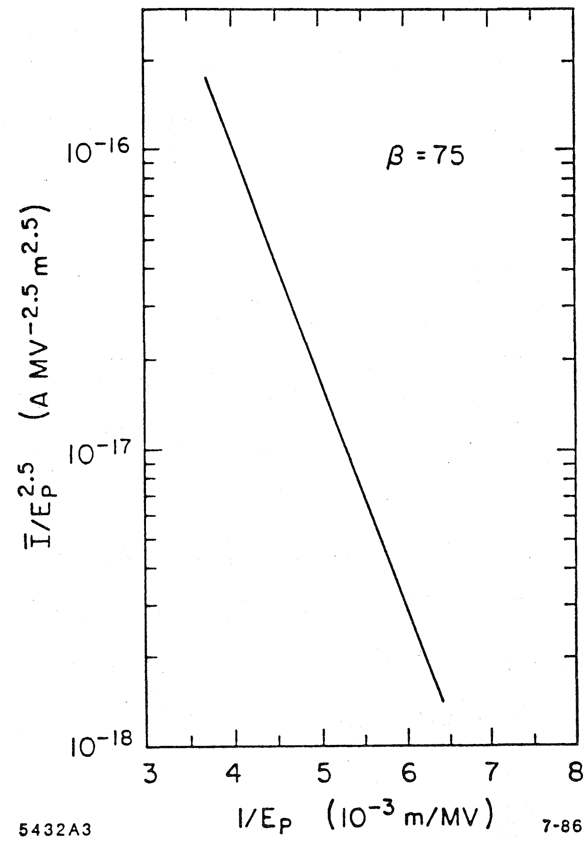

Fig. 4. Modified Fowler-Nordheim plots for C-band cavity.

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References

1. E. Tanabe, "Voltage Breakdown in S-band Linear Accelerator Cavities," IEEE Tran. Nucl. Sci. **NS-30**, 1983, pp 3351.
2. J. W. Wang and G. A. Loew, "Measurements of Ultimate Accelerating Gradients in the SLAC Disk-Loaded Structure," IEEE Trans. Nucl. Sci. **NS-32**, 1985, pp 2915.
3. W. P. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both RF and DC." VCRL-2321, Sept. 1953.
4. Y. N. Nikolaev, "Investigation of a High Voltage Vacuum Discharge at 25 Mc," Sov. Phys., Vol. 8, No. 4, Oct. 1963.
5. R. M. Hutcheon, *et al.*, "Operation of a CW High-Power RFQ Test Cavity," Proceedings of the 1984 Linear Accelerator Conference, pp 74.
6. S. W. Williams, *et al.*, "Voltage Breakdown Testing for the RFQ Accelerator," Proceedings of the 1979 Linear Accelerator Conference.
7. J. W. Wang, "Some Problems in RF Breakdown in Room Temperature Accelerator Structures, A Possible Criterion." SLAC/AP-51, April 1986.