

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  $\mu$ sec pulsed operation.<sup>1,2</sup> 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."<sup>3</sup> 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.<sup>4,5,6</sup> These experimental studies also indicate that the breakdown threshold level increases with the frequency.

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

| Investigators    | Frequency (MHz) | Pulse Width ( $\mu$ sec) | 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                           |

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 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

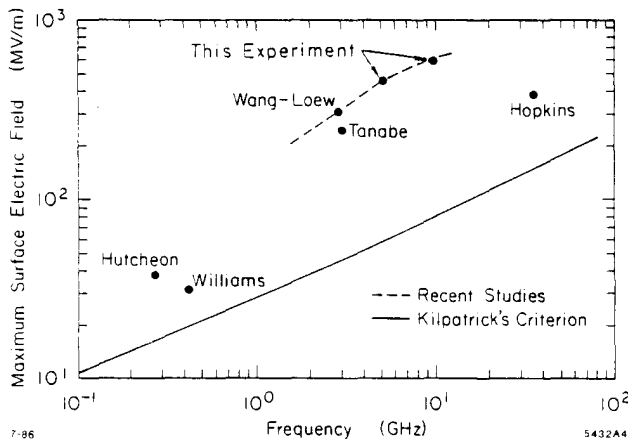


Fig. 1. Kilpatrick breakdown criterion and some experimental results.

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 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.

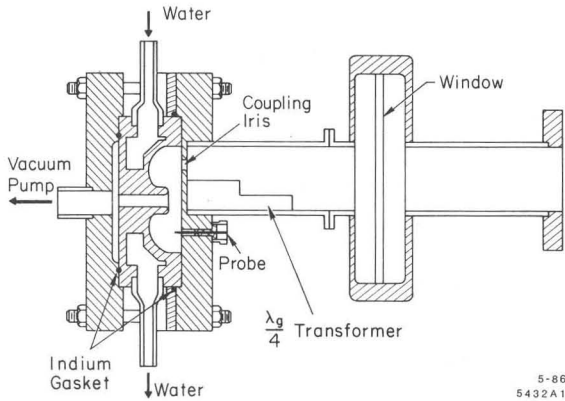


Fig. 2. A cross-sectional view of the C-band demountable, single-cavity tester.

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

|   | 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 $\Omega/\text{cm}$         | 158.8 $\Omega/\text{cm}$         |
| Energy stored, $W$                            | $3.915 \times 10^{-5} \text{ J}$ | $7.205 \times 10^{-6} \text{ J}$ |
| 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                             |

**Experimental Results**

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

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

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  |

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  $\mu\text{sec}$ .

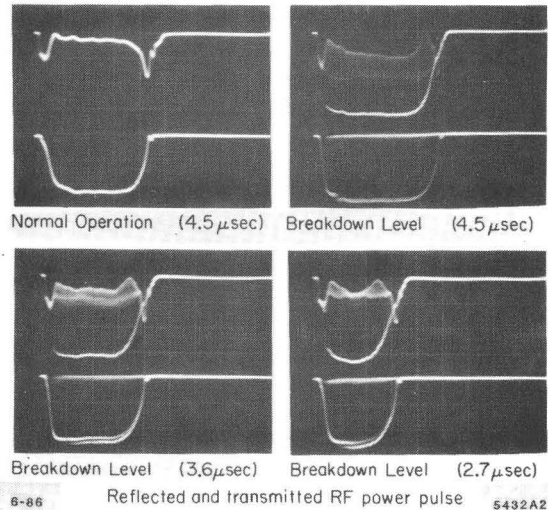


Fig. 3. Reflected and transmitted RF pulses for C-band cavity.

Figure 4 shows a modified Fowler-Nordheim plot of field emission current measured at the probe of the C-band cavity. The slope of  $\log_{10} \bar{I}/E_P^{2.5}$  versus  $1/E_P$  has the following form:<sup>7</sup>

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

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

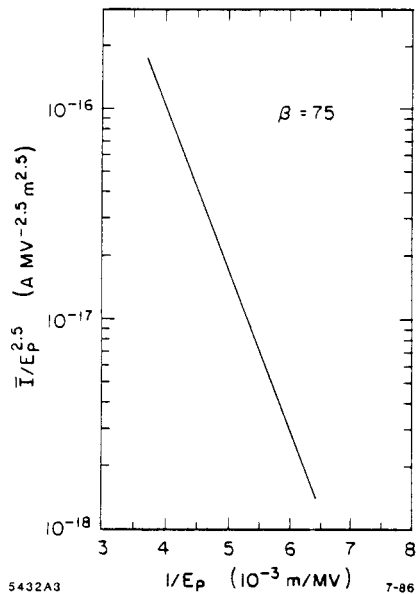


Fig. 4. Modified Fowler-Nordheim plots for C-band cavity.

**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  $\mu$ sec) and repetition rate (between 70 to 350 pps). The field enhancement factor,  $\beta$ , 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.

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