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CRITERIA FOR VACUUM BREAKDOWN IN RF CAVITIES

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Summary

A new high-voltage scaling based on Kilpatrick's criterion is presented that suggests that voltages more than twice the Kilpatrick limit can be obtained with identical initial conditions of vacuum and surface cleanliness. The calculations are based on the experimentally observed decrease in secondary electron emission with increasing ion impact energy above 100 keV. A generalized secondary-emission package has been developed to simulate actual cavity dynamics in conjunction with our 2½-dimensional fully electromagnetic particle-in-cell code CEMIT. The results are discussed with application to the suppression of vacuum breakdown in rf accelerator devices.

Introduction

Electrical breakdown is a serious constraint in radio-frequency linear accelerators and microwave cavities. It limits the electrical field strength, or gradient, which can be maintained in practice, and so, therefore, the power of such devices. For many years, the design of cavities has been predicated on a semi-empirical formula known as the Kilpatrick criterion.[1] Recent experimental data has led many investigators to conclude that voltages up to twice the Kilpatrick limit are possible in clean, well-prepared systems.[2] In fact, work in the Soviet Union indicates operation of a 25-MHz cavity at up to eight times the Kilpatrick limit.[3] It is the intent of this study to investigate the problem of voltage breakdown in evacuated cavities and to propose methods of its suppression in high-current accelerating devices.

The idea that electrical breakdown is dependent upon high-energy ion bombardment was first proposed by Trump and Van de Graff[4] in 1947. In this dc theory, electron emission from the cathode and ion emission from the anode initiate a cascade process by means of secondary emission. If A is the probability that an electron is liberated by ion impact and B the probability that an ion is liberated by electron impact, particle multiplication will occur if $AB > 1$. Later experimental work[5] showed that the probability for electron emission A is generally less than 10, and the probability for ion emission is less than 0.001, so that this scheme is quantitatively inadequate.

Somewhat later an experiment by Dyke and Trolan[6] suggested that field emission current may be the dominant criterion in the initiation of breakdown. In this experiment, breakdown occurred between electrodes when the average current density exceeded some critical value, even under the best initial conditions of vacuum and surface cleanliness.

Under general conditions, however, vacuum breakdown occurs at much lower voltages than would be expected if field emission alone were the mechanisms for initiation.[1] Because of this, an increase in the emitted currents by means of energetic ion bombardment was incorporated by Kilpatrick into his criterion. Let A be the probability for secondary electron emission by high-energy ion impact. Then, including for the probability of field emission due to a field gradient of magnitude E, a breakdown threshold

$$AE^2 \exp(-K_1/E) = K_2 \qquad (1)$$

was hypothesized, where K_1 and K_2 are empirical constants. In accordance with the unpublished data of Bourne, Cloud, and Trump[7] in 1953, Kilpatrick took the secondary emission coefficient A to be proportional to the ion energy W. Equation (1) was also fitted to early experimental data to determine K_1 and K_2. The result is

$$WE^2 \exp(-17/E) = 1.8 \qquad (2)$$

where E is in MV/meter and W is in MeV.

It is interesting to analyze Kilpatrick's criterion for small gaps and dc voltages. From Eq. (2) we have $V = Cd^{2/3}$ where V is the voltage, d is the gap, and C is a constant. Alpert et al.[8] and Hill[9] have measured dc voltage breakdown levels and have obtained the empirical relation $V = Cd^{0.7}$. Moreover, in the general relation $V = Cd^{\alpha}$, Maitland[10] and Little and Smith[11] analyzed published measurements and determined that 0.7 was the most frequently determined value of α. This is in close agreement with the value $\alpha = 0.67$ predicted by Kilpatrick.

In the next section we will discuss necessary modifications to the Kilpatrick theory for ion energies greater than 100 keV, and a new secondary emission algorithm that is being used to simulate particle dynamics in cavities of arbitrary design.

Discussion of Results

If A is the probability for secondary electron emission, Eq. (1) describes the threshold for which secondary emission currents enhance the field emission currents to the point of breakdown. Kilpatrick assumed that the secondary emission yield was proportional to the energy of the incident ion. However, this is true for energies $W \leq 100$ keV only. For higher incident energies, there is a marked decline in secondary electron yield.[5,12,13] On the basis of a high-energy ($W > 100$ keV) secondary emission theory of Sternglass,[14] we have constructed the following criterion[15]

$$f = (62/E) \exp(17/E) \qquad (3)$$

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where f is the rf frequency in the cavity in MHz, and E is the electrode field gradient in MV/meter. Equation (3) is a modification to the well-known Kilpatrick scaling

$$f = 1.6\, E^2 \exp(-8.5/E) \tag{4}$$

in the high-energy, high-frequency parameter regime. Equations (3) and (4) are plotted in Fig. 1 together with experimental data points[3,9,16,17] in the 20-60 MHz frequency range. Both curves are seen to be over-pessimistic in their prediction of vacuum breakdown, but Eq. (3) seems to be in more qualitative agreement with the experimental results. Better agreement between theory and experiment may be possible by refitting the breakdown threshold equation with more recent experiments, instead of those analyzed by Kilpatrick. These latter experiments did not have the same initial conditions of vacuum and surface cleanliness as is common today. A more complete discussion of these results will be included elsewhere.[15]

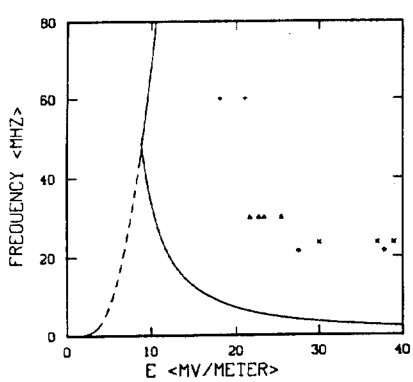

Fig. 1. Breakdown thresholds predicted by Kilpatrick (dashed curve) and by this study (solid curve) with experimental data points.

We have also constructed a generalized secondary emission physics package that can be used in conjunction with our 2½-dimensional fully relativistic and electromagnetic particle-in-cell code CEMIT.[18] This package now includes secondary electron emission due to electron bombardment, but will also include a generalized emission package with both ion and electron physics in the future. This emission package will be used as a part of our effort to understand the effect of particle dynamics in the breakdown of rf cavities.

To numerically model the secondary electron yield when a primary electron hits a conducting boundary, we have adopted the semi-empirical universal yield curve due to Agarwal.[19] This seems to be in better agreement with experiment than any other universal yield curve to date.[20] If the secondary electron yield σ (due to a primary electron of energy E_p) is normalized to its maximum value σ_m (corresponding to an energy E_{pm}), the following relation is adduced,

$$\frac{\sigma}{\sigma_m} = \frac{2(E_p/E_{pm})}{1 + (E_p/E_{pm})^{1.85(2Z/A)}} \tag{5}$$

where Z is the atomic number of the electrode material, and A is its atomic weight. If the electrode material is a compound and not an element, an effective Z and A can be deduced from a simple arithmetic mean calculation.[20] The good agreement between Eq. (5) and experimental data is shown in Fig. 2.

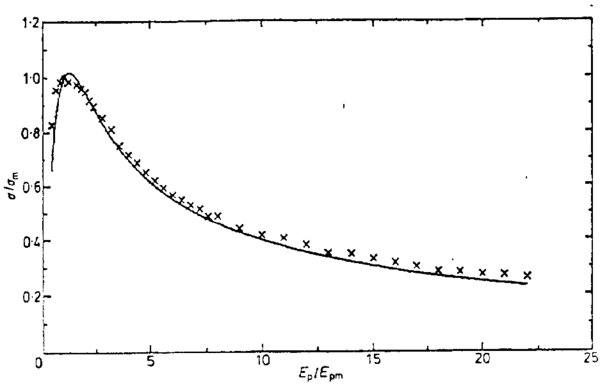

Fig. 2. Agarwal's universal yield curve for secondary emission as a function of primary energy with corresponding data points (Ref. 20).

To demonstrate the utility of our code for real cavities, we have begun simulations on a 1300-MHz resonator now under study at Los Alamos.[21] An r-z plot of the cavity is shown in Fig. 3 (the figure has azimuthal symmetry about the z-axis). The rf fields are simulated by a TEM wave that is launched into the cavity from the entrance channel on the top right-hand side of the computational grid. Field-emitted particles are accelerated into the gap (Fig. 3), and upon striking the opposite electrode, give off secondaries. The results of these simulations are expected to be of considerable help in understanding multipactor effects in breakdown phenomena.

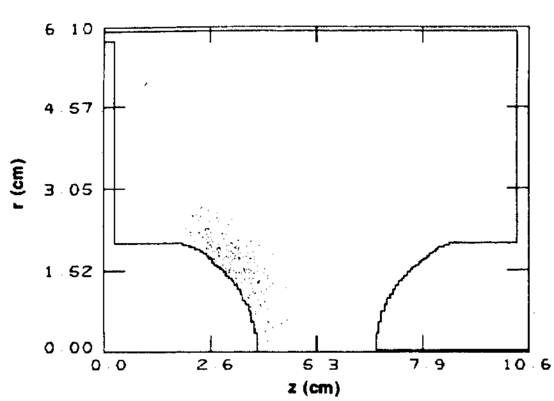

Fig. 3. Cavity simulation of the 1300 MHz resonator at Los Alamos (Ref. 21). Field emission (shown) and secondary emission (not shown) are important features of coding.

Finally, interest in the development of the breakdown process itself has led to a study of high-density rf plasma dynamics. It has been suggested[22] by nonlinear analysis of the pressureless plasma equations that plasma mass acceleration within the rf cavity results in the formation of shocks. Whenever such a shock forms, a delta-function singularity in the plasma density will be present. This singularity, once formed, will continue to propagate with the shock velocity. As a result of oscillations in the electric field, a striated plasma featuring high-density sheets may form, resulting in intense bursts of secondary emission when primaries impact the wall.

Conclusions

Kilpatrick's criterion for vacuum breakdown assumes that secondary electron emission by ion bombardment initiates a cascade process that increases emitted currents to the point of breakdown. However, many rf experiments observe larger breakdown voltages than are predicted by this theory. Though modern experiments employ better surface and vacuum techniques than earlier ones, there are other factors contributing to the experimental observation of breakdown voltages higher than the Kilpatrick limit. On the basis of this study, higher threshold gradients should be possible by restricting the number of secondary electrons off the surface. This can be done by increasing the ion impact energy above 100 keV, or by choosing high-Q electrode surfaces that are known to be poorer emitters. Another technique is suggested by the fact that surface heating decreases the yield of secondary electrons.[23,24] Accordingly, experimental results[25,26] indicate that electrode heating can in some circumstances increase breakdown voltages by up to 20%.

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