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ANODE INITIATED BREAKDOWN

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At the present time there does not exist a comprehensive theory which satisfactorily explains the mechanism of vacuum breakdown. Nevertheless, many hypotheses have been put forward, and all have been used by various workers to account for some, of the many experimental results.

These hypotheses may be divided into two main categories :

i) Field emission theories and

ii) Clump theories.

The former appears to have the best experimental evidence, although the actual mechanism involved, which is complex, may well be comprised of the two effects.

The main basis of the field emission theory is the Fowler-Nordheim equation, which is well verified experimentally[1]. When an intense electric field is applied to a metal surface, the width of the potential barrier becomes finite, and electron may tunnel through the barrier and hence be emitted.

However, it has been conclusively shown[2], that the field required for this effect to occur is $\sim 10^7$ volts/cm, when the surface is carefully cleaned by outgassing at 10^{-11} Torr.

In vacuum breakdown experiments, breakdown may be found to occur at a gross field of less than 200 kV/cm, which would seem to imply that the field emission hypothesis is incorrect.

However, evidence obtained by many workers, using various types of microscopy, has shown that even on very carefully prepared electrodes, there exist micro-protrusions of varying height, and the effect of these, as shown later, is to produce an enhanced field at the protrusion tip, much higher than the gross gap field. For this reason, a field enhancement factor β is defined as the ratio of the field at the protrusion tip to the gross gap field.

The field emission theories may also be further sub-divided into two groups, the first of which is the case where the field emitted electrons cause either evaporation of electrode material, or evolution of adsorbed gases; and the second that of charge-exchange hypotheses, where electrons hitting the anode give rise to charged particles which then travel to the cathode and cause emission of particles there. If the net effect of this is an increase in the number of charged particles, finally a spark will pass and cause breakdown. The experimental verification of this latter hypothesis is very limited, however, and it is not held to be of major importance in causing breakdown. The former theory however, has been adopted by the great majority of workers in the field, and has successfully explained a very large proportion of the experimental results.

This theory is still not the end of the matter, for it is further subdivided into categories.

a) Cathode initiated breakdown. This hypothesis postulates that the field emitted electron current causes resistive heating in the cathode protrusion and when the field (and thus the current density) reaches a certain level, this heating is enough to cause evaporation of the protrusion. Further electrons can then ionise this vapour and an electrical discharge will occur in the vapour and lead to breakdown.

b) Anode initiated process. This hypothesis postulates that the field emitted current heats the anode, and at a certain critical field, the current will become high enough to cause either :

i) Emission of adsorbed gases, or

ii) Evaporation of anode material

An electrical discharge and breakdown will then occur as above.

It is clear that presuming the field emission hypothesis is the correct one, that both these processes can occur. However, the question that is still being argued over is which of these will occur first, and under certain specified conditions, it appears that either of the two can occur[3].

The present report deals with results obtained using a computer to calculate the potential at points in a given electrode geometry, namely that of a cylindrical protrusion on a plane cathode.

The programme was developed at CERN[4] in a general form to solve partial, elliptic, differential equations of the type

$$a \frac{\partial^2 u}{\partial x^2} + b \frac{\partial^2 u}{\partial y^2} + c \frac{\partial u}{\partial x} + d \frac{\partial u}{\partial y} + eu + f = 0 .$$

In the case under consideration, we simply have to solve Laplace's equation in two dimensions (since we have cylindrical symmetry)

i.e. $$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0 .$$

The solution is obtained by the method of successive over-relaxation, also known as the extrapolated Liebmann method. A mesh is constructed to cover the electrode system, and values of the potential specified for each point in the domain, consisting of specified values at the boundaries and guesses at every other point. A correction procedure is carried out at each mesh point in turn and when this has been applied, an improved value of u exists for each mesh point. This process is continued until values of u are found with the specified accuracy (0.1 o/o).

A protrusion of height 10^{-4} cms was considered as being typical, although evidence as to their actual size is lacking. The geometry considered for the protrusion was that of a cylinder, with a semi-spherical tip, and two cases of height/width ratio were considered, namely 5 to 1 and 500 to 1.

The interelectrode distance considered was 1 cm and the voltage across the electrodes taken as 200 kV. (This is typical of the gaps and voltages used under test conditions at CERN). Since the interelectrode distance was so great compared to the height of the protusion, it was necessary to use the programme several times to compute the value of the field at the tip. In fact, three programmes were carried out, using mesh distances of 10^{-4} cm, $2 \cdot 10^{-5}$ cm and $4 \cdot 10^{-6}$ cm, for both height/width ratios. For the two cases of 5 to 1 and 500 to 1 height to width ratios, the values of the field enhancement factor were respectively $\beta \approx 95$ and $\beta \approx 155$. These values give fields at the protrusion tip of approximately $2 \cdot 10^7$ and $3 \cdot 10^7$ volts/cm, which are of the right magnitude to produce field emission.

The actual aim of the work being carried out was to find the radius of the electron beam at the anode. This beam is parabolic in shape since the initial irregular field gives a transverse velocity to the electrons, and once in the uniform field region, they have a uniform longitudinal acceleration and transverse velocity.

A method of calculating this radius is given by Chatterton[5], and also a programme which traces particle paths for a given electrode configuration is available at CERN[6]. However, due to lack of time, it was not possible to implement these calculations.

Finally, several theories are presented in the literature to calculate the heating caused at the anode by the electron beam, for example by Chatterton[5]; Utsumi and Dalman[3], Boyle, Kistink and Germer[7], and Charbonnier[8]. However, experimental justification for these theories is rather limited, and much more work needs to be carried out to evaluate their respective merits. In all these theories it is assumed that breakdown will proceed automatically, once the evaporation temperature of the anode material is exceeded.

The reason that anode breakdown has been considered here is that recent experiments at CERN, seem to show its presence. When a magnetic field of 13 kilogauss acts parallel with an electric field across a 1 cm gap, the breakdown voltage is considerably reduced. It would appear that only anode breakdown can explain this result.

The mechanism by which this occurs is that the magnetic field pinches in the electron beam, giving a smaller radius at the anode, according to the equation[3]

$$\frac{r_B}{r_o} = 3.39 \frac{\sqrt{v}}{d} \sin 2.96 \times 10^{-1} \frac{B \cdot d}{v}$$

where r_B, r_o are the radii with and without a magnetic field B, v is the gap voltage, and d is the interelectrode distance.

Obviously, if the mechanism proposed above is correct, the effect of this pinching will be to give a great power density to the beam at the anode, and give rise to the evaporation temperature, at a lower field strength. Hence breakdown will occur at a much lower field.

From these considerations it seems that the anode induced breakdown hypothesis is feasible and it is to be hoped that the necessary theoretical and experimental work will be carried out, to put these arguments on a much firmer basis.

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