One-Dimensional Simulation Studies of Breakdown and Electron Beam Generation Processes for a Hollow Cathode Pseudospark Discharge*

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Abstract

We have developed a 1-D model to study the importance of some of the basic physical processes involved in a low pressure discharge. Our results show that during the early stage of the discharge, the emitted electron current comes mainly from the secondary emission off the cathode. Meanwhile, a quasi-neutral plasma column is being formed in the gap via ionization. The growing plasma oscillations are excited by the fast electrons from the cathode as they pass through the plasma due to the two-stream instability. The oscillation heats the background electrons to energies above the ionization threshold and ultimately leads to a rapid increase in both the plasma density and electron current at the anode. To our knowledge previous pseudospark models have not included ionization of the ambient gas due to the heated background charged particles within the dense quasi-neutral plasma region. Under this 1-D model, the discharge approximately satisfies a Paschen's Law in the low pressure regime.

I. INTRODUCTION

There has been an increasing interest in pseudospark devices [1-5]. One of the potential applications of this kind of a device is as a high current, high brightness electron beam source. At the University of Maryland a series of experiments were performed to determine some of the properties of such a pseudospark discharge. It was found that electron beams of current on the order of 1 kA/cm^2 and brightness as high as 10^{10} A/m^{2}rad^2 can be produced from a low pressure discharge in a hollow cathode geometry [4,5].

Besides experiments, progress has also been made in theoretical studies of pseudospark discharges [6-8], although no existing theory is comprehensive. A recent model, based on the experimental observation that a melted area was found on the cathode surface, proposed that the high current originates from electric-field-enhanced thermionic emission from the cathode [9]. However, in order to melt the cathode surface, an ion flux of the order of 10^9 W/cm^2 is required over a 10 nsec period [10]. Such a flux is equivalent to 100 A/cm^2 if the applied voltage is 10 kV. Also, in order for the electric-field-enhanced thermionic emission to emit the measured current, the electric field at the cathode surface has to be above 10^6 V/cm. The mechanism which brings the discharge to reach the required high current flux and electric field is still unclear.

The present study is aimed at determining the most important basic physical processes involved in the pseudospark discharge. While the hollow cathode has a 2-D structure, we believe that the basic physics involved should not be sensitive to the actual geometry. Thus a rather simple 1-D model is used. The description and the results of the study are given in the following two sections.

II. NUMERICAL MODEL

The numerical model is a 1-D particle-in-cell (PIC) model, which simulates an infinite parallel plate system with a background helium gas maintained at pressure p. A constant negative voltage $-V_0$ is applied on the cathode which is located at $z = 0$, and the anode located at $z = d$ is grounded. An initial uniform plasma of 10^8/cm^3 is present between the plates. The motion of the charged particles is non-relativistic and is governed by the equation of motion

$$\frac{d^2 z}{dt^2} = \frac{q}{m} E(z), \qquad (1)$$

where z is the location of the particle, q and m are the charge and mass of the particle, respectively, $E(z)$ is the electric field at z. The electric field $E(z) = -dV/dz$ is obtained by solving the Poisson equation

$$\frac{d^2 V(z)}{dz^2} = -\rho(z)/\epsilon_0 \qquad (2)$$

with boundary conditions $V(z = 0) = -V_0$, $V(z = d) = 0$, and where ρ is the net charge density.

Because pseudosparks usually operate at low gas pressure and high voltage, we only take into account ionizing collisions. The ionization cross-sections for electrons and ions in He are obtained from Ref. [11].

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When an ionization occurs, the incident particle's energy is reduced. In addition, when ions hit the cathode, secondary electrons are emitted. The secondary emission coefficient is dependent on the ion energy and is obtained from Ref. [12], assuming that the cathode is made of Mo. When a new particle is created, we assume that it has no initial kinetic energy.

III. SIMULATION RESULTS

The 1-D PIC code is used in a series of simulations of high voltage, low pressure discharges. Figure 1 shows a typical plot of electron current collected at the anode versus time. The total current is composed of contributions resulting from ion-neutral ionizations, electron-neutral ionizations, and secondary emissions. In Fig. 1, a rapid increase in the total current occurs at about 108 nsec after the onset of the -20 kV voltage. The simulation was stopped when the current reached ~ 1 kA/cm^2 where the number of particles in the system becomes computationally prohibitively large. It is also observed that during the early stage of the discharge, the current mainly is a result of the secondary emission. But just before the sudden increase in the total current, the contribution from the electron-neutral ionizations becomes dominant. This new observation can be explained as follows.

Figures 2(a) and 2(b) show the potential and the charged particle densities in the gap at $t = 105.8$ nsec. By this time, a quasi-neutral plasma column has formed in the gap. The plasma density in this case is of the order of $2\times 10^{13}/\mathrm{cm}^3$. When the high energy electrons emitted from the cathode pass through this plasma, it can excite a plasma oscillation due to the two-stream instability. The growing plasma oscillation is clearly shown in Fig. 3, where the electric field at $z = 0.85$ cm from the cathode is plotted as a function of time. Note that the oscillation frequency $f \sim 3.3 \times 10^{10}$ Hz matches well with the electron plasma frequency, taking $n_e = 2 \times 10^{13}/\mathrm{cm}^3$. The plasma oscillation heats the background electrons. Figure 4 is a plot of the electron energy distribution at $t = 105.8$ nsec. It shows that at this time, a large portion of the plasma electrons have been heated to above the threshold energy of 24.6 eV. The electron ionization cross-section increases rapidly when the electron energy is above the ionization threshold and reaches a maximum at about 100 eV. When a significant amount of electrons are heated to above the threshold, ionizations due to these hot electrons will also rapidly increase and further increase the electric field associated with the plasma oscillation. This in turn leads to a rapid increase in the electron current.

In addition to the above typical case where "breakdown" occurs, we have also performed parametric studies of the pseudospark discharge with this 1-D model. We looked for a critical voltage where the typical breakdown behavior is observed for a given gap length d and gas pressure p and plotted the results in Fig. 5. We see that our simple 1-D model obeys Paschen's Law fairly well, namely that the critical voltage for breakdown is a function of the product of the gap length d and gas pressure p. More studies need to be done on this subject to quantify the dependence on d and p.

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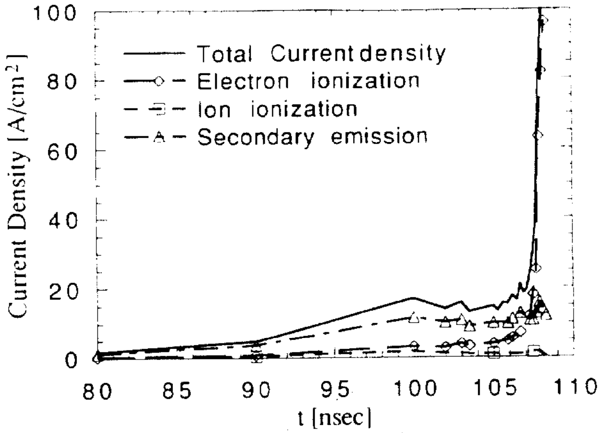

Figure 1: Total electron current density at the anode and its components versus time. The system parameters are $p = 2$ torr, $V_0 = 20$ kV, $d = 1$ cm and an initial plasma density of $5\times10^7/\mathrm{cm}^3$.

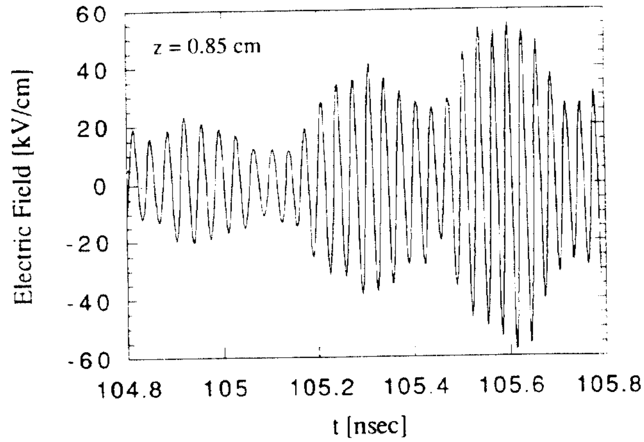

Figure 3: The electric field at $z = 0.85$ cm versus time. Note the growing plasma oscillation. Same system parameters as in Fig. 1.

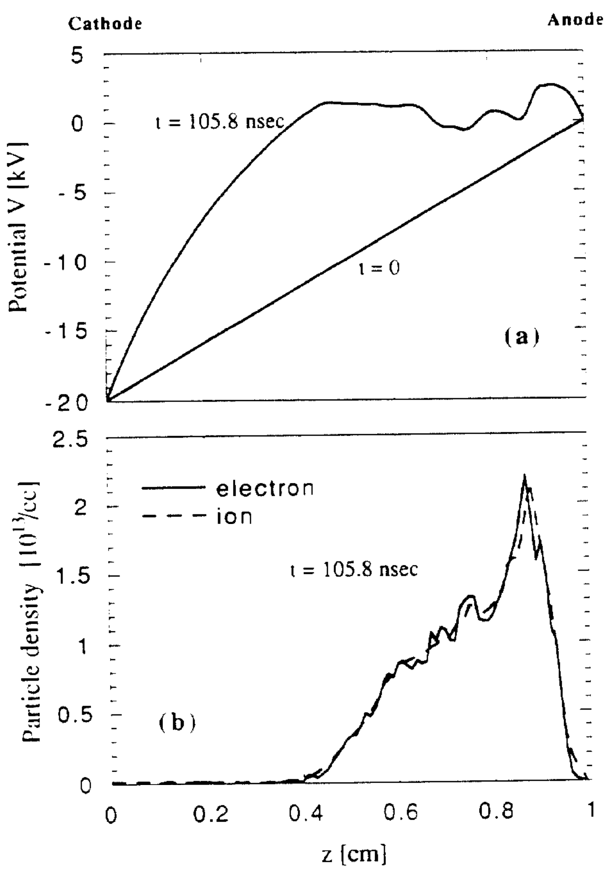

Figure 2: Electric potential (a), and charged particle densities (b) versus position at $t = 105.8$ nsec. The $t = 0$ potential profile is shown for reference. Same system parameters as in Fig. 1.

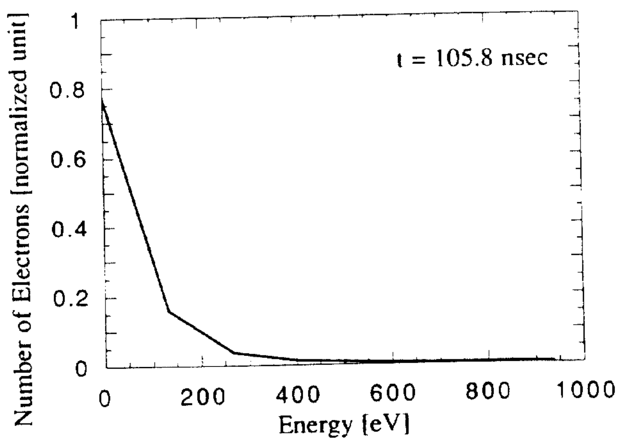

Figure 4: The electron energy distribution at $t = 105.8$ nsec. Same system parameters as in Fig. 1.

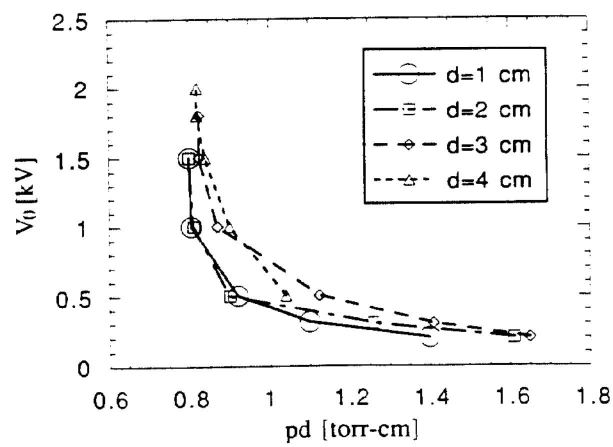

Figure 5: Breakdown Voltage as a function of gas pressure times gap length for gap lengths from 1 to 4 cm.