Theoretical and Experimental Study of Pseudospark Electron Beam Generation*

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Abstract

Pseudospark hollow cathode discharges (HCD) are sources of intense electron beams. Reported in this paper are theoretical and experimental studies of the HCD processes and the related electron beam production. The purpose of the work is to develop a predictive model to guide the development of this high brightness electron beam. According to the model, the initial, rapid current rise is associated with the formation of a plasma and its expansion in the hollow cathode region (HCR). The space charge distortion of the applied field just as the plasma begins to fill the HCR is such that electron multiplication is maximum at this point in time, and there is a consequent rapid increase in the charged particle densities. The electron beam observed experimentally during the current rise is predicted by the model. Electrons created in the HCR are largely confined by the high field sheaths until they lose most of their total energy in collisions. These low energy electrons are trapped in the low field region on axis behind the cathode hole through which they diffuse into the cathode-anode gap, and then are accelerated in the remaining potential within the gap. These electrons comprise the observed electron beam. The model indicates that the beam is a direct consequence of HCD and is therefore produced by a plasma cathode. The difficulty in modeling an actual electron emitting metal surface can therefore be overcome. Experimental results of a hydrogen HCD electron beam are also presented. The pulse-length is usually 10's of nsecs, peak beam current of 170 A, efficiency of 21% was measured at -20 kV applied voltage. The experimental results and model predictions are in good qualitative agreement, and demonstrate the potential for developing a first principles predictive model for electron beam current, emittance and brightness.

I. INTRODUCTION

Pseudosparks are transient gas discharges which occur in a special hollow cathode geometry and can produce electron beams of very high brightness ($>10^{10}$ A/m^{2}rad^2).[1-3] Two electron beam components can be observed in a pseudospark discharge. The first one is produced immediately following the breakdown event (which is usually triggered), and is typically a beam with energy comparable to the voltage switched, and peak current of ~ 10-1000 A. The width of this component in time and its spread in energy depend on the evolution of the plasma produced in the discharge, or more precisely, the evolution of the potential distribution in the gap. Measurements of the properties of this component of the electron beam provide not only data needed for its eventual optimization in terms of current and brightness, but also provide a stringent test of the prediction of numerical model of pseudospark discharges.

A second component of the pseudospark electron beam is related to the operation of super-emissive cathode mode.[4,5] An electron beam with current ≈ 200 A, duration on the order of μsecs, energy of several hundred eV has been experimentally observed.[6]

Our focus to date is to develop a predictive model to guide the development of high energy, high brightness electron beams generated in the initiation phase of the pseudospark discharge. In this paper we present a semi-qualitative description of this component of the electron beam and show comparison between model prediction and measurements.

II. THEORETICAL MODEL

An essential phenomena during the initiation phase of pseudospark discharge is the development of space charge. At this moment the plasma is collisional even though the electron mean free path can be on the order of the discharge dimension. The collisions between electrons and neutrals will dominate and the coulomb collisions between charged particles can be neglected. The energy distribution of electrons is therefore more energetic than that of ions. The result is a non-Maxwellian electron energy distribution. For this reason the model must be able to take into account the non-equilibrium charged particle transport and electric field distribution in a self-consistent manner.

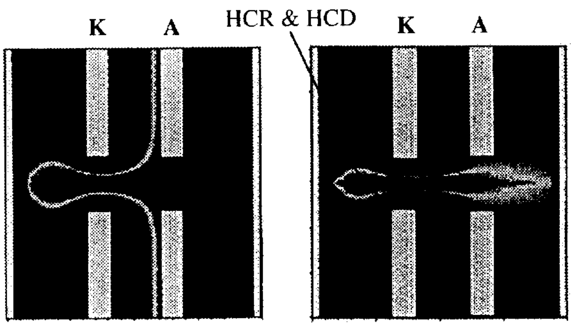
A two dimensional, self-consistent model of the electrical properties of transient HCD which is used to describe the initial phases of a pseudospark discharge has been developed. The model consists of Poisson equation for the electrical field coupled to a fluid description of the electron and ion transport, with the important feature that the ionization source term in the electron and ion fluid equations is determined through a Monte Carlo simulation. The fluid equations determine the time and space dependence of the charged-particle densities. The space charge and self-consistent field from Poisson equation yield the particle currents. With the knowledge of electron current density distribution leaving the cathode and the electrical field distribution within the cathode-anode gap, the Monte Carlo simulation determines the ionization source term which, in turn, is input to the fluid equations. This model is referred as a hybrid fluid-particle model.[7]

Figure 1 shows a snap shot of both the equipotential contours and the electron density contours for a 0.6 Torr helium at a constant applied voltage of 2 kV. The contours

* The work supported in part by the U.S. Army Research Office, SDIO through the U.S. Office of Naval Research, the Joint Services Electronics Program through the Air Force Office of Scientific Research, NATO and DRET.

0-7803-1203-1/93$03.00 © 1993 IEEE

were taken at 50.4 nsec after the application of voltage. In this particular calculation, the geometry is symmetrical (with a hollow cathode and a hollow anode). The electrode thickness and cathode-anode separation is 2.5 mm and 4.5 mm. Both electrode central holes are 5 mm in diameter. The HCR has a dimension of 3 cm in diameter and 0.7 cm in length. A trigger pulse is assumed to produce a uniform initial charged particle density in the HCR at the time when the voltage is applied (t=0). The electrical field at t=0 is almost uniform in the gap, with a small distortion in the region of the holes. As the initial electrons are pulled out of the cathode and towards the anode, they produce ionization in the gas. The secondary electrons are accelerated towards the anode, leaving behind a growing ion space charge field. If the trigger pulse is of sufficient amplitude, a plasma will form in the gap and distort the geometrical field. This will in term increase the potential in the HCR as shown in Figure 1-a. The space charge distortion of the applied field just as the plasma begins to fill the HCR is such that the electron multiplication is a maximum at this point in time, and there is a rapid increase in the charged particle densities. The result is shown in Figure 1-b where a high electron density core (on the order of 10^{13} cm^{-3}) can be observed. During this time a large displacement current spike has also been observed due to the increase in the field corresponding to this space charge.



(a) Equipotential contours (b) Electron density contours

FIG. 1 Snap shot of equipotential contours and the electron density contours in a 0.6 Torr helium gas with 2 kV applied voltage. The pictures were taken at 50.4 nsec after the application of voltage.

In general, with the application of a high enough voltage the plasma will begin to form first in between the cathode-anode gap or close to the cathode hole. The plasma expands from this point of formation towards the cathode. The potential which existed at the position where the plasma is first formed is pushed into the HCR as the plasma expands. Electrons created in the HCR are largely confined to oscillate between the high field sheaths until they lose most of their total energy in collisions. These low energy electrons are trapped in the low field region on axis behind the cathode hole through which they diffuse into the gap and then are accelerate in the remaining potential within the gap. These electrons comprise the observed electron beam. From simulation an electron beam with current density ≈ 20 A/cm^2 and peak energy of 700 eV was observed at 30.8 nsec after the trigger with an applied voltage of 2 kV.

III. EXPERIMENTAL RESULTS

Figure 2 shows the experimental setup. The HCR was made of copper with a cylindrical structure, a cathode on one end and a quartz window on the other. The HCR has a dimension of 3.5 cm in diameter and 2.5 cm in length. The electrode central hole size and the thickness of insulators were both 3 mm. The discharge was initiated with a UV flash lamp at the back of cathode near the central hole through a quartz window. Cathode current was monitored through a 5 mΩ current viewing resistor (CVR) and the cathode voltage through a Tektronix P 6015 high voltage probe. The electron beam was generated with an RC discharge circuit (22 Ω, 16 nF). The electron beam current was measured with a fast Rogowski coil (≤ 1 nsec) at ≈ 1 cm behind the anode hole. A fast Faraday cup (≤ 2 nsec) is also available. Permanent magnets were used only for beam energy measurements.

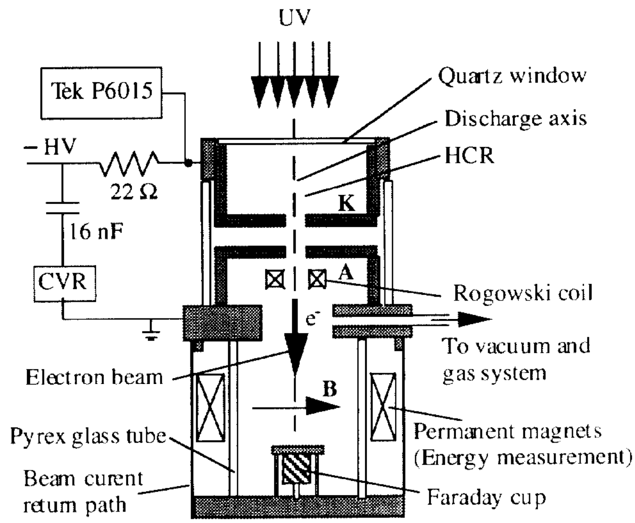


FIG. 2 The experimental setup for electron beam measurement.

The drift tube is a 41 mm Pyrex glass tube. Two copper screen cylinders were used to cover both sides of the glass tube. The inner copper screen was to provide the plasma electrons return path and was directly connected to the grounded anode. The outer screen provides the beam current return path to the anode and can be detached from the anode when necessary.

Figure 3 shows the typical discharge current and the electron beam current with -20 kV applied voltage with 80 mTorr H_2. The peak of the discharge current is ≈ 800 A and the electron beam ≈ 170 A which gives a beam current to discharge current ratio of 21%. The pulse length is ≈ 50 nsec. The pulse length is associated with the plasma formation processes within the cathode-anode gap and not readily controllable with external circuitry. The discharge current has a slower rise at the beginning of the pulse which corresponds to the build-up phase of the transient HCD. After this moment the discharge current increases over-exponentially as a result of fast increase of charge multiplication inside the HCR. The electron beam current has a similar behavior and the peak is coincided with the peak of discharge current.

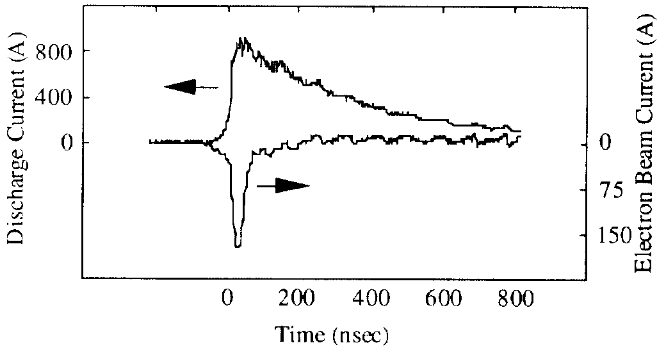


FIG. 3 The discharge current and the beam current at 1 cm behind anode . The turn-off of beam current is associated with the decrease of cathode voltage.

Beam current dependence on gas pressure was also studied. A dramatic increase was observed when operated at lower gas pressure. The beam current increases by a factor of 4 with a pressure reduction of only ≈ 40% (from 140 mTorr to 80 mTorr). The beam current was also found to increase with increasing applied voltages. The beam current increases from 10 A to 45 A when the voltage is varied from -14 kV to -20 kV in a 135 mTorr H_2. These results suggest that when operated at a -40 kV voltage and 50 mTorr hydrogen, an electron beam with current of kA is feasible.

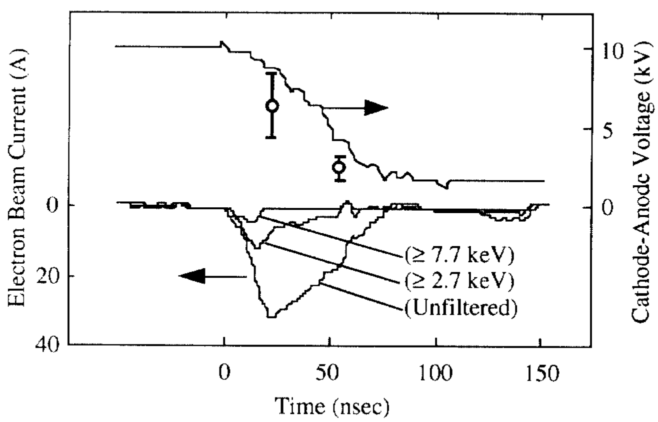


FIG. 4 Electron beam energy measurement with high-pass filtering method.

The electron beam energy was estimated with a high-pass filtering technique. The technique utilizes the VxB deflection that beam electrons experience when traversing a transverse magnetic field. Only those electrons with high enough energies can survive the deflection and still be collected by the Faraday cup. With different strength of the magnetic field different electron energy can be estimated. The spatial distribution of the magnetic field was measured and used as the prescribed field for a single electron trajectory computer simulation with electron energy as input parameter. With a 16 nF and 500 Ω capacitor discharge at -10 kV in 400 mTorr He gas the peak beam current is ≈ 32 A at 2 cm behind anode. With increasing transverse magnetic the beam current is observed to decrease accordingly. The electron beam decreases both in beam current and pulse length. The latter portion of the beam current is observed to diminish first and the vanishing point represent electron beam with minimum energy set by the magnetic field. Figure 4 shows the experimental results. The minimum beam energy is found to be 1.2 keV $\leq E_1 \leq$ 2.7 keV for one pair of the permanent magnets and 4.2 keV $\leq E_2 \leq$ 7.7 keV for two pairs of magnets. The source of error comes from the possible uncertainty of the precise position of Faraday cup in the transverse direction (≈ ∓ 1 mm). The upper curve of Figure 4 is the cathode voltage. On the same curve the minimum energy from trajectory simulation was plotted at the time where electron beam corresponding to different magnetic field vanished. The results indicate that the electron beam has energy close to and below the cathode voltage as predicted from the theoretic model.

The propagation of this electron beam in an 80 mTorr H_2 was studied with radiachromic films at various locations behind anode. The method is time-integrated in nature and a beam divergence half angle ≈ 5.0° is measured. Emittance can also be estimated with the assumption that the beam waist is at the anode position.[8] At 170 A and instantaneous energy of 10 keV a normalized emittance of 25 mm-mrad is found and a normalized brightness of 2.7×10^{10} A/m^2rad^2 is calculated.

IV. CONCLUSION

In conclusion a theoretical model for the initiation phase of the pseudospark discharge has been developed. The results of the simulation correlate with the experimental observations. The evolution of the discharge and the observed electron beam are found to be in good qualitative agreement. The model is important because the electron beam generated from HCD is basically from a plasma cathode. The emission can therefore be modeled with microscopic details which are usually difficult to obtain when associated with a metal cathode. In principle the model can be developed to predict beam parameters including emittance and brightness based on a microscopic description of collisional, dissociative and ionizational processes. The future work will include the theoretical study of beam emittance, dependence on circuits, applied voltage, gas pressure, and gas species.

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