Multi-beam-bulk model for electron transport during commutation in an optically triggered pseudospark thyratron

Hoyoung Pak and Mark J. Kushner
University of Illinois, Department of Electrical and Computer Engineering, 1406 West Green Street, Urbana, Illinois 61801

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The electron energy distribution in low-pressure pulsed power plasma switches is typically not in equilibrium with the local electric field. To simulate electron transport under these conditions a computer model has been developed and has been applied to the optically triggered pseudospark, or back-lit-thyratron (BLT). The model uses many groups of electrons divided into the "bulk" and the "beam". The bulk is represented by a fluid while the beam electrons are ballistic in nature and have not undergone significant energy-loss collisions after generation. To account for beam electrons being generated at arbitrary locations in the BLT, multiple beams are employed in the model. The commutation phase of switching in the BLT is investigated and the onset of a hollow cathode effect during switching is predicted.

Low-pressure (< 1 Torr) plasma switches are critical components of pulse power devices which require high holdoff voltages ($>$ 10's kV), large currents ($>$ 10's kA), and high rates of current rise ($> 10^{11}$ A s^{-1}). The back-lit-thyratron, or BLT, is one such device currently being developed as a possible replacement for conventional thyratrons and spark gaps.[1-9] The BLT is essentially an optically triggered psuedospark which has the switching characteristics of thyratrons and current densities approaching that of spark gaps. It mechanically consists of opposing hollow cylindrical electrodes with an axial hole, see Fig. 1. This nonplanar geometry is essential to its operation. Currents of >50 kA, $dI/dt \geqslant 10^{12}$ A s^{-1}, current densities $\geqslant$ 10's kA/cm^2, single gap holdoff voltages $\geqslant$40 kV, and jitter $\leqslant$ 1 ns have thus far been demonstrated.

The electron energy distribution (EED) in low-pressure plasma devices, such as the BLT, is typically not in equilibrium with the local electric field. The facts that the BLT is inherently multidimensional, and that the EED is not in equilibrium, make any analysis of the device difficult due to the complexity of fully resolving Boltzmann's equation. Modeling techniques must therefore be developed which contain the pertinent physics but which also include multidimensional effects. In lower pressure discharges (less than a few hundred mTorr) Monte Carlo or PIC simulations[10] have been successfully applied to analyzing nonequilibrium behavior but their extension to multiple dimensions may be difficult.[11] At higher gas pressures ($\geqslant$ 1 Torr) fluid representations in which multidimensional effects can be easily included are appropriate.[12] In fluid models, one often assumes that the EED is in equilibrium with the local electric field [the local field approximation (LFA)], or assumes that the EED can be well represented by an average energy [average energy representation (AER)], which enables some nonequilibrium effects to be simulated. Hybrid Monte Carlo fluid models are beginning to appear which combine the advantages of both methods.[13,14] The breakdown of the LFA and AER in pseudosparks such as the BLT results from the fact that there may exist a "beam" component to the EED containing ballistic electrons, much like that in a cathode fall.[9,15] In this letter we describe a computer model which simulates a BLT during the commutation phase of switching while including nonequilibrium effects resulting from ballistic electrons.

Our model is a 2 1/2-dimensional time-dependent simulation in which electrode geometries and material properties may be arbitrarily specified, and which uses the

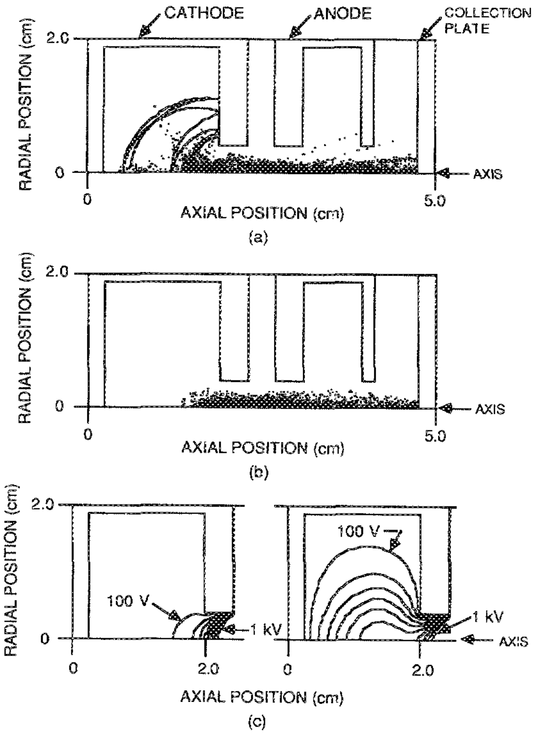

FIG. 1. Electron current density as a function of position in the BLT 30 ns after triggering. The gas is H_2 at 0.4 Torr with 10 kV holdoff. (a) Current density of the secondary beams (maximum value 8 A cm^{-2}) and typical primary beam trajectory. (b) Advective bulk electron flux (maximum value 60 A cm^{-2}). (c) Electric potential contours before triggering (left) and at switching (right). The contours are at 100 V intervals. The trajectory of the primary beam shows that these electrons are usually trapped in the hollow cathode. They undergo collisions which generate secondary electrons, a fraction of which are accelerated as secondary electron beams, shown by the dots, and emanate from the cathode.

"beam-bulk" method for electron transport.[16] The bulk represents lower energy electrons for which fluid equations may be used for their transport. The beam contains electrons which may have ballistic trajectories and are not well described by fluid equations. Beam-bulk models for radio frequency and dc discharges,[16,17] and the conduction phase of the BLT[18] have been reported in which the beam is composed of electrons emitted from the electrodes or generated in the sheaths. Our model differs from those works in that we have extended the concept to multiple dimensions, thereby requiring many beams, and that the beam component is actually composed of two groups of beam electrons, a primary group and a secondary group. The primary beams are generated at the cathode, while the secondary beams are created in the bulk plasma adjacent to regions of high electric field gradients.

The BLT is triggered by illuminating the back side of the hollow cathode with UV light and generating photoelectrons. During commutation, electrons continue to be emitted from the cathode due to ion bombardment and plasma generated photons. In our model all electrons emitted from the cathode surface are initially classified as primary beam electrons. The trajectories and velocities of the primary beam electrons are then obtained by integrating their equations of motion. The paths of the beam electrons change as space charge or gradients in conductivity deform the local potential, which is determined by solving Poisson's equation. Beam electrons that undergo inelastic collisions with the neutral gas are taken out of the beam component and placed into either the bulk or a secondary beam. This allocation depends in large part on the location of emission. Electrons which are emitted in or near regions of high electric field gradients are placed into secondary beams. Secondary beams may also contribute to other secondary beams, so once created are treated in the same manner as primary beams.

To model the trajectories of the beam electrons, we work on a separate computational grid from that used for transport of the bulk electrons and for the electric potential, which is cylindrical with azimuthal symmetry. The grid for the beam electrons consists of a mesh parallel to the beam trajectories. A beam, labeled i, is associated with every source location, whether it is at the cathode or in the plasma. The beam follows a path $\mathbf{s}_i$ on the grid. The (r,z) position on the bulk grid underlying the mesh point j along beam trajectory $\mathbf{s}_i$ is $\mathbf{r}(s_{ij})$. The beam electron flux in the beam i at location s_{ij} is

$$\Gamma_i(s_{ij}) = A(s_{ij})\Gamma_{i0}\exp\left(-\int_{\mathbf{s}_i} N\sigma_T(\epsilon(s_{ij}))ds\right), \qquad (1)$$

where Γ_{i0} is the initial beam flux for trajectory i, N is the neutral gas density, σ_T is the total inelastic electron scattering cross section, and the integral is along the path i to location s_{ij}. The initial beam flux Γ_{i0} for primary beams includes the emission of electrons due to all processes at the cathode. For secondary beam electrons, it is the sum of all contributions made by all beam electrons. The energy of the beam, $\epsilon(s)$, is obtained by integrating the equations of motion. The integral in Eq. (1) accounts for the loss of electrons out of the beam by collisions.

In the absence of collisions the total electron beam current along a given trajectory is conserved. The cross-sectional area of the beam, though, may change, thereby changing the magnitude of the flux in a given beam while the total current in the flux tube is conserved. $A(s_{ij})$ in Eq. (1) is the ratio of the cross-sectional area of the flux tube at its source to that locally, and accounts for these effects.

The time rate of change of the bulk electrons at location $\mathbf{r}_b$ due to the collisions of the beams is

$$\left(\frac{\partial n_e(\mathbf{r}_b)}{\partial_t}\right)_b = \sum_{i,j}(1-\gamma_{ij})\{N[\sigma_T(\epsilon_{ij}) + \sigma_I(\epsilon_{ij})]\Gamma_{ij}R_v(s_{ij})\}\delta[\mathbf{r}_b - \mathbf{r}(s_{ij})], \qquad (2)$$

where the sum is over beam i and beam locations j, σ_I is the ionization cross section, and R_v is the ratio of the volume of the computational cell of the beam to that for the bulk electrons. γ_{ij} is the fraction of ionizations which feed secondary beams (as opposed to the bulk), and represents the proportion of secondary electrons which are emitted along the trajectory of the local beam and therefore are not decelerated by the local field. Its value is typically 0.1. The transport of bulk electrons and ions is described using conventional fluid equations as in our previous model.[19] As an improvement to that model, we include the momentum and energy conservation equations to obtain the advective velocity and average energy of the bulk electrons, $\overline{\epsilon}$. Transport coefficients are then a function of $\overline{\epsilon}$. The contribution of beam electrons to $\overline{\epsilon}$ is

$$\left(\frac{\partial(n_e\overline{\epsilon})}{\partial_t}\right)_b = \sum_{i,j}(1-\gamma_{ij})\sum_m [N(\epsilon_{ij}-\Delta\epsilon_m)\sigma_m(\epsilon_{ij})] \times\Gamma_{ij}R_v(s_{ij})\delta[\mathbf{r}_b - \mathbf{r}(s_{ij})], \qquad (3)$$

where the sum is over inelastic processes having energy loss $\Delta\epsilon$.

The beam-bulk model has been used to simulate electron transport during the commutation phase of switching in the BLT. The electrodes of the BLT we modeled consisted of a cylindrical hollow cathode and hollow anode with a central hole and a collection plate for the beam, as shown in Fig. 1. The cathode was grounded, and the anode and collection plate were charged to 10 kV. The gas is hydrogen at 0.4 Torr unless stated otherwise. The anode-cathode separation was 0.4 cm, and the radii of the cathode and anode holes were 0.4 cm. We define the switch to be closed when its resistance falls to $\simeq 10\ \Omega$. Switching is initiated by illuminating the inner backside of the cathode by a laser (13 ns FWHM).

The secondary electron beam flux (displayed using a dot plot) and one of the trajectories of the primary electron beams (displayed using lines) 60 ns after illumination of the cathode are shown in Fig. 1(a) as a function of position. The advective bulk electron flux is shown in Fig. 1(b). Primary beam electrons emitted from the cathode tend to become trapped inside the hollow structure with only a small fraction escaping from the cathode. Primary beam electrons oscillate within the potential trap formed

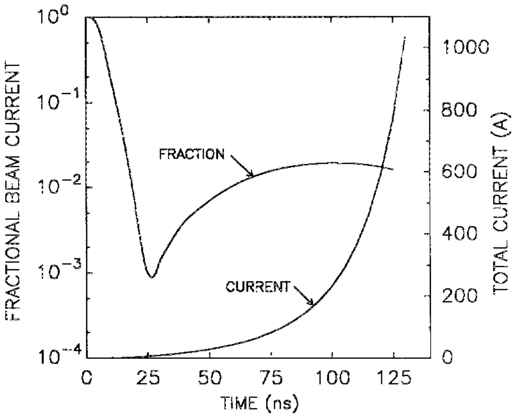

FIG. 2. Total current and the fraction of the current in the beam component at the anode.

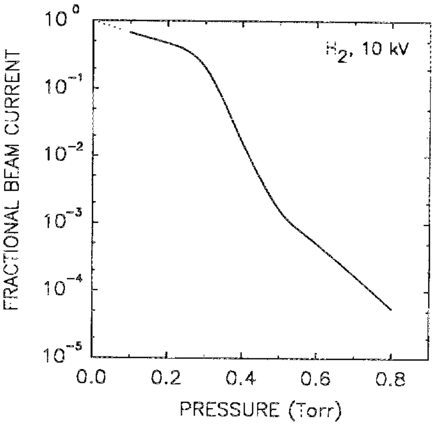

FIG. 3. Fraction of current carried by the beam component at the anode as a function of gas pressure at the end of commutation.

by the hollow cathode and generating both bulk and secondary beam electrons, as shown in Fig. 1(c). This is the well known hollow cathode effect.[20] Although the bulk electrons have a directed component, they have lower energies and a higher emittance than the beam. The beam of electrons which are typically detected along the axis of experimental devices consist, according to our model, dominantly of secondary electrons. The secondary electrons are generated in the vicinity of the cathode hole, and are not subject to the hollow cathode effect. These devices operate similarly to the hollow cathode beam generators developed by Rocca *et al.*[21]

The total current and fractional current in the beam are shown in Fig. 2 as a function of time from the onset of triggering to switch closure. Early during commutation when the cathode is being illuminated, current is dominantly in the beam but that dominance dies out after the illumination ends. The fractional beam current then builds as secondary electrons are generated near the cathode hole. Beam current at switch closure is 16.7 A, representing 1.6% of the total, which agrees well with the experimental results of Kirkman and Gundersen.[22] After switch closure, the voltage begins to collapse and the fraction of current in the beam begins to decrease. Due to the decreasing rate of collisions of the beam with decreasing gas pressure, one would expect a larger fraction of the total current to be carried by the beam at lower pressures. This scaling is shown in Fig. 3 where the fractional beam current at the anode at switch closure is plotted as a function of gas pressure. At pressures <0.2 Torr, the current is composed primarily of beam electrons, whereas at pressures $\geqslant 0.8$ Torr, the beam makes a neglible contribution. The fractional beam current at any pressure, though, increases with increasing hold-off voltage.

In conclusion, we have developed a model which uses two groups of electrons, bulk and multiple beams, to describe the transport of electrons in an optically triggered pseudospark. The onset of a hollow cathode effect during commutation, which has been inferred from experimental results, is predicted by the model. The majority of primary beam electrons are trapped by the hollow cathode effect but do generate secondary beam and bulk electrons which may escape from the cathode. Our results indicate that experimentally measured beam currents are composed primarily of secondary beam electrons.

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