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Improvement on the Physical Description of the Boundary Conditions between the Hollow Cathode Region and the A-K Gap in a Transient Hollow Cathode Discharge

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ABSTRACT

An important connection between the main gap and the hollow cathode region (HCR) in a pulsed hollow cathode discharge is in the positive ions created in the main gap which subsequently enter the HCR through the cathode aperture. These energetic ions control the ionization growth rate inside the HCR through both secondary electron production and in the formation of a positive space charge immediately behind the cathode aperture. The result is the creation of a highly localized plasma on axis inside the HCR, from which the injection of a large electron flux leads to the final breakdown. A 2-D fluid code reported previously modelled the ionization growth within the HCR using swarm parameters based on a local field approximation and the growth of this on axis plasma source was predicted. The model adopted to treat the ion flux was based on continuity with the electron flux leaving the HCR. This assumption ignores the ionization events within the main gap. In this paper, we report on a new model which tackles the physics of collisions in the main gap using a 1-D description in order to return a proper ion flux for the 2-D calculation in the HCR. The methodology is computationally efficient and corrects the discrepancy observed in the relationship of breakdown delay and operating pressure.

Introduction

In a high voltage low pressure discharge, the collision mean free path of an electron under the applied field is large compared with the inter-electrode separation and Townsend ionization is not sufficient to lead to the charge multiplication necessary for the breakdown of the gas. Secondary events must take place in order to produce an electron population large enough for discharge formation. In a presence of a hollow cathode geometry, the situation can be completely different. Within the hollow cathode region (HCR) the ionization and collision parameters are drastically different as the electric field inside is smaller and the lower E/N value favours local ionization growth. The magnitude of this leakage electric field is determined by the cathode aperture and has a crucial importance. This small but finite field ensures the creation of events within the HCR which control the initiation of breakdown in the main gap region. Thus, the actual breakdown formation process in the main gap is coupled to events occurring within the HCR. An important connection between the main gap and the HCR is in the positive ions created in the main gap which subsequently enter the HCR through the cathode aperture. These energetic ions control the ionization growth rate inside the HCR through both secondary electron production and in the formation of a positive space charge immediately behind the cathode aperture. The result is the creation of a highly localized plasma point on axis within the HCR. It is the injection of a sufficiently large number of electrons from this plasma source into the main gap which leads to the formation of the breakdown channel in the main discharge region.

Previous Work

In an earlier work, we described the simulation of the ionization growth phenomena in a transient hollow cathode discharge. The 2-D numerical code, SPARK 2, was developed to model the ionization growth phenomena within the HCR region.[1] It is based on a fluid model using swarm parameters in local field approximation. The model comprises the time-dependent continuity equations for ions and electrons with the equations of motion replaced by a drift parameter. Both primary and secondary ionization processes are included. In addition Poisson's equation is solved for the whole of the HCR taking into account of both the detailed geometry and the effect of space charge using a boundary-fitted coordinate technique. The coupling between the A-K gap and the HCR is treated by a continuity assumption. The model produces good agreement with the general features of the ionization growth process inside the hollow cathode region, including the formation of a point like plasma region immediately behind the hollow cathode hole. It identifies the importance of the divergence of the electron flux at this region and the resulting ion space charge in enhancing the local ionization growth, thus controlling the electron beam production and the breakdown formation in the main gap. Some of the key prediction of the code and the corresponding experimental observations are shown in Table I. As it is shown, the major short-coming in the simulation is in the dependence of ionization growth with pressure.

Table I	SPARK 2 Predictions	Experimental Observations
	point like plasma formation on axis inside HCR	☑
	on axis high current density electron beam injection into A-K gap	☑
	rate of ionization growth increases with voltage	☑
	rate of ionization growth increases with size of cathode aperture	☑
	rate of ionization growth decreases with thickness of cathode electrode	☑
	rate of ionization growth decreases with A-K gap spacing	☑
	rate of ionization growth increases with initial charge distribution (pre-ionization)	☑
	rate of ionization growth decreases with pressure	☒

In the simulation, the role of primary and secondary coefficients in current density growth were examined. The flux of ions, returning through the hole from the main gap into the HCR, was found to be of great importance in controlling the ionization within the HCR and therefore the delay to breakdown. The treatment of this flux in the previous model was simplistic, using continuity argument to balance the ion flux with the flux of electrons leaving the HCR. The assumption of isolating the physics in the A-K gap, is not entirely satisfactory. It assumes that the amount of fast ions is related totally to the electron leaving the HCR which in turn means that the dependence is only on ionization phenomena within the HCR. This assumption is the underlying physics which leads to the code predicting that the breakdown delay would be increased as the operating pressure is increased, which is opposite to what is observed in experiments at pressure below 1 Torr. The prediction, however, is entirely physical for the condition within the HCR. The reason being that the ionization coefficient is increasing with increasing E/N at the regime of operation inside the HCR and for a constant operating voltage, when the operating pressure is increased, the E/N decreases and hence the ionization rate also decreases.

Present Model

In a more realistic assessment, the presence of the coupling between the A-K gap and the HCR means that the ionization within the main gap will always be augmented by the injection of electrons from the HCR while the ionization within the HCR will be influenced by the fast ions, created in the main gap and returning into the HCR. For the treatment of the high E/N condition in the A-K gap, the use of a local field approximation is no longer valid. A Monte Carlo approach was used in the work of [2] in order to describe the collision parameters in the main gap in 2-D but the method is highly computational intensive even at moderately high E/N values. To resolve this problem, the new model tries to tackle the physics of collisions in the main gap in 1-D and hence return a proper ion flux into the HCR, which remains being modelled in 2-D. In this way, the overall ionization growth includes a suitable description of the ionization in the A-K gap.

In the present scheme, the treatment of the ion production rate is based on the injected electron beam from the HCR. The ionization is described in terms of collision mean free path and ionization cross-section in the main gap region. We take into account the flux of ions returning from the main gap to the HCR. This treatment of the collisions in the main gap is done by an additional subroutine coupled to the main calculation. The stages of this subroutine are as follows:

1. The main gap is divided into a fine mesh with cell dimensions which are of the same order of magnitude as the mean free path for elastic collisions, and smaller than the mean free path for ionization in the pressure range relevant to our conditions.
2. The potential in each mesh point is calculated by the Poisson solver and thus the electric field in each mesh point is known.
3. We enter the subroutine with the rms values of the velocity and flux of the electrons traversing from the HCR into the main gap.
4. In each cell five species are treated: (I) electrons having no collisions in the cell. (II) electrons having only ionizing collisions in the cell. (III) electrons having only elastic collisions in the cell. (IV) electrons newly born in the cell. (V) positive ions newly born in the cell.
5. The movement of these species is treated using Newton's laws of motion and the cross sections for ionization and momentum transfer.

   - The electrons are moved from cell to cell. In each cell new electrons and a same number of positive ions are created through ionization.

   - The new electrons join the total electron flux advanced to the next cell.

   - At the end of this stage, the flux and velocity of electrons accelerated towards the anode and of ions drifting towards the HCR and entering the hole, are known at each mesh point.
6. The positive ions are advected to the hole, taking into account their drift velocity and a "loss cone" of ions removed through transverse diffusion. The ion flux is accumulated at the HCR boundary.

7. The rms values of the ion flux and velocity at the HCR boundary is calculated and their density derived.

8. The value of the ion density on the HCR boundary is fed back into the main program and added to the ion density in the cells inside the HCR adjacent to the boundary.

Results

As it was expected, the major change in the incorporation of the collisions in the main gap region is to resolve the discrepancy of the ionization growth rate with pressure. This is illustrated in Fig.1, which shows the on axis current density leaving the HCR and entering into the main gap region for 5 different pressures between 100 mTorr and 800 mTorr. Only the periods when this current density is above 10 mA.cm^{-2} are shown. The simulation is for an A-K gap of 10 cm at an applied voltage of 25 kV. The hollow cathode region is separated by an aperture of 5 mm diameter and 6 mm depth. Two minimum time step limit of 2 ps and 0.1 ps have been used in the runs in order to assess the possible errors introduced by high drift parameters in the transport of the fast ions at very high E/N values. In general, for a given pressure, the data for higher and lower voltages show similar trend. At low pressure, the delay to breakdown becomes a sensitive function to the exact value of the secondary coefficient for electron production by ion impact which takes place primarily at the wall opposite to the cathode aperture.

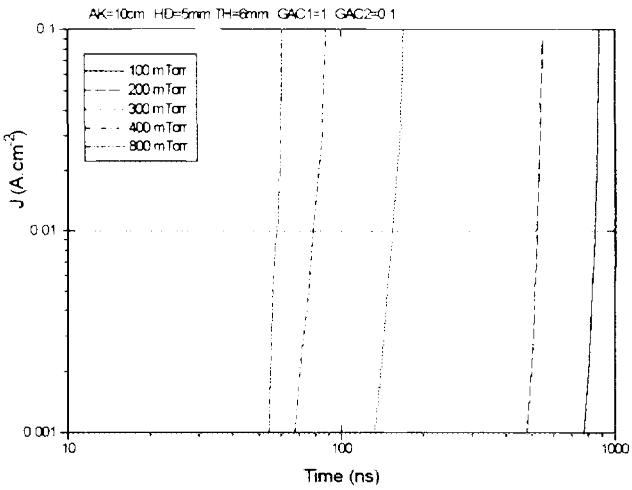

Fig.1 Growth of on-axis current density for different operating pressures

Discussion

While the present treatment of the collision parameters in the main gap is relatively simple, the limitation of fluid code has been overcome by separate treatment of ionization growth in the main gap region where the fluid approximation is not valid. The overall simulation of ionization growth in a transient hollow cathode discharge now includes a coupled description of the ionization processes in both the main gap region and the HCR. Correct dependence of the rate of ionization growth with pressure is obtained when ion feedback is included. The methodology is computationally efficient and allows the treatment of discharge condition at very high E/N and very low pressure conditions. The 1-D description, while less precise, enables more extensive set of collision phenomena in the A-K gap region to be treated. It also allows different geometry of the hollow cathode and different coupling geometries to be explored with realistic computational resources.

Reference

[1] K. Mittag, P. Choi & Y. Kaufman, Nucl. Instrum. & Methods, A292(1990)p.465

[2] J.P. Boeuf & L. Pitchford, IEEE Trans. Plasma Sci., 19(1991)p.286