

Particle-in-cell simulation study of PCE-gun for different hollow cathode aperture sizes

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Pseudospark (PS) discharge is promising source for high brightness and high intensity electron beam pulses. In the present paper, an effort has been made to analyse the temporal behaviour of discharge current, applied voltage, plasma density in the PS discharge based PCE-Gun at different hollow cathode aperture sizes using 3-D particle-in-cell (PIC) simulation code "VORPAL". The peak discharge current in the PS discharge is a function of hollow cathode dimensions. The plasma generation process by self ionization discharge is examined at different operating conditions. Argon is taken as the background neutral gas. It has been observed that the decrease in the aperture size from 8 mm to 3 mm increases the discharge current, the electron confinement time and the plasma density.

Keywords: Hollow cathode, Pseudospark discharge, Plasma electron gun, Self ionization, VORPAL

1 Introduction

Pseudospark (PS) discharge is an axially symmetric, self sustained, transient, low pressure gas discharge in a hollow cathode (HC) with a planar anode configuration. The PS discharge¹ is capable of producing a rapid current rise up to 10^{12} A/s with the current densities greater than 10^4 A/cm². The PS discharge is characterized by very rapid breakdown phase during which high density particle beams can be extracted. Based on these characteristics, it is widely used in plasma processing, ion etching, surface processing, laser, X-ray generation, microwave generation, etc.^{2,3}. In fact, the PS is, generally, composed of a hollow cylindrical cathode with a hole on the axis facing the planar anode. The aperture size is of few millimetre orders. The PS discharge operates on the left branch of Paschen's curve (low pressure, high voltage situation), where the reduced electric field (E/N) is $\sim 10^{11}$ Vcm² which shows the scaling of the breakdown voltage as a function of $P \times d$, where P is the gas pressure and d is the anode-cathode gap distance^{4,5}. Generally, the behaviour of Paschen's curve is similar for all kind of gases. The PCE-Gun has several advantages over conventional electron guns⁶. In applications such as in plasma assisted microwave sources where neutral gas or plasma is

present in the slow wave structure (SWS). A plasma cathode can be used to eliminate damage and erosion of the cathode surface by back ion bombardment⁶. It has been reported that plasma assists electron beam propagation inside the plasma filled drift region of microwave sources and enhances the overall efficiency of microwave generation⁶⁻⁸.

During the PS discharge, low temperature plasma is formed as a plenteous source of electrons and can be regarded as a low work function surface that facilitates electron extraction^{8,9}. However, in spite of its simplicity, the operation of the PS discharge depends on many parameters like the cathode material, dimension of cathode, gap distance between cathode and anode, gas type and pressure, etc.^{9,10}. The PS discharge can be initiated by two means. The first one is the self discharge method in which gas breakdown is initiated in the discharge gap between the cathode and anode when sufficient breakdown electric field is reached in the gas gap. This type of discharge starts due to the presence of cosmic electrons. In fact, any sample of gas under normal condition contains an average of 10^9 m⁻³ electrons and ions due to ultraviolet, cosmic radiations, etc¹. In this region, the mean free path for ionizing collisions of the electrons starting from the cathode is comparable

or larger than the electrode separation, making an avalanche ionization type process and consequent electrical breakdown. An electron beam is generated during this phase with the beam voltage being nearly equal to the applied voltage. In the second type discharge method, a trigger source is used to inject sufficient seed electrons to initiate the discharge process which is a controlled PS discharge process. Indeed two types of electron beams have been known which is produced in the PS discharges: a high-energy pulsed beam during initiation of the discharge and a low-energy long pulse beam during steady-state conduction of the discharge. In the present paper, the temporal behaviour of discharge current, applied voltage and plasma density arriving at the anode for different HC aperture sizes, is analyzed. The discharge current, the electron confinement time and the plasma density increase with decrease in aperture size from 8 mm to 3 mm.

2 Simulation Model Description

The current investigation is performed to analyse the PS discharge using 3-D electrostatic kinetic PIC simulation code 'VORPAL' which provides better understanding of the discharge kinetics. It is well validated software developed at Tech-X Corp. It solves the fields on the grid and calculates the particle trajectories including self-consistently the effects of charged particles on the fields with respect to the space and time variations. It is a new plasma simulation code designed using advance C++ techniques. The plasma model includes both PIC and fluid models. In this software, a single code can be used to simulate 1D, 2D and 3D systems with no loss of performance¹⁰.

Monte Carlo Collision (MCC) Model has been used for all the simulations. The data for electron collision cross-section is taken from Tech-X corp. inbuilt library. For secondary electron emission, ion impact has been considered and the parameters require for secondary emission from the wall is also taken from Tech-X corp. inbuilt library. The parameters used for ion induced secondary electron models assume stainless steel cavity and electrodes. The simulation parameters such as cell size, time step and super particles have been selected to minimize the impact of fluctuations and grid heating and also to increase the simulation speed. The kinetic simulations at different operating conditions have been carried out for different times to analyse the peak electron current.

The simulation model has a hollow cathode cavity with inner diameter (C_{id}) = 50 mm, outer diameter (C_{od}) = 52 mm and cavity depth (C_d) = 57 mm. The anode-cathode gap (G_{ca}) = 3 mm and cathode wall thickness (C_{th}) = 3 mm. The small cathode aperture (C_a) facing the anode plate is variable in the simulation study. The anode is a planar disc having diameter (A_d) = 52 mm. Perspex is used as the insulating material to separate the hollow cathode cavity and planar anode. Argon is used as the background neutral gas for all the simulations. The 2-D view of the simulation model is shown in Fig. 1. To analyse the temporal behaviour of discharge current, applied voltage and plasma density at the anode, the hollow cathode dimension and the aperture size have been varied in the simulation.

3 Computational Results and Discussion

Variation in the dimension of HC cavity of PS discharge based PCE-Gun generally changes the peak discharge current and time of peak discharge current appearance at anode. It has been reported that number of seed electrons¹ needed to initiate a discharge is of the order of 10^9 - 10^{10} m^{-3} . In this simulation model, 10^9 m^{-3} electrons have been distributed in the PCE-Gun with 2.5eV random thermal energy which represents the presence of electrons in the system due to ultraviolet, cosmic rays, etc.

It has been observed that before breakdown, the charging voltage is uniformly distributed between the cathode and anode gap and also penetrated up to some extent in the aperture region. The penetration of the electric field into the hollow cathode is weak due to the small dimension of the cathode hole, typically 3 to 8 mm. The penetration of the electric field inside the aperture is dependent on the aperture diameter and depth. The electric field penetration will be more for larger diameter of the aperture. In fact, the electrons

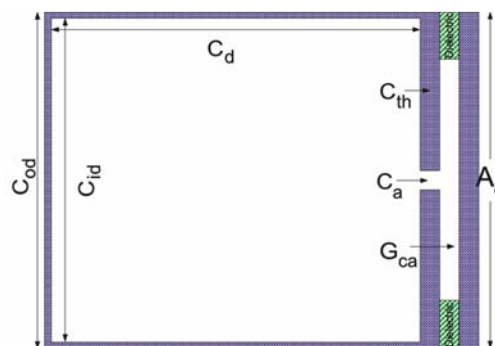


Fig. 1 — Schematic 2-D view of PIC kinetic simulation model

in vicinity of the cathode hole are extracted towards the anode and undergo ionizing collisions in this gap region. Initially, the ionization rate is very small causing small current at anode because the electrons generated by ionization drifted towards anode without ionization. The potential close to the cathode aperture increases with time due to the build-up of an excess space charge of positive ions. This space charge region increases the electric field penetration inside the hollow cathode and increases the number of ionizations⁸. This changes the potential distribution and the field distribution inside the hollow cathode cavity and also in the main gap. As the space charge region inside the cathode increases, the field at anode side decreases accordingly. The potential distribution in the PCE-Gun is shown in Fig. 2 (a-d) for 0 ns, 17 ns, 21 ns and 24 ns, respectively.

The positive charge region grows and further increases the electric field penetration inside the hollow cathode cavity with time as shown in Fig. 2(b). Further, due to this large penetration of electric field inside the cathode, more electrons get

accelerated towards anode causing more avalanches of ionization. This results in further increase of discharge current at the anode. Since the positive space charge field leads to a decrease in the potential difference between the cathode and anode, the electrons no longer accelerated from the cathode to the anode and slowed down in the region of positive space charge inside the cathode cavity. The plasma penetrates inside the cavity and the fields contracted along the surface which results in larger anode voltage appearance inside the cavity as shown in Fig. 2 (c). At this point, the pendulum electrons come into effect having radial velocity more than axial velocity. They have gained sufficient KE for higher collisional ionization inside the HC cavity and generate more electrons before getting diffused through the hole¹⁰.

The PIC simulation study has been carried out to analyse the effect of hollow cathode aperture on the discharge characteristics of PCE-Gun. Variation in the hollow cathode aperture plays a very significant role on electron beam generation and extraction¹¹.

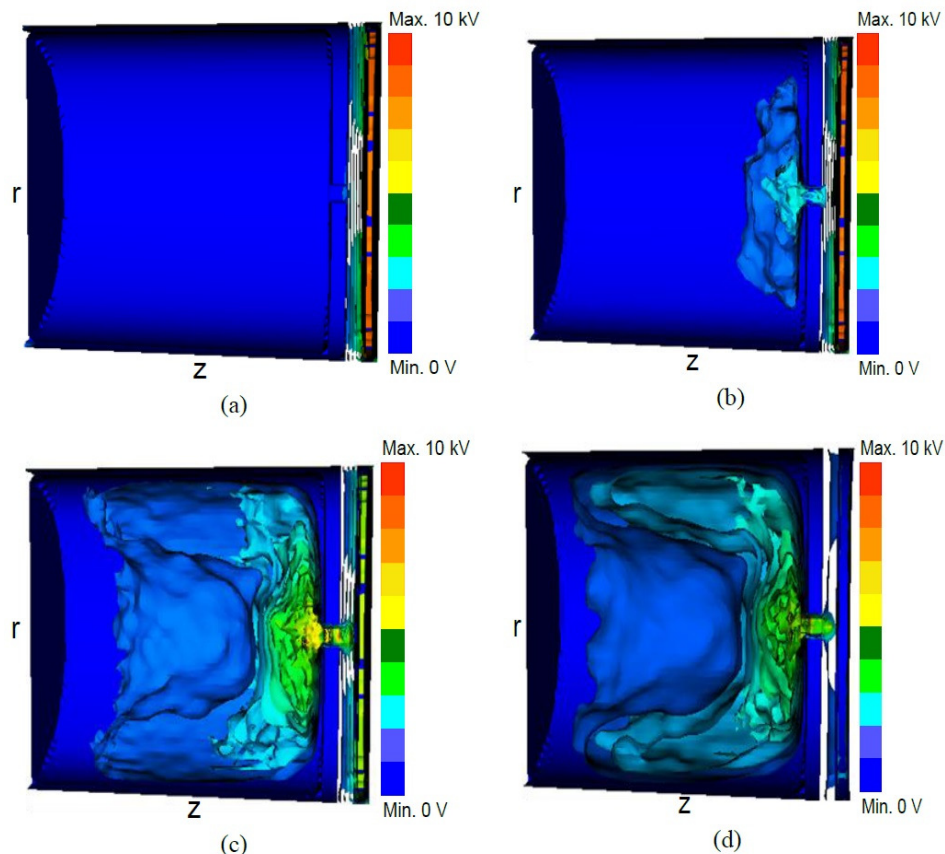


Fig. 2 — Potential distribution in PCE-Gun for 5 mm aperture size at different simulation times, (a) 0 ns (b) 17 ns (c) 21 ns (d) 24 ns (Applied voltage: 10 kV)

Simulations have been carried out by varying the size of aperture from 3 mm to 8 mm. The temporal behaviour of discharge current for different aperture sizes has been shown in Fig. 3 keeping same all other parameters such as applied voltage, gas pressure, etc. The simulation results clearly show that the discharge current increases with the decrease in the aperture size from 8 mm to 3 mm.

Actually, the hollow cathode cavity design facilitates the higher electrons confinement time. The aperture size plays a major role in confinement of the electrons. The electron confinement time increases with decrease in aperture size. At higher applied voltages, formation of positive space charge region near the aperture takes less time. This positive space charge region increases the electron confinement time, which results in a high plasma density formation inside the cavity¹¹. The higher plasma density supplies more electrons due to which a higher discharge current appears at the anode. While in case of larger aperture size, the electron confinement time is less. In fact, due to large area of aperture, the extraction of electron is high which results in the less density plasma formation and appearance of low discharge current at anode. The variation in the peak discharge current at different applied voltages for different aperture sizes is shown Fig. 4.

It is also very important to know the electron confinement time in the HC cavity which plays significant role in high density electron beam generation. It has been observed that the electron confinement time is higher for lower aperture sizes^{1,11}. The appearance of the peak discharge current at the anode delayed with increase in the electron confinement time. Several simulations have been run

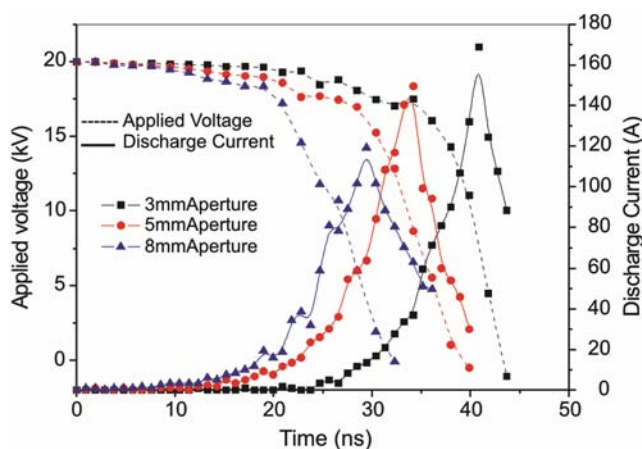


Fig. 3 — Temporal behaviour of applied voltage and discharge current for different hollow cathode aperture sizes at 20 kV

to analyze the variation in the total time of the appearance of peak discharge current at the anode for different aperture sizes keeping all the other simulation parameters same. The total time taken to reach the maximum discharge current for different aperture sizes at different applied voltages is shown in Fig. 5.

The breakdown has been initiated in the cathode anode gap. Initially, the discharge is not very efficient and the plasma density is very low. The secondary electrons generated by the volume ionization are accelerated and absorbed by anode, leaving behind a growing ion-space-charge field. After some time, the field penetrates inside the cavity leading to the ionization of neutral gas and increase in the plasma density. Fig. 6 clearly shows that the plasma density inside the cavity increases rapidly with the anode voltage inside the cavity.

In the PS discharges, the electrons confinement time is greater in low aperture size as compared to

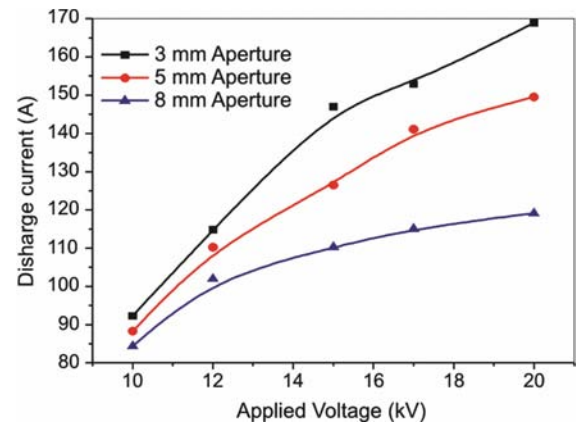


Fig. 4 — Variation of peak discharge current for different aperture sizes at different applied voltages

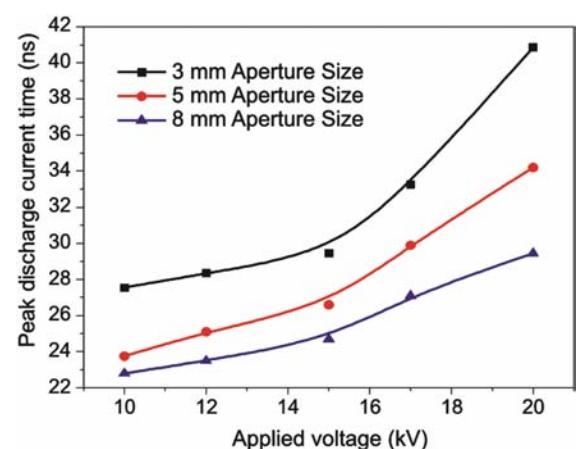


Fig. 5 — Variation of peak discharge current time for different aperture sizes at different applied voltages

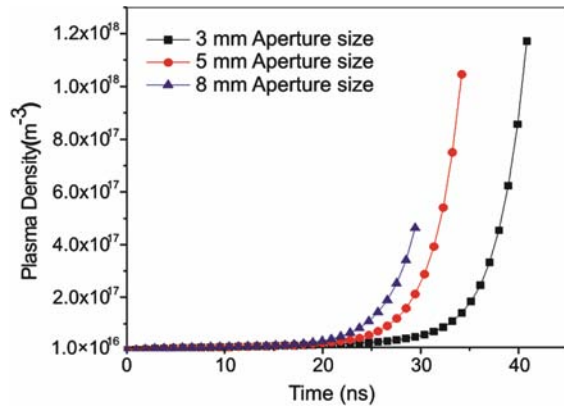


Fig. 6 — Plasma density variation for different aperture sizes at 20 kV applied voltage

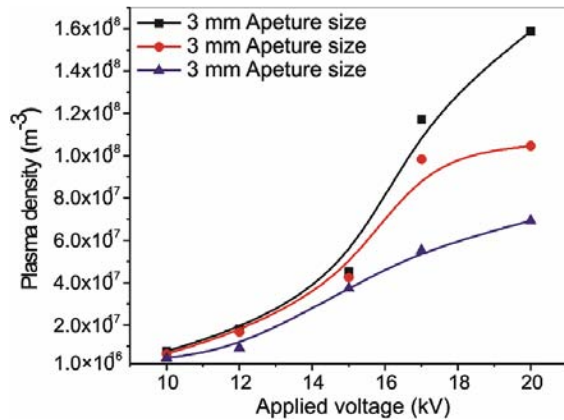


Fig. 7 — Plasma density for different aperture sizes at different applied voltages

larger dimension. As the confinement time increases, the number of collisions made by electron also increases which results in a higher plasma density. The plasma density for different aperture sizes at different applied voltages is shown in Fig. 7. This shows that the plasma density is higher for the lower aperture size. We have observed the electron density $\sim 10^{18} \text{ m}^{-3}$ in the PCE-gun which is sufficient for the PS discharge based cold cathode plasma electron gun development for plasma assisted microwave sources.

4 Conclusions

A single gap pseudospark sourced plasma cathode electron gun (PCE-Gun) for different aperture sizes has been successfully simulated by using particle-in-cell software VORPAL. The plasma discharge parameters like discharge current, discharge voltage, potential distribution, peak discharge current time and plasma density has been analyzed for 3 mm, 5 mm and 8 mm aperture sizes at different applied voltages. It is found that the discharge current and plasma density increase with decrease in aperture size from 8 mm to 3 mm. It has also been observed that the electron confinement time is higher at the lower aperture size.

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