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A multiple gap plasma cathode electron gun and its electron beam analysis in self and trigger breakdown modes

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In the present paper, a pseudospark discharge based multiple gap plasma cathode electron gun is reported which has been operated separately in self and trigger breakdown modes using two different gases, namely, argon and hydrogen. The beam current and beam energy have been analyzed using a concentric ring diagnostic arrangement. Two distinct electron beams are clearly seen with hollow cathode and conductive phases. The hollow cathode phase has been observed for ∼50 ns where the obtained electron beam is having low beam current density and high energy. While in conductive phase it is high current density and low energy electron beam. It is inferred that in the hollow cathode phase the beam energy is more for the self breakdown case whereas the current density is more for the trigger breakdown case. The tailor made operation of the hollow cathode phase electron beam can play an important role in microwave generation. Up to 30% variation in the electron beam energy has been achieved keeping the same gas and by varying the breakdown mode operations. Also, up to 32% variation in the beam current density has been achieved for the trigger breakdown mode at optimized trigger position by varying the gas type. [http://dx.doi.org/10.1063/1.4943293]

I. INTRODUCTION

In the recent past, pseudospark (PS) discharges have been utilized for different applications, such as pulsed-power switching, electron and ion beam generation, free electron masers, extreme-ultraviolet radiation sources, and micro-thrusters due to their unusual and interesting discharge properties.[1–8] The PS discharge is an axially symmetric, self-sustained, transient, low pressure (typically 50–500 mTorr) gas discharge. It has a hollow cathode/planar anode configuration, which operates on the low pressure side of the hollow cathode analogy of Paschen curve.[2] During the PS discharge, the plasma is formed as a copious source of electrons which can allow extraction of electron beam depending on the applied voltage.[9]

The generated electron beam can be propagated in the gaseous atmosphere where low energy diverging electrons usually ionize the gas.[9] When the space charge neutralization balances the repulsive electrostatic force, there is formation of an ion channel on the envelop of the electron beam and beam is self-consistently focused by the self-magnetic field of the electron beam.[7–11] This helps in reducing the requirement of external magnetic field for focusing the electron beam and is highly useful for compact and light weight microwave sources.[10] Nevertheless, the control of the electron beam energy and beam current in the hollow cathode phase of the PS discharge based plasma cathode electron (PCE) gun is quite challenging. The operational range of the microwave source requires effective control of beam energy during the hollow cathode phase[2] and its interaction mechanism with radio frequency (RF) wave.[3] Worldwide efforts are underway and different PCE guns have been researched.[1–12]

In this paper, a multiple gap plasma cathode electron (MG-PCE) gun is presented which has been operated in self and trigger breakdown modes. Accordingly, electron beam analysis has been carried out for two different gases (i.e., argon and hydrogen). The generated electron beam has clearly shown hollow cathode phase (low current density, high energy) followed by conductive phase (high current density, low energy). Basically, the hollow cathode phase is the starting point for the secondary electron emissions from the interior surfaces of the cathode, which sustains the discharge.[13] During their drift towards the anode, the resultant secondary electrons and seed electrons cause excitation and ionization during the collision process with the gas in the main gap, however, with a small probability because ionization mean free paths are comparable to or larger than the dimensions of the discharge.[13] Initially, ionization occurs in the main gap and also inside the hollow cathode backspace where the seed electrons attain energy greater than the ionization potential before they exit the hollow cathode. These resultant electrons get accelerated by the applied voltage out of the cathode cavity through the aperture and it further results into generation of highly intense and energetic electron beam from the anode aperture.

The emphasis is laid on the effective control of the electron beam energy and electron beam current in the hollow cathode phase operation of the PS discharge by changing different breakdown mechanisms and discharge operation conditions without any geometrical changes. The beam energy is effectively controlled up to 30% of the applied potential during short pulse operation of the developed MG-PCE gun whereas the beam current is controlled up to 32% by changing the gas type in trigger breakdown mode at the same operating conditions. Section II illustrates the experimental setup and diagnostic arrangements whereas Section III contains results and discussion. Finally, the obtained results are concluded in Section IV.

II. EXPERIMENTAL SETUP AND DIAGNOSTIC ARRANGEMENTS

The schematic view of the experimental setup is shown in Fig. 1. The developed MG-PCE gun comprises of a hollow cathode of 50 mm dia and 54 mm length, floating anodes of dia 30 mm and thickness 3 mm, insulators of dia 120 mm and thickness 5 mm, and anode disc of dia 50 mm and thickness 3 mm. A single aperture of size 3 mm on hollow cathode and planar anode surfaces have been cut in the circular form. The three floating electrodes with same circular aperture size of 3 mm are placed with a gap spacing of 3 mm in between the hollow cathode and planar anode disc that are isolated by intermediate Perspex having central aperture size 5 mm. The 2D-schematic view of the MG-PCE gun is shown in Fig. 2. The developed gun assembly has been connected with the drift space region for its characterization which is a circular glass tube (see Fig. 1). Before plasma discharge creation, the entire assembly has been evacuated up to base pressure $\sim 10^{-6}$ Torr with the help of turbo molecular pump (Pfeiffer Model TC 400) and rotary pump (Pfeiffer Model Duo 5M). Ar and H_2 gases are filled inside the MG-PCE gun using two separate control needle valves (Swagelok C 79921).

Successive breakdown is achieved between the cathode and floating anodes (see Fig. 2). These floating anodes are equally spaced between insulators of the gun assembly for similar potential distribution during the breakdown. It leads to delay in breakdown of the applied gap voltage between the hollow cathode and the anode. This further enhances hold-off voltage and the number of gaps is decided accordingly. Due to delay in the breakdown voltage and also successive breakdown between the gaps, the field penetration inside the back space of hollow cathode region becomes significant.

For plasma gas discharges under normal conditions, typically 10^3 cm^{-3} free electrons are available due to ultraviolet radiations, cosmic radiations, radioactivity, etc. and act as seed electrons.[14] The anode is kept grounded while a negative high

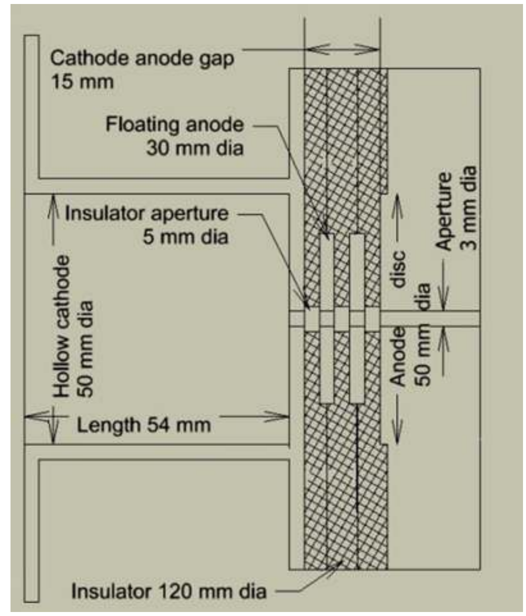

FIG. 2. 2D schematic view of the MG-PCE gun.

voltage ranging 5-30 kV is applied to the hollow cathode. In triggered breakdown condition, the energetic seed electrons are also emitted from a ferroelectric cathode surface based trigger unit in the hollow cathode region when a potential difference of 0 to −3 kV between the metal fingers and the base metal electrode is applied.[15] On application of the high electric field, these preliminary energetic seed electrons along with the PS discharge electrons are accelerated and collide with the neutral gas atoms inside the drift space region, which lead to focus the electron beam self-consistently without use of any external magnetic field.[6]

During the electron beam propagation, the electron beam current has been analyzed using two circular ring diagnostic arrangement as shown in Fig. 1 (see zoomed view). The technique comprises of two stainless steel metallic-rings (C_i and C_o with corresponding areas 20 mm^2 and 165 mm^2, respectively) mounted on Teflon base and are connected to the axial motion feedthrough (see Fig. 1). These rings are facing anode aperture

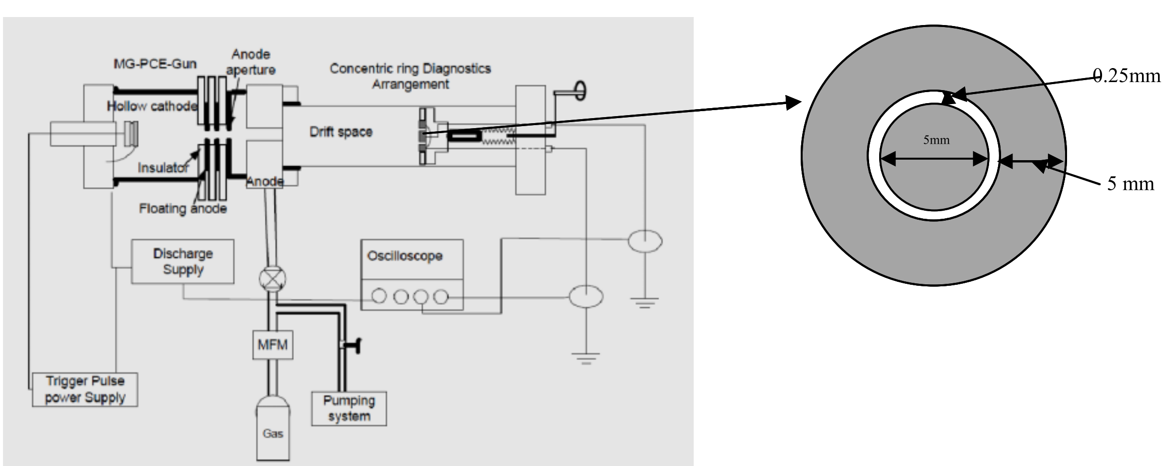

FIG. 1. Schematic view of the experimental setup along with front view of the two circular ring diagnostic arrangement (gray: metallic rings; white: Teflon base and isolation).

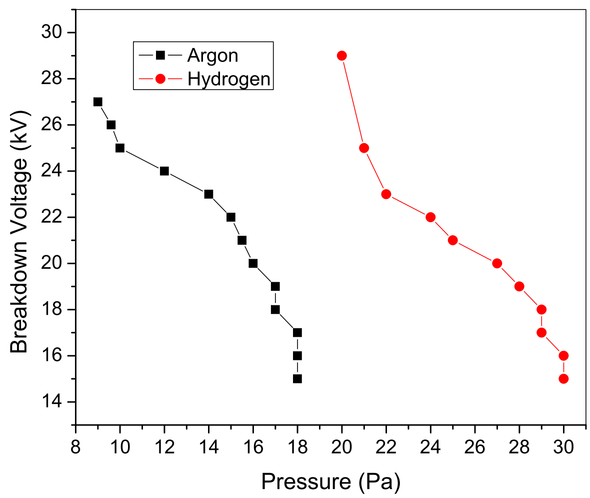

FIG. 3. Breakdown voltage vs pressure curve for fixed cathode-anode gap 15 mm.

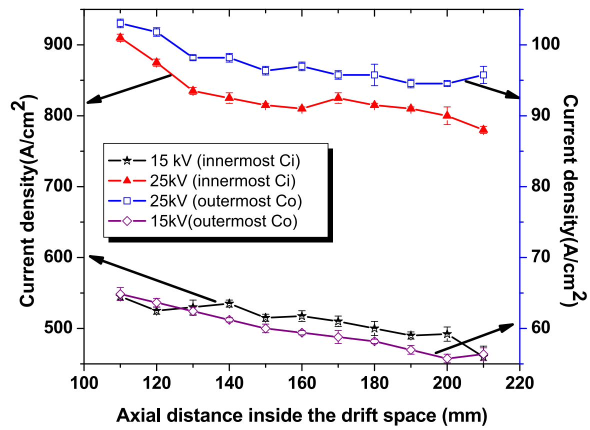

FIG. 5. Beam current density vs z (axial position from cathode aperture).

and are separated by 0.25 mm distance for isolation. The rings are connected with insulated ports and wires passing through two isolated calibrated current transformers (CTs) (Model 110, Pearson Current Monitor). The currents corresponding to the electron beam collected by these rings have been measured using oscilloscope (Tektronix DPO 4054).

III. RESULTS AND DISCUSSION

To obtain the operating range of voltage and pressure for the developed MG-PCE gun, its self-breakdown characteristic has been analyzed for the fixed inter-electrode gas gap. The discharge is induced by slowly increasing the applied voltage to the hollow cathode from −1 kV to −30 kV at fixed gas pressure. The voltage is recorded as a self breakdown voltage at a specific gas pressure and later plotted at different pressures by keeping the self-breakdown voltage knowledge. These results are shown in Fig. 3 for argon and hydrogen gases, respectively. The gas pressure and the type of gas play a very important role in the self breakdown process for the corresponding applied voltages.

Figure 4 shows V-I characteristics of the MG-PCE gun in the self breakdown condition for argon gas when no external trigger is applied. The hollow cathode phase (low current density, high energy) and the conductive phase (high current density, low energy) are clearly visible in this figure. Since there is no enhancement in the ionization region in the hollow cathode phase discharge, the propagation of the electron beam between the gap takes place until the conduction phase.[1] Nevertheless, in this phase, there is charge enhancement in terms of charge multiplications and the hollow cathode acts as a source of electrons.[13] This leads to flow significant transient current (i.e., for around 50 ns or so) with high hold-off voltage. The conduction phase current (see Fig. 4) is due to the applied gap potential and the emitted electrons get accelerated accordingly.

The beam current has also been propagated inside the drift space region up to z = 210 mm from the cathode aperture and the estimated current density using two circular ring diagnostic arrangements at different locations is shown in Fig. 5. The average of 5 data samples has been taken and the axial variation of the beam current density on the innermost and the outermost ring during the conductive phase formation inside the drift space region has been accounted. Evidently, the current density on the innermost ring is ranging from 85% to 91% of the total beam current density. It confirms the space charge neutralization effect, which is assisting in focusing the obtained electron beam during its propagation.

For the trigger breakdown discharge operation, a typical V-I characteristic from the developed MG-PCE gun is shown

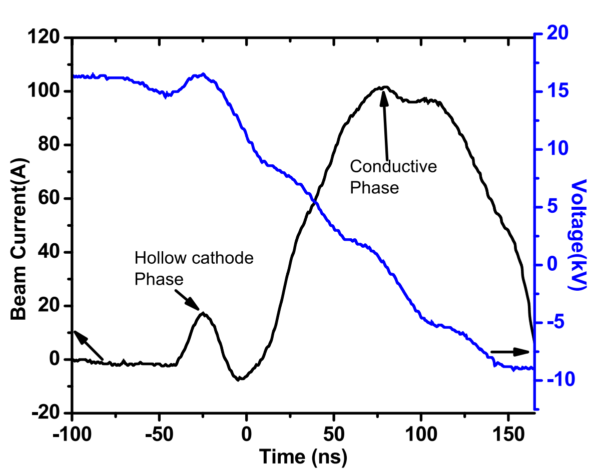

FIG. 4. V-I characteristics for self breakdown for Ar pressure 18 Pa.

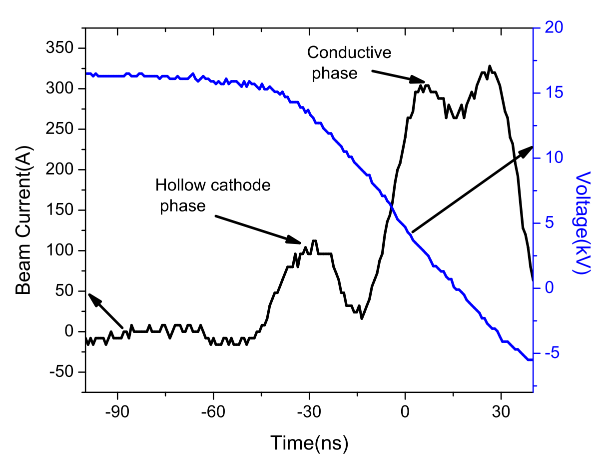

FIG. 6. V-I characteristics for trigger based breakdown at 15 Pa Ar pressure.

in Fig. 6. Though similar hollow cathode phase followed by conductive phase has been clearly observed, the beam current density in the trigger based breakdown having lower energy level is more (see Fig. 6) than that of the self breakdown mode (see Fig. 4). In the trigger breakdown mechanism the energetic seed electrons change the space charge field dynamics and consequently affect the breakdown. This further helps in tailoring the beam energy in hollow cathode phase. As clearly seen from Figs. 4 and 6, the beam energy change is found to be 1 to 0.7 eV_0 from the self breakdown mode to the trigger breakdown mode, where V_0 is the maximum applied gap voltage. To illustrate it further, for the self breakdown case, as shown in Fig. 4, the hollow cathode phase occurs for the maximum value of the applied voltage (i.e., ∼16 kV) and the peak of the beam current profile corresponds to the maximum applied gap voltage in the V-I curve. This gap accelerating voltage is equivalent to the kinetic energy of the generated electron beam in the hollow cathode phase, that is, 1 eV_0. On the other hand, for triggered breakdown case, as shown in Fig. 6, the maximum value of the beam current in the hollow cathode phase corresponds to ∼70% of the maximum applied voltage. This depicts 0.7 eV_0 beam energy.

The beam energy mainly depends on the delay of the voltage breakdown condition where seed electrons play an important role. Moreover, the position of the trigger (i.e., seed electron) source also controls the breakdown of the gases and obviously the formation of the electron beam. Therefore, the trigger position β (i.e., distance between cathode aperture and trigger surface) has been optimized for different pressures, which are always lower than the self breakdown pressures. Accordingly the maximum electron beam current obtained on the inner collector C_i for different trigger positions is shown in Fig. 7. For this measurement the applied voltage is fixed at 20 kV and argon gas pressure has been varied. The beam current is found to be maximum at β = 8 mm. Furthermore, beyond β = 12 mm, no such beam current exists for different applied voltages even up to 25 kV.

In the trigger discharge operation, the applied voltage between the cathode and anode leads to a positive accelerating field which penetrates inside the hollow cathode through the aperture and interacts with the seed electrons. Based on the applied potential, the energetic seed electrons lead multiple collisions and plasma discharge occurs. As the position between the trigger surface and these accelerating fields will be closer, it will result into greater extent of discharge. But if the position of the trigger surface is within the accelerating field region, as observed for β = 6 mm (see Fig. 7), the seed electrons emitted from the trigger surface would not participate much into the collisions and consequently many electrons will directly diffuse through the cathode-anode aperture. This results into lower beam current as seen in Fig. 7 for β < 8 mm. For β > 10 mm, the seed electrons are not able to create the discharge inside the hollow cathode back-space region and again results into a lower beam current.

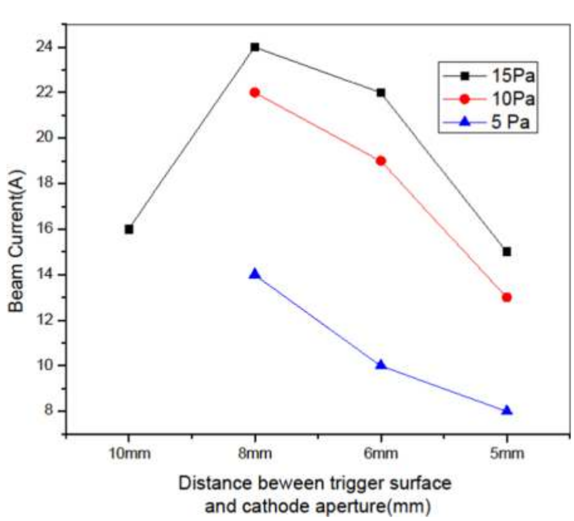

FIG. 7. Maximum electron beam current on the collector during hollow cathode phase obtained at different trigger positions and argon pressures for fixed applied voltage 20 kV.

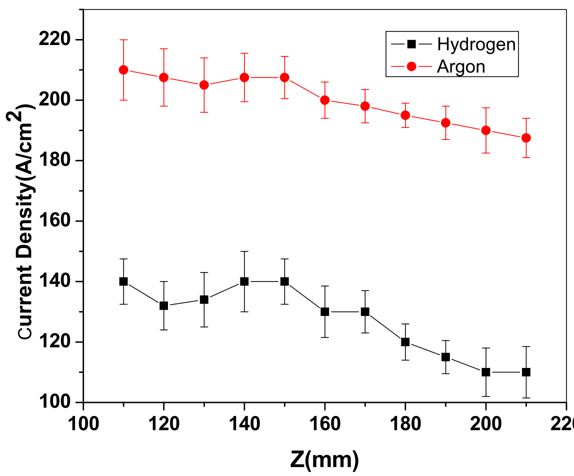

FIG. 8. Total beam current density vs z at pressure 10 Pa, gap voltage 22 kV during hollow cathode phase.

At the optimized trigger position β = 8 mm, the beam current density has also been tailored using different gases keeping the same operating conditions in the trigger breakdown mode operation. The variation is shown for argon and hydrogen gases at different axial locations inside the drift space region (see Fig. 8). The total beam current density is measured by summing the beam currents obtained from the innermost ring C_i and the outermost ring C_o of the circular metallic diagnostic arrangement. For this measurement, the argon and hydrogen gas pressures are kept same as 10 Pa for both gas cases and also the same operating voltage 22 kV has been applied during the discharge. Around 32% variation in the beam current has been achieved and the same is depicted clearly in Fig. 8.

IV. CONCLUSION

A pseudospark discharge based MG-PCE gun has been successfully developed for short pulse energetic electron beam generation. The multi-gap structure of the developed PCE gun leads to effectively generate two phases electron beam, i.e., the hollow cathode phase followed by conductive phase. The hollow cathode phase energy and current density of the electron beam have been controlled by different breakdown methods where seed electrons play an important role in the space charge field dynamics inside the hollow cathode. Accordingly the position of the trigger has also been optimized at $\beta = 8$ mm. It is accomplished that the beam energy is more for the self breakdown method whereas the current density is more for the trigger breakdown case. The electron beam energy has been controlled in the range of 1-0.7 eV_0 whereas the electron beam current density has been controlled up to 32% without geometrical changes in the developed MG-PCE gun. The generated electron beam has also been propagated more than 200 mm in the plasma filled drift space region without assistance of any external magnetic field.

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