Development of low-pressure high-current plasma cathode electron gun and use of associated techniques

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Abstract

A plasma cathode electron (PCE) gun has capabilities for generating high-current, broad, and focused beams for plasma-assisted microwave sources. A pseudospark-based hollow cathode PCE gun has been designed and developed for microwave generation which is operated in argon atmosphere. An analysis of the electron beam profile inside the drift space at different operating conditions has been carried out. This has been performed at several axial and radial locations inside the drift space which shows coherent phases of beam profiles in radial direction. The focusing and defocusing points in axial direction are also obtained. The beam current at different axial location for different applied voltages has been estimated. The obtained beam current is in close agreement with the beam current estimated by the particle-in-cell simulation code for the same geometry.

Keywords: Plasma cathode electron gun, Electron beam, Pseudospark, Hollow cathode

PACs: 52.25.Jm, 52.40.Mj, 52.59.Mv, 52.59.Tb

Background

The pseudospark (PS) discharge is recognized as a unique type of discharge [1] which is capable of producing electron beams with highest combined current density and brightness of any known type of electron source. The PS discharge-based plasma cathode electron (PCE) gun has potential applications in microwave generation, electron beam melting, welding, surface treatment, plasma chemistry, radiation technologies, laser pumping, and where material cathode cannot be used [2,3]. This type of gun has longer life as compared with that of material cathode. PS discharge is a specific type of gas discharge, which operates in hollow cathode geometry on the left-hand side of the Paschen curve with axially symmetric parallel electrodes and central holes on the electrodes [4]. The discharge system for PCE guns does not have hot filament or a similar kind of

thermionic solid cathode, so it is 'filament less' or 'cold cathode'. This is a primary distinction between a plasma cathode electron gun and a thermionic electron gun. Due to the absence of hot electrode, the plasma cathode system is basically more reliable, with a longer lifetime, and can generate electron beams at much higher background gas pressure, even in the fore-vacuum pressure ranges.

A potentially useful property of this type of discharge is the formation of an electron beam during the breakdown process [5]. During a pseudospark discharge, a low-temperature plasma is formed which acts as a copious source of electrons and can be regarded as a low work function surface that facilitates electron extraction. We have developed and demonstrated a PCE gun which generates the required electron beam. Some simulation studies have also been done on the influence of seed electrons and physical dimension of hollow cathode on pseudospark discharge at the same experimental conditions [6].

In this work, an effort has been made to analyze the electron beam profile of the PCE gun inside the drift space at different operating conditions. We have also estimated the beam current at different axial locations

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for different applied voltages. The obtained beam current is matched with the beam current estimated by the particle-in-cell (PIC) simulation code for the same geometry which is in close agreement.

Methods

Experiments have been performed for the single-gap pseudospark-sourced PCE gun for electron beam generation. Figure 1 shows the schematic view of the experimental setup. The hollow cathode and anode geometry has been used to design and fabricate the PCE gun. The hollow cathode is cylindrical in shape, having a total height of 59.7 mm. The inner and outer diameters are 59.4 and 65.4 mm, respectively. The thickness of the cylinder and the diameter of the aperture are 3 mm each. The anode dimensions are the same as those of the cathode. The anode and cathode are assembled in a ceramic casing with a 3-mm gap between them. Circular ring arrangement has been developed for beam current diagnostics in radial as well as in axial directions. The hollow cathode is connected to the DC power supply 25 kV/1 mA through a 5-MΩ charging resistor. The anode is connected to the ground. The PCE gun has been evacuated using a TMP (Varian Turbo V-301, Varian, Inc., Palo Alto, CA, USA) and then refilled with argon gas in a controlled manner using a mass flow meter (model 8272–0453, MATHESON, Basking Ridge, NJ, USA). There was no external-guiding magnetic field applied to the drift space. The charging voltage was measured using a voltage probe (P6015A, Tektronix, Inc., Beaverton, OR, USA). The beam current reaching collector has been measured with the help of current transformers (model 110, Pearson current monitor, Pearson Electronics, Palo Alto, CA, USA). These transformers are connected to the digital oscilloscope (DPO 4054, Tektronix) which synchronously displays the voltage and current waveform. Figure 2 shows the typical traces of the discharge voltage and discharge current
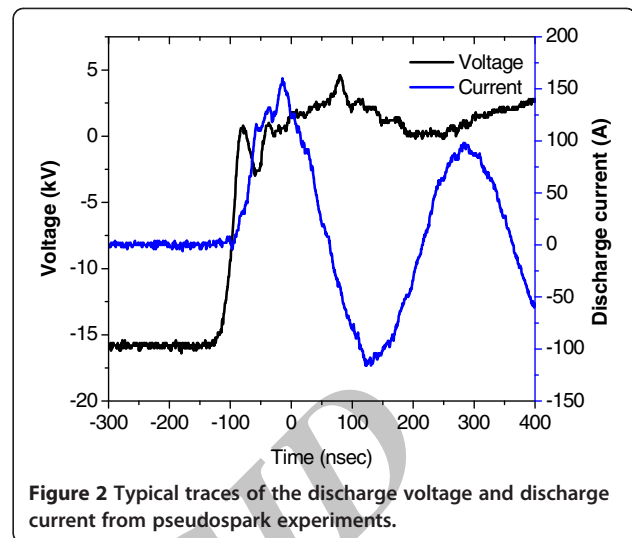
Figure 2 Typical traces of the discharge voltage and discharge current from pseudospark experiments.

from the experiments which clearly demonstrate the pseudospark characteristics.

Results and discussion

Experiments have been performed for the analysis of the beam current distribution inside the drift space connected to the PCE gun. Initially, the PCE gun has been evacuated up to approximately 10^{-6} mbar. Argon gas is then filled inside the pseudospark chamber in a controlled manner. The high voltage applied across the pseudospark chamber was then increased slowly until a breakdown occurred. The pseudospark discharge takes place around a pressure at 10^{-1} mbar. A typical trace of the different breakdown voltages and pressures has been deduced experimentally and is shown in Figure 3.

Measurements of the beam current diagnostics inside the drift space are realized using three concentric circular rings where each ring is connected to a wire which passes through a current transformer. These circular rings are mounted on a Teflon disc as shown in Figure 4a where the shaded portion represents conducting metal rings which are connected to the measuring electrical wires. A typical sample of the waveforms of the applied voltage and beam current collected by the different metallic rings is shown in Figure 4b where the beam current profile for different rings has been measured. There is phase synchronism between beam profiles, and that confirms simultaneous electron beam collection by the three rings. It is found that the axial and radial distribution of beam current is mainly dependent on breakdown voltage and discharge pressure inside the drift space. With the help of current transformers which are connected to the different rings, beam current distribution has been analyzed. The radial profile of the current density generated by a 1.5-mm radius plasma electron gun is measured at z = 110 mm axial
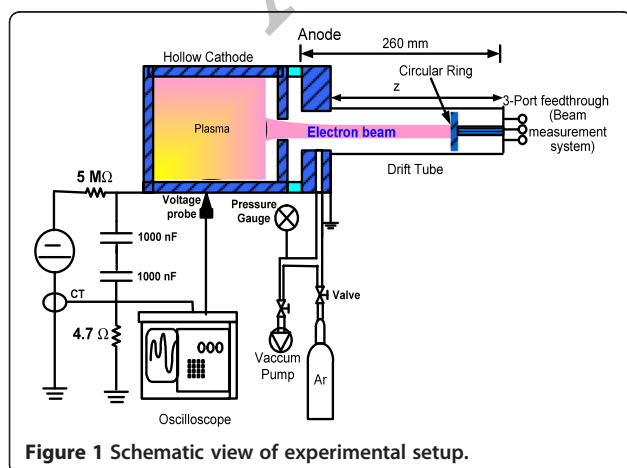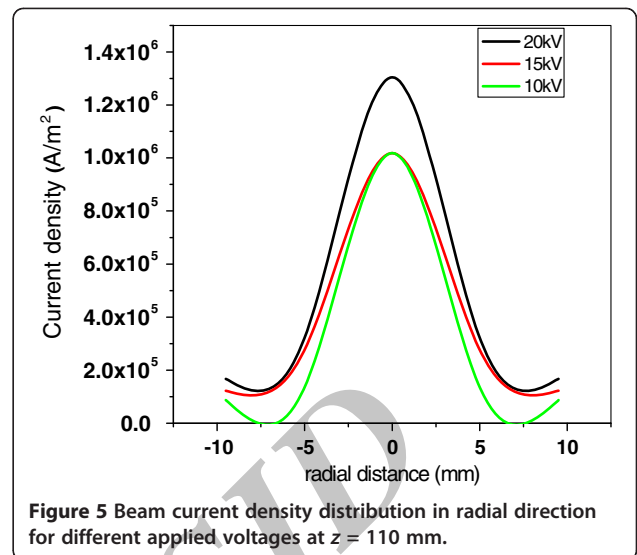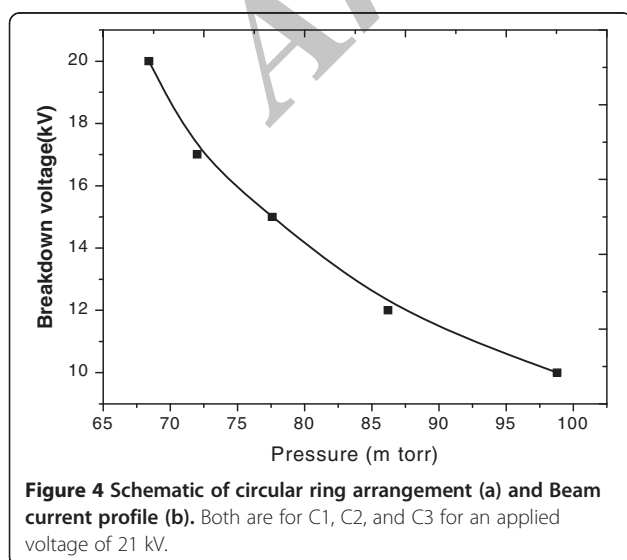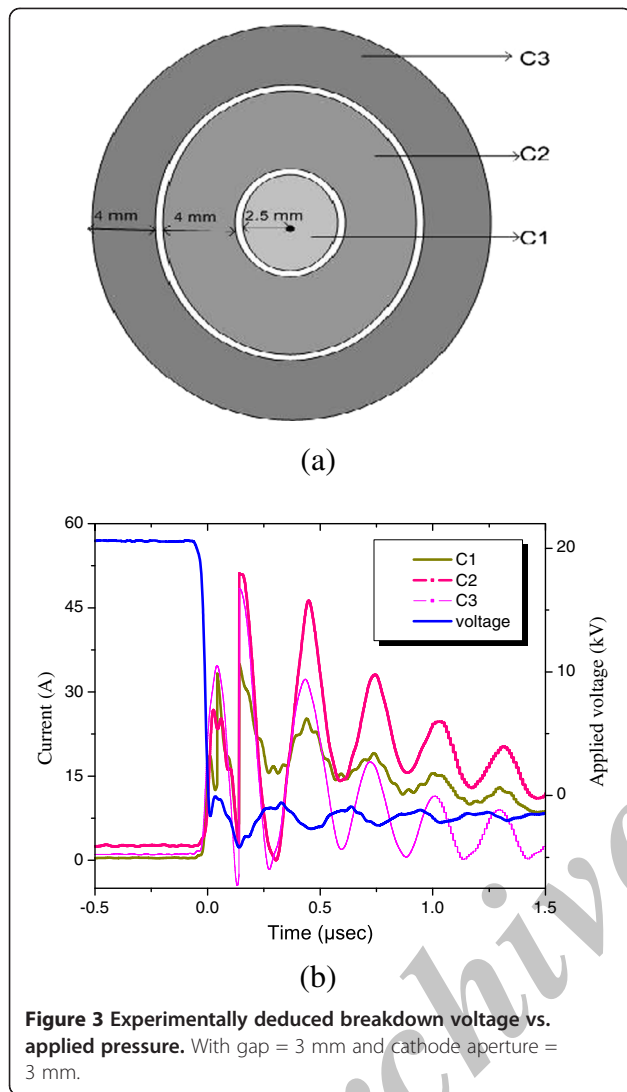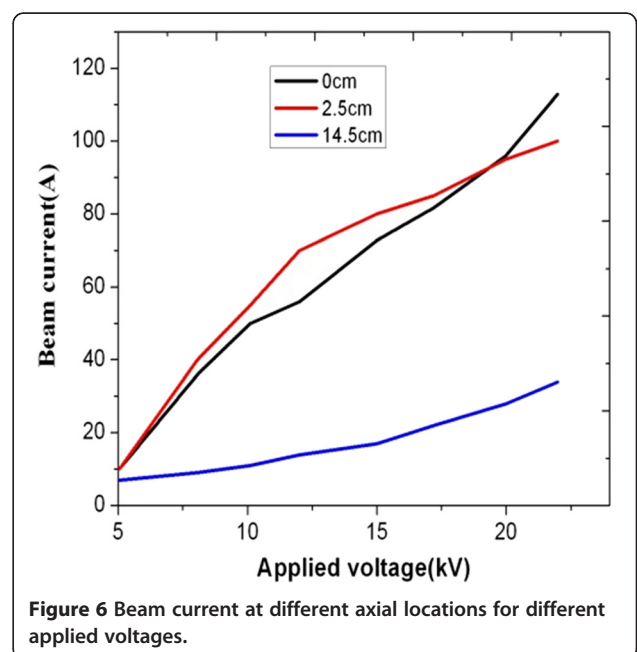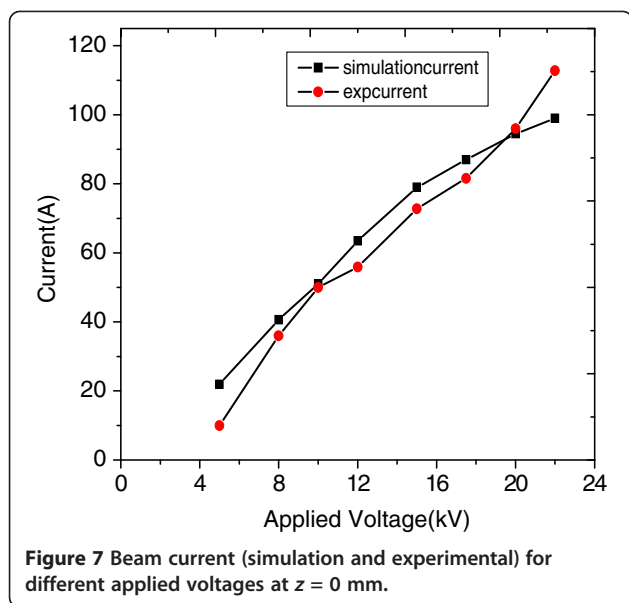

Figure 1 Schematic view of experimental setup.

(a)

(b)

Figure 3 Experimentally deduced breakdown voltage vs. applied pressure. With gap = 3 mm and cathode aperture = 3 mm.

Figure 5 Beam current density distribution in radial direction for different applied voltages at z = 110 mm.

location inside the drift space. The entrance ($z = 0$) of the drift tube is at a distance of 145 mm from the anode aperture.

Radial current density distribution for the different applied voltages inside the drift space has been estimated at $z = 110$ mm axial distance as shown in Figure 5. The electron beam is more focused in the case of 20 kV of applied voltage compared with that of 15 and 10 kV of applied voltages. From these results, it is also observed that the beam is almost focused inside the drift space [6]. Dependency of the beam current on different applied voltages for different axial locations inside the drift space is shown in Figure 6. The graph is plotted for the

Figure 4 Schematic of circular ring arrangement (a) and Beam current profile (b). Both are for C1, C2, and C3 for an applied voltage of 21 kV.

Figure 6 Beam current at different axial locations for different applied voltages.

Figure 7 Beam current (simulation and experimental) for different applied voltages at $z = 0$ mm.

voltage variation from 5 to 22 kV at different axial locations. In all cases, the beam current is found to be minimum at $z = 14.5$ cm.

We did some simulation studies on the influence of the seed electrons and physical dimensions of hollow cathode on the PS discharge [5], and keeping the same experimental conditions further, PIC plasma simulation has been carried out using OOPIC-Pro code to investigate the beam current inside the plasma-filled drift space. A good agreement has been found between experimental and simulation results at different applied voltages as shown in Figure 7 at $z = 0$ mm in the drift space, showing the trace for variation of beam current.

Conclusions

A pseudospark-based PCE gun has been designed and developed for the generation of solid electron beam useful for plasma-assisted microwave sources and surface applications. The analysis of the electron beam profile inside the drift space has been carried out at different operating conditions, and it shows that there is an increment in the beam current with the applied voltage. The beam current is estimated, i.e., approximately 65% of the discharge current. The focusing and defocusing points at different applied voltages are analyzed, and they show periodic behavior. It has been shown that there is a close agreement between experimental and simulation results of beam current at different applied voltages for fixed experimental conditions.

Competing interests
The authors declare that they have no competing interests.

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