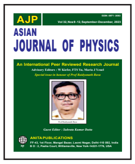

Asian Journal of Physics

Vol. 32, Nos 9-12 (2023) 479-485

Available on: www.asianjournalofphysics.com

Development and characterization of pseudospark discharge based plasma cathode electron (PD-PCE) source for high density and energetic e-beam generation for pulsed power applications

Varun[a,b], Akhilesh Mishra[a,b], Navin Kumar Sharma[c], Ram Prakash Lamba[a,b] and Udit Narayan Pal[a,b]

[a] *CSIR-Central Electronics Engineering Research Institute, Pilani-333 031, India*

[b] *Academy of Scientific and Innovative Research (AcSIR), Ghaziabad-201 002, India*

[c] *School of Physics, Devi Ahilya Vishwavidyalaya, Indore-452 001, India*

Dedicated to Prof B N Basu

The development and characterization study of a multi-gap pseudospark discharge based plasma cathode (PD-PCE) has been carried out for the generation of high density, energetic and short pulsed electron beams, suitable for potential applications in EUV/Soft X-ray, and surface modification studies. The investigations of multi-gap PD-PCE sources with different gas pressures, applied voltages (20–35 kV), and electrode aperture sizes (2–6 mm) for the generation of required short pulse electron beams have been carried out. The proposed analysis has helped in the design and development of multi-gap (4-gap) PD-PCE sources having uniform sequence of electrode apertures diameters (4 mm). The developed PD-PCE source has shown the capability of repeatable generation of high pulsed electron beam current of ~1.4 kA with current density of ~ 1.1 $\times 10^4$ A/cm^2 at 35 kV applied voltage with 4 mm electrode aperture. The developed PD-PCE source also generated and propagated the required high density and energetic pulsed electron beam by controlling the geometrical and operating parameters. The investigations and findings of the present work would be useful for the optimisation of the design and development of multi-gap PD-PCE sources required for the efficient generation of EUV/soft X-ray radiation.

Keywords: Pseudospark discharge, Pulsed e-beam, Electron source.

doi.10.54955/AJP.32.9-12.2023.479-485

1 Introduction

Pseudospark discharge (PD) is recognized as a special kind of low pressure gas discharge that can only produce electron beams with higher current density (~10^4 A/cm^2) as well as high brightness (~ 1012 Am^{-2} rad^{-2}) [1-2]. In addition, pseudospark discharge also offers the unique characteristics of electron beams such as, fast current rise (up to 10^{12} A/s), high power density (~10^9 W/cm^2) and low emittance (~15 mm·mrad) [1-2]. These typical features of the generated electron beams from pseudospark discharge based plasma cathode electron sources makes the door open for the pulsed power applications [1,2]. The unique configuration and geometry of PD based devices has the ability to generate combined high density and high brightness e-beams most suitable for the potential applications in the emerging areas of microwave and THz radiation generation, extreme ultraviolet (EUV) sources, intense X-ray sources, electron beam lithography and surface modifications [1-3]. In addition, the PD based devices have applications in the other potential areas as well [4-5].

Corresponding authors

e mail: varundixit1992@gmail.com (Varun), *udit@ceeri.res.in* (Udit Narayan Pal)

Pseudospark discharge is low pressure (1-80 Pa), self-sustained and transient nature of gas discharge happening in the left side (with respect to minimum) of Paschen's curve [1]. The special geometry of PD consists of hollow cathode (HC) with on-axis centered hole on one side while hollow and/or planer anode on the other side [2]. For the configuration having only one HC and anode electrodes is known as single gap PD. The other configuration, a multi-gap PD consists of stacked floating electrodes between the HC and anode to facilitate the operation in the high voltage conditions for the generation of energetic electron beam [6]. The generated electron beam during the breakdown process in the PD-PCE source can propagate without using any external magnetic field because of the formation of ion channel [2].

The development and characterization of a 4-gap PD-PCE source for the generation of high density and high energetic electron beam for the pulsed power application has been presented in this paper. The developed source has the ability to produce high energetic pulsed e-beam suitable for the microwave/THz and EUV/Soft X-ray radiations and also facilitated the generation of high current electron beam which can be used in the surface modification of various materials. The energetic and high current e-beam has been generated by controlling the operating parameter by keeping the same geometrical parameters. The description of a 4-Gap PD-PCE source along with characterization setup is described in section 2. The results and discussion are presented in section 3 and conclusion is given in section 4.

2 Experimental set-up and characterization

The schematic for the characterization of a multi-gap (4-Gap) pseudospark discharge based plasma cathode electron (PD-PCE) source for the generation of high density and energetic e-beam is shown in the Fig 1. The PD-PCE source consists of anode and cylindrical hollow cathode (HC) with central hole of 4 mm diameter. The 4-gap arrangement has been made by using three floating electrodes of 3 mm thick and isolated by insulating material Perspex. The anode, the intermediate floating electrode and the HC have on-axis hole of 4 mm diameter.

The external storage capacitors (C_{eq}) are connected across the gap of the PD-PCE. The hollow cathode cavity is powered (0-35 kV) by a negative high voltage supply (Technix make-CCR80kV-600J) while anode is grounded in such a way that the intermediate electrodes act as floating electrodes. The valves V1,V2, V3 and V4 are used to maintain vacuum and filling of required gases at desired pressures into the PD-PCE chamber.

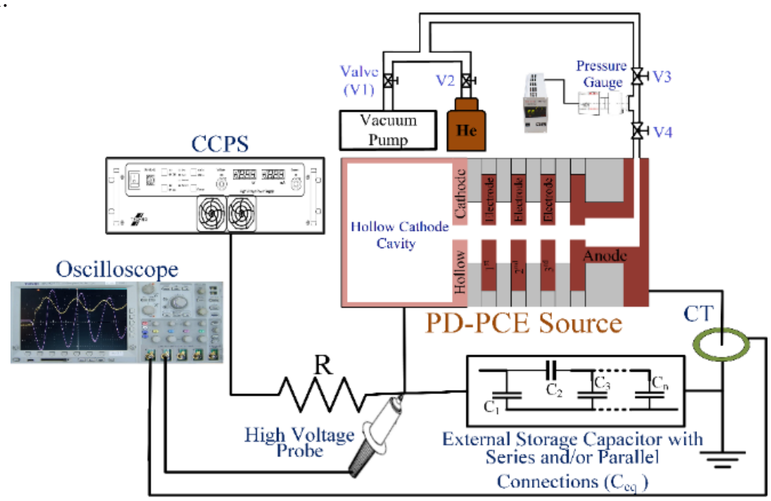

Fig 1. Schematic of PD-PCE source along with the experimental measurement arrangement.

The voltage at the HC was measured through the high voltage probe (North Star, PVM-1 DIFF) and total current was measured using current transformers (CT – Pearson 150 and 110). The voltage and current waveforms were recorded using digital phosphor oscilloscope (Tektronix DPO4054). Care has been taken for the measurement of short pulsed, high density and energetic electron beams. The schematic of the complete measurement setup is also shown in the Fig 1.

3 Result and Discussion

The characterization of the e-beam generations has been performed in a multi-gap (4-gap) PD-PCE source. The source was operated in self-breakdown mode such that no extra seed electrons were introduced into the hollow-cathode (HC) cavity, and the discharge was initiated by the presence of electrons resulting from the phenomena such as ultraviolet radiation or cosmic rays. After evacuating the PD-PCE source in a pressure range of about 10^{-5} mbar, the external storage capacitors were charged to a value of -5 kV to -35 kV depending on the desired operating conditions. In order to validate the operating region of the PD-PCE source, the breakdown characteristics of the source were analyzed and plotted on the Paschen's curve, which describes the voltage required to initiate a discharge as a function of gas pressure and gap distance. The observed breakdown characteristics of the source were located on the left side of the Paschen's curve, confirming that the PD-PCE source operates in the pseudospark region, as per the Paschen's curve validation [1]. This information is important for the development of electron beam sources for various applications such as material processing, particle acceleration, and plasma devices.

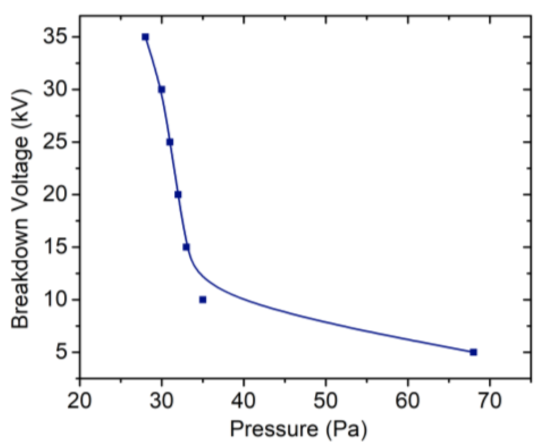

Fig 2. Breakdown voltages against the varied gas pressures for 72 nF external storage capacitor (C_{eq}).

The pseudospark discharge is characterized by three complex phases namely; pre-breakdown phase, hollow cathode phase and conductive phase [1,6-8]. The initiation of discharge inside the hollow cathode (HC) cavity is carried out by the self-breakdown process and termed as pre-breakdown phase of the pseudospark discharge. The ignition of discharge leads to the formation of plasma by achieving the avalanche condition inside the HC cavity. The energetic electron beam is extracted from the plasma due to special distribution of the potential profile into the PD-PCE source. The generation of the energetic electron beam is achieved in the hollow cathode phase of the PD-PCE Source. However, the high current e-beam can be generated in the conductive phase. The three phases of pseudospark discharge have been characterized in the developed PD-PCE source and presented in the Fig 3. The discharge current of ~ 129 A in hollow cathode phase and ~123 A in conductive phase has been observed. Electron beam current of 52.4 A in hollow cathode phase and 50 A in conductive phase were measured through the CTs and recorded in the oscilloscope. The characteristic of such e-beam is preferred in the area where high energetic e-beam is required like, generation of microwave and THz radiation, EUV/ Soft X-ray radiation, etc.

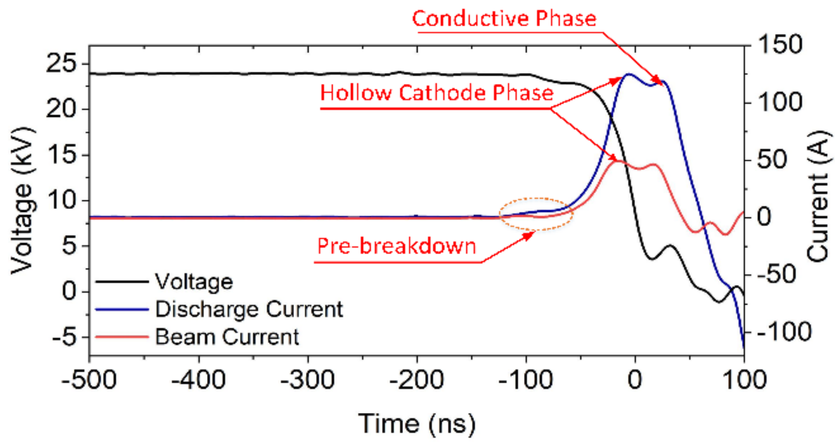

Fig 3. V-I characteristics of developed PD-PCE source for the generation of electron beam at 250 pF for 25 kV charging voltage.

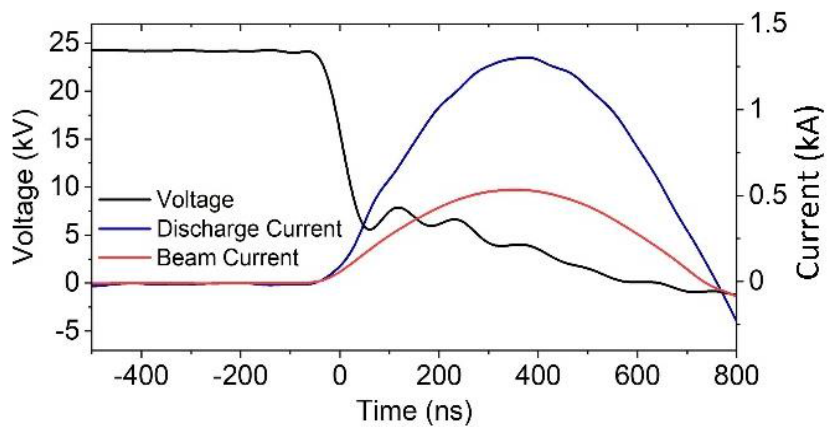

Fig 4. V-I characteristics of developed PD-PCE source for the generation of electron beam at 18 nF for 25 kV charging voltage.

It is found that the external storage capacitance plays significant role for the hollow cathode phase generation. On increasing the capacitance value, the phases of the PD-PCE source starts separating into the hollow cathode phase and the conductive phase. For the capacitance value of 2 nF to 18 nF, the PD-PCE source acts as the generator of high current electron beam purely in the conductive phase. The V-I characteristics of 4-Gap PD-PCE source has been presented in the Fig 4 in which the conductive phase is observed for 18 nF external storage capacitance. Such characteristics of generated high current e-beam are suitable for the surface modification applications.

To further analyze the PD-PCE source, the beam current characteristics were measured, and the influence of various combinations of external storage capacitors in the parallel of the discharge gap was examined. It was observed that the voltage-current (V-I) characteristics during the breakdown process varied depending on the capacitance of the external storage capacitors. Higher capacitance values, such as 36 nF, led to an early breakdown compared to lower capacitance values, like 7.2 nF, as shown in Fig 5.

The maximum electron beam current of 1.1 kA at 35 kV applied voltage could be collected from the PD-PCE source within the range of 7.2 nF to 36 nF external storage capacitor, while a discharge current of 2.8 kA was measured. The measured electron beam current density varied from 2.2×10^2 A/cm^2 to 1.1×10^4 A/cm^2 during the experimental investigation for external storage capacitors ranging from 7.2 nF to 72 nF. Additionally, energy spreads ranging from 840 eV to approximately 9 keV were observed for the peak electron beam currents.

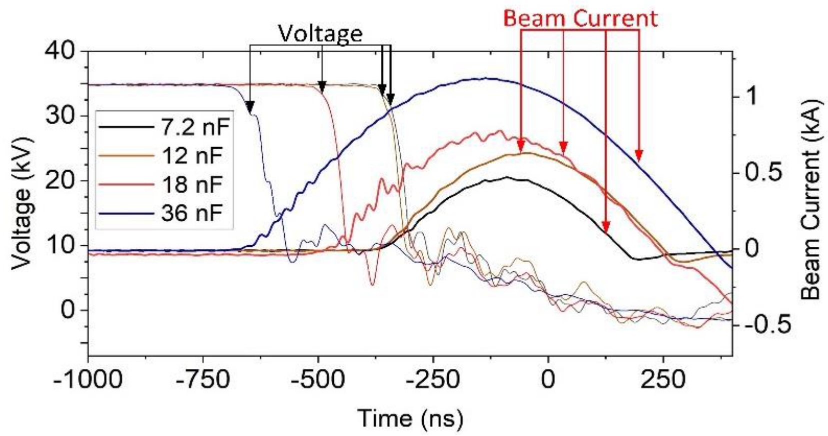

Fig 5. V-I characteristics of 4-gap PD-PCE source at 35 kV breakdown voltage.

The experimental investigations demonstrate the generation and measurement of electron beams of both high energy with low peak current and low energy with high peak current from the same PD-PCE source. Such electron beams are very much suitable for potential and growing applications in EUV/Soft X-ray, microwave and surface modification studies [1-3]. For the condition of 25 kV charging voltage of 150 pF to 18 nF capacitance, the achieved parameters of the generated electron beam are presented in the Table 1.

Table 1. Energy and current of generated pulsed electron beam at different external storage capacitors across the gap of the 4-gap PD-PCE source at ~25 kV discharge voltage.

External storage capacitance (C_{ex})	Max. Discharge current (A)	Beam current in HC phase (A)	Beam current in conductive phase (A)	Energy of electron beam during the HC phase (keV)
150 pF	~ 112.2	~ 41	-	~ 19.6
250 pF	~ 125	~ 49.6	~ 46.5	~ 16.9
500 pF	~ 184	~ 60	~ 73.5	~ 14
2 nF	~ 452	-	~ 183	-
18 nF	~ 1304	-	~ 534	-

The discharge process in the multi-gap PD-PCE source is closely related to the distribution of the electric field within the system. In order to further characterize the discharge process, PIC (Particle-in-Cell) simulations were performed using 2-D axis-symmetric OOPIC Pro simulation code [11,12]. When a voltage is applied to the anode, the electric field is uniformly distributed across the gaps. However, the potential lines near the cathode aperture undergo changes due to the unique geometry of the electrode configurations. The simulations were carried out for applied voltages ranging from 10 kV to 35 kV, which correspond to the range of voltages used in the experiments.

The potential lines within the PD-PCE source play a crucial role in the breakdown process and in shaping the electrons to form an electron beam, which depends on the applied voltage [11]. The equipotential lines are essential for controlling the beam properties, such as its size and shape. As the applied voltage increases, the equipotential lines become closer to each other, resulting in a tighter confinement of the electron beam. This effect is observed in the simulation results, where the electron beam becomes more focused as the applied voltage is increased from 10 kV to 30 kV.

Figure 6 illustrates the distribution of electrons inside the HC cavity and the confined electrons for the formation of the electron beam at an applied voltage of 30 kV. The plasma electrons within the HC cavity and the electrons propagated from the multi-gap electrodes are confined along the equipotential lines that have penetrated through the system. The strength of this potential penetration is dependent on the applied voltage and is distributed in a manner similar to the capacitor voltage divider rule. Specifically, for applied voltages of 10 kV, 20 kV, and 30 kV, the plasma electrons are confined by the 8 kV, 16 kV, and 27 kV equipotential lines, respectively, while the electron beam is shaped by 8.5 kV, 17 kV, and 28 kV equipotential lines, respectively.

It is worth noting that the PIC simulations provide valuable insight into the behavior of the PD-PCE source and its underlying physics, which can be used for optimising its performance and design.

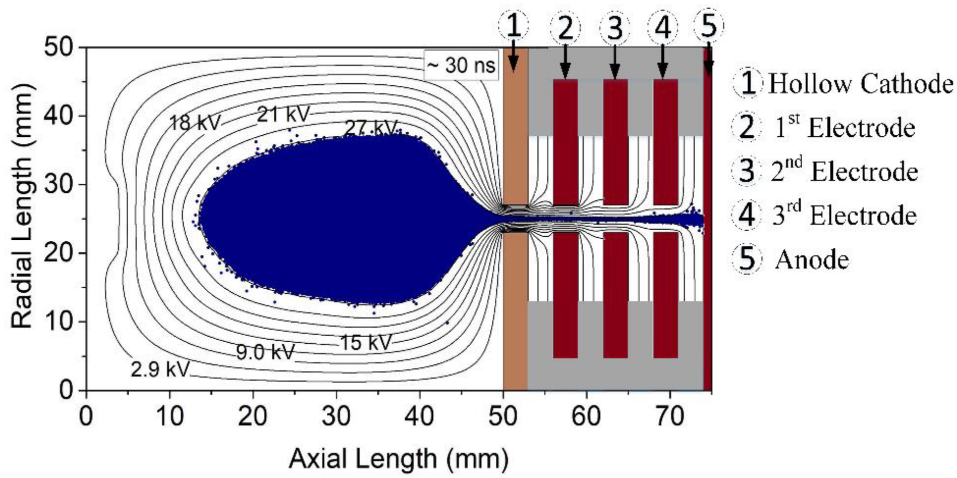

Fig 6. Distribution of electrons and formation of e-beam along with the potential line profile for the application of 30 kV.

4 Conclusion

Characterization of an experimental multi-gap (4-Gap) PD-PCE source for high density and energetic e-beam generation has been presented. The experimental study has been carried out for the characterization and generation of electron beam from the multi-gap (4-gap) PD-PCE source for a wide range of operating parameters, such as, breakdown voltages: –5 kV to –35 kV, gas pressures: 5 Pa to 70 Pa and external circuit capacitors: 200 pF to 72 nF. The complex phases of pseudospark discharge have been presented in which the external storage capacitance has played significant role for deciding the phases. Higher capacitance values led the separation of hollow cathode phase for the generation of high energetic e-beam and conductive phase for generation of high current density e-beam. The developed PD-PCE source has shown the capability to generate repeatedly the high pulsed electron beam current of ~1.4 kA with current density of ~ 1.1×10^4 A/cm^2 at applied 35 kV voltage. The PIC simulation has indicated that the focusing of electrons in the electron beam increases at higher applied voltage. The plasma region inside the HC cavity and formation of e-beam has also been presented that depends on the density of the equipotential lines. The investigations are expected to provide a promising solution for the development of multi-gap PD-PCE source which would be suitable for the potential and growing applications in the EUV/Soft X-ray, microwave, and surface modifications.

Acknowledgement

The authors wish to acknowledge Mr Gulab Singh, Mr Pramod for their help in the experimental setup, and other plasma team members for scientific discussions. This work was supported by the CSIR Young Scientist Award Scheme of Extramural Research (EMR) under Grant P90807.

References

1. Cross W, Yin H, He W, Ronald K, Phelps A D R, Pitchford L C, Generation and application of pseudospark-sourced electron beams, *J Phys D Appl Phys*, 7(40)1953–1956.
2. Christiansen J, Schultheiss C, Production of high current particle beams by low pressure spark discharges, Zeitschrift *Phys A, Atoms Nucl*, 290(1979)35–41.
3. Fu Y, Hu J, Zhang X, Huo W, Cao X, Zhao W, "Surface modification of AISI 1045 steel by pseudospark based pulsed electron beam, *Nucl Instrum Methods Phys Res Sect B: Beam Interact with Mater Atoms*, 434(2018)88–92.
4. Mishra A, Misra S, Lamba R P, Tillu A R, Pal U N, Performance of a Multigap Multiaperture Pseudospark Switch in Series With the Saturable Inductor, *IEEE Trans Electron Devices*, 69(2022)5879–5885.
5. Pal U N, Lamba R P, Varun, Meena B L, Frank K, A multigap multiaperture pseudospark switch and its performance analysis for high-voltage applications, *IEEE Trans Electron Devices*, 67(2020)5600–5604.
6. Varun, Cross A W, Ronald K, Pal U N, PIC simulation of pseudospark discharge-based plasma cathode electron source for the generation of high current density and energetic electron beam, *IEEE Trans Electron Devices*, 67(2020)1793–1796.
7. Varun, Pal U N, PIC Simulation to Analyze Peak Electron Current Generation in a Triggered Pseudospark Discharge-Based Plasma Cathode Electron Source, *IEEE Trans Electron Devices*, 65(2018)1542–1549.
8. Varun, Pal U N, Investigation of Electron Beam Generation in Pseudospark Discharge-Based Plasma Cathode Electron Source, *IEEE Trans Plasma Sci*, 46(2018)2003–2008.
9. Varun, Dwivedi H K, Pal U N, Breakdown Characteristics of Triggered Pseudospark Discharge-Based Multigap Plasma Cathode Electron Source, *IEEE Trans Electron Devices*, 65(2018)4607–4613.
10. Varun, Lamba R P, Pal U N, Characterization of Pseudospark Discharge-Based Multigap Plasma Cathode Electron Source for the Generation of Short Pulsed Energetic Electron Beam, *IEEE Trans Electron Devices*, 69(2022)4572–4578.
11. Varun, Pal U N, Impact of irregular electrode apertures in multigap pseudospark discharge geometries for the generation of high density and energetic electron beams, *IEEE Trans Electron Devices*, 67(2020)2182–2187.
12. Varun, Sharma N K, Pal U N, Design of multigap pseudospark discharge-based plasma cathode electron source at different configurations of electrode apertures, *IEEE Trans Electron Devices*, 68(2021)5799–5806.

[*Received*: 21.04.2023; *accepted*: 15.12.2023]

Varun received the B Tech degree in electronics engineering from Dr Ambedkar Institute of Technology for Handicapped, Kanpur, India, in 2014, and the M Tech degree in high-power microwave devices and system engineering from the AcSIR, CSIR CEERI Campus, Pilani, India, in 2017, and the Ph D degree in engineering science from the AcSIR, CSIR CEERI Campus, Pilani, India, in 2022. His current research interest includes low-pressure pseudospark discharge-based high-density and energetic electron beam generation, extreme ultraviolet (EUV) sources, and dielectric barrier discharge (DBD)-based sources

Akhilesh Mishra received his B Tech degree in electrical & electronics engineering from Cochin University of Science and Technology, Kerala, India, in 2017, and the M Tech degree in advanced electronics engineering from the AcSIR, CSIR CEERI Campus, Pilani, India, in 2021, where he is currently pursuing the Ph D degree in engineering science. His primary interest is Pseudospark discharge-based High power Switches and Electron beam generation for pulsed power applications

Navin Kumar Sharma received the M Sc degree in physics from the School of Physics, Devi Ahilya Vishwavidyalaya, Indore, India, in 2017, where he is currently pursuing the Ph D degree in physics. His current research interests include cold atmospheric pressure plasma sources, extreme ultraviolet (EUV)/vacuum ultraviolet (VUV)/ultraviolet (UV) radiation sources, plasma simulation, and diagnostics.

Ram Parkash Lamba received B Tech (Electronics and Communication Engineering) and M Tech (High Power Microwave Devices & System Engineering) degrees in the year 2010 and 2013 with distinction from G.J.U.S.&T, Hisar and AcSIR, CEERI, Pilani, respectively. Currently, he is principle scientist at Council for Scientific and Industrial Research (CSIR) – Central Electronics Engineering Research Institute (CEERI), Pilani, India. His research interests are in the design, simulation, and development of plasma devices and pulse power generation.

Udit Narayan Pal received the B E degree in electronics and communication engineering from M M M Engineering College (Presently, Madan Mohan Malaviya University of Technology), Gorakhpur, India, in 2003, M Tech degree in electronics engineering from the Institute of Technology (Presently, Indian Institute of Technology (IIT)), Banaras Hindu University, Varanasi, India, in 2006 and a Ph D degree in plasma physics from Birla Institute of Technology (BIT), Mesra (Ranchi), India, in 2014. Since 2005, he has been a regular scientist with Council for Scientific and Industrial Research (CSIR) – Central Electronics Engineering Research Institute (CEERI), Pilani, India. He is currently a Senior Principal Scientist in CSIR-CEERI, Pilani, and Professor in Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, U P, India. His current research interests include cold atmospheric pressure plasma technologies, plasma-based water treatment technologies, pseudospark (PS) discharge devices, high-power plasma switches, electron beam generation, beam–plasma interaction, and extreme ultraviolet (EUV)/X-ray sources.