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Performance evaluation of self-breakdown-based single-gap plasma cathode electron gun

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Abstract. This paper presents the experimental studies on self-breakdown-based single-gap plasma cathode electron (PCE) gun (5–20 kV/50–160 A) in argon, gas atmosphere and its performance evaluation based on particle-in-cell (PIC) simulation code 'OOPIC-Pro'. The PCE-Gun works in conducting phase (low energy, high current) of pseudospark discharge. It produces an intense electron beam, which can propagate more than 200 mm in the drift space region without external magnetic field. The profile of this beam in the drift space region at different breakdown conditions (i.e., gas pressures and applied voltages) has been studied and the experimental results are compared with simulated values. It is demonstrated that ∼30% beam current is lost during the propagation possibly due to space charge neutralization and collisions with neutral particles and walls.

Keywords. Pseudospark discharge; hollow cathode; electron beam; plasma cathode electron gun; particle-in-cell simulation.

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1. Introduction

In conventional high-power microwave tubes, the explosive electron emission cathodes are generally used for electron beam emission because these cathodes 'turn on' at relatively low electric fields (∼100 kV) and deliver very high current densities (∼100 A/cm^2) that allow microwave tubes to generate extremely high power [1–4]. However, the surface that serves as the electron source eventually expands and shortens the anode–cathode gap [5,6], limiting the pulse width. On the other hand, the conventional thermionic cathodes can provide long pulse electron beam operation, but have limited current density, not adequate for high-power microwave sources. In order to achieve high-power microwave sources with longer pulse operation, these limitations should be rectified or the cold cathodes should be replaced by alternative high-current cathodes. One such alternative is to replace the conventional cathode by plasma hollow cathode [7].

The plasma cathode electron gun (PCE-Gun) can provide both high current density ($>$50 A/cm^2) and long-pulse operation without gap closure by generating a controlled plasma discharge that acts as the electron source. In the PCE-Gun, the plasma is generated in an enclosed volume and the electron beam is extracted out by small-aperture electrodes. As the plasma exists in the hollow cathode, the damage due to back-streaming high-energy ions become minimal compared to the conventional electron gun [2]. The PCE-Gun can control the electron density in the source and the plasma can eliminate the closure of the accelerator gap.

In the PCE-Gun, plasma is generated by pseudospark (PS) gas discharge, which is axially symmetric, self-sustained and transient and works with low-pressure (typically 50–500 mTorr) gas discharge that takes place in a hollow cathode/planar anode configuration and operates on the left-hand side (with respect to the minimum) of the hollow-cathode analogy to the Paschen's curve [8]. A potentially useful property of this type of discharge is the formation of an electron beam during the breakdown process. The beam so formed has the unique feature of self-focussed propagation by space–charge neutralization [4] owing to the ionization of the background gas, which reduces the requirement of external magnetic field, making the device compact. There are two phases for electron beam generation in PS discharge, named as hollow cathode phase (HCP) and conductive phase (CP). In the former, beam current will be less but energy of the beam will be high, but in the latter case energy of the beam will be low with high current. The HCP- and CP-based beam generation is possible in trigger-based controlled discharge, while in self-breakdown mode only CP-based beam generation is possible.

Recently, we have developed a single-gap PCE-Gun, which is operated at 5–20 kV and 65–90 mTorr argon gas pressure [9]. The gun works in self-breakdown mode where the beam energy is low and current is high. Experimental studies are performed on this device for the beam current, discharge current, breakdown behaviour and their results are compared with PIC simulation code 'OOPIC-Pro' for the same geometry. The results obtained are in close agreement with each other and validate the experiments.

2. Experimental set-up

The schematic view of the experimental set-up is shown in figure 1. The hollow cathode geometry with a central aperture facing a planar anode forms the PCE-Gun. The cylindrical hollow cathode has inner and outer diameters of 59.4 mm and 65.4 mm, respectively, and length of 59.7 mm. The anode diameter is taken to be the same as that of the cathode. The anode and cathode are assembled in a ceramic casing with a 3-mm gap between them. The hollow cathode is connected to a negative DC power supply 25 kV, 1 mA through a 5 MΩ charging resistor, while the anode is grounded. The electron beam originating from the cathode–anode aperture during discharge has been propagated in the drift space region. The drift space region is 100 mm long, having cylindrical geometry with an internal diameter of 40 mm and is placed symmetrically with the cathode bore hole (see figure 2). A grounded circular copper disc of diameter 30 mm is used in the drift space region to collect the electron beam. The beam current at the collector is measured with

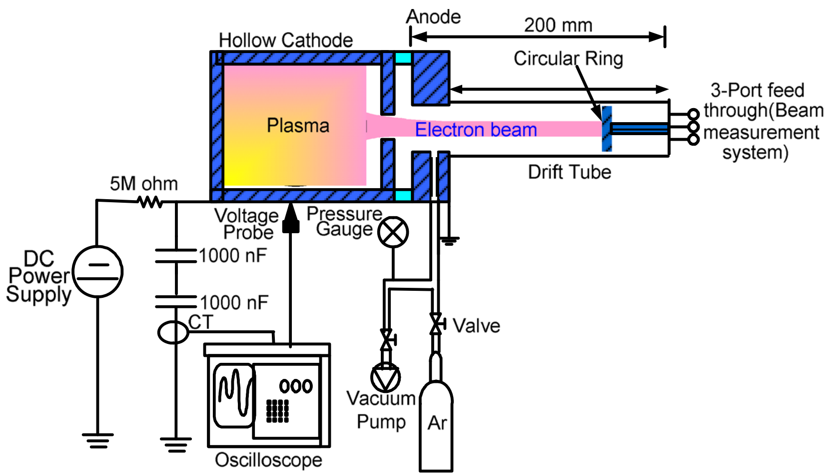


Figure 1. Schematic view of the experimental set-up.

the help of current transformers (Model 110, Pearson Current Monitor). The side view of the single-gap PCE-Gun is shown in figure 2.

The PCE-Gun was evacuated up to 10^{-6} mbar using TMP (Varian Turbo V-301) and then refilled with argon gas in a controlled manner using mass flow controller (Matheson: 8272-0453). The discharge voltage applied across the PS chamber was increased slowly until breakdown occurred. There was no external guiding magnetic field applied to the drift space. The charging voltage (or gap voltage) was measured between cathode and anode using a voltage probe (Tektronix P6015A, attenuation: 1kX) connected to the digital oscilloscope (Tektronix DPO 4054), which synchronously displayed the voltage and current waveforms. The profiles of the discharge current and gap voltage were obtained for different operating conditions. A sample waveform of 17 kV gap voltage is shown in figure 3, which depicts the discharge current, beam current (measured at $z = 107$ mm) and gap voltage behaviour. The duration of discharge current depends on

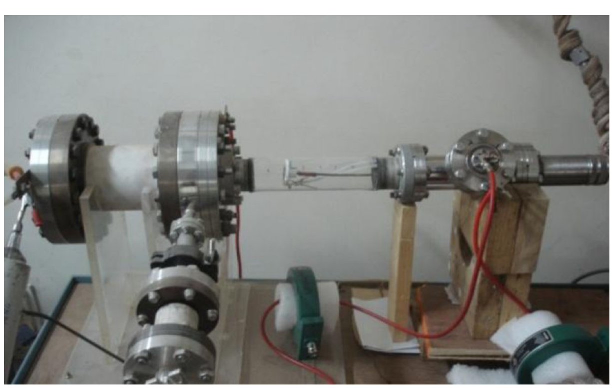


Figure 2. Developed single-gap pseudospark sourced PCE-Gun.

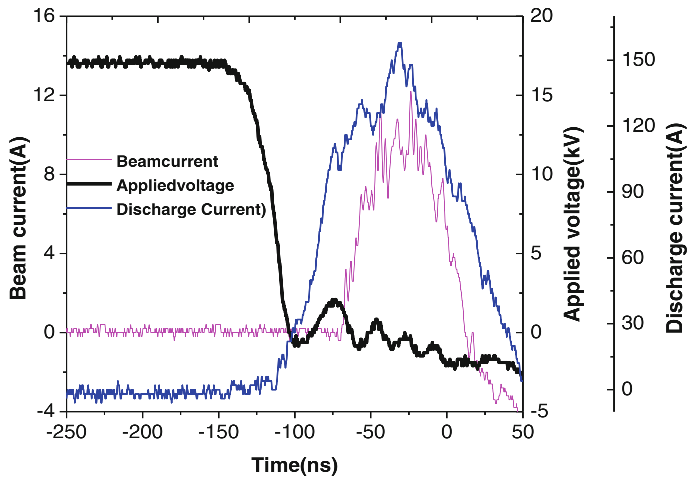


Figure 3. Experimentally observed profile of discharge current, beam current (measured at $z = 107$ mm) and gap voltage.

the LCR circuit value. Additional inductance is not added in the discharge circuit, however, the circuit inductance will come into effect, which will only result in a lag behind discharge current (I_d) with respect to voltage. It is clearly seen in figure 3. The circuit inductance measured in our case is ∼4.5 nH, while the charging/discharging capacitor is ∼0.5 μF. Beam current is measured at different axial positions inside the drift space using the collector that is kept grounded.

3. Simulation model

The simulations were carried out using the PIC simulation code OOPIC-Pro, which is based on the Monte Carlo collision (MCC) method [10]. The physical geometry specified in the code, appears as illustrated in figure 4 and is similar to the configuration adopted in

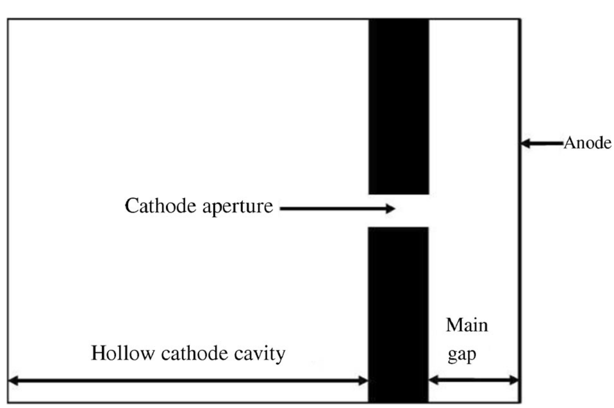


Figure 4. Electrode geometry of PCE-Gun as taken in the simulations.

the experiment. Cylindrical coordinates system was adopted for this study. The inner diameter of the electrodes (cathode and anode), cathode aperture diameter and the distance between the electrodes were kept exactly equal to the corresponding experimental parameters. In this model, dark colour strip showed the hollow cathode face containing the circu lar aperture, and inside the cathode argon gas was is filled along with primary electrons. In fact, any sample of gas under normal conditions contains $\sim 10^3$ cm^{-3} electrons and ions due to ultraviolet and cosmic radiations, radioactivity, etc. [11]. Also, the knocking-out of electrons from the cathode cavity surface by the omnipresent cosmic radiations may result in electrons in the hollow cathode cavity [12]. Therefore, an electron density of $\sim 10^4$ cm^{-3} was loaded in the hollow cathode cavity to initiate the discharge. These electrons are randomly distributed over the entire hollow cathode cavity. The hollow cathode was kept grounded, while a high voltage, ranging 5–20 kV, was applied to the anode corresponding to different discharge gas pressure values. In the experiment and simulation model, the potential difference and the direction of the electric field are the same. In order to run the simulation, we have kept the cathode at ground potential, while the anode at positive potential. The pressure and voltage values specified in the simulation are similar to the experimental conditions.

By applying high electric field these primary electrons were accelerated and collided with the neutral gas atoms. Secondary electrons were also considered, which were generated due to the back-ion bombardment on the cathode walls. Initially, electrons were generated due to the avalanche ionization of the argon gas by the secondary electrons [5,6] (emitted from the inside surfaces of the hollow cathode due to ion bombardment) and also primary electrons present due to the cosmic rays. These resultant electrons got accelerated by the applied voltage out of the cathode cavity through the aperture. As a result, a net positive charge was left behind in the hollow cavity, called as the virtual anode [13]. Formation of virtual anode causes the net electric field to increase in the hollow cathode and to decrease in the main gap. The increase in this field inside the cathode cavity causes the ionization rate to increase. Also, because of the decrease in the field of the main gap,

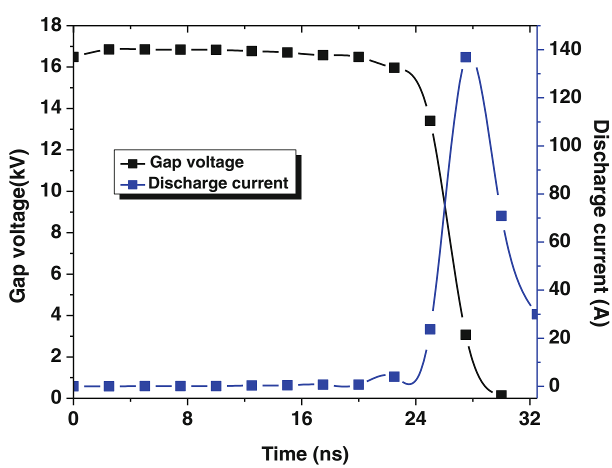


Figure 5. Trace of discharge current and gap voltage obtained from simulations.

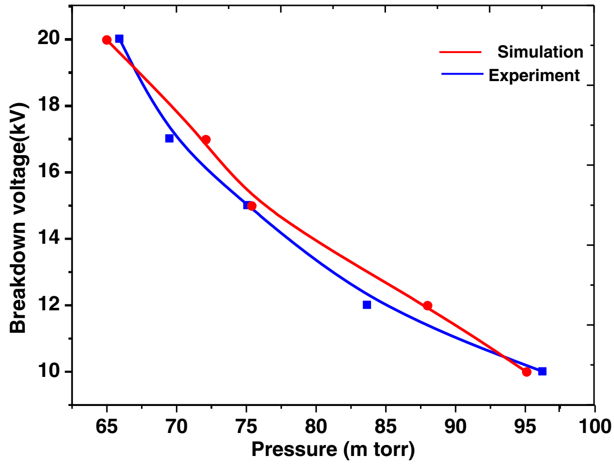


Figure 6. Breakdown voltage with gas pressure for argon at 59.7 mm cathode cavity depth, 3 mm gap separation and 3 mm cathode aperture.

the electrons are slowed down and they stay in the cavity for a longer time. Hence, space charge was created which was enough to sustain the discharge, leading to form the plasma. The plasma was formed close to the anode and later extended towards the hollow cathode.

Figure 5 presents the typical plot for simulated discharge current and discharge voltage profile at 72 mTorr argon gas pressure and 17 kV applied voltage. The pattern obtained from the simulations show behaviour similar to that obtained from the experiments (see figure 3). The rise in discharge current has been observed with decrease in the gap voltage similar to the experiments. Nevertheless, it is to be mentioned that the time-scale of the discharge current depends on the external circuit used in the experiment [14]. The effect

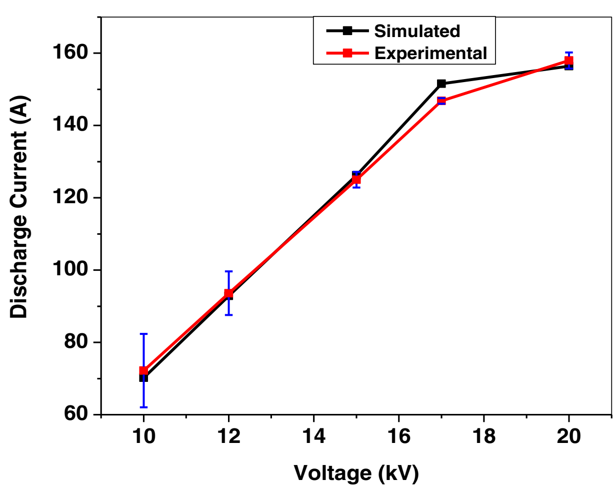
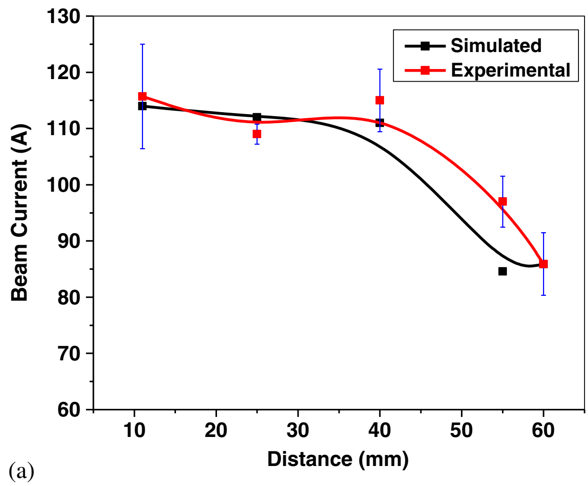


Figure 7. Variation of discharge current with applied voltage.

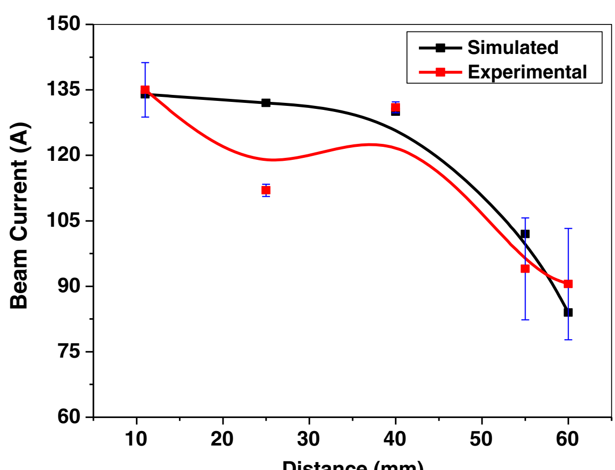
of external circuit has not been considered in the simulation model. Therefore, a variation in the discharge time-scale is observed in the experiment and the simulation plots.

4. Results and discussion

Experimental and simulated results were compared in self-breakdown mode at the same applied conditions, such as applied voltage, gas type and pressure, pulse voltage duration



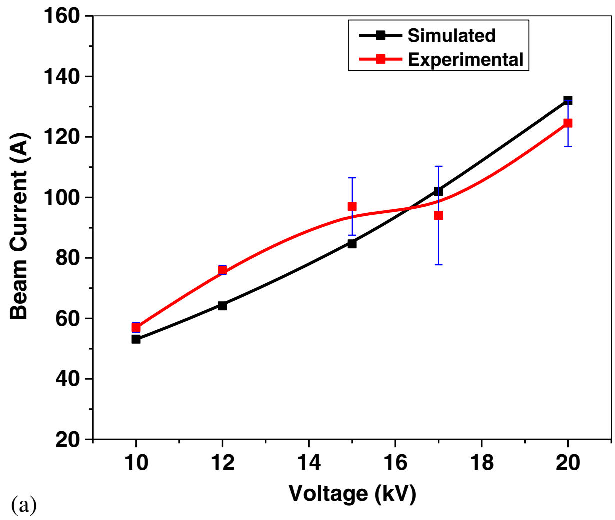
(a)



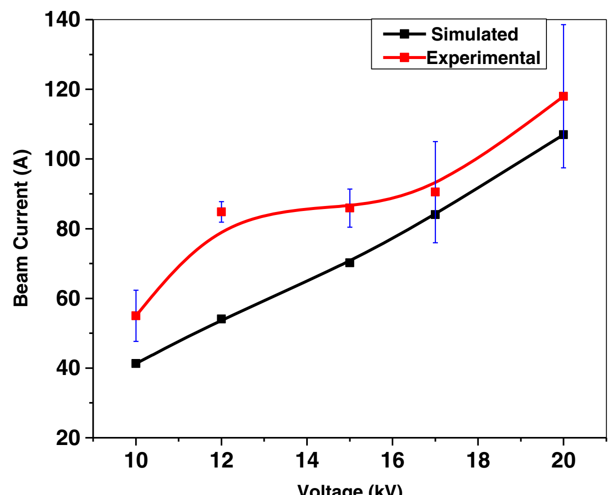
(b)

Figure 8. Beam current in the drift space at different axial positions with **(a)** 15 kV and **(b)** 17 kV applied voltages.

and geometry, which is essentially required for the discharge. All the results that are presented here are based on a single-shot experiment. So, only one single discharge pulse per shot has been taken into account. A plot of experimental and simulation breakdown voltage vs. gas pressure of argon for fixed 3 mm PS gap is shown in figure 6, which confirms the pseudospark analogy [15]. The higher applied voltage detains the discharge in reaching the steady state, resulting in attaining higher peak value of the discharge current, which is measured at the anode. 'Steady state' means equipotential state



(a)



(b)

Figure 9. Beam current in the drift space at different applied voltages measured at (**a**) 55 mm and (**b**) 60 mm axial positions.

for cathode and anode. For higher voltage it will take more time to reach the steady state resulting in more discharge. Figure 7 shows variation of discharge current with the applied voltage for both the experiment and simulation, which are in close agreement with each other. The data points with error bars presented are the average of five single-shot experiments for the same applied conditions. The electron beam obtained under different operating conditions were made to travel through the central aperture in the anode to the drift space region of the PCE-Gun. It is to be mentioned that drift space starts at 100 mm away from the anode aperture and hence the beam has been travelled more than 200 mm which has been reported earlier [8]. The beam current in the drift space was measured by placing collectors at different positions while keeping the applied voltage constant. The beam current is observed to decrease ∼30% over 60 mm distance as shown in figure 8 with the increase in axial direction. This can be due to collisions with the walls and neutral particles. Beyond 60 mm, due to the generation of a large number of particles during beam propagation, simulation could not be performed. Consequently, the comparative results have been reported up to 60 mm of electron beam propagation. The collision of neutral gas with electron beam results in the formation of plasma and ion channels [16]. The results obtained from experiments and simulations are shown in figures 8a and 8b for 15 kV and 17 kV applied voltages, respectively.

Investigations on the beam current have also been carried out by fixing the position of the collector at different axial locations inside the drift space for different applied voltages. The results are represented in figures 9a and 9b for the collector placed inside the drift space at 55 mm and 60 mm, respectively. The beam current was found to increase with the applied voltage, confirming more discharge at higher potential. The simulation and the experimental results follow similar trends and are in good agreement.

5. Conclusion

A single-gap self-breakdown-based, pseudospark-based, plasma electron gun was shown to successfully generate high current electron beam, i.e., 50–160 A at 5–20 kV applied voltages. The electron beam propagated more than 200 mm in the drift space region with no support from externally applied magnetic field. The performance evaluation of the developed PCE-Gun was validated by PIC simulation. The beam current, discharge current, breakdown behaviour and their results were in good agreement.

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References

[1] G S Nusinovich, Y Carmel, T M Antonsen, D M Goebel and J Santoru, *IEEE Trans. Plasma Sci.* **26**, 628 (1998)

[2] D M Goebel, Y Carmel and G S Nusinovich, *Phys. Plasmas* **6**, 2225 (1999)
[3] G S Nusinovich, Y Carmel, A G Shkvarunets, J C Rodgers, T M Antonsen, V L Granatstein, Y P Bliokh, D M Goebel and J P Verboncoeur, *IEEE Trans. Plasma Sci.* **52**, 845 (2005)
[4] W H Bennett, *Phys. Rev.* **45**, 890 (1934)
[5] J P Boeuf and L C Pitchford, *IEEE Trans. Plasma Sci.* **19**, 286 (1991)
[6] Xiaowei Gu, Lin Meng, Yang Yan and Yiqin Sun, *J. Infrared Millimeter and Terahertz Waves* **30**, 1083 (2009)
[7] E M Oks and P M Schanin, *Phys. Plasmas* **6**, 1649 (1999)
[8] K Frank and J Christiansen, *IEEE Trans. Plasma Sci.* **17**, 748 (1989)
[9] N Kumar, U N Pal, D K Verma, J Prajapati, M Kumar, B L Meena, M S Tyagi and V Srivastava, *J. Infrared Millimeter and Terahertz Waves* **32**, 1415 (2011)
[10] Tech X Corporation, OOPIC-Pro, Boulder, CO
[11] A M Howatson, *An introduction to gas discharge*, 2nd edn (Pergamon, New York, 1976)
[12] A Bogaerts, E Neyts, R Gijbels and J V Mullen, *Spectrochim. Acta Part B* **57**, 609 (2002)
[13] R Tkotz, A Górtler, J Christiansen, S Dóllinger, K Frank, F Heine, U Herbleb, S Insam, R Kowalewicz, T Mehr, A Polster, U Pruker, M Schlsug and A Schwandner, *IEEE Trans. Plasma Sci.* **23**, 309 (1995)
[14] H Yin, W He, A W Cross, A D R Phelps and K Ronald, *J. Appl. Phys.* **90**, 3212 (2001)
[15] K Frank and J Christiansen, *IEEE Trans. Plasma Sci.* **17**, 748 (1989)
[16] W Xie, X Li, L Meng, Y Yan, X Gao, S Chen and S Liu, *Int. J. Infrared and Millimeter Waves* **23**, 1149 (2002)