

ION TRACKING IN A HIGH-VOLTAGE DC PHOTO-GUN*

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Abstract

The photocathode lifetime of GaAs in a high voltage DC gun is limited primarily by ion back bombardment. Ions produced in collisions of the electron beam with residual gas in cathode-anode gap and downstream of the anode are accelerated toward the cathode and strike the cathode surface. Systematical studies suggest that ion back bombardment is determined by gas pressure, gun voltage, laser spot and electric field profile. This paper presents a study of ion back bombardment in a high average current DC photocathode gun. This study is based on numerical analysis and particle tracking simulation. The results implies that ion generation can be suppressed by improving vacuum condition as well as gun voltage, and the back bombardment can be reduced by the optimization of laser spot position and electric field profile.

INTRODUCTION

A high average power THz-FEL is currently under construction at China Academy of Engineering Physics (CAEP) [1]. To achieve the THz wave with the average power of 10 W, a high-voltage DC gun with a negative electron affinity GaAs cathode is constructed as the high brightness electron source [2, 3]. Experiments at high average current suggested that the ion back bombardment could be a dominant mechanism that causes the degradation of the quantum efficiency (QE) and limit the operating lifetime [4, 5]. Ions bombarding the photocathode may either sputter away the surface chemicals and destroy the negative electron affinity or implant into the bulk and damage the cathode material.

In previous studies, particle tracking and theory model were used to estimate the ion production and distribution on the cathode surface [6-8]. Those studies provided powerful tools to analyze the generation and dynamics of ions inside the gun. J. Qiang has systematically studied the ion back bombardment in a high average current RF photocathode gun by simulation [9]. However, no systemic simulation was reported to analyze the generation and dynamic of ions in a DC gun, which is important to the operation lifetime of photocathode. In this paper, ion generation and back bombardment are studied in a high voltage DC photocathode injector, which is under commissioning at CAEP. The study puts emphasis on the gas pressure inside the gun, gun voltage, off-axis illuminated

spot and positive potential barrier. The results demonstrate that ion back bombardment damages to the emission spot of the cathode can be minimized by choosing proper operation parameters.

SIMULATION MODEL

Mostly, ions are produced in the collisions between electron beam and residual gas molecules. As shown in Fig. 1, the motion of ions depends on the position where ions are generated. The path of ions is determined by the overall effect of the electric field, the voltage drop produced by the electron beam and the initial kinetic energy. Ions created within the cathode/anode gap will be accelerated by the electric field immediately. Meanwhile, those created downstream of the anode can migrate into cathode-anode gap and be accelerated [10].

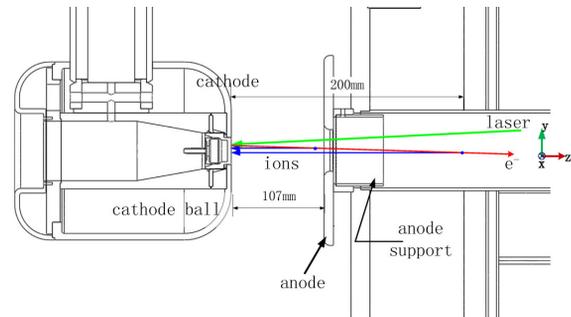


Figure 1: Layout of electron beam emission and ion back bombardment in a DC gun at CAEP.

The gas species mostly observed in a DC gun are H_2 , H_2O and CH_4 . To simplify the calculations, only H_2^+ is considered in this study. The probability of ion generation is given by [11]

$$\frac{dN}{dQ} = \frac{1}{e} \int_{z_0}^z n_g(z) \sigma_i(z) dz, \quad (1)$$

where e is the electron charge, N is the number of ions generated with charge Q and $n_g(z)$ is the density of residual gas. σ_i is the ionization cross section as a function of beam energy [11], as shown in Fig. 2.

The pressure is assumed to be constant in radial direction and uniform inside the gun. The pressure is considered as 10^{-9} Pa inside the gun and 1.51×10^{-6} Pa at 0.5 m from the cathode surface. Then the distribution of gas pressure in the gun can be calculated by solving the steady state diffusion equation, as shown in Fig. 3.

The longitudinal distribution of ions can be calculated from Eq. (1). The radial distribution is assumed to be the

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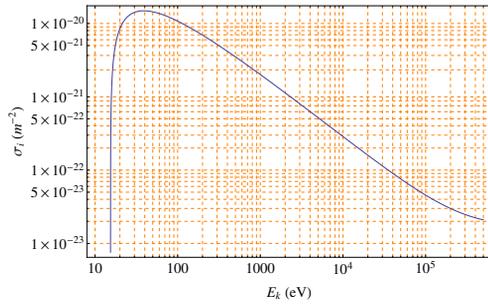


Figure 2: Electron impact ionization cross section of H₂ as a function of beam kinetic energy.

same as the electron beam's. The initial velocity of ions is given by the gas temperature of 20°C. Because the flux of ion is much smaller than that of the electron, the space charge field of ions and charge neutralization are neglected.

The simulation code ASTRA [13] is used in particle tracking. Bunches of electron emitted from photocathode with a repetition of 54.167 MHz will transport through the DC gun with external electric field forces and self-consistent space charge until the flux of ions on the cathode is constant. Then, the flux n_f , line density ρ_l and power line density ρ_p of ions on the cathode are calculated and analyzed.

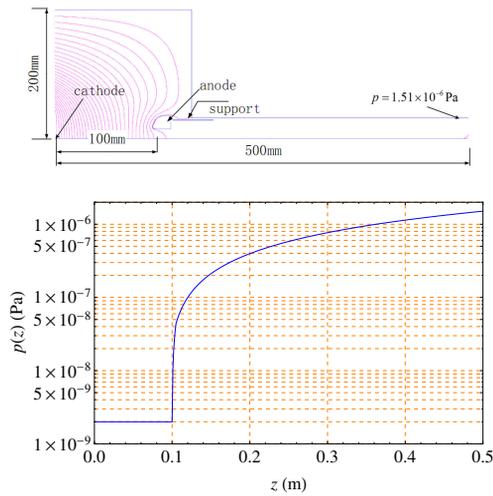


Figure 3: Basic geometry of DC gun (top) and the H₂ pressure distribution across DC gun (bottom). Here, the anode and support can be biased with independently power supply.

SIMULATION OF ION IN THE HIGH VOLTAGE DC GUN

The geometry of the DC gun is shown in Fig. 1. The gun is designed to operate at 200~500 kV with an average beam current of 5 mA.

Effects of Gas Pressure

Experimentally, the cathode lifetime will decrease quickly when the vacuum inside the gun is worse than 10⁻⁸ Pa. The simulation is under conditions of different pressure p_0 inside the gun. The line density of H₂⁺ ions on the cathode in y -direction, as shown in Fig. 4, is in proportion to the gas pressure. The result is consistent with some previous theory analysis [12], which demonstrated that the gas pressure only affects the production of ion.

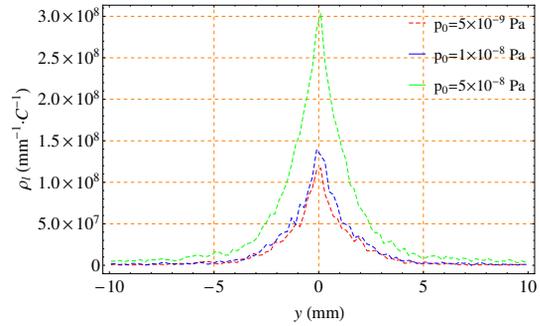


Figure 4: Line density of H₂⁺ ions in y -direction (normalized to the extracted charge 1C).

Effects of DC Gun Voltage

The DC gun can be operated at different high voltages. Figure 5 shows the line density and power line density of H₂⁺ ions with a gun voltage of 250 kV, 350 kV and 500 kV, separately. The flux of ions decreases with the voltage rising due to the smaller cross section at higher voltage. However the power of ions implanted on the cathode increases with the higher voltage because the kinetic energy of ions is increased.

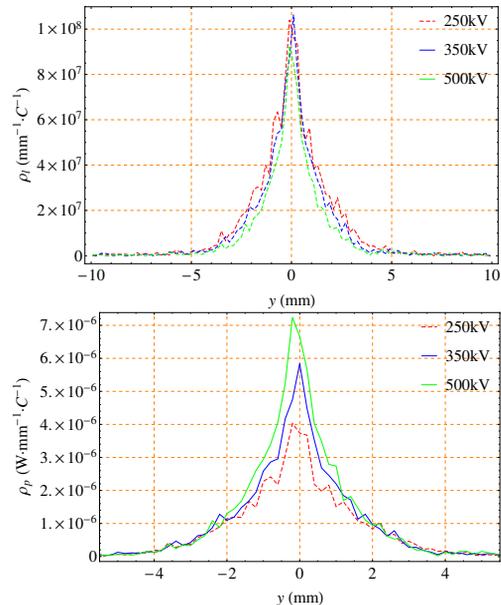


Figure 5: Line density (top) and power line density (bottom) of H₂⁺ ions with different gun voltage.

Effects of Off-axis Illuminated Spot

One of the methods usually used to improve the cathode lifetime in experiment is to keep the laser spot away from the electrostatic center (EC), i.e. the center of the cathode ball. The line density of H_2^+ ions on the cathode is shown in Fig. 6 with the laser illuminated spot at $y = 2$ mm, 4 mm and 6 mm, separately. It is seen that the density's peak is around the EC but not the laser spot. That is because much more ions produced in the beam line downstream of the anode. Those ions could be trapped by electron bunches and drift to the axis by the electric potential downstream of the anode. Finally, They will follow a ballistic trajectory and arrive at the EC of cathode. Thus, the ions damage to laser illuminated spot could be efficiently suppressed by off-axis laser illuminating.

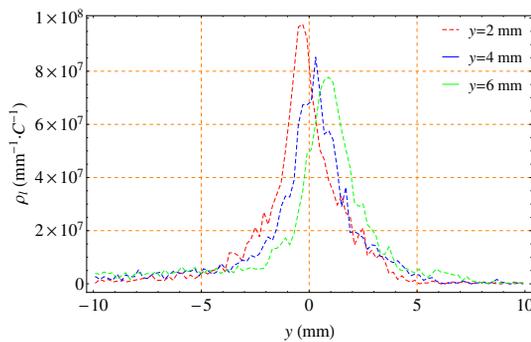


Figure 6: Line density of H_2^+ ions on the photocathode with laser spot at $y=2$ mm, 4 mm, 6 mm.

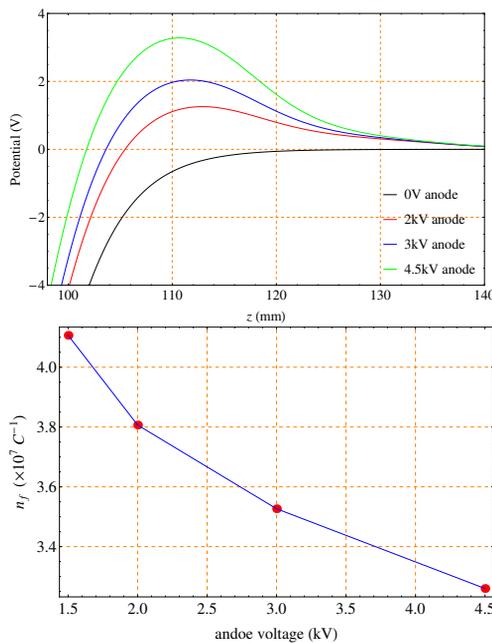


Figure 7: On-axis electrostatic potential near the anode (top) and the flux of H_2^+ ions on the photocathode versus biased voltage (bottom). The anode support is biased to 300 V.

Effects of Positive Potential Barrier

Figure 6 also implies that most of the ions are produced beyond the anode. Those could be trapped by the electron beam, drift into the cathode-anode gap and be accelerated toward the cathode. E. Pozdeyev has proposed an effective solution to the problem of trapped ions, the positive potential barrier by the biased anode and the anode support [8]. The electrostatic potential on the axis of gun near the anode and the H_2^+ ions arriving at the cathode surface with the anode biased to different voltages are shown in Fig. 7. Comparing with the anode and its support at zero potential, the flux is reduced by an order of magnitude with higher anode biased voltage. Most of the ions remained should be produced in the cathode-anode gap.

The combination of off-axis illuminated spot and positive potential barrier is also considered. The results are shown in Fig. 8 with different laser spot. The maximum of the line density corresponds to the position of laser spot but its amplitude is reduced by more than one order of magnitude compared with Fig. 6. It implies that this method could effectively reduce the ions bombardment damage to both the laser spot and the EC.

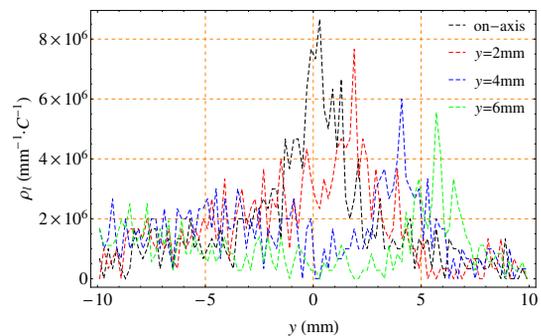


Figure 8: Line density of H_2^+ ions across the y -direction with laser illuminated at $y=2$ mm, 4 mm and 6mm (anode biased to 2 kV and support biased to 300 V).

CONCLUSION

In this paper, the effects of gas pressure, DC gun voltage, off-axis illuminated spot and positive potential barrier on the ion back bombardment to the photocathode in a high voltage DC gun are studied by simulation. The results demonstrate that improving the vacuum inside the gun is a direct way to suppress the ion back bombardment. Higher voltage in the DC gun will lead to fewer ions on the photocathode but with more power. Off-axis illuminated spot can reduce the ion back bombardment at the emission spot although the total flux on the photocathode is hardly changed, while positive potential barrier can reduce the ion back bombardment on the whole photocathode. The back bombardment on the emission spot could be reduced further more by the combination of off-axis illuminated spot and positive potential barrier.

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