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Particle-in-cell simulation of electron trajectories and irradiation uniformity in an annular cathode high current pulsed electron beam source

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ABSTRACT

In order to study electron trajectories in an annular cathode high current pulsed electron beam (HCPEB) source based on carbon fiber bunches, the transmission process of electrons emitted from the annular cathode was simulated using a particle-in-cell model with Monte Carlo collisions (PIC-MCC). The simulation results show that the intense flow of the electrons emitted from the annular cathode are expanded during the transmission process, and the uniformity of the electron distribution is improved in the transportation process. The irradiation current decreases with the irradiation distance and the pressure, and increases with the negative voltage. In addition, when the irradiation distance and the cathode voltage are larger than 40 mm and −15 kV, respectively, a uniform irradiation current distribution along the circumference of the anode can be obtained. The simulation results show that good irradiation uniformity of circular components can be achieved by this annular cathode HCPEB source.

1. Introduction

In recent decades, many experimental and theoretical studies are being devoted to the modification of material surface properties using high current pulsed electron beam (HCPEB) [1–3]. HCPEB irradiation is accompanied by different physical phenomena, which include extremely fast heating and cooling of the surface layer [4,5], change of the surface morphology and phase transitions. As a result of this HCPEB irradiation process, significant improvement in various properties, such as the hardness, wear and corrosion resistance of the material surface layer, can be obtained [6–9]. The carbon fiber, which possesses low threshold voltage, high emission current density, good emission uniformity and long lifetime, has shown great potential as cathode materials of the HCPEB source [10–13]. However, since most of current HCPEB irradiation facilities use a planar cathode, only cylindrical electron beams can be obtained. In order to realize uniform high current pulsed electron beam irradiation for a circular component, we designed an annular cathode for HCPEB irradiation, in which commercial carbon fiber yarns (T300-3K, 7 μm) were used as the emission material of the annular cathode [14].

Because measurement of the electron transportation process in the annular cathode HCPEB source is very difficult, simulations of the HCPEB process is the key way for obtaining an optimized configuration of this HCPEB source. Particle-in-cell model with Monte Carlo collisions (PIC-MCC) has been used extensively in simulations of collisions between different particles [15–17]. Because collisions between electrons and gas moleculars are inevitable in this HCPEB irradiation process, PIC-MCC method is employed in this study. Electron trajectories in the annular cathode HCPEB source were simulated and influences of the working parameters on the irradiation uniformity were obtained.

2. Model

In the annular cathode HCPEB source, the cathode and anode form a coaxial cylinderical diode, and electrons are emitted and accelerated in the radial direction of the cathode cylinder. Four basic assumptions are made for the electrons. Firstly, the electrons generated in this HCPEB source are obtained completely by an explosive emission mechanism. Therefore, the electron emission current density of the cylinderical cathode is given by the Langmuir–Blodgett law [18].

$$J = \frac{8\pi\varepsilon_o\sqrt{2}}{9}\sqrt{\frac{e}{m_e}}\frac{V^{\frac{3}{2}}}{r\beta^2} \quad (1)$$

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where e is the elemental charge, m_e is the electron mass, V is the voltage at any point P, r is the radius at P, $\beta = f(r/r_c)$ is a quantity of zero dimensions, and r_c is the radius of the cathode. The values of β as a function of r/r_c for the cylindrical diode was obtained from Langmuir's calculations [18]. Secondly, the self-induced magnetic field formed by the high electron current is considered, and the movement of the electron is controlled by the electromagnetic force. Thirdly, because the maximum acceleration voltage in our experiment is smaller than 60 kV, the electron motion in the simulation is non-relativistic. Lastly, because the total simulation time is about 10 ns and the gap between the anode and cathode is larger than 40 mm, and other study showed that the expansion velocity of the anode plasma was about 3 cm/μs [19], the influence of the anode plasma on irradiation process in this simulation period should be very small. Therefore, the effect of bipolar flow of ions emitted from the anode is ignored in this simulation.

The electric field and the magnetic field distribution can be derived using Maxwell's equation [20]:

$$\begin{aligned} \nabla \times E &= -\frac{1}{c}\frac{\partial B}{\partial t} \\ \nabla \times B &= \frac{1}{c}\frac{\partial E}{\partial t} + \frac{4\pi}{c}J \\ \nabla \cdot E &= 4\pi\rho \\ \nabla \cdot B &= 0 \end{aligned} \tag{2}$$

where J is the current density, ρ is the charge density, E is the electric field, B is the magnetic induction field, c is the speed of light.

The particle positions and velocities are governed by Newton-Lorenz's equations of motion [20]:

$$F = q(E + v \times B) \tag{3a}$$

$$F = m_e a \tag{3b}$$

$$\Delta r = v_a \Delta t + \frac{a}{2}(\Delta t)^2 \tag{3c}$$

$$v_b = v_a + a\Delta t \tag{3d}$$

where v_a and v_b are the velocities before and after the time step Δt, q is the electron charge, v is the instantaneous velocity of the electron, m_e is the electronic mass, E and B are the electric field and the magnetic field.

The collisions between electrons and neutral background gas atoms are elastic scattering, ionization and excitation [21]. We assume that the working gas in the vacuum chamber is complete argon, therefore, a set of collisions between electron and Ar atom listed as follows were included in this model.

$$\text{Elastic Scattering}: e^- + Ar \rightarrow e^- + Ar \tag{4a}$$

$$\text{Excitation}: e^- + Ar \rightarrow e - + Ar^* \tag{4b}$$

$$\text{Ionization}: e^- + Ar \rightarrow e^- + Ar^+ + e^- \tag{4c}$$

A brief description of the simulation scheme follows. First, Poisson's equation (2) is approximated using a finite difference representation. Next, the electrons were emitted from the cathode in every time step, where its emission current density is calculated according to Langmuir–Blodgett law (1), and electrons are advanced using their velocities and accelerations at the current time through Eq. (3). The moleculars are fixed uniformly inside the simulation area, and collisions between the electrons and moleculars are calculated according to Eq. (4) when their distances are small enough. The potential distribution at the next time step is then calculated and the position and velocity of each particle is advanced using Eqs. (2) and (3).

The annular carbon fiber cathode is shown in Fig. 1a, where several rows of 24 carbon fiber bunches are installed uniformly around the circumference of the cathode. In order to save the simulation time, we assume that the electron density along the axial direction of the cathode is uniform, so we only simulate the electron trajectories along the radial direction. A 2-Dimentional Cartesian coordinate is used in this simulation, and the schematic of the simulation region is shown in Fig. 1b. The simulation region is a square of $300 \times 300\ mm^2$, and 24 carbon fiber bunches are distributed uniformly along the circumference of a cylinder with a radius of 200 mm, and the potentials on them are set to a predefined value. The anode is located in the center of the cathode, where its radius is set to different values, and its potential is fixed to the ground. The total simulation area is divided evenly into 600×600 cells, and the potential applied on the carbon fiber bunches is varied from -15 to -60 kV. The total simulation time is 10×10^{-9} s with a time step Δt of 2.7×10^{-13} s. Macro-particles were used in this simulation. The initial velocity of the macro-particles from the cathode emitted satisfies the Gaussian distribution, and the macro particle weight factor in this simulation is 1×10^7.

In order to study the peripheral uniformity of the electron current to the anode, as Fig. 1c shows, the surface of the anode is evenly divided into forty-eight regions and numbered from 1 to 48. The irradiation uniformity for the annular cathode is characterized by the relative standard deviation of the irradiation electron current at different positions of the anode surface.

3. Results and analysis

In the HCPEB process, electrons are emitted and accelerated by an electric field formed by the large negative voltage applied on the annular cathode. The electrons then travel across the space, collide with the residual gas moleculars, and eventually impact on the anode. In this section, we first discuss the trajectories of the electrons. We then study the potential distributions in the simulation region. These simulation results are obtained with a negative voltage of -30 kV, an anode diameter of 30 mm and a gas pressure of 0.06 Pa. Finally, the influences of different parameters on the irradiation uniformity are shown, in which the anode diameter, negative voltage and pressure in these simulations are varied.

3.1. Electron trajectories

The electron distributions at different simulation time are shown in Fig. 2. At the beginning of the simulation (Fig. 2a), it can be found that electrons are emitted from the tip and the side surface of the carbon fiber, and accelerated to the anode. It is clear from Fig. 2b that the electron flow expands rapidly in the transportation process, and the uniformity of the electron distribution is improved in the leading end of the electron flow. As we know, the expansion of the electrons in the HCPEB process is controlled by the Coulomb force between different electrons and the Lorenz force caused by the self-induced magnetic field. Because the current density in this process is not very high, the Coulomb force is larger than the Lorenz force. Therefore, the electron emitted from the carbon fiber can be repelled obviously by neighboring electrons, and the electron flow is expanded. At the simulation time of 1.3×10^{-9} s, as shown in Fig. 2c, the electrons are transported to the surface of the anode and the electron distribution becomes uniform. When the simulation time increases more, as Fig. 2d and e shows, an equilibrium of electron loss and emission in the simulation region has been obtained, and the distributions of electrons do not change obviously.