Numerical Analysis of Electron Behavior in Beam Diode Driven by Intense Pulsed Power Device

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ABSTRACT

Electron beam behavior in beam diode gap was investigated numerically using electrostatic particle-in-cell model based on the normalized value and experimental results of intense pulsed power discharge device ETIGO-II. Numerical results of the space charge limited electron emission expose the electron beam behavior in diode gap alone with the electrostatic field. Compilation of numerical result shows that due to the space charge limited current, virtual cathode is formed near the cathode surface, which is liable for the low output beam current. Numerically it is also observed that the beam current is significantly change with the change of diode gap distance and the change of emission radius at the cathode surface. Comparison of experimental results with the numerical results revealed the approximate electron emission radius at the cathode surface. Numerical results also qualitatively satisfy the experimental results of pulsed power discharge device ETIGO-II.

Keywords

Electron beam behavior, Space-Charge limited emission, Pulsed-power generator

1. Introduction

The next-generation energy source to solve the energy problem is nuclear fusion by inertial confinement scheme. In inertial confinement fusion (ICF), materials of a fuel pellet pass through a warm dense matter (WDM) regime during the implosion process [1, 2]. Properties in the temperature-density region known as WDM are so important and have a great impact in implosion dynamics [3, 4]. For this reason, a generation method of WDM using an intense pulsed power generator with an electron beam diode was proposed to research the WDM property at comparable pulse duration to the ICF implosion [5, 6, 7]. Conversely the intense pulsed power generator can produce high electron beam current which is necessary for high power devices within the desired short time for high energy research applications [8, 9, 10, 11]. Clarified physical properties and behavior of electron beam is needed to utilize this technology properly and understand the WDM research data significantly.

The electron beam diode behaves as impedance, which regulates the input power and energy into the sample load. Though, the input power control with the electron beam diode was investigated experimentally, however the beam electrons behavior in the diode gap are not understood [6, 7]. Therefore, the clear understanding of the electron beam characteristics in electron beam diode gap with relativistic effect, a numerical analysis is done based on an electrostatic particle-in-cell (PIC) method, corresponding to the experimental results and experimental conditions of intense pulsed power device ETIGO-II.

2. Numerical model

The beam dynamics of an electron in gap are relatively complex, for the case of a gap with uniform electric field. Eventually the beam dynamics become more complicated, if the gap has a changing electric and magnetic field. Figure 1 show the typical numerical model of electron beam diode and it is

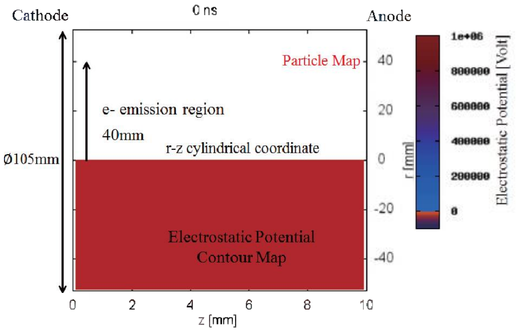


Fig. 1. Schematic diagram of numerical results: electron beam is emitted from the cathode surface and travel through the vacuum and reach to anode. Cathode radius is 55 mm. Gap distance d = 10 mm. Beam radius r_{emit} = 40 mm.

considered that the phenomena involved in cylindrically axisymmetric. The numerical simulation is done based on the 2 dimensional electrostatic PIC model. In this numerical study electron beam emission feature is based on space charge limited emission. So, satisfying the space charge limited conditions, the numerical simulation is done with the deliberation of time dependent relativistic particle motion. The electric field components are E_r, E_z and velocities v_r, v_z and positon (r, z). Those are solved using the Poisson equation, which is solved by successive over relaxation (SOR) method and weighting for the calculation of electron charge

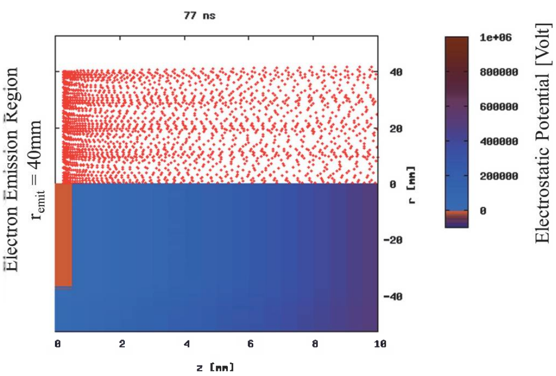


Fig. 2. Particle map with the electrostatic potential contour map at t =77 ns for electron emission radius of 40 mm. Dots show the electrons, and contour shows the electrostatic potential, respectively.

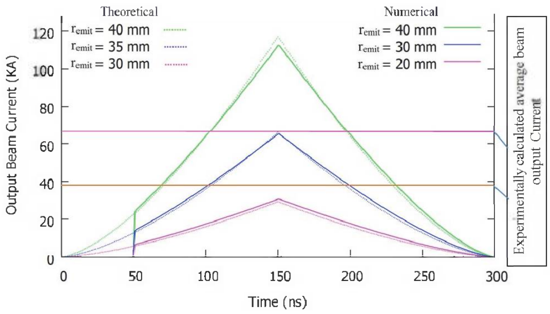
density is done by the cloud-in-cell (CIC) method, and relativistic equation of motion (Leaf-frog method is used for the calculation of velocity and position) [12, 13, 14]. In the calculation condition, the external applied voltage is 1 MV at maximum, and is the experimental value in the intense pulsed power device ETIGO-II [15]. The pulse width is 300 ns, and the rise and fall times are 150 ns, respectively. The peak voltage is 1 MV at 150 ns, and the output beam current is 50 ns lack by the applied voltage [7, 15]. Initially, the self-magnetic force is zero due to the zero electron beam velocity (v_z = 0), and the self-magnetic force with the increase of velocity is not increased considerably. The electron motions are dominated by the Lorentz force ($\boldsymbol{F} = q\boldsymbol{E} + q\boldsymbol{v}\times\boldsymbol{B}$), and are determined by the ratio of the force induced by the electric field ($\boldsymbol{F}_{\mathrm{E}} = q\boldsymbol{E}$) to the force induced due to the magnetic field ($\boldsymbol{F}_{\mathrm{M}} = q\boldsymbol{v}\times\boldsymbol{B}$). From the preparatory consideration for $\boldsymbol{F}_{\mathrm{E}}$ / $\boldsymbol{F}_{\mathrm{M}}$, it is expected that the force induce by the magnetic field is smaller enough than the force induced by the electric field in this study. For this reason, the self-magnetic force is assumed as negligible.

The initial beam radius is 40 mm, which is framed as well as 30 mm and 20 mm according to numerical condition. The electrons are emitted from the cathode surface and travel through vacuum due to electrostatic potential. The diode gap is 10 mm and is set as 15 mm and 20 mm according to experimental condition. Computational area is $0 \le z \le d$ and $0 \le r \le$ 55 mm, where centerline is the cylindrical axis.

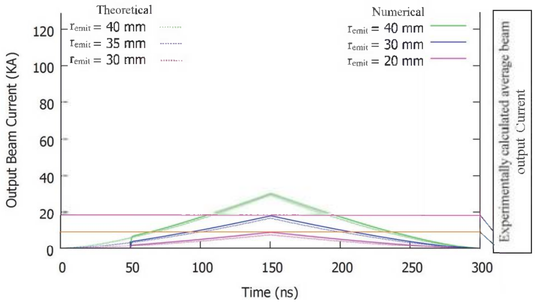
In the intense puled power generator "ETIGO-II", the maximum beam output current is calculated theoretically. The classified theoretical equation of space-charge-limited current is commonly known as "Child-Langmuir Law" [16].

3. Results and Discussions

Figure 2 shows the numerical results of particle map with the electrostatic potential at 77 ns. Here upper part shows the electron map, and lower part shows the contour map of the combined external and internal potential. Figure 4 shows the particle map for the beam electrons and the beam envelope line,

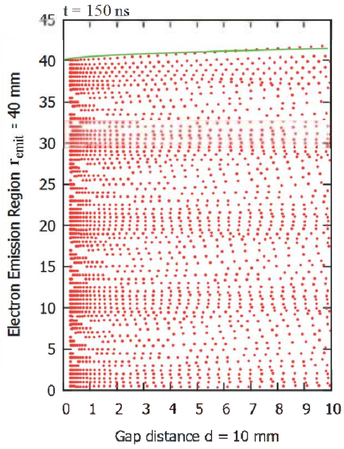


(a) Diode gap distance d = 10 mm

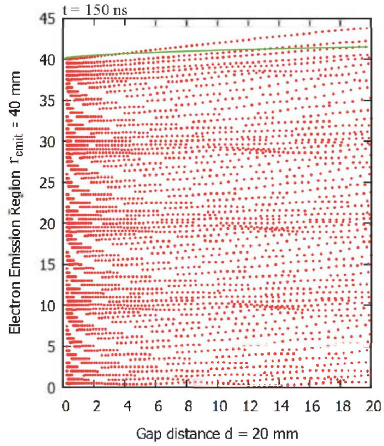


(b) Diode gap distance d = 20 mm

Fig. 3. Comparison in theoretical and numerical results for electron beam current; (a) diode gap d = 10 mm and beam output current measured at z = 9 mm (b) diode gap d = 20 mm and z =19 mm. Here for the case of (a) and (b) only electron emission radius is changed to 40 mm, 30 mm and 20 mm.



(a) Diode gap distance d = 10mm



(b) Diode gap distance d = 20 mm

Fig. 4. Charged particle map of beam electrons: (a) at t = 150 ns for diode gap d = 10 m (b) at t = 150 ns for diode gap d = 20 mm. The beam envelope line is drown using envelope equation and the beam radius is expanded gradually by the self-space charge effect

which is obtained from the envelop equation [17, 18]. As shown in Fig.4, the beam radius expands gradually by the space charge effect.

In the parallel-plate vacuum diode gap once free electron enter, they produce the local electric field potential [18]. The emitted free electrons affected by both the external and the internal mutual electric forces. Negatively the electrons are emitted from the cathode surface, and move to the right (anode) side, and create a steady electric current density to the left (cathode) side [18]. The steady conventional electric current flow forms from the anode to the cathode. According to the numerical calculation result for the particle map, it is indicated in Fig. 2 that the virtual cathode is created near the cathode. Because of the space-charge limited condition, the virtual cathode is created. At the point of virtual cathode, the beam electrons come to a stop, and start to move backward (left), which limits the output beam current.

Figure 3, comparison of the numerical and theoretical results, shows that the emission area is around 30 mm. Experimental result shows that the average output beam current is 50 ~ 60 kA [7], which qualitatively satisfies the above numerical results and confirm the electron emission radius in the experimental case. Though the real cathode is really big and diameter is 105 mm but electron is not emitting from the entire cathode surface. Eventually the electron emission region is really small in real condition and from the experiment emission radius is also not clear. From Fig. 3, it is seen that especially for the r_{emit} = 30 mm, the output beam current is limited by the space charge limited current and it qualitatively satisfies the experimental results. However, in the cases of r_{emit} = 40 mm and r_{emit} = 20 mm, the discrepancy between the numerical and theoretical results becomes large, because it is due to the localized emission area of electrons at the cathode in case of numerical simulation. As a result, the beam current does not increase along with the space charge limited current; even in the cathode area is large enough. From the overall evaluation of theoretical and numerical results, electron emission radius of cathode surface is estimated around 30 mm in the case of experiment with the standardized condition of intense pulsed power generator ETIGO-II.

According to the numerical result, when the current density in the electron beam diode gap exceeds a certain critical value, the beam indicates a unique behavior. Normally, all the electrons emitted from the cathode are accelerated in the cathode layer by the discharge potential difference, move alone the electrical field and reach the beam collector to anode. However, when the electron beam current reached the critical value of space-charge limited current, the electron beam becomes unstable. At this point the current of the electron beam from the cathode layer remains practically constant, but the anode current decrease sharply. From Fig. 2 shows that because of the space charge limited current virtual cathode is created near the cathode surface, which is responsible for the low electron beam output current.

Figure 3 shows that the theoretically calculated maximum space charge limited current with the function of gap distance and electron emission radius. The space charge limited current is decreasing so sharply with the increase of gap distance. Those numerical results also show that the space charge limited current for 10 mm gap distance, with the decrease of electron emission radius, the current is also decreased. Fig. 3(b) shows the current for 20 mm gap distance and the phenomena is analogous to the case of 10 mm gap distance. However, the maximum space charge limited current is decrease considerable for the case of 20 mm gap distance compare to the result of 10 mm gap distance, which is deliberated to be the cause of low beam output current in experiment as well as in numerical calculation also.

4. Conclusions

The numerical simulation was carried out using 2D electrostatic PIC model to investigate the relativistic electron behavior, space charge limited emission of electrons, lower beam output current, and electron emission radius from the cathode surface and partially confirm the experimental results. In comparison with the numerical and theoretical results, the electron emission radius from the cathode surface was expected as around 30 mm. Numerically as well as theoretically, the electron beam output current varied with the change of diode gap distance, which qualitatively satisfies the experimental results. With the increase of diode gap distance, the beam output current decreases in both the numerical and experimental cases. Numerically it is seen that the space charge limited current decreases with the increase of gap distance and oppositely with the decrease of electron emission radius.

The analyses of numerical, theoretical and experimental results explain the physical phenomena of electrons in the diode gap with the varied electric field, and partially satisfies the experimental results with the experimental setup and normalized value of ETIGO-II.

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