Three-dimensional PIC/MCC simulation of electron deposition in JAEA 10 A ion sources*

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(Received 17 December 2013; revised manuscript received 12 February 2014; published online 16 July 2014)

A systematic research on the electron deposition process in the JAEA 10 A ion source is carried out by using a particle-in-cell/Monte Carlo collision simulation, which is based on a full three-dimensional self-developed code. Two parts are studied. One is the space and energy distribution of fast and slow electrons, the other is the vibration excitation collisions between electrons and hydrogen moleculars. The results show that the inhomogeneity of electrons comes from the Y direction drift of the fast electrons ($T_e \geqq 25$ eV) due to the action of the magnetic fields. This drift also increases the number of vibration excitation collisions in the $-Y$ direction, and results in the increase of H_a in the $-Y$ direction, eventually leading to the $-Y$ drift of H^-. It explains the spatial non-uniformity in the JAEA 10 A ion source.

Keywords: JAEA 10 A ion source, particle-in-cell/Monte Carlo collision simulation, spatial non-uniformity

PACS: 52.65.Pp, 52.50.Dg, 29.20.Ej **DOI:** 10.1088/1674-1056/23/9/095201

1. Introduction

With the promotion of the international thermonuclear experimental reactor (ITER) program, a lot of experiments of neutral beam injection used in the thermonuclear fusion are launched all over the world.[1] Many domestic and abroad scholars in this field pay great attention to the negative hydrogen ion due to its high efficiency of neutralization.[2] Currently, there are some popular ion sources, such as Camembert III, JAEA 10 A, 15–20 mA multi-cusp ion sources, and penning ion sources. The electric field can be ignored in the simulation for the previous three ion sources where the particles are constrained by a multi-cusp magnetic field, and their simulations are relatively convenient. Therefore, it is easy to obtain and explore the law of the discharge process, and the ion source can be optimized. As a result, the convenience leads to extensive researches for this kind of ion sources. It is necessary for us to model the simulation of the ion source effectively with a large number of iterations and varied numerous particles. Moreover, it is reported that H^- in JAEA 10 A ion source is spatially non-uniform ($-Y$ drift). This non-uniformity is rooted in the non-uniformity of the H atoms caused by the non-uniformity of electrons.[3,4] H^- is produced when H atoms bombard the plasma grid. Based on the above analysis, a systematic research on the electron deposition process in the JAEA 10 A ion source is carried out by using particle-in-cell/Monte Carlo collision (PIC/MCC) simulations based on a full three-dimension and self-developed code.[2] It helps us to explore the regularity of electron deposit within the ion source.

2. Algorithm and model description

Figure 1 shows a full three-dimension electromagnetic PIC/MCC programming sequence diagram. The PIC is used to process the Lorentz force on the particles and store the particles. The MCC is used to calculate the collisions of the particles (including Coulomb collisions of heterologous particles and scatter collisions of homologus particles). The Newton motion equation is used to solve the interaction between the particles and the fields,[5,6] the analytical formula of the magnetic charge model[5] is used to compute the multi-cusp magnetic field, the null collision model[7] is used to solve the non-homogeneous particle collisions, the Takizuka and Abe's model[8] is used to solve the Coulomb collisions between the same particles, and an empirical formula is used to calculate the interaction between the electron and the conductor boundary. In order to discuss the spatial variation of the electron energy distribution function (EEDF), the discharge volume is divided into small spatial cells along the Z direction as shown in Fig. 2. The figure shows the cross-sectional view in the Z plane of the numerical cells used in the simulation.

Specifically, the electromagnetic force of the particle is solved inside A and B, and the field is interpolated on the grids by the volume weight; the particle information is updated by the effect of the field inside C, and the particle velocity is corrected by the calculation of the collisions; the particle emission and the boundary condition are handled inside D, the influence of the plasma potential to the boundary particle is considered at the same time to confirm the balance of the particles.

*Project supported by the National Natural Science Foundation of China (Grant No. 11176032), the China Academy of Engineering Physics (CAEP) THz Science and Technology Foundation (Grant No. CAEPTHZ201209), the Scientific Reserch Fund of Sichuan Provincial Education Department, China (Grant No. 12ZA183), and the Southwest University of Science and Technology Doctor Fund, China (Grant No. 13zx7106).

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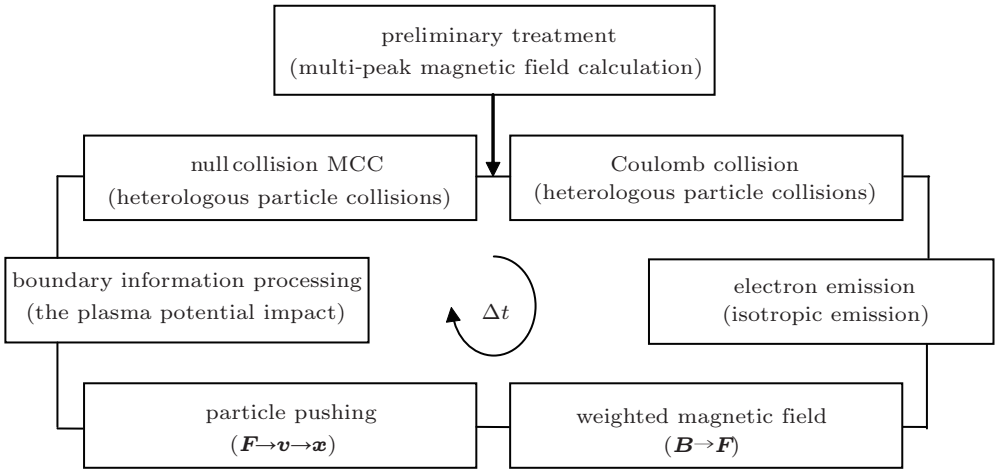


Fig. 1. The full 3D PIC/MCC algorithm.

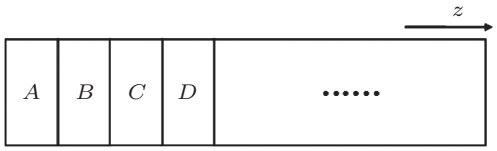


Fig. 2. (color online) Schematic diagram showing the spatial division.

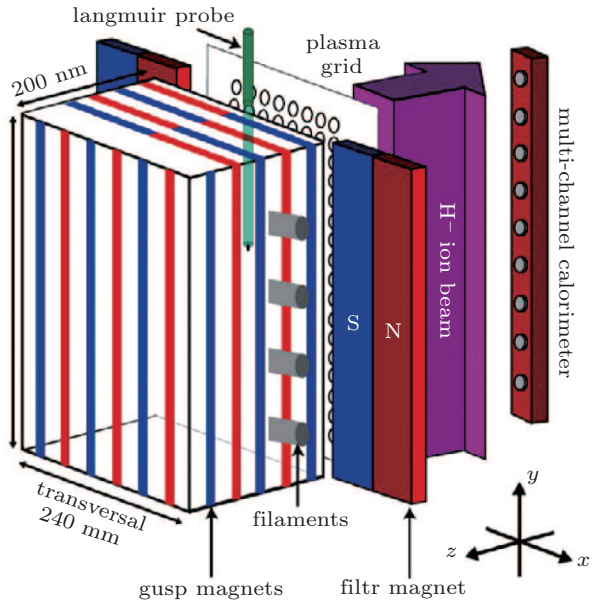


Fig. 3. (color online) Distribution of permanent magnets in JAEA 10 A ion source.

Figure 3 shows the distribution of the permanent magnet in JAEA 10 A.[9–12] The model dimensions of the plasma chamber are 240 mm in width, 480 mm in height, and 200 mm in depth. The extraction electrode is coated with tungsten, and the extraction holes with a 14×27 lattice pattern lay in the extraction area which is 140 mm in length and 340 mm in width. Each extraction hole has a diameter of 9 mm. The size of gridding in X, Y, Z is 2 mm, and the boundary, which is surrounded by magnets, is set to have perfect conduct. At the beginning of the simulation, 100 electrons are emitted isotropicly every 10^{-8} s from (0, 0, 100 mm). The time step in PIC is set to be 10^{-10} s, and the time step of collision is set to be 10^{-8} s. This simulation assumes that the distributions of H_2, H, and various hydrogen ions are uniform and independent with time, the H_2 temperature is 300 K, and the number densities of H_2^+ and H_3^+ are 1.0×10^8 mm^{-3} and 5.0×10^8 mm^{-3}, respectively. The number ratio between H and H_2 is 10:1.[1] The reactions in the simulation are similar to those in Ref. [12].

3. Simulation results and analysis

During the simulation, the time steps and the collision processes are repeated until the electron density obtains a steady state. The electron density versus the simulation time is shown in Fig. 4. At 4×10^{-5} s, the electron density is in the steady state. Figure 5 shows the $-Y$ drifting of the electrons, which is in accordance with the experimental results in Refs. [1]–[4].

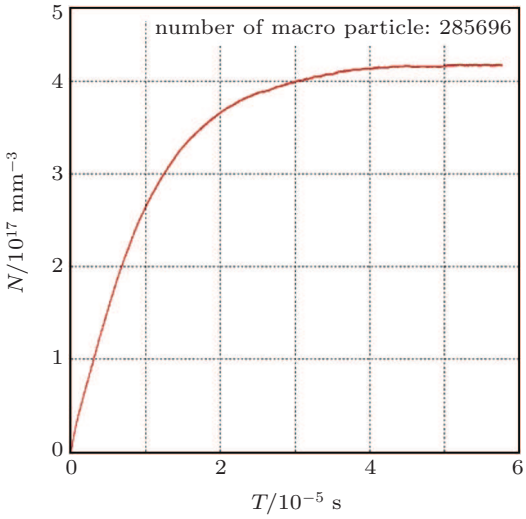


Fig. 4. (color online) Time evolution of the electron density.

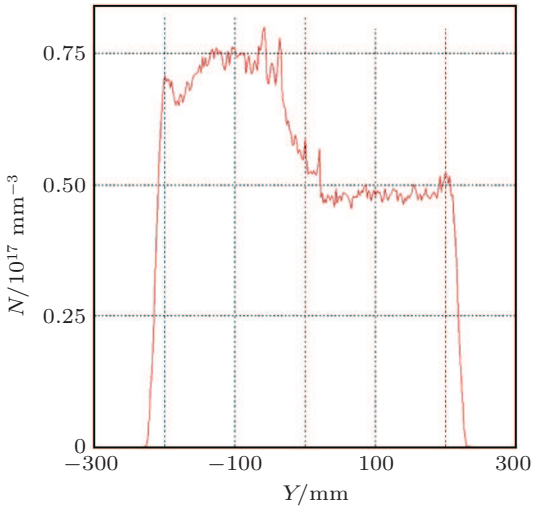


Fig. 5. (color online) Density distribution of the electrons in the region of $X = 10$ mm and $Z = 70$ mm.

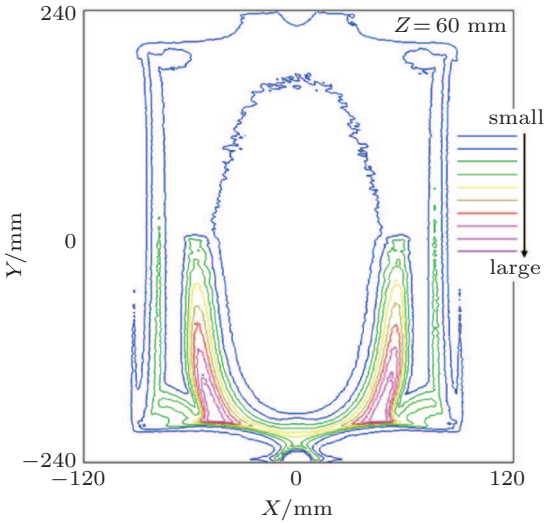


Fig. 6. (color online) Electron numbers in plane $Z = 60$ mm.

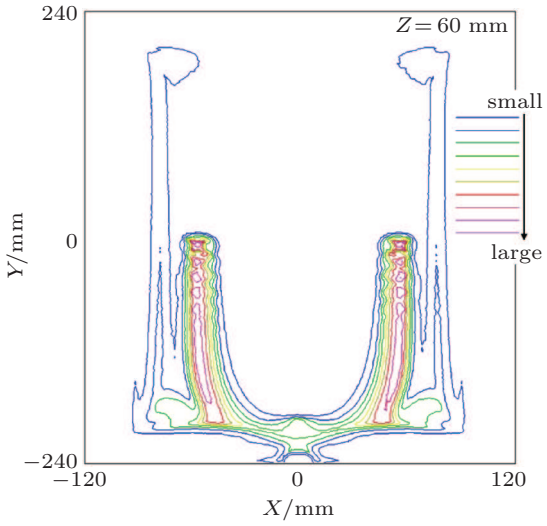


Fig. 7. (color online) Electron energy in plane $Z = 60$ mm.

Figures 6 and 7 show the contours of the electron number and energy in plane $Z = 60$ mm, respectively, by statistical analyses of 200 time steps. We can obtain that the electron number in $-Y$ is larger than that in $+Y$ and the electron energy in $-Y$ is higher than that in $+Y$. Both figures show a similar curve, which suggests that the number of electrons in some sector is larger and the energy is higher.

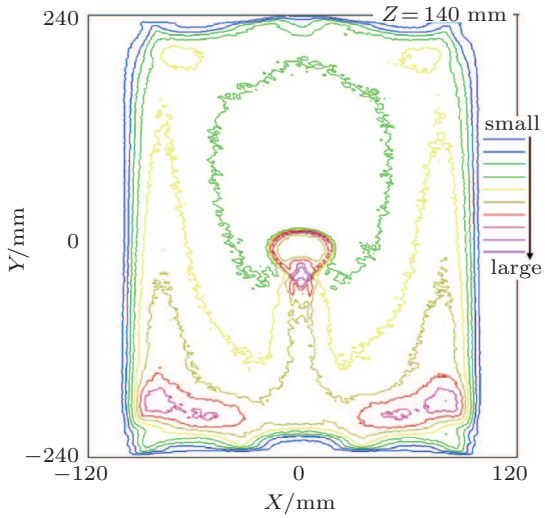


Fig. 8. (color online) Electron energy in the XY plane.

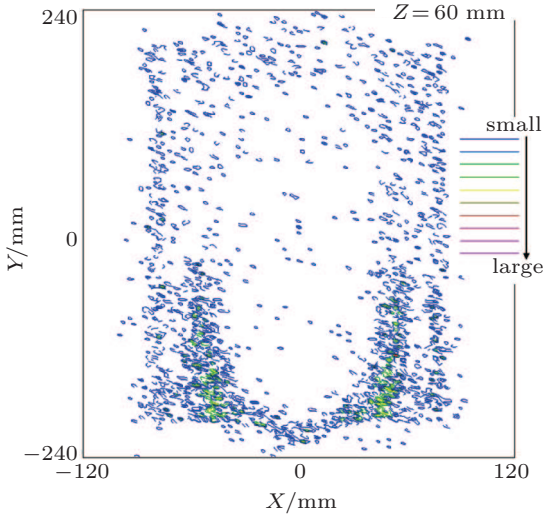


Fig. 9. (color online) Vibration excitation collision probability in the XY plane.

Figure 8 shows the contour of electron energy in plane $Z = 140$ mm by a statistical analysis of 200 time steps. Due to the large distance to the plane of the filter magnet, the area of the electronic activity at $Z = 30$ mm is larger than that at $Z = 60$ mm, which is shown in Fig. 7. In other words, low energy electrons appear in the $+Y$ region with higher probability. This figure also shows that the drifting in JAEA 10 A ion source is induced by the filter magnets, which is consistent with the report in Ref. [12]. Figure 9 shows the contour of the

probability of vibration excitation collisions between electrons and H_2 in plane $Z = 60$ mm. We can obtain that the probability in the area of $-Y$ is higher than that in the area of $+Y$. According to Refs. [9] and [10], H_α is produced more in this area. As a result, the number of H^- produced is larger on the surface, which is the reason for the spatial non-uniformity.

Figure 10 shows the electron distribution in the XZ plane, Figures 10(a) and 10(b) describe the distributions of fast electrons ($T_e \geqq 25$ eV) and slow electrons ($T_e < 25$ eV),[9] respectively. Obviously, the distributions of fast and slow electrons in the X direction are symmetrical in Fig. 10. There is no drift in the X direction. Figure 10(a) also shows that the fast electrons have a greater proportion in the filter magnetic field hysteresis, which suggests that the filter magnetic field has the effect of blocking the fast electron. It is consistent with the multi-cusp source design concept and conforms to the principle of physics, i.e., fast electrons can be easily magnetized. The research in Refs. [9], [11], and [12] also support this view.

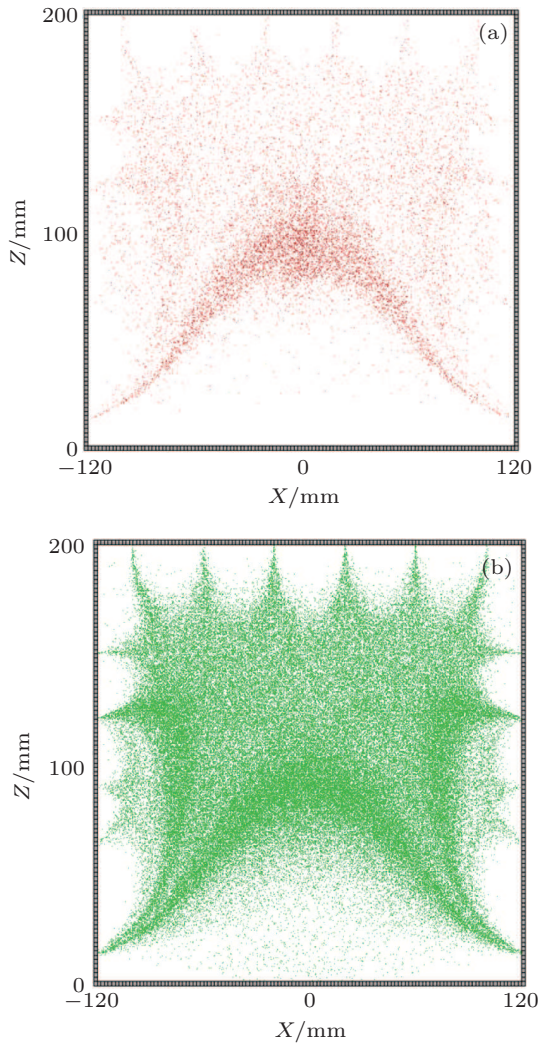


Fig. 10. (color online) Electron phase space diagrams in the XZ plane: (a) fast electrons, (b) slow electrons.

Figure 11 describes the distribution of electrons in the XY plane. Figures 11(a) and 11(b) describe the distributions of fast electrons and slow electrons, respectively. We can see that the $-Y$ drift of the fast electrons is significant and that of the slow electrons is not obvious.

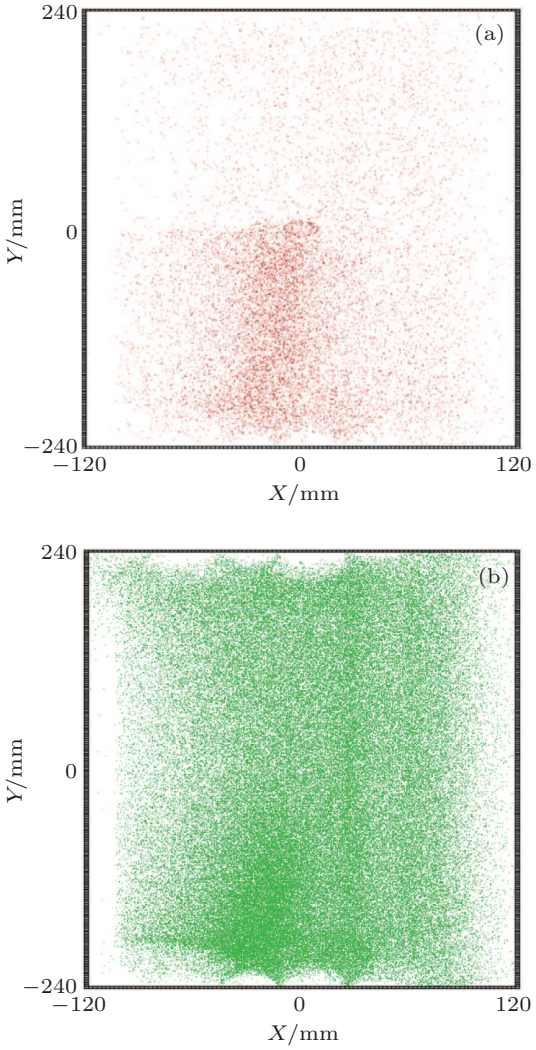


Fig. 11. (color online) Electron phase space diagrams in the XY plane: (a) fast electrons, (b) slow electrons.

In summary, the inhomogeneity of electrons comes from the Y direction drift of the fast electrons because of the action of the magnetic fields. This drifting also increases the number of vibration excitation collisions in the $-Y$ direction, which results in the increase of H_α in the $-Y$ direction, eventually leading to the $-Y$ drifting of H^-. An analysis on the experimental results from the point of the electron deposition process reveals the discharge mechanism and the characteristics of multi-cusp sources, and supports the correlative theoretical study at home and abroad.

4. Conclusion

In this paper, a systematic research on the electron deposition process in the JAEA 10 A ion source is carried out by PIC/MCC simulations based on a full three-dimensional and

self-developed code, and we give a reasonable physical interpretation for the results of simulations. The results indicate that the $-Y$ drift of H^- in JAEA 10 A multi-cusp negative hydrogen ion source comes from the magnetic drifting of the fast electrons in the filter magnetic field. Under the quasi-neutral condition, we can obtain simulation results with certain accuracy by an empirical analysis for the scatter of the boundary particles. In order to improve the accuracy, we will introduce the self-consistent calculation module to simulate the boundary barrier in further research. Besides, the theory of ion source discharge has been studied in this paper, which certainly promotes the relevant experimental studies in China, especially provides the theory support for the research and test of multi-cusp sources in the Chinese Atomic Energy Research Center.

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