Effect of H^- ion extraction on a plasma sheath under an external weak magnetic field *

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Abstract: The extraction of negative ions inevitably leads to the destruction of the original plasma state. To understand the effect of extraction on a plasma sheath under a weak magnetic filter field, the time-dependent behavior of H^- ion extraction from a negative ion source has been studied by particle-in-cell simulation in the collisionless limit. The simulation results have shown that the plasma sheath would undergo a transient process, in which there exists an edge electrostatic wave that propagates counterclockwise along the wall with a velocity of 4 mm/ns until it reaches the other side of extraction aperture. The thickness of the plasma sheath and the plasma potential both increase greatly at the final quasi-steady-state. For comparison, the results of extracting positive ions are also given.

Key words: negative ion source, plasma sheath, ion extraction, particle-in-cell simulation

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1 Introduction

In the development of a negative ion source e.g., for H^- ion cyclotron or negative-neutral beam injection into fusion plasma, extraction physics is one of the critical problems that researchers in this field must face [1]. In the usual case, negative ions can be extracted by applying a positive bias voltage between the plasma and the extraction electrode. Generally, the plasma parameters in the source upstream are difficult to be diagnosed precisely, so nowadays the majority of the development efforts are still devoted to enhancing the beam current extracted from the source for which the primary diagnostic is the ion beam itself [2]. Since the underlying plasma physics involved is complicated and not fully understood, an empirical approach is as yet unavoidable in the design of a new ion source.

In order to extract negative ions from plasma, the direction of sheath field by the wall needs to be inverted, and electron saturation current must be absorbed so as to ensure the reversion of this sheath field at steady state. Because of the light mass and higher density, the electron saturation current is much bigger than the current of negative ions. For the purpose of obtaining a pure negative ion beam, a weak magnetic field perpendicular to the beam direction is often applied to filter the electrons [2, 3]. However, several nonlinear plasma physical problems emerge due to the introduction of the magnetic field. For example, low energy electrons in the cross-field plasma sheath would have sheared particle drifts, as a result, a change of sheath structure may occur. In addition, the free emission surface, which is also called the plasma meniscus, would be distorted by the magnetic field. These nonlinear problems make the theoretical study of extraction physics very difficult.

The extraction and transport of negative hydrogen ions have been investigated by using particle-in-cell (PIC) [4] simulation in many published papers [1, 5–11]. Among these studies, the authors mainly focused on the design of the extraction system and the optimization of ion optics. The effect of negative ion extraction on the plasma source and especially on the plasma sheath under a weak magnetic field is less researched. In the present paper, we present our simulation results on this topic, with the emphasis on the transit behavior of plasma sheath evolution under the common drive of an extraction field and an external magnetic field. The PIC method is also used, but a full plasma model, rather than a semi-infinite plasma model [12], is built to track the motions of ions and electrons in both plasma source and ion acceleration regions.

2 The simulation model

The model geometry used in the simulation is shown in Fig. 1. The extraction electrode is simplified to be a

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slab with a positive potential, which generates an electric field in the extraction gap. Plasma is produced uniformly in a rectangular chamber with ground potential. Negative ions and electrons are extracted by the electric field through a small aperture and finally hit the opposite extraction anode. The model is two dimensional in x-y plane, with the same system length of 1 cm in both x and y directions. The width of extraction gap and aperture are set to be 5 mm, and 3 mm respectively. The thickness of the wall near the extraction aperture is 0.5 mm.

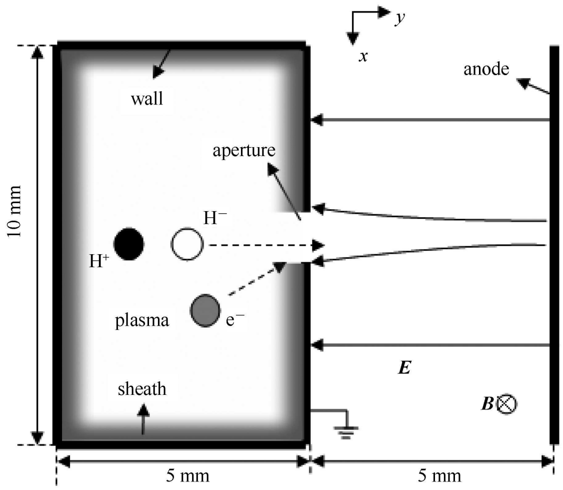

Fig. 1. Schematic diagram for the simulation model.

The motion of the charged particles in their self-consistent electric field is calculated by an electrostatic PIC simulation code. The Poisson's equation for the electrostatic potential is solved by the finite difference method with a uniform mesh. To ensure the electric field generated in the extraction gap is uniform, a linear distribution of potential is employed for the boundary condition. So no electric field in the y direction exists, i.e., $\partial\phi/\partial y=0$ at the boundary of extraction region (y=0 and y=10 mm). Initial plasma is distributed uniformly in the rectangular chamber, ions and electrons are continuously created in the chamber to compensate the particle loss due to extraction and collision with walls. This is done by creating ions and electrons spatially at random but at a variable temporal rate R. The choice of R is such that in the steady state, the total number of electrons in the source would remain close to the initial value. The source strength ratios i.e., the ratios of H^+ ions, H^- ions and electrons we consider in the present paper, remain unchanged when adding new particles into the system.

The particles move in x-y plane, in which they interact with each other and collide with the metal walls and electrode. The ions and electrons are given random and uncorrelated velocities, chosen from Maxwellian distributions with thermal spreads determined by their temperatures. Both particle velocities and coordinates are restricted to two components, with $\boldsymbol{v}=(v_x, v_y)$ and $\boldsymbol{x}=(x, y)$. Once collisions with walls or electrode occur, the particles would be completely absorbed and removed from the system.

The parameters used in the numerical simulation are displayed in Table 1. Relatively low plasma density and extraction field are chosen, as a result of the balance between the numerical accuracy and the spatial scale of simulation. However, this does not mean the simulation results cannot be extended to other plasmas with higher parameters. The ratio of the source strength is assumed to be $S_{0H+}:S_{0H-}:S_{0e-}$=10:1:9, as in Refs. [8–10]. A weak magnetic field, which is uniformly distributed in the whole calculation domain, is set to be 0.03 T and perpendicular to the x-y plane.

Table 1. Parameters used in the simulation.

ion-electron mass ratio	1836
uniform mesh size (Δl)/mm	0.1
time step/ps	0.267
total step number	100000
plasma density/m^{-3}	2.0×10^{16}
positive-ion temperature/eV	0.1
negative-ion temperature/eV	0.1
electron temperature/eV	2
source strength ratios	$S_{0H+}:S_{0H-}:S_{0e-}$=10:1:9
anode potential/V	1000
magnetic field/T	0.03

3 The result and discussion

The time evolution of the distribution of charge density ρ in the whole system is shown in Fig. 2. The system reaches a quasi-steady-state after the time $t\approx26.7$ ns. So the time interval $0\leqslant t\leqslant26.7$ ns roughly corresponds to the transition phase that we intend to study.

Figure 2(a) taken at t=1.6 ns, shows that the trajectories of emission electrons are built at the beginning of the evolution of the system, with a right-facing direction in the crossed $\boldsymbol{E}$ and $\boldsymbol{B}$ field. The plasma sheath with a Debye length of a few hundred micrometers is also formed due to sudden loss of electrons near the walls. However, the plasma sheath on the left of the extraction aperture, which is shown in deep color in Fig. 2(a), is quite different from the usual plasma sheath in formation and evolution processes. Along with the extraction of electrons and negative ions, the plasma sheath on the left of the extraction aperture begins to get thicker, then very quickly transmits to the adjacent sheath and propagates counterclockwise along the wall until the whole sheath layer has approximately the same thickness. The transition from the usual plasma sheath to the propagating sheath occurs almost instantaneously over a time scale less than 0.5 ns. The evolution of the sheath is similar to the propagation of a space charge wave that starts from the left side of the extraction aperture and ends on the right side of the extraction aperture, as shown in Fig. 2(a)–(d). A rough calculation suggests that the velocity of sheath propagation is close to 4 mm/ns, and the total propagation time is about 6.7 ns.

After a fairly long transient, at the final stage, the system settles into a quasi-steady-state as shown in Fig. 2(f). In this process, the propagation of the sheath finishes, and the thickness of plasma sheath expands up to approximately 1 mm. It is interesting to note that an outlet, which is surrounded by the positively charged plasma sheath, appears just like a funnel for the outflow of negative ions and electrons from the center plasma. In addition, the emission surface is no longer like a symmetrical meniscus, but becomes a distorted one.

For comparison and discussion, the numerical simulation of the extraction of H^+ ions is also carried out, and the distribution of charge density is given in Fig. 3. All parameters stay the same except for the polar of the extracting electric field. One can see clearly that positive ions are extracted by the electric field and slightly left deflected by the magnetic field. The concave emission surface, which directly connects with the usual plasma sheath by the wall, shields off the extracting electric field. So the plasma sheath in other places is not markedly affected by the external $\boldsymbol{E}\times\boldsymbol{B}$ field. These phenomena are in sharp contrast to those which have appeared in extracting H^- ions, where the sheath not only around the aperture, but also far from the aperture would be affected by the extraction field.

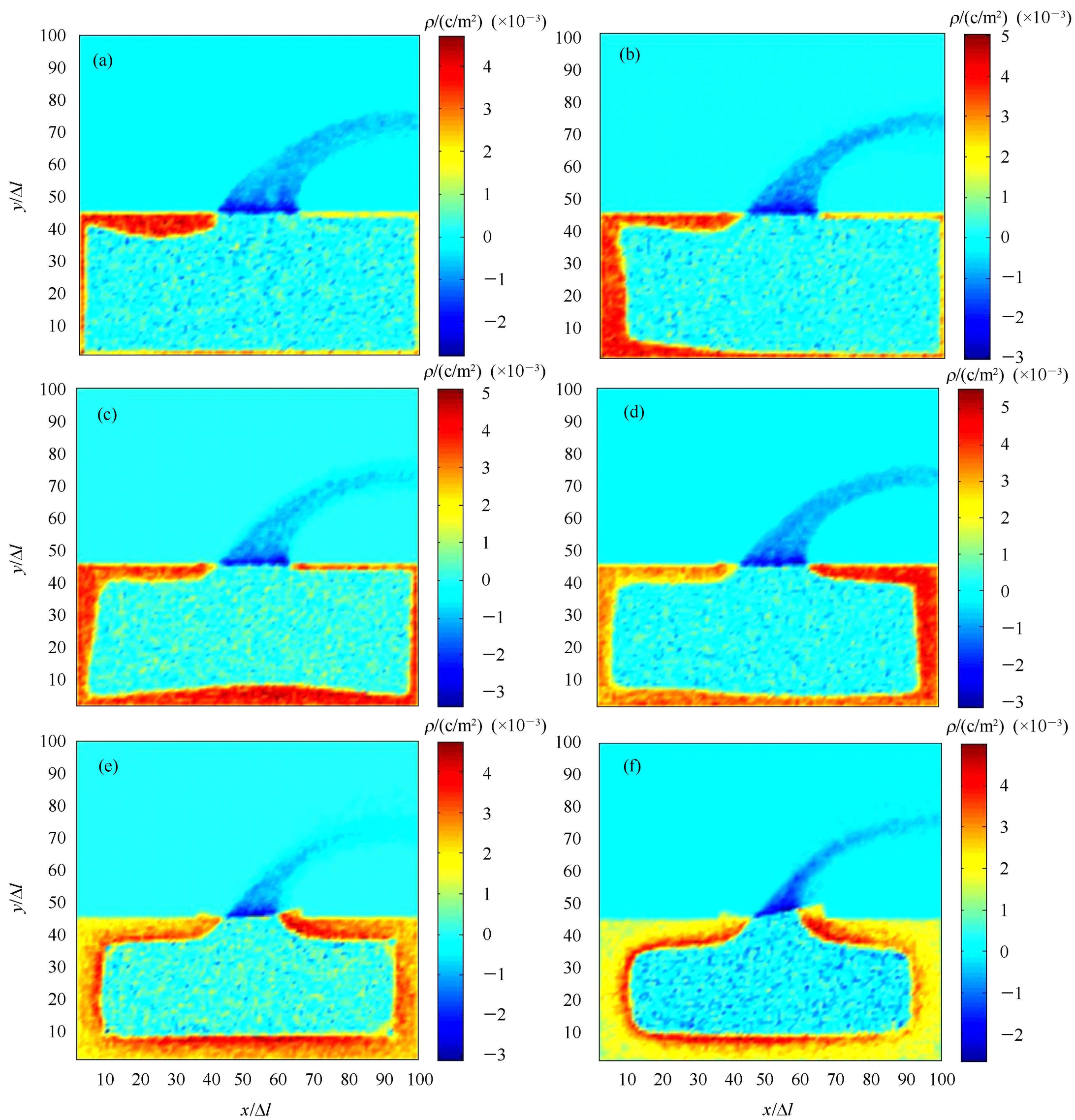

Fig. 2. Snapshots of the charge density distribution at different moments: (a) t=1.6 ns; (b) t=3.2 ns; (c) t=4.8 ns; (d) t=6.4 ns; (e) t=16 ns; (f) t=26.7 ns.

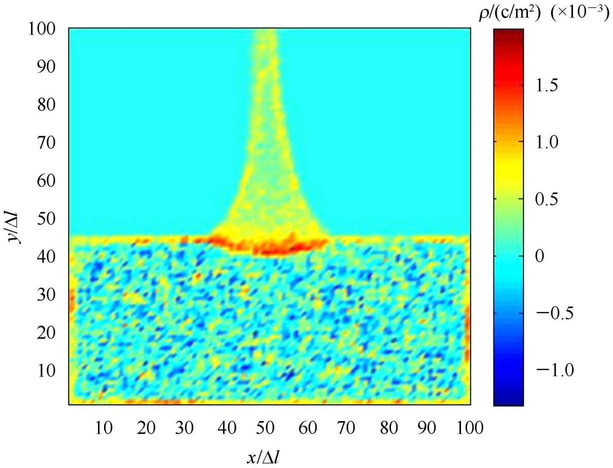

Fig. 3. The distribution of charge density in the case of H^+ extraction from plasma at steady state.

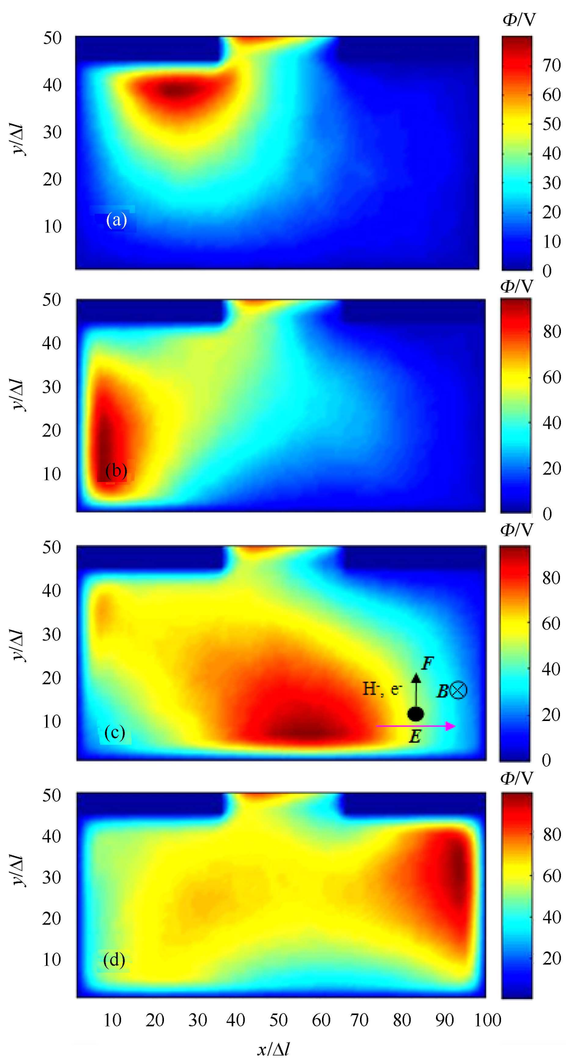

Fig. 4. Snapshots of the electric potential distribution at different moments: (a) t=1.6 ns; (b) t=3.2 ns; (c) t=4.8 ns; (d) t=6.4 ns.

Figure 4 shows the evolution of electric potential distribution, with the focus on the changing process of potential in the plasma source region. Fig. 4(a) taken at t=1.6 ns presents the initial penetration of the external electric field into the plasma through the extraction aperture. At this early time stage, electrons near the aperture incline to drift from left to right in the local $\boldsymbol{E}\times\boldsymbol{B}$ field, leading to a partial separation of positively and negatively charged particles. As a result, the plasma quasineutrality is destroyed and the electric field on the fringe of the plasma is enhanced locally. With time progressing, the electrons near the sheath move towards the inner area under the acting forces of local $\boldsymbol{E}\times\boldsymbol{B}$ field, which conversely enhances the nearby electric field. Ultimately, the edge electrostatic wave propagates to the extraction aperture, with a general increase of plasma potential as shown in Fig. 4(d).

The electric potentials of plasma along the line y=2.5 mm recorded at different moments are shown in Fig. 5. The lowest curve is the result of extracting H^+ ions. For extracting H^- ions, with the propagation of an edge electrostatic wave, the amplitude of plasma potential continually rises until it undergoes saturation by forming stable sheath structure. At the final steady state, the plasma potential can reach more than 120 V, much higher than the case of extracting H^+ ions. In Ref. [2], extracting an ion beam in a magnetic filter field was observed to increase the potential near the plasma grid. The results presented in this paper maybe can provide a qualitative explanation of this phenomenon. It is almost impossible for the electrons and negative ions with low energies to overcome this potential barrier. So the negatively charged particles in the plasma tend to keep away from the wall, which in the end would greatly reduce the opportunity of their wall loss. However, the behavior of positive ions is basically opposite. Because

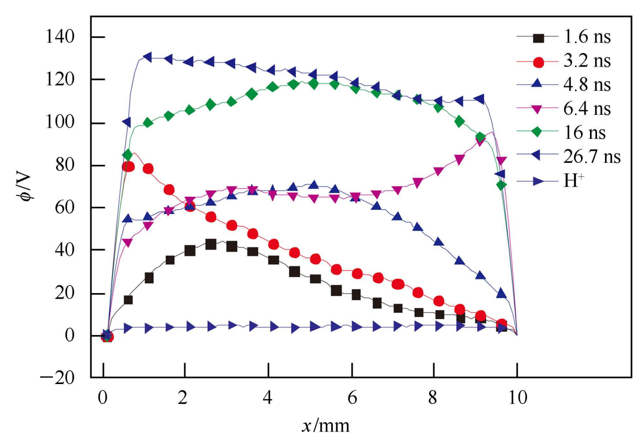

Fig. 5. Time evolution of the electrostatic potential along the line y=2.5 mm, the case of H^+ extraction at steady state is also given for comparison.

of the greater magnetic rigidity, positive ions in the source are mainly affected by the electric field. In order to maintain the balance of the number of particles, the structure of the usual plasma sheath needs to change. Surprisingly, the broadening of sheath thickness and the enhancement of sheath field precisely meet the requirement of accelerated wall loss of positive ions. If we reduce the width of extraction aperture or weaken the extraction electric field, the sheath would also be adjusted accordingly.

Figure 6 taken at t=26.7 ns, depicts the distributions of electric potential and the electric field along the line x=5 mm. The center plasma still maintains quasineutrality. The electric potential monotonously increases along this line. Thus the electric field on the right side of the center plasma has the same field direction as that near the left wall. For the usual plasma sheath or in the case of extracting positive ions, the result is exactly opposite.

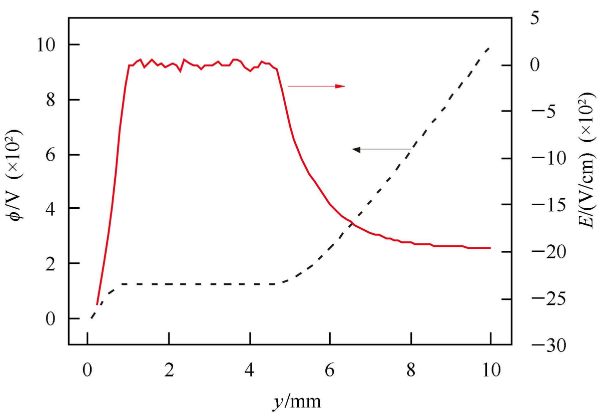

Fig. 6. Distributions of the electric potential and the electric field along the line x=5 mm through the center of the extraction aperture at t=26.7 ns.

4 Conclusion

The tremendous change of plasma sheath structure caused by the extraction of H^- ions has been investigated in detail by particle-in-cell numerical simulation. The simulation results show that in the transition phase there exists an edge electrostatic wave which starts from the left side of the extraction aperture and propagates counterclockwise along the wall until it reaches the right side of the extraction aperture. For our given initial plasma condition and the parameter setting of magnetic field, the propagation velocity is close to 4 mm/ns. At the final quasi-steady-state, both the thickness of plasma sheath and plasma potential would greatly increase, which is in sharp contrast to those which have appeared in extracting H^+ ions. In this study, we have neglected many effects, such as the collisions of charged particles and neutral particles, and the nonuniform production and destruction processes of particles. These effects possibly affect the physical mechanism discussed here. More overall simulations which take into account these effects will be needed in the future.

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