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Analysis of H⁻ Ion Emissive Surface in the Extraction Region in Hydrogen Negative Ion Sources

水素負イオン源の引き出し領域における表面生成水素負イオンの解析

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To optimize the H^- production and extraction condition is one of the key issues for developing negative ion sources. The profile of plasma density and electrostatic potential with and without extraction grid (EG) voltage are analyzed with 2D PIC modeling for a NIFS-R&D source. The results make clear the processes forming double ion (H^+ and H^-) and electron poor plasma in the vicinity of the plasma grid (PG) which has been recently observed in the experiments of the NIFS R&D source. In addition, the present numerical modeling gives useful insight into the formation mechanism of the plasma meniscus and H^- extraction process in such a double ion plasma.

1. Introduction

In negative ion sources of neutral beam injectors (NBI) for large fusion devices such as LHD, one of the key issues is to optimize the H^- production and extraction condition. For the optimization, it is indispensable to understand the formation mechanism of the ion emissive surface (so-call plasma meniscus) and its location/shape around the extraction hole. Recently, in a NIFS-R&D ion source scaled a half size of the LHD ones, the following interesting experimental observations have been reported under the "surface" H^- production case with the Cs-seeding [1] : (1) Plasma layer consisting of H^+ and H^- ions (i.e., electrons are excluded from the layer.) is formed in the vicinity of the PG, and (2) the thickness of the plasma layer is relatively large (at least the layer has a thickness of ~15mm from the PG by Langmuir probe measurements).

The purpose of this study is to understand the formation mechanism of the plasma meniscus and its location/shape around the extraction hole with 2D Particle-in-Cell (PIC) modeling. The profile of plasma density and potential with and without EG voltage are analyzed with 2D PIC model in a model geometry near the PG of the NIFS-R&D source.

2. Simulation Model

The motion of charged particles (H^+ ions, H^- ions, and electrons) is solved in their self-consistent electric field using the PIC method [2]. The trajectories are first calculated with the equation of motion for each particle with a leap-frog integrator [3]. The charge density is obtained at each mesh point from the particle location by using a linear interpolation. The Poisson equation is then solved at each mesh point by the Bi-CGSTAB method [4].

Figure 1 shows the model geometry used in the following numerical calculations. The model geometry is based on the NIFS-R&D ion source. The system size of the present simulation is scaled as 1/38. The *x*-axis is taken parallel to the direction of the H^- extraction beam through the aperture, while the *y*-axis is parallel to the PG surface.

The space coordinates (x, y) and the time t are normalized as follows: $\tilde{x} = x/\lambda_{De}$, $\tilde{y} = y/\lambda_{De}$, and $\tilde{t} = \omega_{pe} t$, where λ_{De} and ω_{pe} are the electron Debye length and the electron plasma frequency, respectively, calculated from the initial electron density n_e and temperature T_e, respectively. The electrostatic potential Φ and magnetic flux density $\boldsymbol{B}$ are also normalized as follows: $\tilde{\Phi} = e\Phi / kT_e$, $\tilde{\boldsymbol{B}} = \boldsymbol{B}/(m_e\omega_{pe}/e)$,where e and k are the unit charge and the Boltzmann const, respectively. Also, the Electron Deflection Magnets (EDM) with an infinite length in the z direction is installed in the EG. The magnetic field is calculated

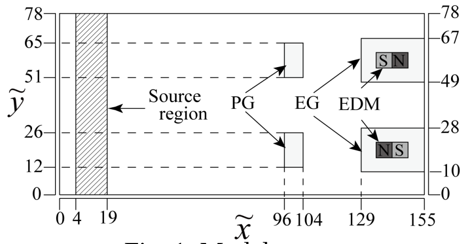

Fig. 1. Model geometry

at each mesh point by using the analytical solution based on the magnetic charge model [5]. Additionally, the ratio of the Larmor radii of charged particles and the characteristic decay length of the magnetic field amplitude is adjusted to be in the same ordering with that in the simulation and experiments.

In the numerical calculation, two extraction holes are modeled to take into account the periodicity of the electron deflection magnets. The Dirichlet boundary condition is imposed on $\tilde{x} = 0$, PG, and EG. The periodic condition is applied to the lower boundary ($\tilde{y} = 0$) and upper boundary ($\tilde{y} = \tilde{y}_{\max}$). For the right-hand side boundary ($\tilde{x} = \tilde{x}_{\max}$), the absorbing boundary condition is adopted. If particles reach the right boundary, they are removed from the calculation domain.

At $\tilde{t} = 0$, 2×10^5superparticles are loaded in the source region. The initial ratio of the superparticle numbers for H^+ ions and electrons assumed to be N_{H+}:N_e = 1:1. Electrons and H^+ ions are assumed to be launched initially as Maxwellian distributions with the initial temperature of 0.6eV and 0.5eV, respectively. Surface produced H^- ions are loaded one particle per one time step at PG surface, and assumed to be launched as a cosine distribution with the temperature of 1eV. For simplicity, some of the collision processes are not taken into account.

3. Results and Disucussion

The beam extraction has been started at the number of time steps N=10^5. Before beam extraction (N<10^5), the potential profile has reached a quasi-steady state after N~8×10^4 time steps. Figure 2 shows the 2D density profiles of (a) electrons and (b) positive H^+ ions before beam extraction. These density profiles have been obtained by averaging the calculated density over the last 5×10^3 steps before beam extraction. As seen from Fig. 2(a), the electron density becomes very small and almost zero close to the extraction hole and the PG. This is mainly because electrons are trapped by the magnetic field. They cannot penetrate deeply into the extraction region due to their small Larmor radii. The positive H^+ ion density also decreases towards the extraction hole and PG surface, but H^+ ion density is still relatively large compared with the electron density. As a result, electron poor plasma is formed in the vicinity of the extraction hole and the PG.

The electron density in the vicinity of the extraction hole after beam extraction becomes larger than that before beam extraction.

These initial results shown above supports the following qualitative explanation of the experimental results in NIFS R&D source proposed in Ref.[1] :(1) since H^- ions are produced on PG surface, bulk electrons are prevented to penetrate

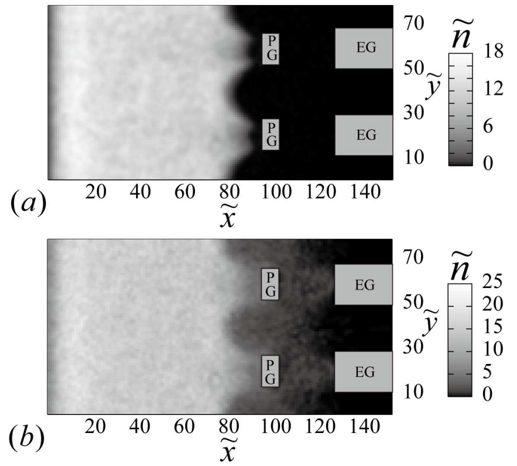

Fig. 2. The 2D density profiles of (a) electrons and (b) positive H^+ ions before beam extraction [6]

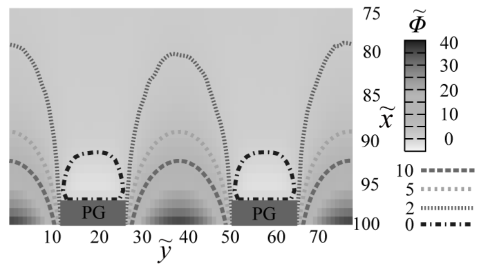

Fig. 3. The potential profile near the PG with EG voltage

the beam extraction region. Consequently, electron-poor plasma is generated in the extraction region without extraction. (2) when the H^- ions are extracted from the region, charge neutrality breaks down and bulk electrons transport from bulk to compensate excess positive ions.

These initial simulation results also give some insight into the H^- ion emissive surface. Figure 3 shows the potential profile near the PG with EG voltage. The shielding of the EG voltage is relatively small due to the small density of the negative charge (mainly H^- ions) in the region 80< $\tilde{x}$ <100. Relatively deep penetration of the EG voltage can be seen in Fig. 3. This makes it possible for the H^- ions to be extracted from the volume even in the Cs-seeded surface H^- production case.

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