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Plasma distribution near the extraction region in hydrogen negative ion sources with surface and volume produced negative ions
表面生成および体積生成負イオンを考慮した水素負イオン源引き出し領域近傍でのプラズマ分布

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Plasma distribution near a wall in a negative ion source is investigated analytically with the surface produced negative ion and volume produced negative ion. The potential distribution is derived analytically by using a plasma-sheath equation and the density distribution is derived from the potential distribution. It is shown that as the production rate of the volume produced negative ions increases the surface produced negative ion density and positive ion density increases, as a result, the double ion plasma layer is formed near the plasma grid (PG) surface.

1. Introduction

In a hydrogen negative ion source, it is important to understand the plasma characteristics near the extraction region in order to extract a large amount of hydrogen negative ions. A recent experiment in a NIFS-R&D ion source has suggested that a “double ion plasma layer” which is a region consisting of hydrogen positive and negative ions exists near a plasma grid (PG) surface [1]. The distribution of the plasma density near the extraction region for the plasma with the surface produced negative ions has been studied analytically. It has been shown that as the production rate of the surface produced negative ions increases the negative ion density increases and the electron density decreases, as a result, the double ion plasma layer is formed near the PG surface [2]. However the effect of the volume produced negative ions on double ion plasma layer has not been clearly understood.

An effect of the volume produced negative ion on the electric potential and the distribution of the plasma density near the extraction region will be studied, where surface produced negative ion and volume produced negative ion are considered in addition to electron and positive ion.

2. Derivation of the Plasma-Sheath Equation

In the hydrogen negative ion source, the surface produced hydrogen negative ions are produced on the PG surface and launched to the interior of the ion source and the volume produced hydrogen negative ions and the hydrogen positive ions are produced whole in the ion source as shown in Fig. 1. The problem is treated as one-dimensional model in x-direction. The electric potential $\phi(x)$ is assumed to be symmetric about x=0 and zero at x=0.

Constant energies E, E_s, E_v of the positive ion, the surface produced negative ion and the volume produced negative ion in the x-direction are

$$E = \frac{1}{2} M \upsilon_x^2 + q\phi(x) \tag{1}$$

$$E_s = \frac{1}{2} M_s \upsilon_{sx}^2 - q\phi(x) \tag{2}$$

$$E_v = \frac{1}{2} M_v \upsilon_{vx}^2 - q\phi(x) \tag{3}$$

where M, M_s and M_v are the masses, υ, υ_{sx} and υ_{vx} are the velocities in the x-direction, and q and $-q$ are the charges of the positive ion and the negative ion, respectively. Where the subscript “s” denotes values belonging to the surface produced negative ion and the subscript “v” denotes values belonging to the volume produced negative ion. The kinetic

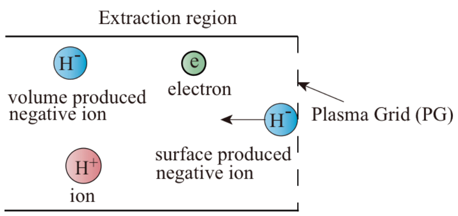

Fig.1 Geometry of the extraction region of the ion source.

equations in the phase space for the positive ion, the surface produced negative ion and the volume produced negative ion are described by

$$\sigma \upsilon_x(x,E)\frac{\partial f(x,E,\sigma)}{\partial x} = S(x,E) \tag{4}$$

$$\sigma \upsilon_{sx}(x,E_s)\frac{\partial f_s(x,E_s,\sigma)}{\partial x} = S_s(x,E_s) \tag{5}$$

$$\sigma \upsilon_{vx}(x,E_v)\frac{\partial f_v(x,E_v,\sigma)}{\partial x} = S_v(x,E_v) \tag{6}$$

where σ (=±1) is the direction of the particle motion, $f(x, E, \sigma)$, $f_s(x, E_s, \sigma)$ and $f_v(x, E_v, \sigma)$ are the distribution functions, and $S(x, E)$, $S_s(x, E_s)$ and $S_v(x, E_v)$ are the source functions, respectively. The distribution functions are obtained by integrating Eqs. (4), (5) and (6) for each particle trajectory on the boundary conditions. The densities of the positive ion and the negative ions n_i, n_s, n_v are obtained by integrating distribution functions for the E, E_s and E_v spaces, respectively. As the electron density n_e, we use a Maxwell–Boltzmann distribution for simplicity. Substituting the densities n_i, n_s, n_v and n_e into Poisson's equation and using the source functions same as Emmert *et al*. [3], the plasma–sheath equation is derived as

$$\begin{aligned}\frac{d^2\phi(x)}{dz^2} &= \frac{n_0 e}{\varepsilon_0}\exp\left(\frac{e\phi(x)}{kT_e}\right)\\ &-\frac{en_0}{2\varepsilon_0 L(1+\beta_s-\beta_v)}\left(\frac{MT_e}{m_e T_i}\right)^{1/2}\exp\left(\frac{e\phi_w}{kT_e}\right)\int_0^L dx' I(x,x')h(x')\\ &+\frac{en_0\beta_s}{2\varepsilon_0 L(1+\beta_s-\beta_v)}\left(\frac{M_s T_e}{m_e T_s}\right)^{1/2}\exp\left(\frac{e\phi_w}{kT_e}\right) I_s(x,L)h_s(L)\\ &+\frac{en_0\beta_v}{2\varepsilon_0 L(1+\beta_s-\beta_v)}\left(\frac{M_v T_e}{m_e T_v}\right)^{1/2}\exp\left(\frac{e\phi_w}{kT_e}\right)\int_0^L dx'_v I_v(x,x'_v)h_v(x'_v)\end{aligned} \tag{7}$$

where

$$I(x,x') = \begin{cases}\exp\left\{\frac{q\phi(x')-q\phi(x)}{kT_i}\right\}\operatorname{erfc}\left[\left\{\frac{q\phi(x')-q\phi(x)}{kT_i}\right\}^{1/2}\right], & q\phi(x')>q\phi(x)\\ \exp\left\{\frac{q\phi(x')-q\phi(x)}{kT_i}\right\}, & q\phi(x')<q\phi(x)\end{cases}$$

$$I_s(x,L) = \begin{cases}\exp\left\{\frac{-q\phi(L)+q\phi(x)}{kT_s}\right\}\operatorname{erfc}\left[\left\{\frac{-q\phi_{min}+q\phi(x)}{kT_s}\right\}^{1/2}\right], & x<x_{min}\\ \exp\left\{\frac{-q\phi(L)+q\phi(x)}{kT_s}\right\}, & x>x_{min}\end{cases}$$

$$I_v(x,x'_v) = \begin{cases}\exp\left\{\frac{-q\phi(x'_v)+q\phi(x)}{kT_v}\right\}\operatorname{erfc}\left[\left\{\frac{-q\phi(x'_v)+q\phi(x)}{kT_v}\right\}^{1/2}\right], & q\phi(x'_v)<q\phi(x)\\ \exp\left\{\frac{-q\phi(x'_v)+q\phi(x)}{kT_v}\right\}, & q\phi(x'_v)>q\phi(x)\end{cases} \tag{8}$$

and x', x_s', x_v' are the positions of ion generation, T_e, T_i, T_s and T_v are the temperatures of the electron, the positive ion and the negative ions, $h(x)$, $h_s(x)$ and $h_v(x)$ are the source strengths of the positive ion and the negative ions, respectively, m_e and T_e are the mass and the temperature of the electron, ϕ_w is the wall potential and $\beta_s=S_{s0}/S_0$, $\beta_v=S_{v0}/S_0$, where S_0, S_{s0}, S_{v0} are average source strengths of the positive ion and the negative ions, and $x=L$ is the wall position.

3. Numerical Solution of the Plasma-Sheath Equation

The plasma-sheath equation (7) is solved numerically and the distribution of the electric potential is obtained. The distribution of the plasma density is obtained from the potential. The effect of the volume produced negative ion on the potential distribution is small. The profile of the particle densities normalized by the electron density at x=0 for various values of $\beta_v=S_{v0}/S_0$ is shown in Fig. 2, where $s=x/L$, $\tau=T_e/T_i=2$, $\tau_s=T_e/T_s=5$, $\tau_v=T_e/T_v=2.5$, $\beta_s=0.4$, and $\lambda_D/L=5\times10^{-2}$, where λ_D is the Debye length. It is shown that as the production rate of the volume produced negative ions increases the surface produced negative ion density and positive ion density increases, as a result, the double ion plasma layer is formed near the PG surface.

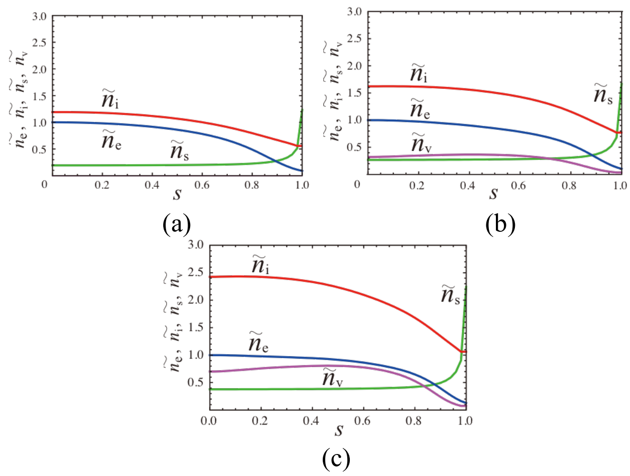

Fig. 2 Profile of the normalized particle densities for various values of β_v, (a)β_v=0, (b)β_v=0.2, (c)β_v=0.3.

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