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Potential Distribution in Surface Produced Negative Ion Source with Magnetic Field Increasing toward a Wall

表面生成負イオン源における壁に向かって増加する磁場中での電位分布

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Electric potential near a wall for the plasma with the surface produced negative ions with magnetic field increasing toward a wall is investigated analytically. The potential profile is derived analytically by using a plasma-sheath equation. It is shown that the negative potential peak is formed in the sheath region near the plasma grid (PG) surface for a case of the strong surface production of negative ions or low temperature negative ions. It is also shown that as the increase rate of the magnetic field becomes large, the negative potential peak becomes small.

1. Introduction

In the surface produced negative ion source, negative ions produced on a plasma grid (PG) are accelerated by potential difference between the plasma and the PG. However, the general sheath potential formed in the plasma accelerates the surface produced negative ions toward an inner of the ion source. It has been shown that a negative potential peak is formed near the PG surface and the negative ions have a possibility to be returned to the PG surface for a case without a magnetic field [1]. In the JT-60U negative ion source in JAEA (Japan Atomic Energy Agency), permanent magnets are embedded in an extraction grid (EXG) in the extraction region to suppress the acceleration of the extracted electrons [2]. These magnets produce the cusp magnetic fields increasing toward the PG surface inside the negative ion source.

The effect of the magnetic field on the potential distribution near the extraction region for the plasma with the surface produced negative ions will be studied analytically, where the magnetic field increasing toward the PG surface is considered. The potential distribution is obtained by using a plasma-sheath equation [3] and dependence on the amount and the temperature of the surface produced negative ions and the profile of the magnetic field is examined.

2. Analysis of the Electric Potential

The magnetic field is assumed to be perpendicular to the wall near the PG surface and the problem is treated as one dimensional model in z-direction. It is assumed that negative hydrogen ions H^- are produced only on the PG surface and the background plasma consists of electrons and positive hydrogen ions H^+. The geometry of analytical model is shown in Fig. 1. The electric potential $\phi(z)$ is assumed to be symmetric about z=0 and zero at z=0. The magnetic field is assumed to be symmetric about z=0 and B_0 at z=0.

Constant energies E and E_- of a positive ion and a negative ion in the z-direction are

$$E = \frac{1}{2}M(\upsilon_\perp^2 + \upsilon_{//}^2) + q\phi(z) \tag{1}$$

$$E_- = \frac{1}{2}M_-(\upsilon_{\perp -}^2 + \upsilon_{//-}^2) - q\phi(z) \tag{2}$$

where M and M_- are the ion masses, $\upsilon_\perp$ and $\upsilon_{\perp -}$ are the velocities perpendicular to the magnetic field, $\upsilon_{//}$ and $\upsilon_{//-}$ are the velocities parallel to the magnetic field, and q and $-q$ are the charges of the positive ion and the negative ion, respectively. The magnetic moments for the positive ion and the negative ion are given by

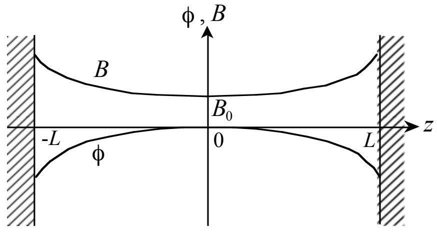

Fig.1 Geometry of potential and magnetic field in the analysis model.

$$\mu = (1/2)\, M\upsilon_{\perp}^{2} / B(z) \tag{3}$$

$$\mu_{-} = (1/2)\, M_{-}\upsilon_{\perp -}^{2} / B(z) \tag{4}$$

where $B(z)$ is the magnetic field at the position z. The kinetic equations in the phase space for the positive ion and the negative ion are described by

$$\sigma\upsilon_{//}(z,E,\mu)\frac{\partial f(z,E,\mu,\sigma)}{\partial z} = S(z,E,\mu) \tag{5}$$

$$\sigma\upsilon_{//-}(z,E_{-},\mu_{-})\frac{\partial f_{-}(z,E_{-},\mu_{-},\sigma)}{\partial z} = S_{-}(z,E_{-},\mu_{-}) \tag{6}$$

where $\sigma\,(=\pm 1)$ is the direction of the particle motion, $f(z,E,\mu,\sigma)$ and $f_{-}(z,E_{-},\mu_{-},\sigma)$ are the distribution functions, and $S(z,E,\mu)$ and $S_{-}(z,E_{-},\mu_{-})$ are the source functions, respectively.

The distribution functions are obtained by integrating Eqs. (5) and (6) for particle trajectory on the boundary conditions. The positive ion density n_{i} and the negative ion density $n_{\mathrm{i-}}$ are obtained by integrating distribution functions over the $E-\mu$ and $E_{-}-\mu_{-}$ spaces, respectively. As the electron density n_{e}, we use a Maxwell–Boltzmann distribution for simplicity. Substituting the densities n_{i}, $n_{\mathrm{i-}}$ 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

$$\begin{aligned}
\frac{\mathrm{d}^2\phi(z)}{\mathrm{d}z^2} &= \frac{n_0 e}{\varepsilon_0}\exp\left(\frac{e\phi(z)}{kT_e}\right) \\
&-\frac{en_0}{2\varepsilon_0 L(1+\beta)}\left(\frac{MT_{\mathrm{e}}}{m_{\mathrm{e}}T_{\mathrm{i}}}\right)^{1/2}\exp\left(\frac{e\phi_{\mathrm{w}}}{kT_{\mathrm{e}}}\right)\int_0^L \mathrm{d}z' I(z,z')h(z') \\
&+\frac{en_0\beta}{2\varepsilon_0 L(1+\beta)}\left(\frac{M_{-}T_{\mathrm{e}}}{m_{\mathrm{e}}T_{\mathrm{i-}}}\right)^{1/2}\exp\left(\frac{e\phi_{\mathrm{w}}}{kT_{\mathrm{e}}}\right)\int_0^L \mathrm{d}z' I_{-}(z,z')h_{-}(z')
\end{aligned} \tag{7}$$

where z' is the position of ion generation, T_{i} and $T_{\mathrm{i-}}$ are the temperatures, $h(z)$ and $h_{-}(z)$ are the source strengths of the positive ion and the negative ion, respectively, m_{e} and T_{e} are the mass and the temperature of the electron, and ϕ_{w} is the wall potential and

$$I(z,z') = \begin{cases}
\exp\left\{\dfrac{q\phi(z')-q\phi(z)}{kT_i}\right\}\mathrm{erfc}\left[\left\{\dfrac{q\phi(z')-q\phi(z)}{kT_i}\right\}^{1/2}\right] \\
+\dfrac{2}{\sqrt{\pi}}\left\{\dfrac{(B(z)-B_0)q\phi(z')-(B(z')-B_0)q\phi(z)}{kT_i(B(z')-B_0)}\right\}^{1/2} \\
\times\exp\left\{\dfrac{q\phi(z')B(z')}{kT_i(B(z')-B_0)}\right\}+\left\{\dfrac{B(z)-B(z')}{B(z')}\right\}^{1/2}\dfrac{2}{\sqrt{\pi}} \\
\times\exp\left\{\dfrac{(q\phi(z')-q\phi(z))B(z')}{kT_i(B(z')-B(z))}\right\}\left[D\left[\left\{-\dfrac{(q\phi(z')-q\phi(z))B(z')}{kT_i(B(z')-B(z))}\right\}^{1/2}\right]\right. \\
\left.-D\left[\left\{-\dfrac{\{(B(z)-B_0)q\phi(z')-(B(z')-B_0)q\phi(z)\}B(z')}{kT_i(B(z')-B(z))(B(z')-B_0)}\right\}^{1/2}\right]\right], & q\phi(z')>q\phi(z), \\
\exp\left\{\dfrac{q\phi(z')-q\phi(z)}{kT_i}\right\}, & q\phi(z')<q\phi(z)\ ,
\end{cases} \tag{8}$$

$$\begin{aligned}
I_{-}(z,z') &= \exp\left\{\frac{-q\phi(z')+q\phi(z)}{kT_{i-}}\right\}\mathrm{erfc}\left[\left\{\frac{-q\phi(z_{\min})+q\phi(z)}{kT_{i-}}\right\}^{1/2}\right] \\
&-\left\{\frac{B(z_{\min})-B(z)}{B(z_{\min})}\right\}^{1/2} \\
&\times\exp\left[\frac{\{-q\phi(z')+q\phi(z)\}B(z_{\min})+\{q\phi(z')-q\phi(z_{\min})\}B(z)}{kT_{i-}\{B(z_{\min})-B(z)\}}\right] \\
&\times\mathrm{erfc}\left[\left\{\frac{\{-q\phi(z_{\min})+q\phi(z)\}B(z_{\min})}{kT_{i-}\{B(z_{\min})-B(z)\}}\right\}^{1/2}\right]
\end{aligned} \tag{9}$$

Where $D(z)$ is the Dawson function.

4. Numerical Solution of the Plasma-Sheath Equation

The plasma-sheath equation (7) is normalized and solved numerically by transforming it into a set of finite difference equations. We assume the mirror ratio $R=B/B_0=\exp[\alpha\{\eta-e\phi_{\mathrm{w}}/(kT_{\mathrm{e}})\}^{1/2}]$ which is similar to the expression used by Sato *et al.* [4], where $\eta=(e/kT_{\mathrm{e}})(\phi_{\mathrm{w}}-\phi)$ and α is a positive constant.

The potential profile for various values of α is shown in Fig. 2, where $\tau=T_{\mathrm{e}}/T_{\mathrm{i}}=2$, $\tau_{-}=T_{\mathrm{e}}/T_{\mathrm{i-}}=10$, $\beta=S_{0-}/S_0=0.8$, where S_0 and S_{0-} are the average source strengths of the positive ion and the negative ion, and $\lambda_{\mathrm{D}}/L=5\mathrm{x}10^{-2}$, where λ_{D} is the Debye length, where the normalized potential $\Phi=-\eta=(q/kT_{\mathrm{e}})(\phi-\phi_{\mathrm{w}})$ is shown. It is shown that the sheath potential has the negative peak near the wall for the case of the increase rate of the magnetic field is small. The potential profiles for various values of β and the temperature ratio $\tau_{-}=T_{\mathrm{e}}/T_{\mathrm{i}}$ are also calculated.

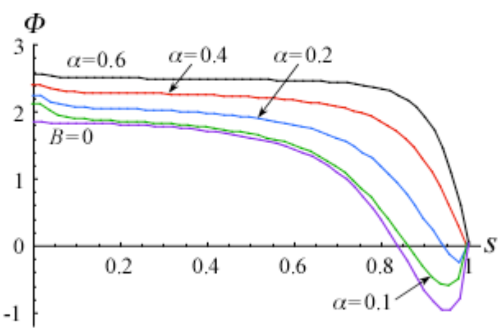

Fig.2 Profile of the normalized potential Φ for various values of α with $\tau=2$, $\tau_{-}=10$, $\beta=0.8$, $\lambda_{\mathrm{D}}/L=5\mathrm{x}10^{-2}$.

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