Electric Potential in Surface Produced Negative Ion Source with Magnetic Field Increasing Toward a Wall

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\textbf{Abstract} Electric potential near a wall for 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, where negative ions produced on the plasma grid (PG) surface are considered in addition to positive ions and electrons. The potential profile depends on the amount and the temperature of the surface produced negative ions and the profile of the magnetic field. The negative potential peak is formed in the sheath region near the PG surface for the case of strong surface production of negative ions or low temperature negative ions. As the increase rate of the magnetic field near the wall becomes large, the negative potential peak becomes small.

\textbf{Keywords:} negative ion source, surface produced negative ion, sheath potential, cusp magnetic field, electric potential, plasma-sheath equation, extraction region

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\section{Introduction}

A hydrogen negative ion is desirable for neutral beam injection (NBI) that is a method of heating plasma confined magnetically, because its neutralization efficiency is much higher than positive ion. In negative ion sources of NBI for large fusion devices such as ITER, high energy and high current negative ion beams are required. Performance required for negative ion sources of NBI for ITER is 1 MeV beam energy and 40 A beam current. In the surface produced negative ion source, negative ions produced on a plasma grid (PG) are accelerated by potential between the plasma and the PG. However, the general sheath potential accelerates the surface produced negative ions toward an inner side of the ion source. Trajectories and extraction probabilities of the surface produced negative ions have been calculated numerically \cite{1,2}. However, the physical mechanism of extraction of surface produced negative ions from the PG has not been made clear.

There is possibility that the potential distribution near the PG in the surface produced negative ion source is different from the general sheath potential because a large number of negative ions are produced on the PG. It has been shown that a virtual cathode is formed near the PG in the surface produced negative ion source by Particle in Cell (PIC) simulations \cite{3,4}. AMEMIYA et al. analyzed the sheath potential for the case of electron emission into plasma consisting of electrons, positive ions and negative ions \cite{5}. R. MCADAMS et al. extended the model of AMEMIYA et al. to the sheath potential including the formation of the virtual cathode \cite{6}. In these analyses, a density of negative ions was given by a Boltzmann distribution. For plasma that consists of electrons and positive ions, EMMERT et al. investigated the sheath potential analytically considering both the plasma and the sheath regions self-consistently by using a plasma-sheath equation \cite{7}. We have investigated the potential distribution near the extraction region analytically by means of the plasma-sheath equation and shown that the virtual cathode is formed, where the negative ions produced on the PG surface are considered \cite{8}. In this analysis, the density of negative ions was derived from the kinetic equation and energy equation.

Plasma in the negative ion source is confined by cusp magnetic fields so as to reduce plasma loss on the wall. SATO et al. extended the method of EMMERT et al. to a case of magnetized plasma \cite{9}. In their analysis, a magnetic field of which the strength decreases monotonically toward the wall was considered. We have investigated the potential near the wall with the magnetic field of which the strength increases toward the wall such as the cusp magnetic \cite{10}. These analyses were performed for plasmas that consist of electrons and positive ions. On the other hand, 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 \cite{11}. These magnets also produce a magnetic field increasing toward the PG surface inside the negative ion source.
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In this paper, effect of the magnetic field on the potential distribution near the extraction region will be studied analytically for the plasma with surface produced negative ions, where the magnetic field increasing toward the PG surface is considered. The potential distribution depends on the amount and the temperature of the surface produced negative ions and the profile of the magnetic field, and the dependence is examined.

2 Model

In surface production negative ion sources, negative hydrogen ions H\(^-\) produced on the PG surface are launched to the interior of the ion source. The cusp magnetic field increases toward the PG surface. It is assumed that the magnetic field is perpendicular to the wall near the PG surface. The background plasma is assumed to consist 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 \(B(z)\) is assumed to be symmetric about \(z=0\) and \(B_0\) at \(z=0\).

![Fig.1 Geometry of the potential and magnetic field in the analysis model](image)

3 Analysis of electric potential

Constant energy \(E\) and \(E_-\) of a positive ion and a negative ion in the \(z\)-direction are

\[
E = \frac{1}{2} M (v_1^2 + v_\perp^2) + q \phi(z),
\]

\[
E_- = \frac{1}{2} M_- (v_{1-}^2 + v_{\perp-}^2) - q \phi(z),
\]

where \(M\) and \(M_-\) are the ion masses, \(v_1\) and \(v_{1-}\) are the velocities perpendicular to the magnetic field, \(v_\perp\) and \(v_{\perp-}\) are the velocities parallel to the magnetic field, and \(q\) and \(-q\) are the charges of the positive and the negative ions, respectively. The magnetic moments for the positive ion and the negative ion are given by

\[
\mu = (1/2) M v_1^2 / B(z),
\]

\[
\mu_- = (1/2) M_- v_{1-}^2 / B(z),
\]

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

\[
\sigma v_{1-} (z, E_-) \frac{\partial f(z, E, \mu, \sigma)}{\partial z} = S(z, E, \mu),
\]

where \(\sigma(= \pm 1)\) is the direction of the particle motion, \(f(z, E, \mu, \sigma)\) and \(f_{-}(z, E_{-}, \mu_-)\) are the distribution functions, \(S(z, E, \mu)\) and \(S_{-}(z, E_{-}, \mu_-)\) are the source functions, respectively. From Eqs. (1) to (4), the velocities parallel to the magnetic field are given by

\[
v_{1-} = [(2/M) (E - \mu B(z) - q \phi(z))]^{1/2},
\]

\[
v_{1-} = [(2/M_-) (E_- - \mu_- B(z) + q \phi(z))]^{1/2}.
\]

We assume a symmetry about \(z = 0\), that is, \(\phi(z) = \phi(-z)\), \(B(-z) = B(z)\), \(S(-z, E, \mu) = S(z, E, \mu)\) and \(S_{-}(-z, E_{-}, \mu_-) = S_{-}(z, E_{-}, \mu_-)\). Furthermore, we assume that particles are not reflected at the wall, then the boundary condition of the distribution functions are \(f(-L, E, \mu, +1) = f(L, E, \mu, -1) = 0\) for \(f_{-}(-L, E_{-}, \mu_-, +1) = f_{-}(L, E_{-}, \mu_-, -1) = 0\).

In the magnetic field of which the strength increases toward the wall, dependence of \(-\mu B(z) - q \phi(z)\) on \(z\) for the positive ion is classified into two cases. In case (i) the increase rate of \(\mu B(z)\) is larger than that of \(-q \phi(z)\), that is, \(\mu B(z) - B_0 > -q \phi(z)\), and in case (ii) the increase rate of \(\mu B(z)\) is smaller than that of \(-q \phi(z)\), that is, \(\mu B(z) - B_0 < -q \phi(z)\). The energy space of the particle is divided into some regions as shown in Fig. 2, which are based on the condition that \(v_{1-}\) and \(v_{1-}\) must be real number, that is, \(E - \mu B(z) - q \phi(z) \geq 0\) and \(E_- - \mu_- B(z) + q \phi(z) \geq 0\). In these energy spaces, particle motion is divided into some regions. In Fig. 2, \(E_{\text{min}} = -[\mu B(z) - q \phi(z)]_{\text{min}}\), \(E_{\text{min}} = -[\mu_- B(z) + q \phi(z)]_{\text{min}}\), and \(z_1\) is the turning point of the particle. We assume that \([\mu B(z) - q \phi(z)]_{\text{min}} = -\mu B(z_{\text{min}}) - q \phi(z_{\text{min}})\) and \([\mu_- B(z) + q \phi(z)]_{\text{min}} = -\mu_- B(z_{\text{min}}) + q \phi(z_{\text{min}})\) hold, where \(z_{\text{min}}\) is the position of \(-\mu B(z) - q \phi(z)\) and \(-\mu_- B(z) + q \phi(z)\) becomes minimum.

![Fig.2 Energy spaces of (a) the positive ion and (b) the negative ion. Here, (i) the case of \(\mu B(z) - B_0 > -q \phi(z)\) and (ii) the case of \(\mu B(z) - B_0 < -q \phi(z)\) (color online)](image)

The distribution functions \(f(z, E, \mu, \sigma)\) and \(f_{-}(z, E_{-}, \mu_-, \sigma)\) for \(\sigma = \pm 1\) are obtained by integrating Eqs. (5) and (6) for particle trajectory on the boundary conditions. For the positive ion, the sum of the distribution functions about \(\sigma = \pm 1\) for each energy region of cases (i) becomes

\[
\sigma v_{1-} (z, E_-) \frac{\partial f(z, E, \mu, \sigma)}{\partial z} = S(z, E, \mu),
\]

where \(\sigma(= \pm 1)\) is the direction of the particle motion, \(f(z, E, \mu, \sigma)\) and \(f_{-}(z, E_{-}, \mu_-)\) are the distribution functions, \(S(z, E, \mu)\) and \(S_{-}(z, E_{-}, \mu_-)\) are the source functions, respectively. From Eqs. (1) to (4), the velocities parallel to the magnetic field are given by

\[
v_{1-} = [(2/M) (E - \mu B(z) - q \phi(z))]^{1/2},
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v_{1-} = [(2/M_-) (E_- - \mu_- B(z) + q \phi(z))]^{1/2}.
\]

We assume a symmetry about \(z = 0\), that is, \(\phi(z) = \phi(-z)\), \(B(-z) = B(z)\), \(S(-z, E, \mu) = S(z, E, \mu)\) and \(S_{-}(-z, E_{-}, \mu_-) = S_{-}(z, E_{-}, \mu_-)\). Furthermore, we assume that particles are not reflected at the wall, then the boundary condition of the distribution functions are \(f(-L, E, \mu, +1) = f(L, E, \mu, -1) = 0\) and \(f_{-}(-L, E_{-}, \mu_-, +1) = f_{-}(L, E_{-}, \mu_-, -1) = 0\).

In the magnetic field of which the strength increases toward the wall, dependence of \(-\mu B(z) - q \phi(z)\) on \(z\) for the positive ion is classified into two cases. In case (i) the increase rate of \(\mu B(z)\) is larger than that of \(-q \phi(z)\), that is, \(\mu B(z) - B_0 > -q \phi(z)\), and in case (ii) the increase rate of \(\mu B(z)\) is smaller than that of \(-q \phi(z)\), that is, \(\mu B(z) - B_0 < -q \phi(z)\). The energy space of the particle is divided into some regions as shown in Fig. 2, which are based on the condition that \(v_{1-}\) and \(v_{1-}\) must be real number, that is, \(E - \mu B(z) - q \phi(z) \geq 0\) and \(E_- - \mu_- B(z) + q \phi(z) \geq 0\). In these energy spaces, particle motion is divided into some regions. In Fig. 2, \(E_{\text{min}} = -[\mu B(z) - q \phi(z)]_{\text{min}}\), \(E_{\text{min}} = -[\mu_- B(z) + q \phi(z)]_{\text{min}}\), and \(z_1\) is the turning point of the particle. We assume that \([\mu B(z) - q \phi(z)]_{\text{min}} = -\mu B(z_{\text{min}}) - q \phi(z_{\text{min}})\) and \([\mu_- B(z) + q \phi(z)]_{\text{min}} = -\mu_- B(z_{\text{min}}) + q \phi(z_{\text{min}})\) hold, where \(z_{\text{min}}\) is the position of \(-\mu B(z) - q \phi(z)\) and \(-\mu_- B(z) + q \phi(z)\) becomes minimum.

![Fig.2 Energy spaces of (a) the positive ion and (b) the negative ion. Here, (i) the case of \(\mu B(z) - B_0 > -q \phi(z)\) and (ii) the case of \(\mu B(z) - B_0 < -q \phi(z)\) (color online)](image)

The distribution functions \(f(z, E, \mu, \sigma)\) and \(f_{-}(z, E_{-}, \mu_-, \sigma)\) for \(\sigma = \pm 1\) are obtained by integrating Eqs. (5) and (6) for particle trajectory on the boundary conditions. For the positive ion, the sum of the distribution functions about \(\sigma = \pm 1\) for each energy region of cases (i) becomes
\[
\sum_{\sigma} f(z, E, \mu, \sigma) = \begin{cases} 
2 \int_{0}^{L} \frac{S(z', E, \mu)}{v_{f}/(z', E, \mu)} \, dz', & (E > \mu B(z_{\text{min}}) + \phi(z_{\text{min}})), \\
2 \int_{0}^{L} \frac{S(z', E, \mu)}{v_{f}/(z', E, \mu)} \, dz', & (E > \mu B_{0}), \\
2 \int_{z_{\text{min}}(E, \mu)}^{L} \frac{S(z', E, \mu)}{v_{f}/(z', E, \mu)} \, dz', & (\mu B(z) + \phi(z) < E < \mu B(z_{\text{min}}) + \phi(z_{\text{min}})), 
\end{cases}
\]  
(9)

and that of case (ii) becomes

\[
\sum_{\sigma} f(z, E, \mu, \sigma) = \begin{cases} 
2 \int_{0}^{L} \frac{S(z', E, \mu)}{v_{f}/(z', E, \mu)} \, dz', & (E > \mu B_{0}), \\
2 \int_{0}^{L} \frac{S(z', E, \mu)}{v_{f}/(z', E, \mu)} \, dz', & (\mu B(z) + \phi(z) < E < \mu B_{0}), 
\end{cases}
\]  
(10)

respectively, where \( z' \) is the position of ion generation. In case (i), although the ions trapped between the turning points go back and forth and lead to infinite ion density, we assumed for simplicity that the trapped ions escape from the system due to collisions. Under this assumption, Eq. (9) is derived by integrating only one cycle of the trapped particle orbit and the results for case (i) are valid only under the condition that this assumption holds true.

For the negative ion, the sum of the distribution functions about \( \sigma = \pm 1 \) for each energy region becomes

\[
\sum_{\sigma} f(z, E, \mu, \sigma) = 2 \int_{0}^{L} \frac{S_{-}(z', E, \mu, -)}{v_{f}/(z', E, \mu, -)} \, dz'.
\]  
(11)

The positive ion density \( n_{+} \) and the negative ion density \( n_{-} \) are obtained by integrating \( f(z, E, \mu, \sigma) \) and \( f_{-}(z, E, \mu, -) \) over the \( E-\mu \) and \( E_{-}-\mu_{-} \) spaces, respectively, as

\[
n_{+}(z) = \frac{2\pi B(z)}{M^{2}} \sum_{\sigma} \int dE \int d\mu \frac{f(z, E, \mu, \sigma)}{v_{f}/(z, E, \mu)},
\]  
(12)

\[
n_{-}(z) = \frac{2\pi B(z)}{M^{2}} \sum_{\sigma} \int dE \int d\mu \frac{f(z, E, \mu, -)}{v_{f}/(z, E, \mu)}.
\]  
(13)

By substituting Eqs. (9) and (10) into Eq. (12) and Eq. (11) into Eq. (13), and interchanging the order of integrations of them, respectively, the densities of the positive and the negative ion can be written as

\[
n_{+}(z) = \frac{4\pi B(z)}{M^{2}} \left( \int_{0}^{L} \frac{dE'}{E_{p}} \int_{E_{p}}^{\infty} \frac{d\mu_{f}}{v_{f}/(z, E, \mu)} \frac{1}{S(z', E, \mu)} \right) + \int_{0}^{L} \frac{dE'}{E_{p}} \int_{E_{p}}^{\infty} \frac{d\mu_{f}}{v_{f}/(z, E, \mu)} \frac{1}{S(z', E, \mu)},
\]  
(14)

\[
n_{-}(z) = \frac{4\pi B(z)}{M^{2}} \int_{0}^{L} \frac{dE'}{E_{p}} \int_{E_{p}}^{\infty} \frac{d\mu_{f}}{v_{f}/(z, E, \mu)} \frac{1}{S(z', E, \mu)},
\]  
(15)

where \( E_{p} = \phi(z') \), \( B_{p} = B(z') \), \( E_{a} = \phi(z) \) and \( B_{a} = B(z) \) for \( z' < z \) and \( E_{p} = \phi(z) \), \( B_{p} = B(z) \), \( E_{a} = \phi(z') \) and \( B_{a} = B(z') \) for \( z' > z \) according to the conditions that \( v_{f} \) must be real number. Here, a case in which the increase rate of the magnetic field is smaller than the decrease rate of the potential is considered.

As for the source functions \( S(z, E, \mu) \) and \( S(z, E, \mu, -) \), we use the same expression as EMMERT et al. [1]

\[
S(z, E, \mu) = S_{0} h(z) \frac{M^{2}}{4\pi (kT_{i})^{2}} v_{f}/(z, E, \mu) \exp \left\{ - \frac{E - \phi(z)}{kT_{i}} \right\},
\]  
(16)

\[
S_{-}(z, E, \mu, -) = S_{0} h_{-}(z) \frac{M^{2}}{4\pi (kT_{i})^{2}} v_{f}/(z, E, \mu) \exp \left\{ - \frac{E - \phi(z)}{kT_{i}} \right\},
\]  
(17)

where \( T_{i} \) and \( T_{i} \) are the temperatures, \( h(z) \) and \( h_{-}(z) \) are the source strengths, and \( S_{0} \) and \( S_{0} \) are the average source strengths of the positive ion and the negative ion, respectively. The averages about \( z \) of \( h(z) \) and \( h_{-}(z) \) are normalized to 1. Substituting Eqs. (16) and (17) into Eqs. (14) and (15), respectively, and integrating them for \( \mu, \mu_{-} \) and \( E, E_{-} \), respectively, we obtain the densities as

\[
n_{+}(z) = S_{0} \left( \frac{\pi M}{2kT_{i}} \right)^{1/2} \int_{0}^{L} dz' I(z, z') h(z'),
\]  
(18)
where $I(z, z')$ and $I_-(z, z')$ are given by

$$I(z, z') = \exp \left\{ \frac{\phi(z') - \phi(z)}{kT_1} \right\} \text{erf} \left\{ \frac{\phi(z') - \phi(z)}{kT_1} \right\}^{1/2} \left( -D \left[ \frac{(B(z') - B_0)q\phi(z') - (B(z) - B_0)q\phi(z)}{kT_1(B(z') - B(z))} \right] \right) \frac{1}{kT_1} \left( B(z) - B(z') \right) \frac{1}{B(z_{\text{min}})} \right\}^{1/2},$$

where $D(z)$ is the Dawson function $^{12}$

$$D(x) = \int_0^x \exp(t^2)dt = \frac{1}{\sqrt{2}} \text{erf}(ix).$$

As for the electron density $n_e$, we use a Maxwell-Boltzmann distribution for simplicity

$$n_e(z) = n_0 \exp \{\phi(z)/kT_e\},$$

where $n_0$ is the density at $z = 0$, $-e$ is the electron charge, $k$ is the Boltzmann’s constant, and $T_e$ is the electron temperature.

By substituting Eqs. (18), (19) and (23) into Poisson’s equation, the plasma-sheath equation is derived as

$$\frac{d^2 \phi}{dz^2} = \frac{n_0 e}{\varepsilon_0} \exp \left( \frac{e\phi(z)}{kT_e} \right) - \frac{qT_0}{\varepsilon_0} \exp \left( \frac{\pi M}{2kT_1} \right)^{1/2} \int_0^L dz' I_-(z, z') h_-(z').$$

The average source strengths $S_0$ and $S_{0-}$ are decided by the equilibrium of the fluxes of the plasma particles at the wall. We consider that $j_{ew} + j_{iw} = j_{iw-} = 0$, where $j_{ew}$ is the electron current density, $j_{iw}$ is the positive ion current density, and $j_{iw-}$ is the negative ion current density at the wall, respectively. Furthermore, we define the ratio of the production rates of negative ions to positive ions to be $\beta = S_{0-}/S_0$. The average source strengths are obtained as

$$S_0 = \frac{en_0}{qL(1 + \beta)} \left( \frac{kT_e}{2\pi m_e} \right)^{1/2} \exp \left( \frac{e\phi_w}{kT_e} \right),$$

$$S_{0-} = \frac{en_0\beta}{qL(1 + \beta)} \left( \frac{kT_e}{2\pi m_e} \right)^{1/2} \exp \left( \frac{e\phi_w}{kT_e} \right),$$

where $m_e$ is the electron mass and $\phi_w$ is the wall potential. Substituting Eqs. (25) and (26) into Eq. (24), we obtain

$$\lambda_D^2 \frac{e}{kT_e} \frac{d^2 \phi}{dz^2} = \exp \left( \frac{e\phi(z)}{kT_e} \right) - \frac{1}{2L(1 + \beta)} \left( \frac{MT_e}{m_eT_1} \right)^{1/2} \exp \left( \frac{e\phi_w}{kT_e} \right) \int_0^L dz' I_-(z, z') h(z'),$$

$$+ \frac{\beta}{2L(1 + \beta)} \left( \frac{MT_e}{m_eT_1} \right)^{1/2} \exp \left( \frac{e\phi_w}{kT_e} \right) \int_0^L dz' I_-(z, z') h_-(z'),$$

where $\lambda_D = (e_kT_e/n_0e^2)$ is the Debye length.

4 Numerical solution of the plasma-sheath equation

Here, we introduce normalized variables: $\eta = (e/kT_e)(\phi_w - \phi)$, $s = z/L$, $\tau = T_e/T_1$, $\tau_- = T_e/T_{1-}$, $Z = q/e$, $R = B/B_0$, where $R$ is the mirror ratio. The normalized plasma-sheath equation is solved numerically by transforming it into a set of finite difference equations $^{[7,8]}$. The boundary conditions are $d\eta/ds|_{s=0} = 0$ and $\eta(s = 1) = 0$. We assume that the positive ion is generated uniformly, that is, $b(z) = 1$, and the negative ion is generated at the wall only. We assume the mirror ratio similar to the expression used by SATO et al. $^{[4]}$
\[ R(\eta) = \exp \left[ \alpha \left( \eta - e\phi_w/(kT_e) \right)^{1/2} \right], \tag{28} \]

where \( \alpha \) is a positive constant.

The potential profile for various values of the ratio of the production rates of negative ions to positive ions \( \beta = S_{0-}/S_0 \) is shown in Fig. 3, where \( \lambda_D/L = 5 \times 10^{-2} \), the temperature ratio \( \tau = T_e/T_i = 2 \) and \( \tau_- = T_e/T_{i-} = 10 \), and the positive constant in Eq. (28) \( \alpha = 0.2 \), and the normalized potential \( \Phi = \frac{\eta}{(q/kT_e)(\phi - \phi_w)} \) is shown. The result for the case without negative ions, which corresponds to \( \beta = 0 \), is also shown. The potential depends on the value of \( \beta \) and decreases and has a negative peak near the wall as the value of \( \beta \) increases. The profile of the potential for various values of the temperature ratio \( \tau_- = T_e/T_{i-} \) is shown in Fig. 4, where \( \tau = 2, \beta = 1.0, \lambda_D/L = 5 \times 10^{-2} \) and \( \alpha = 0.2 \). It is found that the sheath potential depends on the value of \( \tau_- \) and has a negative peak near the wall for large \( \tau_- \). This may be because that the low energy negative ions stay a long time near the PG surface. The profile of the potential for various values of the positive constant in Eq. (28) \( \alpha \) is shown in Fig. 5, where \( \tau = 2, \tau_- = 10, \beta = 0.8, \) and \( \lambda_D/L = 5 \times 10^{-2} \). The result for a case without the magnetic field is also shown. It is shown that the sheath potential has no negative peak near the wall for the case in which the increase rate of the magnetic field is large.

### 5 Conclusions

The potential distribution near the extraction region for the plasma with the surface produced negative ions and the magnetic field increasing toward the wall is studied analytically. The plasma-sheath equation is derived theoretically and solved numerically. It is shown that the potential decreases as the surface produced negative ions increase and a negative potential peak is formed near the PG surface for the case of strong surface production of the negative ions. This negative potential peak is also formed for the case of low energy negative ions. This may well come from the fact that low energy negative ions stay a long time near the PG surface. On the other hand, the negative potential peak is not formed near the PG surface for the case in which the increase rate of the magnetic field is large.

### References


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