Influence of surface produced negative ions on sheath structure

Sejal Shah and M. Bandyopadhyay
ITER-India, Institute for Plasma Research, Bhat, Gandhinagar-382428, Gujarat, India
E-mail: sejal013@gmail.com

Abstract. Surface production of negative ion is a dominating process in a high current negative ion source. In presence of surface produced negative ions, the plasma sheath near a metallic plane is modified and has been analysed in this report. The multivalued nature of electric potential at the sheath edge in electronegative plasma, determined by Bohm criterion is pursued in presence of surface produced negative ions.

1. Introduction
Neutralization efficiency of negative ions above 100 keV/amu makes them essential in fusion reactor [1]. In negative ion source, negative ions are generated mainly by surface production mechanism [2]. For that reason the electrodes or special emitters with a very low work-function are used for enhancement of negative ion production. An electrostatic sheath is formed at the interface between plasma and a solid metallic surface, where charge neutrality of the plasma diminishes [3] and therefore a potential profile is developed, which can be determined using Bohm criterion. The presence of negative ions in plasma modifies this sheath zone and is determined by many researchers in diverse situations [4, 5]. Braithwaith and Allen [4] explained that plasma sheath shows a complex structure and becomes multivalued for \( T_e / T_n > (5 + \sqrt{24}) \). Where \( T_e \) and \( T_n \) are electron and negative ion temperature respectively. Later Fernandez Palop et al. [6] gave new model to explain certain unsolved problems by Braithwaith and Allen. All the previous works dealt with volume produce negative ions. Present work is an extension to this model which incorporates the effect of surface produced negative ions on sheath structure.

2. Model
Figure 1 shows the proposed model in which the direction and nature of the motions of positive and negative charged particles have been depicted. Plasma in the volume is considered to be neutral and because of higher mobility of electrons, the metallic plate is considered to be negative with respect to plasma in the volume. In this model, collisions and ionizations among the charged particles in sheath is neglected. To cast the problem in 1D, the metallic surface is considered to be infinite. Let \( \phi(x) \) is the potential profile inside the sheath. The potential on the plate is \( \phi_p = \phi(0) \) with respect to (w.r.t) plasma-sheath edge. It is assumed that the plasma is positive with respect to the wall and negative ions which are produced on the wall will be accelerated towards plasma due to the nature of the sheath potential. Inside the plasma these surface produced negative ions collide with the background particles and eventually get thermalized [7].

© 2010 IOP Publishing Ltd
Following dimensionless variables are defined and used to explain the model in dimensionless form.

\[ \gamma = \frac{T_e}{T}, \quad \alpha_0 = \frac{n_{-0}}{n_{e0}}, \quad X = \frac{x}{\lambda_D}, \quad \lambda_D = \sqrt{\frac{e_k n_{e0} T_e}{e^2 n_{e0}}}, \]

\[ \psi(X) = -\frac{e\phi(x)}{kT_e}, \quad \psi_s = -\frac{e\phi_s}{kT_e}, \quad \psi_p = -\frac{e\phi_p}{kT_e}, \quad \psi = \psi(X), \]

where, \( n_{e0} \) is the electron density, \( n_{-0} \) is the negative ion density in the plasma volume, \( \lambda_D \) is the Debye-length. Let consider \( n_{s+}, n_{s-} \) and \( n_{es} \) be the positive ion, negative ion and electron density near the sheath edge respectively and \( \phi_s \) is the electric potential at the sheath edge. Subscript ‘s’ refers to the sheath edge. It is assumed that, charge neutrality is also maintained at sheath edge like in plasma volume and can be written as,

\[ n_{s+} = n_{s-} + n_{es} \]

(2)

Positive ions entered into the sheath region and accelerated towards the wall. Positive ion density inside the sheath can be written in dimensionless form considering positive ion flux conservation, energy balance equation and continuity equation as,

\[ n_{s}(x) = n_{s+} \frac{\psi_s}{\psi(x)} \]

(3)

where \( n_{s}(x) \) is the positive ion density at any point \( x \) inside the sheath.

Negative charged particles approaching from the bulk plasma can be described by Maxwell-Boltzmann distribution inside the sheath. In dimensionless form, it can be written as, \( n_{e}(x) = n_{e0} \exp[-\psi(x)] \) and \( n_{-}(x) = n_{-0} \exp[-\gamma\psi(x)] \) for electrons and negative ions respectively. In case of surface produced negative ions, the surface production is assumed to be proportional to the flux of positive ions [8]. Therefore,

\[ n_{-p}(x) = \delta n_{es} v_{s+} \]

(4)

where, \( \delta \) gives the surface production yield from positive ions.

Since the plasma is positive w.r.t. the wall, negative ions from the wall will be accelerated towards plasma after being generated on the surface. The surface produced negative ions inside the sheath also maintain flux conservation and also follow energy balance equation. Their density inside sheath zone can be written in dimensionless form as,

\[ n_{-p}(x) = \delta n_{es} \frac{m_e}{m_p} \frac{\psi_s}{\sqrt{\psi_p - \psi(x)}} \]

(5)
It is assumed that the presheath zone is quasi-neutral like bulk plasma in the volume, the electric field at the sheath edge must be zero. Therefore the boundary conditions for Poisson’s equation is,
\[
\phi(0) = \phi_p, \quad \left( \frac{d\phi(x)}{dx} \right)_{\phi(x) = \phi_p} = 0
\]  
(6)

If negative hydrogen ion source is considered here, positive ions are H\(^+\) ions and negative ions are H\(^-\) ions, i.e. \(m_p/m_e = 1\). Using equations of positive ion, negative ions and electron density equation (3-5), Poisson’s equation at the sheath edge in dimensionless form can be written as,
\[
\frac{d^2\psi}{d\chi^2} = \frac{n_{e+}}{n_{e0}} \left[ \psi - e^{-\psi} - \alpha_o e^{-\gamma \psi} - \delta \frac{n_{e+}}{n_{e0}} \sqrt{\psi - \psi_p - \psi_s} \right]
\]  
(7)

where,
\[
\frac{n_{e+}}{n_{e0}} = \left( e^{-\psi} + \alpha_o e^{-\gamma \psi} \right) \left( 1 - \delta \sqrt{\psi - \psi_p - \psi_s} \right)
\]  
(8)

Let define \( \left( \frac{d\psi}{d\chi} \right)^2 = F(\psi, \psi_s) \); where \( \frac{d\psi}{d\chi} \), is dimensionless electric field. From equation (7) and using boundary conditions in equation (8) we get,
\[
F(\psi, \psi_s) = 4 \frac{n_{e+}}{n_{e0}} \left[ \sqrt{\psi - \psi_s} + 2 \left( e^{-\psi} - e^{-\psi_s} \right) + 2\alpha_o \left( e^{-\gamma \psi} - e^{-\gamma \psi_s} \right) + 4\delta \frac{n_{e+}}{n_{e0}} \sqrt{\psi - \psi_p - \psi_s} \right] \frac{\psi - \psi_p - \psi_s}{\psi_p - \psi_s}
\]  
(9)

Bohm criteria can be defined by,
\[
\left( \frac{d \psi}{d\chi} - \frac{dn_e}{d\psi} - \frac{dn_{e+}}{d\psi} \right) \left( \frac{d^2 F}{d\psi^2} \right)_{\psi = \psi_p} \geq 0
\]  
(10)

From equation (3) the potential at the sheath edge, \( \psi_s \) can be obtained using following equations,
\[
\left( \frac{d^2 F}{d\psi^2} \right)_{\psi = \psi_s} = -\frac{n_{e+}}{n_{e0}} \frac{1}{\psi_s} + 2e^{-\psi_s} + 2\gamma \alpha_o \left( e^{-\gamma \psi_s} \right) + \delta \frac{n_{e+}}{n_{e0}} \left( \psi_p - \psi_s \right)^{\frac{3}{2}} \geq 0
\]  
(11)

3. Results and Discussion

By solving equation (11) with equal sign, electric potential at the sheath edge \( \psi_s \) can be estimated for positive values of \( \alpha_o \). Figure 2 shows that, in the case of \( \gamma > (5 + \sqrt{24}) \) and for \( \delta = 0 \), the solution is multi-valued. This “multi-value” scenario holds well, if surface production of negative ions is also considered (\( \delta > 0 \)). In the case of electropositive plasma, where volume production of negative ions is negligible; i.e. \( \alpha_o < 1 \), sheath potential \( \psi_s \) is single valued and value close to 0.5 for \( \delta = 0 \) case. In case of pure surface production scenario, where fraction of volume negative ions very small, \( \alpha_o \ll 1 \), the value of \( \psi_s \) increases with surface production yield \( \delta \) and remains independent of \( \gamma \) as revealed from figure 3.

In absence of surface production (i.e. \( \delta = 0 \)), square of the dimensionless electric field \( F(\psi, \psi_s) \) is negative for certain range of \( \alpha_o \), which violets the Bohm Criteria [6]. While considering the case with having finite surface production (i.e. \( \delta = 0.2 \)), \( F(\psi, \psi_s) \) is always positive as shown in figure 4 for \( \gamma = 15 \) and therefore Bohm criteria is always satisfied.
4. Conclusion

Present study shows the effect of surface produced negative ions on the sheath structure. In case of pure surface production scenario, where fraction of volume negative ions very small, $\alpha_o << 1$; it is observed that the dimensionless electric potential at the sheath edge, $\psi_s$ increases with the increase of surface production yield, $\delta$ and remains independent of $\gamma$. Presence of both volume and surface produce negative ions does not change the nature of multi-valued solution of $\psi_s$ as a function of $\alpha_o$.

But in that multi-valued range, square of the dimensionless electric field $F(\psi_s, \psi_s)$ inside the sheath never becomes negative and thus Bohm criterion is never violated in presence of surface produced negative ions.

References

[1] Berkner KH, Pyle R V, Stearns J W 1975 Nucl. Fusion 15 249.
[2] M. Bandyopadhyay 2004 PhD Thesis, IPP Report 4/284, www.ipp.mpg.de/ipcms/de/kontakt/bibliothek/ipp_reports/IPP_4_284.pdf.
[3] Stangeby P C 1995 Phys. Plasmas 2(3) 702.
[4] Braithwiate N St J and Allen J E 1988 J. Phys. D: Appl Phys. 24 1733.
[5] Rieaman K. U 1997 Phys. Plasmas 4 4158.
[6] Fernandez Palop J I, Ballesteros J, Hernandez M A, Morales Crespo R 2002 J. Appl. Phys 91 2587.
[7] Fukumasa O and Nishida R 2006 Nucl. Fusion 46 S275.
[8] Isenberg J S et. al. 1992 Proc. 6th Int. Symp. Prod. & Neutralization of Neg. Ion, AIP 38.