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The magnetised plasma-wall transition: Theory and PIC simulation

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We consider the plasma-wall boundary conditions in the presence of a strong magnetic field and discuss realistic examples when they can strongly deviate from the well-accepted classical ones.

1. Classical model of the magnetised plasma-wall transition

The plasma-wall transition (PWT) is the narrow layer between the "bulk" plasma and a conducting wall. The PWT strongly affects the particle and heat fluxes to the wall, thus influencing all plasma-wall interaction processes [1, 2]. Hence, investigation of the PWT has become a genuine branch of plasma physics. In describing the PWT it is usually assumed that $\lambda_D << \rho_i << l$, where λ_D, ρ_i and l are the Debye length, the ion Larmor radius and the charged-neutral particle collision mean free path, respectively. Under these conditions, the one-dimensional PWT can be divided into the following three parts: the Debye sheath (DS), the magnetic presheath (MP), and the collisional presheath (CP). Due to the strongly kinetic nature of the DS and the MP, fluid and gyrokinetic numerical codes are inappropriate to describe this region self-consistently. Thus, establishing realistic boundary conditions (BCs) at the MP entrance (MPE) is becoming of top importance. In addition, these BCs can be used for direct (analytical) calculations of the particle and energy fluxes to the wall [2].

The classical model of the combined DS-MP region [2,3] assumes a cut-off Maxwellian velocity distribution for the electrons, and neglects cross-field drifts. Then, the BCs at the MP entrance are

$$\Delta\phi_{MP} = \frac{T_e}{2e}\ln\frac{M_i}{2\pi m_e}\frac{T_e}{T_i+T_e}, \quad V_{MP} = \sqrt{\frac{T_i+T_e}{M_i}}\sin\alpha,$$

$$\gamma_e = \frac{\Theta_e}{T_e\Gamma_e} = 2+\frac{e\Delta\phi_{MP}}{T_e} \approx 5, \quad \gamma_i = \frac{\Theta_i}{T_i\Gamma_i} = 2{,}0 \div 3.5,$$

where $\Delta\phi_{MP}$, V_{MP} and $\gamma_{e,i}$ are the potential drop between the MPE and the wall, the ion fluid velocity component normal to the wall at the MPE, and the electron and ion sheath heat transmission coefficients, respectively [3]; α is the angle between the wall and the magnetic field, e is the positive elementary charge, m_e and M_i are the electron and ion masses; $T_{e,i}$, $\Gamma_{e,i}$ and $\Theta_{e,i}$ are the temperature, the electron and ion particle and energy fluxes at the MPE. The second equation is the Bohm-Chodura condition. For simplicity we restrict ourselves to the floating case.

The aim of our work is to demonstrate that in reality the BCs at the MPE can strongly deviate from the classical ones listed above. All analytical results presented below have been checked against PIC kinetic simulations and found to be in good agreement with the latter.

2. Effects of superthermal electrons

The first question arising is the following: How correct is the assumption of Maxwellian electrons inside the PWT? Due to the low collisionality of high-energy electrons, the electron distribution at the MPE can contain a non-Maxwellian high-energy tail. In fusion plasmas this happens, e.g., during ELM (Edge-Localised Mode) activity, or during Lower Hybrid current drive and heating. In order to model a PWT of this kind one can assume that the plasma contains three electron populations [4], namely the thermal one and two high-energy electron beams propagating towards and away from the wall. The second beam corresponds to the electrons of the incoming beam, having been reflected in the DS and MP. Using the quasineutrality and the particle-conservation constrains, one can obtain the modified plasma BCs at the MPE. For low concentrations of the high-energy electron population (C_f) we get the following implicit BCs:

$$C_f = \frac{\alpha - cF(0,\sqrt{\Delta\varphi})}{F(\beta,\delta) - cF(0,\sqrt{\Delta\varphi})}, \quad \alpha = \sqrt{\pi\frac{T_i+T_e}{T_b}\frac{m_e}{M_i}}$$

$$\gamma_e = \frac{c}{\alpha}\left((2+\Delta\varphi)F(0,\sqrt{\Delta\varphi}) + \frac{C_f}{c^3}\left(F(\beta,\delta)(2.5+\beta^2)-\right.\right.$$

$$\left.\left. c^3(2+\Delta\varphi)F(0,\sqrt{\Delta\varphi}) + \frac{\alpha^2\Delta\varphi + \alpha\beta\sqrt{\Delta\varphi}-0.5}{1+2erf(\beta)+erf(\delta)}e^{-\delta^2}\right)\right),$$

$$\beta = \sqrt{\frac{m_e}{T_b}}V_b, \quad \delta = c\sqrt{\Delta\varphi}-\alpha, \quad c = \sqrt{\frac{T_e}{T_b}}, \quad \Delta\varphi = \frac{e\Delta\phi_{MP}}{T_e},$$

$$F(\alpha,\beta) = \frac{\exp(-\beta^2)+\sqrt{\pi}\alpha(1-erf(\beta))}{1+2erf(\alpha)+erf(\beta)}.$$

where T_b and V_b are the temperature and the velocity of the high-energy electron beam, respectively. $\Delta\varphi$ and γ as functions of C_f are given in Fig. 1, from which we see that even a very low concentration of the high-energy electron population can dramatically change the BCs at the MPE.
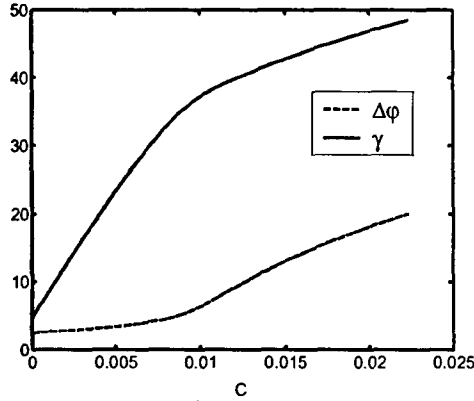
Figure 1.

3. Drift effects

Other candidates for affecting the BCs are the cross-field drifts. Here we consider the ExB drift as the most important one for fusion plasmas [2].

We consider a half-bounded plasma with the MPE located at $z \rightarrow -\infty$, where z is directed along the normal to the wall (Fig. 2). Let us assume that there exists an electric-field component parallel to the wall (E_y). Then, neglecting pressure terms, we can write the ion particle and momentum conservation equations for the MP [5] in the form

$$\frac{\partial}{\partial \vec{r}} n \vec{V} = 0, \quad \left(\vec{V} \frac{\partial}{\partial \vec{r}} \right) \vec{V} = \frac{e}{M_i} \left(\vec{E} + \vec{V} \times \vec{B} \right),$$

$$n \cong \exp\left(-\frac{e\phi}{T_e} \right), \quad \frac{\partial}{\partial \vec{r}} = \left(0, 0, \frac{\partial}{\partial z} \right),$$

$$\vec{E} = \left(0, E_y(z, y), E_z(z, y) \right), \quad \vec{B} = \left(B_x, 0, B_z \right).$$

The corresponding BCs at the MPE have the following form:

$$V_x^0 = V_{\parallel}^0 \cos\alpha + \frac{E_y^0}{B} \sin\alpha, \quad V_y^0 = 0, \quad \vec{V}^0 \equiv \vec{V}\big|_{z \rightarrow -\infty}$$

$$V_z^0 \equiv V_{MP} = V_{\parallel}^0 \sin\alpha - \frac{E_y^0}{B} \cos\alpha, \quad E_y^0 = E_y\big|_{z \rightarrow -\infty},$$

where $V_{\parallel}^0$ is the ion parallel velocity at the MPE, which is unknown yet.

It is possible to show that the system given above has a solution only if

$$V_{\parallel}^0 = \left(\sqrt{1 + \eta^2} - \eta \right) \sqrt{\frac{T_i + T_e}{M_i}} + \frac{E_y^0}{B} \cot\alpha,$$

$$\eta = \pm \frac{1}{2} \frac{\cot\alpha}{\sqrt{1 + T_i / T_e}} \frac{\rho_i}{L_y}, \quad L_y = \left| \frac{E_z}{\partial_y E_z} \right|_{z \rightarrow -\infty}.$$

(1)

Here, ρ_i is the Larmor radius and the sign of η depends on the direction of the ExB drift: If the drift is directed towards the wall, then η is positive, and in the opposite case it is negative.

From Eq. (1) we immediately obtaina new BC at the MPE:

$$V_{MP} = \left(\sqrt{1 + \eta^2} - \eta \right) \sqrt{\frac{T_i + T_e}{M_i}} \sin\alpha .$$

For small angles ($\alpha \ll 1$), η can easily become of the order of unity (or larger), hence the corresponding V_{MP} can significantly differ from the classical one.
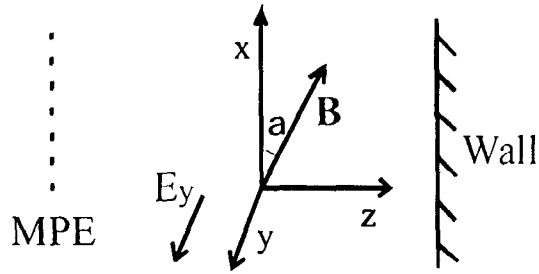

Figure 2.

Let us conclude by noting that in the extended version of this paper we will discuss two additional aspects, namely (a) the effects of a magnetic field almost parallel to the wall, and (b) the instabilities caused by secondary electrons.

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