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Attenuation of secondary electron emission from divertor plates due to magnetic field inclination

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Abstract

The effect of the magnetic field inclination to the divertor/limiter plate on the efficiency of secondary electron emission has been analysed. The dependence of the emission current on the magnetic field angle and the sheath potential is considered in a self-consistent manner. It is shown that for small inclination angles the electric field at the sheath cannot effectively pull out the emitted electrons from the plate, thus protecting them from being captured back to the plate. The reason for this is a weakness of the electric field due to the widening of the sheath at shallow inclination angles and the reduction of the positive charge in the sheath layer.

Keywords: Edge plasma; Plasma wall interaction; Sheath potential

1. It is well known that secondary electrons emitted from a divertor plate can significantly reduce the potential drop at the plasma edge (see e.g. [2,5]). On the other hand the efficiency of electron emission is strongly affected by electric field in the sheath region in the case when the magnetic field is inclined towards the plate [1–3]. This, in turn, affects the sheath potential, thus requiring a self-consistent consideration of this non-linear problem. In this paper we will be primarily interested in the efficiency of the secondary electron emission in case of small angels of the magnetic field inclination, which is typical for tokamak divertor configurations.

It was found [5] that the ambipolar wall potential is essentially independent of the angles of magnetic field inclination to the plate, α, whereas the electric field drops with decreasing α. The main reason for that is the change in the sheath thickness from Debye size at a normal angle of incidence to the size of the order of the ion gyro-radius at shallow angles. In [4] the reduction of the emission current was estimated for electric field values independently of secondary electron emission. As it will be clear from this paper, the self-consistent treatment of the sheath potential and the secondary electron emission significantly changes the result.

First we describe the trajectories of emitted electrons and define the range of initial electron velocities required to avoid the intersection of trajectories with the plane at given magnetic field inclination. Having this condition we estimate the emission current from the plate. The attenuation of the electric field due to sheath widening and due to the secondary electrons is taken into account. Finally we estimate the efficiency of the electron cooling due to the replacement of hot plasma electrons by cold ones, released from the plate.

2. Let α be the angle of incidence of the magnetic field with respect to the plate (see Fig. 1). When $\alpha = \pi/2$, (e.g. the magnetic field lines are normal to the plate) the magnetic field does not effect the electron emission and the emission current remains the same as in the absence of the magnetic field. In the opposite limiting case $\alpha = 0$, when the magnetic field is parallel to the surface, the emission current goes to zero because the emitted electrons are captured back onto the surface due to cyclotron motion. The number of emitted electrons at arbitrary value of α is affected by the fact that some electrons can be recaptured on the plate. Recapture does not happen if, for a time less than or equal to the

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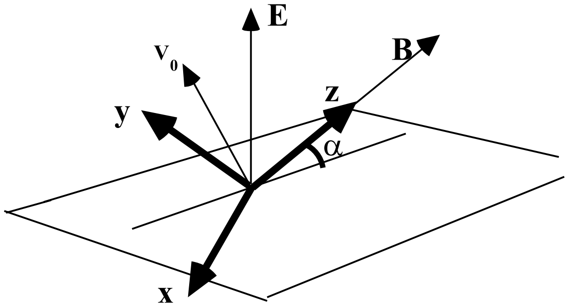

Fig. 1. Cordinate system on the emitter plane; v_0 is the initial velocity of the emitted electron; α is the inclination angle of B to the plate. The x-axis lies on the plane.

gyro-cycle time, an electron moves sufficiently far away to avoid the intersection of its trajectory with the emitting plate. At each moment the velocity can be expressed as [1,2]:

$$\vec{V} = \vec{V}_{//} + \vec{V}_{\mathrm{d}} + \vec{V}_{\omega}, \tag{1}$$

where $\vec{V}_{//}$ is the velocity along the magnetic field line, $\vec{V}_{\mathrm{d}}$ a drift velocity and $\vec{V}_{\omega}$ is an oscillatory velocity. The values in (1) are

$$\begin{aligned}
&\vec{V} = \vec{h}(\vec{h}, \vec{V}_0 - \vec{V}_{\mathrm{d}}) + \frac{e\vec{h}}{m_{\mathrm{e}}}\left(\vec{E}\vec{h}\right)t,\\
&\vec{V}_{\mathrm{d}} = \frac{c\left[\vec{E}\vec{h}\right]}{B},\\
&\vec{V}_{\omega} = \left\{\left[\vec{h},\vec{x}\right]\sin\omega_{\mathrm{c}}t + \left[\vec{x} - \vec{h}\left(\vec{h}\vec{x}\right)\cos\omega_{\mathrm{c}}t\right]\right\},\\
&\vec{x} \equiv \vec{V}_0 - \vec{V}_{\mathrm{d}}.
\end{aligned} \tag{2}$$

Here V_0 is the initial velocity of the emitted electron. We choose a reference system with the origin on the plate at the electron launching point and with the z-axis along the magnetic field B. The x-axis we will choose to lie on the plate as shown in Fig. 1. The advantage of the chosen coordinate system is that the capturing condition for electrons can be expressed in a rather simple way.

In Eq. (2) $\vec{h} \equiv \vec{B}/B$, $\omega_{\mathrm{c}} = eB/m_{\mathrm{e}}c$, and in the chosen coordinate system the components of the electric field and the drift velocity are $\vec{E}(0, -E\cos\alpha, -E\sin\alpha)$ and $\vec{V}_{\mathrm{d}}(-eE\cos\alpha/B, 0, 0)$.

The parallel component of electric field $\vec{E}_{//}$ provides the constant acceleration of electrons. In that case the trajectory of the electrons are gradually extending helical curves. The perpendicular component of the electric field to B causes an electron drift with drift velocity, $\vec{V}_{\mathrm{d}}$, which is directed along the emitter plane, and a cyclotron rotation on the circumference of the radii $\left|\vec{V}_{0\perp} - \vec{V}_{\mathrm{d}}\right|/\omega_{\mathrm{c}}$, where $\vec{V}_{0\perp}$ is the velocity normal to B. Integrating (2) over time, one gets the equation of the electron trajectory as a function of time and initial velocity:

$$\begin{aligned}
\vec{r} &= \int_0^t \vec{V}\,\mathrm{d}t\\
&= \vec{h}\left\{\left(\vec{h},\vec{x}\right) + \frac{e\vec{h}}{2m_{\mathrm{e}}}\left(\vec{E}\vec{h}\right)t^2\right\} + \vec{V}_{\mathrm{d}}t\\
&\quad + \left[\vec{h},\vec{x}\right]\frac{(1-\cos\omega_{\mathrm{c}}t)}{\omega_{\mathrm{c}}} + \left\{\vec{x} - \vec{h}\left(\vec{h},\vec{x}\right)\right\}\frac{\sin\omega_{\mathrm{c}}t}{\omega_{\mathrm{c}}}.
\end{aligned} \tag{3}$$

Further we will need the y-component of the rotation velocity $V_{\omega y}$ and the y projection of $\vec{r}$:

$$V_{\omega y} = V_{\omega 0}\cos\omega_{\mathrm{c}}t + (V_{0x} + V_{\mathrm{d}})\sin\omega_{\mathrm{c}}t, \tag{4}$$

$$y = \frac{V_{0y}}{\omega_{\mathrm{c}}}\sin\omega_{\mathrm{c}}t + \frac{(V_{0x} + V_{\mathrm{d}})}{\omega_{\mathrm{c}}}(1 - \cos\omega_{\mathrm{c}}t). \tag{5}$$

Equating $V_{\omega y}$ to zero, one gets a distance of maximum deviation of the emitted electron from the plate. This happens at a time, when

$$t_{\min} = \frac{k}{\omega_{\mathrm{c}}} - \frac{1}{\omega_{\mathrm{c}}}\,\mathrm{arctg}\frac{V_{0y}}{V_{0x} + V_{\mathrm{d}}}, \tag{6}$$

where

$$k = \begin{cases} 2\pi & \text{at } V_{0y} > 0,\ V_{0x} + V_{\mathrm{d}} > 0,\\ \pi & \text{at } V_{0x} + V_{\mathrm{d}} < 0,\\ 0 & \text{at } V_{0y} < 0,\ V_{0x} + V_{\mathrm{d}} > 0. \end{cases} \tag{7}$$

The condition for electron capture on the plate surface then can be given as

$$\left(V_{//}t_{\min}\right)tg\alpha - y_{\min} < 0. \tag{8}$$

This condition can be easily understood. Under this condition the electron orbit intersects the emitter plane (see Fig. 1). The inequality indicates the range Σ of initial velocities of electrons, which will be captured by the plate. The boundary of this region depends on the angle α and the value of the electric field. The attenuation of the emission current can be characterized as $\eta \equiv j^{\alpha}_{\mathrm{em}}/j_{\mathrm{em}}$. Here j^{α}_{em} is an emission current at arbitrary value of α, related to that, j_{em} at $\alpha = 0$. Parameter η can be defined as

$$\eta(\alpha, E) \equiv 1 - \int^{\Sigma} V_{0\perp}f_{\mathrm{em}}\,\mathrm{d}\vec{V}_0 \bigg/ \int V_{0\perp}f_{\mathrm{em}}\,\mathrm{d}\vec{V}_0.$$

Here f_{em} is a distribution function of electrons emitted from the plate. We use the expression from [6] $f_{\mathrm{em}}(v) \propto \mathrm{Const}|v|^3\mathrm{e}^{-2|v|}/v_{//}$, which is rather different from the Maxwellian one, and $v_{0//}$ is the initial velocity projection along B. It is convenient to use another coordinate system by turning the previous one around the x-axes so that the new Z-axis becomes normal to the plane and the new Y-axis lies on the emitter plane. In the new coordinate system the range of integration in velocity space, Σ, of the initial velocities corresponds to the non-negative values V_z. This range can be found from (7) which in the new coordinate system reads as

$$\xi \sin\alpha\left\{\left(u_z \sin\alpha - u_y \cos\alpha\right) + \frac{\xi}{2}\sin\alpha\beta\right\}$$
$$-\frac{\cos\alpha\left(u_y \sin\alpha + u_z \cos\alpha\right)^2}{\sqrt{\left(u_y \sin\alpha + u_z \cos\alpha\right)^2 + \left(u_x + \beta\cos\alpha\right)^2}}$$
$$+\left(1 - \frac{\left(u_x + \beta\cos\alpha\right)}{\sqrt{\left(u_y \sin\alpha + u_z \cos\alpha\right)^2 + \left(u_x + \beta\cos\alpha\right)^2}}\right) \leqslant 0. \tag{9}$$

Here $u_x = V_{0x}/V_{\mathrm{Te}}$, $u_y = V_{0y}/V_{\mathrm{Te}}$, $u_z = V_{0z}/V_{\mathrm{Te}}$, $\xi = \omega_c t_{\min}$ and $tg\xi = -(u_y \sin\alpha + u_z \cos\alpha/(u_x + \beta\cos\alpha))$.

Here the electric field in the sheath area can be expressed as the dimensionless quantity:

$$\beta = \frac{V_{\mathrm{d}}}{V_{\mathrm{Te}}\cos\alpha} = \frac{eE}{m_{\mathrm{e}}\omega_{\mathrm{c}}V_{\mathrm{Te}}}. \tag{10}$$

The electric field in the sheath in case of arbitrary inclination angle of B can be estimated following [5] as $E \approx \varphi_{\mathrm{D}}/L$, where the sheath thickness can be approximated by $L = \delta_{\mathrm{D}}(\sin\alpha + (\rho_{\mathrm{i}}/\delta_{\mathrm{D}})\cos\alpha)$. This shows that at small angle the sheath thickness is of the order of the ion gyro-radius, ρ_{i}. In the opposite case it is equal to the Debye length, λ_{D}. Since the sheath potential is affected by the secondary electron emission the electric field must be taken into account self-consistently. Bearing in mind the charge conservation at the edge ($j_{\mathrm{i}} + j_{\mathrm{em}} = j_{\mathrm{e}} \equiv j_{\mathrm{e0}}\exp(-e\varphi_{\mathrm{D}}/T_{\mathrm{eh}})$) the electric potential drop can be written as

$$\varphi_{\mathrm{D}} \approx \frac{T_{\mathrm{eh}}}{e}\, ln\left(\sqrt{\frac{m_{\mathrm{i}}}{2\pi m_{\mathrm{e}}}}\frac{1}{1+\Gamma_\alpha}\right),$$

where Γ_α is the emission coefficient which is equal to the ratio of the total emission current j_{em} (due to various emission mechanisms) to the ion thermal current j_{i} and $j_{\mathrm{e0}} = n_{\mathrm{e}}v_{\mathrm{eT}}/2\sqrt{\pi}$. Γ_α can be expressed through the secondary electron emission coefficient γ_{e} of the incident electrons and γ_{i}, the emission coefficient due to the incoming ions, and the emission caused by the incident photons, γ_Φ as $\Gamma_\alpha = (\gamma_{\mathrm{i}} + \gamma_e + \gamma_\Phi/(1-\gamma_e))$. The maximum value of $\Gamma_{\pi/2}$ is limited due to the charge saturation and is equal to 9.78 [2,3]. Then the beta parameter can be written as

$$\beta = \frac{e\varphi_{\mathrm{D}}}{2T_{\mathrm{eh}}}\frac{\omega_{\mathrm{pe}}}{\omega_{\mathrm{ce}}}\left(\frac{T_{\mathrm{eh}}}{2T_{\mathrm{ec}}}\right)^{1/2} \times \left\{1\Big/\left(\frac{\omega_{\mathrm{pe}}}{\omega_{\mathrm{ce}}}\left(\frac{T_{\mathrm{i}}}{T_{\mathrm{eh}}}\right)^{1/2}\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}\cos\alpha + \sin\alpha\right)\right\}. \tag{11}$$

Here V_{Te} is the thermal velocity of emitting electrons, ω_{ce} the electron gyro-frequency, ω_{pe} the electron plasma frequency, T_{eh} the electron plasma temperature near the target and T_{ce} is the temperature of the secondary electrons. Two parameters, namely, the inclination angle, α, and the dimensional parameter β, which characterize the electric field, are the main parameters of the problem. One can notice that parameter beta is not independent. It depends on the coefficient of secondary emission, γ_{em}, which can be expressed as $\gamma_{\mathrm{em}} = \eta(\alpha,\beta)\gamma^0_{\mathrm{em}}$, where γ^0_{em} is a coefficient taken from the reference book. This makes the problem non-linear and requires iteration. The results of numerical calculations are shown below. Only a few iterations are needed to achieve a good convergence. The calculation was carried out for typical edge plasma conditions: $T_{\mathrm{eh}} \approx T_{\mathrm{i}}$, $T_{\mathrm{eh}}/T_{\mathrm{ec}} \approx 0.1$, $n \approx 1 \times 10^{19}$ to 5×10^{19}, $B \approx 1$ to 2 T. In this case the variation of beta is in the range of 0–0.1. We compare two cases: the first, when electric field is not influenced by secondary electrons and is independent of α; the second, when the electric field is taken self-consistently. In the first case, a noticeable decrease of the emission current occurs at relatively low values of the inclination angle α and the emission current drops nearly linearly with α. In that case

$$\beta = \beta_0 = \left(\frac{e\varphi_{\mathrm{D}}}{2T_{\mathrm{eh}}}\frac{\omega_{\mathrm{p}}}{\omega_{\mathrm{c}}}\right)\sqrt{\frac{T_{\mathrm{eh}}}{2T_{\mathrm{ec}}}}$$

and for the typical tokamak conditions this parameter varies from 0 to 10. At higher electric field near the plate, β_0, electrons are rapidly accelerating away from the plate and can be recaptured only at very shallow angles. Thus, for $\beta_0 = 10$, a significant decrease of the emission current is expected only at $\alpha \leqslant 2°$ (Fig. 2). Under such conditions the surface roughness must be taken into account. The dependence of $\Gamma_\alpha/\Gamma_{\pi/2}$ for various values of $T_{\mathrm{eh}}/T_{\mathrm{ec}}$ is shown in Fig. 3 for a given edge density $n \approx 10^{18}$ m^{-3} and a given magnetic field $B = 5.5$ T. From Fig. 3 it follows that under a typical tokamak edge conditions a significant reduction of the emission current is expected only at low angles ($\alpha \leqslant 10°$).

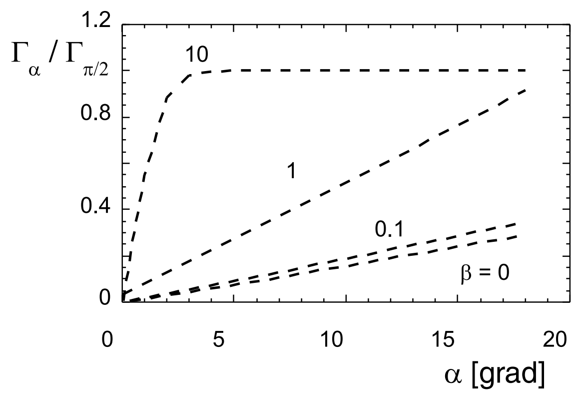

Fig. 2. Emission coefficient, $\eta \equiv \Gamma_\alpha/\Gamma_{\pi/2}$ vs. angle of magnetic field inclination to the plate, α for the different values of the parameter β_0, which characterizes the fixed electric field at the plate.

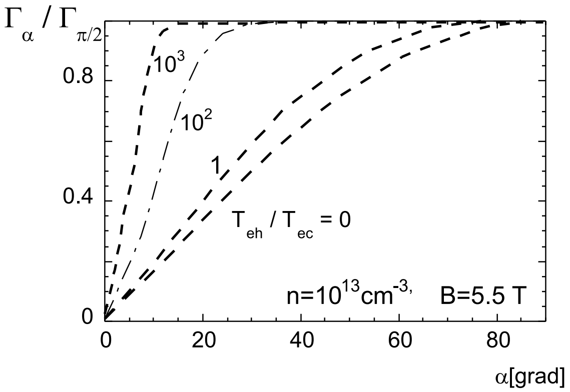

Fig. 3. Effect of the inclination angle on electron emission coefficient Γ_α; $T_{\rm eh}$ and $T_{\rm ec}$ are the temperatures of the plasma electrons and the secondary electrons, respectively; edge density $n \approx 10^{12}$ cm^{-3} and $B = 5.5$ T.

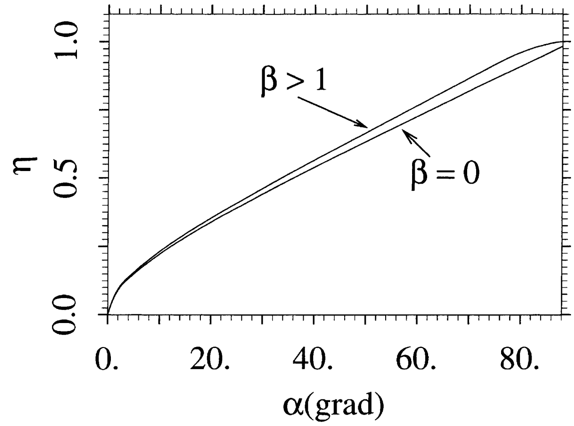

Fig. 5. The attenuation factor $\eta(\alpha, \beta)$ for different values of inclination angle, α; the sheath widening and the attenuation of the sheath charge are taken into account.

In the second case we took into account the fact that electric field decreases due to the emission itself and due to the widening the sheath region at shallow angles. The result is shown in Figs. 4 and 5. It is seen that attenuation is much stronger than in the case of a fixed electric field. The main reason is that the force due to electric field pulling out of the plate drops sufficiently, first, due to the widening of the sheath layer, and second due to the secondary electrons, reducing the positive charge in the sheath. Fig. 4 shows how the electric field, $\beta(\alpha, \gamma_{\rm em})$, decreases with inclination angle at the maximum available secondary electron emission ($\gamma_{\rm em} \approx 0.9$ [3]).

3. The electron emission can cause edge plasma cooling due to the replacement of hot plasma elections by cool electrons emitted from the plate (effect of the electron 'shower'). The incident heat flux from the plasma (assuming for simplicity that $T = T_{\rm e} = T_{\rm i}$) can be written as

$$q = 2Tj_{\rm i} + (2T + e\varphi_{\rm D})j_{\rm e} - e\varphi_{\rm D}j_{\rm em}. \tag{12}$$

The heat flux includes first, the energy transferred by ions, second the energy transferred by electrons, which consists of the average energy $2T$ and the energy spent to build up the sheath potential at the edge, $e\varphi_{\rm D}$. The heat flux can be written as $q = fTj_{\rm i}$, where the factor

$$f(\Gamma_\alpha) \equiv 2(1 + \Gamma_\alpha) + 2 + e\varphi_{\rm D}(\Gamma_\alpha)/T \tag{13}$$

describes the increase of the average energy carried by electrons and ions from the plasma to the plate due to the existence of the Debye layer between the plasma and the plate. The factor f characterizes the cooling effect of the plasma due to the electron emission, $T \approx q/(fj_{\rm i})$. The dependence of f on Γ_α is shown in Fig. 6 for two values of α in the case of a fixed electric field. In the case

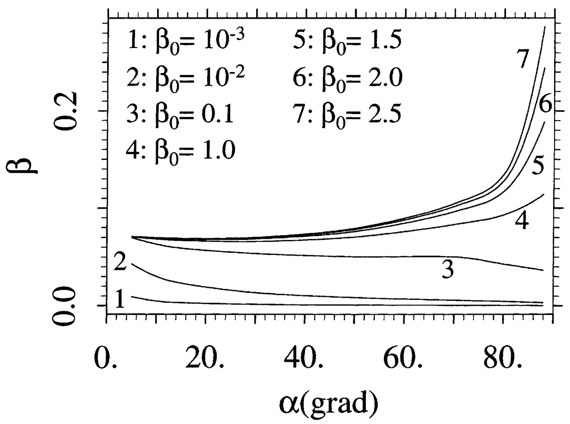

Fig. 4. Effect of the sheath widening on the electric field $\beta(\alpha, \gamma)$ at different values of nominal sheath electric field, β_0 ($\gamma_{\rm em} \approx 0.9$).

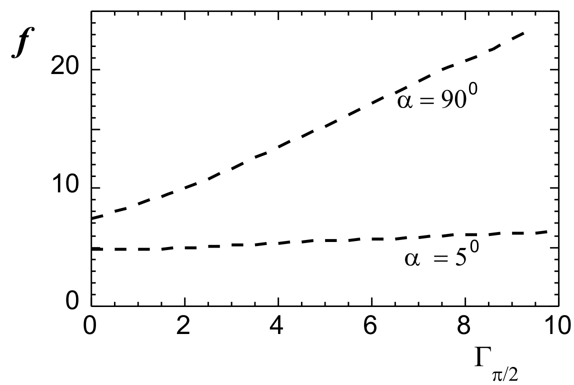

Fig. 6. Dependence of the factor f on electron emission coefficient $\Gamma_{\pi/2}$ for different α ($T_{\rm i} = T_{\rm e}$).

when $\alpha = \pi/2$, the edge plasma temperature can be almost 24 times lower (at a given heat and particle flux). However, in the case of divertor plates, when $\alpha = 1$ to 5° the expected cooling effect is rather moderate (only ~6 times or less). This implies that the inclination angle significantly diminishes the cooling efficiency. Therefore a significant cooling effect due to electron emission could not be expected for edge plasmas in divertor tokamaks. Thus, this effect will not be able to contribute significantly in lowering the edge temperature in order to protect the ITER-FEAT divertor plates from thermal sputtering.

Calculation shows that the attenuation of the sheath electric field, due to the negative charge of secondary electrons emitted to the plasma, and due to the widening the sheath layer at low inclination angles considerably decreases the influence of electric field on electron emission from the plate. This implies that the effect of inclination can be roughly estimated without taking into account the pulling effect of the electric field in the sheath. Even in the case of fixed Debye potential the effect of electron cooling seems to be too weak to reduce electron temperature at the plasma edge significantly.

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