Influence of the oblique magnetic field on the secondary electron emission from the plasma facing materials in fusion reactor

I E Berezina and I V Tsvetkov

National Research Nuclear University MEPhI Moscow 115409, Kashirskoe sh. 31, Russia

E-mail: ira.berezina@mail.ru

Abstract. The effect of the magnetic field inclination on the energy and angular distribution of electrons impinging on the first wall is modeled. It demonstrates the necessity to take into account the dependences of average energy and incident angle of electrons bombarding the wall on the magnetic field inclination in calculation of coefficient and the yield of secondary electron-electron emission.

1. Introduction
The studying of plasma – surface interaction processes is a very important task for realization of the international project ITER. To determine hydrogen isotopes implantation and reflection, plasma – facing materials sputtering and secondary emission, as well as to analyze the experimental data in the plasma sheath it is necessary to determine correctly the inflow and outflow of charged particles at the surface [1].

The oblique magnetic field has a substantial influence on the electron motion in the sheath. Taking into account the oblique magnetic field is important for the calculation of the sheath potential drop. It determines the energy of incident ions and therefore influences the surface sputtering. The electric field potential distribution depends on the reflection and secondary electron – electron emission, since these processes change the electron fluxes to and from the wall. The reflection and secondary electron – electron emission are dependent on parameters of electrons incidence onto the surface, in particular, the energy and angular distributions of impinging electrons [2]. That's why our purpose is to estimate dependences of parameters of electrons incidence onto the surface on the magnetic field inclination and then reveal the magnetic field influence on the coefficient and the yield of secondary electron emission.

2. Simulation model
The transport of electrons in the sheath layer is calculated by solving the equation of motion for electrons in the electric and magnetic fields near the wall. In the modelling it is assumed that electrons are injected from the boundary of the pre-sheath layer in the XY plane with the velocities **V** at angles β with respect to the normal. Emitted electrons have uniform angular distribution and the Maxwell velocity distribution. The plasma ion and electron temperatures are equal. The magnetic field is

uniform with a certain inclination angle α with respect to the surface normal $\mathbf{H} = \mathbf{H}(H_x, 0, H_z)$. The electric field is perpendicular to the wall $\mathbf{E} = \mathbf{E}(E_x, 0, 0)$.

The following form of the equation of electron motion is used:

$$
\begin{cases}
\dfrac{d^2}{dt^2}x = -\eta \cdot E - \dfrac{\eta}{c}\cdot\left(\dfrac{d}{dt}y\right)\cdot H_z \\[2mm]
\dfrac{d^2}{dt^2}y = \dfrac{\eta}{c}\cdot\left(\dfrac{d}{dt}x\cdot H_z - \dfrac{d}{dt}z\cdot H_x\right) \\[2mm]
\dfrac{d^2}{dt^2}z = \dfrac{\eta}{c}\cdot\left(\dfrac{d}{dt}y\cdot H_x\right)
\end{cases}
\tag{1}
$$

where $\eta = q/m = 5.3\times10^{17}$ SGSE/g, $c = 3\times10^{10}$ cm/s, $H_x = -H\cos(\alpha)$, $H_z = H\sin(\alpha)$.

To describe the potential distribution in the plasma sheath we use Poisson's differential equation:

$$
\left(\dfrac{d}{dx}\phi\right)^2 = -8\cdot\pi\cdot e\cdot n_o\cdot\left[2\cdot\phi_o\cdot\left(\sqrt{\dfrac{\phi(x)}{\phi_o}} - 1\right) - \dfrac{k\cdot T_e}{e}\cdot\left[\exp\left[e\cdot\dfrac{(\phi(x) - \phi_o)}{k\cdot T_e}\right] - 1\right]\right]
\tag{2}
$$

with boundary condition on the plasma side, which is derived from Bohm criterion:

$$
\left|\phi_0\right| \geq \dfrac{k\cdot T_e}{2\cdot e}
\tag{3}
$$

and boundary condition on the wall, which is derived using the fact that the ion flux must be balanced with the electron flux (the expression for the floating potential):

$$
\phi_w = \dfrac{k\cdot T_e}{2e}\cdot\left[\ln\left[2\pi\cdot m_e\cdot\dfrac{(T_e + T_i)}{m_i\cdot T_e}\right] - 1\right]
\tag{4}
$$

For solving the Poisson's equation we use the dimensionless form of equation (2):

$$
\dfrac{d}{d\xi}\lambda = \sqrt{8\cdot\left[\sqrt{-\lambda} + e^{(\lambda+1)\div2} - 2\right]}
\tag{5}
$$

where $\lambda = \varphi/\varphi_0$ represents the normalized potential and $\xi = x/r_d$ gives the distance from the surface in units of the Debye length. The equation was solved by Runge–Kutta method of third power.

Then we approximate the equation solution by extent function of the forth order:

$$
A(\xi) = a_0 + a_1\cdot\xi + a_2\cdot\xi^2 + a_3\cdot\xi^3 + a_4\cdot\xi^4
\tag{6}
$$

$$
\begin{aligned}
a_0 &= -5.98 \\
a_1 &= 2.08 \\
a_2 &= -0.374 \\
a_3 &= 0.032 \\
a_4 &= -1.044\cdot10^{-3}
\end{aligned}
$$

The approximation of this kind is quite useful for modeling the charged particles behaviour in the sheath. If you know plasma parameters, you can obtain the potential distribution in the sheath without solving Poisson's equation. The solutions of the dimensionless equation (5) by numerical method and

by approximation function (6) are shown in figure 1. These solutions agree satisfactorily along the whole plasma sheath length equal to 10 Debye lengths.
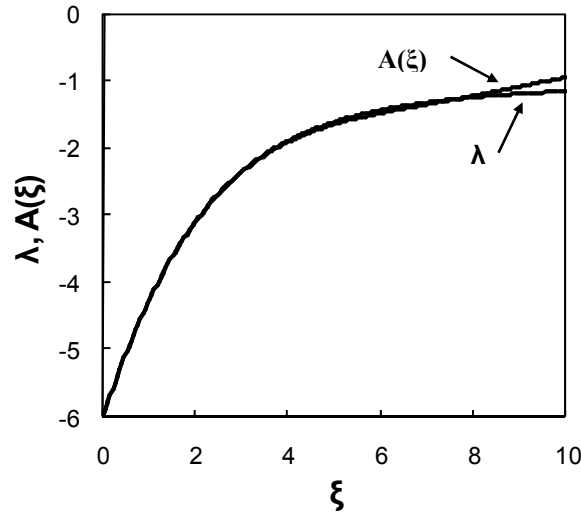

Figure 1. Potential distributions obtained by numerical solution λ of equation (5) and by approximation function $A(\xi)$ (6).

Then we return to the dimension values of potential and the distance from the surface and obtain the dependences of potential and electric field in the sheath on the distance from the surface and on the plasma parameters:

$$\phi(x) := -8.64 \cdot 10^{-3} \cdot T + 4.28 \cdot 10^{-6} \cdot \sqrt{n \cdot T} \cdot x - 1.1 \cdot 10^{-9} \cdot n \cdot x^2 + 1.34 \cdot 10^{-13} \cdot \frac{n^{\frac{3}{2}}}{\sqrt{T}} \cdot x^3 - 6.26 \cdot 10^{-18} \cdot \frac{n^2}{T} \cdot x^4 \qquad (7)$$

$$E(x) = -4.27 \cdot 10^{-6} \cdot \sqrt{n \cdot T} + 2.19 \cdot 10^{-9} \cdot n \cdot x - 4.02 \cdot 10^{-13} \cdot \frac{n^{\frac{3}{2}}}{\sqrt{T}} \cdot x^2 + 4.56 \cdot 10^{-18} \cdot \frac{n^2}{T} \cdot x^3 \qquad (8)$$

The values of distance, plasma density and temperature are given in cm, cm^{-3}, eV. The potential and electric field distribution in the sheath can be obtained from these approximation functions without solving Poisson's equation.

3. Influence of magnetic field inclination on the energy distribution of electrons reaching the wall

To determine a minimal initial energy of electrons impinging on the wall the electrons emitted along the surface normal were considered. These electrons reach the wall faster than other electrons emitted in XY plane with different velocities. In the absence of the magnetic field or when the magnetic field inclination equals zero the minimal initial energy of impinging on the wall electrons corresponds to the potential drop in the sheath layer. For given plasma parameters $T = 30$ eV, $n = 10^{12}$ cm^{-3} the potential drop equals 64.5 eV. However, with the magnetic field inclination the minimal initial energy increases. In this case the electron motion in the electric and the magnetic field is considered. Electron drifts along the wall and moves to the wall along the magnetic lines with velocity equal to its velocity projection on the magnetic field direction $V_\parallel = V \cdot \cos(\alpha)$. The condition of reaching the wall is excess of kinetic electron energy above the potential drop in the sheath layer. Using this condition we derive

the formula of dependence of minimal initial energy of electrons impinging on the wall on the magnetic field inclination angle α:

$$W_{min}(eV) = e(\varphi_w {}^- \varphi_0)/\cos(\alpha)^2 . \qquad (9)$$

The values calculated from this formula (9) and the results of numerical experiment for angles α less than 60° are in good agreement. For following calculations we consider the electrons from "Maxwell tail" with energies $W_0 > W_{min}$.

Energy distribution of electrons reaching the wall for different cases of the magnetic field inclination are shown in figure 2. Electrons are injected in the XY plane. The distributions are normalized to the number of emitted by plasma electrons. The magnetic field strength is $H = 5$ T. Electrons have the Maxwell velocity distribution on the boundary of the sheath layer. The electrons with energies from 64.5 eV to 370 eV were considered. These values correspond to minimal initial energy of electrons reaching the wall for α = 0° and energy equal to $E_{av}+3\sigma$, where σ represents the root-mean-square deviation and E_{av} gives the average electron energy in Maxwell distribution for $T = 30$ eV. One can see that the quantity of electrons bombarding the wall reduces. The fraction of the electrons reaching the wall is calculated as an area under the curve. So, for the magnetic field angle equals 30° the fraction of the electrons reaching the wall is equal to 0.03, and for 60° it is equal to 10^{-4}.

The minimal initial energy of electrons impinging on the wall increases with the magnetic field inclination. The values of average energy of electrons impinging on the wall for different angles α were calculated. Figure 3 presents the substantial increasing of the average energy of the electrons bombarding the first wall with the magnetic field inclination.
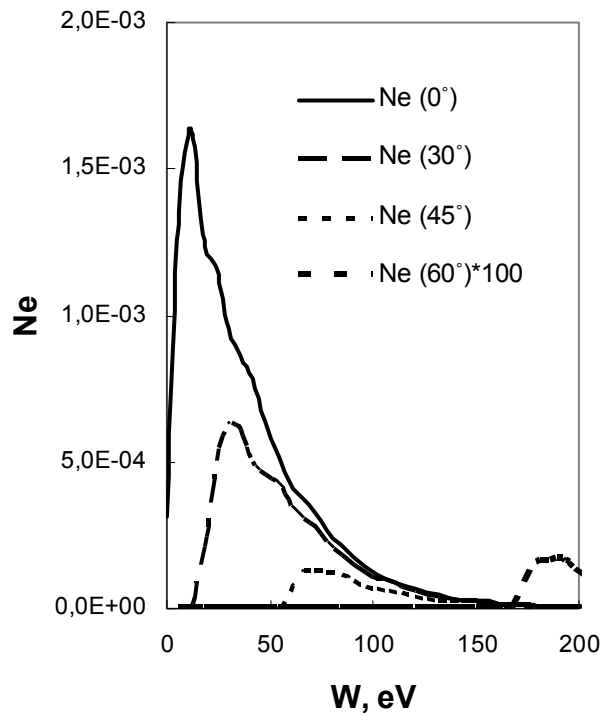

Figure 2. Energy distribution of electrons reaching the wall for different cases of the magnetic field inclination α. W – energy of electrons bombarding the wall, Ne – the fraction of the electrons with the given energy of the number of emitted by plasma electrons
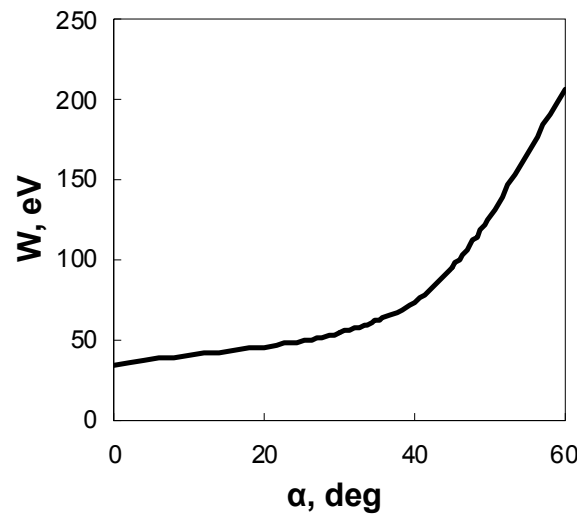
Figure 3. Dependence of the average energy W of the electrons bombarding the first wall on the magnetic field inclination angle α

The average angles of electron incidence for different magnetic field angles are calculated. It is shown that the average angle of electrons incidence does not depend substantially on the magnetic field inclination.

4. The influence of the magnetic field inclination on the coefficient and the yield of secondary electron emission

For each magnetic field inclination angle α the coefficients of secondary electron-electron emission δ_e, reflection η_e and the total coefficient of secondary electron emission $\gamma_e = \delta_e + \eta_e$ were calculated from the empirical formulae [3–5]:

$$\delta(Wp, \theta) := \delta\,emax \cdot 2.72^2 \cdot \frac{Wp}{Wmax} \cdot \frac{e^{-2 \cdot \sqrt{\frac{Wp}{Wmax}}}}{\cos(\theta)^{1.4}} \tag{10}$$

$$\eta(Wp, \theta) := \left(\frac{Wp^{m(z)} \cdot C(z)}{0.891} \right)^{\cos(\theta)} \cdot 0.891 \tag{11}$$

$$\gamma(Wp, \theta) := \delta(Wp, \theta) + \eta(Wp, \theta) \tag{12}$$

These coefficients are dependent on the electron energy and angle of incidence, that as was shown are dependent on the magnetic field inclination angle. Tungsten was considered as a surface material for calculations. Figure 4 shows the dependences of these coefficients on the magnetic field inclination in the case of electron injection in XY plane. With the magnetic field inclination the total secondary electron emission coefficient increases. The coefficient of secondary electron emission gives the main contribution to the growth of the total coefficient. The reflection coefficient does not substantially depend on the magnetic field inclination angle. However, with the magnetic field inclination increasing the number of reaching the wall electrons decreases due to the suppression of the electron flux to the surface by oblique magnetic field. That is why the yield of secondary electron emission decreases with the magnetic field inclination increasing despite the increasing of the secondary

emission coefficient (figure 4). For $\alpha = 0°$ the fraction of the secondary electrons from the number of emitted by plasma electrons is 6.7×10^{-2}, for $\alpha = 60°$ the fraction of secondary electrons is 2×10^{-4}.
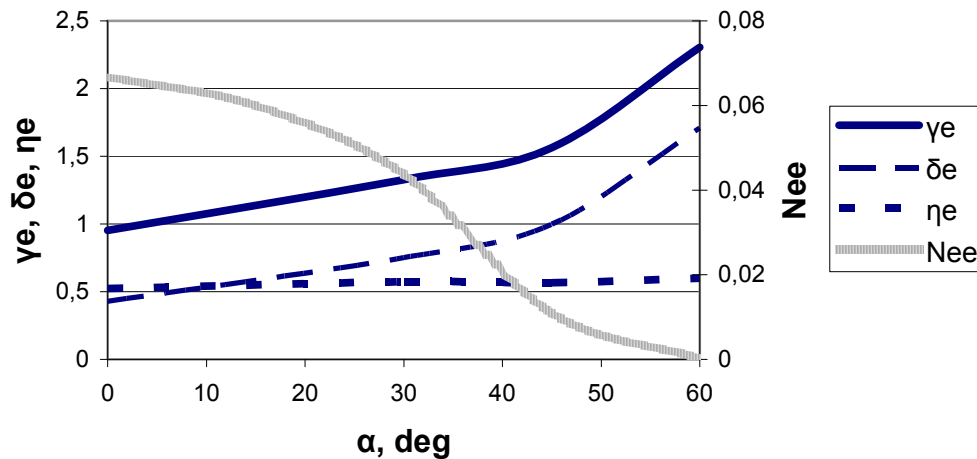

Figure 4. Dependences of the coefficients of secondary electron-electron emission δ_e, reflection η_e and the total coefficient of secondary electron emission γ_e on the magnetic field inclination angle α

5. Conclusions

Thus we study the influence of the magnetic field inclination angle on parameters of electrons incidence onto the surface in the case of flat electron injection. It was shown that the average energy of the electrons substantially increases with the magnetic field inclination. Therefore the secondary electron emission coefficient increases. At the same time due to the suppression of the electron flux to the surface by oblique magnetic field the secondary electron yield decreases with the magnetic field inclination increasing despite the increasing of the secondary emission coefficient. The potential distribution is dependent on the densities of electron inflow and outflow at the wall. That's why it is important to take into account the magnetic field in calculation of a self-consistent potential distribution in the sheath. The self-consistent potential determines the energy of ions bombarding the wall and therefore it is substantial for the calculation of the wall sputtering. Our further researches will be aimed at this problem.

References

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