Magnetic Presheath in a Turbulent Plasma

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ABSTRACT

Fluid model of the magnetic presheath in a turbulent boundary plasma is presented. Turbulent transport corrections of the classical three-dimensional fluid transport equations, which can be used to study magnetic presheaths in various geometries, are derived by means of the ensemble averaging procedure from the statistical theory of plasma turbulence. The magnetic presheath in front of an infinite plane surface is then analysed in detail, by using linearised planar magnetic presheath equations for studying the plasma presheath-magnetic presheath boundary, i.e., the magnetic presheath edge, and the original non-linear planar magnetic presheath equations for studying the entire magnetic presheath when various sets of experimentally relevant free input parameters of the model are applied. Important new results of this study are, among others, new expressions for the fluid approximation of the Bohm criterion at the electrostatic sheath edge and for the ion flux density perpendicular to the wall, which include corrections due to the turbulent charged particle transport. These results can qualitatively explain electric currents measured by Langmuir probes in the boundary regions of nuclear fusion devices and in various low-temperature plasmas, which are anomalously enhanced in comparison with those expected or predicted by other theoretical models, when the angle between the magnetic field and the wall is very small (i.e., several degrees), or when the magnetic field is parallel to the wall. The boundary conditions of the fluid transport codes, which are used for tokamak boundary plasma modelling, can be improved by using the results of this study.

1 INTRODUCTION

In the fluid transport models of the tokamak boundary plasma and related computer codes, such as B2-SOLPS, EDGE2D, TECXY, UEDGE, etc., it is usually assumed that the plasma transport along the magnetic field \( \hat{B} \) is classical, whereas the transport perpendicular to \( \hat{B} \) is turbulent (see, e.g., pp. 450-458 in [1] and references therein). Turbulent transport corrections of the classical fluid transport equations are usually implemented in these codes by replacing the classical perpendicular transport coefficients with the turbulent ones, or by adding some phenomenological terms into the original equations, which describe additional...
sources of particles, momentum, and energy due to the turbulent transport. The turbulent transport coefficients are treated as free input parameters of the model, “guessed” or calculated with some semi-empirical relations and approximate theoretical models of the plasma turbulence, or calculated with some plasma turbulence codes, which can be coupled with the transport codes. This way of turbulent plasma transport modelling is based on the assumption that the characteristic scale lengths and times of the plasma turbulence are shorter than the characteristic scale lengths and times of the macroscopic transport described with the fluid transport equations.

Nevertheless, the boundary conditions in these fluid transport models near the solid material walls in contact with the plasma, or, more precisely, at the boundary between the plasma presheath and the magnetic presheath [1-3], where the validity of the fluid transport equations is terminated, do not include any corrections due to the turbulent transport. Instead of these rather important corrections, some other corrections with questionable validity are introduced ad hoc. For example, some fluid transport codes include “intuitive boundary conditions” to account for the presence of the $\vec{E} \times \vec{B}$ and diamagnetic drifts, i.e., appropriate components of the ion drift velocities $\vec{v}_{\text{exb}} = \vec{E} \times \vec{B} / B^2$ and $\vec{v}_{\text{p}i} = \vec{B} \times \nabla p_i / (e n_i B^2)$ are simply added to the ion acoustic velocity at the magnetic presheath edge (see, e.g., p. 645 in [1] and references therein). Namely, according to the existing theoretical models of the magnetic presheath near a solid electrically conducting wall, in contact with a two-component plasma consisting of singly-charged positive ions and electrons, the ion flux density to the wall $\Gamma_{i,z}$ is given by the “marginal” Bohm-Chodura-Riemann criterion [2]:

$$\Gamma_{i,z} = n_{\text{MPSE}} v_{z,\text{MPSE}} = n_{\text{MPSE}} c_s \sin \alpha,$$

(1)

where $n_{\text{MPSE}}$ is the plasma density, i.e., a concentration of the charged particles, at the entrance of the magnetic presheath, i.e., the magnetic presheath edge (MPSE), $v_{z,\text{MPSE}}$ is perpendicular to the wall component of the ion fluid velocity at the entrance of the magnetic presheath, $\alpha$ is the grazing angle of the magnetic field $\vec{B}$ (figure 1), and $c_s$ is the ion acoustic velocity,

$$c_s = \sqrt{(k_B T_e + \gamma_e k_B T_i) / m_i},$$

(2)

where $k_B$ is Boltzmann’s constant, $T_e$ is electron temperature, $T_i$ is ion temperature, $m_i$ is ion mass, and $\gamma_e = 1$ for isothermal ion flow, $\gamma_i = 5/3$ for adiabatic flow with isotropic pressure, and $\gamma_i = 3$ for one-dimensional adiabatic flow. It means that the ion flux density to the wall is zero, when $\vec{B}$ is parallel to the wall, i.e., for $\alpha = 0^\circ$. This result is not correct when $\vec{B}$ is parallel or almost parallel to the wall, because Langmuir (electrical) probe measurements in the boundary regions of nuclear fusion plasmas, technological plasmas and other low-temperature laboratory plasmas confined by magnetic fields have shown significantly higher charged particle fluxes to the walls than predicted by means of equation (1), especially at very small grazing angles $\alpha$, i.e., for $\alpha < 5^\circ$ (see, e.g., pp. 634-643 in [1] and references therein). The measured ion saturation currents to the probes could be up to 10 % of the ion saturation currents at the normal incidence, i.e., for $\alpha = 90^\circ$, and the electron saturation currents to the probes could even be comparable with the ion saturation currents.

In this study we present an improved fluid model of the magnetic presheath, which includes the turbulent transport corrections of the classical fluid transport equations. The equations of our magnetic presheath model and some important results of the asymptotic analysis of the magnetic presheath edge are presented in Section 2. Numerical solutions of the
planar magnetic presheath equations for some experimentally relevant sets of free input parameters of the model are presented in Section 3. Conclusions are given in Section 4.

2 MAGNETIC PRESHEATH MODEL

After the turbulent ensemble averaging [4] of the continuity equation, the momentum conservation equation, and the thermodynamic closure relation, and assuming isothermal ion flow, i.e., \( T = \text{constant} \), the following equations are obtained for the regular (average) components of the plasma parameters:

\[
\frac{\partial n_i'}{\partial t} + \nabla \cdot (n_i' \vec{v}_r') = S_{n}^{\text{turb}},
\]

\[
m_i n_i' \frac{\partial \vec{v}_r'}{\partial t} + m_i n_i' (\vec{v}_r' \cdot \nabla) \vec{v}_r' = -k_B T_i n_i' + e n_i' (\vec{E}_r' + \vec{v}_r' \times \vec{B}_r') + \vec{S}_m^{\text{turb}},
\]

\[p_i' = n_i' k_i T_i,
\]

where the turbulent particle density source \( S_{n}^{\text{turb}} \) and the turbulent momentum source \( \vec{S}_m^{\text{turb}} \) are given by equations

\[
S_{n}^{\text{turb}} = -\nabla \cdot \left( n_i' \vec{v}_r' \right) \equiv -\nabla \cdot \vec{\Gamma}_i^{\text{turb}}
\]

and

\[
\vec{S}_m^{\text{turb}} = e \left( n_i' \vec{E}_r' \right) + e n_i' \left( \vec{v}_r' \times \vec{B}_r' \right) + e \vec{\Gamma}_i^{\text{turb}} \times \vec{B}_r' + e \left( n_i' \vec{v}_r' \times \vec{B}_r' \right) - m_i \left( n_i' \frac{\partial \vec{v}_r'}{\partial t} \right) - m_i \left( \vec{\Gamma}_i^{\text{turb}} \cdot \nabla \right) \vec{v}_r' - m_i \left( n_i' \left( \vec{v}_r' \cdot \nabla \right) \vec{v}_r' \right) - m_i \left( \vec{v}_r' \left( \vec{v}_r' \cdot \nabla \right) \vec{v}_r' \right) - m_i \left( n_i' \left( \vec{v}_r' \cdot \nabla \right) \vec{v}_r' \right)
\]

respectively, with \( \vec{\Gamma}_i^{\text{turb}} = < n_i' \vec{v}_r' > \) the turbulent ion flux density. In principle, the ensemble averages in equations (3)-(7) can be expressed as functions of the regular values of the plasma parameters by using theoretical models assuming the plasma turbulence in the magnetic presheath is caused by some specific plasma instability. This, however, is a very difficult task, not only because the existing models cannot perfectly describe the plasma turbulence in the bounded plasma systems, but also because of the inherent complexity of the plasma turbulence in such systems, which may result from the interplay of several plasma instabilities excited simultaneously. Another important question is the applicability of the ensemble averaging procedure in itself. We assume that the characteristic wavelengths of the turbulent fluctuations are shorter than the characteristic length scale of the magnetic presheath, i.e., \( l_{\text{MPS}} \geq \rho_s = m_i c_s / (e B) \), and the characteristic times are shorter than the characteristic ion transit time in the magnetic presheath, i.e., \( \tau_{\text{MPS}} = l_{\text{MPS}} / c_i \). In such cases we may expect that the ensemble averaging will not eliminate any important information about the macroscopic plasma transport, or significantly distort the physical picture.

We will continue the derivation of our model by using the following assumptions and approximations.

- Only quasi-stationary states will be modelled, so all terms in equations (3)-(7) with explicit time derivatives “\( \partial / \partial t \)” will be dropped. For the turbulent quantities this means that quasi-stationary plasma turbulence will be assumed, in which temporal variations of the turbulent quantities are negligible on the macroscopic time scale.
• The magnetic presheath is macroscopically stable, so that only spatially monotonic (i.e., uniform) or spatially non-oscillatory stationary solutions are possible.

• The turbulent plasma transport is mostly caused by $\vec{E} \times \vec{B}$ convection due to the fluctuating electrostatic potential, so that in equation (7) all terms with $\vec{B}'$ will be neglected.

• The last three terms in equation (7) will be replaced with the phenomenological term $-m_i(\vec{v}' \cdot \nabla)\tilde{\Gamma}_{i\text{ turb}}$, which describes the momentum source due to the turbulent ion flux density.

Assuming Boltzmann equilibrium for the electrons and quasi-neutrality for the magnetic presheath, the ion density is given by

$$n_i = n_e \equiv n = n_\infty \exp\left(\frac{e\Phi}{k_B T_e}\right),$$

where $n_\infty$ is the charged particle density at the magnetic presheath edge and $\Phi$ is the electric potential. Thus, using equation (8), the continuity and the momentum conservation equations for the regular charged particle density $n'$ and the regular ion velocity $\vec{v}'$ in the magnetic presheath can be written as

$$\nabla \cdot (n' \vec{v}' + \tilde{\Gamma}_{i\text{ turb}}) = 0$$

and

$$\left(\left(n' \vec{v}' + \tilde{\Gamma}_{i\text{ turb}}\right) \cdot \nabla\right)\vec{v}' = -c_s^2 \nabla n' + \omega_{Bi} \left(n' \vec{v}' + \tilde{\Gamma}_{i\text{ turb}}\right) \times \vec{b'} - (\vec{v}' \cdot \nabla)\tilde{\Gamma}_{i\text{ turb}},$$

respectively, where $c_s = \sqrt{k_B(T_e + T_i)/m_i}$ is isothermal ion acoustic velocity, $\omega_{Bi} = eB'/m_i$ is ion gyro-frequency, and $\vec{b'} = \vec{B}'/B'$ is unit vector in the direction of the regular magnetic field.

The turbulent ion flux density $\tilde{\Gamma}_{i\text{ turb}}$ can be written as a sum of the conductive, or the diffusion-like term, and the convective term,

$$\tilde{\Gamma}_{i\text{ turb}} = -\tilde{D}_{i\text{ turb}} \cdot \nabla n' + n' \tilde{\vec{v}}_{i\text{ turb}} \cdot \nabla n'_\text{MPSE},$$

where $\tilde{D}_{i\text{ turb}}$ is the turbulent diffusion tensor and $\tilde{\vec{v}}_{i\text{ turb}}$ is the turbulent pinch velocity, which are non-linear functions of various plasma parameters and magnetic field. In our calculations we neglected the pinch term because we could not justify its relevance to the magnetic presheath and we could not find an appropriate theoretical model describing the dependence of the turbulent pinch velocity on the plasma parameters and the magnetic field. On the other hand, the assumption about the diffusion-like turbulent transport in the magnetic presheath could be justified, since, from the macroscopic viewpoint, the motion of the charged particles in the fluctuating electric field is similar to the random motion due to the particle collisions, which is a microscopic cause of the classical diffusion transport.

Equations (9)-(11) can be used for studying magnetic presheaths in various geometries (e.g., planar, cylindrical, spherical, etc.). The boundary conditions for these equations specify the regular charged particle density, $n'_\text{MPSE}$, its gradient, $\nabla n'_\text{MPSE}$, and the regular ion fluid velocity, $\vec{v}'_\text{MPSE}$, at the magnetic presheath edge. The gradient of the charged particle density at the magnetic presheath edge, $\nabla n'_\text{MPSE}$, which, according to equation (8), is proportional to the presheath electric field, will be zero, if the presheath electric field is infinitesimal on the
magnetic presheath scale. In that case, the ion fluid velocity at the magnetic presheath edge \( \vec{v}_{\text{MPSE}} \) is parallel to the magnetic field \( \vec{B} \).

In a planar magnetic presheath, i.e., in a semi-infinite plasma in front of an infinite plane surface (figure 1), all plasma parameters depend only on a spatial coordinate perpendicular to that surface, so that the set of non-linear partial differential equations (9)-(10) can be reduced to a set of non-linear ordinary differential equations. If the magnetic field vector lies in the \( x-z \) plane, i.e., \( \vec{B} = \vec{B}_s (\cos \alpha, 0, \sin \alpha) \), the following equations are obtained:

\[
\frac{d}{dz} \left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) = 0, \tag{12}
\]

\[
\left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) \frac{d v'_{z}}{dz} = \omega_{z} \left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) - v'_{z} \frac{d \Gamma_{i,z}^{\text{turb}}}{dz}, \tag{13}
\]

\[
\left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) \frac{d v'_{y}}{dz} = \omega_{y} \left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) - \omega_{z} \left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) - v'_{z} \frac{d \Gamma_{i,y}^{\text{turb}}}{dz}, \tag{14}
\]

\[
\left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} - n'_{z} c_{s}^2 \right) \frac{d v'_{x}}{dz} = -\omega_{x} \left( n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \right) - v'_{z} \frac{d \Gamma_{i,x}^{\text{turb}}}{dz}, \tag{15}
\]

where \( \omega_{x} = \omega_{B_i} \cos \alpha \) and \( \omega_{z} = \omega_{B_i} \sin \alpha \). The solutions are formally defined for \( z \in [-\infty, 0] \).

At the magnetic presheath edge, i.e., for \( z \to -\infty \), the boundary conditions for the regular charged particle density and its spatial derivative are \( \lim_{z \to -\infty} n'_{z} = n'_{\infty} \) and \( \lim_{z \to -\infty} (dn'/dz) = 0 \) respectively. The regular ion fluid velocity at the magnetic presheath edge \( v'_{z} \) is parallel to the magnetic field \( \vec{B} \), so that \( \lim_{z \to -\infty} v'_{x} = v'_{w,z} \cos \alpha \), \( \lim_{z \to -\infty} v'_{y} = 0 \), and \( \lim_{z \to -\infty} v'_{z} = v'_{w,z} = v'_{\infty} \sin \alpha \).

The electrostatic sheath edge at \( |z_{\text{SE}}| \geq 0 \) is defined by the singularity condition

\[
n'_{z} v'_{z,\text{SE}} + \Gamma_{i,z,\text{SE}}^{\text{turb}} - \frac{n'_{\infty} c_{s}^2}{v'_{z,\text{SE}}} = 0. \tag{16}
\]

Integration of equation (12) yields

\[
\Gamma_{i,z} = n'_{z} v'_{z} + \Gamma_{i,z}^{\text{turb}} \tag{17}
\]

where the integration constant \( \Gamma_{\infty,z} \) is perpendicular to the wall total ion flux density at the magnetic presheath edge, which is conserved in the magnetic presheath. Using this result in equation (16), the regular ion fluid velocity and the total ion flux density at the sheath edge, which are perpendicular to the wall, can be written as

\[
v'_{z,\text{SE}} = \frac{n'_{\infty} c_{s}^2}{\Gamma_{\infty,z}} = c_{s} \sqrt{1 + \left( \frac{\Gamma_{i,z,\text{SE}}^{\text{turb}}}{n'_{\infty} c_{s}^2} \right)^2 - \frac{\Gamma_{i,z,\text{SE}}^{\text{turb}}}{2 n'_{\infty} c_{s}^2}} \tag{18}
\]

and

\[
\Gamma_{i,z,\text{SE}} = \Gamma_{\infty,z} = n'_{\infty} c_{s} \sqrt{1 + \left( \frac{\Gamma_{i,z,\text{SE}}^{\text{turb}}}{2 n'_{\infty} c_{s}^2} \right)^2 + \frac{\Gamma_{i,z,\text{SE}}^{\text{turb}}}{2}}. \tag{19}
\]
respectively. Equations (18) and (19) are fluid approximations of the Bohm criterion in a turbulent plasma in a magnetic field. Asymptotic analysis of the magnetic presheath edge with the linearised planar magnetic presheath equations yields the following local criterion for $v_{m,z}^r$, which must be satisfied in order to obtain spatially non-oscillatory (monotonic) solutions for $n^r$ and $\bar{v}^r$:

$$c_s \sin \alpha \leq v_{m,z}^r \leq c_s.$$  \hspace{1cm} (20)

Thus, the following relation can be written for the ion flux density perpendicular to the wall, $\Gamma_{i,z}$:

$$\Gamma_{i,z} \geq n_{\text{MPSE}}^r c_s \sin \alpha + \Gamma_{i,z, \text{MPSE}}^\text{turb},$$  \hspace{1cm} (21)

which is a generalisation of the Bohm-Chodura-Riemann criterion for a turbulent plasma. The practical importance of relation (21) is that it can be implemented in its marginal form, i.e., with the equality sign, in the boundary conditions of the fluid transport codes mentioned in Section 1, if there is only one type of positive ions in the boundary plasma.

3 SOLUTIONS OF THE PLANAR MAGNETIC PRESHEATH EQUATIONS

Equations (12)-(15) can be re-written in dimensionless form by introducing the following dimensionless quantities:

$$\delta = \tan \alpha = \frac{\omega_c}{\omega_x}, \quad Z = \frac{\omega_c}{c_s} \frac{\cos \alpha}{\rho_s} z, \quad N = \frac{n^r}{n_{\infty}^r} = \exp(-\chi), \quad \chi = -\frac{e\Phi}{k_BT_e}, \quad \bar{\nu} = \frac{\bar{v}^r}{c_s}, \quad \bar{G} = \frac{\Gamma_i^t}{n_{\infty}^r c_s}, \quad \bar{G}' = \frac{\Gamma_i^{\text{turb}}}{n_{\infty}^r c_s}, \quad d_{\beta, z} = \frac{\omega_c D_{\beta, z}^{\text{turb}}}{c_s^2}.$$  \hspace{1cm} (22)

for $\beta = x, y, z$. After integrating equation (12) and using the dimensionless quantities (22), the planar magnetic presheath equations can be written as:

$$N V_z - d_{zz} N^r = G_{m,z},$$  \hspace{1cm} (23)

$$\left(N V_z - d_{zz} N^r \right) V_x' - \delta \left(N V_y - d_{yz} N^r \right) - V_x d_{x,z} N^r = 0,$$  \hspace{1cm} (24)

$$\left(N V_z - d_{zz} N^r \right) V_y' + \delta \left(N V_x - d_{xz} N^r \right) - \left(N V_z - d_{zz} N^r \right) - V_y d_{y,z} N^r = 0,$$  \hspace{1cm} (25)

$$\left(N V_z - d_{zz} N^r \right) \frac{N}{V_z} V_x' + \left(N V_y - d_{yz} N^r \right) - \left(V_z - \frac{1}{V_z} \right) d_{zz} N^r = 0,$$  \hspace{1cm} (26)

where the prime indicates differentiation with respect to $Z$ and $G_{m,z} = V_{m,z} - d_{zz} N_{m}^r$ is perpendicular to the wall dimensionless total ion flux density at the magnetic presheath edge.

We solved equations (23)-(26) for $Z \in [Z_{\text{MPSE}}, 0]$, where we chose $Z_{\text{MPSE}} = -10$. The analytical solutions of the asymptotic analysis of the magnetic presheath edge were used to calculate the boundary conditions at $Z_{\text{MPSE}}$, i.e., $N(Z_{\text{MPSE}})$, $N'(Z_{\text{MPSE}})$, and $\bar{V}(Z_{\text{MPSE}})$. For the dimensionless turbulent diffusion coefficients, we used the following analytical approximations:

$$d_{xz} \approx \frac{\Delta n}{n^r} \left(1 - F_i \right) \frac{1}{\left(1 + \delta^2 \right)^{3/2}}, \quad d_{yz} \approx \frac{\Delta n}{n^r} \frac{1}{1 + \delta^2}, \quad d_{zz} \approx \frac{\Delta n}{n^r} \frac{1 + F_i \delta^2}{\left(1 + \delta^2 \right)^{3/2}}.$$  \hspace{1cm} (27)
where $\Delta n/n' \equiv r_{nn}/\Delta$ is the plasma density fluctuation level and $F_{c} - \omega_{Bi}\tau_{d} \geq 1$ can be interpreted as a measure of the anisotropy of the turbulent diffusion. In our numerical calculations we used all combinations of the following values of the free input parameters: $\Delta n/n' = 10^{-2}$ and $\Delta n/n' = 10^{-3}$, $F_{c} = 1$ and $F_{c} = 100$, $\delta = \tan\alpha = 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5, 10$, assuming that these forty combinations can represent the majority of experimentally relevant cases. Calculated plasma parameters at the sheath edge are presented in figures 2–6.

Figure 1: Geometry of the planar magnetic presheath model ($\vec{B}$ is in the x-z plane)

Figure 2: $N_{SE} = n'_{SE}/n''_{SE}$ vs. $\delta = \tan\alpha$ for various free input parameters

Figure 3: $\chi_{SE} = -e\Phi_{SE}/k_{B}T_{e}$ vs. $\delta = \tan\alpha$ for various free input parameters

Figure 4: $V_{xSE} = v'_{xSE}/c_{s}$ vs. $\delta = \tan\alpha$ for various free input parameters

Figure 5: $V_{ySE} = v'_{ySE}/c_{s}$ vs. $\delta = \tan\alpha$ for various free input parameters

Figure 6: $V_{zSE} = v'_{zSE}/c_{s}$ vs. $\delta = \tan\alpha$ for various free input parameters
For very small grazing angles, i.e., for $\delta \leq 10^{-3}$, or $\alpha \leq 0.06^\circ$, we obtained spatially oscillatory solutions, which means that the magnetic presheath is macroscopically unstable and our quasi-stationary model is not applicable in such cases.

4 CONCLUSIONS

We developed an original fluid model of the magnetic presheath in a turbulent boundary plasma, which self-consistently takes into consideration turbulent transport corrections of the classical fluid transport equations, usually used for modelling of boundary plasmas. Main scientific motivations for this study were the deficiencies of the previous theoretical models to successfully explain many experimental results and a need for improved, more realistic, boundary conditions near solid material walls in contact with the plasma in the fluid transport models of bounded plasma systems and related computer codes, in particular, in the fluid transport codes for tokamak boundary plasma modelling and future fluid transport codes for integrated tokamak modelling.

The most important results of our study for modelling of bounded plasma systems are the following:

- the total ion flux density perpendicular to the wall, which is a sum of the regular and the turbulent ion flux density perpendicular to the wall, is conserved in the planar magnetic presheath (equation (17));
- the fluid approximation of the Bohm criterion for a turbulent plasma in a magnetic field, which includes expressions for perpendicular to the wall components of the regular ion fluid velocity (equation (18)) and the total ion flux density (equation (19)) at the entrance of the electrostatic sheath, is derived;
- the generalised Bohm-Chodura-Riemann criterion for a turbulent plasma, which gives the relation for the total ion flux density perpendicular to the wall (equation (21)), is derived;
- typical values of the plasma parameters at the entrance of the electrostatic sheath are calculated for experimentally relevant free input parameters of the model (figures 2-6).

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