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Modelling of the plasma parameters in the divertor region close to MARFE

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Introduction

The edge density limit is one of the most challenging constraint for the operation of fusion devices and many different physical mechanisms have been theoretically explored in order to explain this phenomenon [1]. One of well known approaches implies a plasma detachment from divertor plate and consequent formation of the X-point MARFE [2]. This happens owing to a thermal instability originated in the increase of the energy loss on ionization and excitation of hydrogen neutrals and impurities released from the divertor plate with decreasing plasma temperature near the target. Stationary states exist only if the plasma density at the separatrix is lower than a critical value [2, 3, 4]. In these studies either the escape of neutrals from the scrape-off layer (SOL) into the confined volume has been neglected [2, 3] or the neutral density at the divertor plate was fixed [4]. Moreover, the sound speed has been taken as the boundary condition for the parallel plasma velocity. However, under the conditions of very strong plasma cooling in the divertor volume a region with supersonic flow can exist near the plate [5]. In the present contribution the divertor detachment is modelled without the limitations imposed previously [2, 3, 4]. It is demonstrated that stationary states exists at any level of the plasma density at the separatrix, but at the detachment the temperature in the divertor becomes so low that neutrals freely escape into the confined volume and that can cause the density limit.

Model

The SOL geometry under consideration is shown in Fig.1. We consider stationary states of quasi-neutral hydrogen plasma. The variation of the plasma density n, parallel velocity V and temperature T, assumed the same for electrons and ions, along magnetic field, direction x, is governed by the following set of transport equations:

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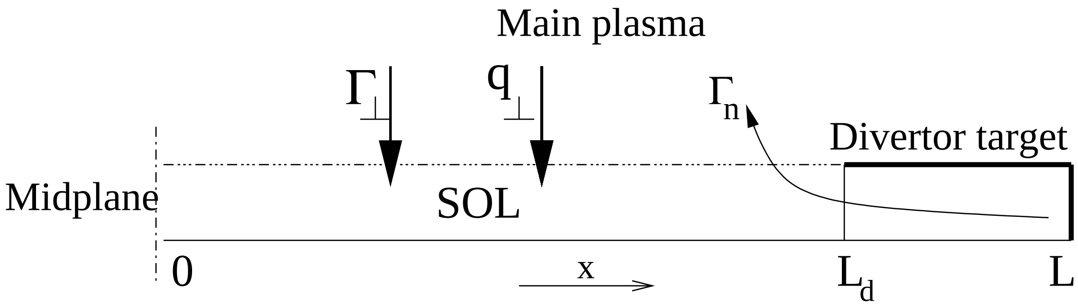

Figure 1: SOL geometry assumed in the model.

$$\frac{d(nV)}{dx} = S_p \tag{1}$$

$$\frac{d(2nT + mnV^2)}{dx} = -mVS_m \tag{2}$$

$$\frac{d}{dx}\left(-\kappa_{\|}\frac{dT}{dx} + 5nVT + \frac{mnV^3}{2}\right) = \frac{q_\perp}{\Delta_s}\theta\left(L_d - x\right) - Q_{loss} \tag{3}$$

Here $S_p = \frac{\Gamma_\perp}{\Delta_s}\theta\left(L_d - x\right) + k_i n n_n - n^2 k_r, S_m = n(n_n k_{cx} + n k_r)$ are the densities of the plasma particle source and momentum sink, $\Gamma_\perp$ and $q_\perp$ the densities of charged particle and heat fluxes into the SOL from the confined plasma due to perpendicular diffusion and heat conduction, Δ_s is the SOL characteristic radial width, m the ion mass, θ the Heaviside step function: $\theta\,(x<0) = 0, \theta\,(x \geq 0) = 1$, k_i, k_r and k_{cx} are the ionization, recombination and charge exchange rate coefficients, $\kappa_{\|}$ is the Spitzer parallel heat conductivity, $Q_{loss} = n n_n k_i E_i + n^2 k_r\left(3T + mv^2/2\right) - n n_n k_{cx}\left(3T/2 + mv^2/2\right)$ the energy loss from charged particles due to interaction with neutrals, $E_i \approx 30eV$; the density of neutral particles recycling from the divertor plate, n_n, is described in a diffusion approximation [5]:

$$\frac{d}{dz}\left(-D_n\frac{dn_n}{dz}\right) = -\frac{n_n V_n}{\Delta_s}\theta\left(L_d - x\right) - k_i n n_n + n^2 k_r \tag{4}$$

Here, $D_n = T/m/n/\left(k_{cx} + k_i\right)$ is the diffusion coefficient of neutrals and the first term in RHS describes the escape of neutrals with their thermal velocity V_n into the confined volume through the separatrix; $z = x\sin\psi$ is the distance from the divertor plate with the pitch angle $\psi = 0.1$ assumed henceforth.

Symmetry boundary conditions are prescribed for equations (1)-(4) at the midplane, $x = 0$:

$$dn/dx = dT/dx = dn_n/dz = V = 0 \tag{5}$$

At the divertor target plate, $x = L$, the plasma velocity is determined by the Bohm criterion [6]:

$$M \equiv V/c_s \geq 1, \tag{6}$$

where $c_s = \sqrt{2T/m}$ is the ion sound velocity; the heat flux continuity with a prescribed heat transmission factor γ has to be satisfied:

$$-\kappa_{\|} dT/dx + 5nVT + mnV^3/2 = \gamma nVT \tag{7}$$

and the influx of neutrals is equal to the outflow of ions:

$$-D_n dn_n/dz = nV \sin\psi \tag{8}$$

Accounting for supersonic flow

As it was mentioned above, normally the exact equality is assumed in the condition (6). However, as it was demonstrated in Ref. [5, 6], under the conditions of very strong plasma cooling due to interaction with neutrals, a region with supersonic flow can exist near the plate. The approach in Ref. [5] to treat such a situation was based on an integration of Eq.(2) as a differential one. Here we apply another method, being numerically less heavy. From Eqs.(1) and (2) integrated from the position x to the target, one can get:

$$\frac{M(x)}{1+M^2(x)} = \Phi(x) \equiv \sqrt{\frac{T(x)}{T_t}} \times \frac{M_t - G_p(x)}{1+M_t^2+G_m(x)} \tag{9}$$

where the subscript t denotes the parameters at the target plate, $x = L$, and $G_p = \int_x^L \frac{S_p}{n_t c_s^t} dx$, $G_m = \int_x^L \frac{VS_m}{n_t (c_s^t)^2} dx$. With some initial approximations for $n(x)$, $T(x)$, $V(x)$ and $n_n(x)$, G_p and G_m are known functions of x. In a standard situation with relatively high temperature at the plate and weak temperature gradient, $\sqrt{\frac{T(x)}{T_t}}$ increases with decreasing x not so fast as the second factor diminishes. Thus, the maximum value of Φ is equal to $M_t/\left(1+M_t^2\right)$ and is approached at $x = L$. This value should be equal to the maximum value of the LHS, 1/2, approached at M=1. Therefore, $M_t = 1$ is the only possibility. If, however, the temperature and, thus, $\kappa_{\|} \sim T^{2.5}$ are very low near the plate, the temperature gradient is here large and $\sqrt{\frac{T(x)}{T_t}}$ varies faster than the second factor in Φ. Therefore, $\Phi_{\max}$ is larger than $M_t/\left(1+M_t^2\right)$ and is reached at some $x_* < L$, which can be easily found numerically. The new approximation for M_t is determined from the requirement $\Phi_{\max} = 1/2$, the maximum value of the LHS, and for the total profile of the Max number - by solving Eq.(9) as a quadratic equation.

Results of calculations

For calculations the following geometrical characteristics $L = 50m$, $L_d = 5m$ and $\Delta_s = 0.05m$ have been assumed. The charged particle flux through separatrix into SOL, $\Gamma_\perp$, has been chosen to reproduce a required value of the plasma density at the midplane, $n_m \equiv n(0)$. Figure 2a shows the n_m-dependence of the plasma temperature near the plate, T_t, for different $q_\perp$. One can see

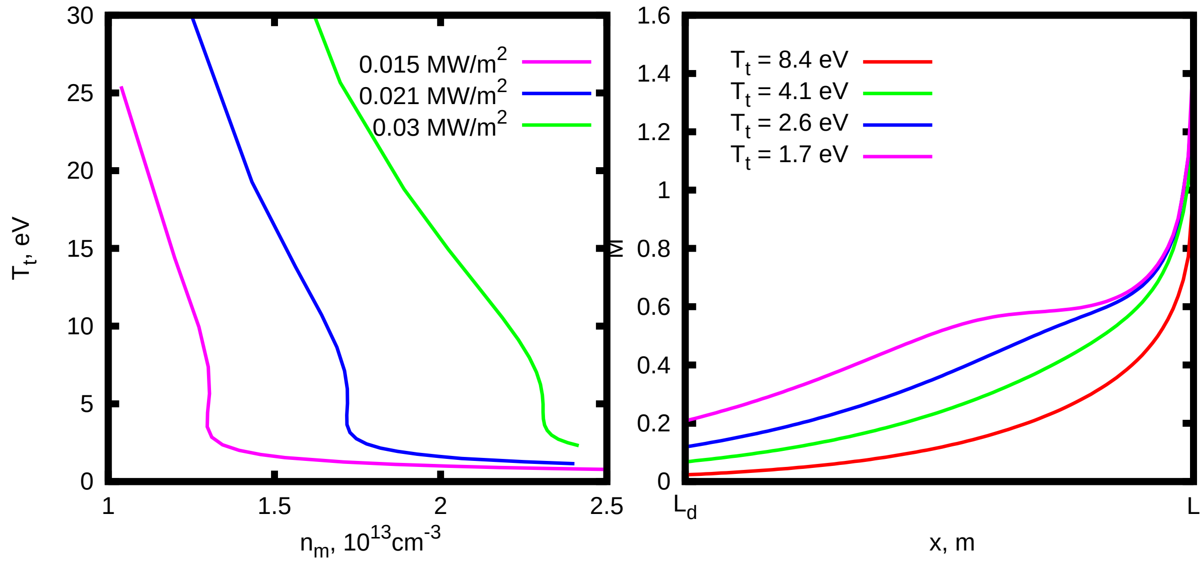

Figure 2: Temperature at the target versus the midplane density at different heat flux to SOL (a) and Max number profiles near the target in the states close to the detachment (b).

that stationary states exists for any n_m, in contradiction to Ref.[2, 3] and in agreement with Ref.[4]. However, T_t drops very fast when n_m exceeds some critical level; even a bifurcation can take place if $q_\perp$ is low enough. These states are characterized by a supersonic flow to the divertor target as it is demonstrated in Fig.2b. At a very low temperature in the divertor leg, neutrals freely escape into the confined volume and this, probably, finally causes the density limit.

Acknowledgments

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