A model for modifications of local plasma parameters induced by impurity injection

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Introduction. For diverse purposes non-hydrogen impurities are deliberately injected into hot plasma of fusion devices. In particular, it is done to investigate and modify transport properties, to cool down the edge region through enhanced radiation losses and weaken plasma-wall interactions, to redeposit new particles of the wall material onto places eroded too intensively, to soften harmful consequences of disruptions caused by MHD instabilities. Normally impurities are injected through small openings in the machine wall and the local impurity density may significantly exceed the plasma density before injection. Under such conditions one has to expect a significant modification of plasma parameters through diverse physical mechanisms, e.g., cooling of electrons due to excitation and radiation, production of electrons by impurity ionization, etc. These processes may affect very noticeably both impurity penetration and global plasma behavior. In this contribution we propose an analytical model describing local plasma parameters in such a cloud of injected impurities.

Basic equations. At a given radial position the density of impurity neutrals n_0 is assumed to be constant in the region $|l| \leq l_0$ in the direction l of the magnetic field and is zero beyond this. Through ionization of neutrals singly charged impurity ions are generated. Their density n_I and flux along the magnetic field, Γ_I, are governed by particle and momentum balance equations:

$$d\Gamma_I/dl = k_{ion}^0 n_0 n_e - \nu_{loss} n_I \quad (1)$$

$$d\left(m_I \Gamma_I^2/n_I + n_I T_I\right)/dl = -\left(\nu_{loss} m_I + \alpha_{iI} n_i\right)\Gamma_I + eE_{\parallel} n_I \quad (2)$$

where n_e is the electron density equal, due to plasma quasi-neutrality, to the sum of n_I and the density n_i of the main ions, $n_e = n_i + n_I$; $\nu_{loss} = \nu_\perp + k_{ion}^1 n_e$ characterizes impurity ion losses with perpendicular transport and ionization into higher charged state, $k_{ion}^{0,1}$ are the ionization rate coefficients, m_I and T_I are the mass and temperature of impurity ions, α_{iI} is the friction coefficient due to coulomb collisions between impurities and main ions [1], e is the elementary electric charge. The parallel electric field is determined from the force balance for "massless" electrons,

$$en_eE_{\|} = -d\left(n_eT_e\right)/dl$$

with T_e being the electron temperature.

In the region where impurity neutrals are present the former source term in the RHS of Eq.(1) significantly exceeds the latter sink term. Thus the impurity ions produced here are lost predominantly due to flow along the magnetic field. By integrating Eq.(1) over the neutral cloud region, $|l| \leq l_0$, one assess the ion outflow density:

$$\Gamma_I^c \approx k_{ion}^0 n_0 n_e^c l_0 = k_{ion}^0 n_0 \left(n_i^c + n_I^c\right) l_0 \tag{3}$$

Here and henceforce the values marked with the subscript c denote the characteristic ones in the impurity cloud. The density of the main ions here, n_i^c, is related through the pressure balance to the plasma density far from the cloud, n_∞:

$$n_i^c\left(T_e^c + T_i^c\right) = n_\infty\left(T_e{}^\infty + T_i{}^\infty\right) \tag{4}$$

By integrating Eqs.(1) and (2) over the half extension of the impurity cloud, $0 \leq l \leq l_c$, we get:

$$k_{ion}^0 n_0\left(n_i^c + n_I^c\right) l_0 = \nu_{loss} n_I^c l_c \tag{5}$$

$$-n_I^c T_I^c = T_e^c\left[n_I^c - n_i^c \ln\left(1 + n_I^c/n_i^c\right)\right] - \left(\nu_{loss} m_I + \alpha_{iI} n_i^c\right)\Gamma_I^c l_c \tag{6}$$

Equations(3), (5) and (6), allow to deduce the following algebraic equation for the characteristic density of impurity ions in the cloud, n_I^c:

$$k_{ion}^0 l_0 n_0 = \frac{n_I^c}{n_i^c + n_I^c}\sqrt{\frac{T_I^c + T_e^c\left[1 - n_i^c/n_I^c \cdot \ln\left(1 + n_I^c/n_i^c\right)\right]}{m_I + \alpha_{iI} n_i^c/\left[\nu_\perp + k_{ion}^1\left(n_i^c + n_I^c\right)\right]}} \tag{7}$$

In order to asses the temperatures of the plasma components in the cloud, T_e^c, T_i^c and T_I^c, the heat balances have to be taken into account. For electrons the main loss channels are due to ionization and excitation of neutral and charged impurities and this balance is as follows:

$$q_e^c = \left(n_0 k_{ion}^0 E_a l_0 + n_I^c L_I l_c\right) n_e^c \tag{8}$$

where q_e^c is the heat influx into the cloud with electron heat conduction along the magnetic field, E_a the energy lost by ionization of one impurity neutral, and L_I the cooling rate of impurity ions. In the case of the main ions the influx with their parallel heat conduction, q_i^c, is transferred to electrons and impurity ions by coulomb collisions:

$$q_i^c = \left[\beta_{ei} n_e^c \left(T_i^c - T_e^c\right) + \beta_{iI} n_I^c \left(T_i^c - T_I^c\right)\right] n_i^c l_c \tag{9}$$

with β being the heat transfer coefficients [1]. Impurity ions assimilate the temperature T_I^0 of neutrals and participate through coulomb collisions in heat exchange with the main ions:

$$k_{ion}^0 n_0 T_I^0 n_e^c l_0 / \left(n_I^c l_c\right) + \beta_{iI} n_i^c \left(T_i^c - T_I^c\right) + \beta_{eI} n_e^c \left(T_e^c - T_I^c\right) = \nu_{loss} T_I^c \tag{10}$$

Finally, one needs to asses the heat fluxes transported by the main plasma components into the impurity cloud. For this the heat transfer beyond the cloud has to be examined. Due to losses to the cloud a field line is cooled down and a perpendicular heat transfer to it is generated. In a steady state this interplay is described by a heat balance equation:

$$d\left(-\kappa_{||}^{e,i} dT_{e,i}/dl\right)/dl = \nu_{\perp}^{e,i}\left(T_{e,i}^{\infty} - T_{e,i}\right) n \tag{11}$$

where $\kappa_{||}^k = A_k T_k^{2.5}$ is the parallel heat conduction and $\nu_{\perp}^k$ characterizes the intensity of perpendicular heat transfer. The plasma density outside the impurity cloud is controlled by the pressure balance, see Eq.(4), where we assume that T_e and T_i are linearly interrelated. For $q_{e,i} = 0$ and $T_{e,i} = T_{e,i}^{\infty}$ far from the cloud, one can get after integration:

$$q_{e,i}^c = 2\sqrt{\frac{A_{e,i}\nu_{\perp}^{e,i} n_{\infty}\left(T_e^{\infty} + T_i^{\infty}\right)\left(T_{e,i}^{\infty}\right)^{3.5}}{1 + \left(T_{i,e}^{\infty} - T_{i,e}^{c}\right)/\left(T_{e,i}^{\infty} - T_{e,i}^{c}\right)} f_{e,i}} \tag{12}$$

with $f_{e,i} = \left[(1+\tau)\left(x^5/5 - \tau x^3/3 + \tau^2 x - |\tau|^{2.5}\varphi\right) - x^7/7\right]_{\sqrt{T_{e,i}^c/T_{e,i}^{\infty}}}^{1}$,

$\tau = \left(T_{i,e}^{c} - T_{e,i}^{c} T_{i,e}^{\infty}/T_{e,i}^{\infty}\right)/\left(T_e^{\infty} - T_e^{c} + T_i^{\infty} - T_i^{c}\right)$,

$\varphi(x, \tau > 0) = \arctan\left(x/\sqrt{\tau}\right)$ and $\varphi(x, \tau < 0) = \ln\sqrt{\left(x + \sqrt{-\tau}\right)/\left(x - \sqrt{-\tau}\right)}$.

It is interesting to note that the RHS of Eq.(7) increases with rising n_I^c but does not exceed its maximum value $\sqrt{\left(T_I^c + T_e^c\right)/m_I}$, i.e., the ion sound velocity of impurity ions. This does not, however, mean that there is no solution to Eq.(7) for a high enough impurity neutral density n_0: with increasing n_I^c and n_e^c the energy losses from impurity cloud grow up and the electron temperature T_e^c drops down, see Eq.(8). As a result the ionization rate coefficient of impurity neutrals $k_{ion}^0 \sim \sqrt{T_e}\exp\left(-I_0/T_e\right)$, where I_0 is the ionization energy, decreases, the LHS of Eq.(7) diminishes and that ensures a solution of Eq.(7). A similar situation takes place by the transition to a strong recycling regime on divertor target plates [2].

Results of calculations. As an example of applications we show here the results of calculations done for the conditions of experiments with puffing of methane into the tokamak TEXTOR

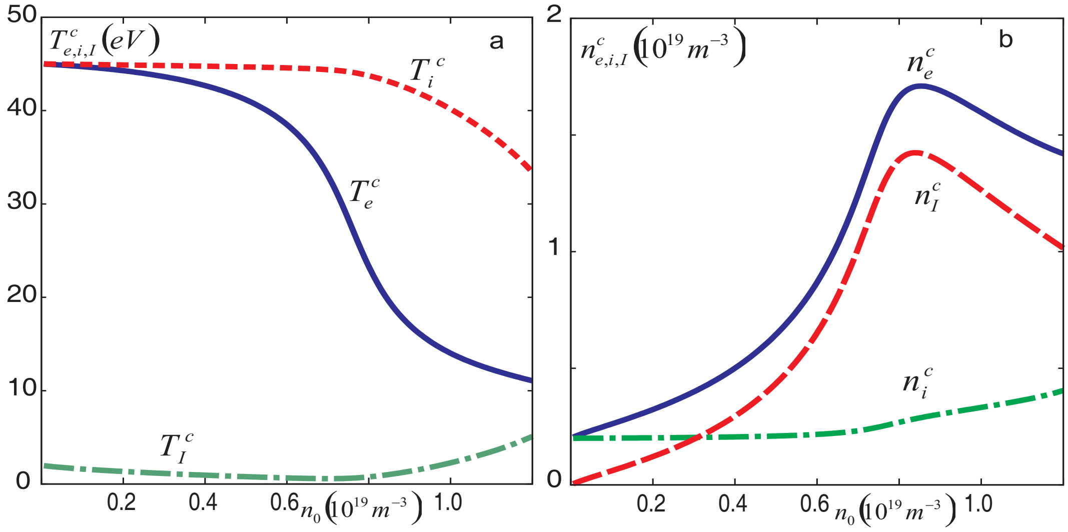

Figure 1: Temperatures (a) and densities (b) of plasma components in the impurity cloud vs the density of impurity neutrals.

[3]. The plasma parameters assumed far away from the injection position correspond those measured before impurity injection: $n_\infty = 2 \cdot 10^{18} m^{-3}$, $T_e^\infty = T_i^\infty = 45eV$. In this analytical study carbon atoms in the cloud with $l_0 = 1.75cm$ and temperature $T_I^0 = 300^0K$ have been considered instead of methane neutrals. Figure 1a demonstrates the n_0-dependences of the temperatures of plasma components in the cloud. One can see that for n_0 below a level of $1.5 \cdot 10^{19} m^3$, corresponding to a total influx of neutrals of $0.5 - 1 \cdot 10^{19} s^{-1}$, the electron and main ion temperatures are close to $T_{e,i}^\infty$. For higher n_0 a significant decrease of T_e^c takes place due to losses on ionization and excitation of impurities. When T_e^c is reduced to a half of T_e^∞ the heat exchange due to coulomb collisions leads to a noticeable reduction of the main ion temperature. Due to collisions the temperature of impurity ions exceeds significantly that of impurity neutrals but is noticeably smaller the temperature of the main ions. In Fig.1b the densities of electrons, main and impurity ions in the cloud are shown. One can see that n_e^c can exceed n_e^∞ by a factor of 8. Both the electron source due to ionization of impurity neutrals and the rise of the main ion density due to the pressure equilibration contribute to this, but the former process is more important.

References

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