Model for plasma distortion by laser-induced ablation spectroscopy

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Introduction

Laser-based diagnostics have been proposed to measure and monitor *in situ* the composition of layers on plasma facing components (PFC) [1,2]. By laser-induced ablation spectroscopy (LIAS) a short, in *ns*-range, intense laser pulse is directed at a PFC *during* plasma discharge. Particles released into the plasma are excited and ionized by electrons. By measuring the intensity of impurity line radiation, one can assess the amount of particles emitted and judge about the wall composition. To interpret LIAS measurements local plasma parameters, especially the electron density and temperature, have to be known. Normally the parameters, measured somewhere at the plasma edge before the LIAS application, are used. However, processes with particles released from the wall may lead to significant disturbances in the plasma: the energy loss on the particle excitation leads to reduction of the electron temperature, the delivery of new electrons by the ionization - to the increase of their density. An assessment of such perturbations is of importance for quantitative interpretation of measurements.

Basic equations

Density of impurity neutrals. First consider the spreading of impurity neutral particles released by the laser pulse from the wall. The penetration depth of these species is usually significantly smaller than the radius of the wall element in question. Therefore, it is convenient to use an orthogonal coordinate system with the axes x directed from the injection spot towards the plasma core, y and l being tangential to the magnetic surface and oriented perpendicular and parallel to the field lines, respectively. The velocity distribution of neutral particles is identical in the directions y and l and the distribution function can be characterized by its dependence on the velocity components V_x and V_ρ in a cylindrical reference system with axes x and $\rho = \sqrt{y^2 + l^2}$. The density Δn of neutrals with the velocity components in the ranges ΔV_x and ΔV_ρ is determined from the continuity equation:

$$\partial_t \Delta n + V_x \partial_x \Delta n + \left(V_\rho / \rho\right) \times \partial_\rho (\rho \Delta n) = -k_{ion}^0 n_e \Delta n \quad (1)$$

where k_{ion}^0 is the ionization rate coefficient and n_e the density of electrons. An approximate solution of equation (1) is searched for in the form:

$$\Delta n(t,x,\rho) = \eta(t,x)\ \times e^{-\rho^2/\lambda^2(t,x)} \quad (2)$$

This form mimics the fact that on each magnetic surface the density of primary particles is localized in some vicinity of the ejection position and approaches to zero far from this due to ionization. Introduce new dependent variables:

$$N(t,x) = \int_0^\infty \Delta n 2\pi\rho d\rho = \pi\lambda^2\eta, \qquad \Lambda(t,x) = \int_0^\infty \Delta n 2\pi\rho^2 d\rho = \frac{\sqrt{\pi}}{2}\lambda N \quad (3)$$

Equations for $N(t,x)$ and $\Lambda(t,x)$ follow from the integration of equation (1) with respect to ρ, with the weights 1 and ρ, respectively, and with Δn substituted in the form (2):

$$\partial_t N + V_x\partial_x N = -k_{ion}^0 n_e N, \partial_t\Lambda + V_x\partial_x\Lambda = V_\varrho N - k_{ion}^0 n_e\Lambda \quad (4)$$

The former of equations (4) can be derived independently on the assumption about the ρ-dependence of the solution and describes the evolution with t and r of the total amount on the magnetic surface, per unit length in the direction r, of neutrals with the velocity components V_x and V_ρ. With known $N(t,x)$ and $\Lambda(t,x)$ one can obtain the original parameters characterizing the local density of neutrals, by using the relations following from the definitions (3):

$$\eta(t,x) = N^3/\Lambda^3, \qquad \lambda(t,x) = 2\Lambda/\left(\sqrt{\pi}N\right) \quad (5)$$

The initial and boundary conditions for equations (4) at $x = 0$ take into account that by LIAS neutral particles are injected very locally and brusquely into the plasma, during a time small compared to the time step τ in our calculations. The latter has to be, however, chosen small enough so that the distance passed by particles during τ remains much smaller than their free path length before ionization. In such a case the actual initial radial profile of Δn is of no importance. We assume that at $t = 0$ the ablated particles fill homogeneously the layer $0 \le x \le h_1$, where h_1 is the first step of the x-grid; along the wall the source region is localized in the irradiation spot with the radius ρ_0. This results in the following initial conditions for the variables N and Λ:

$$N(0 \le x \le h_1) = \frac{N_{tot}}{h_1} f\left(V_\rho, V_x\right)\Delta V_x \Delta V_\rho;\ \Lambda(0 \le x \le h_1) = \frac{\sqrt{\pi}}{2}\rho_0 N$$

where N_{tot} is the total number of injected particles. Measurements [3] can be firmly described by assuming a Maxwellian distribution function at a temperature T_0 with respect to V_ρ and a one-side Maxwellian one for V_x shifted by a drift velocity V_m:

$$f\left(V_\rho, V_x\right) = \frac{M}{T_0} V_\rho e^{-mV_\rho^2/2T_0} \times \sqrt{\frac{2M}{\pi T_0}} \frac{e^{-M(V_x - V_m)^2/2T_0}}{1 + erf\left(\sqrt{MV_m^2/2T_0}\right)} \quad (6)$$

By integrating equations (4) numerically and finding $\eta(t,x)$ and $\lambda(t,x)$ according to (5) for all V_x and V_ρ, the profile of the total density of neutrals is defined analogously to (2):

$$n_0(t,x) = \eta_0(t,x)\ \times e^{-\rho^2/\lambda_0^2(t,x)}$$

with $\eta_0 = \sum_{V_x,V_\rho} \eta,\ \lambda_0 = \sqrt{N_0/\pi\eta_0}$ and $N_0 = \sqrt{\sum_{V_x,V_\rho} N}$.

Densities of charged species. The characteristic time for processes in questions, of several tens of μs, is too short for a noticeable reaction of the main ions. Therefore their density n_i is considered as unperturbed. The electron density n_e may be, however, significantly distorted by the generation of new electrons through the ionization of impurity neutrals; due to the plasma quasi-neutrality one has $n_e = n_i + n_1$. Here n_1 is the density of singly charged impurity ions assessed by solving fluid transport equations:

$$\partial_t n_1 + \partial_x \Gamma_{1x} + \partial_l \Gamma_{1l} = k_{ion}^0 n_e n_0 - k_{ion}^1 n_e n_1 \quad (7)$$

$$\partial_t \Gamma_1 + \partial_x(\Gamma_{1x}\Gamma_{1l}/n_1) + \partial_l(\Gamma_{1l}\Gamma_{1l}/n_1 + n_1 T_1/m) = -k_{ion}^1 n_e \Gamma_1 + e n_1 E_l/m \quad (8)$$

where $\Gamma_{1x,l}$ are the corresponding components of the ion flux density and the parallel electric field E_l is determined from the electron force balance, $e n_e E_l = -\partial_l(n_e T_e)$. In this study we apply the "shell" approximation, see Refs. [4,5], to find the profiles of n_1 and Γ_1 along the magnetic field, by solving equations (7) and (8).

Temperatures of plasma components. Due to the rapid decay of the plasma distortion induced by the outburst of impurity neutrals the temperatures of the main and impurity ions do not change noticeably. The electron temperature T_e is, however, perturbed much stronger, especially in the cloud of impurity neutrals and singly charged ions. To take this into account we use a "two zone" approximation, see Ref. [5], where the whole magnetic surface is separated in two parts: (i) the "cold zone" where the electron energy is directly lost on the excitation and ionization of impurity species and (ii) the "hot zone" which is cooled down by the parallel heat conduction to the impurity cloud. The temperatures of electrons in both zones, $T_{ec}(t,x)$ and $T_{eh}(t,x)$, respectively, are governed by the heat balance equations deduced by integrating 3-D heat transport equations over the zones, see Ref. [5]:

$$1.5\partial_t(S_c n_{ec} T_{ec}) + S_c \partial_x q_{ex} = Q_{hc} - W_{loss},\ 1.5\partial_t(S_h n_{eh} T_{eh}) + S_h \partial_x q_{eh} = -Q_{hc} \quad (9)$$

Here $S_c = \pi\lambda_0 l_1$ and $S_h = S_s - S_c$ are the areas of the zones, with S_s being the total area of the magnetic surface; $n_{ec} = n_i + n_1$ and $n_{eh} = n_i$ are the electron densities in the zones; the parallel electron heat conduction was assumed in the form $\kappa_l^e = A_e T_e^{2.5}$ and the heat flux transported from the hot zone to the cold one was assessed according to Ref. [5]: $Q_{hc} =$

$16/7 \times A_e\left(T_{eh}^{3.5} - T_{ec}^{3.5}\right)S_c/S_s$; the energy losses due to inelastic collisions with impurity species

$$W_{loss} = n_{ec}\sum_{j=0,1} N_j \left[L_c^j(T_{ec}) + k_{ion}^j(T_{ec})E_{ion}^j\right]$$

where $N_j(t,x)$ are the total numbers of neutral (j=0) and singly charged (j=1) impurity species on the magnetic surface per unit length in the direction x, provided by the "shell" model for impurity spreading; L_c^j and E_{ion}^j are the cooling rate and the ionization energy of the species, respectively.

Results of calculations. Calculations have been performed for the conditions of LIAS in Ohmic TEXTOR discharges [2] with a line-averaged plasma density of $3 \times 10^{19} m^{-3}$ and the electron temperature of $1 keV$ and $30 eV$ at the plasma axis and last closed flux surface defined by the limiter, respectively. The laser radiation has been concentrated on a wall spot with fine grain graphite bulk material of $0.15 cm^2$ area and $\rho_0 \approx 0.22 cm$; typically $N_{tot} \approx 10^{17}$ C atoms were released per pulse. Time of flight measurements are interpreted by the velocity distribution (6) with $T_0 \approx 1.5\ eV$ and $V_m \approx 8.7 km/s$. The results of LIAS are normally quantified by measuring the total radiation emitted by C^+ species with a particular wave length [2]. To calculate this one has to apply a firm collision-radiation model that is out of scope of the present study. In Figure 1 we display the total energy radiated till time t by singly charged carbon ions, W_{rad}, calculated without and with the plasma reaction taken into account. One can see that in the latter case the rise of W_{rad} is significantly delayed but the overall emitted energy is much higher. The delay is explained by the plasma cooling with losses on radiation and ionization of impurity neutrals and significant decrease of the ion excitation rate; the larger cumulative ion radiation - by the increased electron density and growth of the ion cooling rate $L_c^1(T_{ec})$ as the temperature T_{ec} in the cold zone recovers due to the heat transfer from the hot one.

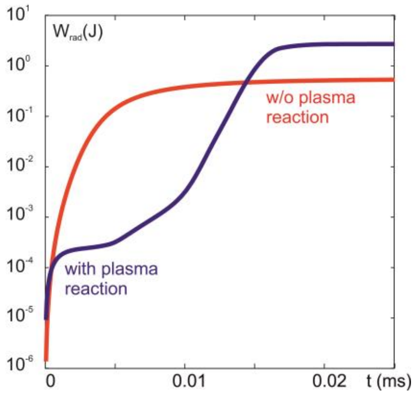

Fig.1. Cumulative energy radiated by C^+- ions vs time.

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