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Modeling of the pellet cloud structure in the presence of ∇B induced drift

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Abstract

Modeling of the pellet ablation cloud evolution with account of the ∇B induced drift motion is performed. The model includes acceleration in the low-field-side direction, Alfven conductivity of the background plasma, compensation of ∇B currents in different parts of the cloud during its propagation along the magnetic field, cloud heating, expansion and ionization and simulation of the pellet ablation rate in a self-consistent manner. The time evolution of density and temperature profiles and the mass deposition after the pellet injection are calculated. The size of neutral part of the cloud, the characteristic values of cloud density and temperature far from the pellet and the fuelling efficiency are in a reasonable agreement with those observed in experiments on ASDEX-Upgrade tokamak.

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1. Introduction

Pellet injection is considered as the most prospective way of refueling future tokamaks and stellarators. The rise of the density after the pellet injection affects both fusion power and confinement regime. The pellet injected into the plasma evaporates rapidly producing a neutral gas around it, which moves together with the pellet with its velocity V_p. The neutral cloud expands mainly spherically, while after the ionization it propagates along the magnetic field lines and drifts towards the low field side (LFS) direction in the self-consistent electric field [1]. This drift is suggested to be responsible for the higher fueling efficiency (which is defined as a ratio of total plasma electrons increment after the pellet injection to the number of atoms in the pellet) for high field side (HFS) injection in comparison with the injection from the LFS [2]. This fact was observed by Lang et al. [3] on the ASDEX-Upgrade, Baylor et al. on DIII-D [4] and confirmed for other tokamaks. Measurements of cloud density, temperature and drift velocity were performed by Müller [5].

Until now a full simulation of cloud pattern with account of $\vec{E} \times \vec{B}$ drifts has been absent. Presented below are the first results of such a simulation obtained by means of LLPD code, which contains drift effects. This code is a modification of LLP code [6], which originally was used for the simulation of pellet ablation in a tokamak. The pellet cloud parameters and the fuelling efficiency computed by the new LLPD code are in a reasonable agreement with that measured on

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ASDEX-Upgrade [3,5]. The obtained results might be used for the optimization of the pellet injection schemes in the future experiments.

2. Model

The present model takes into account all relevant effects, which influence the process of plasma cloud evolution, such as neutral and ionized gas expansion, ionization, magnetic confinement, collision energy transfer, radiation losses. The presence of a self-generated electrostatic field in the cloud and the electrostatic sheath at the cold cloud–hot plasma interface is also taken into account. The particle and energy flux depletion of hot background particles in the shielding cloud due to collision interaction with the cold particles is determined by the stopping length calculations applied to both electrons and ions. The model includes calculation of the energy transport (both convective and conductive) in the direction normal to the magnetic field. For a given set of background plasma and pellet parameters and a magnetic flux surface topology, this approach allows determination of the cloud evolution and the ablation rate history in a self-consistent manner.

In the traditional model, the pellet is shifted from flux tube to flux tube, the latter being defined by the local ionization radius, and kept stationary in a given flux tube for the local residence time given by $\tau_{\mathrm{res}} = 2r_{\mathrm{i}}/V_{\mathrm{p}}$, where r_{i} is the local value of the ionization radius and V_{p} is the pellet velocity.

In the inhomogeneous magnetic field due to cloud polarization the electric field is formed inside the ablation cloud, which causes the drift of the ablating materials in a direction opposite to ∇B. As a result the ablated material after fast mass averaging processes is shifted significantly with respect to the flux surfaces, where the pellet ablation took place. In [1,4] it was demonstrated that this shift was mainly determined by the acceleration of a cloud in the low field side direction and the reduction of the cloud polarization due to the Alfven wave propagation in the ambient plasma along the magnetic field lines.

To define the drift velocity V_{D} towards the LFS direction the following current balance equation integrated along the magnetic field lines was derived with an assumption of almost constant ablation rate (see [1] and references therein)

$$\frac{m_{\mathrm{I}}N}{B}V_{\mathrm{D}}\frac{\partial V_{\mathrm{D}}}{\partial x} = -2\Sigma_{\mathrm{A}}B(V_{\mathrm{D}} - V_{\mathrm{p}}) + 2\frac{\tilde{\alpha}(L_{\mathrm{c}})}{BR}\int_{-\infty}^{+\infty} n_{\mathrm{I}}(T_{\mathrm{e}} + T_{\mathrm{I}})\,\mathrm{d}z, \qquad (1)$$

(x-axis directed outward the torus, i.e. opposite to the direction of ∇B). Here $N = \int_{-\infty}^{+\infty} n_{\mathrm{I}}\mathrm{d}z$ is the density of the ablatant ions integrated along the magnetic field lines, T_{e} and T_{I} are the cloud electron and ion temperatures, R is the tokamak major radius. $\Sigma_{\mathrm{A}} = \frac{1}{B}\sqrt{\frac{m_0 n_0}{\mu_0}}$ is a so-called Alfven conductivity, n_0 and m_0 are the density and the ion mass of the ambient plasma, L_{c} is the cloud length along the magnetic field. Function $\tilde{\alpha}(L_{\mathrm{c}})$ was introduced to model how the ∇B induced current inside the cloud vanishes while the cloud expands along B. The value of $\tilde{\alpha}$ depends on the longitudinal temperature and density profiles inside the cloud and poloidal component of the magnetic field.

The l.h.s. of Eq. (1) is the polarization current inside the cloud, the last term in the r.h.s. is the vertical ∇B current and the first term in the r.h.s. is the polarization current of the Alfven wave in the ambient plasma. Far from the pellet the drift velocity becomes large enough, while the coordinate derivative in the l.h.s. becomes negligible. Thus the value of the drift velocity there comes from equating two terms in the r.h.s. of Eq. (1).

After a poloidal turn of π radians due to expansion along $\vec{B}$, the ∇B induced current is cancelled, and the motion in the x direction comes to a full stop according to the balance between the l.h.s. and the first term in the r.h.s. (see [1] for the details). Note that the drift does not affect the neutral gas near the pellet, and it is taken into account in Eq. (1).

In the present paper the results of the numerical modeling of the pellet cloud structure by means of the LLPD code are presented. In this code the cloud expansion equations coming from the LLP code [6] are extended in order to include the drift motion of the ionized cloud according to Eq. (1). This important effect allows the new code to calculate in a self-consistent manner not only an ablation rate and time evolution of all important pellet cloud parameters along and across the magnetic field but also the final mass displacement of the ablating material and thus the fueling efficiency.

The initial MHD equations together with the drift motion equation (1) are solved in the slab geometry. The transverse heat conduction coefficient is chosen to be $\chi_{\mathrm{anom}} = 1\,\mathrm{m}^2/\mathrm{s}$. The Lagrangian coordinate system is used to model the pellet cloud expansion along and across the magnetic field. A pellet with known radius r_{p} is assumed to be injected into the certain poloidal cross-section of the tokamak with the velocity V_{p} not changing in time. The magnetic field lines are straight and directed along the z-axis. The y-axis is directed vertically. The background plasma density and temperature profiles along the pellet path as well as the shape of magnetic flux surfaces are assumed to be known.

To model the effect of spatial variation in the ∇B-induced current, a cloud length L_{c} was defined as the z coordinate of the last physical cell and function $\tilde{\alpha}(L_{\mathrm{c}})$ in Eq. (1) was chosen in such a way that

$$\tilde{\alpha}(L_{\mathrm{c}}) = \begin{bmatrix} L_{\mathrm{c}}, & L_{\mathrm{c}} < \pi R, \\ 0, & L_{\mathrm{c}} > \pi R. \end{bmatrix}$$

3. Results of the simulations

Calculations were made for the plasma and pellet parameters corresponding to ASDEX-Upgrade shot #9684, which is a typical LFS injection scenario for modern tokamaks. ($B = 2.5$T, central temperature and density are $n_0 = 3.7 \cdot 10^{19}\,\mathrm{m}^{-3}$, $T_0 = 3.6$keV, $I_p = 1$ MA, $P_{\mathrm{NBI}} = 5.53$MW, last close surface position is at $r = 41.96$cm) The pellet characteristics were $r_p = 1.2$mm, $V_p = 560$m/s.

Results of the simulation show that an ablation rate ($2.2 \times 10^{24}\,\mathrm{s}^{-1}$) and the corresponding penetration depth obtained by means of the new code correspond to the predictions of NGS scaling and to the experimentally observed values [8]. This fact confirms the conclusion made in [7] that in the case of LFS pellet injection scenarios the impact of the ∇B-induced drift on the ablation rate of the pellet is rather modest.

In Fig. 1(a)–(c) the obtained density, temperature and ionization degree profiles are presented. The time instant corresponds to the maximum in the ablation rate. One can see the cigar-shaped dense cloud elongated along the magnetic field lines with the transverse size of about 1cm and longitudinal size of about (15–20) cm (double side). These values coincide well with the ionization radius l_i and the length equal to $2\sqrt{l_i R}$, respectively. It is also demonstrated that the particle shift in the pellet wake starts at the distance $\sim \sqrt{l_i R}$ from the pellet, which was predicted in [7]. Results of the simulations show that the size of the neutral cloud formed around the ablating pellet corresponds to the experimentally observed value (of the order of several cm) whereas in the previous version of the code without drift (LLP) this value was unreasonably large (see [7]). Thus one can conclude that the new pellet-drift code can qualitatively reproduce the most important characteristics of the pellet cloud.

In Fig. 1(a) arrows show the directions of particle fluxes. Since the neutral particles surrounding the pellet don't drift (don't move across the magnetic field), a pressure hollow appears just behind the pellet. Consequently, the particle flux is directed first from the pellet along the magnetic field (driven by the pressure gradient), then across the magnetic field (due to drift), and then some fraction of the particles are returned back to the cloud axis ($z = 0$).

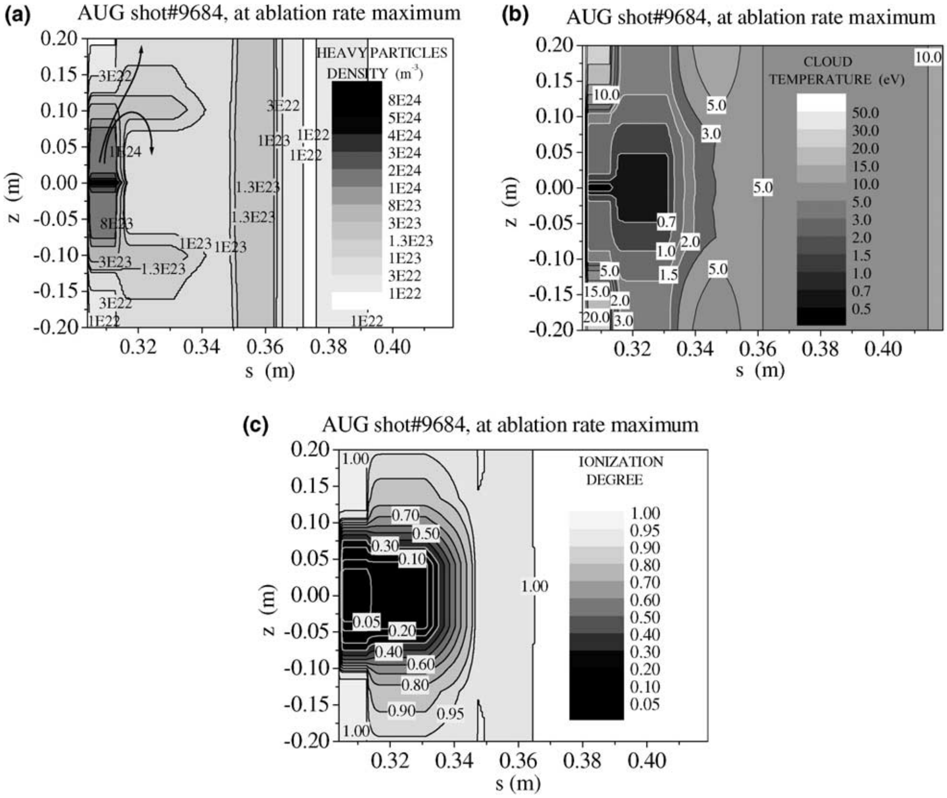

Fig. 1. (a) Density distribution at the moment of the ablation rate maximum. Pellet is moving to the left, *s* is the coordinate along the pellet trajectory, which for the LFS shot corresponds to minor radius. Arrows show the direction of particle fluxes near the pellet. (b) Temperature distribution at the moment of the ablation rate maximum. (c) Ionization degree distribution at the moment of the ablation rate maximum.

The cloud temperature at the moment of maximum ablation rate remains rather low, about 2eV. Corresponding ionization degree is about 40%. Full ionization and cloud temperatures above 5eV occur a distance of about 5cm behind the pellet. The neutrals are ionized at a distance of about 2cm behind the pellet, however their density in this region is an order of magnitude smaller than that near the pellet. These typical values of density and temperature in the pellet wake (see Fig. 1) qualitatively correspond to those measured by Müller [5].

The drift velocity V_D, calculated according to Eq. (1), is shown in Fig. 2. The value of V_D also of the order of that measured by Müller [5].

The calculated density rise (mass deposition) after the pellet injection is demonstrated in Fig. 3 with a dotted line. For comparison solid line shows the same value obtained under the assumption that ablated particles don't drift from the place of ablation. The value of the fuelling efficiency calculated on the base of simulation results (12.9%) is in reasonable agreement with one reported by Lang [3] for LFS injection scenarios in ASDEX-Upgrade (10–15%).

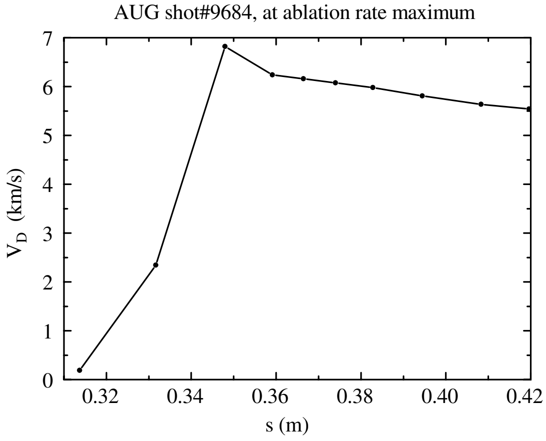

Fig. 2. Drift velocity at the moment of ablation rate maximum.

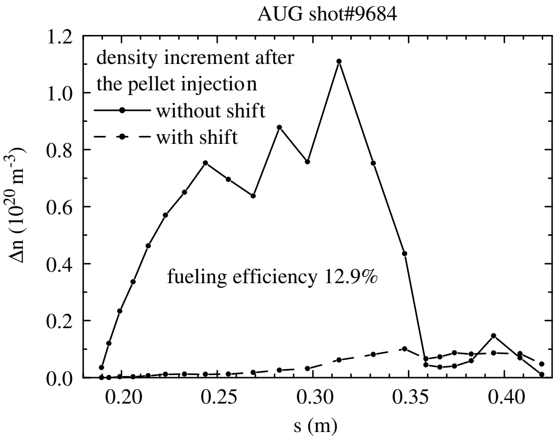

Fig. 3. Density rise after the pellet injection. Dotted line – including the drift, solid line – under the assumption that particles are deposited at the place of ablation (i.e. without drift).

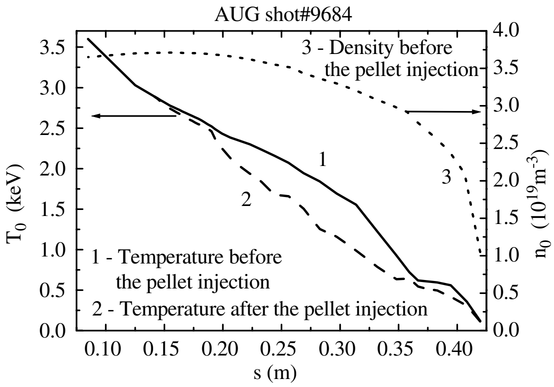

Fig. 4. Effect of an ambient plasma cooling. Shown are the temperature profiles before (solid line) and after the pellet injection (dash line). Dotted line represents an ambient plasma density before the pellet injection.

The calculated effect of background plasma cooling is shown in Fig. 4. One can see that the temperature drop is rather modest, at least at the time just after the density redistribution (500 μs after the pellet injection). The explanation of this fact could be relatively low number of particles to be heated.

Simulation results demonstrate that the ∇B induced drift strongly affects the process of the pellet cloud motion and the mass deposition after the pellet injection.

4. Conclusions

The new code (LLPD) is developed to model the cloud pattern in the presence of $\vec{E} \times \vec{B}$ drift. Numerical simulation of the pellet ablation and following ablated material redistribution is performed by means of the new code. Calculation results have confirmed the earlier prediction that the ∇B induced drift strongly affects the structure of the cloud and mass deposition profile, while its impact on the ablation rate is rather modest. It is demonstrated that the code can reproduce with acceptable accuracy the ablation rate profile and the penetration depth. It is shown that the pellet cloud structure obtained in the simulation is in reasonable agreement with that reported in the experiments on LFS pellet ablation scenarios in the ASDEX-Upgrade tokamak. The fueling efficiency computed on the base of the numerical results is in the same range as in the experiment.

Acknowledgments

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References

[1] V. Rozhansky et al., PPCF 46 (2004) 575.

[2] L. Garzotti et al., Nucl. Fusion 37 (1997) 1167.

[3] P.T. Lang et al., Phys. Rev. Lett. 79 (1997) 1487.

[4] L.R. Baylor et al., Phys. Plasmas 7 (2000) 1878.

[5] H.W. Müller et al., Nucl. Fusion 42 (2002) 301.

[6] L.L. Lengyel et al., Nucl. Fusion 39 (1999) 791.

[7] I.Yu. Senichenkov et al., Proceedings of the 29th EPS Conference on Plasma Phys. Control. Fusion, Montreaux, 2002, ECA 26B P-4.081.

[8] I.Yu. Veselova et al., Proceedings of 28th EPS Conference on Control. Fusion Plasma Phys., Madeira, 2001, ECA, 25 A, p. 701.