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Modelling of the Pellet Rocket Acceleration Effect

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1. Introduction

The drift displacement of ablated pellet material clouds (plasmoids) caused by the magnetic field gradient has proven to be crucial for the calculation of realistic pellet source profiles and for improvements in estimating the fuelling efficiency. A consequential phenomenon that has been investigated in theory [1] and in the experiment [2,3], might also influence the pellet particle transport: because of the ∇B-drift displacement of the surrounding plasmoid, the pellet is better protected on the low field side (LFS) of the pellet, and the different ablation rate with respect to the high field side (HFS) leads to a horizontal outward acceleration of the pellet itself. The kinetics is comparable to that of a rocket. It can lead to enhanced pellet penetration for HFS injections, depending on various parameters such as the injection geometry, pellet size and plasma parameters such as temperature and density, and is supposed to explain some of the remaining differences between the observed pellet deposition and model predictions.

Implemented into a first-principles pellet code, the influence of the pellet rocket acceleration has been evaluated for typical tokamak scenarios in section 2. In section 3, a scaling law for the barycentre displacement of the pellet deposition profile caused by the rocket effect is formulated. Finally, the expected pellet rocket drift displacement in the case of ITER will be discussed.

2. Influence on Particle Deposition

The semi-empirical acceleration term for the pellet rocket effect derived by Szepesi et al. [3] has been integrated into a recently developed pellet code, which is based on enhanced versions of an NGPS-type ablation [4] and a four fluids Lagrangian drift model [5]. The exact position of the pellet is updated each time when a plasmoid has been released and deposited; that way, the influence of previous plasmoids on the plasma density and temperature, which in turn may change the amplitude of the pellet rocket drift, can be taken into account. Simulations have been carried out for typical tokamak discharges in Tore Supra [6], assuming a constant asymmetry factor $\varepsilon = 0.05$. The results have been compared with code predictions without pellet rocket acceleration and with an analytic approximation of a purely theoretical description of the pellet rocket effect developed by Senichenkov et al. [1]. The corresponding ablation and deposition profiles are shown in Fig.1-3. The first-principles model predicts a rocket acceleration ~3-4 times higher than the semi-empirical model, with roughly similar parameter dependencies. For the Tore Supra HFS injection case, the same kind of simulations with different pellet radii and plasma temperatures has been performed; the net pellet rocket drift displacement shown in Fig.4-5 reaches up to 25% of the total pellet displacement in all cases. The pellet rocket effect has been tested in full transport simulations using JETTO combined with the pellet code. Simulations of the JET shot #58337 described in [7] (L-mode discharge fuelled with 8 pellets for each injection line: LFS, HFS, and vertical HFS = VHFS) were done using the JETTO mixed Bohm / gyroBohm standard model implementation (see Fig.6). As expected, the pellet rocket acceleration leads to slightly decreased particle confinement for LFS injections (the smaller penetration due to the pellet rocket effect is partly compensated by smaller ∇B-drift displacement close to the plasma boundary) and increased confinement for (V)HFS injections.

3. Scaling Law

The change of the pellet deposition profile barycentre due to the pellet rocket acceleration effect has been calculated in terms of the normalised flux coordinate $(R_{max} - R_{min})/2$ for a variety of pellet injections into Tore Supra-like target plasmas (~ ±30% of standard parameter settings), and processed by a least square fit in order to ascertain the main parameter sensitivities. The following equation has been set up:

$$\Delta(\lambda_{\text{dep.}}) = C_1 V_p^{C_2} r_p^{C_3} n_{e0}^{C_4} T_{e0}^{C_5} \left(C_7 \cos(C_6 \alpha) + C_8\right)(1-\Lambda)^{C_9} a_0^{C_{10}} R_0^{C_{11}} B_0^{C_{12}} .$$

V_p is the injection velocity (100 m/s), r_p the pellet radius (mm), n_{e0} the axial density (10^{19} m^{-3}), T_{e0} the axial electron temperature (keV), α the injection angle ($\in [-\pi,\pi]$; $\alpha=0$: HFS injection), Λ the impact parameter of the pellet trajectory (norm. minor radius), a_0 the minor radius (m), R_0 the major radius (m), B_0 the toroidal field (T). The scaling constants C_1-C_{12} and the error of the fit are listed in Tab.1, together with more specific constant settings matched to LFS, HFS and VHFS injections in Tore Supra. The absolute value of $\Delta(\lambda_{\text{dep.}})$ is strongly correlated with the ablation time, which increases with r_p and decreases with n_{e0} and T_{e0}. The R_0-dependence can only be explained by pre-cooling, which diminishes the rocket acceleration more effectively in small-volume plasmas.

4. ITER Predictions

Unfortunately, the pellet rocket acceleration effect does not seem to be exploitable in the case of typical ITER discharges to improve the fuelling efficiency for HFS injections. As can be seen in Fig.8 for the case of 5 mm pellets injected at 500 m/s (which is supposed to correspond to the maximum values achievable by the ITER HFS pellet injector) into an ITER ohmic L-mode plasma at high average density level (~ $9.5 \cdot 10^{19}$ m^{-3}) and average temperature (~ 10 keV) [8], the ablation process takes place at the very edge of the plasma. Therefore, the ablation time is too short for the pellet rocket drift to develop, and only the ∇B-drift of the plasmoids leads too deeper particle penetration.

5. Conclusions

As was demonstrated in section 2, the pellet rocket acceleration has a significant influence on the pellet particle deposition behaviour. Similar to the ∇B-drift mechanism, the particle penetration is increased for HFS injections and decreased for LFS injections. Semi-empirical and theoretical descriptions predict different pellet rocket acceleration quantities. For the case of Tore Supra, a scaling law could be determined for the change in particle confinement caused by the pellet rocket effect. Because of the short ablation time in ITER, the rocket drift displacement of the pellet remains negligible. However, it still plays an important role for pellet source predictions in ITER scenarios in an indirect way, as the pellet codes are validated on experiments, in which its influence can become comparable to that of the ∇B-drift. If it is not taken into account in these cases, one might tend to overestimate the importance of the ∇B-drift in ITER.

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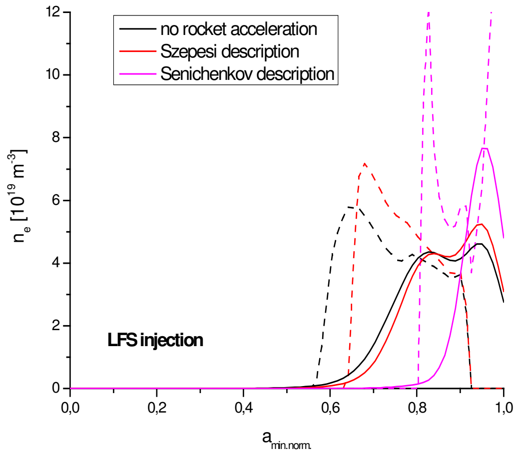
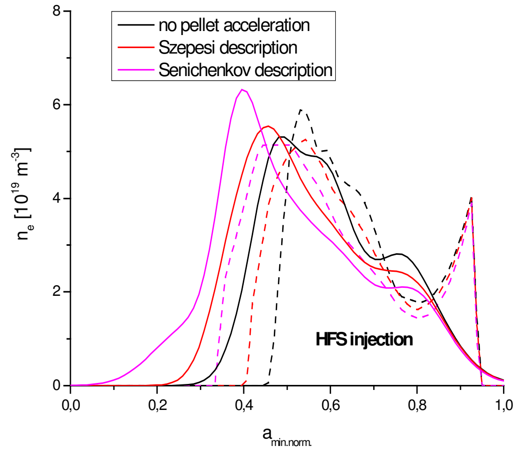
References

[1] Senichenkov et al., 34th EPS, P-4.094 (2007)
[2] P.T. Lang et al., Nucl. Fusion 41 (2001) 1107-1112
[3] Szepesi et al., 34th EPS, P-4.037 (2007)
[4] Pégourié B. et al., Plasma Phys. Control. Fusion 47 (2005) 17
[5] Pégourié B. et al., Nucl. Fusion 47 (2007) 44-56
[6] Pégourié B. et al., EPS 2007, P4.092
[7] Géraud A. et al., EPS 2003, 27A P-1.97
[8] ITER Physics Basis, Nucl. Fusion 38 (1999) 2137

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	<Δ>	σ
$\Delta(\lambda_{dep.})$	0.102	-0.098	1.303	-0.653	-0.788	1.224	2.350	0.515	1.435	-0.123	0.790	-0.349	-0.002	0.019
Δ_{LFS}	-2.541	-0.733	4.148	-1.450	-3.425	0	0	0	0	0	0	0	-0.011	0.013
Δ_{HFS}	0.065	0.085	1.705	-0.081	-0.520	0	0	0	0	0	0	0	0.041	0.019
Δ_{VHFS}	0.022	0.844	2.184	-0.435	-0.780	0	0	0	0	0	0	0	0.016	0.005

Table 1 – Constants $C_{1\text{-}13}$, mean value <Δ> and standard deviation σ for the calculation of the position change of the pellet deposition profile barycentre in Tore Supra-like discharges in terms of normalised minor radius flux coordinates. The pellet rocket acceleration was calculated using the semi-empirical description in [3]. Constants are also given for the barycentre position change in Tore Supra for LFS, HFS and VHFS injections resp..





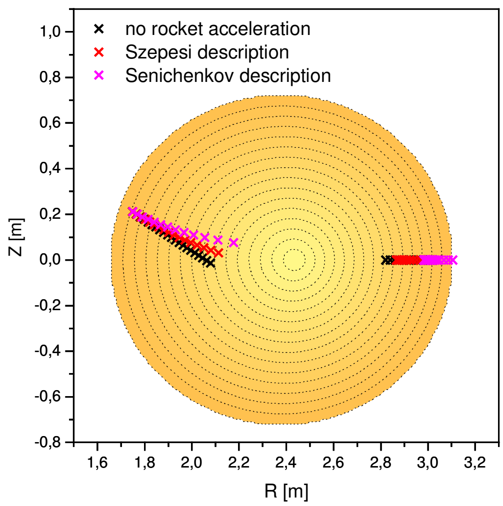
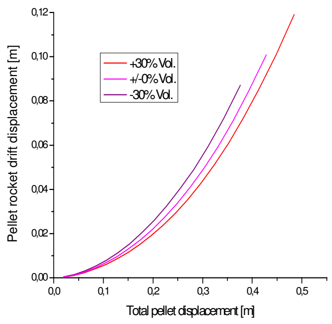


Fig.1-3 (up): Pellet ablation (dotted lines) and deposition profiles (solid lines) for LFS and HFS pellet injections in Tore Supra plasmas (V_p=200m/s, r_p=1.3mm, T_{e0}~4keV, ne0=4.5·$10^{19}$$m^{-3}$), using different assumptions for the pellet rocket acceleration effect; the corresponding positions of pellet plasmoid releases are displayed below.

Fig.7 (right): Simulation results for the pellet ablation (dotted lines) and deposition profiles (solid lines) in ITER after injection of a 5mm-sized pellet with 500m/s from the HFS, using different assumptions for the pellet rocket acceleration effect.



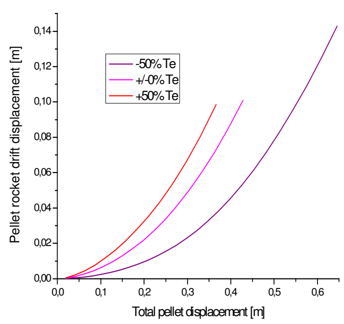


Fig.4-5 (up): Pellet rocket drift displacement for HFS injection in Tore Supra (V_p=200m/s, r_p=1.3mm, T_{e0}~4keV, n_{e0}=4.5·$10^{19}$$m^{-3}$) with varying pellet volume (left) and plasma temperature (right), using the semi-empirical model from Szepesi et al..

Fig.6 (down): Simulation results for the line-integrated density evolution in JET shot #58337, calculated with NGPS and the pellet code with and without consideration of the pellet rocket acceleration effect (using the semi-empirical model from Szepesi et al.); below, the relative difference in density obtained by the pellet code with and without the pellet rocket acceleration effect is given.