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Radial acceleration of solid hydrogen pellets in hot tokamak plasmas

T. Szepesi[1], S. Kálvin[1], G. Kocsis[1], P.T. Lang[2] and ASDEX Upgrade Team[2]

[1] *KFKI – Research Institute for Particle and Nuclear Physics, EURATOM Association, P.O. box 49, H-1525 Budapest-114, HUNGARY*

[2] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, GERMANY*

The type-I ELMy H-mode is foreseen as the standard ITER operation scenario. Type-I ELMs (edge localised modes) are MHD instabilities causing a fast (~ms) expulsion of plasma particles and energy. A large fraction of the energy – an extremely high peak load of power – is concentrated onto the surface of plasma facing components; a threat to the lifetime of these components especially in large machines [1]. However, ELMs also remove impurities from the plasma, allowing for a stable and robust state, meaning that ELMs can be used as a tool to control the plasma edge and impurity content.

Nevertheless the harmful effects of ELMs must be mitigated in order to be able to use this tool. Cryogenic fuelling pellets were observed to trigger ELMs immediately after being injected into the plasma, and so the ELM frequency can be increased above the natural ELM frequency with a sufficiently high pellet injection rate (pellet pacing) [2]. The ELM size (energy loss per ELM) was observed to decrease with increased frequency, indicating that pellet ELM pacing could be a method to mitigate ELM effects. In order to be able to estimate pellet requirements for ELM mitigation in larger machines, the thorough understanding of ELM triggering mechanism is inevitable.

One aim of the ELM triggering experiments conducted at ASDEX Upgrade tokamak was to determine the location of the pellet when the ELM was triggered. In these studies pellets were injected from the magnetic high field side (HFS) of the torus, their position was determined using a fast framing camera system [3]. The pellet trajectory was observed to bend considerably for pellets with lower velocities (240-600 m/s). The bending is caused by radial acceleration of the pellets, while the vertical component of their velocity remains roughly constant [3]. This means that the pellet track differs considerably from the designated path (a straight line), and therefore the pellet (and the perturbation caused by it) touches different areas of the plasma. Also the dynamics of the ablation (perturbation) is changed: faster pellets penetrate deeper into the plasma therefore the local density perturbation caused by the ablation is smaller.

To study the radial acceleration of pellets in the plasma, a database of pellets was created containing pellet trajectory data (radial and vertical coordinates *R, z*, respectively) as well as plasma parameters such as magnetic structure and electron temperature and density profiles. The fast cameras, viewing tangentially to the poloidal plane of the pellet injection, were run in the 'long exposure' mode, resulting in an image on which the whole pellet trajectory is visible (in the *R*-*z* plane) with the light emitted by the pellet integrated over its whole lifetime. In this way the toroidal bending of the pellet path could not be detected. Although this image contains no explicit time information, the radial velocity and acceleration of the pellet can be determined by assuming that the vertical component of the pellet velocity

$$v_z = v_{z0} = v_o \sin(\alpha)$$

is constant, where α is the angle of pellet injection, v_0 and v_{z0} are the initial pellet velocity and its vertical component, respectively. Equidistant (dz) points in the z direction on the pellet path correspond to time points separated by the same time difference dt:

$$dt = \frac{dz}{v_{z0}} = \frac{dz}{v_0 \sin(\alpha)}.$$

To get rid of numerical errors in the pellet trajectory (caused by the resolution of the image), the following curve was fitted to the pellet path:

$$R(z) = R_0 + \frac{z - z_0}{\tan(\alpha)} + b\left(\frac{z - z_0}{\sin(\alpha)}\right)^a \quad (1)$$

where a and b are free parameters, R_0 and z_0 are the coordinates of the pellet injection tube end. The fitted trajectory was sampled with a uniform distance dz in the z direction as mentioned above to get $R(t)$ and $z(t)$. Radial pellet velocity v_R and acceleration a_R was calculated by numerical differentiation of the sampled-fitted trajectory.

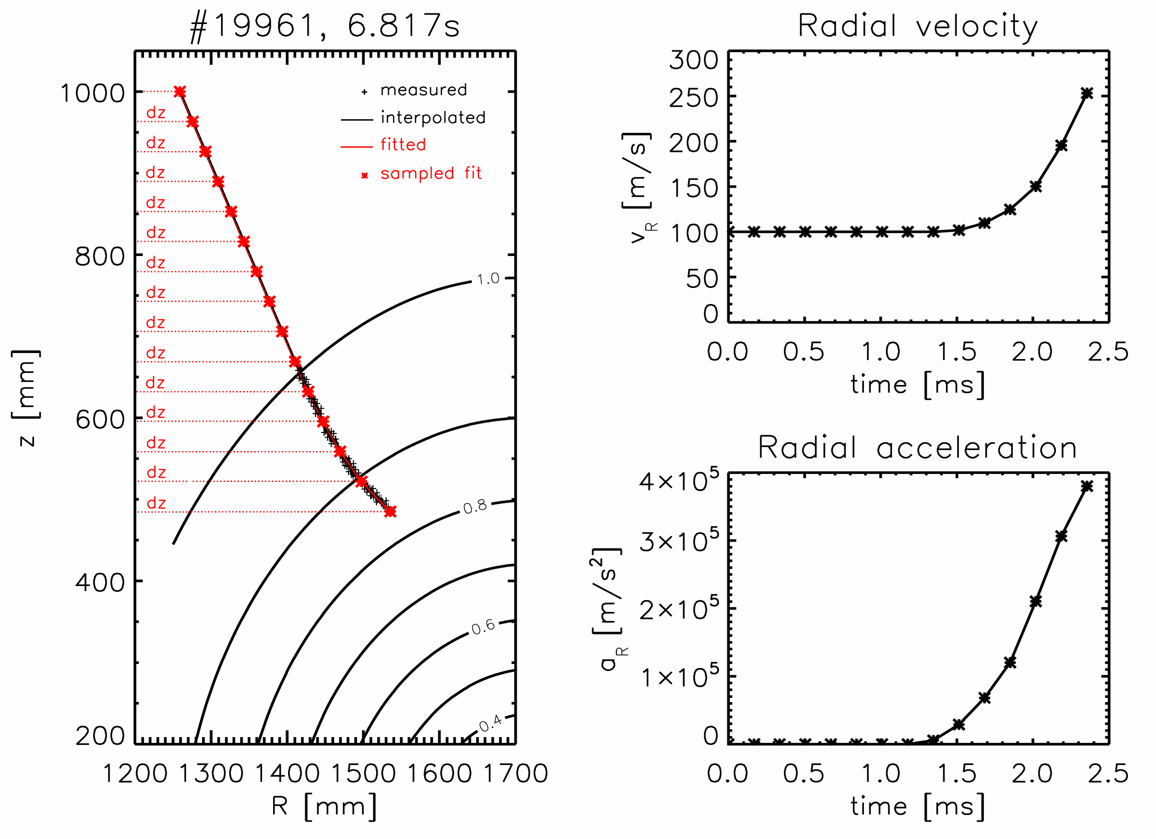

Figure 1.: Left: Pellet trajectory data derived from the camera diagnostic. The poloidal flux coordinates are also overplotted. To avoid numerical errors, the fitted trajectory was sampled for the derivation of radial velocity and acceleration (right).

The exact mechanism of radial pellet acceleration is yet unknown; one idea is that due to drift effects [4], the pellet cloud is shifted horizontally towards the LFS relative to the pellet, therefore the ablation will be different on the LFS and HFS side of the pellet. This will result in a pressure difference exerting a force F on the pellet, which will also accelerate towards the LFS (major radius direction):

$$F = (p_1 - p_2) \cdot A_p = \varepsilon \cdot p_0 \cdot A_p \tag{2}$$

where p_1 and p_2 are the pressures on the two sides of the pellet and $A_p = r_p^{\ 2}\pi$ is the pellet cross-section. Assuming the cloud shift is small, the pressure difference (p_1-p_2) can be related to the pressure of the ablation cloud on the surface of the pellet (p_0) by introducing the asymmetry parameter ε, and p_0 given by the Neutral Gas Shielding (NGS) model [5]:

$$p_0 = 1.3825 \cdot 10^{-12} \cdot n_e^{\ 2/3} \cdot T_e^{\ 1.54} \cdot r_p^{\ -1/3} \ [\mathrm{N/cm^2}] \tag{3}$$

where n_e [cm^{-3}] and T_e [eV] are the electron density and temperature of the background plasma, respectively, and r_p [cm] is the pellet radius.

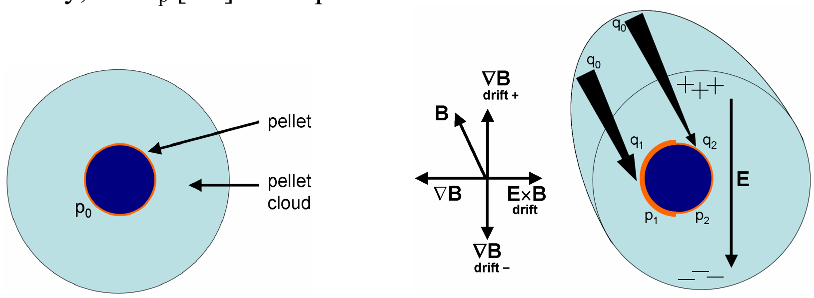

Figure 2.: Left: Ablating pellet with neutral pellet cloud (normal state). Right: the pellet cloud is shifted due to the radial drift, which results in different heat fluxes (q) reaching the LFS and HFS side of the pellet. Therefore a net pressure difference is induced between the two sides.

In our simulations the following model was used to calculate pellet acceleration:

$$a_R(t) = \frac{F(t)}{m_p(t)} = \frac{(p_1 - p_2) \cdot A_p}{m_p} = \frac{\varepsilon \cdot p_0(t) \cdot A_p(t)}{m_p(t)} \tag{4}$$

where m_p is the mass of the pellet and a_R is the acceleration in the R direction. However, the initial mass m_{p0} of the injected pellet is not known precisely. Therefore a separate NGS simulation was performed to find the pellet mass (see below). Then, knowing m_{p0}, pellet acceleration simulations were performed to determine the asymmetry necessary to reproduce the observed curved pellet trajectory. An example is shown below:

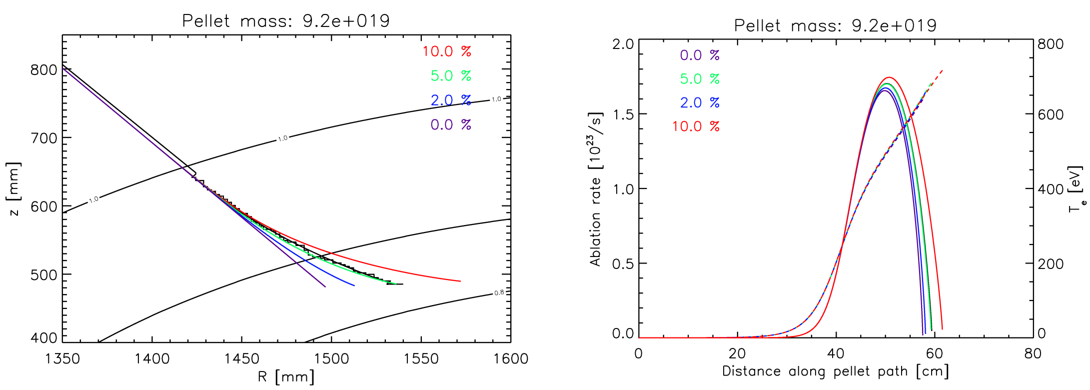

Figure 3.: Left: a measured pellet trajectory (black) and four simulated paths with different asymmetry values. In this special case an asymmetry of 5% is necessary to reproduce the measured bending of the path. On the right figure the corresponding ablation rates are presented. Clearly, acceleration caused by the asymmetry makes the penetration deeper.

However, if we do not assume the asymmetry to be constant, equation (4) can be reformulated to determine the asymmetry along the measured pellet trajectory:

$$\varepsilon \cdot p_0 \cdot A_p = F = m_p \cdot a_R \quad \rightarrow \quad \varepsilon = \frac{m_p \cdot a_R}{p_0 \cdot r_p^{\,2} \pi} \tag{5}$$

To be able to do this, the acceleration can directly be calculated from the trajectory, but the pellet radius (and mass) can only be derived by the above mentioned separate simulation: from the measured $R(z)$ curve the distance along the pellet path $l(t)$ can be derived as well as $T_e(l)$, $n_e(l)$, and the total (constant vertical + increasing radial) speed of the pellet $v_{tot}(l)$ which is always tangent to the pellet path. From these data the (initial) pellet mass is calculated by fitting the length of the simulated pellet trajectory to the measured one; this simulation also gives $r_p(l)$. Finally the asymmetry variation along the pellet trajectory can be calculated using (5). A comparison of the constant and this varying asymmetry cases for the same pellet trajectory is shown on Figure 4.

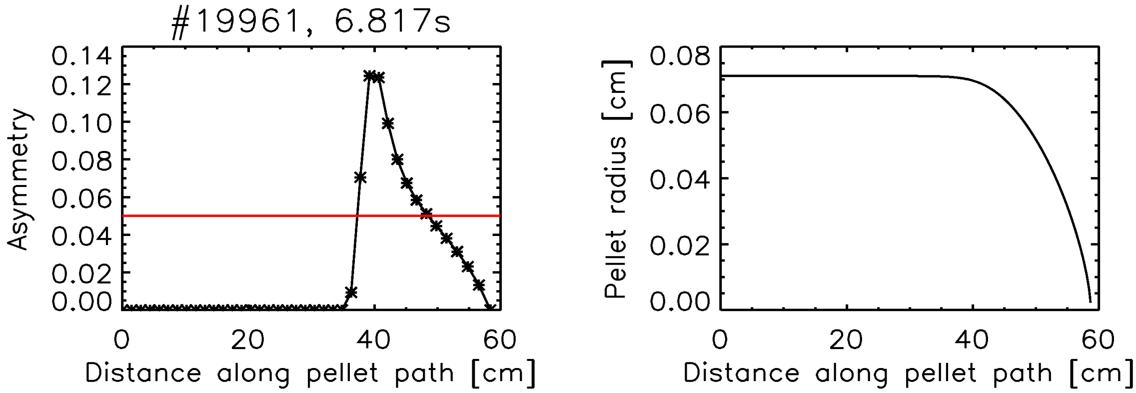

Figure 4.: Left: the asymmetry calculated with eq. (5) as a function of the pellet path. Overplotted in red is average asymmetry calculated in the simulation. Right: the quick decrease in the pellet radius is in good agreement with the drop in the asymmetry value.

Studying 16 pellet events within the same ASDEX Upgrade plasma discharge, asymmetry values similar to what were presented here were found. Constant asymmetry values fell in the range of 2.6 – 8.8 %, with an average of 5,3 % for the processed 16 pellet events.

The results show that pellet acceleration does not have any significant effects on ELM triggering because ELMs are triggered within the pedestal region [6] where the ablation asymmetry plays no significant role (Fig. 3.). However, taking pellet acceleration into account in penetration studies can be important, esp. in LFS injection scenarios where the pellet is decelerated, yielding a significantly lower penetration depth.

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