*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-4.080 (2007)*

Pellet Induced Perturbations in the Plasma Edge

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Solid hydrogen isotope pellets are used for fueling in tokamaks, but recently they are applied for ELM mitigation as well. Increasing the ELM frequency by external pacemaking using pellet injection results in a reduced ELM energy, which is essential for the target lifetime in ITER and a future fusion reactor. As the exact mechanism of the ELM release by pellets is not yet fully understood, the minimum pellet imposed perturbation required for pacemaking is not easy to predict for actual and future experiments. The determination of the minimum pellet size is of importance as the use of bigger pellets will cause a fueling burden. On the other hand the value of minimum pellet velocity is also critical, because this may influence the magnitude of the local perturbation through the pellet residence time in the plasma edge.

There are several pellet induced mechanisms which may play a role in the ELM formation as the local density perturbation (the number of deposited particles per meter) or the cooling due to the high energy request of the pellet ablation and cloud expansion. This work concentrates on the determination of the local density perturbation induced by the ablated material in the edge plasma, where the ablation rate may have different dependence on the pellet size and velocity as in the core plasma.

To determine the pellet induced perturbation strength one should understand how the pellet evaporates in the edge region. The present work considers the number of deposited particles per meter as a measure of perturbation. Once the pellet enters the plasma a spherically expanding neutral cloud forms around it, which will turn a channel flow as the particles gets ionized at the cloud periphery (i.e. at the cloud radius). The simulation of this complex phenomena was performed employing a hybrid code [1, 2] describing the spherical neutral cloud according to the neutral gas shielding model. The detailed dynamics of the field line elongated ionized cloud is included in a one-dimensional Lagrangian cell code. The NGS model is a quasi steady state model, and the ablation rate is independent on the pellet velocity. On the other hand, parameters of the ionized cloud and its effect on the ablation rate has a strong dependence on the cloud radius which determines the time which the pellet spends at one location in the plasma. If the pellet is assumed to have constant velocity and its path is a straight line the residence time equals the diameter of the cloud divided by the pellet velocity.

In this case the shielding effects of the ionized cloud part is time dependent, i.e. correlates with the material deposited during the time interval the pellet spent in the flux tube. Increasing the pellet size the cloud radius increases as well thus by increasing the pellet radius and lowering the pellet velocity the time spent in each plasma location gets longer, consequently the ionized cloud part of the pellet will get more and more important in this parameter regime. Most of the models which concentrated on fueling issues neglected the velocity dependence of the ablation rate. This is true for example in the high velocity limit where the ablation rate given by the hybrid code (N'_{HYB}) equals the ablation rate given by the NGS formula (N'_{NGS}), and N'_{HYB}/N'_{NGS} depends slightly on the velocity as it is shown in figure Fig 1.

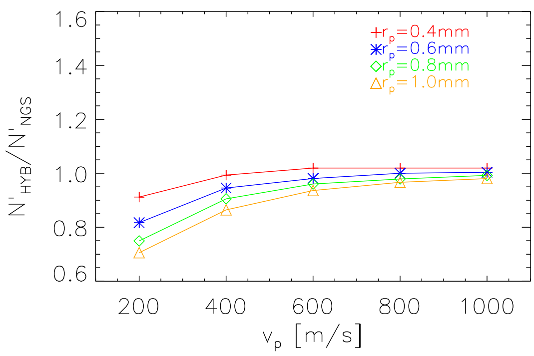

Figure 1: *The ratio of the hybrid ablation rate and NGS ablation rate as a function of velocity is plotted for four pellet sizes:* $r_p = 0.4$ mm *(plus),*$r_p = 0.6$ mm *(star),* $r_p = 0.8$ mm *(rhomb),* $r_p = 1$ mm *(triangle). The target plasma temperature is 800* eV and density s $2 \cdot 10^{19}$ m^{-3}.

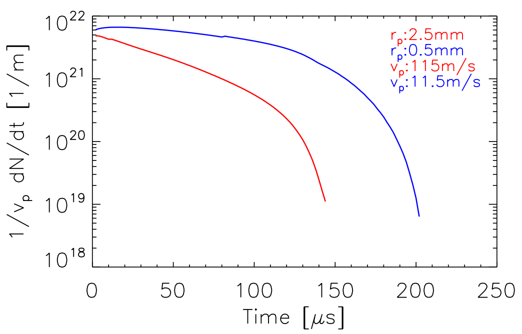

Figure 2: *The time evolution of the perturbation strength for pellets with radius* $r_p = 2.5$ mm *and* $r_p = .5$ mm *and with a velocity of* $v_p = 115$ m/s *and* $v_p = 11.5$ m/s *in a plasma having an electron density of* $n_e = 2 \cdot 10^{19}$ m^{-3} *and temperature of* $T_e = 800$ eV.

Lowering the pellet velocity the above mentioned ratio starts to decrease, showing that the ablation rate has a strong dependence on the pellet velocity. The deviation of the ablation rate given by the pellet code from the one given by the NGS formula increases with the pellet size. For a pellet with 1 mm radius the ablation rate is just 70% of the one predicted by the quasi steady state model. In ITER the expected pellet velocities will be 300 and 500 m/s respectively. The pellet radius will be far above 1 mm, thus the effect of the ionized pellet cloud can be even higher that in the submilimiter regime. By increasing the pellet size the residence time within each plasma section raises. On the other hand, as the ablation rate increases with the pellet radius as well, this causes a higher cloud density. As the cloud becomes denser, ablation evoking electrons become diluted in the cloud and the ablation is fading while the pellet crosses its own cloud as shown in Fig 2. As the line integrated density of the cloud depends on the pellet radius, the resulting time averaged ablation rate is proportional with approximately the square root of the pellet radius for very low velocities. We should emphasize here that this effect is less important in the core plasma where particles escape from the cloud due to drift effects.

Estimates based on power laws [2] shows that the strength of the perturbation $dN/dr = (1/v_p) * dN/dt$ for the same plasma depends on the pellet mass and velocity as $dN/dr \sim v_p^{-.82} \cdot r_p$. Thus to have the same perturbation for a 5 times smaller pellet radius we have to reduce the velocity 7 times or even more. This preliminary result would show that by reducing the pellet velocity, which would mean lowering the costs for the injection system, one could obtain the same perturbation, i.e. trigger ELMs. By analyzing the dependence of the perturbation strength on pellet velocity it has been showed that if the pellet velocity is very low the residence time in the plasma edge becomes very long, thus the pellet cloud absorbs all the energy and ablation is collapsing before the pellet crosses its own cloud, resulting in a smaller average ablation rate.

Experimental investigations performed at ASDEX Upgrade and JET revealed that pellets trigger ELMs when only a small per cent age of the pellet mass is ablated, consequently this small amount of particles trigger ELMs. Similarly the recent experiments showed [3] that all the pellets trigger ELMs which reach the pedestal top. According to the simulations all of the above mentioned pellets will cross this region, which is in accordance with the observations.

The determination of the minimum perturbation strength is also of importance. We calculated the number of deposited particles per meter for the most frequently used pellet velocities used in ASDEX Upgrade (240, 600 and 1000 m/s), which means different pellet sizes also (for smaller pellets the corresponding radius is of $7.2 \cdot 10^{-4}$, $6.6 \cdot 10^{-4}$, $5 \cdot 10^{-4}$ m and for the bigger ones is $9.1 \cdot 10^{-4}$, $9 \cdot 10^{-4}$, $6.9 \cdot 10^{-4}$ m). In the pedestal region the perturbation strength is similar for pellets with the same velocity. The perturbation strength of fast pellets with small radius is the smallest as it is shown in Fig 3.

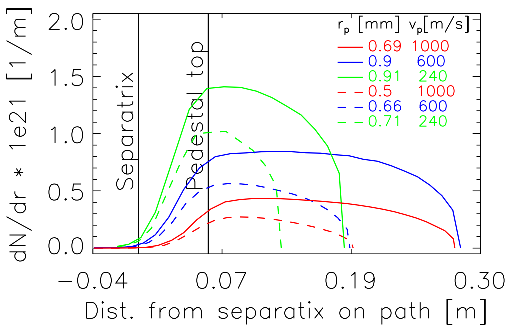

Figure 3: *The calculated perturbation strength on the pellet path of the most frequently used pellets in an ASDEX Upgrade plasma (profiles from* #20041*).*

For JET experiment high resolution data where just available for high field side injection, thus the simulation were performed for a JET like profile for the above mentioned pellet [4]. It has been assumed that the pellet is traveling on the outer horizontal midplane with its radial velocity of 115 m/s. The pellet mass taken was the experimentally one (yielding 2.45 mm radius). By reducing the pellet mass to 1% of its original mass (the pellet radius was 0.53 mm) we calculated the strength of the perturbation which was much less compared to the experimentally used one. We tried to compensate the reduction of the perturbation strength by reducing the pellet velocity to 30 m/s and this way we may reach the same perturbation level as the original one. As the ablation rate depends on the pellet velocity the velocity can't be reduce to much as the ablation will stop, and both the average ablation rate and the perturbation strength will decrease.

The smallest perturbation in ASDEX Upgrade is caused by the smallest and fastest pellets, with a radius of $5 \cdot 10^{-4}$m corresponding to a particle content of $3.1 \cdot 10^{19}$ particles. The simulation performed for JET like plasmas showed the minimum perturbation strength in this bigger machine is quite similar to the middle sized ASDEX Upgrade tokamak. In the pedestal region, where the pellet radius determines the ablation rate for the same temperature, the ablation rate is similar for slower pellets, while the fast pellets with small radius ablates moderately as it can be seen on Fig 3.

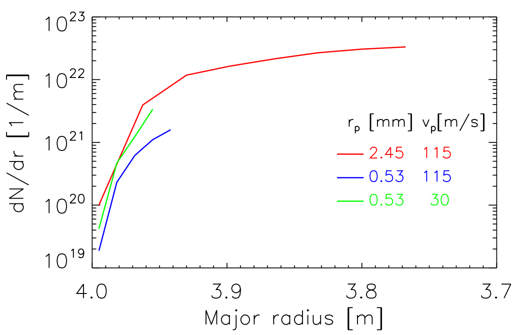

Figure 4: *The pellet induced strength of the perturbation for a reference case of experimentally benchmarked pellet with a radial velocity of* $v_p = 115$ m/s *and radius of* $r_p = 2.45$ mm *and for pellets with a reduced particle content with* 1% *of its original value for two different velocities* $v_p = 115$ m/s *and* $v_p = 30$ m/s *is shown as well.*

Taking into account the experimental observation that ELMs are triggered when the pellet is in the pedestal one should calculate the minimum perturbation strength when the pellet is in the pedestal. Both ASDEX Upgrade and JET calculations show that a minimum perturbation strength of the order of $\sim 10^{20}/$ m is enough to trigger ELM (ASDEX Upgrade $2 \cdot 10^{20}/$ m and JET $8 \cdot 10^{20}$ /m). As in ITER the pellet velocities are expected to be similar with the ones used at JET and ASDEX Upgrade we expect that this minimum strength should be equal to the strength of perturbation found at the two machines.

Simulations [1, 2] performed applying a hybrid model which describes the formation of the neutral cloud according to the NGS ablation model and the dynamics of the ionized cloud part treated by a one-dimensional Lagrangian cell code showed that the minimum perturbation strength which trigger ELMs in ASDEX Upgrade and JET-like plasmas is of the order of $10^{20}/$ m . For the pellet sizes expected to be used in ITER, the strength of the perturbation is similar, thus if the determining parameter is the strength of the perturbation the expected pellet sizes can trigger ELMs in ITER.

References

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