

Room Temperature Solid State Pellets for ELM Mitigation Studies

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Heat and particle loads accompanying ELM events can cause severe threat to the divertor of fusion devices. Methods have been worked out to control and mitigate ELMs based on magnetic perturbation [1, 2] and deuterium pellet injection [3]. These methods are suitable to control plasmas in existing tokamaks, but their use for a device at the scale of ITER has still some open questions. Even though such methods would be useful in ITER they could come with unwanted side effects like e.g. density pump out or confinement degradation due to overfueling.

A novel method under consideration is the application of room temperature solid state pellets (RTSPs) instead of cryogenic deuterium pellets. The use of RTSPs has the advantage that their preparation does not require complicated cryogenic techniques and their size and velocity as well as their injection path can be varied over a large parameter range. On the other hand impurities contaminate the plasma and consequently can cause a performance degradation, thus these side effects have to be estimated and taken into account. However, if RTSPs reaching the pedestal top of an H-mode plasma can trigger an ELM we would have at hand a technically less complicated and probably more reliable ELM mitigation method than the actual ones.

The ITER inner wall is foreseen to be Beryllium therefore the use of high speed Beryllium (Be) pellets seems to be a good candidate for ELM mitigation in ITER. The Hybrid pellet code [4, 5] was upgraded to model Be pellets. This code is a 1.5 dimensional Lagrangian code describing the pellet cloud evolution and pellet ablation. Radiation losses, the main energy loss for impurity pellet clouds, are described by the collisional radiative model. Benchmark of the code for Be pellets is not yet possible, therefore worst case scenario was modeled by assuming that the pellet is unshielded in the beginning of the local ablation process. The maximum particle content as well as the corresponding particle flux caused by Be pellets reaching the ITER pedestal top at a

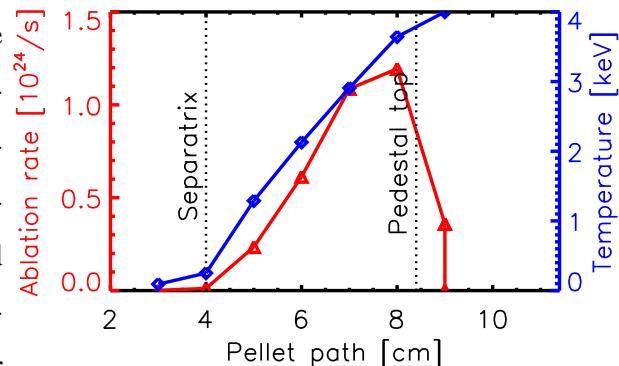


Figure 1: Pellet ablation rate on the pellet path for Be pellets in ITER like plasma. Pellets with 1000m/s and $3.3 \cdot 10^{19}$ atoms were simulated.

sufficient rate for ELM mitigation (40Hz) was estimated. Be pellets injected with 1000m/s and a radius of 0.4mm ($3.3 \cdot 10^{19}$ atoms) penetrate beyond the ITER pedestal top as shown in figure 1 and hence might be able to trigger ELMs. To estimate the impact of Be pellets on the plasma we compared the particle flux due to these pellets to the wall erosion flux (10^{22-23} Be/s) and we estimated the Z_{eff} increase as well. Only a slight increase in the total Be flux (a few per cent) was found and the maximum increase of Z_{eff} was calculated (0.01) to be negligible as well. This shows that no significant plasma performance degradation is to be expected by injection of Be pellets for ELM pacing in ITER.

However, the potential of RTSPs to trigger ELMs has not been demonstrated yet and a first proof of principle experiment was suggested for ASDEX Upgrade (AUG). Due to their toxicity Be pellets are not suitable for this task and other less toxic RTSPs with similar material properties (sublimation energy and density) had to be considered. To avoid a too large radiation increase and energy confinement degradation only low Z materials were considered. The properties of the candidate materials are collected in table 1.

The upgraded pellet code [4, 5] was used to explore these candidate materials. By comparing the different pellet materials the Hybrid code was run with the same assumption set. First simulations were performed by supposing pellets to enter a plasma with constant electron temperature (800eV) and density (10^{19} m^{-3}). The penetration depth was calculated for Beryllium, Carbon, Boron and Aluminum pellets containing $\sim 5 \cdot 10^{17}$ particles. The pellet injection velocity was assumed to be 500m/s.

As seen in figure 2, all the other materials penetrate deeper than Beryllium, so their particle content reaching the pedestal top is expected to be smaller. Boron would contaminate the plasma the least and Aluminum would penetrate the plasma similarly to Beryllium. At the end, the pellet material was chosen, according to the technical feasibility, to be Aluminum (Al) pellets with $4 \cdot 10^{18}$ atoms.

An estimation of the pellet penetration depth and of the energy degradation resulting from the

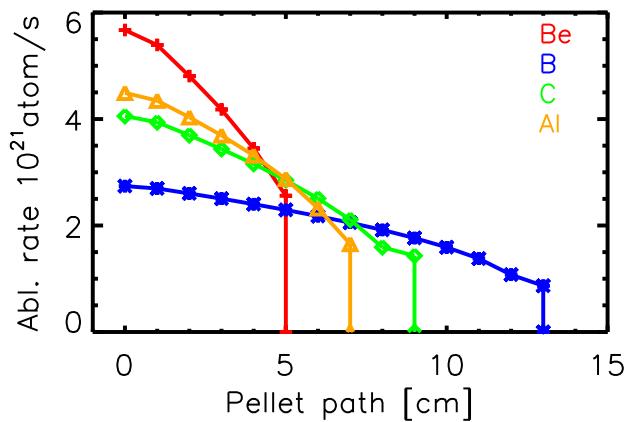


Figure 2: The pellet ablation rate on the pellet path for Be (red), Al (orange), B (blue), C (green). The target plasma temperature was 800 eV and its density 10^{19} m^{-3} . The pellet velocity was assumed 500m/s and its particle content was fixed to $5 \cdot 10^{17}$ atoms.

| Material | Sublimation energy ε (eV) | Density(kg/m ³) | Status |
|-----------|---------------------------------------|-----------------------------|----------|
| Deuterium | 0.005 | 200 | proved |
| Beryllium | 2 | 1850 | aim |
| Boron | 5 | 2400 | question |
| Carbon | 4 (2-8) | 900 | question |
| Aluminum | 3.3 | 2700 | question |

Table 1: *Candidate materials for room temperature solid state pellets*

impurity radiation had to be provided in advance based on typical conditions of type-I ELMY H-mode scenarios in ASDEX Upgrade. For such scenarios the pellet code predicts a penetration of 10-25cm for the proposed pellet size, depending on the target plasma and the pellet velocity. An example is shown in figure 3.

The radiated energy of Aluminum particles was calculated for two phases: during the first phase the particles are trapped in the cold pellet cloud ($T_{\text{cloud}} \sim 1\text{eV}$), while in the second phase they are assumed to be distributed in the background plasma. In the first phase the radiation losses given by the pellet code are in the range of a few kJ for each pellet.

For simplicity it was assumed that in the second phase the impurity profile is proportional to the initial plasma density profile [6]. Using the 1D energy transport equations for Deuterium, Aluminum and electrons we have calculated the radiated energy losses as well as the according temperature reduction. The collisional energy exchange between different species, heat diffusion ($\chi = 1\text{m}^2\text{s}^{-1}$) and Ohmic heating were taken into account. The radiated energy loss in 1ms is in the order of kJ in this phase as well. If no additional heating would be applied for a low temperature H-mode plasma with a pedestal temperature of 500eV the plasma could have been cooled to 100 eV in less than 200 μs by the radiation losses of the Aluminum. Figure 4 shows the radiated power density and the plasma electron temperature as

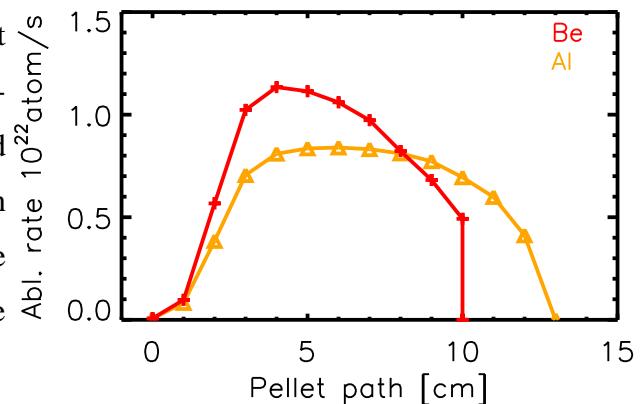


Figure 3: The pellet ablation rate on the pellet path for a typical H-mode AUG plasma with a pedestal temperature of $\sim 1\text{keV}$. Red refers to Beryllium and orange to Aluminum pellets. The pellet velocity was assumed to be 200m/s and its particle content was fixed to $4 \cdot 10^{18}$ atoms.

a function of the minor radius and time for an H-mode plasma with a low pedestal top temperature. Of course in an H-mode additional heating is applied, therefore both the radiation losses as well as the plasma temperature reduction are overestimated.

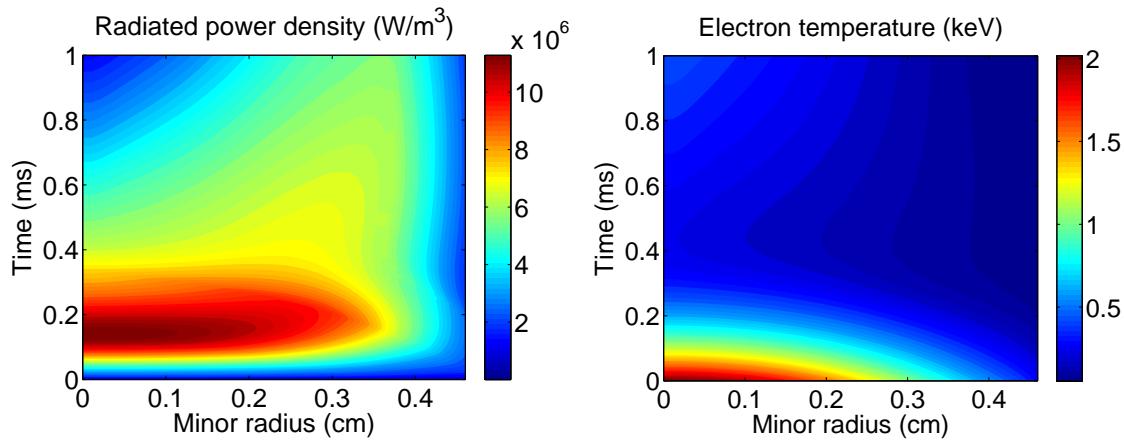


Figure 4: The radiated power density of $4 \cdot 10^{18}$ Aluminum atoms as a function of time and minor radius for an H-mode AUG plasma with a pedestal temperature of .5keV on the left. The resulting plasma temperature is shown on the right.

Similar results were obtained by Strahl calculations showing that $4 \cdot 10^{18}$ Al atoms radiating for 0.1-1ms in a plasma with constant temperature and density would cause a radiated energy loss of the order of 1-30kJ. Thus, pellet induced losses are expected less than typical energy losses caused by type-I ELMs (50kJ or more).

As Aluminum pellet injection leads to temporal degradation of the plasma performance it was concluded that Al pellets at AUG can be applied to probe their ELM trigger potential but only with repetition times much longer than the impurity confinement time. This way single Al pellet injection was proposed and the according experiments are now under way.

References

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