# Transition from no-ELM response to pellet ELM triggering during pedestal build-up — insights from extended MHD simulations

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## 1. Introduction

ITER operation is based on the H-mode regime with controlled Edge Localized Modes (ELMs), i.e., ELM power losses which do not cause excessive erosion of plasma facing components. One control method foreseen for ITER is to increase the ELM frequency by periodic injection of small pellets, thereby reducing the energy losses by each individual ELM [1]. Reliable pellet ELM pacing has been demonstrated by experiments in JET, ASDEX Upgrade and DIII-D [1-3]. This technique allows to reduce energy losses by each individual ELM and is considered for ITER [4]. However, further understanding of the physics principles guiding the interaction of ELMs with pellets and of the requirements for pellet conditions (size, speed, etc.) are needed to guarantee reliable ELM triggering.

Experimental observations show that the frequency of ELM pacing by pellet injection cannot be increased arbitrarily due to a so-called lag-time. During this time after a preceding natural or triggered ELM crash, neither a natural ELM crash occurs nor the triggering of an ELM crash by pellet injection is possible. Recently, simulations of periodic type-I ELM cycles in ASDEX Upgrade were performed for the first time [5]. Based on this setup, ELM triggering simulations were carried out by injecting pellets at various times in the inter-ELM phase to analyze the lag-time and the transition into the ELM triggering regime for the first time [6]. Comparisons to simulations of natural ELM crashes were performed [7].

## 2. Simulation setup

Pellets are injected from the top of the high field side (HFS) in the pellet ELM pacing experiments in the ASDEX Upgrade tokamak [8]. Pellets are prepared in the cryogenic system. The pellet size can range from $1.5\times10^{20}$ to $3.7\times10^{20}$ (particles/pellet) and the injection velocity can range between 240 and 1040 $ms^{-1}$ (dependent on the pellet size) according to the technical capabilities of the pellet injector at ASDEX Upgrade. In the simulations, a pellet size '$0.8\times10^{20}$D' corresponds to about double the amount of material in the experimental pellet, as we are assuming that ~50% of the pellet particles are lost in the 17 m long guide tube on the way between the cryogenic system and the HFS.

Simulations are carried out with the non-linear MHD code JOREK [9,10]. The JOREK code allows to perform 3D simulations of ELM triggering by pellets [11] in a self-consistent way by solving extended non-linear MHD equations and the pellet ablation process.

3. Pellet injections at different times during pedestal build-up

Simulations were performed with a pellet size of $0.8\mathrm{x}10^{20}$D atoms injected at 560 $\mathrm{ms}^{-1}$ considering different injection times. Figure 1 shows the time evolution of pressure, temperature and density at the pedestal top during the inter-ELM period in the JOREK ELM cycle simulation [5] used as basis. The post-ELM profiles build up until they reach the MHD stability limit and a spontaneous ELM crash occurs at about 16 ms, causing a significant loss of particles and thermal energy. Figure 1 also shows profiles of the toroidally averaged pedestal pressure for time slices 0.5, 2, 4, 6, 8, 10, 12, 14, and 15 ms. Pellet injections are simulated at different times during pedestal build-up which correspond to evolving MHD stability conditions.

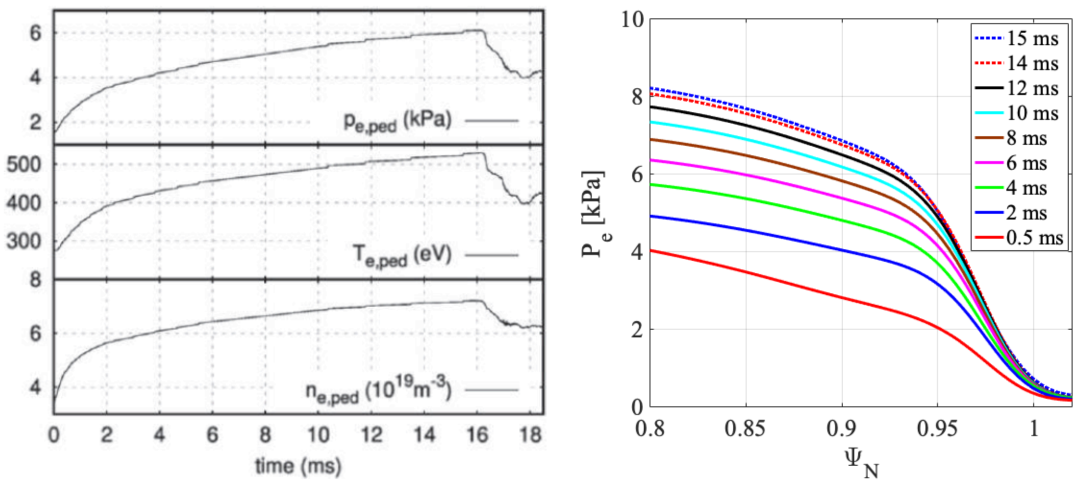


Figure 1. (Left) The time evolution of the pressure, temperature and density at the pedestal top of the base spontaneous ELM case [5]. (Right) Profiles of toroidally averaged electron pressure at the injection times.

Figure 2 shows the power load onto the inner and outer divertor targets which is caused by the pellet injections. There is a sharp transition in the peak of the integrated power load onto the divertor targets between cases where no ELM is triggered ($t_{injection}$ < 12 ms) and the case where an ELM is triggered ($t_{injection} \geq$ 12 ms). For the present set-up, a spontaneous ELM appears at ~16 ms and, therefore, all pellets are injected into stable plasma conditions. Figure 3 shows the heat flux to the outer divertor versus the divertor length and time at the toroidal angle corresponding to the injection location. It is clearly visible that the cases without ELM triggering ($t_{injection}$ < 12 ms) do not show a prominent increase of divertor heat flux. On the other hand, the case of pellet injection at 12 ms shows a strong increase of the heat flux (~20 $\mathrm{MWm}^{-2}$) at the strike point for 12.1-12.5 ms. This is the first simulation which qualitatively reproduces the experimentally observed lag-time in the self-consistent pedestal build-up [6].

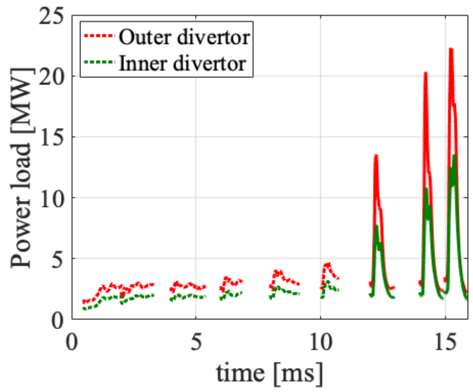


Figure 2. Time evolution of the power load onto inner and outer divertor targets caused by the 0.8x10$^{20}$D pellet injection with a velocity of 560 ms$^{-1}$, for various injection times.

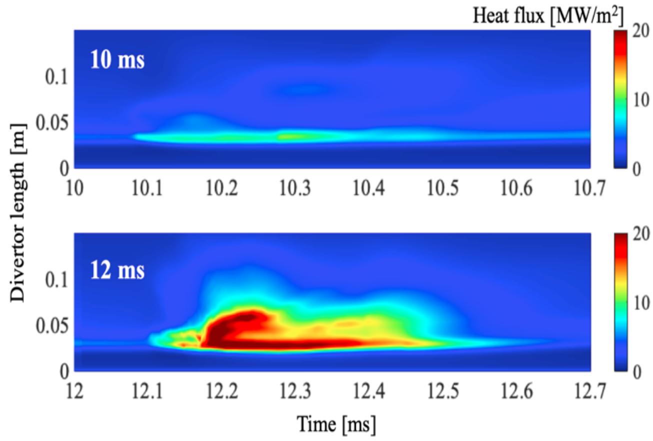


Figure 3. Time-evolution of the heat flux onto the outer divertor targets caused by the 0.8x10$^{20}$D pellet injection with a velocity of 560 ms$^{-1}$. Two cases are compared with no-ELM response (10 ms) and ELM triggering (12 ms).

Figure 4 shows the toroidal spectrum of the magnetic energies time-averaged over the pellet ablation process (spectrum insensitive to exact averaging time window). In the ELM triggering cases (12-15 ms), the nonlinear spectrum is significantly broader than in cases without an ELM being triggered. In the pellet-triggered ELM case (12 ms), a lower connection length to the divertor targets becomes visible. Figure 5 shows the Poincaré plot at the times when the pellet is located at $\Psi_N$=0.91, for the injection times of 10 ms (non-ELM triggering) and 12 ms (ELM triggering). As the pellet enters the plasma, the magnetic field starts to become perturbed and reconnection takes place. Therefore, a stochastic region is formed at the edge of the plasma due to the pellet-induced perturbation. While the stochastic region reaches only slightly lower connection length to the divertor targets becomes visible.

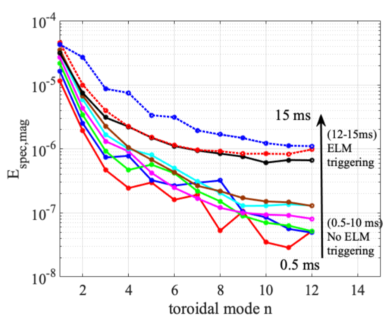


Figure 4. Time-averaged toroidal spectrum over the pellet ablation process.

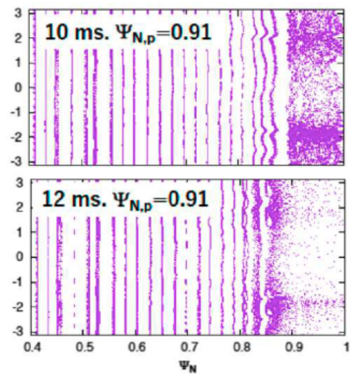


Figure 5. Poincaré plot when the pellet has reached $\Psi_N$=0.91, for the injection times 10 and 12 ms.

Similarities and differences between simulated spontaneous and pellet-triggered ELMs from [5] and [6] were studied in [7], revealing differences in the mode spectrum and wetted area. Figure 6 compares heat fluxes to the inner and outer divertors and Poincaré plots for spontaneous and pellet-triggered ELMs. While triggered ELMs have a reduced peak heat flux, the wetted area is narrower. This observation, which is undesirable for pellet-ELM triggering as a control method, is qualitatively consistent with experimental observations [12].

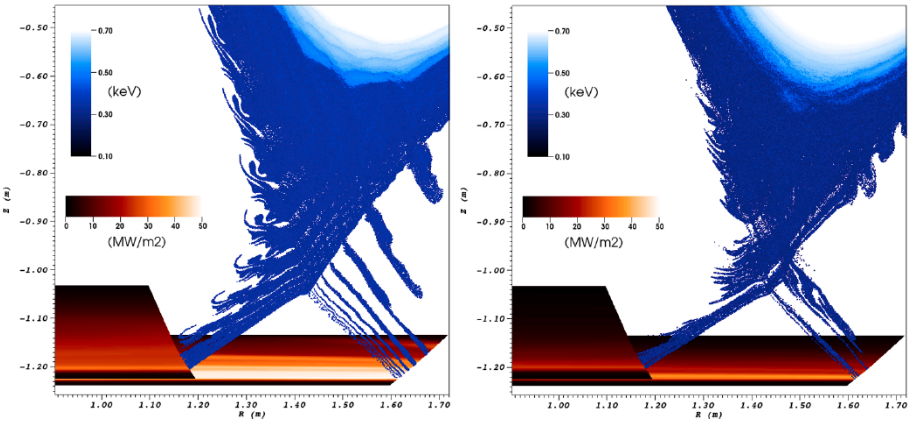


Figure 6. Heat flux to the inner and outer divertor targets and real space Poincaré plot. The left panel shows the spontaneous ELM and the right panel shows the pellet triggered ELM (14 ms).

## 4. Conclusion

Simulations with $0.8x10^{20}$ deuterium atoms injected (corresponding to a $1.5x10^{20}$ pellet before guide tube losses in the experiment) show a sharp transition of the energy losses between early (t<10 ms) and later (t>12 ms) injection times which correspond to different stages of pedestal build-up. The toroidal mode spectrum is significantly broader when an ELM is triggered, enhancing the thermal energy losses by perpendicular convection as well as parallel conduction in the stochastic magnetic field. Simulations show reduced ELM sizes for pellet injection right after lag-time, albeit with a slightly narrower wetted area on the divertor.

**Acknowledgements**

This work was carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. Simulations were performed using the Marconi-Fusion supercomputer.

**References** [1] Lang, P.T. et al. Nucl. Fusion 43 (2003) 1110; P.T. Lang et al., Nucl. Fusion 53 (2013) 073010. [2] D. Frigione et al., J. Nucl. Mater. 463, 714 (2015). [3] Baylor, L. et al., Phys. Plasmas 20, 082513 (2013). [4] Loarte, A. et al., Nucl. Fusion, 54, 033007 (2014). [5] Cathey et al., Nucl. Fusion 60, 0124007 (2020). [6] Futatani et al., Nucl. Fusion 61 046043 (2021). [7] Cathey et al., Plasma. Phys. Control. Fusion 63, 075016 (2021) [8] H Meyer et al., Nucl. Fusion 59 112014 (2019) [9] GTA Huysmans and O Czarny, Nucl. Fusion 47, 659 (2007) [10] M Hoelzl, GTA Huijsmans et al., Nucl. Fusion 61, 065001 (2021). [11] S. Futatani et al., Nucl. Fusion 54, 073008 (2014); S. Futatani et al., Nucl. Fusion 60, 026003 (2020). [12] RP Wenninger et al., Plasma Phys. Control. Fusion 53, 105002 (2011).