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# Investigation of pellet-driven plasma perturbations for ELM triggering studies

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The transient power load on plasma facing components caused by edge localised modes (ELMs) in H-mode plasmas can be critically high for large size toroidal machines like ITER, therefore it is of high importance to develop methods to mitigate this effect. Pellet ELM pacemaking - the injection of frequent small and shallow penetrating cryogenic pellets - has been found to be a promising mitigation technique. Pellets injected into ELMy H-mode plasmas have been found to be able to trigger prompt ELMs. To be able to predict the capability of the pellet ELM triggering in future toroidal machines and to optimise the ELM pacemaking tool the understanding of the trigger mechanism is indispensable.

At present it is known that the potential candidates for the pellet ELM triggering mechanism can be the high pressure non-axisymmetric pellet cloud, the cooling of the pedestal region causing a sudden increase of the pedestal plasma pressure gradient driving the plasma to the unstable region of the ballooning instability or the strong MHD perturbation generated by the high beta pellet cloud triggering an instability developing into an ELM. Therefore our aim is to investigate these pellet caused plasma perturbations in view of the understanding of the ELM triggering mechanism.

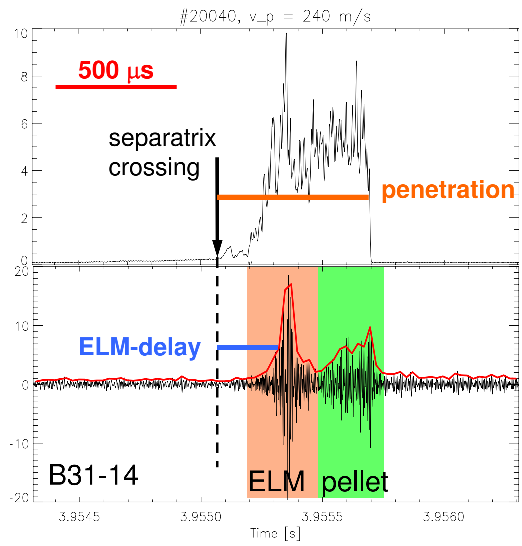


Figure 1: *The ablation monitor (upper fig.) and the pick-up coil signal (lower fig.) together with the calculated amplitude (red curve) for a slow pellet ablating in type-I ELMy H-mode.*

At ASDEX Upgrade tokamak a system of Mirnov and magnetic pick-up coils positioned at different poloidal, toroidal and radial positions measures the MHD perturbation strength during pellet ablation. Calibrated Electron Cyclotron Emission (ECE) profiles are measured in second harmonic X-mode with a fast 60-channel heterodyne radiometer. The use of multi-chord soft X-ray (SXR) system detecting the radiation above 1keV photon energy makes possible the tomographic reconstruction of the radiation distribution with good time resolution. These diagnostics allow us to deduce the spatio-temporal variation of plasma temperature during pellet ablation. A pellet observation system was also developed to localise the pellets during their flight in the plasma therefore the induced perturbations can be parameterised by the magnetic surface of the instantaneous pellet position.

In our investigations presented in this contribution pellets with different velocities and mass were injected with low frequencies (5-6Hz) into standard ohmic and ELMy H-mode scenarios (type-I and type-III) of the ASDEX Upgrade tokamak and the effect of the pellet injection detected by the above diagnostics will be analysed in details.

In these studies the envelope of the high-frequency component from pick-up coil signals was adopted to characterise the magnitude of the MHD activity (Fig. 1). Low-frequency components were filtered out by subtracting a 10-point (5 us) moving boxcar average from the original signal. The envelope of this filtered signal was calculated as the peak-to-peak value (divided by 2) in a moving box of 50 data points (25 us). The resulting envelope signal has clearly shown a good qualitative agreement with the spectral power density of the original signal integrated in the 100-300 kHz range, indicating that the envelope may be used as a measure of the high-frequency MHD activity.

The analysis of the MHD activity magnitude during pellet ablation showed that in the ELM-free ohmic plasma the induced MHD perturbation rises gradually as the pellet penetrates deeper and deeper into the plasma independently of the pellet velocity, while in the type-I ELMy H-mode it shows an additional explosive growth after the pellet has reached a certain position in the H-mode pedestal triggering an ELM (yellow zone marks the ELM signature on Fig. 1). Applying a pellet time of flight method allowed us to determine the most probable location of the seed perturbation of the pellet ELM triggering for this scenario [1]. The type-III ELMy H-mode case more resembles to the ohmic one: the magnitude of MHD activity of these small and frequent ELMs is usually smaller than that of the directly pellet driven, the magnitude is determined again by the instantaneous pellet location in the plasma. To compare all three scenarios the magnitude of the MHD activity is plotted on Fig. 2 as function of the plasma (electron) pressure value at the instantaneous location of the pellet until it burns out. This figure supports that the magnitude depends on the plasma parameters but not on the pellet parameters: it increases with the plasma pressure and only the location of the type-I ELM representing explosive growth shows pellet velocity dependence.

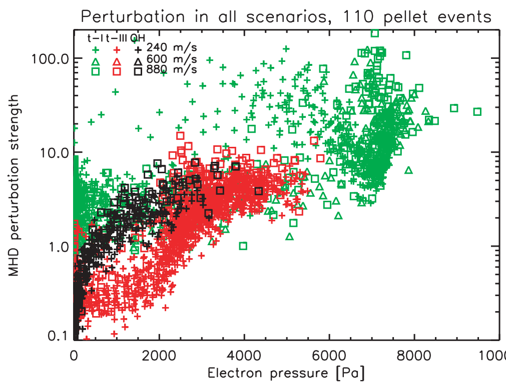


Figure 2: *The magnitude of the MHD activity as function of the electron pressure at the instantaneous location of the pellet for all scenarios.*

After pellet burn out the pellet driven MHD activity relaxes on a 100$\mu s$ timescale. No scenario dependence of this relaxation time was found at least the variation stays within the error bars.

STFT spectrograms and Morlet wavelet scalograms of the pick-up coil signals revealed that in ohmic plasmas the ablating pellet (the gradB drift polarised pellet cloud) intensifies the inter-pellet TAE mode (at ∼120kHz) driven by drift Alfvén turbulence [2] by launching broadband Alfvén waves. The toroidal mode number of this coherent mode was determined by the method based on the phase of the continuous analytical wavelet transform [3] using a toroidal array of the pick-up coils. Being time-shift invariant, this method is very much suited for the study of transient signals, like ELMs and pellets. Fig. 3 shows the result of the toroidal mode number analysis for an ohmic shot for the time window around the pellet injection. For 120kHz frequency a toroidal mode number of n=-6 was obtained, the pellet ablation broadens the frequency range and after the pellet burn out the mode is missing for few 100$\mu s$ than it recovers. For type-I ELMy H-mode a washboard mode was recognised in the 60-100kHz frequency in earlier study [4]. Our results confirm this observation and toroidal mode number of n=4 and n=3 were found for 100kHz and 70kHz, respectively. These coherent modes disappear at the beginning of the triggered ELM and are missing for about 1ms. For low velocity the pellet lives longer than the ELM signature is visible on the pick-up coil signals and in this case the n=-6 mode observed on the ohmic discharges appears again until the pellet burns out. For the type-III discharges the mode number determination suffers from the large uncertainty, but it seems to be that the structure resembles rather to the ohmic case (n=-6 for 120kHz) but sometimes the n=3,4 modes become visible as well.

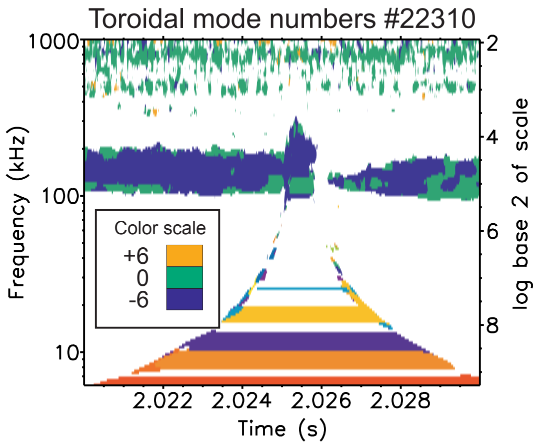


Figure 3: *Toroidal mode numbers for an ohmic shot for time window around the pellet injection ($t_{PEL} \simeq 2.025s$).*

The non MHD perturbation caused by the ablating pellet is accompanied with a large local particle deposition spreading with ion sound speed ($\approx 10^5 m/s$) and with a local cooling which is homogeneously distributed on the magnetic surface on a few 10$\mu s$ timescale because the fast electron cooling wave travels along the magnetic field lines with electron thermal speed ($\approx 10^7 m/s$). Therefore the local cooling should appear on fast ECE electron temperature measurement located toroidally 90° from the location of the pellet injection on a few 10$\mu s$ timescale without any significant density increase. This can be observed on Fig. 4, 5 where the time evolution of the type-I ELMy H-mode temperature profiles is plotted together with pellet trajectory for two different pellet velocities (600m/s and 240m/s). It is obvious that the pellet caused cooling appears almost immediately after the pellet reached the according magnetic surface (note that the ECE data are sampled with 31.25kHz and the pellet cloud radius perpendicular to the magnetic field is about 1cm) causing remarkable temperature drop on a short timescale and the cooling front moves together with the pellet for all pellet velocities (240-1000m/s). The time scale of the the temperature fall is inversely proportional to the pellet velocity. As the pellet - penetrating into the H-mode pedestal - almost immediately triggers an ELM, the ELM collapse induced temperature reduction is also seen on the ECE temperature evolution. Analysing natural ELM events it was revealed that their cooling time scale is much longer - typically ms timescale - allowing us to discriminate between these two cooling effects.

The pellet plasma cooling lasts until the pellet is completely ablated and the plasma starts to recover but on a ms timescale. The relative temperature drop is in the range of few 10%. Model calculations predicts that at least the sudden (before the deposited ablatant is distributed on the magnetic surface) local plasma cooling - the relative temperature drop - should be larger for smaller velocities, because the slower pellets reside longer at a magnetic flux tube cooling it longer. Our observations seem to support this expectation, but detailed investigation should be conducted especially in ELM free L-mode to confirm it which is the subject of near future work.

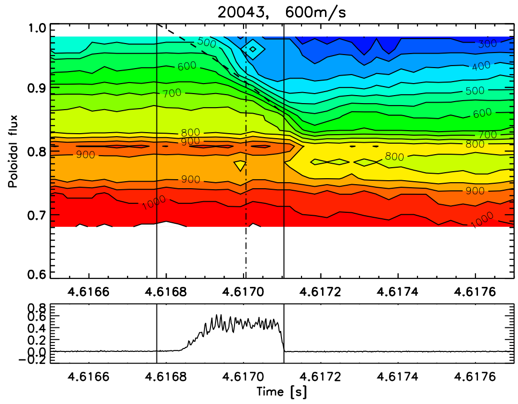


Figure 4: *ECE electron temperature profile evolution together with the pellet ablation monitor signal (lower fig.). The dashed curve represents the pellet trajectory, the vertical dash-dotted line the onset of the triggered ELM.*

Preliminary analysis of tomographic reconstruction of the SXR signals during pellet ablation confirms the above pellet related cooling observations as well.

To summarise, we observed that the ablating pellet intensifies the inter-pellet TAE modes in ohmic discharges. For type-I ELMy H-mode the inter ELM washboard mode dominates the magnetic spectra at high frequencies and the direct pellet driven mode can be detected only after the termination of the ELM magnetic signature until the pellet burns out. The high density type-III ELMy H-mode more resembles to the ohmic case than to the type-I. The pellet caused cooling appears almost immediately after the pellet reached the according magnetic surface causing remarkable temperature drop on a short timescale and the cooling front moves together with the pellet.

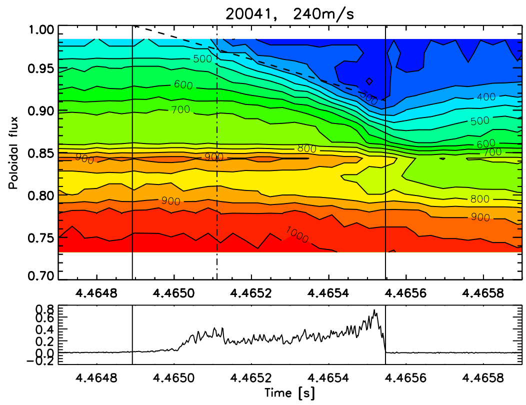


Figure 5: *The details see at Fig. 4*

## References

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