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** See annex of F. Romanelli et al, "Overview of JET Results",*
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INTRODUCTION

The aim of this study is to identify threshold parameters required for a deuterium pellet to trigger an ELM in H-mode plasmas using the new JET High Frequency Pellet Injector1-4. By measuring signals with fine time resolution, unambiguous temporal correlations between pellets injected into the plasma and ELM occurrence can be made and subsequently thresholds in pellet size and velocity can be estimated. These thresholds, having been determined for the first time here, can enable an informed strategy to be developed to provide a mechanism for controlling the ELM frequency on ITER through the injection of a stream of pellets, a technique called pellet-ELM pacing. If the pellets are small enough then, in principle this could be implemented with only minimal increase in the plasma density.

Vertical High Field Side (VHFS) pellet injection into H-mode plasmas on JET is studied here using a range of diagnostics providing data with sampling rates up to one MHz. D_α emission from the pellet ablation cloud as it enters the plasma from the VHFS is illustrated in Figure 1 which shows the viewing setup. The ablation cloud appears in the field of view just prior to the pellet reaching the last closed flux surface. In Figure 2 time traces of the D_α emission from a pellet entering the plasma from the VHFS in H-mode (upper) and Ohmic (lower) are plotted. From the duration of pellet ablation (~350µs and ~2ms respectively) and the pellet velocity, an estimate of the pellet penetration can be made. Using the nominal launch velocity of ~150m/s maximum penetration depths of ~5cm in H-mode and ~30cm in Ohmic are found. (Penetration depths are discussed in more detail in Refs: 1&4.) The Ohmic value is consistent with fast ECE T_e measurements in Ohmic/L-mode plasmas which show a rapid drop in temperature at a major radius of 3.71m on the LFS. This is also supported by the detection of very small local LFS density perturbations (≤ 1 10^{18} m^{-3}) which penetrate the plasma as far as 3.7m using a new swept reflectometer diagnostic5. The relevant ablation region is illustrated in green in Figure 1.

Using fast D_α pellet ablation signals and correlating them in time with fast D_α and edge SXR signals from an ELM, studies of pellet-ELM triggering can be made. These traces are shown in Figure 3 for Pulse No: 79566. In this case the ELM is almost certainly triggered by the pellet with the rapid onset in $D\alpha$ light and fall in edge SXR appearing near the end of the pellet ablation emission as it penetrates a few cm beyond the last closed flux surface. (Note: it is observed that any stray light from an ELM into the pellet monitor produces only a negligible signal in the latter.)

In JET Pulse No: 78606, a train of small (pacing-sized) pellets was generated at 20Hz for injection into the plasma via the VHFS. At present the injector is unable to produce a reliable stream of such pellets and only a small fraction enters the plasma. Those that do enter are clearly seen on the pellet D_α monitor. They can be finely correlated in time with D_α from the ELM and a fall in edge SXR emission. Their relative size can be determined from the signal-level in the Da monitor. In Figure 4 is plotted the peak pellet monitor pulse-height against the pellet launch number. It is seen that less that 1 in 5 of pellets reaches the plasma – typical of this series of experiments. Those that trigger an ELM (9 in total) are shown in red. They generally have a pulse height ≥ 1V;

those that do not are typically below 1V. This pulse was in a "Low-Triangularity (LT)" configuration. Similar statistics were found for other discharges in the series even those with nominally higher triangularity; though edge barrier measurements for these pulses showed little variation.

Results from these studies show for the first time in any tokamak that there is a threshold in the size of pellet required to trigger an ELM. The nominal launch size of these pellets was ~2mm^3 (1.2mm diameter by 1.8mm long) corresponding to ~1.2×10^{20} D atoms though the largest VHFS pellets to reach the plasma4 are estimated to have only ~5×10^{19} D. If these pellets correspond to the highest monitor signal (5V) and if this pulse height is roughly proportional to pellet mass entering the plasma then the threshold for pellet triggering in these pulses is ~1×10^{19} D or ~0.5 mm^3. Using the total integral emission from the monitor rather than peak emission gives similar results but raises the estimated threshold to ~1.6×10^{19} D.

Pellet speeds are evaluated in Figure 5a. The initial speed is compared with that determined from the flight time from mwave cavity C2 (before the path selector) to the time the pellet is detected in the plasma by the D_α monitor. The initial velocity of ~170m/s falls by about 35% to ~110m/s averaged over the flight path. Those pellets which trigger an ELM are identified in red. They have a similar velocity distribution to the complete sample of pellet fragments.

Fast edge density measurements using the FIR interferometer6 provide values at 100kHz. In LT discharges, short-lived ELM precursors (typically ~1ms but occasionally up to 5ms), prior to spontaneous ELMs, are present as illustrated in Figure 6. These are not seen before most pellet triggered ELMs in Pulse No: 78606. For Low Field Side (LFS) injected pacing pellets no fast signal is available to identify which pellets penetrate the plasma and when they do. However, the absence of an ELM precursor in the fast edge density measurements has been used in a nominally identical Pulse No: 78605 to identify those ELMs that were triggered by a pellet. Figure 5b shows a plot of the estimated speed of each pellet for this pulse. The mean speed from μwave cavity (C2) to cavity 4 (C4) which is located roughly midway along its flight path is displayed for all pellets detected at cavity 4. The mean speed from C4 to the ELM onset for those ELMs identified as pellet-triggered is shown in red. These indicate a slowing down in the last half of the track (C4 – ELM) to ~120m/s. Using these and the VHFS values would reduce the penetration depths estimated above to 3.5cm (H-mode) and 20cm in L-mode. (Note four ELMs were not detected in cavity C2 either because the pellet signal was below the cavity trigger threshold or because the ELM was in fact spontaneous but without a precursor). Nonetheless in these two pulses the indication is that a similar number of ELMs have been pellet-triggered from the LFS and the VHFS (10-14 vs. 9).

A comparable study, using ELM precursors to differentiate spontaneous from triggered ELMs with LFS injection in plasmas in the same session with higher mean triangularity (0.41 versus 0.26), could not be applied. Figure 7 shows a density-time trace for Pulse No: 78603 (VHFS pellet injection). Here the precursor mode is seen to be of much longer duration (>50ms), so pellet triggered ELMs are here regularly found to interrupt this mode. It is worth noting however, that using data from the pellet D_α monitor, a similar threshold of ≥ 1.2V pulse height is required to trigger an ELM in this discharge. From magnetic analyses, the toroidal mode number for the short lived mode (LT) was n = 10 (at ~20kHz) and the long lived mode discussed here was n = 3 at (~10kHz).

SUMMARY

a threshold pellet size for pellet-ELM triggering in these discharges is estimated to be ~1-2×10^{19} D atoms (<1mm^3). This value holds at least for isolated ELM triggering. These small pellets, being only a few percent of the size of a fuelling pellet, are not found to contribute to any net increase in plasma density. The triggering efficiency in these cases does not appear to depend strongly on entry port (VHFS or LFS), on pellet velocity over the range 100-140m/s or on plasma configuration but these pellets do penetrate ~3cm into the edge H-mode barrier. The pellet-ELM triggering mechanism is independent of precursor modes seen with spontaneous ELMs.

Whether independent control of ELM frequency and plasma density in ITER, through the corresponding injection of pacing and fuelling sized pellets would be possible, largely depends on how the pacing thresholds scale with triggered-ELM frequency and edge barrier parameters. This is to be studied in future JET operations.

Given the small size required for a pacing pellet and the difficulty in maintaining its integrity over long flight paths (less than 10% of the requested pellets actually reached the plasma from the VHFS to trigger an ELM) it is proposed that materials other than D2 e.g. non-cryogenic carbon or polythene could be considered for this purpose.

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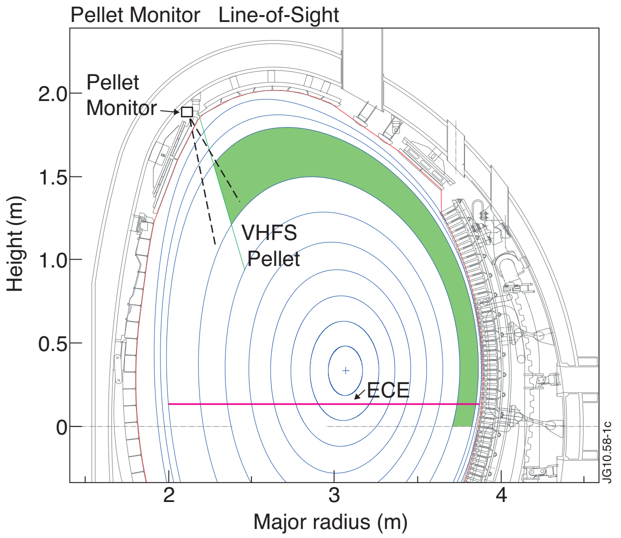

Figure 1: Pellet Monitor Views The mapping of the ablation region to the ECE line of sight for Ohmic discharges is indicated in green.

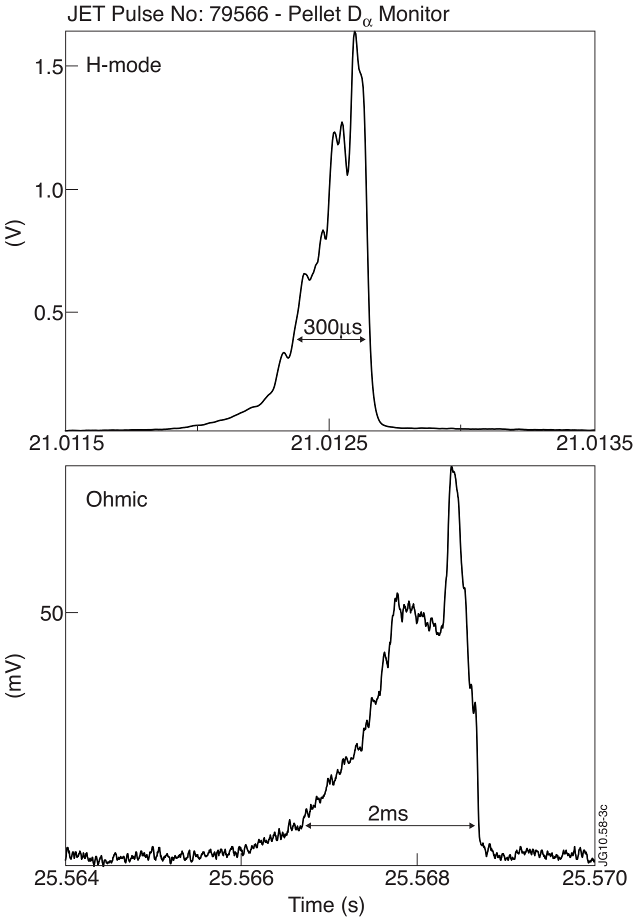

Figure 2: Pellet Ablation in H-mode and Ohmic plasmas.

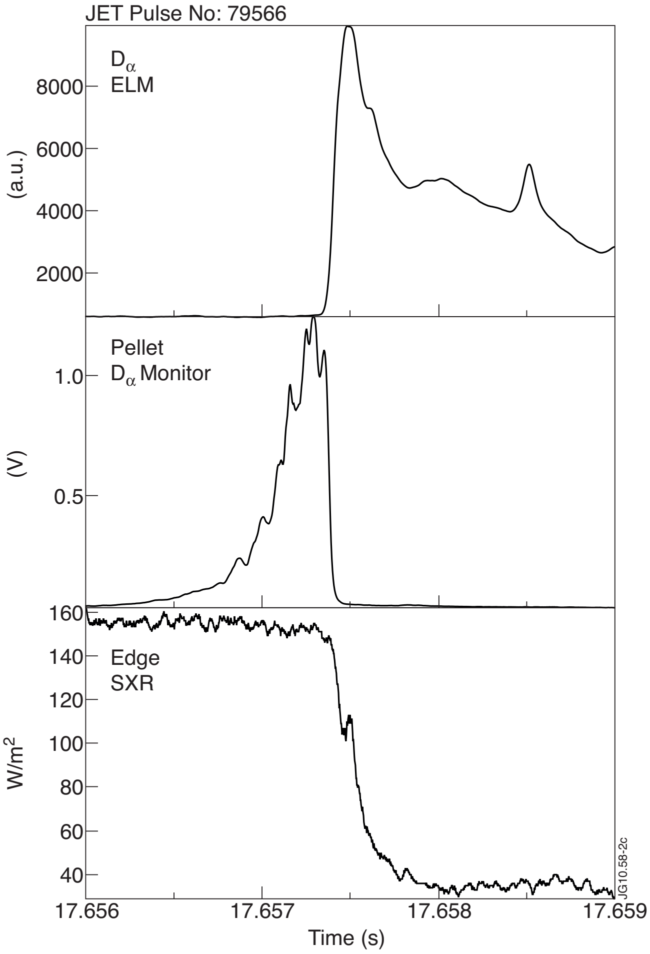

Figure 3: Pellet ELM trigger signals.

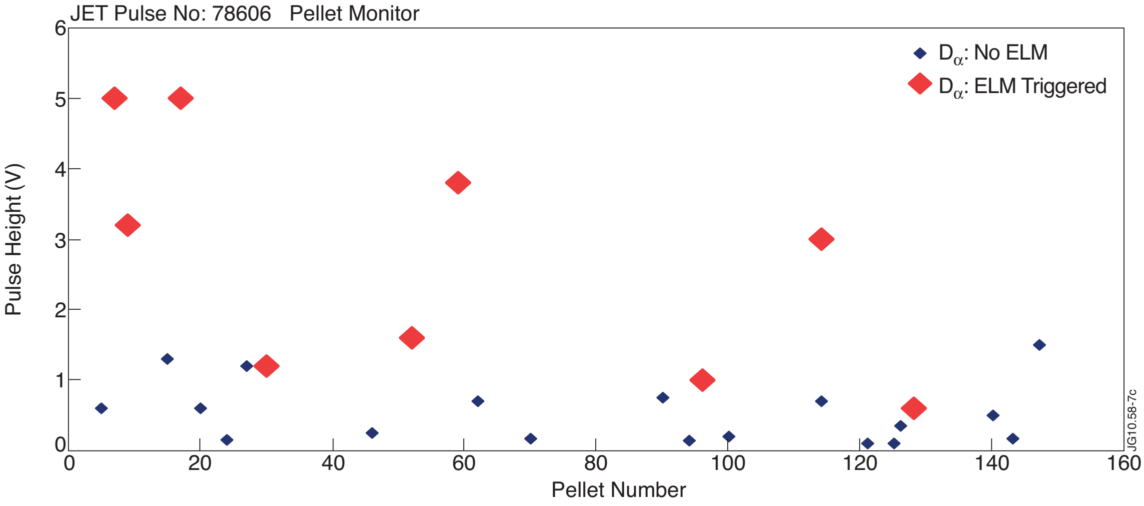

Figure 4: Pellet monitor pulse height against pellet number. Those that trigger an ELM are shown in red and typically are >1V.

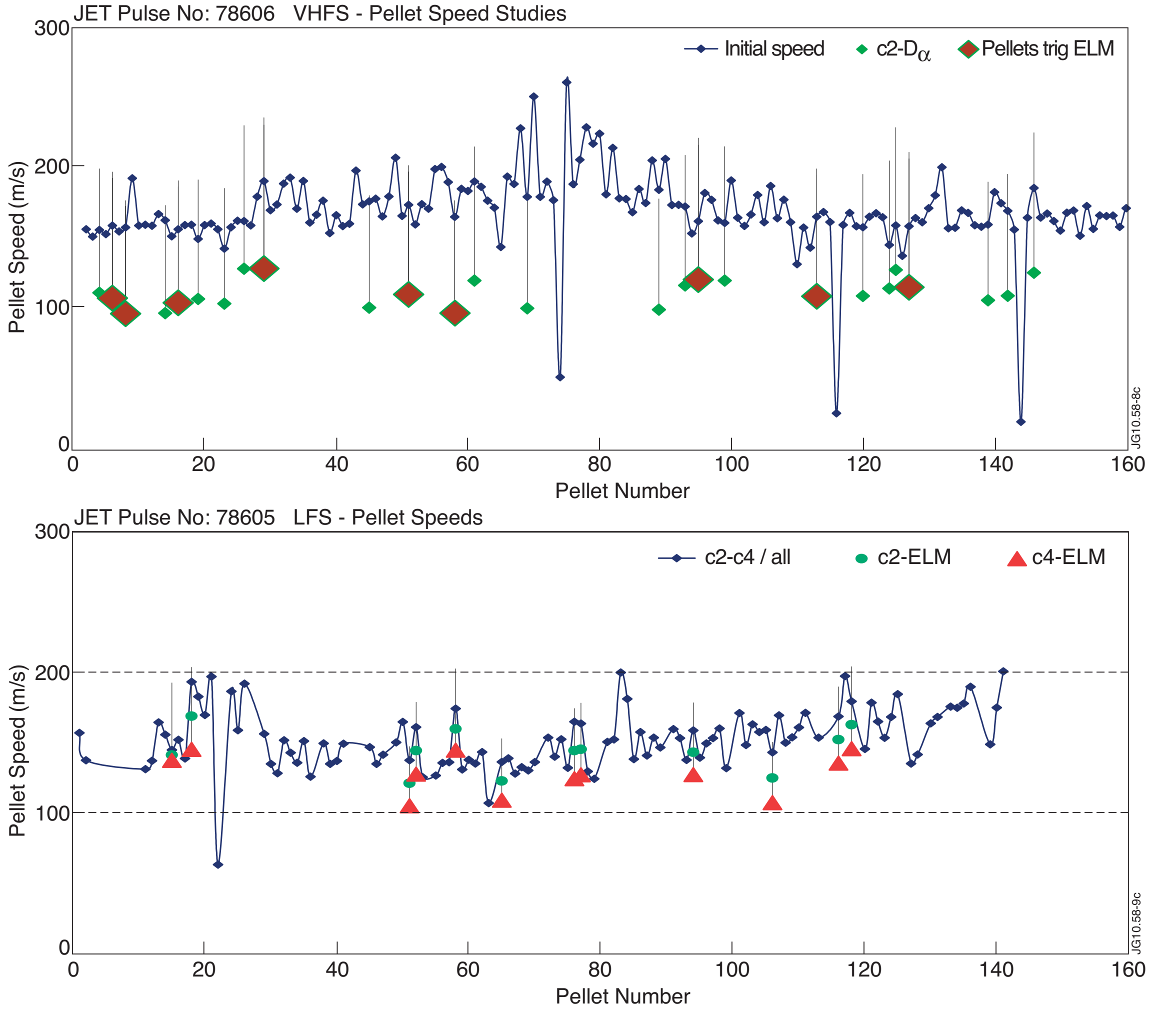

Figure 5 Pellet launch velocity is compared with mean speeds determined from flight times to arrival in the plasma for a) VHFS and b) LFS pellets. Note in both cases less than 1 in 10 pellets launched survive to trigger an ELM.

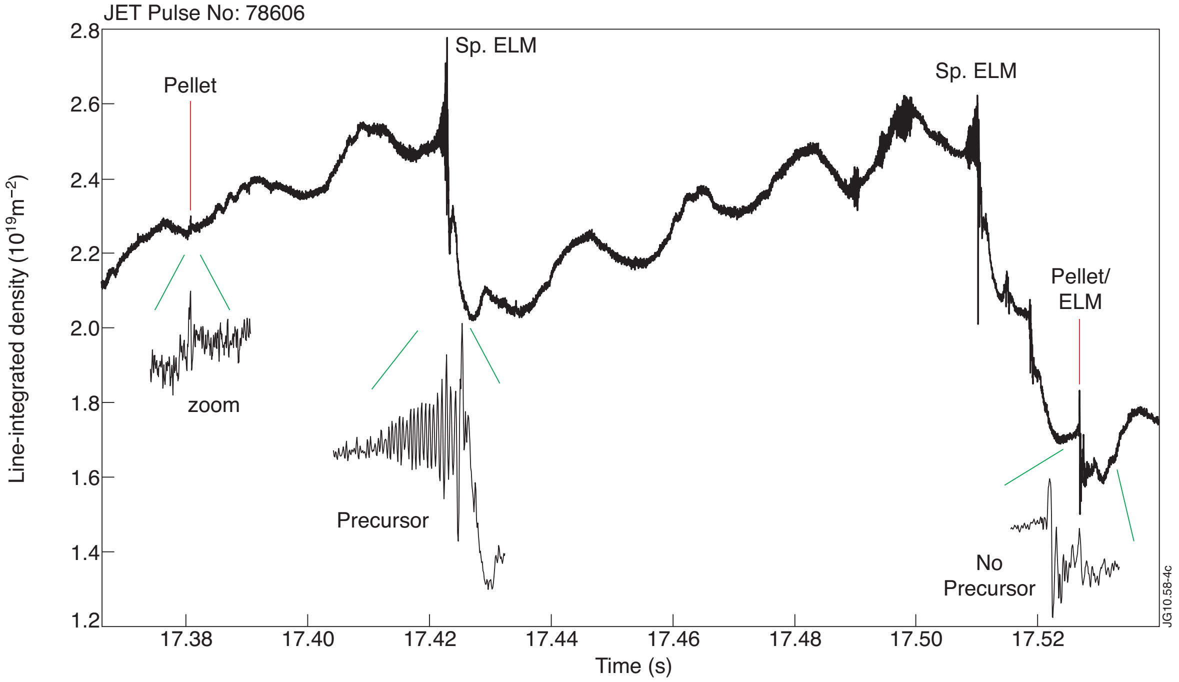

Figure 6: Fast Edge density traces. Only spontaneous ELMs are found to have a short lived n=10 precursor.

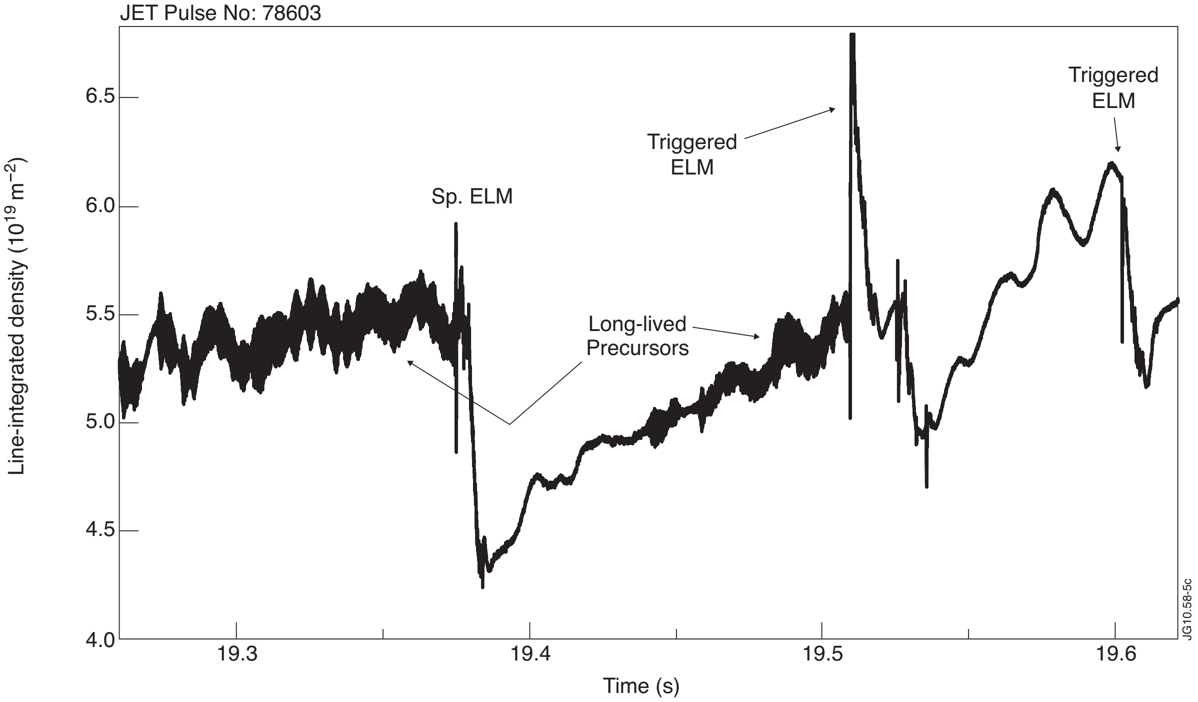

Figure 7: Long lived n=3 precursors are seen in this High Triangularity discharge which can be interrupted by a pellet which triggers an ELM.