ELM pacing investigations at JET with the new pellet launcher

P. T. Lang 1), A. Alonso 2), B. Alper 3), E. Belonohy 1), A. Boboc 3), S.Devaux 1), T.Eich 1), D. Frigione 4), K. Gál 5), L. Garzotti 3), A. Geraud 6), G. Kocsis 5), F. Köchl 3,7), K. Lackner 1), A. Loarte 8), P.J. Lomas 3), M. Maraschek 1), H.W. Müller 1), G. Petravich 5), G. Saibene 9), J. Schweinzer 1), H.Thomsen 1), M. Tsalas 10), R. Wenninger 11) and JET EFDA Contributors*

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK
1) MPI für Plasmaphysik, EURATOM Association., 85748 Garching, Germany
2) Laboratorio Nacional de Fusion, Euratom-CIEMAT, 28040 Madrid, Spain
3) Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
4) Associazione EURATOM-ENEA sulla Fusione, CP 65, Frascati, Rome, Italy
5) KFKI RMKI, EURATOM Association, P.O.Box 49, H-1525 Budapest-114, Hungary
6) CEA Cadarache, Association Euratom/CEA, 13108, St Paul-Lez-Durance, France
7) Association EURATOM-ÖAW, Atominstitut, TU Wien, 1020 Wien, Austria
8) ITER Organization, 13067, St Paul-Lez-Durance, France
9) FUSION FOR ENERGY, Joint Undertaking, 08019 Barcelona, Spain
10) JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK
11) Universitätssternwarte der LMU, Scheinerstr. 1, D-81679 München, Germany
E-mail contact of main author: peter.lang@aug.ipp.mpg.de

Abstract. A new pellet injection system was installed at JET designed for both fuelling and ELM pacing. The purpose of the pacing section was to validate pellet ELM pacing as a suitable tool for ELM mitigation in ITER. Pellet pacing was confirmed at the large size scale of JET, and an enhancement of the intrinsic ELM frequency up to a factor of 4 was achieved. Investigations of the dynamics of triggered ELMs were performed with respect to their spontaneous counterparts. Triggered ELMs essentially show features also typical for spontaneous ELMs in several operational regimes, a strong hint for compatibility with other plasma control tools. Observations and modelling results indicate the ELM triggering occurs by the pellet ablation plasmoid evolving into the first ELM filament followed by a poloidal spread of the instability. An ELM obviously can be forced by a pellet due to the strong local perturbation imposed already under unusual onset conditions but then evolves like any ELM typical for this plasma regime. For tool optimization the pellet mass and hence the convective confinement losses imposed have to be minimized. In our experiments, a lower mass threshold was observed for the first time. It has been found that to reliably trigger an ELM the pellet needs to be sufficiently large (and fast) to penetrate to the top of the pedestal. Recent investigations are clear steps forward to validate the pellet pacing approach for ITER. Pellet pacing is a robust and reliable tool deployed in many tokamaks, however a full demonstration in an ITER relevant parameter regime has not been achieved yet.

1. Introduction

Type-I ELMs can, due to their transient nature and the amount of energy involved, form a severe threat. Their destructive potential increases with increasing tokamak size [1], reaching worrying dimension at ITER. Significant target plate erosion due to vaporization or loss of the melt layer for metals can occur under type-I ELM-like energy loads [2]. Several approaches to solve this problem are considered, one of them is the pacing concept. Thereby the ELM energy W_{ELM} is reduced by raising in a controlled manner the ELM frequency f_{ELM} relying on the empirically observed relation $W_{ELM} \times f_{ELM}$ = const [1]. Successful ELM pacing and mitigation by the injection of cryogenic Deuterium (D) pellets was demonstrated first at ASDEX Upgrade [3] and applied over a broad parameter range. Despite this demonstration, confirmed on several other tokamaks like DIII-D [4], several questions still need to be answered in order to validate the approach for ITER. The most important are: can a suitable frequency enhancement be achieved under ITER relevant conditions, is the ELM related

* See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

energy flux to the divertor tiles also reduced and what is the minimum unavoidable inherent fuelling constraint?
A new pellet launcher system was installed at JET [5] to implement pacing investigations in order to clarify these questions. However, essential restrictions of the operational capabilities found for the installed system enforced an adaptation of these objectives. One major goal was to verify pellet pacing at the scale of JET, climbing one stage on the step ladder AUG-JET-ITER. Furthermore to investigate trigger features, in particular try to find conditions under which a pellet can trigger an ELM (and when not) and compare the dynamics of triggered ELMs to their spontaneous counterparts.

2. Experimental boundary conditions

The new High Frequency Pellet Injector (HFPI) was designed to meet both requirements for fuelling and ELM pacing. It comprises two sections operated alternately (no concurrent pacing/fuelling). One is serving on fuelling by delivering pellets 4 mm in diameter. The pacing section consists of a twin rod extrusion both 1.2 mm in diameter and their allocated barrels alternately firing pellets. Nominal pellet size (adjusted by the pellet length) and speed (adjusted by the propellant gas pressure) are fixed for any train injected during a plasma discharge. Design parameters are 21 – 42 × 10^{20} D at 100 – 500 m/s for the fuelling and 0.6 – 1.2 x 10^{20} D at 50 – 200 m/s for the pacing section. Maximum projected repetition rates were 15 and 60 Hz, respectively [5]. The HFPI is connected to the torus by a guiding tube system accessing three launching sites inside the torus: outboard or (magnetic) low field side (LFS), inboard or high field side (HFS) and vertical high field side (VHFS). A mechanical selector directs the pellets to one of the tracks or into a dump, switching during on plasma operation is possible within about 0.5 s allowing usage of different launch positions within a single plasma discharge. HFS access is inhibited due to a potential risk of uncontrolled ingress of air. Several diagnostic sections are incorporated to the guiding system to enable pellet parameter monitoring at these locations.

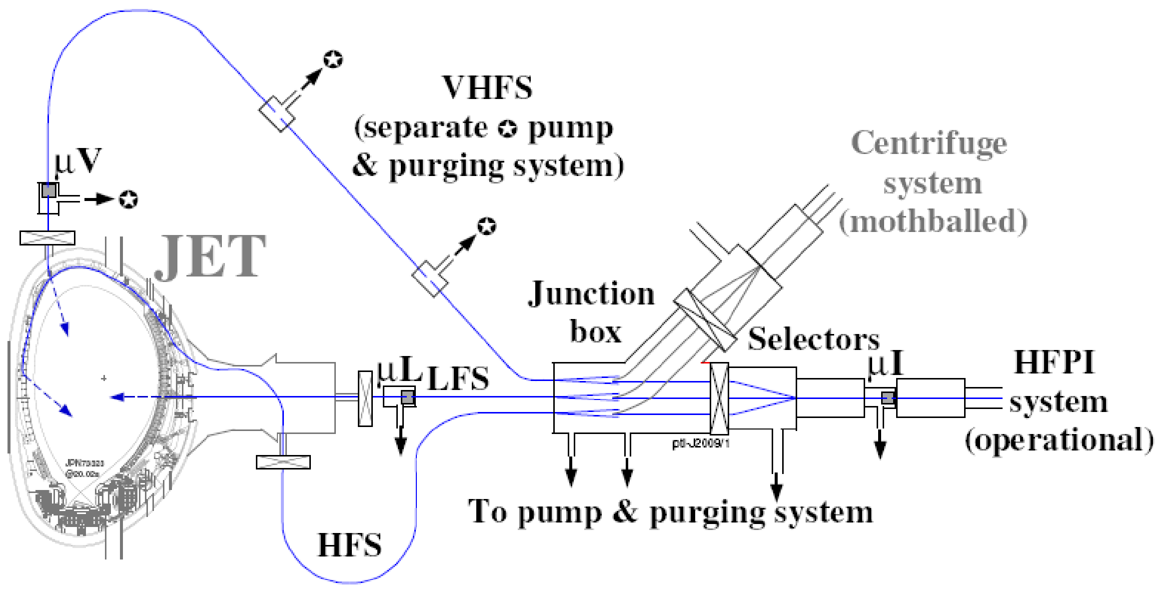

FIG. 1: Launcher set up operated during campaigns C20-C27 (2008/09). Access to the HFS launch track was inhibited for safety reasons, the "Junction box" simplified by disconnecting the centrifuge before C27. Location of microwave cavities used for pellet mass and velocity measurements are indicated.

Commissioning on plasma revealed several shortcomings and limitations of the system. In particular, pellet repetition rates and delivery reliability did not achieve values required.

Hence, the system was operated in its "preliminary" form with operational restrictions. Remaining issues are addressed and the system mended during the 2009-2011 shut down.
For the first campaigns (C20-C26) only the fuelling system was available. Sustaining reliable pellet trains could be established solely for LFS launch using pellets of 3×10^{21} D nominal particle content in the speed range 100 – 200 m/s and repetition rates up to 10 Hz. Only spurious pellet VHFS launching was possible allowing sample ELM trigger investigations. For pacing experiments relying on the fuelling system, thus 10 Hz LFS injection was applied with pellet speeds of about 150 – 200 m/s, imposing a (real) particle flux of about 1.5×10^{22} D/s, achieving pellet trains lasting for several seconds with delivery efficiencies (number of pellets arriving in plasma/pellet requests) larger than 0.9 – 0.95.
After an intervention the pacing section became useable for C27 only. Due to one barrel leaking and restrictions in the ice extrusion speed, the repetition rate was limited to 20 Hz. Like for the fuelling section, reasonable performances could be established in a narrow region of pellet parameters only. The launcher delivered reliable and persisting pellet trains, however many pellets disintegrated during the flight. Strong temporal dynamics was found for the delivery efficiency, best phases reaching up to about 0.4 for LFS and about 0.15 for VHFS launch. Such phases are show in figure 2. Hence pacing and ELM trigger investigations experiments were typical run by applying long phases with pellet launch using the most favorable injector setting. In the case of LFS pellets, statistically appearing sequences of a few pellets within a 20 Hz sequence could be obtained. For the VHFS, just occasional pellet impact on the ELM evolution was obtained since $1/\Delta t_{Pel} << f^0_{ELM}$ (Δt_{Pel}: temporal distance pellet to pellet, f^0_{ELM} unperturbed ELM frequency).

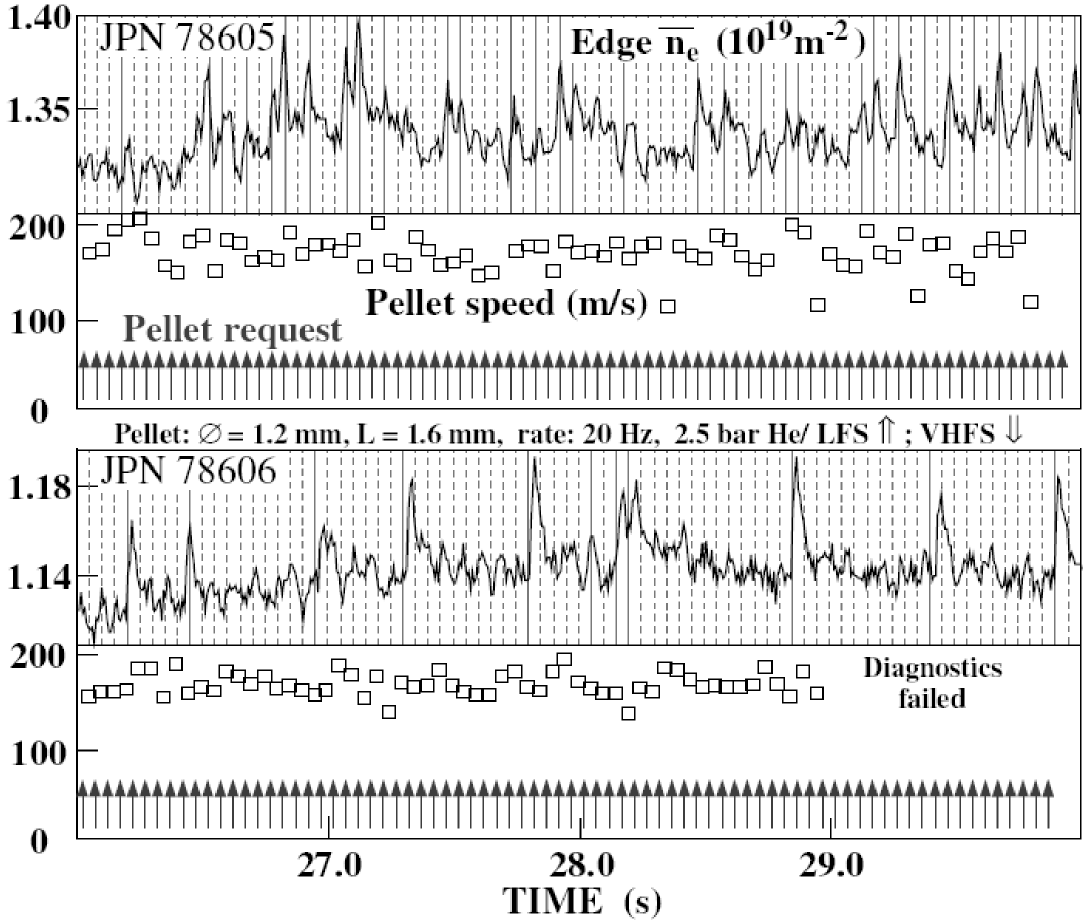

FIG. 2: Performance of pacing size pellets (nominal mass 1.1 x 10^{20} D) on plasma for LFS (upper part) and VHFS site launch . For these 20 Hz sequences into a L-mode plasma (for better arrival detection) delivery efficiencies of 0.4 and 0.14 are found, respectively.

3. ELM pacing attempts

The first pacing attempt using LFS pellet launch was made taking the ITER relevant baseline scenario at a moderate plasma current. This configuration with strong shaping (high triangularity) was developed to achieve good energy confinement at high density. Here it was chosen for the potential to establish a low f^0_{ELM} in an adequate ITER like pacing scenario. Pellets of the smallest reasonably useful size from the fuelling system were chosen (3 mm length, nominal 2.2×10^{21} D per pellet) at a rate of 10 Hz and at about 150 m/s speed. This came with a slight reduction of delivery efficiency with respect to the peak performance requiring several repetitive attempts in order to achieve a reasonable persistent train as in the example shown in figure 3. The target plasma was run at $I_P = 2.5$ MA and $B_t = 2.7$ T, yielding $q_{95} = 3.5$. The strong shaping produced an upper triangularity of $\delta_u = 0.42$, a lower triangularity of $\delta_l = 0.40$, the elongation was $\varepsilon = 1.76$ and the plasma volume $V_p = 75$ m^3. In the initial phase a Neutral Beam Injection power of $P_{NI} = 13$ MW was applied; to avoid density profile peaking and impurity accumulation in the core additionally central Ion Cyclotron Resonance Heating with $P_{ICRH} \approx 1.5$ MW in dipole configuration at a frequency of $f_{ICRH} = 42$ MHz was applied. To stabilize the ELM frequency, a small gas puff of $\Gamma_{gas} = 3 \times 10^{21}$ D/s was applied. This resulted in a stable initial pre-pellet phase with good confinement ($H_{98} \approx 1$) and the desired low $f_{ELM} = 7$ Hz. Pedestal top electron densities and temperatures were about 6×10^{19} m^{-3} and 1.3 keV, respectively. Into this initial plasma the 10 Hz pacing sequence was launched, producing strong fuelling (nominal $\Gamma_{Pellet} = 2.2 \times 10^{22}$ D/s, the real value estimated is about 1×10^{22} D/s). To recover the initial plasma energy P_{NI} was increased to 16 MW in the final phase of the pellet sequence. Pellet related fuelling resulted in significantly higher densities and lower temperatures in particular at the edge, expected also to increase the spontaneous ELM rate. The combination of pacing and fuelling drives f_{ELM} up to about 18 Hz into a phase composed of triggered and spontaneous ELMs. Roughly every other ELM was triggered or spontaneous. During this first pacing phase, plasma energy and hence confinement is reduced, attributed to the additional convective losses introduced by the pellet particle flux. When compensating for this loss by increasing P_{NI} during the final pacing phase the plasma stored energy was retrieved, but the initial phase was at higher density and accordingly reduced temperature. Increasing the power flux crossing the separatrix further raises f_{ELM} to 29 Hz with still 10 Hz contributed by triggered ELMs, leading to a larger fraction of spontaneous ELMs. Reckoning the evolution of f_{ELM} during the pellet phases the attempt for full pacing by gaining full control of the ELMs has fallen short, because fuelling side effects resulted in a similar or even stronger change of the ELM behavior. Nevertheless, the experiment allows for direct comparison of spontaneous and triggered ELMs under identical plasma parameters, which will be discussed in the next chapter. But furthermore it also confirms the approach relying on the initial layout of the pacing system. Pacing pellets were designed to arrive at a rate of 60 Hz (instead of 10 Hz) carrying a nominal $\Gamma_{Pellet} = 0.6 \times 10^{22}$ D/s (instead of 2.2×10^{22} D). Hence the expected impact on plasma density and temperature and as a consequence on f_{ELM} would have been less than found in this approach. Thus, a HFPI pacing section reaching the nominal performance will be capable of demonstrating a tenfold enhancement of ELM frequency by pellet pacing in a ITER relevant scenario.

In the ITER relevant scenario it turned out that pellet fuelling obscures the pacing effect. To overcome this deadlock it was required to reduce the fuelling impact. Without the option to bring the pellet particle flux further down, the particle confinement had to be deteriorated. This was done by taking a less shaped configuration at reduced current. The best attempt is shown in figure 4, again with 3 mm (nominal 2.2×10^{21} D) pellets at 10 Hz, but at about 200 m/s speed. Further attempts to establish an even higher pellet frequency f_{Pel} and do pacing with $f_{Pel} > f^0_{ELM}$ failed as the extrusion limit obviously was hit. The plasma was run at $I_P = 2.0$

MA, B_t = 2.3 T (q_{95} = 3.8) with δ_u = 0.30, δ_l = 0.24, ε = 1.70 and V_p = 80 m^3. The only auxiliary heating was P_{NI} = 11 MW, no gas puffing. This resulted in a stable initial pre-pellet phase with reasonable confinement ($H_{98} \approx 1.1$) and $f^0_{ELM} \approx 10$ Hz, pedestal top electron densities and temperatures were about 4 × 10^{19} m^{-3} and 1.1 keV, respectively. In this case the pellets did not cause a significant lasting alteration of the initial plasma parameters once the perturbation was imposed by switching on the pellet train. ELM pacing cannot increase the initial ELM frequency since f_{Pel} = 10 Hz ≈ f^0_{ELM} but it becomes clear the ELMs are generally synchronized to the pellet injection. All sound pellets arriving in the plasma do trigger ELMs and almost all ELMs appearing during the pellet sequence are triggered by pellets – with the exception of one ELM occurring spontaneously on time despite the arrival of a fragmented pellet and one additional spontaneous ELM incidence just about 10 ms before the next pellet triggers another ELM. Although the ELM frequency could not be increased by the pellets for obvious reason the ELM evolution got locked to the pellet appearance and the pacing attempt achieved control over the ELM evolution. Such pellet ELM pacing was established confirming the technique in principle also applicable in a large size tokamak like JET.

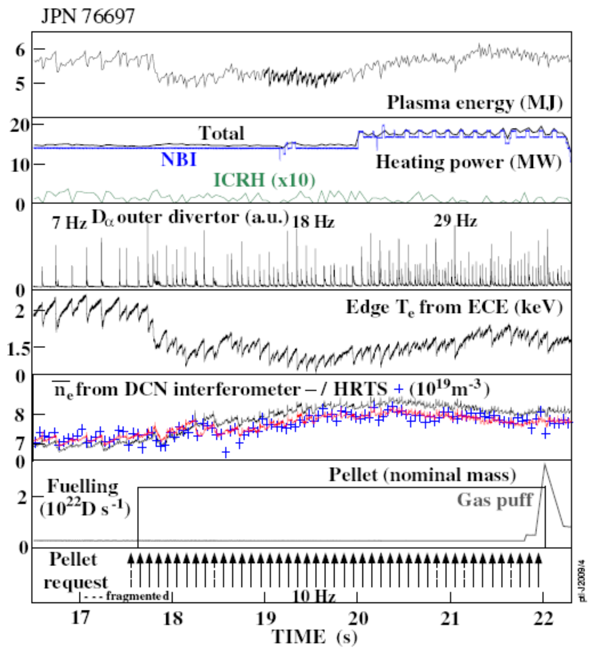

FIG. 3: Pellets injected at 10 Hz rate during a typical type-I ELMy H-mode ITER baseline scenario. Low fuelling and an accordingly adjusted heating power establish a 7 Hz initial ELM frequency. Due to the high confinement, fuelling pellets cause significant fuelling resulting in enhanced ELM frequency. During the pellet phase, f^0_{ELM} is increased by a factor of 4 while the triggered and spontaneous ELMs are mixed.

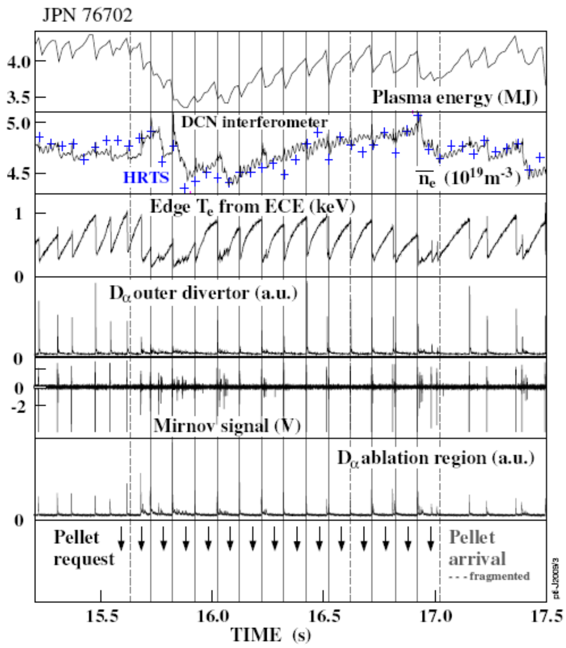

FIG. 4: Confirmation of the ELM pellet pacing technique at JET. Pellets injected at 10 Hz rate establish a full control of the ELM frequency. Using the fuelling system results in significant density enhancement and convective losses reducing the confinement. With the revised design parameters of the pacing system a pellet frequency of 50 Hz is envisaged applying only 15% of the pellet particle flux requested here.

4.1 Comparison of triggered and spontaneous ELMs

Investigations of the dynamics of triggered ELMs and their spontaneous counterparts but also of the pure pellet plasmoid perturbation in cases no ELM was triggered were performed. Investigated plasma scenarios span a wide range. In the high triangularity configuration both ELM types were mixed, a similar behaviour was observed with the triggered ELMs showing only small differences and some additional features with respect to their spontaneous

counterparts. Observations are in good agreement with a proposed triggering mechanism assuming the first filament releasing the ELM grows directly from the high pressure plasmoid generated by the ablating pellet. Bright spots can be observed on limiter elements located at the outboard wall of the torus by a fast framing camera observing this region in the case of LFS pellet injection [6]. The onset of these spots corresponds to the onset time of strong MHD activity at the edge coming with the ELM. Similar structures are observed at the onset of sufficiently strong spontaneous ELMs, though these pellet induced spots are field aligned. But different to their spontaneous counterparts showing strong spatial scatter for different events, in the pellet triggered case the onset is always observed at the same fixed position coinciding with a field line passing the pellet ablation zone close to the separatrix. It is hence concluded these bright spots are caused by the impact of filaments evolving from the plasmoid created by the pellet close to the separatrix [6]. Further experimental evidence for this single filamentary structure following the field line is provided from measurements of the ELM induced divertor heat loads. It is found that the heat flux footprints of a pellet triggered ELM in some cases shows a dominant additional peak. The location of this peak can be field line traced undoubtedly from the pellet injection location as proven by toroidal magnetic field ramps changing the field line geometry at the edge [7]. In case of small pellets not triggering an ELM, the resulting small pressure pulse to the divertor shows the same dynamics as an ELM. Once the ELM onset is initiated by the pellet its further evolution is very similar to a spontaneous one. This is found e.g. by analyzing the toroidal mode number n spectra of modes dominantly unstable during an ELM crash. Pellet triggered ELMs and spontaneous type-I ELMs have similar features. In both cases two components are detected, one at low frequency and low mode number, typically n=1, the other at higher frequencies, with n values typically negative. The value of n at which the spectrum of triggered ELMs peaks saturates at approximately n=6, in spontaneous type-I ELMs the value of n may be higher [8]. All observations are in good qualitative agreement with modeling results applying the non-linear MHD code JOREK to study the possible cause for the pellet trigger of an ELM [9]. The pellet leads to a density perturbation expanding along the field line, the pressure inside this partially ionized plasmoid rising due to parallel heat conduction. It shows a large enough pellet can destabilize a ballooning-type mode triggering an ELM-like event. For a large enough pellet put into a H-mode pedestal this plasmoid deforms into a filamentary structure moving density outward while the ballooning instability spreads poloidally over the whole flux surface [9].
Obviously, a pellet can trigger the onset of an ELM due to a strong local seed perturbation already under conditions where the unperturbed plasma edge is still stable. However, pellets do trigger ELMs typical for the according plasma regime with only minor changes compared to their spontaneous counterparts. Such minor differences are e.g. an accelerated onset of the MHD activity or the absence of precursors [10] and can be explained by the forced ELM onset. Trigger experiments performed in different ELM regimes further support this interpretation. Scenarios with the spontaneous ELM dynamics changing due to the application of an enhanced toroidal field ripple or imposed n = 1 error fields showed triggered ELMs follow the spontaneous ELM evolution. In consequence this is a strong indication for the compatibility of pellet pacing with other control approaches as demonstrated already by pellet fuelling of EFCC phases or pellet enforced ELM sustainment during radiative scenarios [11].

4.2 Trigger threshold investigations

It is thought the minimum possible pellet size and hence unavoidable fuelling is determined by the minimum pellet penetration required to establish a sufficient perturbation for the triggering. Using the pacing section of the launcher for the first time investigations to find out the according pellet size became possible. Injecting pacing size pellets into scenarios where fuelling size pellets achieved reliable triggering showed that some but not all pellets trigger

ELMs. Hence it became clear for the matching plasma parameters pellet size and velocity were in the vicinity of the trigger threshold. Since there is a strong mass scatter already within the pellets of a single train launched with a fixed nominal size and speed a dedicated pellet mass scan was not practicable and could be obtained from a single train – even for fixed pellet speed and plasma conditions. Pellets that do enter the plasma from the VHFS 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 [10]. Their relative size can be determined from the signal-level in the D_α monitor. In Figure 5 the peak pellet monitor pulse-height is plotted against the number of pellet requests (only about 20% reaching the plasma). This shows for the first time in any tokamak that there is a threshold in the pellet size required to trigger an ELM [10].

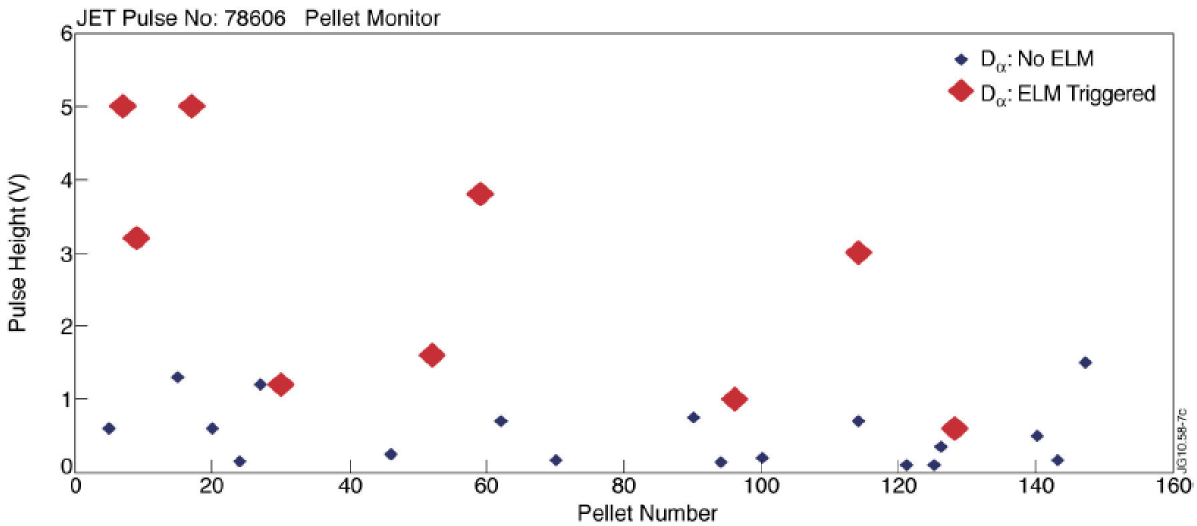

FIG. 5: Pellet monitor pulse height against pellet request number for a train launched from the VHFS. Pellets trigger an ELM are shown in red and typically are large in size (monitor signal >1V) [10].

The intensity of the D_α radiation is known to follow the pellet ablation rate in a wide plasma parameter range. Assuming a linear correlation of radiation to ablation and normalizing to the maximum observed pellet size to the maximum monitor response (5 V) the observed signal threshold of about 1 V can be converted into a mass threshold. During ELMy H-mode phases these small pellets are not found to produce any net plasma density increase and their impact on any observed plasma parameter was undetectable. Thus, pellet injection was continued in same cases using a L-mode plasma phase for monitoring. For L-mode phases showing a more quiescent evolution of edge parameters the pellet impact was emerging compared to the dynamic cyclic changes imposed by the ELMs during H-mode phases. Applying the JET Integrated Transport Suite of Codes JINTRAC including the pellet ablation and deposition code HPI2, these L-mode phases were modeled [12]. Compared with measurement data to determine the range of effective pellet masses reaching the plasma a maximum value of 4 – 5 $\times 10^{19}$ D was obtained for the pacing pellets arriving in the plasma. If the D_α pulse height is proportional to pellet mass entering the plasma the trigger threshold is above $\sim 10^{19}$ D, or instead using the total integral D_α emission above $\sim 1.6 \times 10^{19}$ D [10]. Pellets of this size do – according to modeling [12] and time of flight estimations [10] using the ablation duration – penetrate to at least half of the pedestal width. Very shallow pellet penetration (few mm) is insufficient for reliable ELM triggering. Caution has to be taken however for further conclusions since this mass threshold is a strong but simple empirical correlation. In order to find out on which parameter the trigger threshold is dependent on, more dedicated investigations with higher precision are required.

5. Status of the validation of pellet ELM pacing for ITER

Dedicated experiments were carried out in many Tokamaks to understand the underlying physics of the ELM triggering by pellets. These investigations cover a wide range of plasma regimes and pellet parameters. There is a high level of consistency in the results of these experiments carried out in different machines, providing a sound experimental basis. But it is also obvious experiments were mostly conducted under conditions still quite far from ITER relevant requirements. Characteristics of triggered ELMs have been intensely analyzed, usually characterizing them with respect to spontaneous events from the same or from similar reference phases. The pacing regime could be established only in few cases, and all experiments were done with rather large pellets. So far there is no experiment yet performed with pacing size pellets reaching the pacing regime. Operational parameters covered by the present experiments do not yet cover ITER requirements, hence the extrapolation to ITER parameters has some risk. This applies in particular to the requested frequency enhancement by a factor of around 30. Optimization of the pellet tool can be achieved by reducing the pellet mass as far as possible while keeping reliable pacing. In this operational mode it has to be investigated if the impact on confinement reduces as expected, for a convective loss dominated effect held responsible for the observed magnitude of confinement losses, or if another energy loss channel starts to play a significant role. The underlying ELM trigger physics is qualitatively understood, but knowledge is still lacking of the required local perturbation magnitude to be imposed by a pellet to trigger an ELM for a given set of pedestal parameters. Pellet technology in the parameter range requested for pacing in ITER is mature, so major technical troubles are not expected. Very likely pellet ELM triggering and frequency control will work in ITER at least within some operational range. However, like any ELM control tool envisaged for ITER pellet pacing has to substantiate its potential to reduce peak power loads below any critical destruction limit. A firm demonstration has not been obtained yet and might require an ELM frequency enhancement even beyond a value prescribed by the relation $W_{ELM} \times f_{ELM}$ = const. Recent investigations have shown the effective ELM energy deposition area depends on the magnitude of the ELM energy loss and increases significantly with W_{ELM} [13]. Hence, for spontaneous ELMs the peak heat flux to the divertor decreases more weakly than $1/f_{ELM}$ consequently changing the ITER requirements for frequency enhancements over the natural ELM frequency to achieve the target ELM density [14].

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