EFDA–JET–CP(12)06/39

P.T. Lang, D. Frigione, A. Géraud, F. Köchl, M. Lennholm, T. Alarcon,
P. Bennett, D. Garnier, L. Garzotti, G. Kocsis, R. Mooney, B. Sieglin
and JET EFDA contributors

ELM Pacing and Trigger Investigations at JET with the New ITER-Like Wall

ELM Pacing and Trigger Investigations at JET with the New ITER-Like Wall

P.T. Lang[1], D. Frigione[2], A. Géraud[3], F. Köchl[4], M. Lennholm[5], T. Alarcon[3], P. Bennett[6], D. Garnier[3], L. Garzotti[6], G. Kocsis[7], R. Mooney[6], B. Sieglin[1]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]MPI für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany
[2]Associazione EURATOM-ENEA sulla Fusione, CP 65, Frascati, Rome, Italy
[3]Association EURATOM-CEA, IRFM, 13108, Saint Paul-Lez-Durance, France
[4]Association EURATOM-ÖAW/ATI, Atominstitut, TU Wien, 1020 Vienna, Austria
[5]JET-EFDA CSU, Culham Science Centre, Abingdon, Oxon OX143DB, UK
[6]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[7]WIGNER RCP RMKI, EURATOM Association, POB 49, 1525 Budapest, Hungary
** See annex of F. Romanelli et al, "Overview of JET Results",*
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

Preprint of Paper to be submitted for publication in Proceedings of the
24th IAEA Fusion Energy Conference (FEC2012), San Diego, USA
8th October 2012 - 13th October 2012

ABSTRACT.
During the installation of the new ITER like wall at JET, the High Frequency Pellet Injector has been optimized. The launching system is now capable of delivering reliable fuelling size pellets from the magnetic outboard side at up to 15Hz repetition rate. Pacing size pellets can be produced at a rate up to 50 Hz but pellet trains suffer some losses during the transfer to the plasma. A significant fraction of the train can arrive at the plasma when launched from the outboard, only a few pellets make it to the vessel inboard launching site. Stable and reliable ELM control was achieved when using outboard fuelling size pellets. This tool was successfully applied for scenario development purposes in the ITER baseline H- mode scenario at 2.5MA. Employed for ELM sustainment and impurity control pellets prevented the ELM frequency from becoming too low finally causing a radiative collapse of the discharge. Despite technical limitations injecting outboard pacing size pellets resulted in an enhancement of the initial ELM frequency by a factor of up to 4.5 times. This could be achieved in cases where a continuous train of sufficiently large and fast pellets were arriving in the plasma at a frequency of up to 31Hz. Pacing size pellets were also used to investigate the ELM trigger threshold. Three basic parameters could be identified for outboard pellet launch. The ELM triggering probability increased with i) the time elapsed since the previous ELM occurred, ii) increasing pellet mass and iii) increasing pellet speed. There is also a strong indication found for a dependence of the pellet's ELM trigger threshold on the poloidal launch position; inboard launched pellets seem to reveal a higher trigger capability than pellets launched from the outboard. Finally, we compared the pellet penetration depth required for ELM triggering in the actual configuration with metallic walls to similar previous experiments performed with a carbon wall. This comparison seems to show that pellet ELM triggering requires deeper penetration in the ILW configuration.

1. INTRODUCTION

Controlling the ELM frequency is an important task for the development of high performance plasma scenarios. ELM control requirements in ITER [1] cover the limitation and mitigation of the large power fluxes to the divertor and the first wall expected during type-I ELMs for H-mode operational scenarios at high plasma current. Also the sustainment of a minimum ELM frequency is required when operating with a W divertor, even in the low current regime, to expel Tungsten (W) from the plasma edge before it diffuses to the plasma core [2]. Since its first demonstration at ASDEX Upgrade [3] and the recent successful adaptation to an ITER relevant 10x higher rate than natural ELMs on the DIII-D tokamak [4], pellet ELM pacing is considered as one of the most suitable tools to achieve these tasks. ELM Triggering is believed occurring due to the local action of the pellet ablation plasmoid, which is expected to be effective even in high performance and high plasma current scenarios. Besides allowing ELM pacing investigations under the most ITER relevant conditions, JET also allows further investigations of ELM triggering conditions and their underlying physics to provide a sound basis for predicting the potential ELM mitigation capability in ITER. To exploit this opportunity, a new High Frequency Pellet Injector system is being optimized at JET.

Its prime aim is to demonstrate ELM pacing in a large size tokamak with the goal being to obtain a tenfold increase in ELM frequency. This injector should furthermore shed light on the required ELM trigger conditions and the minimum remaining pellet induced fuelling burden resulting in convective confinement losses.

2. SET UP AND EXPERIMENTAL BOUNDARY CONDITIONS

The High Frequency Deuterium Pellet Injector (HFPI), part of the JET programme in support of ITER (JET EP2), has been installed on JET at the end of 2007. The HFPI is designed to launch pellets of variable size and speed for fuelling and ELM pacing purposes from three different injection locations. First put into operation in 2008 and used for preliminary investigations [5], it was optimized during the shutdown 2009 – 2011 [6]. The modified injector now in operation remains very similar to the prototype designed at the beginning of the project [7].

A sketch of the experimental set up as used during the first campaign with the newly installed ITER like wall (ILW) is shown in figure 1. A single screw extruder produces either one continuous large ribbon of ice for the production of fuelling size pellets or two simultaneous continuous narrow ribbons to provide pacing size pellets. A set of electromagnetic cutters and fast valves is used to respectively cut and accelerate the pellets. The high injection frequency for the small pellets is obtained by cutting alternately pellets in the two small ribbons of ice. The pellet injector is connected to the JET torus through an injection line and different flight tubes. The injection line transfers pellets to a selector able to change to any of the three flight tubes. Flight tubes are connecting to the designated launch sites at different poloidal positions. The Low Field Side (LFS) position is located about 9m downstream from the injector exit; the last section of this flight tube had to be installed inside the new ITER like ICRH antenna and is a bit tortuous due to the geometry of the antenna. About 18m transfer is required to reach the Vertical High Field Side (VHFS) injection position, a separate pump and purging system is attached to this section to pump the gas produced by the pellet erosion inside the flight tubes. Operation of the High Field Side (HFS) injection position is not yet possible. The pellet injection system is equipped with a set of diagnostics to measure the injection parameters. A CCD camera monitors quality and dimensions of the extruded ice as well as the extrusion speed. A set of light barriers measure the pellet velocity at the injector exit. Several microwave cavities are installed for pellet size measurement. Prior to the entrance of the pellet into the selector an initial measurement is performed by two cavities, tuned for small and large pellets respectively (location indicated as μI in figure 1). Additional single cavities are installed at the end of both the LFS (indicated as μL) and the VHFS flight tubes (indicated as μV). According to their primarily assigned purposes, the fuelling VHFS track is tuned for large pellets while the pacing LFS track is optimized to monitor small pellets.

For monitoring the ablating pellet in the plasma the visible light emitted by the pellet cloud particles are recorded by a wide angle view diode and a fast framing camera (KL8).

The pellet launching system can currently be operated either in a configuration using large pellets with a repetition rate up to 15Hz or up to 50Hz with much smaller pacing size pellets. More than 90% of the requested pellets are reliably fired when operating with one specific fuelling setting at 15Hz (nominal size 22×10^{20} D, launch speed 150 m/s). An example is shown in figure 2; displaying results from a discharge solely run for monitoring the arriving pellets. Stable steady L-mode conditions with moderate auxiliary heating allow for the precise analysis of the pellet mass deposited inside the plasma avoiding disturbing impacts by any ELM activity while auxiliary heating prevents too strong cooling by the pellets. For the case shown, a train of pellets was requested at a frequency of 10Hz for 9s. 87 out of these 90 pellets arrived in the plasma, corresponding to a delivery reliability of 0.97. Taking only pellets delivering more than half of the average mass, 79 pellets are counted (reliability of 0.88).

For small pellets also one specific pacing setting could be established working well at 50Hz (2.1 $\times10^{20}$ D, 170 m/s). However, the installed transfer system causes a reduced performance inside the torus. While virtually all the launched fuelling pellets arrive in the plasma when they are injected from the outboard (LFS) only 30-50% of pacing size pellets make it through the same flight line. These pacing pellets furthermore arrive with reduced speed (60 – 110 m/s) and showing a significant mass scatter. From monitoring the particle inventory of small pellets in L-mode discharges it turned out that the maximum size found for arriving pellets reached the design value. Launch speed variations and different deceleration in the tube also results in a significant variation in the intervals between successive pellets arriving at the plasma. When using the vertical inboard launch (VHFS) track, only few pacing size pellets arrive in the plasma, ruling out ELM pacing with pacing pellets via this flight tube. Enough pacing pellets do, however, enter the plasma through the VHFS track to allow ELM triggering investigations. For fuelling pellets, on the other hand, a lot of pellet fragmentation is observed so far, preventing any efficient injection from the VHFS. Despite these restrictions, important results on pellet ELM pacing and ELM triggering have been achieved in pellet experiments performed on JET in the ITER like wall configuration during the 2012 campaigns as reported in the following.

3. ELM PACING INVESTIGATION

Dedicated pacing experiments using small LFS pellets were carried out in a reference scenario (low shaping, 2.0MA, 2.1T, $q_{95} = 3.3$) in which low ELM frequencies of 6–8Hz could be sustained without impurity accumulation and radiation induced confinement degradation. Pellets were seen to cause an increase of the ELM frequency with increasing pellet rate. This increase is partly due to the fuelling impact of the pellets but the ELM frequency is increased above the ELM frequency achieved in a gas fuelled reference experiment. It was demonstrated that pellet injection can cause a stronger ELM frequency enhancement than a similar amount of particles introduced via gas puffing. This is shown in figure 3. The left case shows an example were two phases within a discharge are matched with respect to the applied fuelling flux – the first one with pure gas puffing and the second one with a pacing size pellet sequence combined with a small residual gas puff. During the second phase the ELM frequency raises from 13 to 20 Hz. In order to match the ELM frequency (right case) the gas flux in the first phase had to be increase from 0.9 to 1.1×10^{22} e-/s.

From the temporal evolution it can be seen that large numbers of ELMs are directly triggered by the pellets, i.e. by the direct interaction while the pellet ablation is still on going. For sequences where several consecutive pellets arrive with consistent shape and speed, direct ELM pacing was found, increasing the ELM frequency by a factor of up to 4.5 with respect to the initial value. Clearly, restrictions in the durations of these pacing phases are due to technical limitations on arrival reliability and speed/size of the arriving pellets. Applying pacing pellets to increase the ELM rate had no significant impact on plasma density or confinement.

The low operational reliability of the pacing pellets enforced the application of the more reliable fuelling size pellets for ELM control in the H-mode base line scenario (2.5MA, 2.65T, $q_{95} = 3.3$) where low ELM frequencies must be avoided in order to prevent impurity accumulation. Both for high and low plasma shaping, pellet injection brought the ELM frequency above the pellet rate of 15 Hz, thereby keeping the impurity and radiation level at its low initial level. While for low plasma shaping it was possible to recover from some early impurity accumulation, the ELM control is required throughout the high performance phase for high shaping plasmas. Though oversized pellets cause extra fuelling (estimated about 2.6 x 1022 D/s) and hence convective losses, the confinement characteristic for this scenario and machine configuration [8] could be maintained with pellet control applied, shown in figure 4.

4. TRIGGERING INVESTIGATION

In the 2.0MA discharges, the pacing pellets are seen to be near the ELM trigger threshold, with the intrinsic mass and speed scatter providing a “free” parameter scan. A statistical analysis of 855 identical requested pellets launched from the LFS at 30 – 50Hz into 14 virtually identical discharges was performed. It turned out that the trigger probability (ELMs triggered by a pellet/number of injected pellets) for a fixed plasma configuration depends essentially on three parameters: pellet speed, pellet velocity and on the time elapsed since the last ELM (spontaneous or triggered) has occurred. 216 pellets were found to trigger an ELM. The triggering probability is increasing with pellet size and also with the measured pellet arrival speed over the observed range of 65 to 110 m/s. In addition an increase in triggering probability with elapsed time since the previous ELM is observed. For the chosen configuration with a spontaneous ELM frequency of about 15 Hz, a strong increase of the trigger probability is found between 10 and 20 ms during the phase of strongest post-ELM recovery. This is followed by a gradual increase until almost saturation is reached towards the end of the spontaneous ELM cycle. Figure 5 is displaying the trigger probability contours as obtained from a fit to the data correlating pellet mass to the time elapsed since the last ELM at the pellet’s arrival in the plasma. For this analysis, no discrimination was made for different pellet speeds. The total integrated visible radiation emitted from the particles inside the pellet cloud is used for monitoring the pellet mass.

The camera KL8 is recording frames of the entire ablation region; by integrating over an according region of interest the temporal evolution of the total ablation radiation is derived (temporal resolution is framing rate). This radiation signal is a monotonic non-linear function of the amount of particles ablated by the pellet and hence the pellet particle contents.

In a similar manner a correlation of pellet mass and speed was obtained showing the triggering probability approaching unity for pellets approaching the initial design values in cases of arrival at least 20ms after the previous ELM. This confirms pellet parameters originally foreseen for the pacing approach are consistent with the request to drive ELMs at a frequency of at least 50Hz for this scenario.

Along with the probability contour lines at trigger probabilities 0.12, 0.25, 0.37, 0.5, 0.63, 0.75 and 0.87 several pellets from the data set were chosen for an analysis of the pellet penetration. Penetration was modelled by the pellet ablation and deposition code HPI2 [9] the same way as in a previous analysis performed for trigger investigations during experimental campaigns C20–C27 while JET was operated still with a carbon (C) wall [5, 10]. The result is displayed in figure 6. It shows the calculated triggering probability as a function of the major plasma radius R (bottom scale) and the normalized minor plasma outboard radius (top scale) respectively to which the pellet penetrates. The black dots represents “Burn out” the position where the pellet is completely ablated – while the grey dots represent the “Barycentre” - the position of the ablation centre of mass. For reference the electron density (left) and temperature (right) as measured by the High Resolution Thomson Scattering (HRTS) system are plotted together with a tanh-fit to these data (solid coloured line), covering the entire phase of the experiment lasting 4 s without any correlation to the ELM induced variations. Both solid black lines are obtained from a fit to data points selected for profile measurements immediately before an ELM took place. The difference between the averaged and pre-ELM profiles indicates the strong profile erosion caused by the ELM collapse. For the modelling, both pre-ELM profiles are adopted; hence the penetration depths given here can be regarded as lower limit of the required penetration in order to achieve the corresponding trigger probability.

Finally, despite the low pellet throughput rate, several discharges were performed with pacing pellets launched from the VHFS. A direct comparison of the achieved trigger probability in several matched discharges to the LFS case was performed. In all cases, pellets had the same requested parameters; due to the longer guiding tube hence VHFS pellets arrive in the plasma with mass and speed most probably handicapped with respect to their LFS counterparts. A summary of the four cases is shown in table I. The first case includes a small residual gas puff while the same discharge run with no gas at all corresponds to case 2. Eliminating the gas puff is seen to reduce the trigger probability in case of LFS pellet injection; this is attributed to an enhanced edge temperature resulting in a reduced pellet penetration. Cases 3 and 4 are discharges like case 1 with simultaneous application of plasma kicks. Plasma kicks by a fast change in the radial magnetic field induce fast vertical motions of the plasma column triggering ELMs, attributed to a rapid increase in edge current and its effect on edge stability [11]. Providing efficient ELM triggering in this scenario, kicks at 21Hz (case 3) respectively 40 Hz rate were employed to raise the ELM frequency. A trigger probability reduction with increasing kick (and ELM) frequency was observed for LFS pellets, attributed here to the reduced averaged time elapsed since the previous (mostly kick triggered) ELM at pellet arrival. As it becomes obvious from the trigger probability data displayed in table I, the VHFS launch shows the same trends as observed for LFS pellets. Despite their technical burden, VHFS pellets seem to have a significantly higher trigger potential than their LFS counterparts.

The observations fit well to recently reported modelling studies by the integrated core / scrape-off-layer (SOL) / divertor transport code TOPICS-IB [12] showing small pellets launched from the inboard can trigger an ELM already with less pellet mass than similar outboard pellets. The difference arises from the ExB drift of the pellet cloud, producing a wider pressure perturbation around an inboard pellet. Moreover, it cannot be excluded that the rocket like acceleration (for VHFS) or deceleration (for LFS) of the pellet [13] plays an important role.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. A. Loarte et al., 24th IAEA Fusion Energy Conference, San Diego 2012, ITR/1-2.
[2]. R. Neu et al., Nuclear Fusion **45** (2005) 209.
[3]. P.T. Lang et al., Nuclear Fusion **44** (2004) 665.
[4]. L.R. Baylor et al., 24th IAEA Fusion Energy Conference, San Diego 2012, EX/6-2.
[5]. P.T. Lang et al., Nuclear Fusion **51**, 033010 (2011).
[6]. A. Geraud et al., 27th SOFT conference, Liège (Belgium) September 2012, P1.31.
[7]. A. Geraud et al., Fusion Engineeriing and Design **82** (2007) 2183.
[8]. F. Romanelli et al., 24th IAEA Fusion Energy Conference, San Diego 2012, OV/1-3.
[9]. F. Köchl et al., 37th EPS Conference on CFPP, Dublin 2010, O4.123.
[10]. B. Alper et al., 37th EPS Conference on CFPP, Dublin 2010, P2.173.
[11]. E. de la Luna et al., 24th IAEA Fusion Energy Conference, San Diego 2012, EX/6-1.
[12]. N. Hayashi et al., 24th IAEA Fusion Energy Conference, San Diego 2012, TH/5-3.
[13]. H.W. Müller et al., Physical Review Letters **83**, 2199 (1999).

Configuration (Case)	LFS pellet launch	VHFS pellet launch
Residual gas (1)	8/18 = **0.44** (JET Pulse No: 82448)	5/5 = **1.0** (JET Pulse No: 82449)
No gas (2)	(20+13)/(63+40) = **0.32** (JET Pulse No's: 82851 + 82852)	4/5 = **0.8** (JET Pulse No: 82890)
21Hz kicks (3)	6/22 = **0.27** (JET Pulse No: 82882)	3/3 = **1.0** (JET Pulse No: 83223)
40Hz kicks (4)	7/43 = **0.16** (JET Pulse No: 82848)	3/5 = **0.6** (JET Pulse No: 83235)

Table I: Comparison of the ELM trigger probability (= ELMs triggered by a pellet/pellets arriving in plasma) for LFS and VHFS launch for different plasma scenarios but identical pellet request parameters. Despite their disadvantage by the longer guiding track (also causing a low number of arriving pellets) a strong indication is found for a higher trigger potential for pellets launched from the VHFS site.

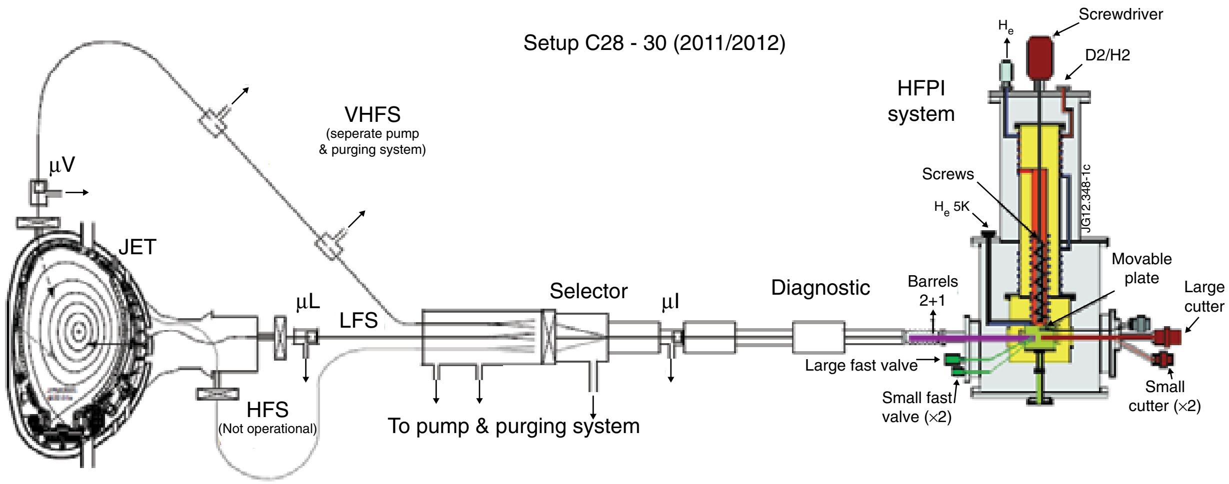

Figure 1: High Frequency Pellet Launcher after the modernization performed simultaneously with the installation of the ITER like wall (ILW). Set up in the first year of operation with the ILW during campaigns C28.

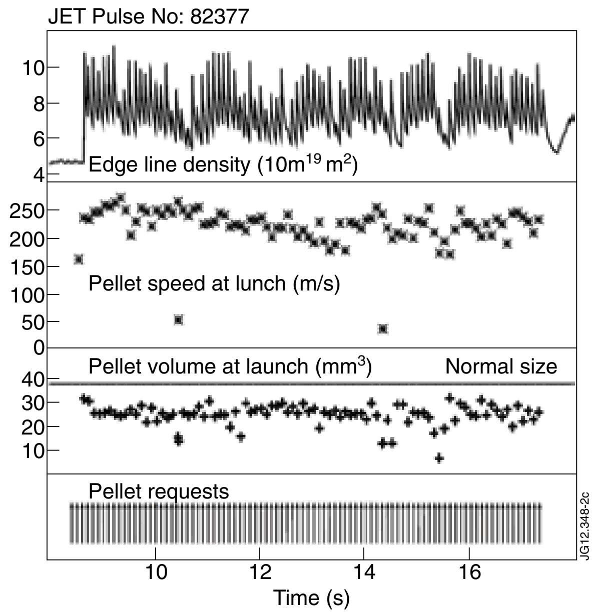

Figure 2: Pellet monitoring discharge showing highly reliable delivery of fuelling size pellets launched at 10Hz. Operating in a moderately heated L-mode allows determining the amount of pellet deposited particles from the sudden jump in plasma particle inventory as estimated from line integrated densities along several chords (only one edge chord shown).

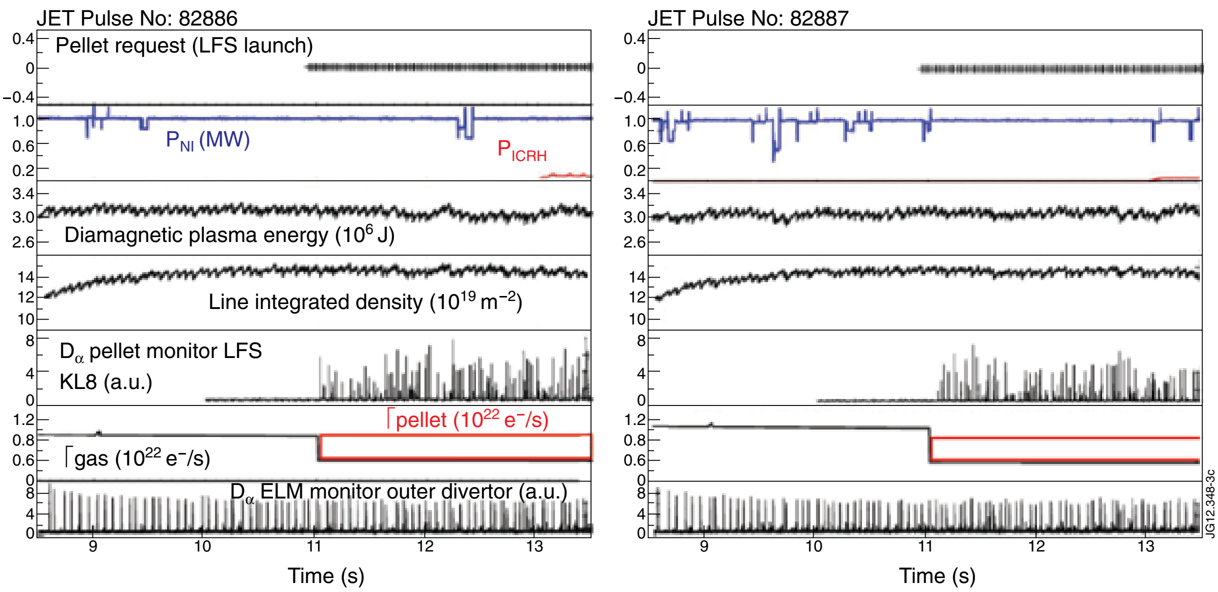

Figure 3: Pair of discharges matching either the total particle flux to the plasma (left) or the ELM frequency (right). It shows clearly compared to gas puffing less pellet flux is required to achieve the same impact on the ELM frequency.

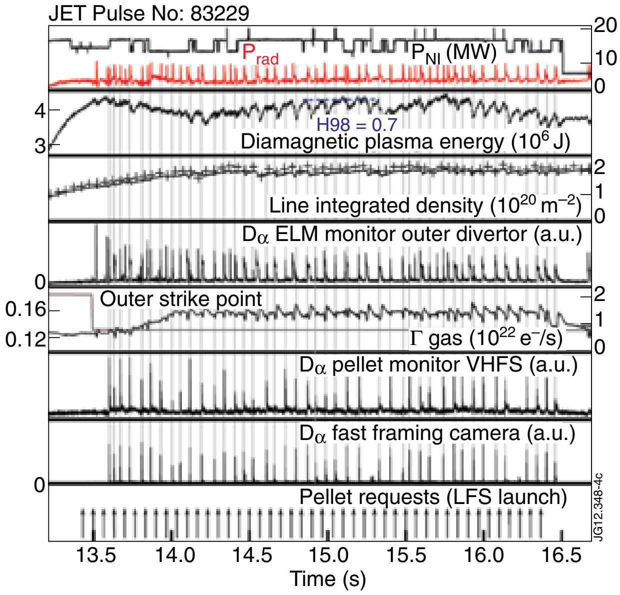

Figure 4: Sustainment of ELM activity preventing impurity accumulation by (fuelling size) pellet pacing at 15Hz rate in the ITER baseline scenario (2.5MA high shaping). Despite the strong extra fuelling introduced by the pellets (estimated about 2.6×10^{22} D/s) only a mild density increase and no reduction of confinement is observed.

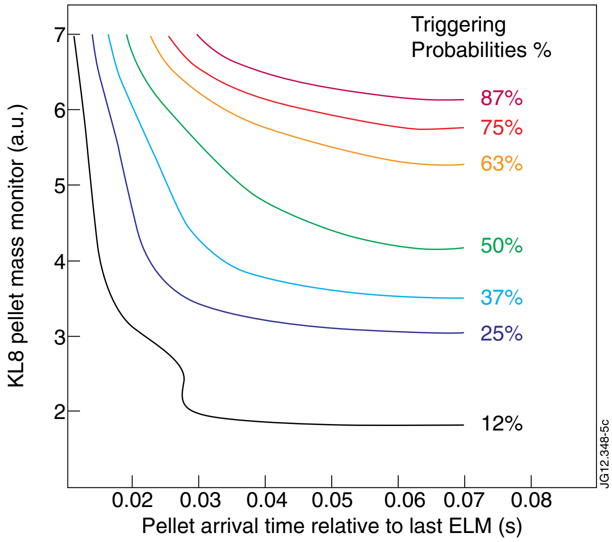

Figure 5: ELM triggering probability with respect to elapsed time since last ELM and size of arriving pellet in 2.0MA discharges. Contour lines are obtained by a fit to a data set derived for 855 pellets with identical requested parameters mass and speed injected into virtually identical plasmas. 216 of these pellets were found to trigger ELMs. No discrimination between different pellet speeds was made in this analysis.

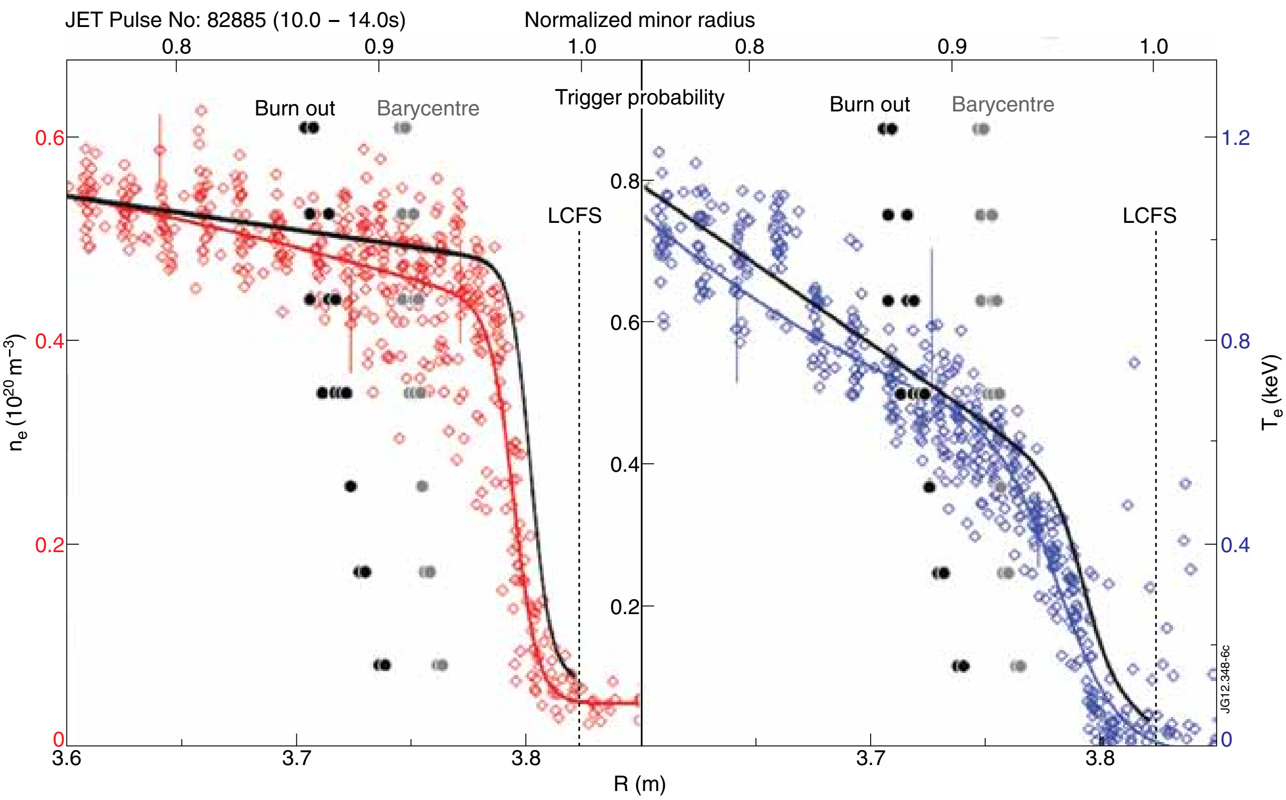

Figure 6: Probability of a pellet (selected events from data set) to trigger an ELM versus penetration from the LFS into the plasma; penetration at full ablation ("Burn out" – black dots) and centre of mass of ablation ("Barycentre" – grey dots). For reference, also time averaged (red/blue data points and according fit) and pre-ELM profiles (solid black lines) for electron density and temperature are displayed. Clearly penetration significantly beyond pedestal top is required for successful triggering in the ILW configuration – this is unlike the situation with the previous carbon wall.