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ABSTRACT.
To get deeper insight into the MHD activity triggered by pellets, a study was carried out, including a wide range of plasma scenarios with and without ELMs based on data from AUG and JET. All presently available experimental evidences are compatible with the hypothesis that the helical perturbation caused by the pellet cloud creates a non-linear trigger at any time during an ELM cycle where the plasma is most of the time in a linearly stable but nonlinearly unstable state. This suggests that pacing can be established beyond the range of present proofof- principle demonstrations under conditions required for ITER, i.e. at a range of ELM rate enhancement that suppresses the ELM impact below the hazard level. It seems that there is also quite some headroom to reduce the associated fuelling contribution coming with pacing. The demonstration of these features requires a dedicated approach at a sufficiently large tokamak that is currently under way at JET. A new pellet launcher was built and integrated into the JET system that is being converted into a multi-injector multi-track system. Being the first of its kind it also becomes the first truly ITER like pellet injection system. Once put fully into operation, it will allow for pacing as well as fuelling investigations.

1. INTRODUCTION

ITER is foreseen to be equipped with 6 pellet injectors capable of injecting H, D and DT pellets into the plasma. Pellet injection in ITER is a tool for both (i) efficient particle fuelling and (ii) mitigation of the ELM size. Fuelling pellet injection has to maintain the plasma density and allow high density operation with a minimum detrimental effect on energy confinement. This requires pellets to penetrate as deep as possible into the core plasma. On the other hand, ELM triggering by pellet injection provides a promising method for reducing the ELM size as demonstrated on ASDEX Upgrade (AUG). Thus, the ELM impact on plasma-facing components can be minimised. This should be achieved with the smallest possible impact on all other plasma parameters (besides ELM frequency). Hence, pellet injection for ELM pacing should use the smallest possible pellets with a shallow penetration. An optimized use of pellets in ITER requires their integration into ITER plasma scenarios in an effective manner being appropriate for both fuelling and ELM pacing. A successful scaling to ITER from results of present day tokamaks however requires sound physics understanding. For this purpose detailed investigations were performed at AUG. The main results and techniques are going to be challenged under most ITER like conditions of the largest available scale at the Joint European Torus (JET).

2. STRATEGY AND EXPERIMENTAL SETUP

A variety of explorations and experiments conducted at AUG for investigations of pellet fuelling as well as ELM control and mitigation via pellet pacing are now challenged and extended at JET. AUG is a mid-sized divertor tokamak with torus radius R_0 = 1.65m, minor plasma radius a_0 = 0.5m, a typical plasma elongation b/a > 1.6, and plasma volume V_{Plasma} = 13m^3 [1]. The pellet injector employed is based on a centrifuge pellet accelerator [2], capable of delivering cubic pellets of nominal size $(1.4mm)^3$ to $(1.9mm)^3$ (nominal pellet masses m_P corresponding to a particle inventory ranging from 1.6 to 4.1 10^{20} Datoms) at velocities v_P from 240m/s to 1200m/s and repetition rates f_P up to 83Hz. In its present configuration, pellets can be launched from the magnetic High Field Side (HFS) only through a bent transfer tube limiting the injection speed to 1000m/s. The system originally designed for fuelling purposes has proven to be very flexible and suited for exploration of the novel ELM pacing techniques and basic investigations of the underlying physics as well. For reliable and persistent operation, a rise of the plasma particle inventory in the range of 5-50 % per pellet can be achieved. It was found to be well suited for fuelling but not optimal for dedicated pacing experiments.

Untainted pellet pacing becomes di cult in smaller tokamaks due to the inevitable fuelling. The ELM frequency necessary to be overcome by pacing however decreases with the machine size. For a baseline operational scenario in the type-I ELMy H-mode regime ITER is expected to develop a spontaneous ELM frequency f^0_{ELM} close to or even below 1 Hz, stable operation can be maintained at JET down to about 4Hz while at AUG suitable target plasmas show at least $f^0_{ELM} \approx 30$Hz. Hence, already the smaller size of AUG enforces pacing at even higher rate than what would be ITER relevant. Rather small pellets carrying little mass with respect to the plasma particle inventory were found potentially sufficient to trigger ELMs at AUG [3] yielding headroom for a relief of the fuelling constraint. Unfortunately smaller tokamaks have the disadvantage of not being able to make full use of this possibility. Production and even more the transfer of pellets becomes extremely troublesome and erratic when trying to enter the sub-mm pellet size domain and reliable pellet delivery into the plasma is bound to a minimum plasma particle inventory increase of about 5 10^{19}. As a consequence, for pacing purposes the smallest pellets technically feasible are oversized in mass at AUG by a factor in the order of about 100 causing significant unwanted fuelling.

In case of the larger JET plasmas pacing pellets are still expected to be oversized but will have a drastically reduced fuelling impact, whereas for ITER an optimization of the pellet size causing only negligible fuelling seems feasible. At the size of AUG, the unfavourable combination of a high pellet repetition rate required to achieve reasonable ELM frequency control and the enforced excessive particle inventory per pellet do make pacing investigations troublesome. The unavoidable fuelling significantly changes the plasma parameters of the scenario hampering investigations. Raising the spontaneous ELM frequency by a factor of about 2 was accompanied by a density rise of about 30% resulting in turn in a reduction of the energy confinement attributed to additional convection losses introduced by the pellets [4]. As ITER requests an enhancement of f^0_{ELM} by at least of a factor of about 10 [5] it becomes obvious ITER relevant pellet pacing investigations can only take place at JET, the largest machine available at present. Besides the advantage of a relief in fuelling burden and the possibility to test pacing at the ITER requested frequency enhancement ratio this allows also access to parameter regimes more relevant to ITER. Mainly for this purpose, a new pellet launcher system, the High Frequency Pellet Injector (HFPI) was designed and built, capable to serve for both pacing and fuelling. It is expected to span a range of pellet induced plasma particle inventory enhancements from 1 to 100% per pellet. In optimized pacing operation it is estimated that in case of an ITER-like 10 fold enhancement of $f^0_{E\,LM}$ the increase in the target plasma density could be limited to about 10%.

With the integration of the HFPI, JET approaches a multi-injector multi-track pellet launching system. This is the first of its kind and as well the first one owing an ITER like configuration. Such a configuration combines several launchers in a matrix like connection to di erent injection tracks according to the actual requirements. Pellets can be requested from a distinct launcher set to appropriate parameters with respect to size, velocity and isotope composition and directed to the according launch position needed for a task like particle fuelling, ELM pacing, radiation control or discharge termination. Moreover, a failing injector can be substituted immediately keeping continuous operation. The JET set up shown in Figure 1 is under commissioning and is being put into operation during the experimental campaigns in 2008. With the previously used centrifuge launcher designed for fuelling only [6] currently mothballed, at present the HFPI launcher only can act as pellet source. It was built by PELIN based on a screw ice extruder and pneumatic acceleration system. Equipped with a flexible extrusion nozzle, the injector can run either in pacing mode (adjustable pellet volume from 1−2 mm^3 = 0.6−1.2 1020 D , 10−60Hz repetition rate, speed range 50−200 m/s) or fuelling configuration (35−70 mm^3 = 21−42 10^{20} D , up to 15Hz, 100−500m/s). Pellets can be either pure H or D. As a stand alone system, pellet delivery efficiencies up to 100 % were achieved at the injector exit in test bed [7].

Meanwhile, the system is installed at JET and integrated into the existing pellet guiding system via the junction box section as shown in Figure 1. Via the selector unit a pellet can be sent to one of the three shown tracks or dumped, switching can take place within less than 100ms. Due to recent hardware extensions at the torus the previous guiding tubes had to undergo minor modi cations. All tubes are multi bended; this might result in a restriction of the accessible pellet parameter range. Most severe restrictions are expected for the HFS track for the complicated intra vessel installation enforcing a minimum bend radius of 220mm. Unlikely to be operational at high velocities and high repetition rates it might still be useful for physics investigations. High performance operation close bend radius of 500mm and its gently curved trajectory predestine VHFS launch for high speed injection and fuelling application. Its long distance (13.5m from the selector unit to the launch position) makes it prone for pellet erosion and required installation of a separate pumping system with Nitrogen purging for safety reasons. Hence, operation at high pellet particle throughput and with small pellets might be limited. Somewhat more bent than the VHFS track, the LFS line (minimum bend radius 490mm, bends within the horizontal plane to deviate several obstacles) might face some speed limitation. Being by far the shortest (7m) one, it comes out as the designated pacing track.

Pellet flight paths as installed for the 2008 campaign are displayed by dashed arrows in figure 1. It comprises as well the plasma configuration run during the first successful pellet injection. Largest pellets launched with a speed of about 150m/s at a rate of 1Hz were directed to the LFS line during a phase with a heating power step down causing a H→Lmode back transition to compare and investigate pellet driven impact on MHD behaviour in ELMing and non-ELMing regime. Although pellet fragmentation was observed first results could be derived. Aiming to improve on this situation, currently commissioning of the pellet system is under way in order to explore the accessible operational range and to establish reliable operation for experimental applications.

3. THE PHYSICS OF ELM CONTROL AND MITIGATION

Broadening previous experimental investigations on the effect of pellet injection for the most relevant type-I ELMs towards other ELM type regimes (type III, ELM-free, radiative cooled type-I) revealed more general features of the onset dynamics of spontaneous and triggered ELMs [8]. Whereas in ELMing regimes frequency and growth time of spontaneous ELMs vary with changing plasma parameters, pellets force an ELM at any time and always with the shortest observed growth time. This indicates that - within the limits of pellet sizes and velocities explored - every pellet imposed perturbation in the above mentioned, intrinsically ELM-prone regimes can provoke a strong non-linear modes growth during any phase of the natural ELM cycle. This hypothesis is further supported by an analysis of the pellet driven magnetic perturbation. Pellets were found to create magnetic perturbations significantly larger than those observed during an initial ELM phase. In Ohmic and L-mode plasmas they do not trigger ELMs and it was found that the magnitude of the pellet driven perturbation depends on the plasma but not on the pellet parameters. An example is shown in figure 2, plotting magnitudes of the pellet driven MHD evolutions observed for different v_P/m_P samples in AUG, versus the pellet position on the injection path with the separatrix intersection defined as 0. There is a clear trend for an increasing mode magnitude with the pellet penetration deeper into the plasma. Only the local plasma parameters appear relevant for the magnitude of the pellet triggered perturbation while changes in the ablation/deposition rates imposed by altered pellet parameters do not show a significant effect. Large/fast pellets create a stronger magnetic perturbation compared to small/slow ones only deep inside the plasma, a region not reached by the small/slow pellets. However at a given plasma position and hence for the same plasma parameters, the same magnetic perturbation is generated by the smallest and largest pellet impacts tested. Obviously, in the investigated parameter regime pellet particle ablation or deposition rates do not matter with respect to the magnitude of the resulting magnetic perturbation. As no direct relation of the driven perturbation strength to the underlying pellet born perturbation was found, it became clear that the driving mechanism reached at every plasma position a saturated regime and the deposition of more pellet particles cannot provoke a stronger Mirnov activity. This implies that there should be still headroom for a reduction of the ablation/deposition rates by injecting smaller/faster pellets while keeping the full drive on the resulting perturbation.

In H-mode plasmas the pellet driven magnetic perturbation at the onset of the triggered ELM is still below the detection limit becoming visible only after the ELM perturbation has declined therefore the strong pellet perturbation can be applied to probe the edge stability against ELMs. H-mode discharges remain permanently at least non-linear unstable, while Ohmic, L-mode and quiescent H-mode plasmas have a stable edge.

These results would indicate that ELM pacing in ITER could be achieved by injecting small high speed pellets from the LFS of the machine, causing only little impact on particle inventory and confinement.

An encouraging result pointing in this direction is shown in figure 3. The figure shows a fuelling size pellet in JET triggering an ELM and as reference, a spontaneous ELM. The ELM is triggered with only about 4×10^{19} D (~1% of the injected pellet mass) ablated. For such large pellets outlasting beyond the ELM triggered an again steadily increasing MHD magnitude is observed with the pellet progressing into the plasma. Assigning this component to the directly pellet driven MHD its extrapolation back to the ELM onset would indicates a tiny perturbation already sufficient for the triggering. Hence, with possible pellet parameter optimization in the next campaigns, regular and reliable ELM triggers can likely be produced with negligible plasma fuelling and density perturbation (and therefore less convective energy loss). In the hot, low collisionality plasma regime the physics of pellet/pedestal interaction is also converging to those of ITER. The pro le evolution towards steady state and the impact of remaining fuelling induced convective losses on the confinement will be examined in detail. Moreover, it will be possible to investigate steady state pellet pacing in an operational regime with intrinsic low natural ELM frequency compared to the pellet injection frequency. Tests whether this can be achieved with a tolerably small perturbation of the total particle and energy balance will be available as well. Experimental investigations in such regimes are most appropriate at JET where they are already hosted in the program. Unfortunately, progress was hampered in 2008 by technical difficulties faced when bringing the new system into operation. Nevertheless, rst encouraging results have already been obtained. As mentioned in the previous section, pellet injection was performed while initiating an H→L back transition by a NBI power step down from 6.2 to 1.5MW during the at top phase of a I_p = 2.0MA, B_t = 2.5T plasma discharge. The aim of the experiment was to challenge AUG findings of strong pellet driven MHD activity in OH and L-mode plasmas with the advantage of allowing for the comparison to the pellet driven MHD causing an ELM event within the same discharge. Although the lacking pellet quality (fragments and debris coming with the main pellet) does not yet allow for a direct correlation of Mirnov signal magnitude and pellet position, JET confirm the basic AUG finding. In the L-mode phase, still strong pellet driven MHD activity was detected reaching a magnitude exceeding that one observed at the onset of spontaneous and triggered ELMs during the preceding H-mode phase. This is shown in figure 4 displaying from bottom to top the D monitor signals for pellet ablation and ELM impact in the divertor and the Mirnov coil record. The left part displays a pellet injected during the H-mode phase triggering an ELM, a pellet driving only transiently MHD activity during ablation not resulting in persistent activity is shown in the right part.

A more detailed analysis of the Lmode pellet driven MHD activity, shown in figure 5, unveiled its likelihood with according AUG results. The dominating component around 100kHz is attributed to toroidicity induced Alfvén eigenmode (TAE)–like sub structures. Present as well before and after the pellet it is enhanced in magnitude during the pellet phase by about a factor of 10. The pellet induced transient density increase is correlated, consistent with the frequency-density scaling $f(\rho_{pol}) \sim \frac{B}{\sqrt{n_e(\rho_{pol})}}$ reported for this modes, with an according transient frequency.

4. PELLET PARTICLE FUELLING AND SCENARIO INTEGRATION

Fuelling studies were guided by the goal of achieving and maintaining a requested plasma density with minimum confinement degradation which is, at the same time, compatible with the goal of minimizing T consumption in ITER. Deep pellet deposition leads to long particle confinement times and allows high density operation with good energy confinement.

The plasma energy is reduced when the density is increased by pellet fuelling under steady state conditions in both AUG and JET low triangularity plasmas [9], as shown in figure 6. The estimated additional convective energy losses introduced by pellet fuelling describe fairly well the observed evolution. Pumping was required to prevent excessive rise of the neutral and edge densities. In addition, abrupt strong plasma cooling had to be avoided by gentle density ramps. Ion gyroradii shrinking with temperature caused - according to the ion polarization model - a reduced onset pressure for tearing modes making the plasma vulnerable to pellet triggered NTMs.

Covering a wide range of pellet velocities and masses and also 3 different injection geometries the JET pellet system is now available to continue these investigations. A direct comparison of inboard and outboard launch - the rst favoured for the inward ∇B drift, the latter technically simpler hence allowing higher launch speed - will allow us to study the role of these effects in the physics underlying pellet ablation and deposition in more detail. A further route to gain better insight into the pellet ablation and deposition process is via comparison of LFS and HFS penetration depth scaling with respect to the machine size. A HFS scaling derived for AUG [11] had been compared to the AUG sub set of a multi-machine LFS scaling [12] and different ablation models. For HFS and LFS pellets, the plasma and pellet parameters included in the scaling di er. The HFS depth scaling is based on a statistical approach and states that the relevant parameters are the electron temperature, pellet mass and velocity, magnetic field and plasma elongation (in the order of statistical significance, electron density dependence is thought to be masked by the strong temperature dependence), whereas the parameters of the LFS scaling have been set a priori based on theory. A proper scaling with tokamak size required for a sound ITER prediction is however not yet at hand. An extension of this study to different machines would therefore be needed with JET naturally supplying data of highest significance.

SUMMARY AND CONCLUSIONS

Our recent investigations on the ELM trigger process by pellets shed new light on the present model of the origin and the dynamics of ELMs. Most likely the plasma spends the largest part of the ELM-cycle in a linearly stable, but non-linearly unstable state, where the finite helical perturbation caused by the pellet cloud act as a non-linear trigger. Thus it appears that there is quite some headroom left to reduce the associated fuelling contribution as the imposed MHD perturbations seem to depend on the pellet penetration depth but not on the ablation rate. This suggests that ITER could therefore employ faster pellets of sufficiently small mass to reach the required penetration depth. The most suitable device to perform the required experiments is at present the largest available tokamak, JET. A new system was built dedicated to this purpose appropriate for both pacing and fuelling studies. In both cases confinement reduction resulting from the additional convective losses introduced by the pellet particle flux has to be minimized. Aiming at an optimized fuelling scenario granting operation at the requested density level with reduced side effects, these studies may contribute to the proper understanding of the underlying physics in comparison with experiments done at different sized tokamaks.

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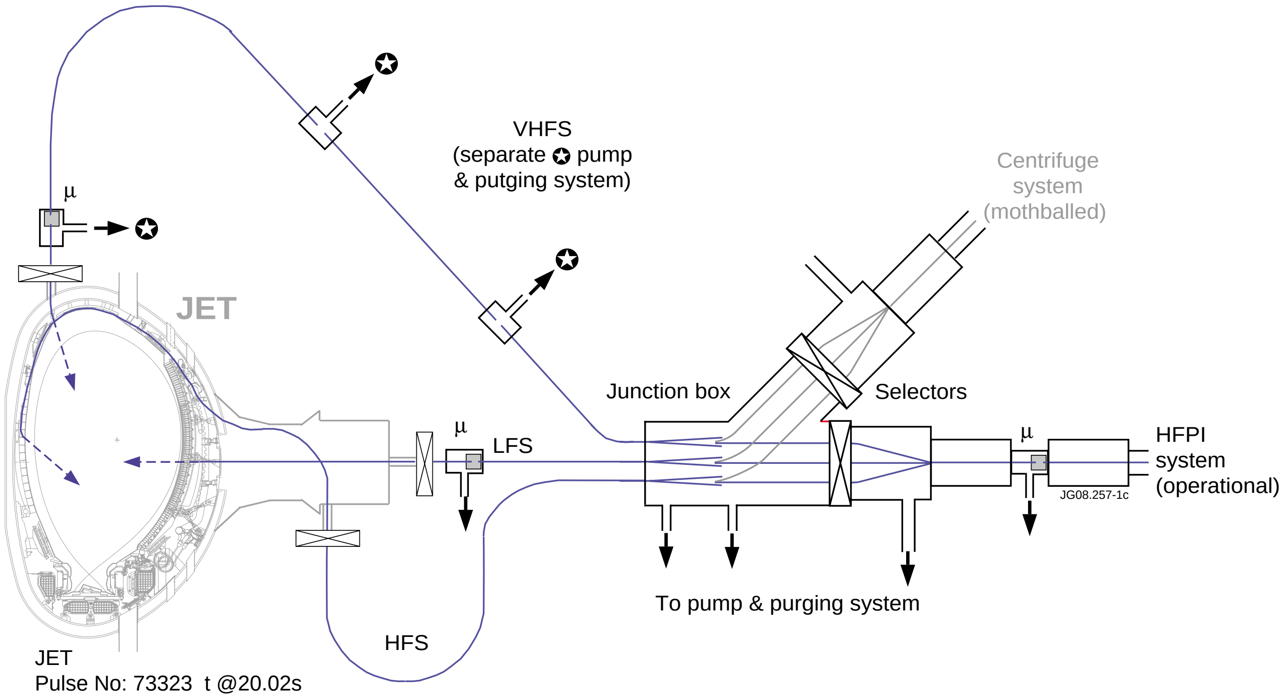


Figure 1: The JET multi-injector multi-track pellet launching system under commissioning and put into operation during the experimental campaigns in 2008. With the new injector (HFPI) it is capable to perform both ELM pacing and fuelling experiments with high relevance to ITER. The available pellet size and velocity operational regime in combination with three injections tracks at different poloidal locations provides potential for dedicated physics experiments with respect to fuelling and ELM control physics.

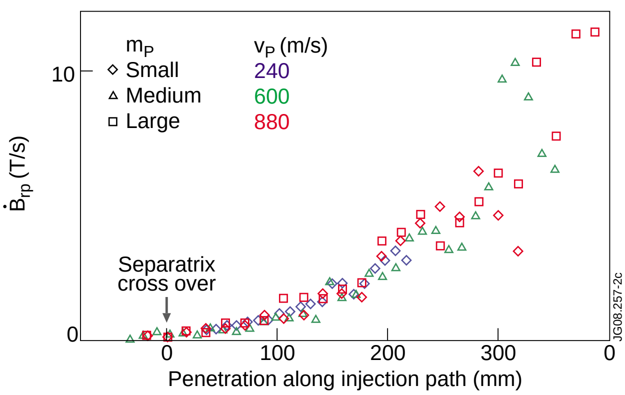


Figure 2: Pellet induced MHD perturbation in AUG versus pellet position along the injection path, separatrix position defines 0. At the same position in the plasma, the same magnitude for the pellet driven MHD response is observed for any pellet speed and/or mass applied.

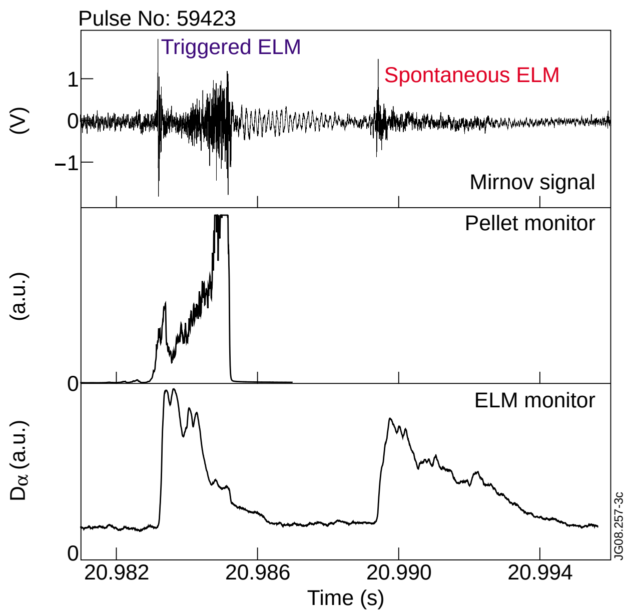


Figure 3: Mirnov coil response, pellet ablation and divertor D_α ELM monitor (top to bottom) for a fuelling size (4×10^{21} D) pellet triggered (left) and a spontaneous (right) ELM in JET.

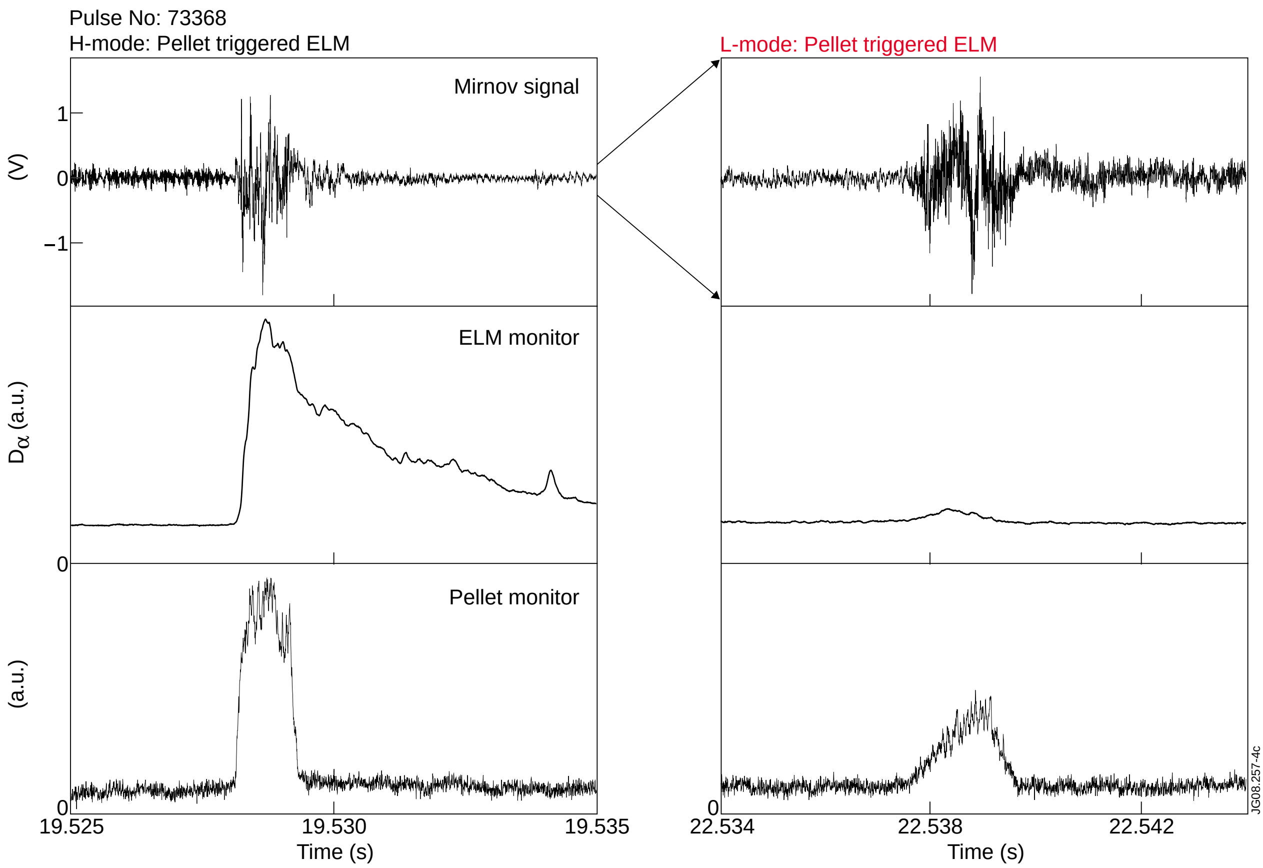
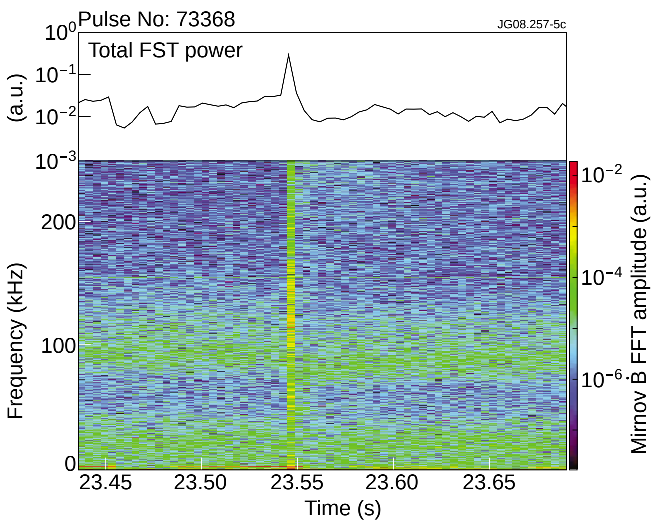


Figure 4: Mirnov coil response, divertor D_α ELM monitor and pellet ablation (top to bottom) for pellets in JET (accompanied possibly by debris) triggering an ELM during an H-mode phase (left) but driving only transient MHD activity declining after burn out (right, note expanded y-scale of upper box).



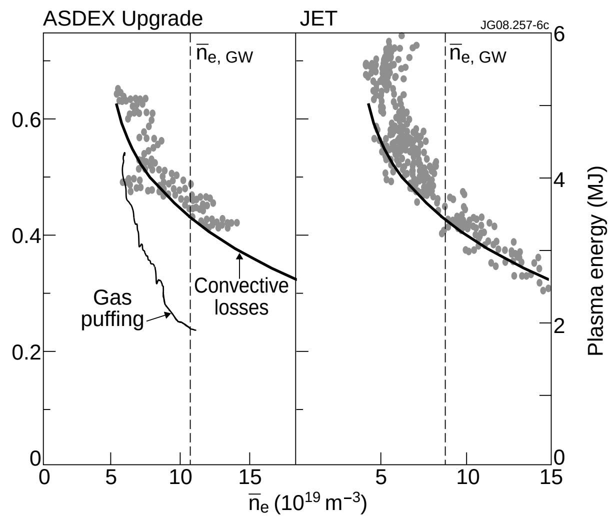


Figure 5: Mirnov coil signal frequency amplitude evolution before, during and after pellet injection into a JET L-mode phase (lower) and according integrated amplitude (upper). The pellet causes a transient short directly driven strong increase of the mode amplitude and a longer lasting drop in the frequency attributed to fuelling.

Figure 6: Plasma energy versus line averaged density reached with steady state pellet injection (Filled circles). Solid curves: expected con nement reduction caused by pellet added convective losses. Operational area limitation for gas puff refuelling in ASDEX Upgrade is also given for comparison.