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Abstract. High repetition rate injection of deuterium pellets from the low-field side (LFS) of the DIII-D tokamak is shown to trigger high-frequency edge localized modes (ELMs) at up to 12x the low natural ELM frequency in H-mode deuterium plasmas designed to match the ITER baseline configuration in shape, normalized beta, and input power just above the H-mode threshold. The pellet size, velocity, and injection location were chosen to limit penetration to the outer 10% of the plasma. The resulting perturbations to the plasma density and energy confinement time are thus minimal (<10%). The triggered ELMs occur at much lower normalized pedestal pressure than the natural ELMs, suggesting that the pellet injection excites a localized high-n instability. Triggered ELMs produce 12x lower energy and particle fluxes to the divertor, and result in a strong decrease in plasma core impurity density. These results show for the first time that shallow, low-field-side (LFS) pellet injection can dramatically accelerate the ELM cycle and reduce ELM energy fluxes on plasma facing components, and is a viable technique for real-time control of ELMs in ITER.

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The high confinement (H-mode) operational scenario is the most promising for producing fusion energy using the tokamak plasma confinement concept. The H-mode is characterized by a steep pressure gradient and 'pedestal' at the plasma edge, which leads to strong self-driven plasma currents that together result in an instability known as the edge-localized mode (ELM) [1]. ELMs cause periodic bursts of energy and particles from the plasma, which can pose a serious limitation to plasma facing component (PFC) lifetime by erosion and melting from the high heat fluxes as well as producing a source of impurities in the plasma. The intensity of ELMs must therefore be controlled in future burning plasma devices such as ITER, and several candidate methods for achieving this control are being explored in present tokamak devices. In addition, the presence of high frequency low amplitude ELMs can be beneficial in increasing the effective edge particle and impurity transport, thus permitting quasi-stationary high plasma performance to be achieved [2]. Without sufficient ELM activity, the impurity and radiation buildup can make the H-mode a transient condition unless the particle transport can be increased by other means as has been observed in the EDA [3], QH [4], and RMP H-modes [5]. Therefore, a mechanism to suppress large uncontrolled ELMs and trigger small ELMs on demand may be necessary to minimize PFC erosion and impurity accumulation.

Both the injection of deuterium pellets [6] and external magnetic perturbations [7] have been used to demonstrate the principle of on-demand ELM triggering. On DIII-D, ELMs have been observed to be triggered by pellets injected from all available locations in H-mode and found to trigger much larger ELMs from the LFS for a given size pellet [8]. These results have suggested that very small shallow penetrating pellets from the LFS may be sufficient to trigger rapid ELMs. The trigger mechanism is hypothesized to be the destabilization of a high-n localized ballooning mode by the local pressure perturbation from the reheating pellet ablation cloud that exceeds the local ballooning stability threshold and triggers a high-n ELM crash [9]. Since the ballooning stability threshold is lowest on the LFS (large major radius side) of the tokamak plasma, we inject the pellets there in a region of high flux expansion near the divertor to minimize penetration and maximize the edge pressure perturbation. We use the pellets to demonstrate reliable ELM triggering in this manner: using high frequency LFS pellet injection to intentionally trigger ELMs on demand at 12x the natural ELM rate. We observe that the triggered ELMs are reduced in intensity by a similar factor and thus there is the possibility of further reduction in ELM intensity by triggering even higher frequency ELMs.

In this Letter, we (1) describe the use of pellets in triggering the ELMs, (2) show the resulting plasma performance and ELM signatures, and (3) describe the pedestal changes from the controlled ELMs and reduced impurity accumulation. While the principle of on-demand ELM triggering by pellet injection has been previously observed on ASDEX-Upgrade [6], DIII-D [10], and JET [11], these new DIII-D experiments have demonstrated unprecedented ELM control with no deterioration in plasma performance and no net fueling from the injected pellets, which is due to the LFS injection location and triggering of an ELM-like event well before the pellets reach the edge pedestal top. On ASDEX_Upgrade an increase of the ELM frequency by a factor of 2 was obtained with 83 Hz pellets from the high field side (HFS) that resulted in strong fueling due to an ExB major radius drift of the pellet cloud [12] and a subsequent decrease in confinement [6]. Similar HFS injection fueling and confinement observations were made on JET [11].

The DIII-D pellet injector [13] was configured to inject deuterium pellets from the LFS near the divertor X-point ("R-2") and outside midplane ("MID") as shown in Fig. 1a. The LFS injection locations were chosen because of the previously observed higher sensitivity to trigger ELMs and much lower fueling efficiency from the ExB drift [8,12] than from HFS (inner wall) injection locations. The pellet size in all three barrels of the injector was set by the barrel diameter to be 1.3 mm. The length of the pellets was also set to 1.3mm by the width of the solid deuterium extrusions that are cut to make the pellets. The repeating pneumatic gun mechanisms of the injector were modified to produce slow pellets (< 200 m/s) in order to minimize the penetration of the pellets and to insure intact pellets during transport through curved guide tubes. One barrel was connected to the midplane port while the other two were connected to the R-2 injection port. The nominal pellet size contains 1.0×10^{20} atoms (0.19 Pa-m^3) of deuterium.

The pellets injected from R-2 where there is significant flux expansion, were observed from ablation and magnetic loop signals to trigger ELMs within 2cm of crossing the separatrix, which is less than half the distance to the edge pedestal top. Images from a tangential viewing fast camera [14] of the pellets entering the plasma show a single plasma filament becoming visible just in front of the ablating pellet cloud as in Fig 1b. These observations are in agreement with the hypothesis and non-linear MHD modeling that the ELM is triggered by a local pressure gradient at the front of the pellet cloud that drives a localized high-n ballooning mode forming a helical structure [9,10,11]. Because of the high flux expansion in this region there is more pellet ablation within the outer flux surfaces and thus higher pressure gradients can be obtained that destabilize a ballooning mode at a shallower depth than from HFS locations. This coupled with the ExB drift of the pellet plasma filament and ballooning mode propagation in the major radius direction leads to minimal fueling. The pellet triggered high-n ELMs are small enough that they also do not result in a plasma density decrease as do the large natural ELMs.

A set of experiments were carried out on DIII-D by injecting the slow (100-150 m/s) pellets on the LFS in an ITER-like shape plasma [15] and a feedback controlled normalized $\beta = 1.8$ with 2.8 MW of neutral beam injection heating. This power is about 10% above the L-mode to H-mode transition power as has also been shown in earlier experiments with this configuration [15] and typically results in a low type-I natural ELM frequency of ~5 Hz.

All three pellet injector barrels injected pellets at 20 Hz, alternating between barrels, giving a total repetition rate of up to 60 Hz. A comparison of the evolution of density, divertor D_α, and other key parameters is shown in Fig 2 for two similar discharges, one with the 60Hz pellets applied and a reference one with no pellets injected. The average plasma electron density is not increased directly by the shallow penetrating pellets compared to the reference discharge indicating very poor pellet fueling efficiency, while each large natural ELM results in more than a 5% decrease in the density. The reference discharge uncontrolled ELM frequency was ~5 Hz with ELM energy losses up to 55 kJ (~8% of total stored energy) while the case with pellets was able to demonstrate 60 Hz ELMs with an average ELM energy loss to the divertor of < 3 kJ (<0.5% of the total). The energy confinement time normalized to the ITER H-mode scaling, IPB98y2 (denoted by *H*98) [16] is found to remain above 1.1 as shown in Fig. 2 and is very weakly affected by the application of the pellets. Total divertor energy deposited by each ELM is reduced by an average factor greater than 10 as measured by an IR camera with a similar reduction in peak ELM heat flux at both the inner and outer divertor targets. Central impurity accumulation of Ni is reduced by more than a factor of 5 by the application of the 60 Hz pellets. Plasma rotation at the edge pedestal location is reduced by up to 50% as a consequence of the injection of the pellet mass and conservation of angular momentum. The pellet mass is expelled from the plasma during the triggered ELM before it is fully thermalized and therefore does not result in a large convective energy loss term.

The divertor heat flux from ELMs is determined from IR camera data taken at one toroidal location [17]. Spatial and temporal integration of the heat flux data provides the energy lost from the plasma for each ELM with resolution less than 0.5 kJ based on the assumption of axisymmetric heat flux in the divertor, since the IR measurement is toroidally localized. The average ELM energy loss deposited at the divertor is plotted in Fig. 3 for different pellet frequencies showing a $1/f_{ELM}$ dependence and a reduction at 60Hz of more than a factor of 12. The peak heat flux in both divertor legs is reduced by a similar factor and has the same frequency dependence. The ELM energy deposited on the outer divertor leg is 25% larger than the inner divertor leg for the natural ELMs, but is twice as large for the much smaller pellet induced ELMs.

All measured impurity ion densities are observed to be significantly reduced in the plasma with the application of the high repetition rate LFS pellets. The Ni impurity density in the core of the plasma has been modeled using the spectroscopic measurement of Ni XXVI 234 Å line intensity with the STRAHL impurity transport code [18] and is found to be reduced by a factor of 3. The reduction of impurity contamination is hypothesized to be due to more effective screening of the edge plasma by the enhanced particle flux stimulated by the frequent pellets and subsequent small ELMs. High naturally occurring ELM rate plasmas with enhanced scrape off layer flows have been observed to have reduced impurity accumulation levels [19]. Lower injection frequencies of the pellets result in less impurity content reduction.

The type I ELMs in the ITER-like shape discharges without pellets are believed to be caused by intermediate wavelength (n ~ 3-30) MHD instabilities that are driven by the sharp pressure gradient and bootstrap current across the edge barrier (pedestal) [15]. The ELMs are then triggered, and the pedestal pressure constrained, by the onset of these “peeling-ballooning” modes [20]. A calculation of the peeling-ballooning stability of these discharges was made with the ELITE code [20] using equilibria based on the experimental pressure profiles, averaged over many ELM cycles for the pellet induced 60 Hz ELM case. The results of this analysis are shown in Fig. 4 where contours of maximum growth rate, normalized to the diamagnetic frequency, for intermediate n (n=5-25) are shown. The axes are normalized with the pedestal width Δ (distance from pedestal top to outer plasma edge) in order to plot stability boundaries together. In the natural ELMing case, the pedestal parameters are approaching the peeling unstable region (red) just before a natural ELM crash (Pre) and are significantly removed from the unstable region just after an ELM crash (Post). In the pellet-controlled ELM case, the pedestal conditions are well within the stable region (blue). A narrower pedestal width is observed, consistent with a picture in which the pellet high-n ELMs are being triggered before the width expands to the critical width at which the natural intermediate-n ELM occurs [21].

The pedestal total plasma pressure is reduced in the pellet ELM induced case to an average 6 kPa compared to a pedestal pressure of 11 kPa just before a natural ELM in the reference discharge and 7.5 kPa shortly after a natural ELM. This reduced pedestal pressure height by the pellet ELM pacing is dominated by a reduction in the electron temperature; however the temperature profiles are not stiff enabling steeper gradients in the core. The energy confinement is maintained by this lack of profile stiffness (changes in profile shape) combined with a lower Z effective. Once the pellets injection ceases, the pedestal pressure and width build up to the non-pellet case levels in ~300 ms (1.5 energy confinement times) and large natural ELM events are observed to be re-established coincident with an increase in impurity accumulation.

The ELM pacing experiments on DIII-D were performed in conditions as closely matching those expected on ITER as is possible with a similar shaped plasma (Fig. 1) and β_N. Since ITER is also expected to operate marginally above the H-mode threshold, it will likely have a low natural ELM frequency in the range of 1-2 Hz and thus will need ELMs to be triggered at up to 30x this rate in the 10-60 Hz range to keep the divertor heat flux to a manageable level. The DIII-D controlled ELM frequency enhancement of 12 achieved in this experiment is approaching that desired for ITER and thus has addressed for the first time key issues of maintaining good H-mode confinement while reducing the ELM heat flux in proportion to the ELM frequency increase. Further investigation on the axisymmetry of observed reduced heat flux in the divertor needs to be carried out since pellet triggered ELMs are hypothesized to produce local plasma filaments that when ejected do not completely contact the entire divertor toroidal surface [22].

In summary, the viability of triggering small localized ELMs on demand by injecting LFS pellets at a rate of 12x the natural ELM rate resulting in strong reduction of ELM heat flux in the divertor has been demonstrated for the first time in DIII-D. This result was facilitated by the injection of 1.3mm pellets at < 200 m/s from the LFS high flux expansion region where the pellets are able to trigger ELMs reliably and well before they penetrate to the pedestal top, thus inhibiting fueling and degradation in confinement. The small pellet induced localized high-n ELMs are able to keep the plasma pedestal from expanding to the critical width at which the large natural global ELMs occur. Continued optimization of the pellet size and frequency are needed to fully extrapolate this ELM mitigation technique for application to ITER.

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List of Figure Captions

Fig. 1. (a) Pellet injection geometry used for pellet ELM on demand triggering on DIII-D. (b) Tangential fast camera image of R-2 pellet triggering an ELM.

Fig. 2. Comparison of 60 Hz pellet case (red) and no-pellet plasma with 5 Hz ELMs (black). Divertor deposited energy and particle flus are shown with nominal pellet times by blue tick marks. Central Ni emission, normalized energy confinement H_{98}, and electron density are shown.

Fig. 3. Averaged energy deposited in the divertor from the IR camera data for pellet triggered and natural ELMs as a function of pellet frequency. The 60Hz case is that shown in Fig. 2.

Fig. 4. Normalized current plotted against normalized pressure for the pedestal location on these pellet and non-pellet comparison discharges in Fig. 2. ELITE calculation of the boundary for peeling and ballooning stability is shown for this plasma configuration. Pellet labeled boxes are for times in the pellet case while Pre and Post are before and after large natural ELMs in the non-pellet comparison.

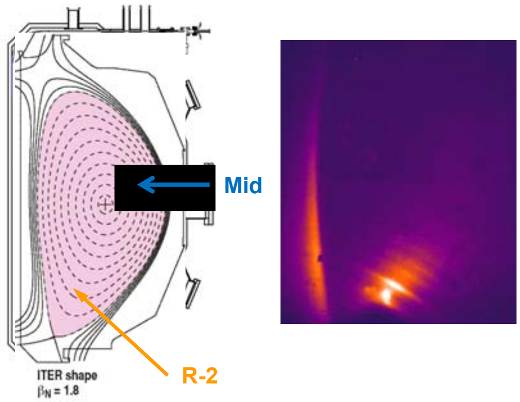

Figure 1.

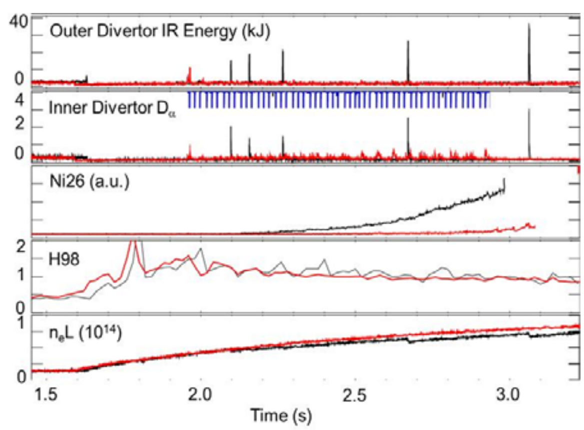

Figure 2

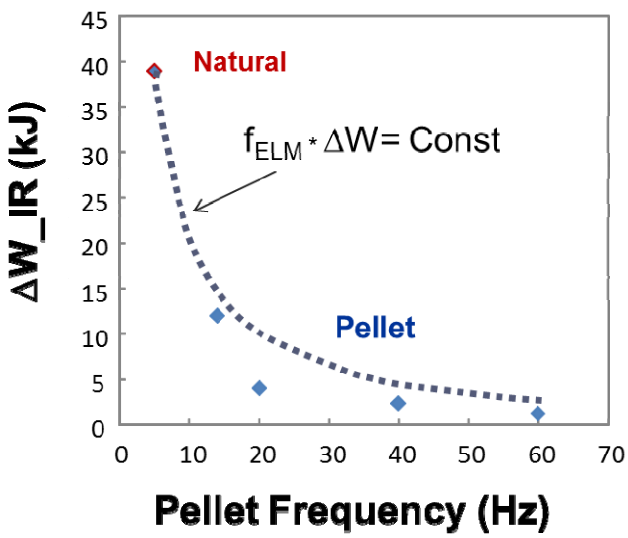

Figure 3

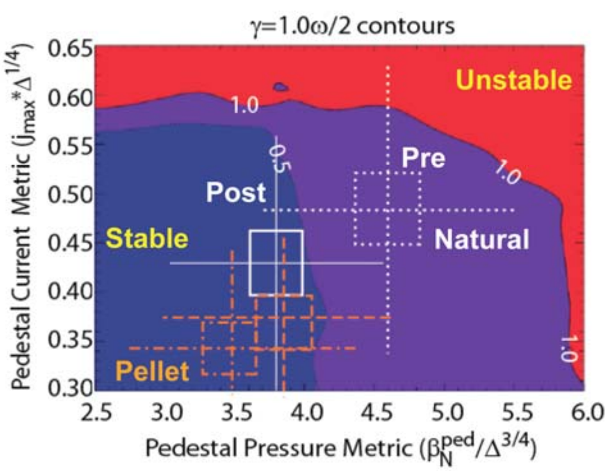

Figure 4