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High Frequency ELM Pacing by Pellet Injection on DIII-D and Implications for ITER

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1. Introduction

Deuterium pellet injection experiments have been performed on the DIII-D tokamak to investigate the on-demand triggering of edge localized modes (ELMs) at rates much higher than the natural Type I ELM frequency. This technique known as pellet ELM pacing has been proposed as a method to prevent large ELMs that can damage the ITER plasma facing components [1]. Previously, ELMs have been triggered on DIII-D using 1.8 mm pellets injected from low field side locations at rates up to 5 times the natural ELM rate [2], but ELMs in addition to those triggered by the pellets were observed indicating a change in the natural ELMing conditions. The pellet injector has since been modified to produce smaller pellets (1.3 mm cylindrical size) and at much higher repetition rates with slower speeds (<200 m/s) using new gas gun mechanisms. Experimental details of the pellet ELM pacing results and implications for ITER are reported here.

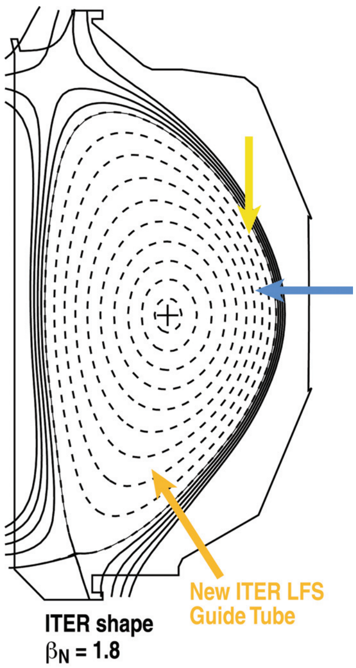

Fig.1. Pellet injection geometry used for EM pacing studies on DIII-D. The lower trajectory is similar to the planned ITER low field side injection line for pellet ELM pacing.

2. Pellet ELM Triggering Configuration

In these experiments, the pellets were injected from the low field side at the midplane (Fig. 1, blue arrow) and at a newly installed lower port (Fig. 1, lower arrow) that is similar to the injection geometry proposed for ITER. The low field side injection locations were chosen because of the higher sensitivity of these locations to trigger ELMs with pellets and low pellet fueling efficiency [2]. One barrel of the injector was connected to the midplane location while the other two barrels were connected to the lower X-point location. The nominal

1.3 mm pellet size contains 1.2×10^{20} atoms (2.4 mbar-L) of deuterium. Both trajectories lead to ELM triggering for this size and speed of pellet and no obvious difference is observed in the ELMs triggered from these locations. The flux expansion near the lower X-point enables a precise measurement of the position of the pellet in the plasma at the time of ELM onset for the x-point injected pellets. The ablation emission and magnetic loop measurements indicate that the pellets trigger ELMs when they reach the steep pressure gradient region of the edge pedestal, which is ~2 cm inside the last closed flux surface along this trajectory.

A tangential viewing fast camera was available to image the injected pellets from both locations [3]. Fast camera images of the pellet entering the plasma from the low field side show the pellets becoming visible from ablation just before the pellet reaches the separatrix. Near the separatrix (±1 cm), a single plasma filament becomes visible just in front of the pellet cloud, similar to what was observed previously for the vertical injected pellets (Fig. 1, top arrow). The filament from the vertical pellets was observed to strike the outer vessel wall within 200 μs of its formation [2]. This is consistent with the hypothesis that the pellet cloud produces a local pressure perturbation that triggers a local ballooning mode instability that manifests itself as the reduced size ELM.

3. Pellet ELM Pacing Investigation

An investigation of ELM pacing was made by injecting the D_2 pellets at 60 Hz from the low field side into an ITER shaped plasma at q_{95}=3.5 with a low natural ELM frequency of 5 Hz, β_N=1.8, and normalized energy confinement factor H_{98}=1.1, with the input power only slightly above the H-mode threshold. The non-pellet similar discharges have ELM energy losses up to 55 kJ (~8% of total stored energy), while the case with pellets demonstrated 60 Hz

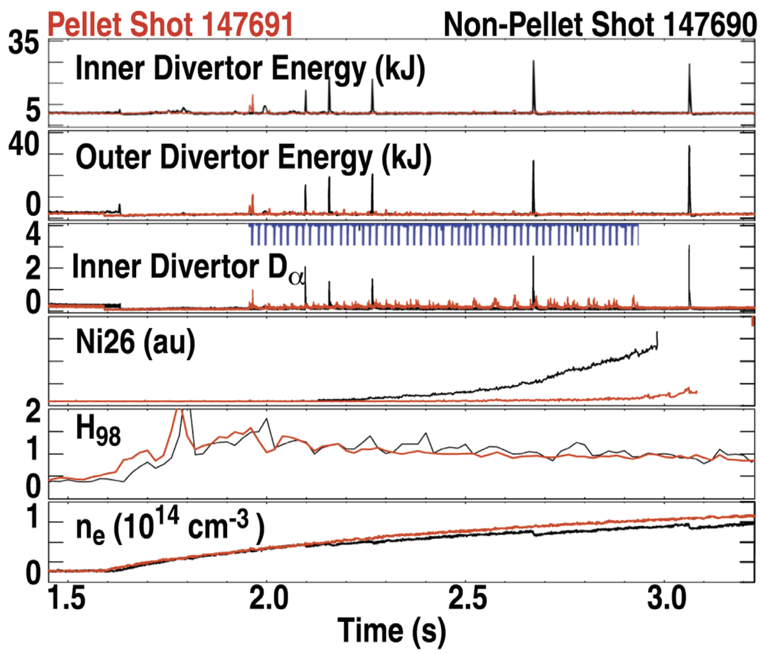

Fig. 2. Comparison of 60 Hz pellet case (red) and no-pellet plasma with 5 Hz ELMs (black). Divertor deposited energies and divertor particle flux are shown with nominal pellet times by blue tick marks. Central Ni emission, normalized energy confinement H_{98}, and electron density are shown.

ELMs with an average ELM energy loss <3 kJ (<1% of the stored energy). Total divertor energy deposited by the ELMs is reduced on average by a factor greater than 10 as measured by an IR camera. Peak particle flux to the divertor from ELMs is also greatly reduced. Central impurity accumulation of Ni and other lower Z impurities is significantly reduced by the application of the 60 Hz pellets. No significant increase in density or decrease in energy confinement was observed with the pellets (Fig. 2). The individual pellets are not observable in the interferometer density measurements due to their small size and the small ELMs that are triggered within 0.5 ms of the pellet entering the plasma that eject the pellet mass.

The plasma energy loss from each ELM in the two discharges determined from high time resolution divertor IR camera data [4,5] assuming toroidal symmetry is shown in Fig. 3. The midplane pellet triggered ELMs have a factor of 2 lower average energy deposited per ELM than the x-point pellets. In the case of triggered ELMs, the ratio of energy deposited on the outer divertor compared to the inner divertor is approximately 2.5:1, while in the case of natural elms that ratio is approximately 1:1.

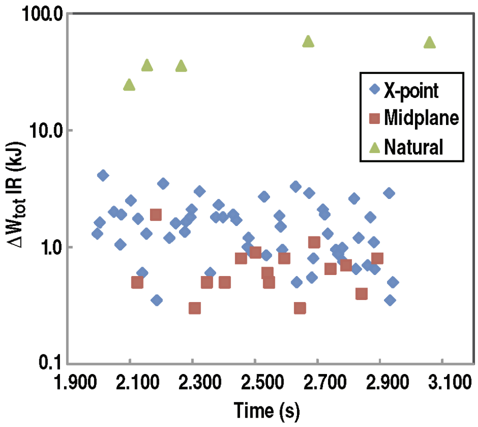

Fig. 3. Energy deposited (log scale) in the divertor from the IR camera data for each ELM in the discharges shown in Fig. 2. The natural ELMs are from the non-pellet comparison discharge.

In the ITER shape discharges without pellet ELM pacing, Type I ELMs 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). The ELMs are then triggered, and the pedestal pressure constrained, by the onset of Peeling-Ballooning modes [6]. A calculation of the peeling-ballooning stability of these discharges was made with the ELITE code [6] using equilibria based on the experimental pressure profiles from the measured temperatures and densities, averaged over many ELM cycles for the pellet induced rapid ELM case. The results of this analysis are shown in Fig. 4 where the contours of maximum growth rate, normalized to the diamagnetic frequency, for intermediate n (n=5–25) are shown. In the natural ELMing case, the pedestal parameters are approaching the peeling unstable region just before a natural ELM crash and are significantly removed from the unstable region just after an ELM crash, consistent with this instability as the trigger for the ELMs. In the rapid pellet-triggered small ELM case, the pedestal conditions are well within the stable region. In the pellet pacing case, a narrower pedestal width is observed that is consistent with a picture in which the pellets are triggering the ELMs before the width expands to the critical width at which the natural ELM occurs. It appears that in the pellet pacing cases, the pellet is triggering the ELM before this critical width is reached. The pedestal total plasma pressure is reduced in the ELM paced case to an average 6 kPa compared to a pedestal pressure of 11 kPa just before a natural ELM in the non-pellet comparison discharge and 7.5 kPa shortly after a natural ELM. This reduced pedestal height by the pellet ELM pacing is primarily in the electron pressure.

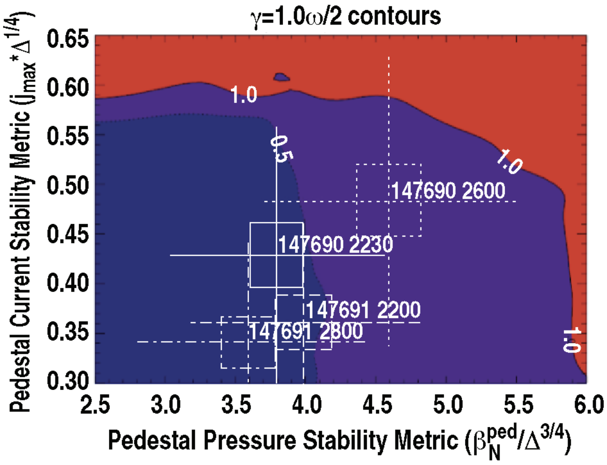

Fig. 4. Normalized shear plotted against normalized pressure for the pedestal location on these pellet (147691) and non-pellet (147690) comparison discharges in Fig. 2. ELITE calculation of the boundary for peeling and ballooning stability is shown for this plasma configuration.

4. Summary

The low field side injected pellets in DIII-D have been found to greatly reduce the ELM intensity and simultaneously greatly reduces impurity accumulation when applied at rates in excess of 10x the natural ELM rate. The pedestal height and width are reduced by the pellet ELM pacing while not appreciably affecting plasma confinement, all of which are promising for ITER. The triggering of the ELMs takes place well before the pellet reaches the top of the pedestal, implying that even smaller pellets can be utilized. Future studies with smaller pellets will elucidate just how far inside the separatrix the pellets need to penetrate. Further optimization and extension to even higher frequency smaller pellet ELM pacing is needed to fully explore and extrapolate this ELM mitigation technique to ITER.

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