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INTRODUCTION

The power load deposited by type-I ELMs on the first wall and the divertor is a severe concern for ITER plasma facing components. The ELM pellet pacing concept is one of the approaches under investigations to solve this problem. By increasing in a controlled manner the ELM frequency, the energy per ELM can be reduced, as already demonstrated in medium size tokamaks [1].

In order to validate this approach at the largest available tokamak size and demonstrate it under local conditions towards those expected in ITER, a new pellet system was developed at JET [2]. The system is designed to launch fuelling pellets (nominal particle content $21-42\times10^{20}$ D) at speed adjustable between 100 and 500m/s and injection frequency up to 15Hz and pacing pellets (nominal particle content $0.6\text{-}1.2\times10^{20}$ D) at speed adjustable between 50 and 200m/s and injection frequency between 10 and 60Hz. Pellets can be injected from the Low Field Side (LFS) and from the Vertical High Field Side (VHFS) of the tokamak.

This paper describes the experiments on ELM pacing performed at JET over the past two years both with fuelling and ELM pacing pellets and extrapolates the results in view of the ELM pacing system foreseen for ITER.

1. EXPERIMENT DESCRIPTION

In the experiments described in this paper a variety of target plasmas were used. The plasma current was varied between 2 and 2.5 MA, the toroidal field between 2.2 and 2.7 T and the additional heating power between 8 and 16 MW of NBI. Both high ($\delta_U = 0.42$, $\delta_L = 0.4$) and low ($\delta_U = 0.18$, $\delta_L = 0.35$) triangularity plasma shapes were used. These parameter ranges were dictated by the necessity to test the system with different q_{95}, ELM frequency and pedestal conditions. In particular, to demonstrate the effectiveness of pellet ELM pacing, it was necessary to keep the target plasma above the L-H transition threshold but, at the same time, to establish a spontaneous ELM frequency below the pellet injection frequency. As mentioned in the introduction, due to the unavailability of the ELM pacing part of the injector, initial experiments aiming at repeating the results of ASDEX Upgrade were performed with the smallest size fuelling pellets injected at ~150m/s from the LFS. After commissioning the ELM pacing part of the injector, experiments with pacing pellets and different target plasma conditions were performed to try and identify the minimum pellet perturbation needed to trigger an ELM.

To characterise the reliability of the injector and the transmissivity of the launch tracks, small pacing pellets were also injected into Ohmic and L-mode plasmas. In this case, due to the lower edge temperature and the absence of ELMs, the actual arrival of pellets in the plasma was clearly detectable. It turned out that, for LFS injection, the reliability of the system composed by the injector and the launch track was about 40% (namely only 40% of the pellets requested effectively reached the plasma). For VHFS injection the situation is much worse and the reliability falls below 10%.

In all experiments a number of diagnostics were deployed to measure and analyse various parameters. A set of four microwave cavities were installed to detect the pellets in the launch track. Two of them (one calibrated to detect fuelling pellets and one to detect pacing pellets) were located close to the exit of the injector. Two other cavities were positioned at the end of the VHFS injection line (optimised for detection of fuelling pellet) and at the end of the LFS injection line (optimised for detection of pacing pellets) respectively. A Thomson scattering system with 50ms time resolution was used to measure the electron density and temperature profiles. Depending on the relative timing between the pellets and the Thomson scattering time slices, it was possible to measure post pellet profiles as close as ~10ms after the pellet ablation. Finally a fast camera was used to look at the low field side injection port from a tangential view. The camera field of view included the full LFS pellet path but only the final part of the path of the pellets injected from the VHFS [3]. The fast camera is complemented by a set of D_α light detectors. These detectors, however, have no spatial resolution and are equally sensitive to ELMs and pellets. D_α emission, line integrated electron density from the interferometer, electron temperature from ECE and SXR emission from the plasma edge were also independently recorded at frequencies up to 1MHz, providing extremely well time resolved observations of the pellet-plasma interaction process [4].

2. FUELLING PELLET RESULTS

Experiments with minimum size fuelling pellets (mass 22×10^{20} D) aimed at reproducing the ASDEX Upgrade ELM pacing results were performed with a type-I ELM H-mode target plasma. The plasma shape was optimised to achieve relatively low particle confinement and good pumping in order to minimise the net fuelling effect. Figure 1 shows the results for a discharge where pellets were injected from the LFS at 10Hz and 160m/s in a plasma with I_p = 2.3MA, B_T = 2T, P_{NBI} = 11MW and spontaneous ELM frequency f_{ELM} = 8Hz. It can be seen that during the pellet train every pellet induces an ELM and the ELM frequency increases from 8 to 10Hz. Although in a limited way, this confirms the results of ASDEX Upgrade and demonstrates the possibility of triggering ELMs in a type-I ELM 'ITER baseline-like' scenario. It should however be noted that the impact of the fuelling induced by the pellets on these plasmas with relatively low NBI power to keep the spontaneous ELM frequency below 10Hz, was significant and in some cases the scenario was terminated by a transition to a type-III ELM regime.

3. PACING PELLETS RESULTS

A second series of experiments was performed using the injector in pacing mode. The size of the injected pellets was small relative to the plasma particle content, the smallest used so far in mid and large size tokamaks and these allowed to study, for the first time, the pellet impact on the plasma edge under conditions similar to those projected for pellet pacing on ITER. Experiments were initially performed in high triangularity ITER-like shape plasmas, I_p = 2.5MA, B_T = 2.7T, P_{NBI} 13MW, P_{ICRH} = 1MW, H_{98} = 1 and spontaneous ELM frequency ~5Hz. Nominal pellet mass was 1×10^{20} D, speed between 150 and 200m/s and injection frequency 20Hz. The results show that pacing size pellets do not longer reliably trigger ELMs in this scenario, in contrast to what observed for fuelling size pellets. Indeed, a statistical analysis based on the correlation between the detection of pellets at the exit of the launch track and the occurrence of ELMs in the plasma indicates that less than 15% of the ELMs are potentially triggered by a pellet.

A detailed analysis based on fast measurements of the pellet plasma interaction dynamics [4] showed that the probability for ELM triggering was correlated with pellet size and pedestal energy. The few ELMs triggered by pacing pellets were induced by the largest pellets arriving during phases of lower edge temperature and penetrating deeper into the plasma pedestal. To test this assumption further, experiments were performed where pellets were launched into plasmas with $I_p = 2.0MA$, $B_T = 2.2T$, $P_{NBI} = 8.5MW$, $P_{ICRH} = 0.75MW$, $H_{98} = 0.9$, spontaneous ELM frequency f_{ELM} ~15Hz and significantly reduced pedestal temperature and density. Because of the lower pedestal temperature and, to a lesser extent, density, using the same pellet parameters resulted in deeper penetration and reliable ELM triggering. Statistical analysis shows that the percentage of potentially triggered ELMs reaches ~50% and a more detailed single pellet analysis indicates that every good quality unbroken pellet triggers an ELM.

The different pellet penetration is illustrated in figure 2 where a neutral gas and plasma shield ablation code [5, 6] has been used to estimate the pellet ablation profile in high and low pedestal temperature and density plasmas. It can be seen that in the first case the peak of the pellet ablation profile lies outside $\sqrt{\phi_N} = 0.98$, whereas in the second case the ablation peak falls inside $\sqrt{\phi_N} = 0.91$, indicating that, if a penetration depth threshold exists for effective pellet ELM triggering, it must lie between these two values. Further experiments with varying pellet and target plasma parameters will be necessary to investigate in more detail the actual position and behaviour of the threshold.

4. IMPLICATIONS FOR ITER

To analyse the implications of the experimental results presented above for ITER, a simulation with the HPI2 ablation/deposition code [7] of ELM pacing pellet injection in ITER was performed. The target plasma was a typical ITER type-I ELMy H-mode plasma (base line scenario). Electron density and temperature were $4\times10^{19}\,m^{-3}$ and 500eV at the plasma separatrix and $8.7\times10^{19}\,m^{-3}$ and 4keV at the top of the edge transport barrier respectively. The pedestal width was assumed to be 6 cm. The pellet mass was set to $7.5\ 10^{20}$ D (10% of the nominal mass of an ITER fuelling pellet) and the injection speed to 300m/s. The results are shown in figure 3. The black line shows the normalised ablation profile for LFS injection. It can be seen that the pellet reaches the critical zone, as deduced from JET results, where it is likely to trigger an ELM, but does not penetrate as deep as the successfully ELM triggering pellets on JET. If the threshold was further inside the separatrix these pellets might not have a high ELM triggering potential. The red and blue line show the normalised pellet deposition in case of HFS injection and taking into account 50% and 100% of the ∇B-drift respectively. It can be seen that already with 50% of the calculated drift the pellet material deposition is beyond the penetration threshold, indicating that in this case every pellet should trigger an ELM.

CONCLUSIONS

The results of the pellet ELM triggering experiments performed on JET confirmed the previous results obtained on ASDEX Upgrade showing that it is possible to achieve ELM pace making in the

ITER base line scenario with fuelling size pellets, although the fuelling is significant and deteriorates the pedestal properties. Experiments with small pacing size pellets indicate that a pellet must penetrate sufficiently deep into the pedestal to trigger an ELM, while shallow penetration is insufficient.

Extrapolation to ITER shows that pellets of mass 10% of the nominal mass of an ITER fuelling pellet and speed ~300m/s should penetrate deeply enough to reach the threshold beyond which pellets start to effectively trigger ELMs. If this is not sufficient HFS injection taking advantage of the ∇B-drift could be considered to further enhance the pellet deposition depth and triggering potential.

Finally, the JET experience has shown that a reliability of the injection system (injector and launch track) close to 100% is an essential ingredient for effective pellet ELM pacing.

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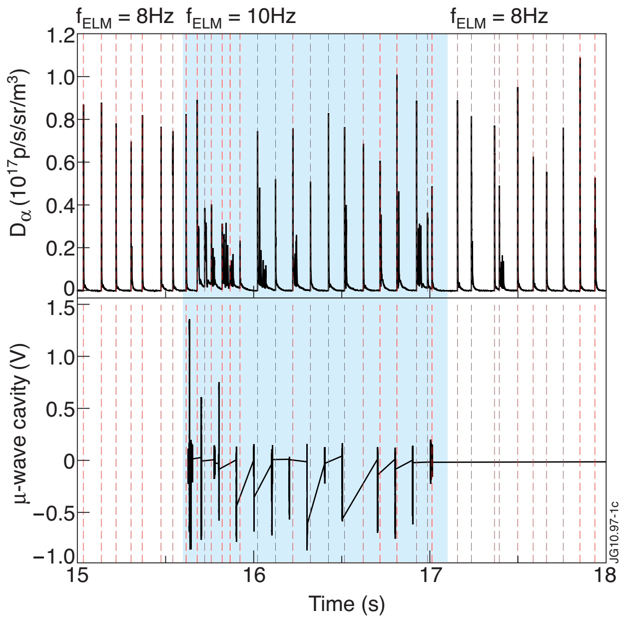

Figure 1: JET shot 76702. ELM pacing by 10Hz LFS fuelling pellets in a type-I ELMy H-mode plasma. ELMs are visible in the D_α emission and marked by vertical dashed red lines (top). During pellet injection the ELM frequency increases from 8Hz to 10Hz and every pellet detected by the microwave cavity induces an ELM when it reaches the plasma (bottom).

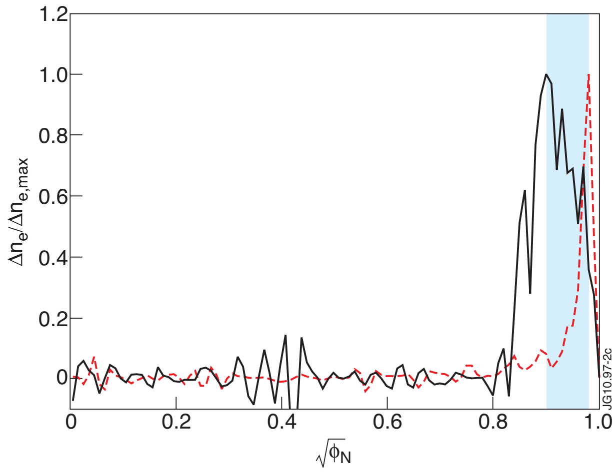

Figure 2: normalised pellet ablation profiles for pellet injected in high (red, JET Pulse No: 78600) and low (blue, JET Pulse No: 79406) pedestal temperature and density plasmas. The shaded interval delimited by the peaks of the two ablation profiles indicates the $\sqrt{\phi_N}$ region where the pellet penetration threshold for effective ELM triggering is likely to lie.

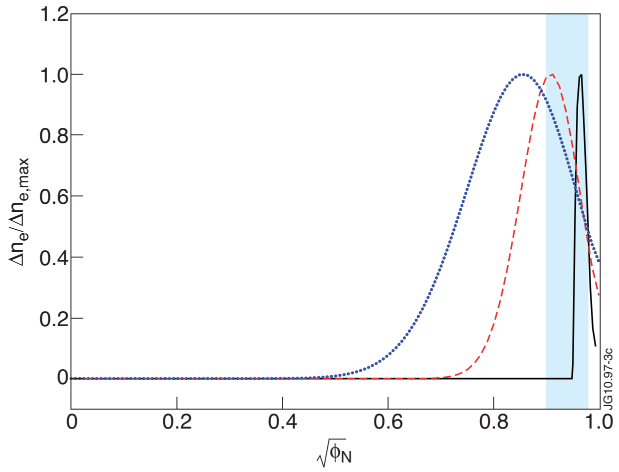

Figure 3: simulated normalised pellet ablation/deposition profiles for pacing pellets injected in ITER. Black line: ablation, LFS injection; red and blue lines: deposition with 50% and 100% ∇B-drift respectively, HFS injection. The shaded area indicates the $\sqrt{\phi_N}$ region where the pellet penetration threshold for effective ELM triggering is likely to lie.