MHD STUDIES IN RADIATING MANTLE PLASMAS ON JET

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Introduction. Plasmas with impurity seeding in order to create a radiating mantle have been investigated during recent campaigns on JET. Experiments performed at the TEXTOR tokamak have shown, that the radiating impurity does not only reduce the power load on plasma facing components, but in addition a regime with improved confinement due to turbulence suppression is established [1]. Radiative mantle experiments on JET have been done in different plasma regimes: (i) Argon was seeded in ELMy H-mode discharges using various configurations (septum, corner, vertical target, ITER-like shape) to obtain high density and high confinement during a quasi-stationary after-puff phase [2, 3], and (ii) divertor L-mode discharges with Ne seeding, a successful approach on the DIII-D tokamak, were explored as well [4].

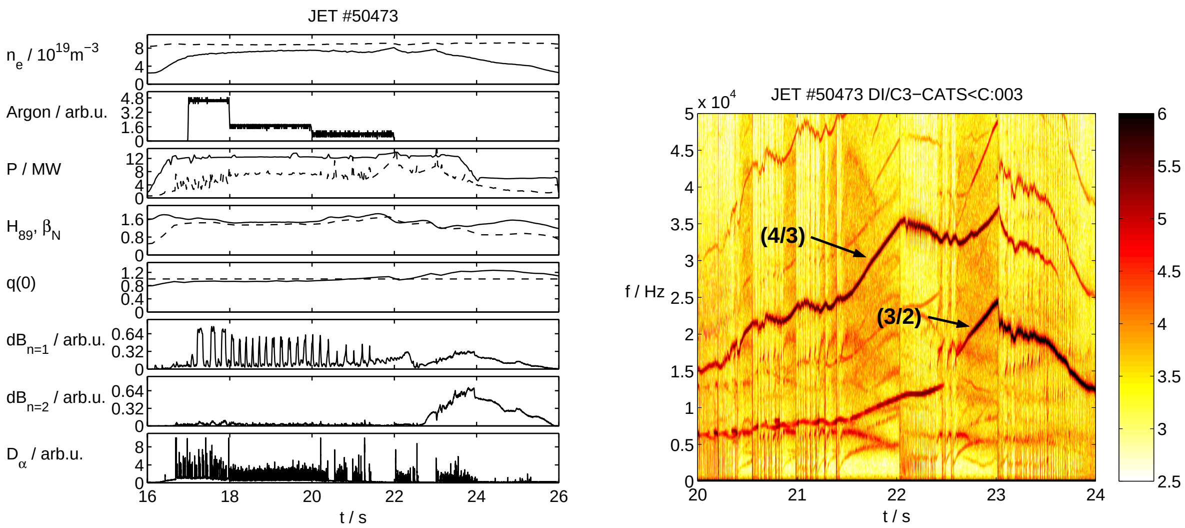

Figure 1: Example of an Argon seeded ELMy H-mode where sawteeth are stabilized and 4/3 as well as a 3/2 modes appear.

ELMy H-modes with Argon seeding. An example for the ELMy H-mode radiating mantle experiments is shown in figure 1. The left part of the figure shows the time traces of line averaged electron density (full curve) and the Greenwald density (dashed curve), Argon gas feed, total heating power (full curve) and radiated power (dashed curve), confinement quality

*see appendix of the paper by J. Pamela *Overview of recent JET results*, Proceedings IAEA Conference on Fusion Energy, Sorrento, 2000 with respect to ITER-89 H-mode scaling (full) and normalized beta (dashed), $n = 1$ and $n = 2$ signals derived from magnetic measurements, and the D_α-emission from the divertor. The right part of figure 1 shows the magnetic spectrogram of one pick-up coil.

The MHD activity in these discharges develops very often like this example. The $n = 1$ signal shows that sawteeth (visible by the bursts due to the precursor) are stabilized at $21.4\,\mathrm{s}$ when the central safety factor $q(0)$ rises to 1. The spectrogram indicates that some 1/1 mode activity is still present. During the phase when the safety factor rises until sawteeth disappear a continuous 4/3 mode develops which starts with a small amplitude at $17\,\mathrm{s}$ and grows around $21\,\mathrm{s}$. $q(0)$ rises further (i.e. a flat or even hollow q profile develops [5]) and at $22.6\,\mathrm{s}$ a 3/2 mode starts. It is important to note, that the 3/2 mode always occurred after the 4/3 mode was destabilized and $q(0)$ was above 1. β_N drops when the 3/2 mode starts, but, as can be seen from the time traces, it was already below it's maximum value. In many of the Argon seeded ELMy H-modes the deterioration of confinement was observed to occur well before the 3/2 mode activity started. Confinement degradation in discharges with high Argon input (as in fig. 1) has been associated with accumulation of impurities in the plasma core, after sawteeth were stabilised. In discharges with lower Argon densities a quasi steady state can be achieved. Here, the detrimental effect of the 3/2 mode is more clearly seen. The core density becomes limited when the 3/2 mode is present. This shows the importance of MHD control in radiative mantle discharges [5].

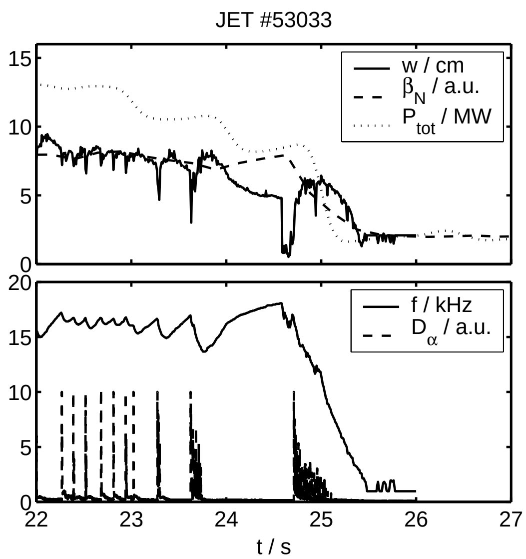

Figure 2: Temporal evolution of the mode width and frequency during step-down of the heating power.

It is of special importance whether the 3/2 modes are neoclassical, i.e. if they are driven by the perturbed bootstrap current once the island has become large enough. An MHD trigger, required to create seed island, could not be identified. The 3/2 mode started normally in a phase where sawteeth were absent. Figure 2 shows on top the island width determined from the magnetic signal (full curve), the normalized beta (dashed) and the total heating power (dotted). The lower part displays the mode frequency in the laboratory frame (full curve) and the D_α signal from the divertor (dashed) which indicates the ELM behavior. In order to check the NTM hypothesis, the heating power was stepped down during a phase where the 3/2 mode was present. The mode amplitude seems in general to follow the evolution of beta and it is stabilised mainly due to the drop in beta, actually around the H-L transition as found in standard H-mode discharges [6]. However, there is an important change in amplitude during the ELM free phase between $24\,\mathrm{s}$ and $24.7\,\mathrm{s}$. The frequency of the mode is strongly influenced by ELMs, as can be seen in the lower part of figure 2. The mode evolution can be explained if one assumes that ELMs are actually contributing to mode destabilisation, probably by reducing the plasma rotation. This would explain why the mode amplitude decays (and decouples from beta) during the ELM free phase and recovers a larger size when ELMs start again.

Divertor L-mode with Neon seeding. In these experiments, the plasma startup and the heating scenario were tailored in order to delay the onset of sawteeth as long as possible by slowing

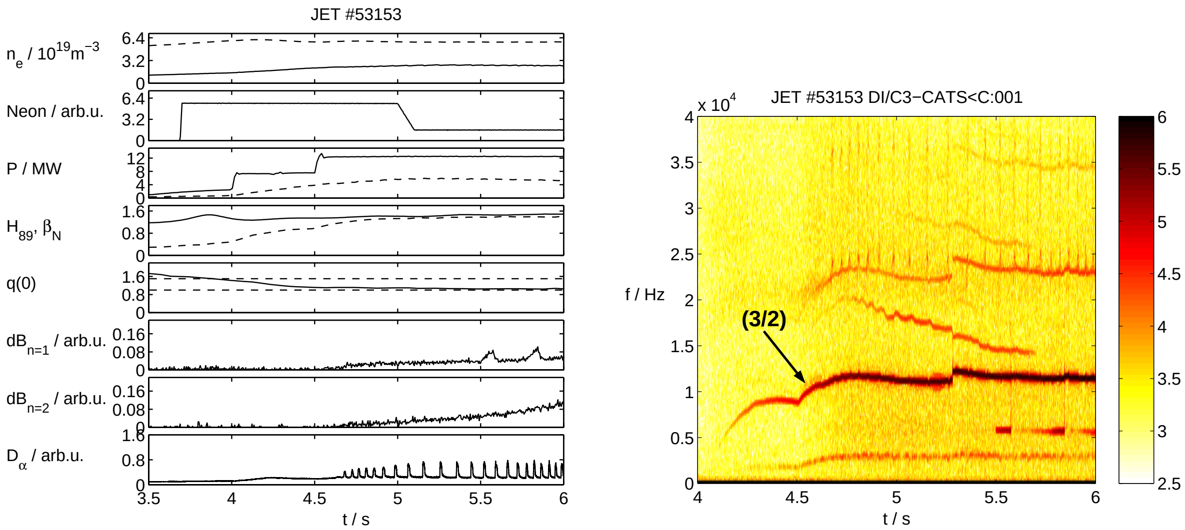

Figure 3: Example of a divertor L-mode with Neon seeding.

down the current diffusion. Neon was seeded early in the discharge with the aim to obtain high core confinement in combination with a radiating edge. In addition, in some of the experiments lower hybrid current drive (LHCD) has been applied to drive part of the plasma current off-axis, thus reducing the central current density and prevent sawteeth. Unfortunately, this lead to a unfavorable modification of the q profile which destabilized strong 2/1 mode activity. A reduction of the LHCD power could again avoid these modes. Figure 3 shows in the left part the time traces (same as figure 1, but Argon is replaced by Neon), and in the right part the magnetic spectrogram of a typical discharge. Shortly after the NBI heating power is applied at $t = 4\,$s a 3/2 tearing mode starts. The increase in frequency is proportional to the increase in toroidal rotation velocity due to the momentum input from the heating beams.

In the example discharge shown here the mode grows out of the noise, other discharges had a rather sudden mode onset with a finite amplitude. Even in that cases no MHD trigger could be identified at mode onset because sawteeth and ELMs were normally not present at this time. A comparison of the mode width evolution with the normalized beta is presented in figure 4. The mode does still grow although beta is saturated, i.e. the mode amplitude does not strictly follow the plasma pressure. Obviously, the 3/2 mode in the divertor L-mode discharges is destabilised by Δ'. The mode amplitude shows that some profiles (most likely Δ') still evolve. A contribution from the perturbed bootstrap current cannot be excluded for the later phase of mode development because the island width is rather large and β_N is in a range where JET discharges are always metastable for NTMs [6]. The 3/2 modes were stabilised again when the auxiliary heating power was switched off and β_N dropped below ≈ 0.5.

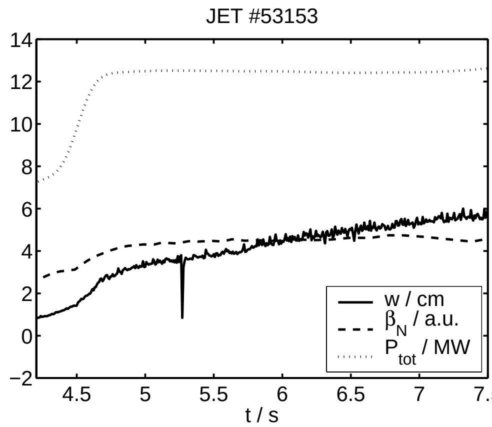

Figure 4: Mode width and normalized beta vs. time.

Different attempts to get rid of this mode have been undertaken. The modification of the current ramp as well as the gas fuelling scenario did not lead to a reproducible stabilization of this mode. In contrast to the impurity seeding experiments in the ELMy H-mode regime the confinement in the divertor L-mode discharges was seriously limited by the onset of the 3/2 tearing modes, which occurred in the majority of discharges and always started early in the heating phase.

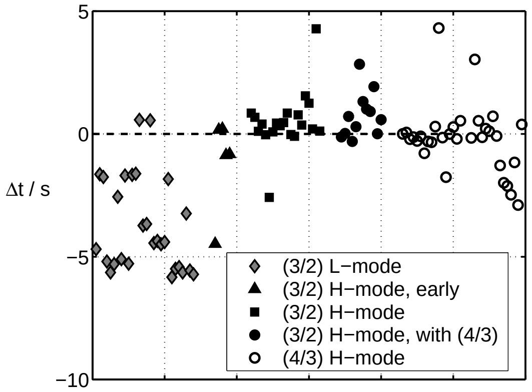

Figure 5: Time difference between mode onset and maximum beta.

Only very few discharges did not suffer from the 3/2 mode onset. In some of them, when ICRF heating was applied, fishbone-like bursts of n=1 modes were observed. These discharges showed the best confinement. The bursts appeared shortly before the start of the sawtooth oscillations when the q profile was rather flat in the center and close to 1.

Summary and conclusion. The radiative mantle discharges showed a lot of MHD activity. In the ELMy H-modes with Argon seeding a slow rise of $q(0)$ followed by sawtooth suppression was often observed. Correlated to the flattening of the q profile 4/3 modes appeared. In many cases a 3/2 tearing mode started later. The main reason for this behavior was the evolution of the q profile in the after-puff phase. MHD control using ICRH was successful in keeping the sawteeth and preventing impurity accumulation [5]. Also by preventing $q(0)$ rising above unity the appearance of 3/2 modes was prevented.

The confinement in the divertor L-mode discharges with Neon injection the confinement was severely limited by the onset of 3/2 tearing modes. This is illustrated in figure 5, where the time difference between mode onset and maximum beta is plotted for the 4/3 and 3/2 modes observed in both regimes. In the ELMy H-modes 3/2 mode onset was mainly after beta had reached the maximum, whereas in the L-mode experiments the mode started in the rising phase of beta. For completeness the graph shows a few cases where 3/2 modes started very early in the ELMy H-mode experiments, and points where the 3/2 mode followed a 4/3 mode or no 4/3 mode was present are discriminated.

Once these modes have reached a rather large size the perturbed bootstrap current may contribute leading to the observed hysteresis in beta for mode stabilisation.

The observations have shown that radiative mantle discharges need current profile control in order to sustain central MHD (1/1 modes and sawteeth) to avoid impurity accumulation as well as to prevent an unfavorable q profile which destabilizes tearing modes.

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