A comparison between H-mode and detaching Wendelstein 7-AS plasmas - a case study (notes, latest edition 5th of June 2001)

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1.Introduction

In these notes we will discuss some points regarding the density fluctuation behaviour in two selected shots. In section 2 we will describe density fluctuations in shot 47114, which had three clear phases, the final one being the ELM-free H-mode (H*). Section 3 contains a density fluctuation analysis performed for shot 51322, which detached towards the end of the shot.
The two major points of concern here are:

- Do we observe ELM-like structures in the detaching shot; and if so, at what times?
- Is the detached phase similar to or in fact identical to an ELM-free H-mode?

A comparison between the two shots mentioned would clarify these questions. If the conclusion is that the detached phase of shot 51322 is indeed an H*-mode, this will be the first experimental realisation of steady-state H*-mode operation without the need for ELMing behaviour to keep the radiation in check.

2.H-mode shot 47114

Shot 47114 was heated by two NI sources, had $\iota_a = 0.558$ and a density ramp throughout the discharge until it was terminated at 600 ms (radiative collapse). The discharge was performed in connection to the 1999 pre-EPS experiments (in May 1999). The shot is suitable for benchmarking against shot 51322 because ι_a was roughly identical. Further, it nicely illustrates the 'traditional' sequence L-mode [0.1, 0.4] s $\longrightarrow$ dithering H-mode [0.4, 0.56] s $\longrightarrow$ H*-mode [0.56,0.59] s.
The CO_2 laser scattering diagnostic has two (roughly) toroidally displaced vertical measurement volumes passing close to the plasma center at $\varphi = 30$ degrees. The detected density fluctuations are aligned parallel to the major radius, and the frequency sign in the following figures indicates the direction of these with respect to the major radius (poloidally rotating fluctuations are measured).
Diagnostic settings for shot 47114 were as follows: Perpendicular wavenumber $k_\perp$ observed was 14 cm^{-1}, toroidally displaced volumes ($\theta_R = 0$ degrees) 29 mm apart (2 w = 8 mm). Positive frequencies are due to fluctuations travelling radially inward along the major radius.
Figure 1 shows the following quantities, from top to bottom:

1. Stored energy (15 degree signal)
2. Radiated bolometer power (lower camera)

3. Crosspower amplitude between the two density fluctuation volumes

The crosspower shows to how large an extent the fluctuations are correlated at given frequencies, and also gives som weak localisation information. The volumes are aligned so that the crosspower is due to correlated fluctuations from the center/top of the plasma; negative frequencies are dominated by fluctuations travelling in the electron d.d. (diamagnetic drift) direction, positive frequencies dominated by fluctuations travelling in the ion d.d. direction.
Our usual interpretation is that the low frequency fluctuations are localised outside the LCFS and rotate in the ion d.d. direction due to $\mathbf{E} \times \mathbf{B}$ rotation caused by the small positive radial electric field there. Conversely, the high frequency fluctuations in the electron d.d. direction stem from radial positions inside the LCFS (large negative E_r) and are correlated with Mirnov coil and H_α bursts.

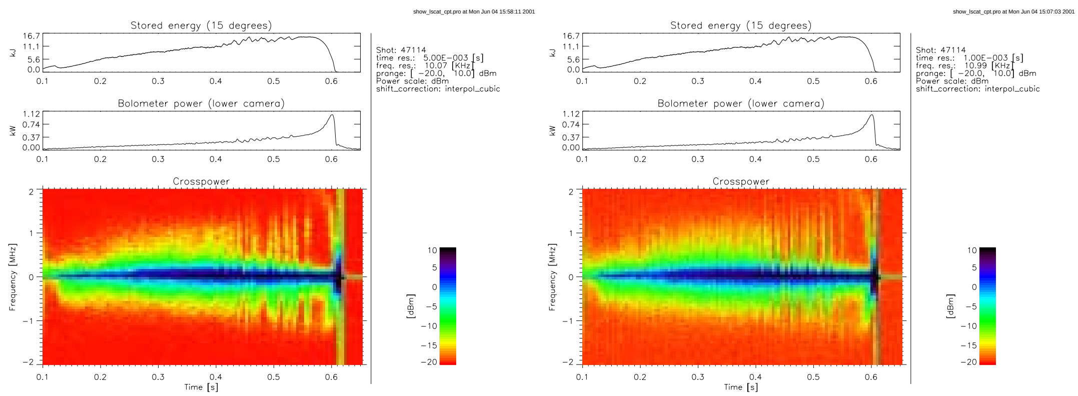

Figure 1: (Colour) Analysis of shot 47114, top to bottom: Stored energy, bolometer power and crosspower amplitude (logarithmic scale). Left: Slow time resolution (5 ms), right: Faster time resolution (1 ms).

The three confinement stages are clearly visible in all parameters; the dithering phase is reflected in the stored energy and bolometer radiation as small dents, while these bunched ELM-like events show up as high frequency components in the crosspower amplitude (vertical lines). As the H^*-mode is entered at 560 ms, these high frequency components die out for a short while, and the radiation increases rapidly.
Note the interesting point that the density fluctuations have a radiative collapse pre-cursor, a high frequency component that spins down and increases in amplitude till the radiation peaks. To further clarify the spectral differences between L- and H^*-mode density fluctuations, figure 2 shows 2D plots of the crosspower and crossphase (**NOTE: We will not discuss the cross phase results in the notes.**). The left-hand plot is up to $\pm$ 4 MHz, right-hand up to $\pm$ 2 MHz. The L-mode phase (thick solid line) is seen to have two features, a low frequency component (up to 500 kHz) and a wide high frequency feature extending up to 1.5 MHz. The H^*-mode phase (thick dotted line) also has a low frequency feature, but the high frequency feature has disappeared. A new high frequency feature is the radiative limit pre-cursor which spins down during the H^*-mode.
To sum up: During L-mode, two density fluctuation components exist; a low frequency feature travelling in the ion d.d. direction outside the LCFS and a high frequency feature travelling in the electron d.d. direction localised inside the LCFS.

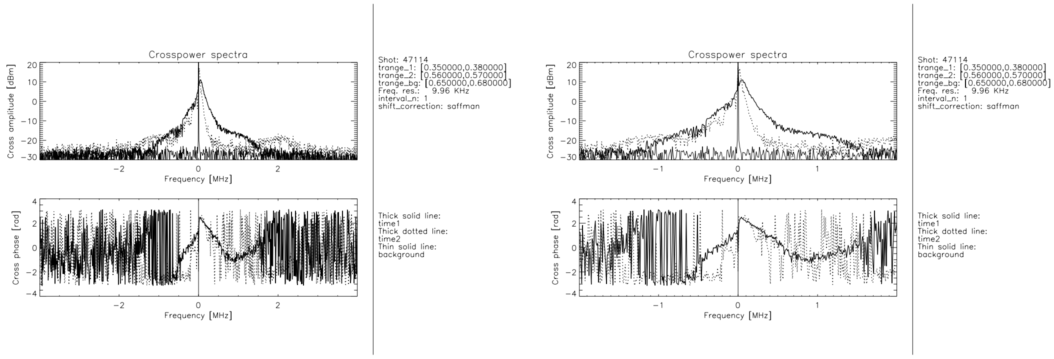

Figure 2: 2D plots of cross amplitude (top) and cross phase (bottom) between density fluctuations in the two volumes. Left-hand shows data up to ± 4 MHz, right-hand side up to ± 2 MHz. L-mode measurements are solid thick lines, H*-mode measurements thick dotted lines.

In the transition to H*-mode, both features are reduced in amplitude and a new high frequency feature appears, which later spins down again and seems to be connected to the radiative collapse.

3.Detaching shot 51322

Shot 51322 was heated by four NI sources, had $\iota_a = 0.556$ and two density plateaus (pre- and post detachment). The discharge was performed in connection to the 2001 pre-EPS experiments (in May 2001). A first attempt to detach was observed at 460 ms, and the final transition to detachment occurred some time after 500 ms, rather gradually.
Diagnostic settings for shot 51322 were as follows: Perpendicular wavenumber $k_\perp$ observed was 20 cm^{-1}, toroidally displaced volumes (θ_R = - 15 degrees) 19 mm apart (2 w = 7 mm). Positive frequencies are now due to fluctuations travelling radially outward along the major radius. Further, it is important to note that notch filters have been used in this discharge, to increase the dynamical range of the 8-bit acquisition system. This damps the carrier signal (0 Hz peak) but also has the disadvantage to damp the fluctuation signal appreciably up to ± 300 kHz.
Since both the sign of the frequency has changed meaning and the magnetic field direction was changed, frequencies in the crosspower plots maintain their previous meaning.
As in section 2, we display plasma traces and crosspower amplitude for shot 51322 in figure 3. As we learned from figure 1, vertical lines in the crosspower amplitude are due to ELMs or ELM-like events. The fluctuation measurements answer our first question posed in the introduction: There is ELM-like activity in the detaching plasma, right from the beginning at 100 ms. The bursts concentrate in the [0.3,0.45] s and [0.5,0.6] s time windows. We note that in entering the final detached phase (which is established at 650 ms), the plasma becomes quiescent, in the sense that these ELM-like bursts disappear.
Since detachment is to some extent triggered by bursts of heavy gas puffing, one could think that the ELMs are directly linked to the gas puffing. To clarify this point, figure 4 shows the total gas puff rate vs. time for shot 51322. Comparing this to figure 3, we observe that the ELMy behaviour is already present before the large increase in puffing

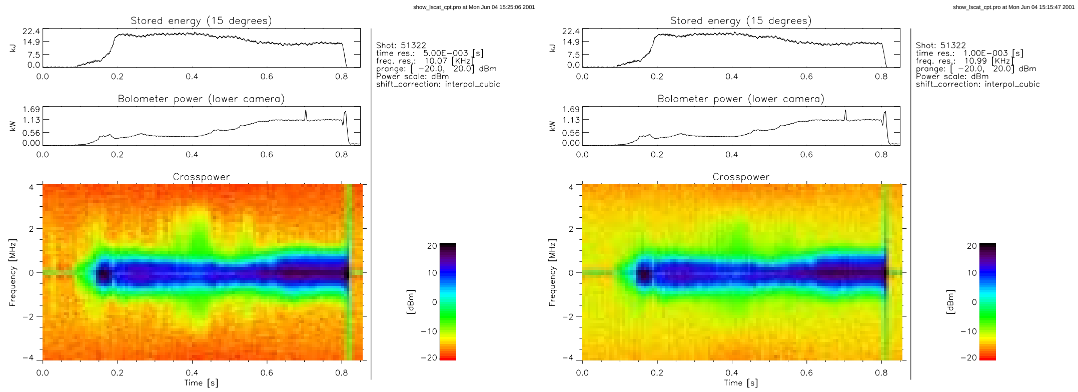

Figure 3: (Colour) Analysis of shot 51322, top to bottom: Stored energy, bolometer power and crosspower amplitude (logarithmic scale). Left: Slow time resolution (5 ms), right: Faster time resolution (1 ms).

at 400 ms. What the puff does to the ELMs is that it seems to smear them out, making them quasi continuous. The causality concerning the next gas puff is more clear in the sense that this puff in fact does seem to create the ELMing activity.

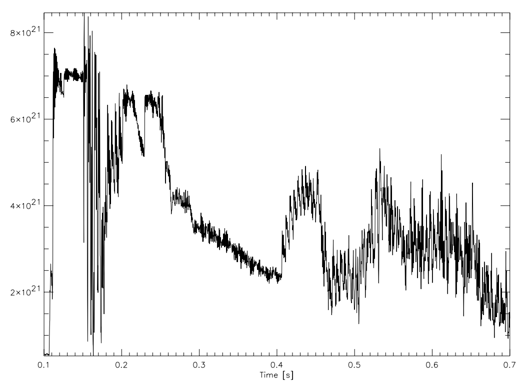

Figure 4: Gas puff rate (in particles per second), shot 51322.

To attack question two in the introduction, two analysis time windows have been selected to ascertain whether detachment features and H*-mode features are compatible. The time windows are [0.35,0.38] s (attached plasma) and [0.7,0.73] s (detached plasma). Figure 5 shows the cross amplitude and cross phase for these two intervals, completing the comparative 47114/51322 figure series. The left-hand plot shows the global behaviour up to high frequencies; the attached phase fluctuations (thick solid line) have two components (as L-mode), a large amplitude low frequency feature (outside LCFS, ion d.d.) and a small amplitude high frequency feature (inside LCFS, electron d.d.). In contrast, the detached plasma only has the low frequency feature, which is most likely outside the LCFS. The dip towards low frequencies is instrumental, due to the notch filters as explained earlier.
The right-hand plot shows a zoom of the left-hand plot, to detect possible MHD activity. We can confirm that such activity is indeed observed, at 160 and 80 kHz, probably rotating in the ion d.d. direction outside the LCFS.

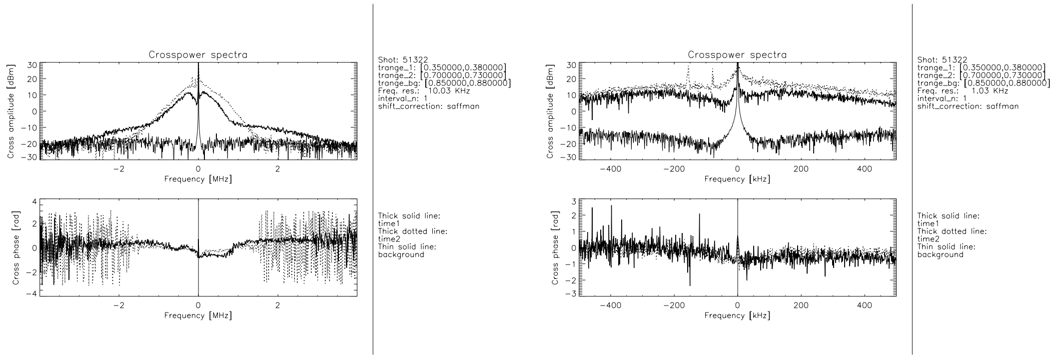

Figure 5: 2D plots of cross amplitude (top) and cross phase (bottom) between density fluctuations in two volumes. Left-hand shows data up to $\pm$ 4 MHz, right-hand side up to $\pm$ 500 kHz. Attached measurements are solid thick lines, detached measurements thick dotted lines.

4.Discussion

We will now briefly attempt to sum up the results presented above, and comment on possible answers to the second question.

Concerning shot 47114, the L- to H*-mode transition is accompanied by a large reduction in density fluctuations, both rotating poloidally inside/outside the LCFS in the electron/ion d.d. direction. From previous evidence we are led to believe that although the low frequency fluctuations have the dominating amplitude, they are benign compared to the high frequency fluctuations in the sense that they are not directly linked to global confinement properties.

If this interpretation remains valid for the detaching shot 51322, it means that the internal rotating mode (which is global confinement relevant) completely vanishes/ is suppressed, leaving only the relatively harmless structure outside the LCFS. The price one has to pay is of course a smaller plasma volume and a reduction in stored energy.

It is obviously tempting directly to make the connection L-mode/attached and H*-mode/detached. However, we must not let ourselves be convinced by a single case study that this is in fact the case.

The points of similarity pointed out are intriguing and it is our belief that they merit further studies.