Comparison of fishbones and fishbone-like frequency changes of the neoclassical tearing mode at ASDEX Upgrade

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Introduction

The maximum stationary β at ASDEX Upgrade is often limited by the onset of neoclassical tearing modes (NTM). The most common NTM is the coupled (3,2) and (2,2) mode. At ASDEX Upgrade the dominant heating is neutral beam injection with a fairly perpendicular injection angle. Therefore, fishbones are usually observed at high enough plasma temperatures, provided the $q = 1$ surface is not too small. Thus, NTMs are in most cases preceded by fishbones. The NTM weakens the fishbones and in most cases they disappear completely. Instead, fast frequency changes of the NTM, called frequency jumps (FJ) in the following, are often observed (fig. 1). The FJs resemble fishbones very much. It seems probable that fast particles interact with the (2,2) component of the NTM.
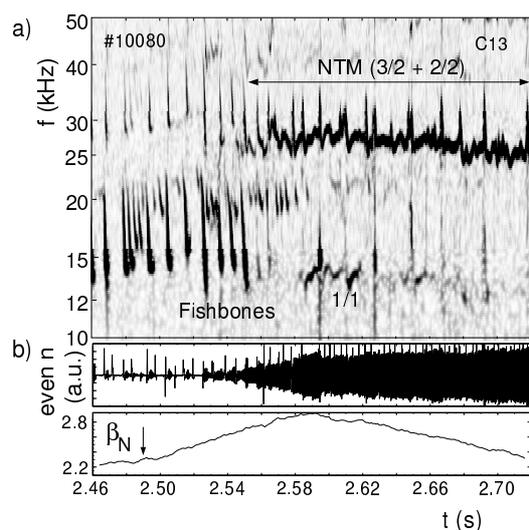

Figure 1: *a) Wavelet plot of an NTM. Fishbones are suppressed as the NTM grows. Frequency jumps are observed in the NTM.*
b) Mirnov signal for even toroidal mode number n and β_N. The arrow indicates the time when the NI power is increased from 7.5 to 10 MW.
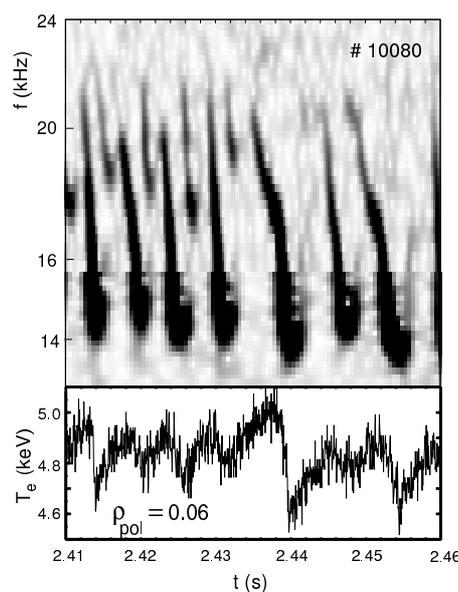
Figure 2: *Wavelet plot of fishbones together with the central electron temperature (T_e). Each strong fishbone in this figure decreases T_e in the centre significantly.*

In this paper we present similarities of and differences between fishbones and FJs with respect to their frequency and amplitude development as well as the thermal losses correlated with these events. For this purpose we investigate the time evolution and radial distribution of thermal losses due to fishbones and frequency jumps together with sawtooth crashes for comparison.

Thermal losses due to sawtooth crashes and fishbones

Fishbones are usually considered an ideal (1,1) kink mode which is excited by a fast ion

resonance. Due to this resonance fast ions are expelled from the plasma. However, it has been shown at ASDEX Upgrade, that fishbones can also lead to thermal losses which are much too fast to be caused by a reduced heating power due to a loss of fast ions (fig. 2) [1]. The fast particle content affects T_e on the slowing-down time scale, which is approx. 50 ms in this case.
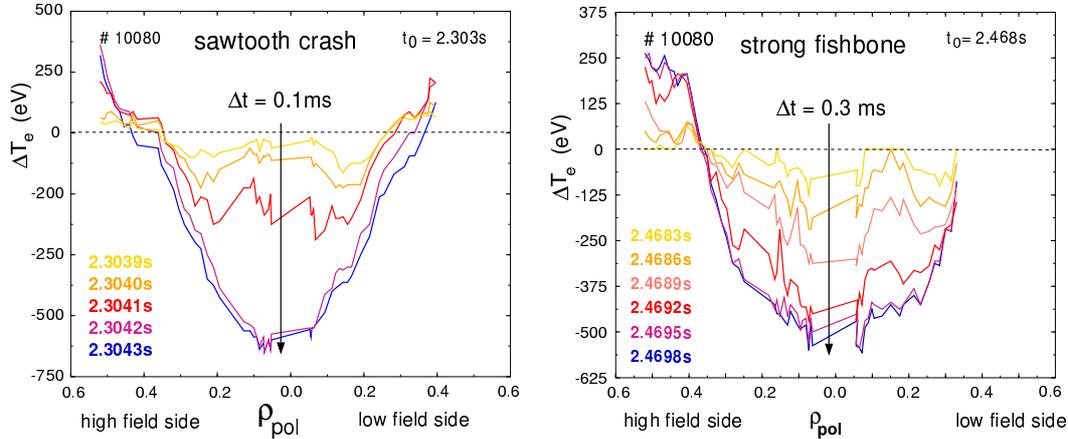

Figure 3: *Evolution of the radial T_e loss profile during a sawtooth crash and a strong fishbone.*
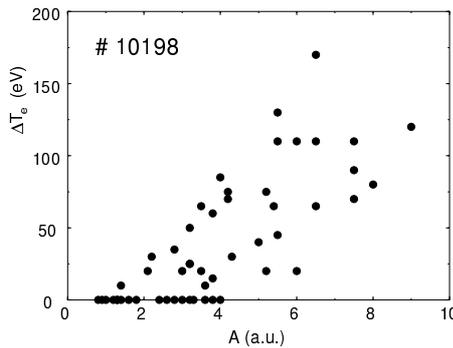

Figure 4: *Central temperature decrease due to fishbones vs. the fishbone mode amplitude.*

Fig 3 shows the time evolution of the radial temperature loss profile due to a sawtooth crash and a strong fishbone, respectively. The temperature decrease for a strong fishbone is similar to that in the sawtooth case, but takes longer (1-2 ms). However, many fishbones are weaker and lead to a smaller or even no detectable decrease in T_e (fig. 4).

Thermal losses due to NTM frequency jumps

During the (3,2) and (2,2) NTM phase fishbones are usually suppressed (fig. 1). Nevertheless the NTM shows frequency jumps, which resemble the second harmonic of the (1,1) fishbone mode. Fig. 1 reveals that for most of these FJs no strong (1,1) mode is observed. Therefore, the FJ is not only a coupling of the (2,2) component of the NTM to the (1,1) fishbone mode, but an independant mode. However, some FJs coincide with a strong (1,1) mode burst. Both types of FJ differ in their temperature loss characteristic and are treated separately.

Fig. 5 shows various data for a (1,1) fishbone and FJs without and with a strong (1,1) mode. The upper and lower part of Fig. 5 reveals that fishbones and FJs are similar in the time evolution of frequency ((1,1) and NTM) and amplitude ((1,1) and (2,2) component). The amplitude grows during the frequency decrease and reaches its maximum near the minimum frequency. One difference is that, contrary to the fishbone burst, the NTM is a continuous mode, which suffers only changes in frequency and amplitude. Furthermore, the frequency change of the NTM is smaller than for the second fishbone harmonic.

The middle part of fig. 5 shows temperature changes at different flux surfaces. FJs, like fishbones, are correlated with thermal losses. In case of fishbones these losses are clearly
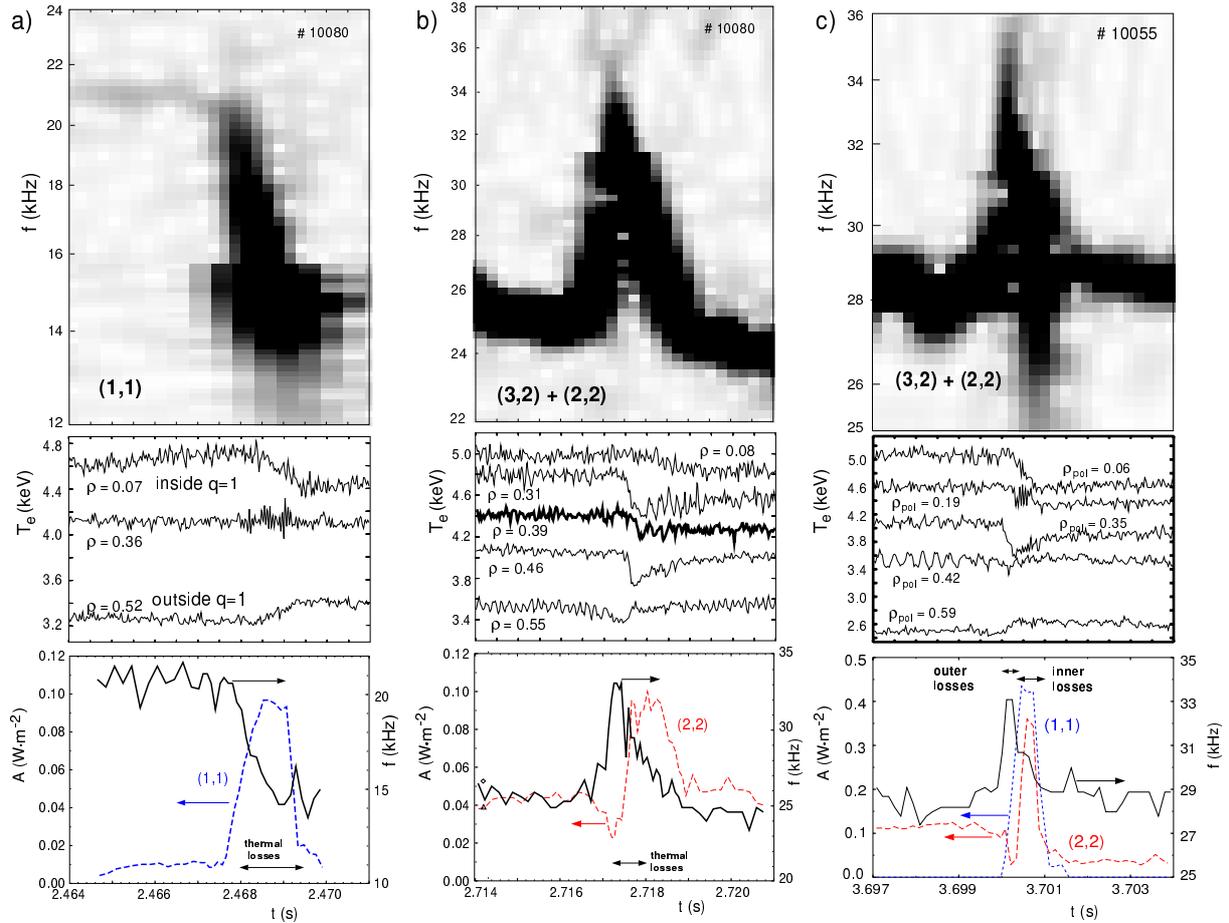
Figure 5: *Wavelet signature and time traces of T_e together with mode frequency and amplitude of a) a fishbone b) an FJ and c) an FJ with strong (1,1) mode burst.*

correlated with the (1,1) amplitude. The FJ losses start already when the frequency is in its maximum, i.e., before the (2,2) amplitude is high. Fishbone losses are inside the $q = 1$ surface while FJ losses are further outside. Fig. 6 a) shows the time evolution of the loss profile for a strong FJ. The T_e losses start approx. at $q = 1.5$, at $\rho_{pol} \approx 0.55$, and extend towards $q = 1$. In case of a strong FJ a second phase follows, in which the losses reach the plasma centre. The first phase lasts for about 0.5-2 ms, the second phase for 1-2 ms, which is similar to the duration of fishbone losses. The first losses (outside $q = 1$) seem to be a necessary trigger for the FJ, which is not observed in the fishbone case. The later losses (inside $q = 1$) might be similar to fishbone losses, since they are also correlated with the amplitude of the mode on $q = 1$ (here the (2,2) component of the NTM). Even for strong FJs these later losses are weak. On the other hand we mentioned that FJs are probably weaker than fishbones, and many fishbones cause small or even no losses. However, we cannot exclude that the later losses are of diffusive origin and only an effect of the first losses.

As mentioned above, some FJs coincide with a strong (1,1) mode burst. Fig. 6 b) shows such a case. The first loss phase of the FJ (reaching from $q = 1.5$ to $q = 1$ for about 0.5-1 ms) is followed by a stronger loss inside $q = 1$, which is similar in magnitude to a strong fishbone loss or a sawtooth crash. It is also correlated with the (1,1) mode amplitude. We consider this to be rather a sawtooth-like event, because the time scale is
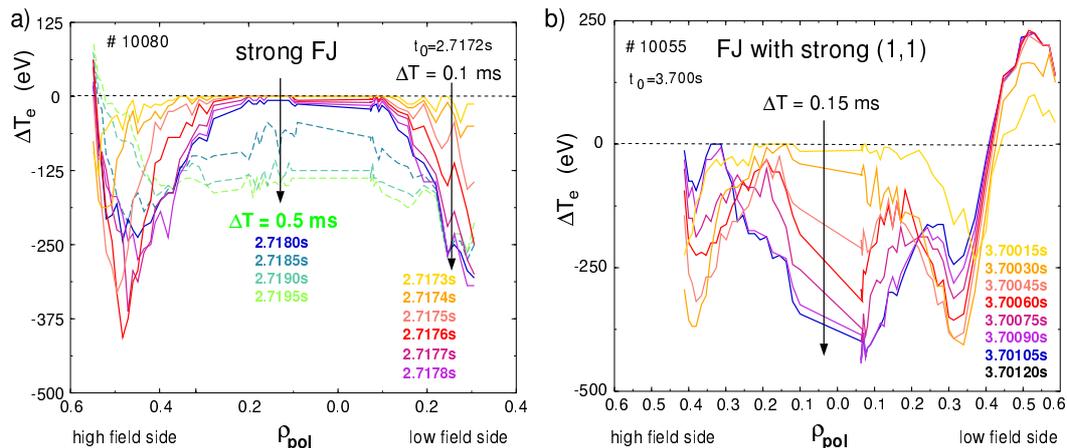
Figure 6: *Evolution of the T_e loss profile during a) an FJ and b) an FJ with strong (1,1) mode.*

quite similar to that of sawtooth crashes. The repetition frequency of FJs is of the order of 100 Hz, while that of the sawtooth-like events triggered by FJs is about 10 times lower and thus similar to sawtooth frequencies for the same plasma parameters. The ability to trigger sawtooth crashes is another similarity of FJs and fishbones (see also [2]).

The energy loss inside $q = 1.5$ for a single FJ is up to 3 % and about 1 % in average. Energy losses for an FJ with strong (1,1) can be 2-3 times higher than for an FJ alone. For an energy confinement time of 60 ms this results in losses of approx. 5-10 % of the energy content inside $q = 1.5$. Here, density changes as well as a possible expulsion of fast ions by FJs are not considered.

In discharges with $q_{95} \approx 8$ to 9 the coupled (2,1) and (1,1) NTM shows a phenomenon similar to the frequency jumps of the (3,2) and (2,2) NTM.

5 Discussion and Summary

Frequency jumps (FJ) of the coupled (3,2) and (2,2) NTM have been observed. These FJs resemble fishbones in their time evolution of frequency and mode amplitude and in their ability to trigger sawteeth and sawtooth-like events, respectively. Furthermore, strong fishbones and strong FJs are both correlated with thermal losses in the plasma centre, which coincide with the increased amplitude of the (1,1) and the (2,2) mode, respectively. Therefore, we have reason to believe that an interaction with fast trapped ions could be responsible for the frequency jumps, in a similar way as fishbones are excited by a fast ion resonance. However, contrary to fishbones, the NTM is a continuous mode, which is not excited by fast particles but only altered in frequency and amplitude. Thermal losses between $q = 1.5$ and $q = 1$ precede the FJs and seem to be a necessary trigger. Furthermore, there is no theory to decide whether (2,2) fishbones are possible in general. Last, we have not yet been able to measure an effect of FJs on the fast particle distribution.

The fact that thermal losses precede the FJ might suggest that the frequency is increased due to the flattening of the pressure profile around $q = 1.5$. However, since significant losses start only when the mode frequency is already in its maximum, this assumption does not seem likely.

References

[1] S. GÜNTER et al., The influence of fishbones on the background plasma, submitted to Nucl. Fusion

[2] M.F.F. NAVE et al., Nucl. Fusion **31** (1991) 697.