NEOCLASSICAL TEARING MODES AND THEIR INTERACTION WITH FISHBONES AT ASDEX UPGRADE

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1. Introduction

The maximum achievable β in ASDEX Upgrade is often limited by neoclassical tearing modes (NTMs) [1,2]. The strongest restriction on stationary β is imposed by the coupled (3,2) and (2,2) NTM. However, for low enough collisionality the (2,1) NTM can be additionally excited, leading to further deterioration of the confinement. The interaction between the (3,2) NTM and MHD activity on the $q = 1$ surface, especially fishbones, has been studied. Theoretical investigations (e.g., [3,4]) show that an NTM only grows if a minimum island size (seed island) is present in the plasma. To study the features and origin of the seed island, the early phase of the (3,2) NTM has been investigated using soft X-ray (SXR) and Mirnov diagnostics. Usually, the NTM begins with a finite amplitude, but in few cases no seed island has been observed [5]. The collisionality dependence of NTMs according to the ion polarization current model [4] has been examined.

2. Interaction between (1,1) and NTM

Fig. 1 shows the evolution of an NTM. (1,1) activity, in many cases fishbone bursts, is always observed before the onset of the NTM. The early NTM frequency decay (of $\approx 100\,\mathrm{ms}$) reflects the reduction of the momentum and energy confinement time due to the NTM. The frequency decrease is in agreement with the experimentally observed reduction of the plasma rotation frequency. The reduced energy confinement shows in the decrease in β_N (Fig. 1 c)) with constant heating power at the onset of the NTM.

During the NTM phase, preceding MHD activity ((1,1) mode, sawteeth, and fishbones) is usually suppressed or weakened. In Fig. 1 a weak (1,1) mode is observed during the NTM phase, which is the subharmonic of the (2,2) component of the NTM.

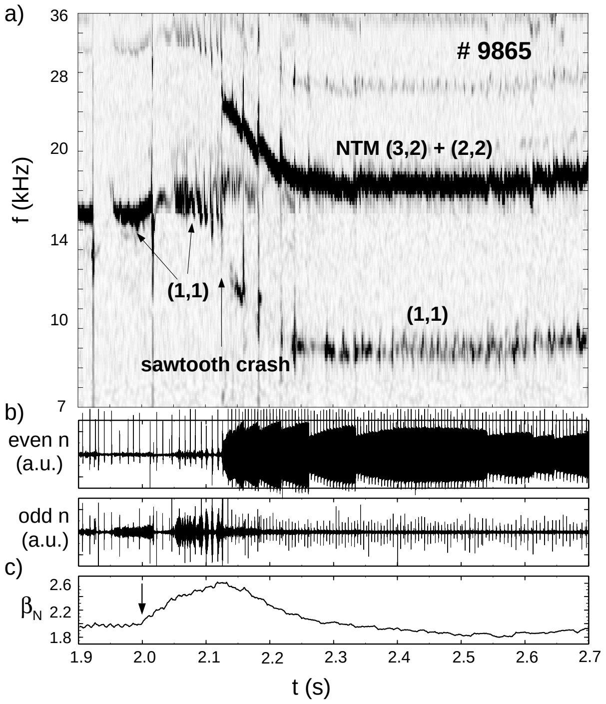

Figure 1. a) Wavelet plot [6] of an NTM. Dark areas represent mode activity. Before the onset of the NTM at 2.126 s fishbone bursts are seen. b) Mirnov signals. The even n signal is dominated by the NTM, the odd n signal by (1,1) modes. c) $\beta_N = \beta_t aB/I$ with $\beta_t = 2\mu_0 p/B_t^2$; the arrow indicates the increase of neutral beam injection power from 5 to 7.5 MW.

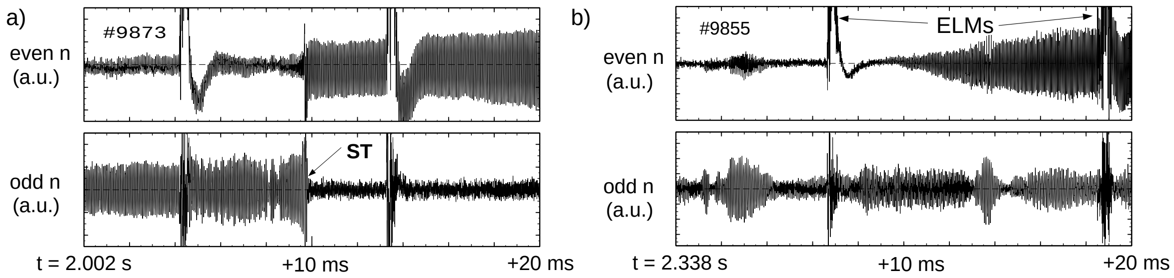

Figure 2. Mirnov signals for even and odd toroidal mode numbers. The spikes in the even n signal and the corresponding fluctuations in the odd n signal indicate ELMs. The NTM begins at $\approx +10$ ms in both cases. a) NTM following a sawtooth crash b) NTM without trigger.

The suppression of fishbones during the NTM can be understood in terms of the fishbone stability diagram [7,8]. The onset of the NTM flattens the plasma pressure between the $q = 1.5$ and the $q = 1$ surface (coupled (3,2) and (2,2) mode). The reduction of the ion diamagnetic drift ω_i^* can shift the plasma into the stable region. When the neoclassical mode disappears, the pressure partly recovers leading again to precessional fishbones and (1,1) sawtooth precursors.

3. NTM after different trigger events

The NTM can be triggered by a sawtooth crash or by fishbone activity. In cases after a sawtooth crash the initial mode amplitude is rather large (Fig. 2 a)), corresponding to a finite seed island size. If the NTM is preceded only by fishbones, several consecutive fishbones seem to be needed to increase the seed island size until it can grow on the neoclassical timescale. The mode starts with a weak amplitude and becomes stronger with a further fishbone. The amplitude directly after the last fishbone trigger is comparable with the mode amplitude directly after a sawtooth crash. In few discharges the NTM begins spontaneously, without a clear trigger event, and grows without a detectable seed island (Fig. 2 b)). In this case the mode amplitude at the beginning is at least ten times smaller than after a sawtooth crash, corresponding to a three times smaller seed island.

In cases with sawtooth or fishbone triggered NTMs, the mode frequency sometimes begins at the second harmonic of the preceding (1,1) mode (fishbones or sawtooth precursor), indicating that the NTM seed island might be produced by toroidal coupling of the preceding (2,2) mode to the $q = 3/2$ surface, as claimed in [1]. However, in many cases the NTM frequency rises during the first 10 to 20 ms (Fig. 3) and stays well below the second harmonic of the preceding (1,1). For some sawtooth triggered NTMs with rising early frequency, a change in the mode character from a nearly pure (3,2) to a coupled (3,2) + (2,2) mode has been observed. Here, the sawtooth crash obviously has produced a (3,2) seed island directly.

The scaling of β_N at the time of the mode's onset ($\beta_{N,onset}$) after a sawtooth crash has been investigated in [2]. For constant q_{95} and self-similar profiles $\beta_{N,onset} \propto \rho_i$ has been found, where $\rho_i \propto \sqrt{T_i}/B_t$ is the ion gyro radius, T_i the ion temperature at the rational surface, and B_t the toroidal magnetic field. $\beta_{N,onset}$ values for NTMs without preceding sawtooth crash are added to this scaling (Fig. 4).

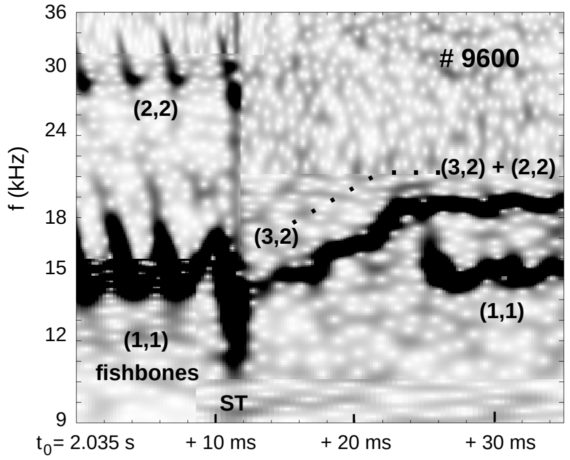

Figure 3. Wavelet plot of an early NTM immediately after a sawtooth crash. The NTM frequency rises during the first 10 ms.

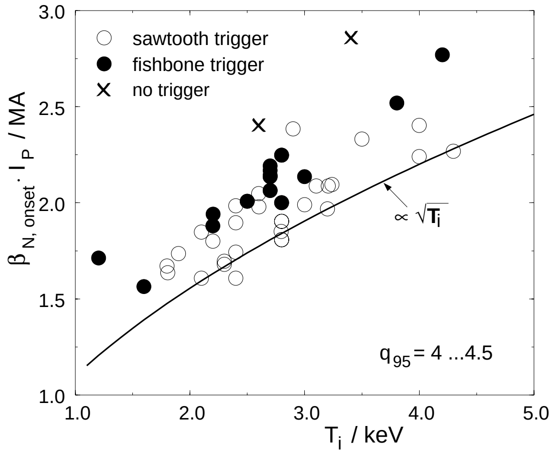

Figure 4. $\beta_{N,onset} \cdot I_p$ vs. the ion temperature at the $(3,2)$ radial position, T_i. Additionally the scaling, $\beta_{N,onset} \cdot I_p \propto \sqrt{T_i}$, is shown [2].

For an NTM following fishbones, β_N is higher than in cases with a sawtooth trigger, indicating that the seed island formation by fishbones is less efficient. This is plausible because on one hand, the fishbone frequency is determined by fast particles and thus strongly different from the rotation frequency of a magnetic island, and, on the other hand, a sawtooth produces a stronger perturbation and thus more readily facilitates the formation of a (3,2) seed island. A higher β where the plasma is less stable against tearing is thus needed to produce a sufficient seed island size by fishbones.

The highest $\beta_{N,onset}$ values correspond to cases where the NTM begins without a trigger event, where no seed island is observed, indicating that with higher pressure the plasma becomes more and more unstable against tearing. An island large enough for neoclassical growth is produced without a prominent MHD event. Therefore, it is not obvious, that to avoid NTMs, it is sufficient to prevent a $q = 1$ surface. To answer this question, one has to find out whether the coupling to the $m = n$ mode, e.g. (2,2), is essential for the existence of NTMs.

4. Collisionality dependence of NTMs

According to the polarization current model [4], the minimum β_p at which neoclassical growth is possible, $\beta_{p,crit}$, and the necessary seed island size, W_{seed}, depend on the poloidal ion gyro radius, ρ_p, but also on the local collisionality at the resonant surface, $\nu_{ii}/m\epsilon\omega_e^*$, through the parameter [4,1]

$$g(\epsilon, \nu_{ii}) = \begin{cases} \epsilon^{3/2}, & \nu_{ii}/m\epsilon\omega_e^* \ll C \approx 1 \\ 1, & \nu_{ii}/m\epsilon\omega_e^* \gg C \approx 1 \end{cases} .$$

$\beta_{p,crit}$ and W_{seed} are both proportional to $\sqrt{g(\epsilon, \nu_{ii})} \cdot \rho_p$. Considering this dependence, a threshold value for $\nu_{ii}/m\epsilon\omega_e^*$ is to be expected. For ASDEX Upgrade at the $q = 1.5$ surface it has been found to be $\nu_{ii}/m\epsilon\omega_e^* \approx 0.03$ for the (3,2)-mode [9]. At very low densities, and hence collisionalities, the (2,1)-mode can be additionally excited, leading to an H to L-transition or even to disruptions. Both neoclassical modes have been avoided at ASDEX Upgrade by increasing the collisionality (Fig. 5).

5. Summary

The neoclassical tearing mode (3,2) + (2,2) at ASDEX Upgrade is often triggered by a sawtooth crash or by fishbones. In few cases the NTM starts spontaneously.

There is an interaction between NTMs and fishbones: NTMs can be triggered by fishbones and sometimes they begin at the second fishbone harmonic. On the other hand, an NTM supresses fishbones.

The β value at the NTM's onset is higher for modes triggered by a fishbone than by a sawtooth and even higher for spontaneous NTMs. The fact that the NTM can grow spontaneously, indicates that to stabilize it, it might be not sufficient to avoid MHD activity that can produce a seed island.

The threshold character for the collisionality dependence of the onset of the (3,2) and the (2,1) neoclassical modes has been found. For the (3,2) mode the threshold has been determined as $\nu_{ii}/m\epsilon\omega_e^* \approx 0.03$. A scenario with high density, and hence high collisionality, has been established, where NTMs could be avoided at ASDEX Upgrade.

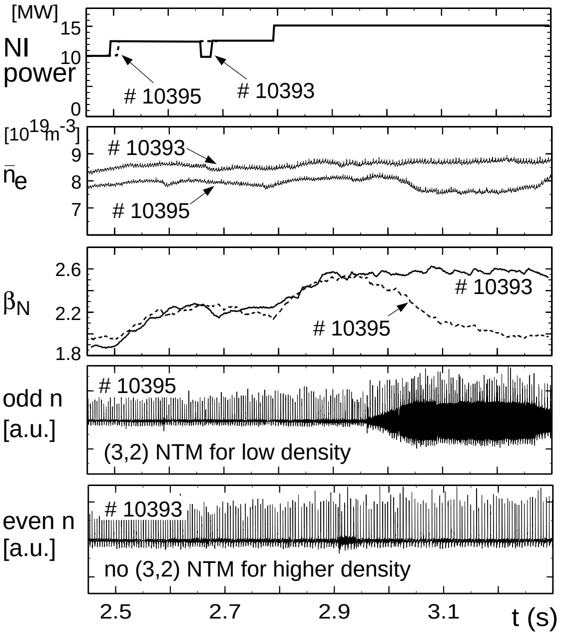

Figure 5. Comparison between two similar discharges ($B_t = 2.0$ T, $I_p = 1.0$ MA, $q_{95} = 3.2$) with only slightly different densities. For #10395 with $\bar{n}_e = 8 \cdot 10^{19}$ m^{-3} the (3,2) mode appears, whereas for #10393 with $\bar{n}_e = 8.5 \cdot 10^{19}$ m^{-3} there is no (3,2) mode.

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