Neoclassical tearing modes in advanced scenarios in ASDEX Upgrade

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Introduction At ASDEX Upgrade advanced tokamak discharges with internal transport barriers (ITB) have been investigated. One has to distinguish between discharges which remain in L-mode by avoiding a L to H-transition and discharges with a double transport barrier with an additional H-mode edge. For discharges with L-mode edge (2/1) mode activity dominates, which can be used to gain information about the minimal q_{min}. In discharges with an H-mode edge mainly the excitation of neoclassically driven (3/2)-modes and (2/1)-modes is the limiting MHD activity which is covered by this paper.

ITB with L-mode edge Discharges with an L-mode edge and a large heating power of $P_{NI} = 5$ MW of neutral beam injection during the current ramp up phase are achieved by an limiter configuration on the inner limiter on high field side resulting in increased L to H-mode threshold.

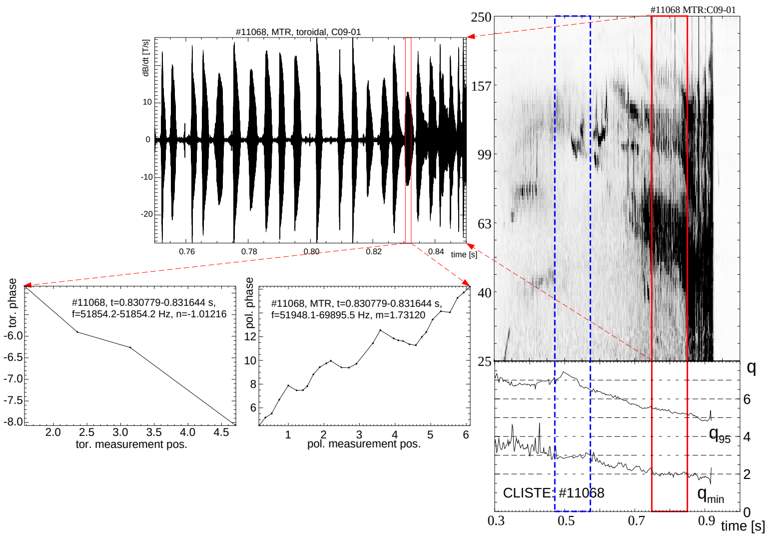

Figure 1: *(2/1)-fishbone-like mode activity in the early current ramp up phase with 5 MW of NBI heating power. From a CLISTE equilibrium reconstruction based on MSE measurements a constant $q_{min} = 2$ can be observed during the phase of this (2/1)-fishbone activity.*

In these discharges fishbone-like mode activity with a high frequency of $f_{fb} \approx 70 - 50$ kHz for (2/1)-fishbones during the ramp up phase can be observed. The CLISTE equilibrium reconstruction based on measurements of the motional Stark effect (MSE) diagnostic shows a q-profile with negative central shear and a constant $q_{min} = 2$ during this phase. The toroidal and poloidal phase on the Mirnov diagnostic and the the spatial phase distribution from soft X-ray measurements show clearly a (m=2 / n=1) structure. In some cases also clear (3/1) fishbone-like mode activity coinciding with a $q_{min} = 3$ from MSE can be observed. In so far these modes can be used as an indication for the minimal q_{min} present in these discharge phases. For a limited period of time they seem to stop for at least some time a further diffusion of current towards the center. The transport barrier is usually lost with the onset of a strong continuous (2/1)-mode, which usually after mode locking to the vacuum vessel leads to a complete loss of confinement.

ITB with H-mode edge Discharges with an H-mode edge show a completely different mode behaviour. The discharges are performed in lower X-point configuration with the ion $\vec{\nabla} B$ drift towards the X-point leading to an early L to H-transition.

Typically strong (1/1)-fishbone activity in the flat-top phase over many energy confinement times are observed [2]. This fishbone activity indicates a $q = 1$ surface in the plasma, whereas no sawteeth are present during this fishbone activity. Their characteristics is similar to that of sawteeth reducing the central electron temperature $T_e(q < 1)$ and leading to a heat pulse further outside ($q > 1$). The fishbones seem to also eject impurities. The raise of the central temperature before the crash and the crash itself is smaller, as the fishbones have a much higher reptition frequency ($f_{fb} \approx 350$ Hz $>> f_{st}$). According to the stability diagram for fishbones [3], for higher densities and/or higher B_T the fishbones disappear. A increase in the density reduces the slowing down time τ_{sd} of the injected fast ions and decreases the pressure produced by the fast particles β_{fast} which drives the fishbones. The increase in the toroidal field also reduces the available free energy of the fast particles, as the confinement time is changed by variation in the toroidal fieldand as the radius of the $q = 1$ surface shrinks and reduces the number of available fast particles.

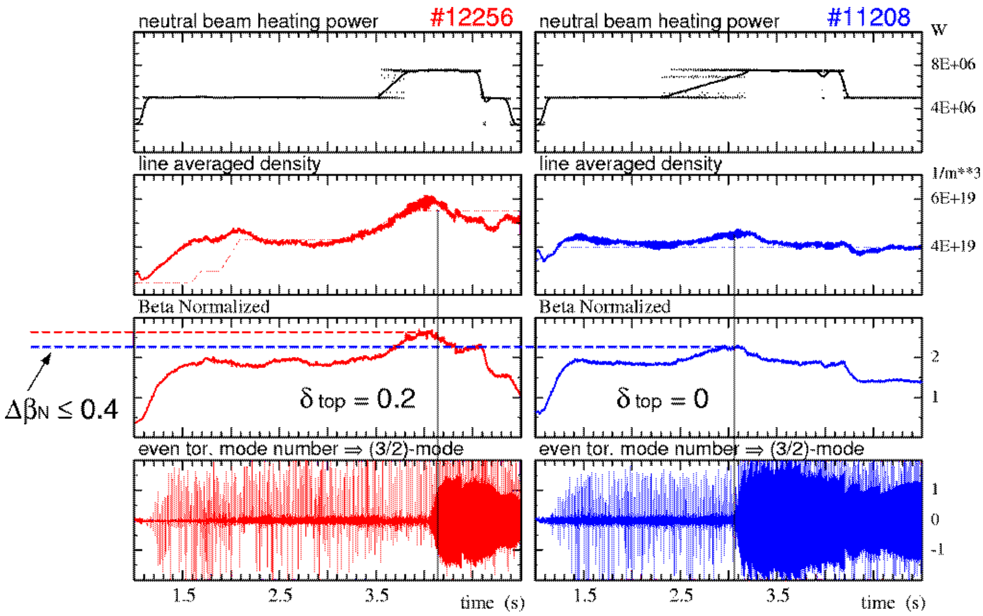

Figure 2: *An increase in the upper triangularity δ_{top} from $\delta_{top} = 0$ to $\delta_{top} \approx 0.2$ results in an increased achievable β_N^{onset} and β_p^{onset} for the onset of a (3/2)-mode.*

These discharges usually have low densities of the order of $\bar{n}_e \approx 4 - 5 \cdot 10^{19}$ m^{-3} and hence low collision frequencies. They tend therefore to be vulnerable for neoclassically driven tearing modes [4]. Indeed an increase in the plasma energy by increasing the applied neutral beam heating power alone leads to a β-limit by a neoclassical (3/2)-mode and eventually followed by a (2/1)-mode leading to mode locking. The locked modes completely destroy the improved confinement phase, but do not necessarily lead to disruptions. With an additional increase of the density simultaniously to the heating power ramp one is able to avoid the excitation of (3/2)-

modes, similar to cases without ITBs [4]. Stationary phases with up to 7.5 MW of NBI heating power without neoclassical modes could be maintained. The stationary achieved β_N remains well below the value before the onset of the mode, but above the value with a saturated (3/2)-mode. A further increase of the density results in an increased energy content in these discharges leading to an excitation of (3/2)-modes at β_N values comparable to cases without gas puff.

An increase of the triangularity δ of the plasma has become possible at ASDEX Upgrade in the present experimental campaign. With this additional freedom higher values of β_N and $\beta_N * f_H$ have been achieved without the excitation of (3/2)-modes [5]. In Fig. 2 two similar discharges with upper triangularity of $\delta_{top} = 0$ and increased triangularity of $\delta_{top} \approx$ 0.2 are compared. For the low δ_{top} case (such as #11208) the mode typically gets excited at $\beta_N^{onset} = 2.2 - 2.4$, whereas in the high δ_{top} case (such as #12256) values of $\beta_N^{onset} = 2.5 - 2.6$ can be reached. Typically an improvement in β_N before the onset of neoclassical modes in the order of 10 % could be gained by the increased triangularity. The density increase parallel to the heating power ramp occurs without any further gas puffing required. This is mainly due to an improved particle confinement in high δ discharges observed in ASDEX Upgrade [6]. Hence the density increase is achieved without a confinement degradation usually observed in gas fuelled plasmas.

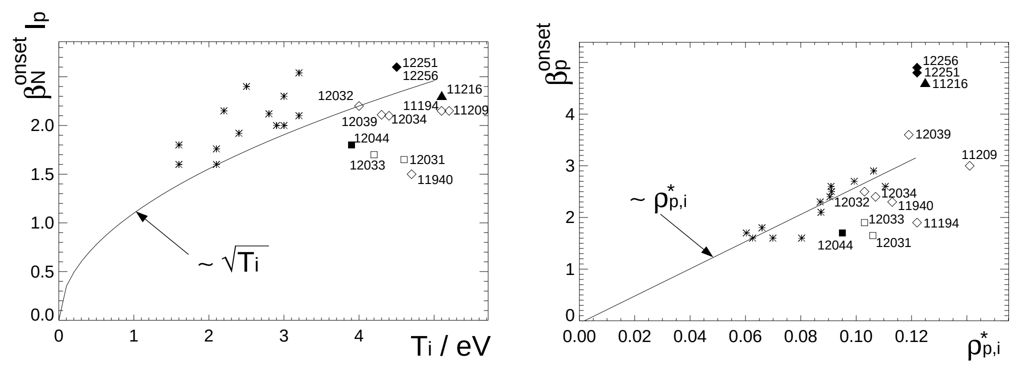

Figure 3: *Scaling of the onset of (3/2) neoclassical tearing modes in ITB-discharges in a* $\beta_N^{onset} * I_p[T_i]$ *(left side) and a* $\beta_p^{onset}[\rho_{p,i}]$ *(right side) diagram [7,8]. The stars mark standard sawtoothing H-mode discharges, where a sawtooth triggers the (3/2)-mode. The other symbols represent the onset of (3/2)-modes in ITB discharges and are discussed in detail in the text.*

In order to get a clearer answer about the onset conditions of neoclassical modes with ITBs, they have been compared with (3/2)-modes triggered by sawteeth in standard discharges with higher density and heating power and with theoretical predictions. The local values for $T_i(q = 3/2)$, $\beta_p(q = 3/2)$ and $\bar{\nu}_{ii}(q = 3/2)$ have been determined at the radial location of the mode taken from soft X-ray measurements. As the modes are often lying in the region of the steep temperature gradients near the ITB this location needs to be known quite well and is the largest source for errors. From the polarization current model the onset of the modes should scale as $\beta_p^{onset} \sim \rho_{p,i}^*$ or as an approximation to global parameters for similar profiles $\beta_N^{onset} * I_p \sim \sqrt{T_i}$ [7]. For sawtoothing standard ELMy H-modes ($q_{95} \approx 4, P_{NI} \geq 7.5$ MW) without ITBs and a trigger by sawteeth this scaling is fullfilled very well. Some standard discharges together with the resulting scaling is shown in Fig. 3 (stars and solid line).

The ITB discharges analysed so far show a much larger scatter. It can be seen that the variation from the sawtooth scaling is larger in the $\beta_N^{onset} * I_p[\sqrt{T_i}]$ diagram, as the profiles are different for ITB discharges. The onset details are therefore discussed in the $\beta_p^{onset}[\rho_{p,i}^*]$ diagram: (i) In one set of discharges a decrease of the density during discharges reduces strongly the collisionality and leads to sawtooth triggered (3/2)-modes (open squares). Similar values are seen in cases with impurity puffing (Argon for #12044, full square), which strongly increase the confinement and hence β. This leads to an excitation of the (3/2)-mode at relatively low β-values. A ramp in the toroidal field from 2.65 T - 2.85 T (#11940) leads to a sawtooth triggered (3/2)-mode. The sawteeth reappear by a modification of the stability for the fishbones together with a shrinking of the $q = 1$ surface. Through the modification of the q profile by the field ramp the strongest discrepancy between the two diagrams is produced. Without any preheating during the ramp up phase of the current the mode is triggered by a large sawtooth resulting in very low achieved β values. (ii) In a second set of discharges the modes are triggered by a combination of fishbones and small sawteeth. They are lying slightly below the scaling. (iii) Discharges with a purely fishbone triggered mode lie on or slightly above the scaling. Over all the trend can be stated that also ITB discharges with fishbone trigger, providing a smaller seed-island, reach higher values in β_N and β_p as discharges with sawtooth trigger and larger seed-islands. (iv) The highest values can be reached with increased triangularity δ_{top}. Values comaparable to otherwise only transient achievable β-values could be reached. In the transient case (#11216, full triangle) the heating power has been increased much faster (several 10 ms) then the typical growth time of the neoclassical (3/2)-mode ($\approx$ 100 ms). In this transient case β still rises strongly while a mode is already growing. To explain the global trend for discharges with $\delta_{top} = 0$ reaching only values below the usual sawtooth scaling the low local collisionalities at the resonant surface may be important. The relevant values of $\bar{\nu}_{ii} = \nu_{ii}/m\epsilon\omega_e^*$ = 0.002 - 0.005 are well below the usual values of $\bar{\nu}_{ii} = 0.03$ for sawtoothing discharges. In addition Δ' is expected to be different, as the q-profile in ITB discharges strongly differs from usual plasmas due to another reconnection process and different density and temperature profiles.

Summary In this contribution the MHD activity in ITB discharges with L and H-mode has been presented. Mainly the onset of neoclassical tearing modes in H-mode ITB discharges has been investigated. With increased triangularity local β_p values before the mode onset could be reached comparable to transient values with power ramps well above the sawtooth scaling. Other events, such as density drops or impurity puffing lead to reduced values compared to the sawtooth scaling. The tendency to show values below the scaling may be explained by different density and q-profiles resulting in different values of Δ' and on the other hand by the low collisionalities in ITB discharges.

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