Scaling of the onset of neoclassical tearing modes in various scenarios in ASDEX Upgrade and ASDEX

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Introduction   Neoclassically driven tearing modes cause a severe limitation to high β fusion plasmas. It is therefore of large interest to get a better understanding about the onset conditions of these modes and fix the dependencies on plasma parameters to distinguish between different models to make predictions for a next step device, such as ITER. All present models have free parameters which need to be fixed by the experiments and the resulting scalings. Especially the stabilising polarisation current term in the generalised Rutherford equation is of interest in this context.

Present state of scalings   The neoclassical tearing modes can be described by the so called generalised Rutherford equations [1,2] [1]

$$
\begin{aligned}
\frac{\tau_{res}}{r_{res}}\frac{dW}{dt} &= r_{res}\Delta'(W) \\
&+ r_{res}\beta_p\left(a_2\sqrt{\epsilon}\frac{L_q}{L_p}\frac{W}{W^2+W_0^2} - a_3\frac{r_{res}}{R_0^2}\frac{L_q^2}{L_p}\frac{1}{W} - a_4 g(\epsilon,\nu_{ii})\left(\rho_p\frac{L_q}{L_p}\right)^2\frac{1}{W^3}\right).
\end{aligned}
$$

The sign and the factor of last term describing the ion polarisation current effect is still under discussion [3,2,4–6]. Under the assumption that the above equation describes the NTM correctly, the following critical local β_p^{onset} value results.

$$
\beta_p^{onset} \geq \beta_{p,crit} = \frac{3\sqrt{3}}{2}\cdot\sqrt{\frac{L_p}{L_q\epsilon^{3/2}}\cdot\frac{a_4 g(\epsilon,\nu_{ii})}{(a_2 - a_3\epsilon^{3/2}L_q/r_{res})^3}}\quad\cdot(-\Delta')\cdot\rho_p \tag{1}
$$

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

This value at least needs to be reached before an NTM may get excited by a large enough seed island. For small enough and constant $\bar{\nu}_{ii} = \nu_{ii}/m\epsilon\omega_e^*$ (stabilising ion polarisation current small) and for similar current and pressure profiles the resulting scaling $\beta_p^{onset}(q=3/2) \sim \rho_{p,i}^*(q=3/2)$ and $\beta_N^{onset} \sim \frac{\sqrt{m_i \cdot T_i(q=3/2)}}{a\cdot I_p}$ is well established on ASDEX Upgrade [7]. Usually discharges with $q_{95} \approx 3.3$ and $q_{95} \approx 4$ with similar profiles and hence similar $\rho_{p,i}^*$ and $\bar{\nu}_{ii}$ are considered. The profile dependencies ($L_i = i/\frac{\partial i}{\partial r}, i = p,q$), the Δ' influence, the fit constants $a_i, i = 2,3,4$ and the exact behaviour of $g(\epsilon,\nu_{ii})$ require a further extension of the considered type of discharges.

Usually the NTMs are triggered by sawteeth. They can also be excited by fishbones or grow more or less without a detectable seed island out of the noise measured with magnetic measurements. The achieved β before the modes onset is increased with decreasing width of the seed island in the following way $\beta_{sawtooth}^{onset} < \beta_{fishbone}^{onset} < \beta_{spontaneous}^{onset}$ [8].

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[1] r_{res}: resonant surface of the considered mode, τ_{res}: resistive time scale on resonant surface, L_p, L_q: pressure gradient and q-gradient scale length, a_i: numerical constants of the order of unity, W: island width, ϵ: inverse aspect ratio of the resonant surface, R_0: axis of the resonant surface, ρ_{pol}: poloidal ion gyro radius, ρ_{pol}^*: normalized poloidal ion gyro radius, ν_{ii}: ion-ion collision frequency, ω_e^*: electron diamagnetic drift frequency

In order to extend the considered range in $\rho_{p,i}^*$ and $\bar{\nu}_{ii}$, scenarios with significantly different T_i and different profile shapes are used to extend the scaling range.

NTM in pellet refuelled discharges   As a first type of discharge pellet refuelled cases are considered. The density is increased by series of pellets to and above the Greenwald density. Within the pellet sequences the first pellets cool the plasma globally and hence reduce also locally at the resonant surface T_i and hence $\rho_{p,i}^*$. Overall the high achieved density should be stabilising through the high $\bar{\nu}_{ii} \approx 0.3$ and hence large polarisation currents. The reduced $\rho_{p,i}^*$ on the other hand has the larger influence and makes the plasma more vulnerable against NTMs (see Fig. 1a). The density profiles are much stronger peaked in the centre compared to cases with gas puffing alone, as the pellet ablation is located within the plasma centre. These strongly peaked density profiles are very unstationary, as each pellet strongly modifies the profile. A subsequent pellet then produces a large enough seed island to excite a NTM. The drifting plasmoid plays a central role in producing this seed island [9].

Looking at the scaling of these modes compared to the sawtooth triggered NTMs in ordinary discharges, the above described time development can be found in the position of the modes in the β_N / I_p - T_i plane (see Fig 1b). As the profiles are developing very fast a clear answer in local variables can not be given yet and the discharges could not be included in the general extension of the scaling. The onset is consistent under the assumption that $\bar{\nu}_{ii}$ remains high enough and the stabilising polarisation current term is therefore small enough.
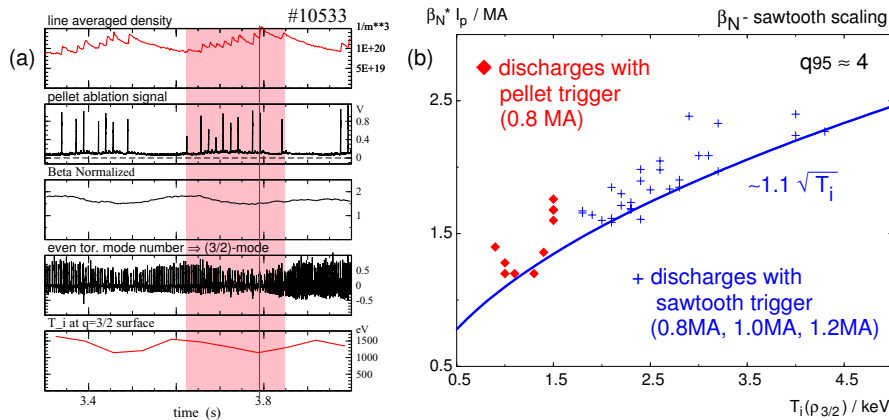

Figure 1: *(a) The first pellets in a sequence cool the plasma and make it more vulnerable for NTMs. (b) The points for pellet triggered NTMs lie at much lower temperature T_i compared to ordinary sawtooth triggered NTMs. A following pellet may then easily trigger the mode.*

NTMs H-mode discharges with improved confinement   The second type of discharges are discharges with improved H-mode confinement. In these discharges the neutral beam heating is already switched on during the current ramp-up phase in order to increase the current diffusion time and produce flat or even hollow q-profiles [10,11]. In the centre of these low density plasmas high ion temperatures $T_i(0)$ can be achieved. High values of $\rho_{p,i}^*$ and very low $\bar{\nu}_{ii}$ are the result. The $\bar{\nu}_{ii}$ values are well below the range for which in ordinary discharges the polarisation current term becomes large enough to prevent NTMs. On the other hand the high values of $\rho_{p,i}^*$ should allow higher β values because of the scaling $\beta_p^{onset} \sim \rho_{p,i}^*$.

Looking at the scaling of NTMs excited in this plasma regime (see Fig. 2a), the global β_N^{onset} values as well as the local β_p^{onset} values are lying below the values predicted from the usual sawtooth behaviour. A comparison for different trigger mechanisms shows the same dependence

on the seed island strength as in other discharges, e.g. $\beta^{onset}_{sawtooth} < \beta^{onset}_{fishbone} < \beta^{onset}_{spontaneous}$ holds also here.

These discharges have been analysed together with ordinary sawtooth triggered cases including the pressure and q gradient length, so that the scaling $\beta^{onset}_p (q = 3/2) \sim \sqrt{L_p/(L_q \cdot \epsilon^{3/2})} \cdot \rho^*_{p,i}$ is considered in the $\rho^*_{p,i} \cdot \sqrt{L_p/(L_q \cdot \epsilon^{3/2})}$ - β^{onset} plane (see Fig. 2b). The remaining factor $\alpha = \sqrt{\frac{a_4}{(a_2 - a_3 \epsilon^{3/2} L_q/r_{res})^2}} \cdot (-\Delta') \cdot g(\epsilon, \nu_{ii})$ needs to fitted to the different discharge types with different current profiles ($\rightarrow \Delta'$) and collisionalities $\bar{\nu}_{ii}$ ($\rightarrow g(\epsilon, \nu_{ii})$). Minimizing the difference between the high $\rho^*_{p,i}$ improved confinement cases and the mid range $\rho^*_{p,i}$ usual sawtooth cases gives this global factor. To bring the two sawtooth data sets together the factor needs to be $\alpha = 1.5$. The square root contains mainly numerical constants and experimental quantities which do not vary very much. The function $g(\epsilon, \nu_{ii})$ should in both cases be well in the low collisionality regime ($g = \epsilon^{3/2}$) and should therefore also not vary signicantly. The main difference should be in the Δ' and therefore in the different current profiles. The steeper current profile outside the $q = 1$ surface can be understood, as these type of discharges have a flat central q-profile arround unity with a large radius of the $q = 1$ surface.
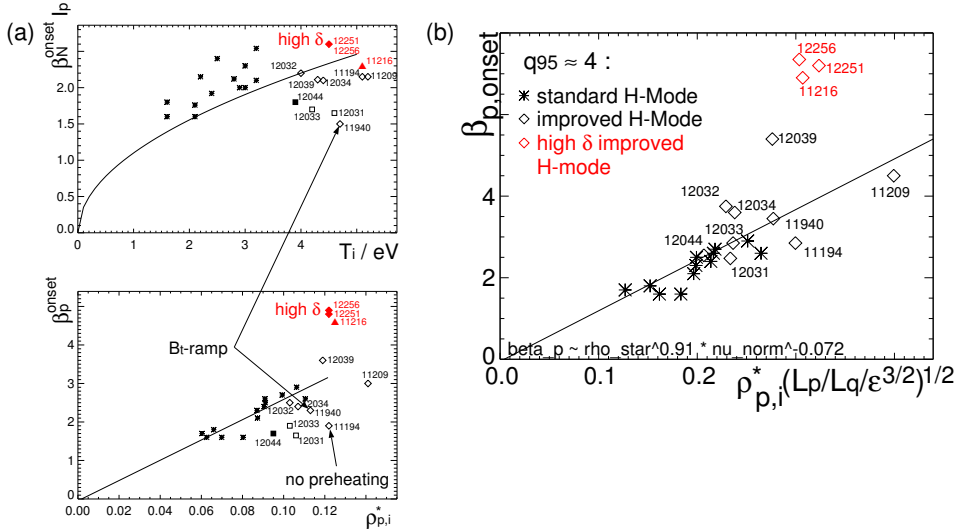

Figure 2: *(a) Scaling of NTMs in H-mode with improved confinement without considering gradient length in global and local parameters. The improved confinement cases are lying below the sawtooth scaling. Both data sets were taken with $q_{95} \approx 4$. (b) Scaling in the $\rho^*_{p,i} \cdot \sqrt{\frac{L_p}{L_q \cdot \epsilon^{3/2}}}$ - β^{onset} plane for taken the gradient length into account. A fit for the remaining factor α is included.*

Some H-mode with improved confinement are located well above the scalings for both type of discharges. These discharges are distinguished from the others by their increased triangularity δ, which improves the performance in the order of $\Delta\beta_N \approx 0.2$ [12].

Onset condition of NTMs in ASDEX and their scaling An inspection of the ASDEX data, the predecessor of ASDEX Upgrade, has shown that also at this machine NTMs were present in high β discharges. Due to the lower temperatures $\rho^*_{p,i}$ and $\bar{\nu}_{ii}$ values are in a range relevant for ITER onset conditions.

The excitation mechanism is very similar to the one observed in ASDEX Upgrade. The (3/2) NTM as well as the (2/1) NTM require a sawtooth as trigger at high enough β_N values (see Fig. 3a). The scaling of β^{onset} shows also a linear dependence on the poloidal ion gyro radius $\rho^*_{p,i}$

(see Fig. 3b). The completely different range in $\rho_{p,i}^*$ and $\bar{\nu}_{ii}$ offers the possibility to complete missing points in the overall scalings for the NTM together with other experiments, such as TEXTOR [13].
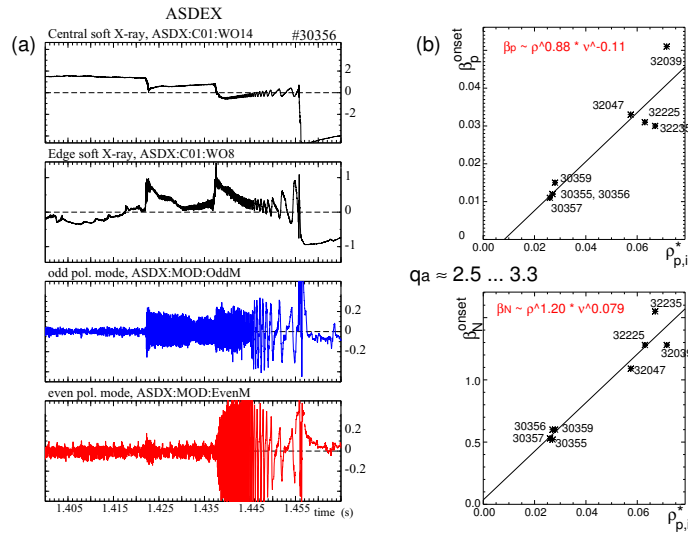

Figure 3: *(a) Neoclassical tearing modes at ASDEX are triggered in the same way by sawteeth as in ASDEX Upgrade. (b) The achieved β^{onset} for $q_a = 2.5...3.3$ scales also linearly with the local poloidal ion gyro radius $\rho_{p,i}^*$.*

Summary and outlook   Within the framework of the generalised Rutherford equation describing NTMs an extension of the accessible plasma parameters with respect to $\rho_{p,i}^*$ and $\bar{\nu}_{ii}$ has been presented. Pellet refuelled discharges and H-mode discharges with improved confinement have been investigated with very low and very high T_i respectively. Profile effects have been partly included. The fit of free parameters (a_i), the Δ' calculations and the isolation of the exact experimental behaviour of $g(\epsilon, \nu_{ii})$ are still remaining tasks for future work in that field. Especially as new discussion on the effect of the polarisation current term has been raised [3–6], reliable experimental results are required.

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