Density dependence of the onset of neoclassical tearing modes in H-mode and pellet refuelled discharges on JET and ASDEX Upgrade

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Introduction Neoclassically driven tearing modes cause a severe limitation to high β fusion plasmas, unless avoided or controlled. A further extension of the present database with respect to the poloidal ion gyro-radius ρ^*_{pi} and the normalized collisionality $\bar{\nu}_{ii}$ has been investigated on JET and ASDEX Upgrade. The two most established theories, the ion polarisation current model and the $\chi_\perp/\chi_{||}$ model, both allow a ρ^*_{pi} scaling for the onset with some weak dependence on the collisionality ν_{ii}.

Models for NTMs The most general accepted model for describing the behavior of an NTM is the generalized Rutherford equation [1]

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

with mainly two stabilizing terms, deriving from the $\chi_{||}/\chi_\perp$ model and the ion polarisation current model. For the ion polarisation current model one arrives at $\beta_p^{onset} \geq \beta_{p,crit} \sim \sqrt{\frac{L_p}{L_q\varepsilon^{3/2}}\cdot g(\varepsilon,\nu_{ii})} \cdot (-\Delta')\cdot\rho_{pi}$, where $g(\varepsilon,\nu_{ii}) = \varepsilon^{3/2}$ or 1 for $\bar{\nu}_{ii} = \nu_{ii}/m\varepsilon\omega_e^* \ll$ or $\gg C \approx 1$. For the $\chi_{||}/\chi_\perp$ model with $\chi_{||} = \chi_{Spitzer}$ and $\chi_\perp = \chi_{Gyro-Bohm} \sim T^{3/2}/B^2$ one gets $\beta_p^{onset} \sim \nu_{ii}^{1/4}\cdot\rho_{pi}^{*1/2}$ or $\nu_{ii}^{1/2}\cdot\rho^*_{pi}$ for large or small seed-island, respectively. It should be noted, that the factor and even the sign of the polarisation current term is still under discussion [1,2]. The present experimental scalings point towards a linear ρ^*_{pi} dependence with a weak collisionality dependence for small collisionalities [3,4]. Depending on the assumed transport models for χ a weak or even no collisionality dependence is predicted for the $\chi_{||}/\chi_\perp$ model [5], whereas for the ion polarisation current a transition from the two extreme regimes is predicted through the g function. Besides the necessary condition $\beta_p \geq \beta_p^{onset}$ an initial perturbation, a seed-island is required for the mode onset.

Density dependence of NTM onset The present data set for JET was restricted to values $\rho^*_{pi} \geq 0.06$ and $\bar{\nu}_{ii} \leq 0.09$ with $q_{95} = 3.4...3.5$. A further extension beyond this range presented in [3] towards lower ρ^*_{pi} and also higher $\bar{\nu}_{ii}$ has been done with low $q_{95} \approx 2.6$ discharges at low $B_t = 1.53...1.22$ T and $I_p = 1.22...0.97$ MA. A first ramp-up in the NBI heating to a maximum power of $P_{NBI} \leq 17$ MW at constant gas puffing rate gave the first possibility for a mode onset. Having

[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_{pi}: poloidal ion gyro radius, ρ^*_{pi}: normalized poloidal ion gyro radius, ν_{ii}: ion-ion collision frequency, ω_e^*: electron diamagnetic drift frequency

reached flat top in heating power a reduction in the gas puff rate reduces the density in order to get a variation in the collisionality $\overline{\nu}_{ii}$ at constant β_N and $\beta_p(q=3/2)$ at the resonant surface (see Fig. 1). The initial gas puff rate has been varied on a shot to shot basis. Besides the critical β_p^{onset} for the mode onset this scenario gives separatly information about the required ρ^*_{pi} and/or $\overline{\nu}_{ii}$ for the onset. In all considered cases the modes are either triggered by a pure sawtooth or a combination of sawteeth and fishbones. Eventually a (4/3)-NTM is excited before the (3/2)-NTM gets excited.

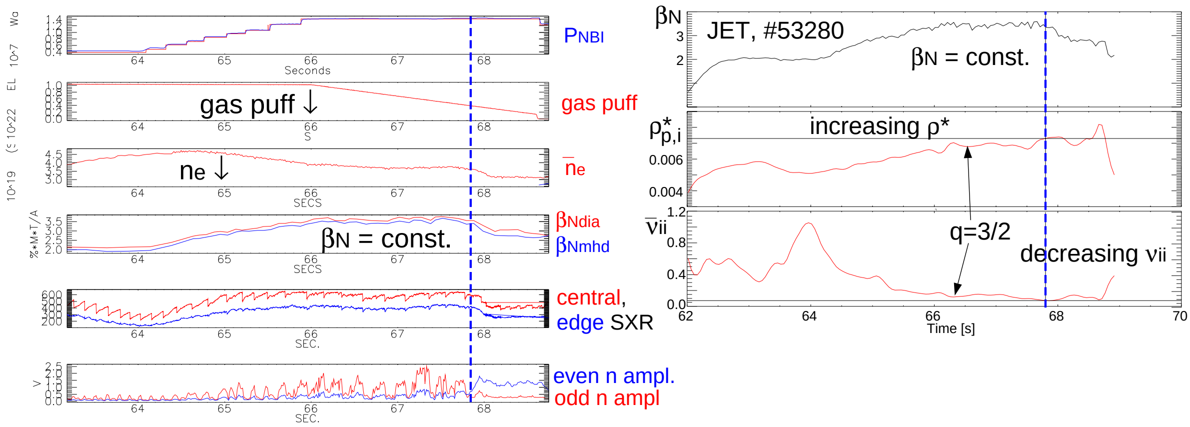

Figure 1: *(a) Typical scenario with gas puff and hence density ramp down during constant high heating power phase. (b) During the ramp phase the local collisionality* $\overline{\nu}_{ii}$ *decreases while* ρ^*_{pi} *and hence the maximum achievable* β_{crit} *even increases.* β_N *remains constant during this phase. The mode gets excited at* $\overline{\nu}_{ii} \approx 0.08$

As local variables β_p and ρ^*_{pi} are used and profile effects are corrected by including L_p and L_q to describe the β limit ($\sqrt{L_q/L_p} \cdot \beta_p^{onset}$ as function of ρ^*_{pi} and $\overline{\nu}_{ii}$), it is possible to combine discharges with different q_{95} values and include these new discharges in the data sets from the MK-II A and gasbox divertor data from JET. The old data set presented in [3] could be described by $\beta_p^{onset} \cdot \sqrt{L_q/L_p} \sim \rho_{pi}^{*1.09} \cdot \overline{\nu}_{ii}^{-0.10}$. The extended data set now shows a dependence of the form $\beta_p^{onset} \cdot \sqrt{L_q/L_p} \sim \rho_{pi}^{*1.01} \cdot \overline{\nu}_{ii}^{0.011}$ for a parameter extension towards $\rho^*_{pi} \geq 0.035$ and $\overline{\nu}_{ii} \leq 0.32$.

Pellet triggered NTMs in high density discharges A further extension of the accessible range towards lower $\rho^*_{pi} \geq 0.02$ and higher $\overline{\nu}_{ii} \leq 0.8$ is achieved by taking discharges into consideration where an NTM is triggered by pellets injected from the magnetic high field side (HFS). Typically discharges with $I_p = 2.5 \ldots 2.8$ MA and $B_t = 2.4 \ldots 2.8$ T with $q_{95} = 3.0 \ldots 3.3$ with up to $P_{NBI} =$ 17 MW have been analysed.

In these discharges a pellet sequence was injected to ramp up the density close to the Greenwald value [6]. During this ramp-up phase the temperature transiently drops and hence also the ion temperature $T_i(q=3/2)$ at the resonant surface drops, while the density profile steepens. Even though the local collisionality $\overline{\nu}_{ii}$ is strongly increased, the reduced gyro radius ρ^*_{pi} dominates in this region and the plasma becomes more vulnerable towards NTMs. A subsequent pellet then may trigger the NTM.

The seed-island seems to be connected to the slowly or even not rotating ablation cloud from the pellet. The ablation cloud is always created with the helicity of the local surface where the material is ablated [7] and therefore has the required helicity for creating a perturbation, which triggers the NTM. As the pellet and the ablated material is influenced by the high-β plasmoid drift [8,9], the perturbation moves from the magnetic HFS towards the centre of the plasma and plasma perturbing material always reaches the (3/2) surface.

The pellet triggered NTMs show a different frequency development than sawtooth triggered NTMs, where the frequency starts at or above the frequency of the (1/1) mode before the sawtooth and then drops to lower frequency. Pellet induced modes start with a very low frequency connected to the slow or almost resting ablation cloud and accelerate to their corresponding frequency at the resonant surface. For ASDEX Upgrade this behavior has also been reported [5].

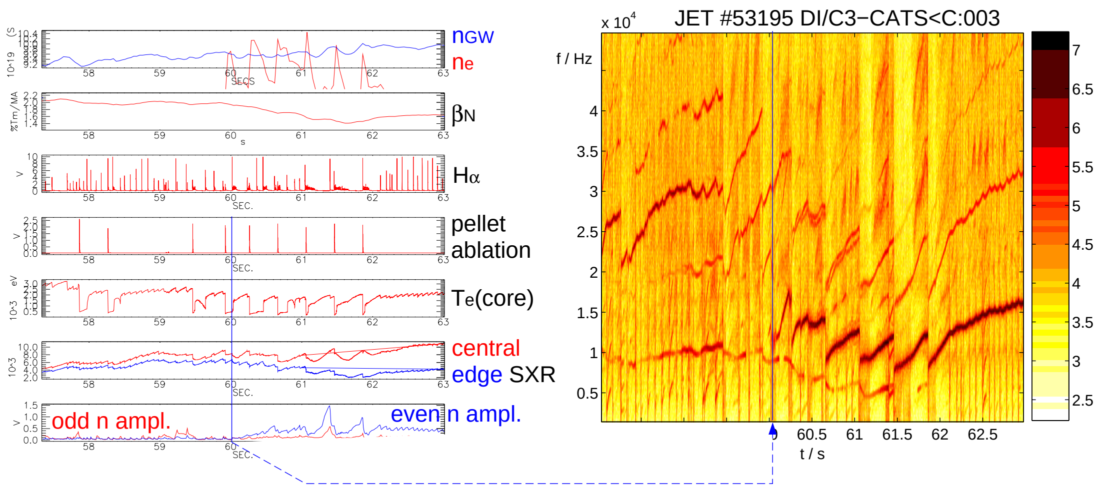

Figure 2: *(a) The first pellets in a sequence cool the plasma and make it more vulnerable for NTMs. A later pellet in the pellet sequence then may trigger the NTM. (b) The NTM typically starts at very low frequencies pointing to the role of the ablation cloud as the major trigger.*

If one includes the pellets in the scaling for the mode onset from the old data and the new low q_{95} data, one arrives at the following scaling $\beta_p^{onset} \cdot \sqrt{L_q/L_p} \sim \rho_{pi}^{*1.08} \cdot \nu_{ii}^{0.069}$ (see Fig. 3a).

Combined scalings for JET and ASDEX Upgrade In the next step ASDEX Upgrade data with sawtooth and fishbone triggered NTMs have been included in the JET scalings (see Fig 3c). As local values have been used for both experiments and L_q and L_p have been taken into consideration, different q_{95} values could be combined. Nevertheless the ASDEX Upgrade data need to be multiplied by a factor of 0.27 to get to a common scaling of the form $\beta_p^{onset} \cdot \sqrt{L_q/L_p} \sim \rho_{pi}^{*0.97} \cdot \nu_{ii}^{0.020}$ by a minimization of the overall error. This could be explained by a global and local definition for L_q for JET and ASDEX Upgrade respectively ($L_q^{JET} = q_{res}/\frac{q_{res}-q_{95}}{r_{res}-a}$ and $L_q^{AUG} = q_{res}/\frac{dq(R_{res}-R_{mag})}{d(R_{res}-R_{mag})}$, R_{res} = major radius of the intersection of the flux surface with a horizontal line through magnetic axis on the low field side, R_{mag} = magnetic axis) and the usage of a different pressure for L_p (L_p^{JET} from p_e, $L_p^{AUG} from p_{tot} = p_e + p_i$). The solution of this inconsitency is straight forward, but had to be left for a future work. Another obvious explanation may be a difference in Δ'. Both effects might sum up and lead to the difference.

The behavior of NTMs triggered by pellets has been reported also from ASDEX Upgrade [10,5]. A sequence of several pellets is also needed for precooling the plasma and a subsequent pellet may then give the trigger through the ablation cloud. ASDEX Upgrade shows the same frequency development of the pellet triggered NTMs in comparison with sawtooth or fishbone triggered NTMs.

Role of the seed-island size for the onset By now only the necessary condition that locally $\beta_p(q = 3/2) \geq \beta_p^{onset,fit}(q = 3/2)$ holds, has been discussed. The second necessary ingredient is the seed-island size. The size of the sawteeth, i.e. the drop on the central soft-X-ray channel however did not give clear correlation to the achieved β_p^{onset}, especially it gave no hint whether the NTM gets excited during the heating ramp or the density ramp. A possible indicator of the size of the perturbation due to sawtooth activity is the sawtooth period, as NTMs are easily destabilised with very long sawtooth periods [11]. The scatter of the achieved β_p^{onset} around $\beta_p^{onset,fit}$ can be explained by the variation of the seed-island size.

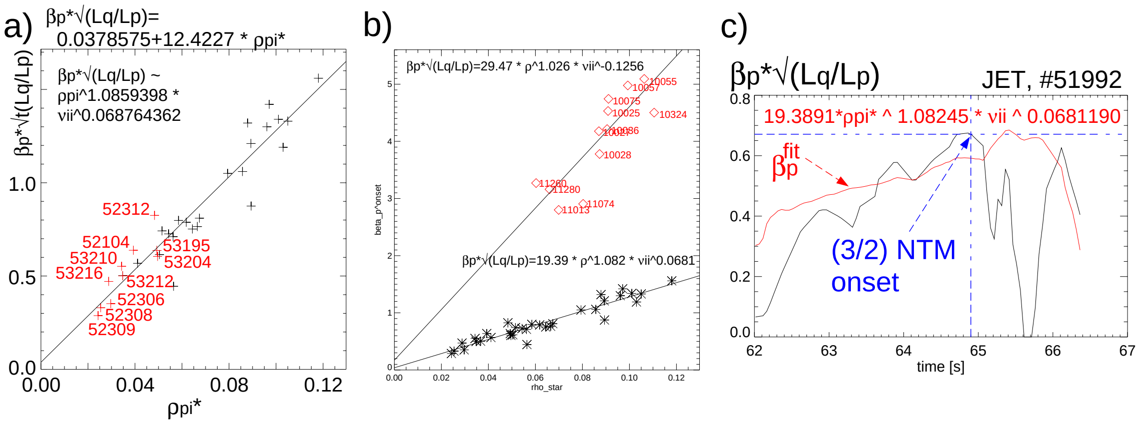

Figure 3: *(a) Inclusion of the low q_{95} cases and the pellet triggered cases for very low ρ^*_{pi} and high $\bar{\nu}_{ii}$ values. Both extension line up on the same $\beta_p^{onset} \sim \rho^*_{pi}$ dependence. (b) Combined scalings for JET and ASDEX Upgrade. For different profile shapes the data would need to be rescaled to be fitted in a common scaling. (c) Time trace of the development of $\beta_p(q=3/2)\cdot\sqrt{L_q/L_p}$ and $\beta_p^{fit}(q=3/2)\cdot\sqrt{L_q/L_p}$.*

Nevertheless in local parameters (ρ^*_{pi}, $\bar{\nu}_{ii}$, β_p) β_p has to approach the predicted $\beta_p^{onset,fit}$ before the NTM gets excited, i.e. β_p and ρ^*_{pi} are not collinear. A typical example is shown in Fig. 3c. It has to be noted, that in global parameters, β_N seems to be more strongly correlated to ρ^*, and β_N behaves almost as $\beta_N \sim \rho^*$ for long durations of the discharge [11]. This again emphasizes the importance of using local parameters.

Summary and outlook For the onset of the (3/2)-NTM an extension of the present data set by low q_{95} and pellet refueled discharges towards lower ρ^*_{pi} and higher $\bar{\nu}_{ii}$ has confirmed the linear dependence of the achievable local β_p^{onset} from ρ^*_{pi} and a weak dependence on $\bar{\nu}_{ii}$. A further combination with ASDEX Upgrade data additionally confirmed this dependence and leads to $\beta_p^{onset}\cdot\sqrt{L_q/L_p} \sim \rho_{pi}^{*0.97}\cdot\bar{\nu}_{ii}^{0.020}$. These results are consistent with the $\chi_{||}/\chi_{\perp}$ model in the heat flux limit using gyro-Bohm scaling, and also with the ion polarisation current model for the mode onset. In local parameters the approach of β_p to $\beta_p^{onset,fit}$ seems to be a necessary condition for the onset.

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