# MHD PHENOMENA AT ASDEX UPGRADE

S. Günter, A. Gude, M. Maraschek, S.D. Pinches, S. Sesnic, R.C. Wolf, Q. Yu, H. Zohm*
and the ASDEX Upgrade-Team

MPI für Plasmaphysik, EURATOM-Association, D-85748 Garching, Germany,
* Institut für Plasmaforschung, Universität Stuttgart, D-70569 Stuttgart, Germany

**Abstract**

The onset of neoclassical tearing modes leads to the most serious $\beta$ limit at ASDEX Upgrade. The $\beta_p$ value for the onset of neoclassical tearing modes is found to be proportional to the ion gyro-radius for collisionless plasmas as proposed by the ion polarisation current model. Larger collisionalities have a stabilizing effect. Sawtooth crashes or fishbones can trigger the mode, and in a few cases it appears spontaneously. Fishbones are shown to be able to cause magnetic reconnection. The fractional energy loss due to a (3,2) mode saturates for large pressures at around 25 %. In discharges with large impurity accumulation unusual MHD phenomena such as cascades of high-n tearing modes and modes driven by positive pressure gradients have been found.

## 1. $\beta$ SCALING FOR THE ONSET OF NEOCLASSICAL TEARING MODES

The maximum achievable $\beta$ in ASDEX Upgrade is often limited by the onset of neoclassical tearing modes (NTM) [1]. If only the equilibrium current gradient is considered, these modes should be stable. The destabilizing effect results from the helical hole in the bootstrap current due to the flattened pressure profile across the magnetic islands. This bootstrap effect should cause arbitrarily small islands to grow. However, two stabilizing effects have been proposed which dominate for small islands: the finite value of $\chi_\perp/\chi_{||}$, which prevents the pressure from being completely flattened in small islands of width $W < W_0$ ($W_0 = 5.1(\chi_\perp/\chi_{||})^{1/4}(r_{res}L_q q/(\epsilon m))^{1/2}$, $\epsilon = r_{res}/R_0$: inverse aspect ratio of the resonant surface, $L_q$: shear decay length, $m$: poloidal mode number) [2], and the ion polarization current, related to the island's movement through the plasma [3]. There is however, an open discussion regarding the sign of the polarisation current term [4]. The results of this paper would imply the polarisation current to be stabilising.

Although a correct theoretical description demands that both the incomplete flattening of the pressure across small islands ($W < W_0$) and the ion polarisation current are taken into account, for simplicity, these two effects are usually considered separately. With such assumptions, one finds two different expressions from the generalised Rutherford equation [5] for the minimum $\beta_p$ at which the stabilising effects can be overcome, generally referred to as $\beta_{p,crit}$. At $\beta_{p,crit}$ the corresponding simplified Rutherford equation for the island growth has only one positive zero.

Within the polarisation current model, assuming $W_0 = 0$, one arrives at [1,5]

$$\beta_{p,crit}^{pol} \propto \frac{g(\epsilon,\nu_{ii})(-\Delta')\rho_p}{\epsilon^{3/4}}\sqrt{\frac{L_p}{L_q}}, \tag{1}$$

where $\Delta'$ is the usual tearing mode stability parameter. The values $\beta_p = 2\mu_0 p/(B_p^2)$ and $\rho_p = \sqrt{2m_i k_B T_i}/(eB_p)$ are evaluated at the rational surface, and $B_p$ is the poloidal magnetic field. The function $g(\epsilon,\nu_{ii})$ in the polarisation current term

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

describes the influence of collisionality on the ion polarisation current [3], $\omega_e^*$ is the electron diamagnetic drift frequency. In contrast to the usual collisionality, the collision frequency is normalised here to the transit frequency of a trapped ion around a magnetic island.

Considering the finite value of $\chi_\perp/\chi_{||}$ and neglecting the ion polarisation current, from $dW/dt = 0$ follows

$$\beta_p^\chi \propto -\frac{\Delta'}{\sqrt{\epsilon}}\frac{L_p}{L_q}\; W_0 \frac{\bar{W}_{seed}^2 + 1}{\bar{W}_{seed}}. \tag{3}$$

As $W_0$ the value of $\beta_p^\chi$ depends on the assumed transport model.

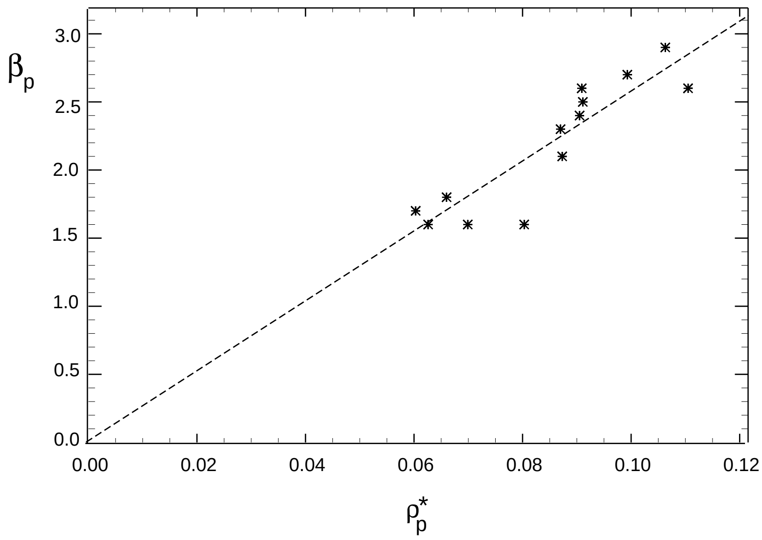


Figure 1: $\beta_p$ at the rational surface at the time of the mode onset vs $\rho_p^*$ for collisionless plasmas ($q_a = 4\ldots4.4$).

According to its definition $\beta_{p,crit}^\chi$ follows from Eq. (3) for the maximum necessary seed island $\bar{W}_{seed} = 1$ leading to $\beta_{p,crit}^\chi \propto W_0$. Taking a Gyro-Bohm scaling for radial transport and Spitzer heat conductivity for parallel transport one finds

$$\beta_{p,crit}^\chi \propto \nu_*^{0.25}\rho^{*0.5}, \tag{4}$$

where $\nu_*$ is the usual normalised collisionality $\nu_* \propto na/T_i^2$. As seen from Eq. (3) the necessary seed island however, strongly depends on $\beta$. In the limit of small seed islands ($\bar{W}_{seed}^2 \ll 1$) $\beta_p^\chi \propto W_0^2$ follows [6], which scales as

$$\beta_{p,crit}^\chi \approx \nu_*^{0.5}\rho^*. \tag{5}$$

In order to discriminate between the two models for the growth of neoclassical tearing modes, the poloidal $\beta$ values at the rational surface $\beta_p$ for the onset of the mode have been investigated for different plasma conditions by varying the ion temperature, the magnetic field, and the mass of the plasma ions. For the collisionless case, that is if the modes are not located near the plasma edge ($q_a = 4\ldots4.4$), one finds a linear dependence of the $\beta$ value on $\rho_p^*$ at the mode onset as seen in Fig. 1 [7]. A fit to the experimental data leads to $\beta_p \propto \rho_p^{*1.02}\nu_{ii}^{-0.02}$ implying that the transport model as given by Eqs. (4) and (5) is not able to explain the experimental data. On the other hand, according to Eqs. (1) and (2) the ion polarisation current model predicts $\beta_p \propto \rho_p^*$ for the collisionless case.

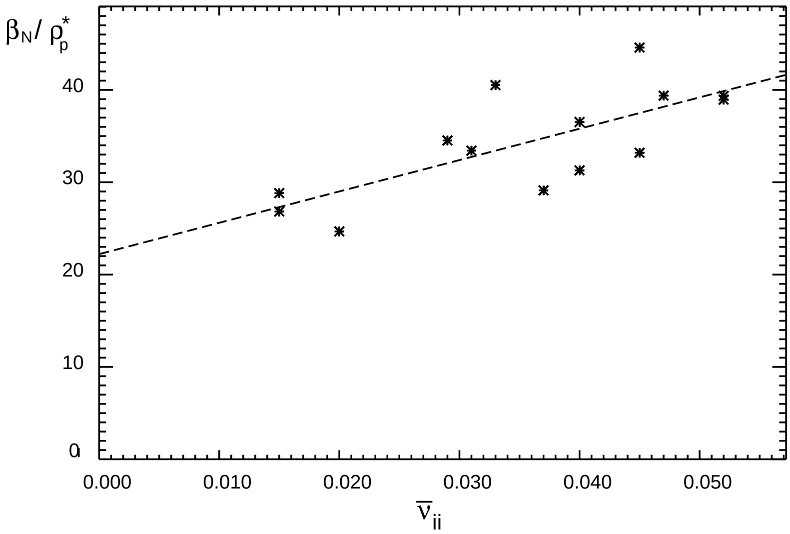


Figure 2: $\beta_N/\rho_p^*$ ($\beta_N = \beta_t aB/I, \beta_t = 2\mu_0 p/B_t^2$) at the rational surface at the time of the mode onset vs $\bar{\nu}_{ii}$ for collisional plasmas ($q_a = 3\ldots3.2$).

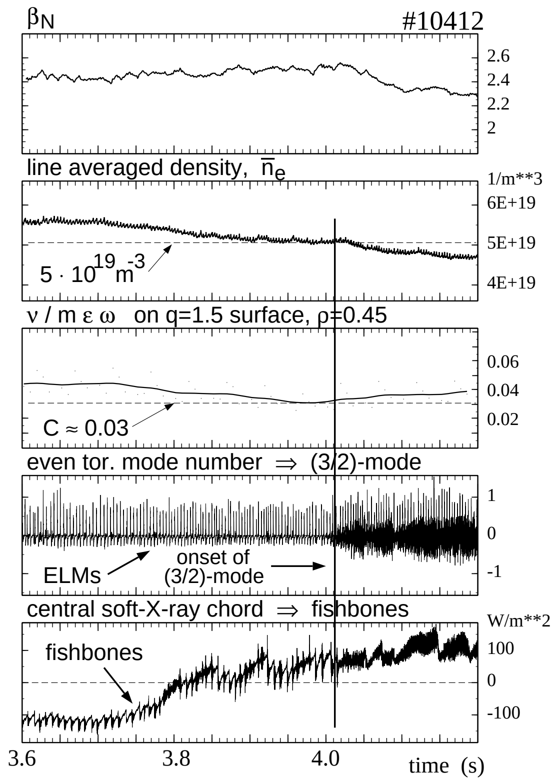


Figure 3: Dependence of the excitation of the neoclassical (3,2)-mode on the collisionality alone. $\beta_N$ remains constant while the density decreases and $\nu_{ii}/m\epsilon\omega_e^*$ is slowly reduced until its threshold is reached.

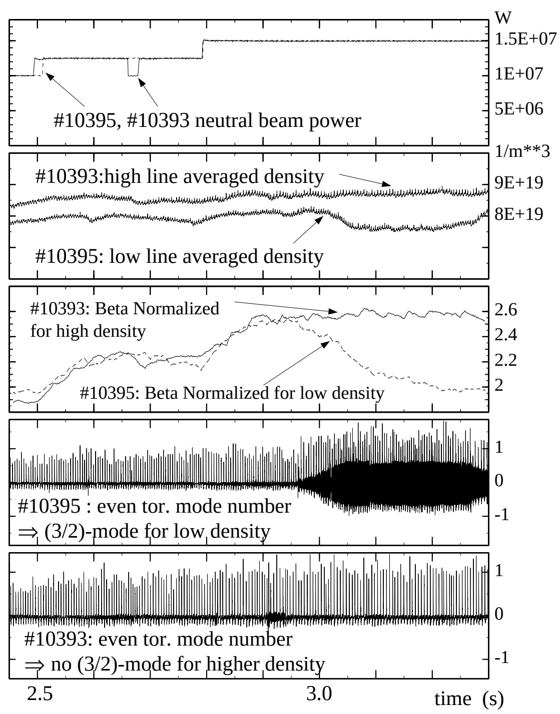


Figure 4: Comparison between two similar discharges with only slightly different densities. For #10395 with $\bar{n}_e = 8 \cdot 10^{19}$ m$^{-3}$ the (3,2)-mode appears, whereas for #10393 with $\bar{n}_e = 8.5 \cdot 10^{19}$ m$^{-3}$ no (3,2)-mode grows.

## 2. COLLISIONALITY DEPENDENCE

Experiments show that for larger collisionalities the $\beta_p$ value at the mode onset is no longer proportional to $\rho^*$. From Fig. 2 it becomes obvious that larger collisionalities have a stabilizing effect. In order to demonstrate the influence of collisionality within one shot, we have changed the plasma parameters, keeping $\beta$ constant. In the shot shown in Fig. 3, with constant neutral beam heating power the density was initially held by gas puffing at a value above that one to which the plasma would relax in an H-mode without any density control. When the gas puff is switched off, the density slowly falls to the natural density in an H-mode and the collision frequencies also decrease. When the collisionality becomes lower than a critical value, a mode can get excited.

Using the dependence of the critical $\beta$ value on collisionality, a scenario has been developed at high density and therefore high collisionality for plasma discharges with large heating power and energy content where the limiting (3/2)-mode can be avoided on ASDEX Upgrade. As shown in Fig. 4 this scenario was successful and has allowed indeed the achievement of stationary high values of $\beta$ [8].

## 3. SEED ISLANDS PRODUCED BY BACKGROUND MHD

Only islands larger than a minimum island, the seed island, have positive growth rates [2,3]. At ASDEX Upgrade the seed island is often produced by sawteeth, although sometimes, neoclassical modes start after fishbones or even grow spontaneously.

Figs. 5 and 6 show the growth of NTMs after a sawtooth crash. In Fig. 5 the NTM frequency starts out near the second harmonic of the (1,1), indicating that the NTM seed island might have been produced by toroidal coupling of the (2,2) harmonic of the sawtooth precursor. The seed island creation by the (2,2) precursor of a sawtooth is regarded as the most common mechanism for the triggering of NTMs. The most common case for ASDEX Upgrade however is shown in Fig. 6 where the NTM frequency starts at lower frequencies and rises during the first 10 ms. The (3,2) mode is clearly identified by Mirnov diagnostics. After some ms additionally a (2,2) mode appears, probably produced by the (3,2) mode via toroidal coupling.

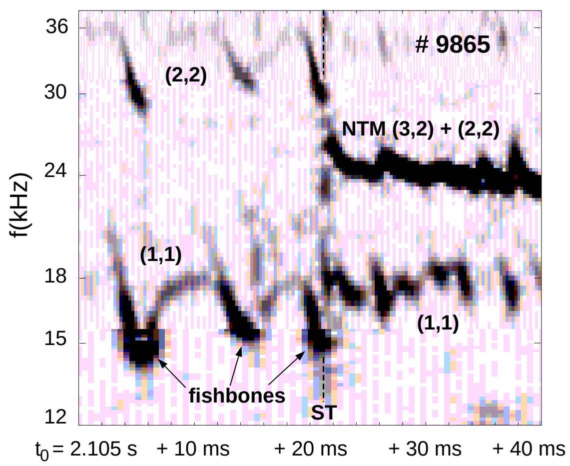


Figure 5: Wavelet plot of an early NTM immediately after a sawtooth crash (ST). The mode starts with a frequency close to that of a (2,2) harmonic of the sawtooth precursor.

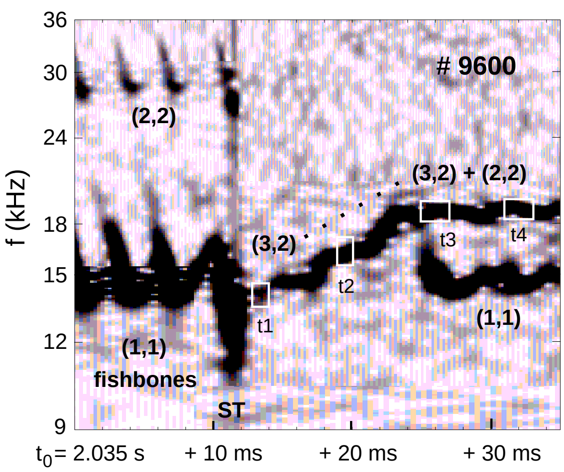


Figure 6: Wavelet plot of an early NTM immediately after a sawtooth crash. The mode starts with a frequency close to that of the (1,1) mode.

In the case where the NTM begins as a pure (3,2) mode with no detectable coupling to a (2,2), and with a frequency far below the second fishbone harmonic, the production of the seed island by toroidal coupling from the second harmonic of (1,1) is hardly probable. Obviously, the sawtooth crash produces a (3,2) seed island directly, without a coupled (2,2) mode. Therefore we believe that in all cases where a sawtooth crash triggers an NTM, the crash - and not the precursor - is the dominant mechanism for the seed island production. In many discharges no sawtooth crash but only fishbones precede the NTM directly (see Fig. 7). Fishbones are however, usually regarded as an ideal instability which affects only the fast particle distribution and should therefore, not be able to produce magnetic islands. Nevertheless, as shown in Fig. 8, fishbones do change the temperature of the background plasma, on a much faster time scale than would just follow from the redistribution of the fast particles, and consequently of the heating power. During a fishbone the temperature in the plasma centre becomes reduced, indicating that fishbones are able to cause magnetic reconnection. Fishbones with the largest amplitudes cause the strongest resistive effects. There is a strong correlation between the fishbone amplitude and the central temperature decrease. Furthermore, the strongest fishbones reach the lowest frequencies and are, therefore, most effective in producing seed islands since their frequency is closer to that of a magnetic island at the $q = 1.5$ surface. For an NTM following fishbones, $\beta_p$ is higher than in cases with a sawtooth trigger, indicating fishbones are less efficient than sawtooth crashes in producing seed islands [9].

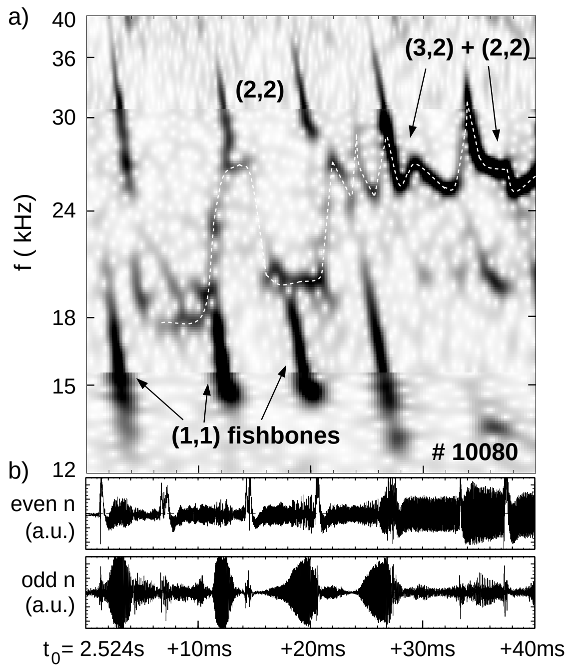


Figure 7: a) Wavelet plot of an early NTM following fishbone activity. The dashed white line depicts the development of the coupled (3,2) + (2,2) mode. The mode becomes strong and starts growing at $t_0 + 27$ ms on a neoclassical timescale from the second harmonic of the last strong (1,1) fishbone.
b) Mirnov signals for even and odd toroidal mode numbers. The odd $n$ signal is dominated by the (1,1) fishbones, whereas the even $n$ signal shows the NTM as well as the second harmonic of the (1,1).

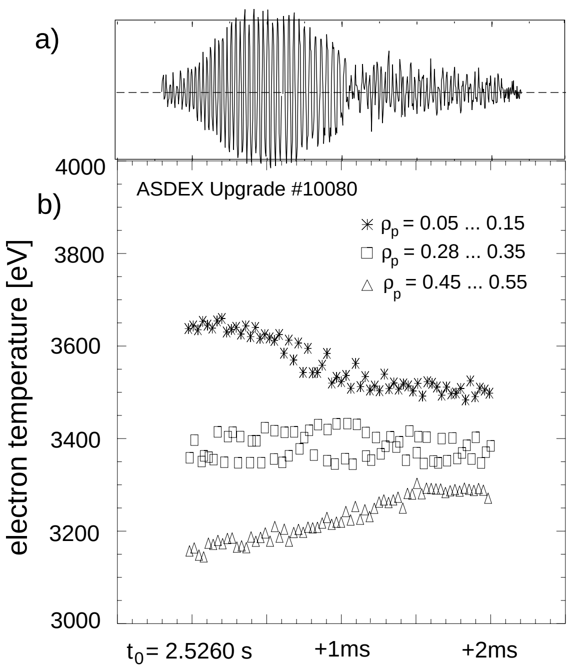


Figure 8: a) Mirnov signal for the odd toroidal mode numbers during the time of the first fishbone in Fig. 7.
b) Temperature evolution during this fishbone. The temperature in the plasma centre (averaged temperature of the ECE channels between $\rho_p = 0.05$ and 0.15) decreases since energy is obviously transported outside the $q = 1$ surface ($\rho_p > 0.35$) where the temperature increases.

## 4. INFLUENCE OF FAST PARTICLES

For high neutral beam powers we observe fishbone like frequency transience in the NTMs. The analysis of these frequency jumps has shown that they are associated with the toroidally coupled (2,2) component of the (3,2) NTM. The (2,2) component is probably a kink which, if the resonance condition is satisfied, can couple to the fast trapped injected ions precessing around the torus, and can extract energy from these ions, in the same fashion as happens during the (1,1) fishbones. Fig. 7 demonstrates this coupling which manifests itself in a sudden jump of the NTM frequency followed by a simultaneous whistling down of frequency and an increase in amplitude of the (2,2) component of the NTM. The absolute change in frequency, the characteristic time of whistle-down and the amplitude increase of the (2,2) component are all of similar magnitude and occur on a similar timescale as for an (1,1) fishbone, indicating that similar physical processes are at work.

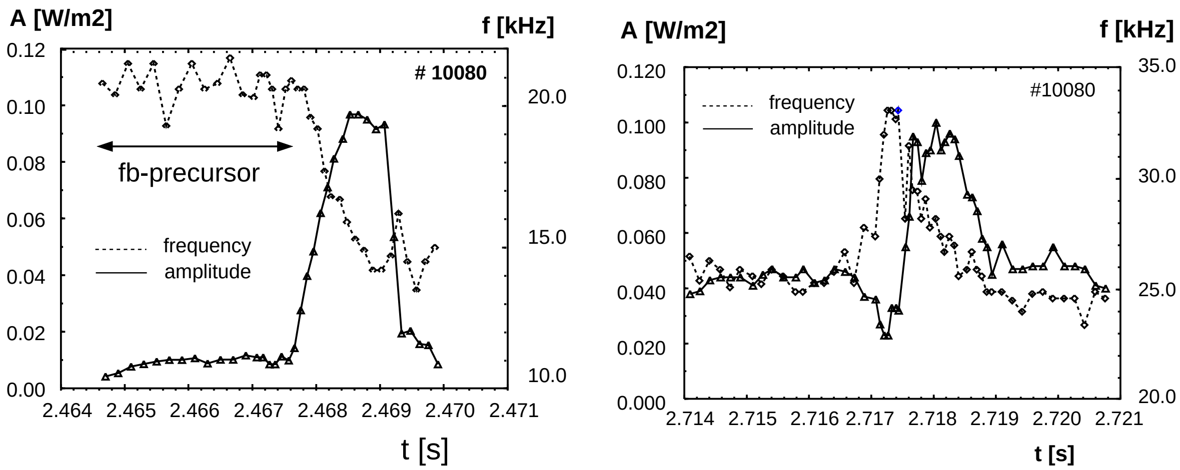


Figure 9: (1,1) fishbone (left figure) and a new kind of (2,2) fishbone (right figure), observed during the NTM. They show a similar behaviour of the mode frequency, f, mode amplitude, A, and comparable characteristic decay times.

## 5. CONFINEMENT DEGRADATION DUE TO NEOCLASSICAL TEARING MODES

As has been shown in the previous section, neoclassical islands can be avoided or even stabilised by high enough collisionalities [8]. In a fusion reactor this would be possible, if at all, only for modes near the plasma edge since it is practically impossible to avoid completely the occurance of seed islands as they can be provided, e.g., by sawteeth, fishbones, ELMs or even grow spontaneoulsy. There is obviously no way to avoid all neoclassical tearing modes in a fusion reactor for positive magnetic shear. We have therefore investigated the degree of confinement deterioration due to neoclassical tearing modes and compared it to corresponding numerical simulations [10,11]. Consistent with the analytical theory [12], the simulations indicate a linear dependence of confinement degradation with the island width.

Combining the theoretical dependence of the island width on the plasma pressure with the confinement deterioration due to an island of width $w$, one finds saturation in the confinement degradation for large $\beta$. There are however, rather large discrepancies between the theoretical and the experimentally observed confinement degradation, see Fig. 8. Besides the increased heat transport across the island there are obviously additional effects which are not included in our simulations. One of these effects is the influence of the magnetic island on the plasma density. Although the density profiles in the shots considered are rather flat, the plasma density decreases by about 10% after the mode's onset. This decrease in density has been shown to result from an enhanced particle expulsion by more frequent ELMs during the mode's growth

[11]. Since the densities of the considered shots are well below the Greenwald limit, we can estimate the influence of the reduced density on confinement by applying the ITERH-97P(y) scaling [13]. In order to compare the theoretical and experimentally observed deterioration in the energy confinement due to the increased heat transport across the magnetic island, we have corrected the experimental data to eliminate of the effect of reduced density on confinement, assuming $\tau_E \propto n^{0.4}$. In doing so, we find good agreement for those experiments with $q_a \approx 3$ which correspond to the conditions chosen in the simulation. As expected from simulations of the island width for large bootstrap current densities at the rational surface [10], the degradation in confinement due to the increased heat transport across the island saturates at about 18 % . Including the confinement degradation due to the density drop, one finds saturation at about 25 % .

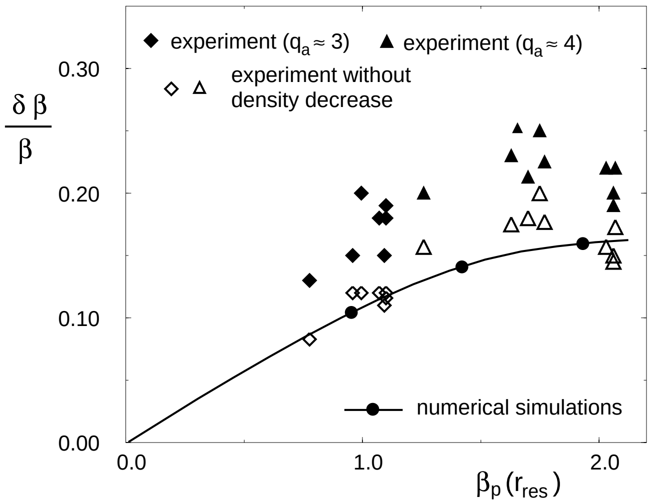


Figure 10: Confinement degradation versus $\beta_p$ at the rational surface. The simulations have been carried out for $q_a \approx 3$. The open symbols correspond to the measured values corrected for the decreased density after the mode's onset.

## 6. ACTIVE STABILISATION

Since neoclassical islands are driven by the vanishing bootstrap current inside the island, the growth of these modes can be influenced by phased heating and current drive into the O-point of the island [1,14]. Recently, a reduction in amplitude of a neoclassical (3,2) tearing mode has been achieved at ASDEX Upgrade using modulated ECCD/ECRH [15]. Including an external driven current into Ohm's law, one finds from numerical simulations that stabilisation of neoclassical tearing modes should be possible if the external current replaces the missing bootstrap current inside the island [16]. The driven current has been calculated using a dynamic model based on a 3D Fokker-Planck code coupled to the electric field diffusion and the island evolution equations [17]. The stabilisation efficiency depends strongly on the width of the driven current layer $\Delta w$. If the current layer width is small enough, one can completely stabilise the island since the pressure is not completely flattened across small islands, resulting in a reduced driving term due to the smaller helical hole in the bootstrap current.

## 7. MHD PHENOMENA IN ADVANCED SCENARIOS

Stationary discharges with H-mode edge and internal transport barrier have been obtained in ASDEX Upgrade [18]. In these discharges the safety factor profile is flat in the center and close to one. Transport calculations suggest that a mechanism is required which keeps the safety factor near one. Since fishbones are able to cause magnetic reconnection as shown in Sec. 3, in the absence of sawteeth, the strong fishbone activity may explain the constant flat q-profile in the plasma center.

Novel MHD phenomena have been found in low and reversed shear scenarios achieved by impurity accumulation of high-Z elements in the plasma centre. These shots are characterized by strong radiation in the plasma centre leading to enhanced resistivity, and the development of a very flat shear region first in the vicinity of the $q = 1$ surface which later moves to higher q-values. When the low shear region is around the $q = 1$ surface, cascades of modes with high toroidal mode numbers, typically up to 20, have been observed [19]. These modes have been shown to be tearing modes. High-n tearing modes are usually stable, however, due to high current gradient and low shear they can become unstable. The coupling of different poloidal harmonics due to the toroidal geometry and plasma shaping supports the mode growth [20]. Due to the strong radiation in the plasma centre, sometimes a positive temperature gradient develops in the low shear region. The resulting positive pressure gradient drives a $(4, 3)$ mode, probably a resistive interchange mode, unstable [21].

## References


[1] ZOHM, H., et al, Plasma Phys. Control. Fusion **39** (1997) B237.

[2] FITZPATRICK, R., Phys. Plasmas **2** (1996) 825.

[3] WILSON, H.R., CONNOR, J.W., HASTIE, R.J., and HEGNA, C.C., Phys. Plasmas **3** (1996) 248.

[4] WAELBROECK, F., FITZPATRICK, R., Phys. Rev. Lett. **28** (1997) 1703

[5] SAUTER, O., et al, Phys. Plasmas **4** (1997) 1654.

[6] ZABIÉGO, M., CALLEN, J.D., Nucl. Fusion 37 (1997) 361

[7] GÜNTER, S., GUDE, A., MARASCHEK, M., SESNIC, S. , ZOHM, H., and the ASDEX UPGRADE TEAM, Nucl. Fusion **38** (1998) 1431.

[8] MARASCHEK, M., GÜNTER, S., ZOHM, H., ASDEX UPGRADE TEAM Collisionality dependence of the neoclassical tearing mode in ASDEX Upgrade, submitted to Plasma Phys. & Control. Fusion (1998)

[9] GUDE, A., GÜNTER, S., SESNIC, S., and the ASDEX UPGRADE TEAM Seed island of neoclassical tearing modes at ASDEX Upgrade, submitted to Nucl. Fusion (1998)

[10] YU, Q., and GÜNTER, S., Modelling of the nonlinear growth of neoclassical tearing modes, accepted for publication in Phys. Plasmas (1998)

[11] GÜNTER, S., GUDE, A., MARASCHEK, M., YU, Q., ASDEX UPGRADE TEAM Confinement degradation due to neoclassical tearing modes submitted to Plasma Phys. & Control. Fusion (1998)

[12] CHANG, Z. et al. 1994 Nucl. Fusion **34** 1309

[13] ITER Physics Basis 1998, to appear in Nucl. Fusion

[14] HEGNA, C. et al., Phys. Plasmas **4** (1997) 2940

[15] ZOHM, H., et al. Active Control of neoclassical tearing modes by electron cyclotron current drive in ASDEX Upgrade, submitted to Phys. Rev. Lett. (1998)

[16] YU, Q. and GÜNTER, S., On the stabilization of neoclassical tearing modes by phased electron cyclotron waves, accepted for publication in Plasma Phys. & Control. Fusion (1998)

[17] GIRUZZI, G., ZABIÉGO, M., GIANAKON, T.A., GARBET, X., Dynamic modelling of tearing mode stabilization by RF current drive acepted for publication in Nucl. Fusion (1998)

[18] GRUBER, O., WOLF, R.C. et al., Stationary H-mode discharges with interanl transport barrier on ASDEX Upgrade
submitted to Phys. Rev. Lett. (1998)

[19] GUDE, A., HALLATSCHEK, K. et al. Plasma Phys. Control. Fusion **40** 1 (1998)

[20] GÜNTER, S., PINCHES, S.D., GUDE, A., HALLATSCHEK , K., LACKNER, K., ASDEX UPGRADE TEAM, Nucl. Fusion **38** 325 (1998)

[21] GÜNTER, S., GUDE, A., STOBER, J. ASDEX UPGRADE TEAM, Resistive interchange modes in low shear regions with locally inverted pressure profiles., submitted to Nucl. Fusion (1998)