Neoclassical Tearing Modes on ASDEX Upgrade: Improved Scaling Laws, High Confinement at high β_N and New Stabilization Experiments

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Abstract. In this paper recent results on the physics of neoclassical tearing modes (NTMs) achieved on ASDEX Upgrade are reported. A scaling law for NTM decay has been found, showing that the minimum local bootstrap current density required for mode growth is proportional to the ion gyro radius. As this scaling law does not depend on the seed island size, and thus on the background MHD activity, it is more reliable than previously derived scaling laws for the NTM onset. Furthermore, the recently reported Frequently Interrupted Regime (FIR) is discussed. In this new regime (m,n) NTMs are characterized by frequent amplitude drops caused by interaction with (m+1,n+1) background MHD activity. Due to the resulting reduced time averaged island size this leads to lower confinement degradation compared to that caused by the usual NTMs. As shown here, the transition into this regime can actively be triggered by lowering the magnetic shear at the $q=(m+1)/(n+1)$ rational surface. Further investigations regard mechanisms to increase the β_N value for NTM onset such as plasma shaping, seed island size and density profile control. Using these studies, a scenario with high β_N ($\beta_N = 3.5$) at high density (n/n_{GW} = 0.83) and confinement ($H_{98(y,2)} = 1.2$) has been developed. Moreover, this scenario is characterized by type II ELM activity and thus by moderate heat load to the target plates. Finally, new NTM stabilization experiments are reported, demonstrating an increase in β_N after NTM stabilization.

1. Introduction

In conventional discharge regimes, the most severe limit to the stationary attainable normalized plasma pressure is given by the onset of neoclassical tearing modes (NTMs) [1, 2]. This is a non-linear instability which requires for its onset the violation of a stability criterion as well as the presence of a trigger perturbation. Over a broad parameter range these modes result in the formation of quasi-stationary, rotating islands, which often strongly degrade the energy confinement. These islands at low-order rational surfaces arise from the helical hole in the bootstrap current which results in turn from the flattening of the pressure gradient over the island region. They are slowly growing (with a typical growth time of 30-70 ms on ASDEX Upgrade) and, being a non-linear instability, show a marked hysteresis between the equilibrium pressure gradients for their onset and their quench.

This paper summarizes recent results on the physics of neoclassical tearing modes achieved on ASDEX Upgrade. In Section 2, a scaling law for the marginal normalized plasma pressure value is derived below which the bootstrap current density is not sufficient any more to drive the growth of a magnetic island. Considering the mode decay instead of its onset, the new scaling law does not depend any more on the background MHD activity which determines the island size at mode onset. Section 3 deals with a recently discovered NTM regime observed at high β_N values ($\beta_N = \beta_t a B_t/I_p, \beta_t = 2\mu_0 < p > /B_t^2, B_t$: toroidal magnetic field , $< p >$: averaged plasma pressure, I_p: plasma current), the Frequently Interrupted Regime (FIR) [3, 4].

In this regime the confinement degradation due to NTMs is strongly reduced. It will be shown that it is possible to force the plasma to enter this regime by changing the magnetic shear at the $q=(m+1)/(n+1)$ rational surface. Active control of the seed island size (Section 4), strong plasma shaping in combination with an active density profile control and reduced sawtooth amplitudes allow for high β_N values at high confinement as shown in Section 5. In Section 6 new results of active stabilization experiments via electron cyclotron current drive (ECCD) are discussed.

2. Scaling Laws to Predict the NTM Stability for Reactor Size Experiments

To predict the stability of ITER against neoclassical tearing modes (NTMs), one has tried to find scaling laws for the NTM onset at various machines. The common result is a nearly linear scaling of $\beta_{N,onset}$ with the normalized ion gyro radius ρ^* [5, 6]. The accuracy of such onset experiments is however limited as the results strongly depend on the presence and the magnitude of seed islands. To avoid these uncertainties, power ramp down experiments have been performed on ASDEX Upgrade. In these experiments the heating power and thus the plasma pressure are slowly reduced until the island size is not correlated with the plasma pressure any more. This β value is considered as the marginal β value below which a magnetic island cannot grow, independent of its size.

In agreement with ealier scaling laws for the NTM onset, the marginal β values for (m,n)=(3,2) NTMs have been found to scale nearly proportional to ρ^* again. As expected, there is however a large hysteresis between the onset and the marginal β values. Instead of the global β_N values, here the local parameter β_p/L_p is considered ($L_p = p/\nabla p$: pressure gradient length). Since density and temperature gradient do not contribute in the same way to the bootstrap current, the scaling law $\beta_p/L_p \propto \rho^*$ is only fulfilled if the density gradients at the $q = 3/2$ rational surfaces are the same in all discharges considered. Otherwise, instead of β_p/L_p the bootstrap current density fraction rises linearely with ρ^*.

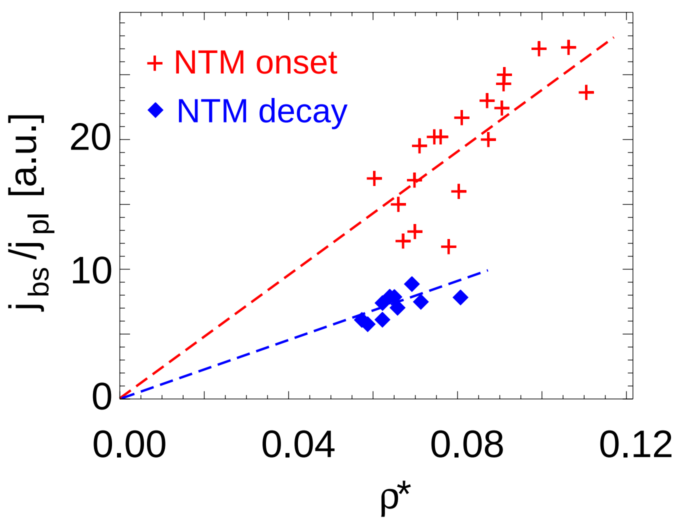

Figure 1: β_p/L_p, *corrected by the factor* $(2T\nabla n + n\nabla T)/\nabla p$, *versus* ρ^* *for the onset of (3,2) NTMs as well as for mode decay.*

3. Reduced Confinement Loss by NTMs due to Transition into the Frequently Interrupted Regime (FIR) at High β_N

According to NTM theory one expects the saturated island size to grow with rising plasma pressure. Recently it has been found however that for high normalized plasma pressures NTMs can enter a more favourable regime. As seen in Fig. 2, in this regime despite the larger neoclassical driving forces, the confinement degradation due to NTMs actually becomes reduced for higher β values [4]. For low β_N values the confinement degradation behaves as expected from theory: it increases linearly with rising β_N values. At about $\beta_N = 2.3$ however, the influence of the NTMs on confinement suddenly reduces from about 30% to less than 10% confinement degradation, reaching an $H_{98(y,2)}$ factor close to 1 at $\beta_N = 2.3$, although $(m,n) = (3,2)$ modes are present. For even higher β_N values the NTMs again cause stronger confinement reduction which however is still much smaller than one would expect from the behavior at small β_N values.

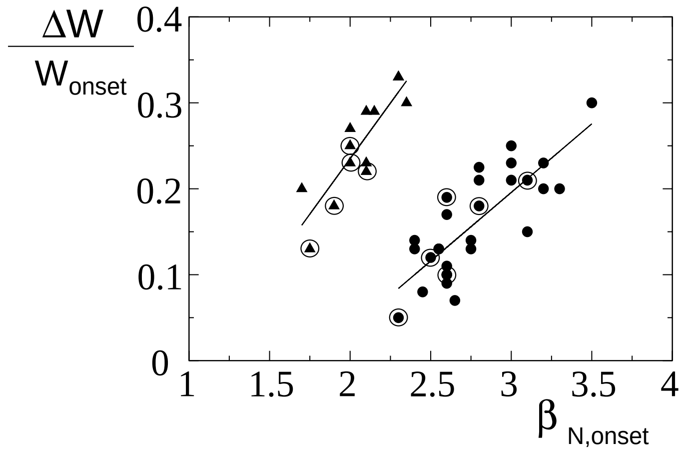

Figure 2: *Fractional confinement degradation due to a (3,2) NTM versus* β_N *at the mode onset.*

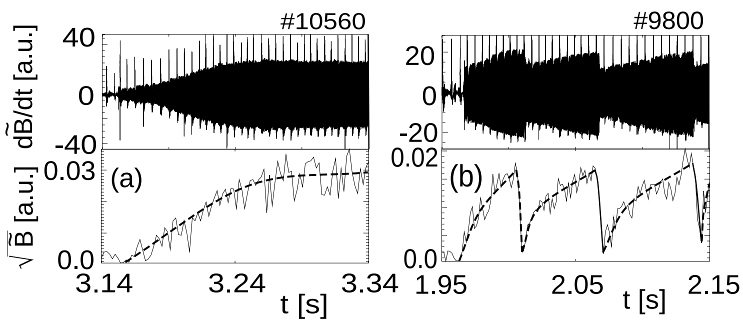

Figure 3: *Raw Mirnov signal* ($\frac{d\tilde{B}}{dt}$) *as well as the square root of the integrated signal* ($\sqrt{\tilde{B}}$) *for a (3,2) NTM at* β_N*=2.3 for a low confinement (a) and a high confinement discharge (b).*

The reason for the less detrimental influence of the NTMs at high β_N values is a change in the NTM behavior as shown in Fig. 3, where the raw Mirnov signals and the mode amplitudes are given for two discharges at about $\beta_N = 2.3$. The left figure corresponds to the low confinement case. Here the NTM is smoothly growing until it finally reaches its saturated island size. In the right figure the mode growth is frequently interrupted by sudden amplitude drops. Therefore the NTM never reaches its saturated amplitude. The time averaged island size thus remains much smaller compared to that of the smoothly growing mode, leading to a reduced influence of the NTM on the confinement. Due to the characteristic behavior of the raw Mirnov signal, this new NTM regime has been called FIR (Frequently Interrupted Regime)-NTM [4]. The amplitude drops seen in Fig. 3 have been shown to be caused by a non-linear coupling of the (m,n) NTM to a (m+1,n+1) mode via (1,1) mode activity [3]. In Fig. 4 an example for this process is shown. The amplitude of a (3,2) NTM suddenly drops as soon as a (1,1) mode and a (4,3) mode burst appear simultaneously. In [3] it has been proven that a non-linear coupling of phase locked modes is required for such a sudden reduction in the NTM amplitude. The occurrence of a (4,3) mode if not phase-locked to the (3,2) was not sufficient. This statement is however only true for the very fast amplitude drops characteristic for the FIR-NTMs. In general, also a large (4,3) mode alone can cause a reduction in the (3,2) NTM amplitude [7, 8].

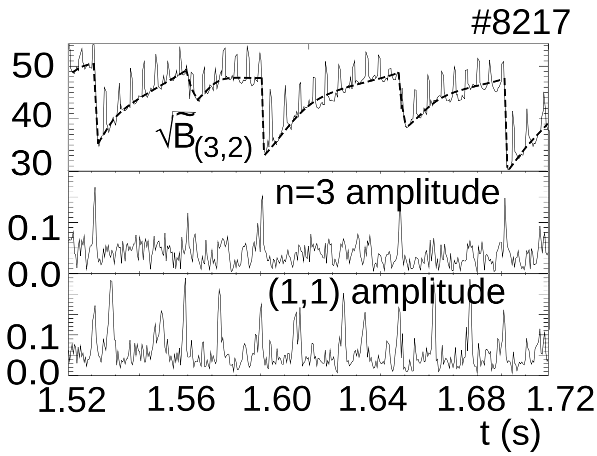

Figure 4: *(3,2) mode amplitude ($\sqrt{\tilde{B}}$) together with the amplitude of the (4,3) and (1,1) mode activity. The (4,3) mode bursts always coincide with (1,1) activity and the amplitude drops of the (3,2) NTM. The spikes on the (3,2) signal are due to strong ELM activity.*

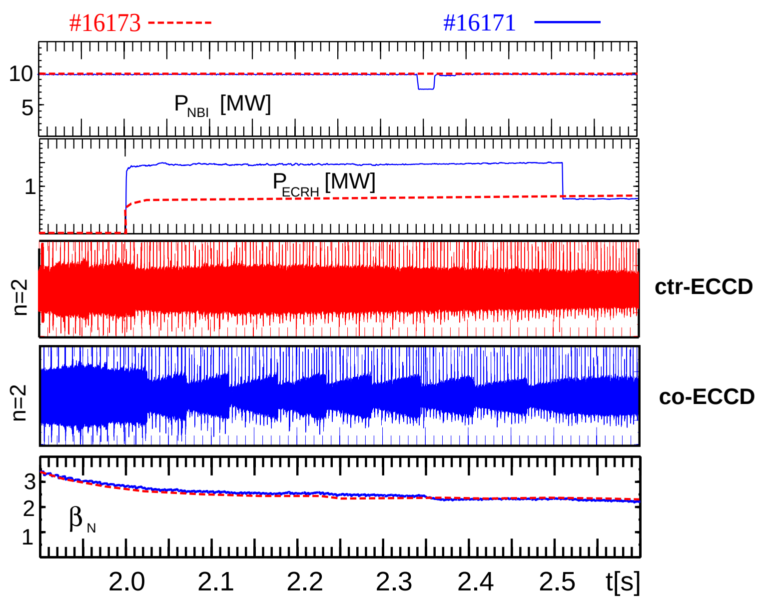

Figure 5: *At constant NBI heating power, ECRH is used to lower (co-ECCD) and increase (ctr-ECCD) the magnetic shear at the $q = 4/3$ rational surface. At highest ECRH power (1.6 MW), in the co-ECCD case the $n = 2$ Mirnov signal shows a clear transition to the FIR-NTM regime. A back transition to normal mode behavior occurs when the ECRH power is reduced to 800 kW.*

The growth time of the (4,3) mode bursts seen in Fig. 4 is only about 200 μs which is a hint that this mode might be an ideal one with the pressure gradient at the $q = 4/3$ rational surface acting as a driving force. As known from stability analyses of infernal modes [9], the driving force of these pressure driven modes increases with decreasing magnetic shear. Assuming the (4,3) mode, triggered here by non-linear mode coupling, were close to marginal stability anyway, lowering the magnetic shear around the $q = 4/3$ surface could drive the (4,3) mode even linearly unstable. Using ECCD parallel to the plasma current, deposited in between the radii of the $q = 4/3$ and $q = 3/2$ rational surfaces, we were able to induce the growth of a (4,3) mode. This mode seemed to be an ideal one as its growth time was quite small ($\tau_{growth} < 300\ \mu s$).

Being able to induce the growth of an ideal (4,3) mode in a discharge without NTM activity, we also tried to trigger the transition to FIR-NTMs by lowering the magnetic shear close to the $q = 4/3$ surface. As shown in Fig. 5, co-current ECCD in between the $q = 1.33$ and $q = 1.5$ rational surfaces triggered the transition to the FIR-NTM regime. A very clear FIR-NTM regime arises about 200 μs after switching on the co-current drive. The NTM stays in the FIR regime until the ECRH power is reduced (from 1.6 MW to 800 kW). The required power for the transition into the FIR regime is thus about the same as for NTM stabilization. The radial deposition of the driven current however does not seem to be as crucial as for NTM stabilization. In the discharge considered, the toroidal magnetic field increases from 2.14 T (at $t = 2.0$ s) to 2.19 T (at $t = 2.5$ s), corresponding to a shift of the ECRH deposition by about 5 cm without any change in the mode behavior.

4. Active Control of the NTM Seed Island Size

As known from NTM theory and recently demonstrated at JET [10], the β_N value for mode onset strongly depends on the seed island size. Since sawteeth are the most severe trigger mechanism for NTMs, its active control might be necessary to avoid NTM onset already at very low β_N values in ITER. Using ECCD such a control possibility has been demonstrated on TCV [11] as well as on JET [10]. Recently ECCD control of the sawtooth amplitude has also been demonstrated on ASDEX Upgrade [12].

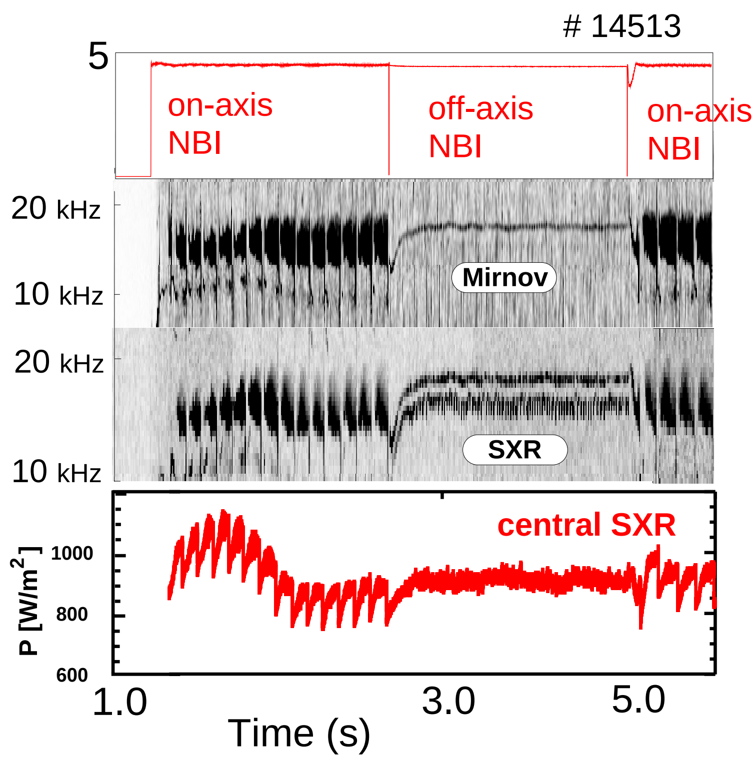

Figure 6: *Change in the (1,1) mode activity due to different injection angles of the neutral beam lines. For more radial beam lines (on-axis NBI) strong fishbone and sawtooth activity is seen. For tangential injection (off-axis NBI) the mode behavior strongly changes.*

On ASDEX Upgrade, another possibility to decrease the seed island size resulting from (1,1) mode activity is the use of our more tangential beam lines. Using these beams instead of the more radial ones strongly changes the (1,1) activity as shown in Fig. 6. The fishbone activity disappears as no trapped particles are deposited within the q =1 surface. In case of purely tangential injection, instead of fishbone and sawtooth activity one finds two (1,1) modes at different frequencies in the Soft X-Ray (SXR) signal. The radial location of these modes differ, the mode with the higher frequency is located outside the lower frequency mode. In the Mirnov signal only the higher frequency mode can be observed. This points to the existence of two q=1 rational surfaces, as in such a case the current perturbation of the inner mode would be shielded by the outer rational surface. Although the (1,1) mode located at the inner rational surface shows sawtooth-like behavior, it hardly produces large seed islands at the q=1.5 surface as these "sawteeth" are very benign, probably due to the very small inversion radius ($r/a \approx 0.1$).

5. Possibilities to Ensure High Confinement at High β_N Values in the Conventional Scenario

One of the main parameters to increase the β_N value for NTM onset is plasma shaping, of special importance is the triangularity δ. Besides its influence on the stability parameter for classical tearing modes (Δ'), it allows for higher β_N values at given local bootstrap current density at the NTM's rational surface. Another important parameter for NTM stability is density peaking. As is well known, the density gradient is much more effective than the temperature gradient in driving bootstrap current [13]. Therefore the β_N value for NTM onset is much lower for peaked than for flat density profiles [14]. An example for this behavior is given in Fig. 7, where the NTM onset already occurs at β_N = 1.5 which is much smaller than in comparison discharges with flat density profiles.

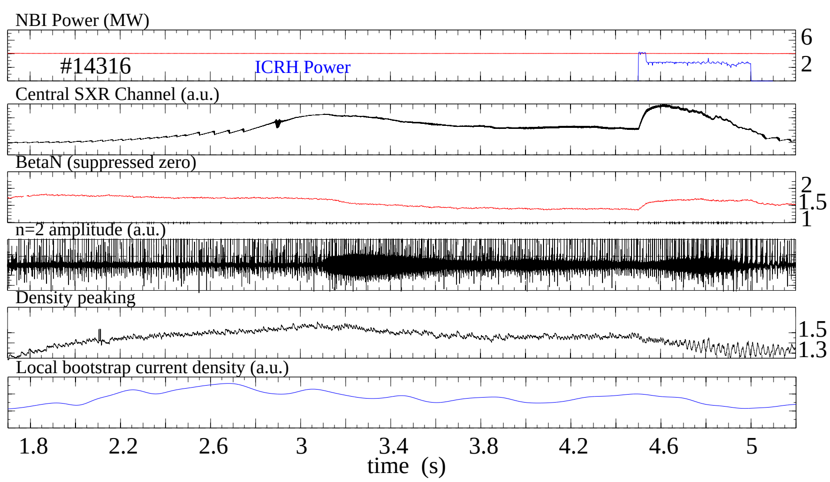

Figure 7: *Shown are the time traces of heating power, a central SXR channel, β_N, the Mirnov signal for $n = 2$ mode activity, the ratio of a central and edge line integrated density measurement from a DCN interferometer as a measure of density peaking as well as the local bootstrap current density fraction at the $q = 3/2$ rational surface. At about 3.2 s a (3,2) NTM occurs at a very low β_N value ($\beta_N \approx 1.5$). The density peaking is reduced by central ICRH (between 4.5 and 5 s). Although the heating power, and thus the normalized plasma pressure, increases during this time, the NTM disappears at about 5 s. At this time the density peaking and therefore the local bootstrap current density are strongly reduced.*

In [15] it has been demonstrated that the density profile effectively can be controlled by central electron heating. The particle diffusion coefficient has been shown to be approximately proportional to the perpendicular heat conductivity. Thus for the nearly stiff temperature profiles in discharges prone to NTM activity, the particle transport strongly increases together with the heat conductivity as the central heating power rises. This behavior has successfully been used to control the density profile and thus the β_N values for NTM onset as shown in Fig. 7. When central ion cyclotron heating is applied (between 4.5 and 5 s) it leads to an increase in β_N as well as a reduction in density peaking. Despite the higher β_N value, the NTM disappears at about 5 s due to the reduced density peaking and therefore lower bootstrap current density at the rational surface.

With strong plasma shaping ($\delta > 0.4$), density profile control by central ICRH, and using the more tangential beam lines we were able to find an integrated scenario in which simultaneously high densities ($n/n_{GW} = 0.83$), high β_N ($\beta_N = 3.5$) values, good confinement ($H_{98(y,2)} = 1.2$) as well as tolerable heat loads to the target plates (type II ELMs) have been achieved [16].

6. Active NTM Stabilization by ECCD

The first successful demonstration of NTM stabilization by local ECCD has been given on ASDEX Upgrade [17, 18, 19]. Although in these early experiments complete NTM suppression has been achieved, the β_N values did not increase to the value before NTM onset. This effect has been explained by the increased particle transport induced by the ECRH as described in Section 5.

To demonstrate that indeed higher β_N values can be achieved by an active NTM stabilization, on ASDEX Upgrade the heating power has been increased after the NTM was stabilized by ECCD. As seen in Fig. 8, it was possible to increase the β_N value by about 30% above that at original NTM onset, before an NTM reappears. The reason for the reoccurrence of the NTM is the shift of the island's rational surface with respect to the ECRH deposition layer due to changes in the equilibrium with β_N, which only partly has been corrected by the toroidal field ramp. A radial feedback system for the ECRH deposition as planned for ASDEX Upgrade is therefore expected to allow for even larger β_N values.

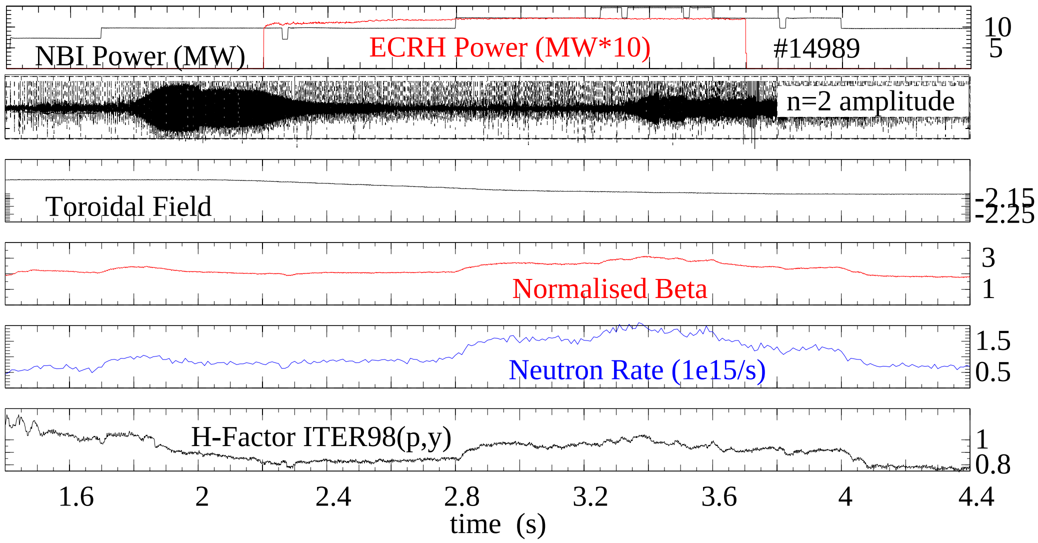

Figure 8: *Demonstration of NTM stabilization by ECCD. Without ECCD an NTM appears at a normalized plasma pressure of* $\beta_N = 2.4$*. After complete stabilization of this NTM the heating power is increased. An NTM reappears at about 3.4 s being triggered at a much higher plasma pressure (*$\beta_N = 3.1$*) compared to the original NTM.*

7. Summary and Conclusion

This paper summarizes recent results on NTM physics on ASDEX Upgrade and possibilities to either avoid the NTM growth or to reduce their influence on confinement. The scaling law for the marginal β_N value derived in Section 2 supports the expectation that NTM growth in larger devices might occur at lower β_N values compared to present day tokamaks. Therefore, possibilities to control NTMs or to reduce their influence on the background plasma remain very important in preparing the ITER inductive scenario. In this paper various possibilities to influence NTM stability have been discussed. Besides its influence on the tearing stability parameter Δ', plasma shaping also affects the local bootstrap current density being the driving force for NTMs. Triangularity reduces the bootstrap current fraction at the island's rational surface at given β_N value via higher plasma current at same q_{95} as well as higher pedestal pressure. As the density gradient is much more efficient in driving bootstrap current than the temperature gradient, it plays an important role in NTM stability even for the only slightly peaked density profiles in H-mode operation. The recently reported relationship between the electron heat conductivity and the particle transport coefficient [15] for stiff temperature profiles allows for an active control of the density profile. Combining strong plasma shaping with density profile control by central electron heating and ensuring only benign (1,1) activity by using the tangential neutral beam injection lines, high β_N values for NTM onset have been achieved. As strong plasma shaping also allows for high density at high energy confinement as well as for transition to the type II ELM regime, the developed scenario ensures high β_N values ($\beta_N = 3.5$) at high confinement ($H_{98(y,2)}$=1.2) combined with tolerable heat loads to the target plates. As for high β_N values only FIR-NTMs occur, in the developed scenario even the onset of NTMs does not change plasma pressure and confinement significantly.

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