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S. Günter, A. Gude, M. Maraschek, S. Sesnic, H. Zohm,
ASDEX Upgrade Team, D.F. Howell
and JET EFDA Contributors

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S. Günter[1], A. Gude[1], M. Maraschek[1], S. Sesnic[1], H. Zohm[1],
ASDEX Upgrade Team[1], D.F. Howell[2]
and JET EFDA Contributors*

[1]*Max-Planck-Insitut fnur Plasmaphysik, EURATOM-Association, D-85748 Garching, Germany*
[2]*EURATOM/UKAEA Fusion Association, Abingdon, OX143DB, UK*
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INTRODUCTION

The onset of Neoclassical Tearing Modes (NTMs) is regarded as the most severe limitation to the maximum achievable normalised plasma pressure $\beta_N(\beta_N = \beta_t a B_t/I_p$, $\beta_t = 2\mu_0 < p > /B^2{}_t$, B_t: toroidal magnetic field , < p >: averaged plasma pressure) in tokamaks. According to a simple analytical description using the generalised Rutherford equation (see e.g. [1]), the saturated width w_{sat} of these islands is expected to grow proportional to the plasma pressure. Although, taking into account non-linear effects, a saturation of this behaviour is expected for very large pressures, w_{sat} should always grow with increasing plasma pressure [2]. On ASDEX Upgrade however, a regime with high confinement at high β_N values has been found although (3,2) NTMs are present. In this regime the amplitude of the NTM does not grow smoothly. As soon as the NTM reaches a certain size, its amplitude suddenly drops to a much smaller value, and the mode growth starts again. This way the NTM amplitude never reaches its saturated value. We call this kind of neoclassical tearing modes FIR(Frequently Interrupted Regime)-NTMs. The reason for the sudden drop in the NTM amplitude has been shown to be the occurrence of an additional ideal instability (a (4,3) mode in case of an (3,2) NTM) leading to these amplitude drops as soon as the two modes lock in phase. [3]

1. IMPROVED ENERGY CON NEMENT AT HIGH B VALUES

In Fig.1 the H-Factor (ITERH-98(y,2)) measured at (3,2) NTM saturation, normalised to the value just before the NTM onset, is given versus β_N. As expected from theory, for low values of β_N the island size grows proportional to the plasma pressure, leading to a linear decrease of confinement with β_N. At $\beta_N \approx 2{:}3$ the degradation in energy confinement is suddenly reduced (from about 30% to less than 10%, compared to the confinement at the time of NTM onset). Thus for β_N values between 2.3 and 2.45 the observed energy confinement is very close to that predicted by the ITER scaling. In this region of β_N, after NTM saturation the averaged H-factor for the discharges considered is 0.98.

As can be seen in Fig.2, the mode signal measured by the Mirnov coils changes with the jump in the energy confinement. Fig.2(a) shows the Mirnov signal for an NTM in a discharge with low energy confinement at $\beta_N = 2{:}3$. The mode amplitude smoothly grows until it saturates. The Mirnov signal in the high confinement case at the same β_N value looks different (Fig.2(b)). Here the mode growth often is interrupted by sudden drops in amplitude. As already mentioned above, we call this state Frequently Interrupted Regime (FIR-NTMs).

As the NTM growth time is quite large (50-100ms for ASDEX Upgrade), due to the frequent amplitude drops, the NTM cannot reach its saturated size. Thus the averaged mode amplitude shown in Fig.2(b) is smaller than that shown in Fig.2(a), although we have chosen a discharge with the same β_N value at mode onset and corrected for different rotation velocities.

In the following it will be investigated whether the reduced averaged island size is sufficient to explain the observed increase in the H-factor. The reduction in energy confinement due to a magnetic island can easily be calculated using a cylindrical one-fluid transport equation, and introducing a thermal short-circuit across the island [4,5]. The confinement degradation resulting from the measured island size according to Eq. (2) is given in Fig.3 for all discharges of Fig. 1 with q_{95} = 4...4.5. For comparison also the regression lines of Fig.1 are given. It becomes obvious that the behaviour of the observed confinement degradation is consistent with that of the averaged island size.

Figure 1 suggests that the β_N value at the mode onset determines the resulting H-factor. However, transitions between the low and high confinement regime are possible. Figure 4 shows a discharge in which the heating power has been changed after the onset of the (3,2) NTM. The increase in heating power at about 1.6s leads to more frequent amplitude drops and hence a smaller averaged island size, whereas the power decrease to 5MW at about 2.1s triggers the transition to a smooth NTM behaviour with the corresponding confinement degradation.

2. THE CAUSE OF THE AMPLITUDE DROPS

The reason for the amplitude drops at large β_N values has been shown to be the coupling of the (3,2) NTM to an additional (4,3) mode, growing on a time scale of less than a millisecond[3]. This mode usually occurs in short bursts (on a timescale of a millisecond), each burst reducing the NTM amplitude significantly. In Fig.5 the influence of the (4,3) bursts on the (3,2) NTM can be seen. Figure 6 shows that a similar mechanism works for a (4,3) NTM. Here the amplitude drops are caused by (5,4) mode bursts. The modes causing the amplitude drops seem to be ideal modes, driven by the pressure gradient at their corresponding rational surface. Such mode bursts are often observed also in discharges without an NTM, but they do not lead to remarkable energy losses there. If an NTM is present, the NTM amplitude only drops during the time in which it is coupled to the ideal (n+1,m+1) mode via an (1,1) mode.

The time in which the amplitude drop occurs is very short (about 500μs), much shorter than the resistive time scale. If one assumes forced reconnection however, the time could be sufficient for stochastisation [6] in the presence of two coupled modes of different helicity as argued in [3].

SUMMARY AND CONCLUSIONS.

A high confinement regime at high β_N values ($\beta_N > 2.3$) has been found on ASDEX Upgrade in spite of the presence of (3,2) NTMs. The reason for the observed con nement improvement are frequent amplitude drops of the (n,m) NTM due to the non-linear coupling to an (n+1,m+1) ideal mode. Therefore, the NTM never reaches its saturated island size, and the averaged island size remains much smaller than the saturated one. The occurrence of this so-called FIR-NTM is quite general. On ASDEX Upgrade it has been found for (3,2) as well as for (4,3) NTMs.

The transition to FIR-NTMs with the beneficial effect on energy confinement has been also found on JET. Figure 8 shows a similar behaviour for JET as it has been found for ASDEX Upgrade (Fig.1). The transition to the high confinement regime at JET occurs however already at a somewhat smaller β_N values ($\beta_N \approx 2.0$). Amplitude drops are also seen in discharges in which the so-called “self-healing” effect for large heating powers is observed, as described in [7].

As the modes causing the amplitude drops seem to be pure MHD modes, their occurrence should be only determined by the current and pressure profiles. As these should be similar also for a reactor scale experiment, a high confinement regime at $\beta_N > 2$ in spite of the onset of NTMs can also be expected for ITER and in a tokamak reactor.

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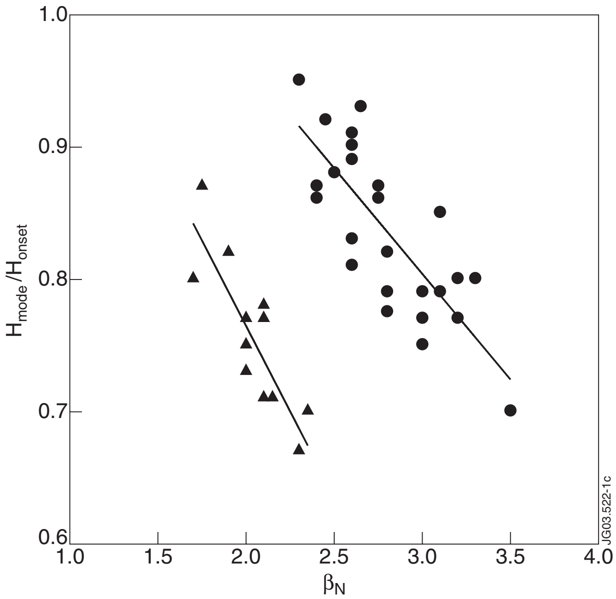

Figure 1: H factor after (3,2) NTM saturation, normalised to the value at the NTM onset, versus β_N at the mode onset for ASDEX Upgrade.

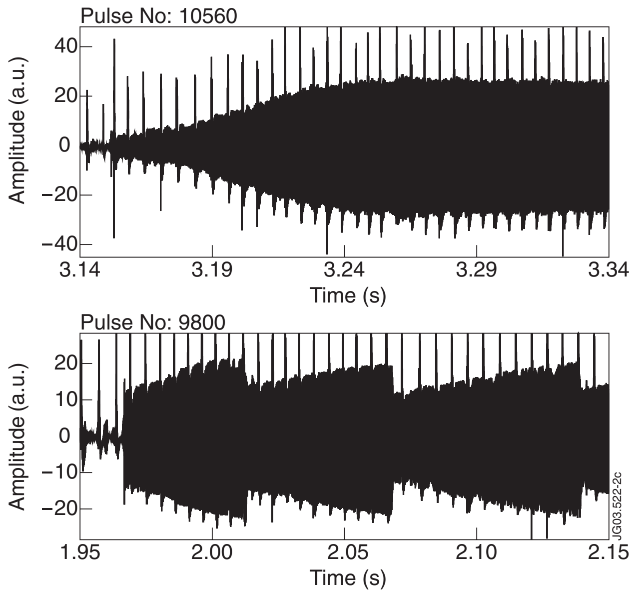

Figure 2: Mirnov signal for the (3,2) NTM at β_N=2.3 for a low confinement discharge (a) and a high confinement discharge (b).

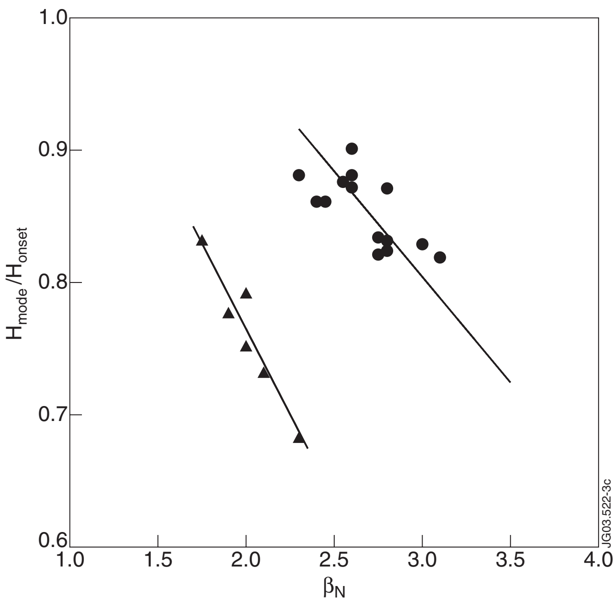

Figure 3: Confinement degradation as estimated from the averaged NTM island size for the discharges with q_{95} = 4...4.5 from Fig. 1. For comparison the regression lines from Fig. 1 are added.

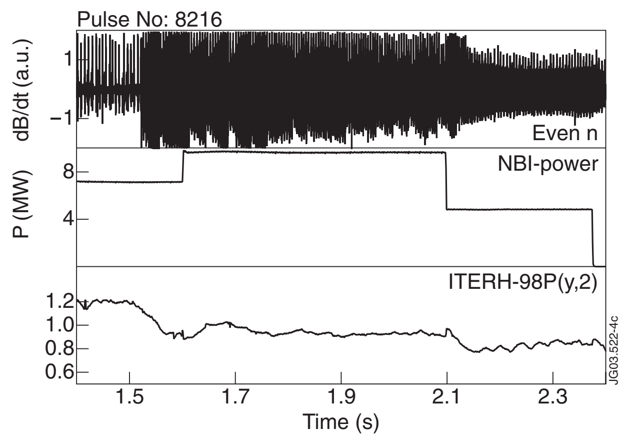

Figure 4: Waveforms of the even-n Mirnov signal, NBI power and H-factor (ITERH-98P(y,2)) for a discharge with a transition between the low and high confinement regime due to a change in heating power.

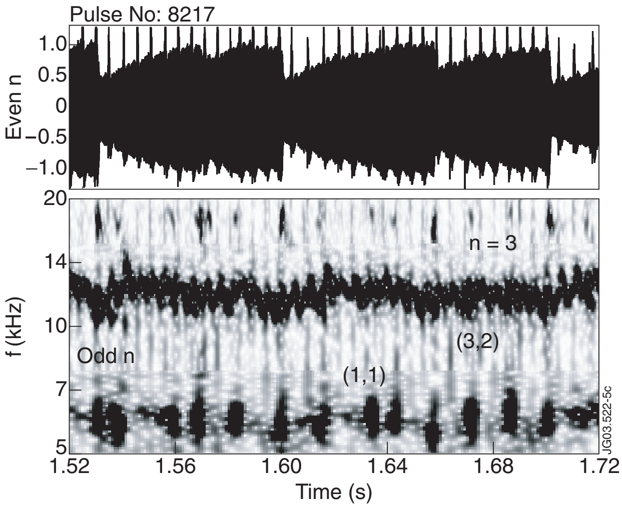

Figure 5: Mirnov signal of the even n mode together with a wavelet plot of the Mirnov measurement. The figure shows (4,3) bursts causing amplitude drops of an (3,2) NTM.

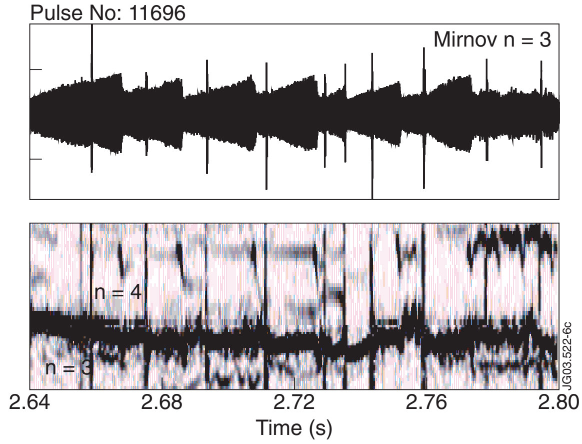

Figure 6: Same as Fig. 6, but the odd n Mirnov signal. Mirnov signal of the even n (a) and the odd n (b) mode together with a wavelet plot of the Mirnov measurement. The figure shows (5,4) bursts reducing the amplitude of an (4,3) NTM.

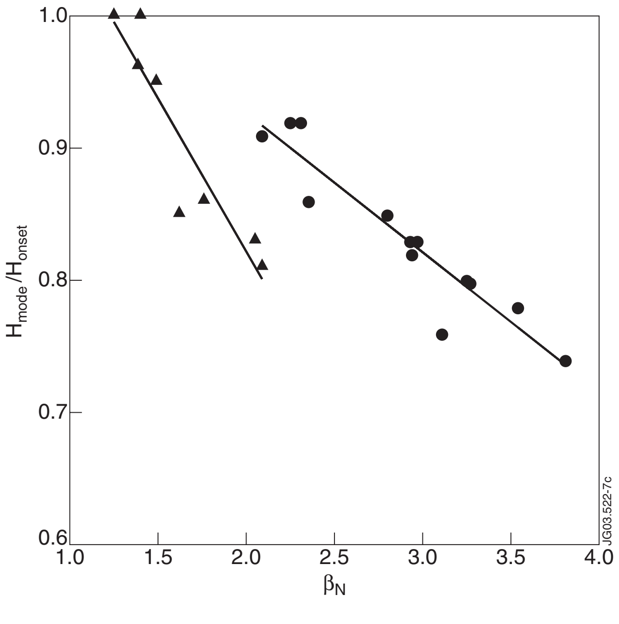

Figure 7: H factor after (3,2) NTM saturation, normalised to the value at the NTM onset, versus β_N at the mode onset for JET.