High-Confinement Regime at High β_N Values Due to a Changed Behavior of the Neoclassical Tearing Modes

S. Günter,[1] A. Gude,[1] M. Maraschek,[1] S. Sesnic,[1] H. Zohm,[1] ASDEX Upgrade Team,[1] and D. F. Howell[2]
[1]*Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748 Garching, Germany*
[2]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom*
(Received 14 June 2001; published 10 December 2001)

High confinement [with $H = 1$, ITERH-98$(y, 2)$] at $\beta_N \approx 2.3$ has been found in ASDEX Upgrade discharges with existing $(m, n) = (3, 2)$ neoclassical tearing modes (NTMs). The reason for the high confinement at high β_N values is a transition of the NTMs into the so-called frequently interrupted regime. In this regime, the NTM growth is frequently interrupted by sudden drops in amplitude. Because of the long NTM growth time, the resulting averaged NTM amplitude remains much smaller than the corresponding saturated value. As this behavior with the beneficial effect on energy confinement has been confirmed at JET, such a high confinement regime at $\beta_N > 2$ might also be expected for ITER.

DOI: 10.1103/PhysRevLett.87.275001 PACS numbers: 52.55.Tn, 28.52.–s, 52.25.Xz, 52.35.Vd

I. Introduction.—The onset of neoclassical tearing modes (NTMs) [1–3] is regarded as the most severe limitation to the maximum achievable normalized plasma pressure β_N ($\beta_N = \beta_t a B_t / I_p$, $\beta_t = 2\mu_0 \langle p \rangle / B_t^2$, B_t: toroidal magnetic field, $\langle p \rangle$: averaged plasma pressure, I_p: plasma current) in tokamaks. As in present day tokamak experiments NTMs are observed even for β_N values well below those planned for ITER-FEAT [4] or a tokamak reactor, one has to expect their occurrence and the resulting confinement reduction also in these machines. This might pose a problem for ITER-FEAT to reach its planned plasma parameters ($\beta_N = 1.8$) at high confinement ($H = 1$) [4]. Therefore, tools to avoid the NTM onset [5] as well as to suppress already existing NTMs are being developed [6].

According to a simple analytical description using the generalized Rutherford equation (see, e.g., [2]), the saturated width $w_{\rm sat}$ of these islands is expected to grow proportional to the plasma pressure. Although, taking into account nonlinear effects, a saturation of this behavior is expected for very large pressures, $w_{\rm sat}$ should always grow with increasing plasma pressure [7]. On ASDEX Upgrade [8], 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. In 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 MHD instability [a $(4, 3)$ mode in case of a $(3, 2)$ NTM] leading to these amplitude drops as soon as the two modes have a common phase velocity [9].

II. Improved energy confinement at high β values.—In Fig. 1 the confinement degradation due to the onset of NTMs is given. In the discharges considered, the neutral beam heating power has been switched on after the current ramp up phase, and has been increased until the onset of a $(3, 2)$ NTM. Afterwards the heating power as well as the other plasma parameters are kept constant. The β values at which the NTM appears can mainly be varied by the heating scenario and the plasma density. A fast ramp up of the heating power usually results in larger β_N values at mode onset, as the trigger events which are required for mode onset (mostly sawteeth) are not very frequent. A low density allows high temperature at the same pressure. As the β_N values for the NTM onset have been found to be proportional to the normalized ion Lamor radius [$\rho^* = \rho/a$, $\rho = \sqrt{2 m_i k_B T_i}/(eB_t)$, a: minor plasma radius] [10] high temperature leads to higher β_N values at mode onset.

As expected from theory, for low values of $\beta_{N,\rm onset}$ the confinement degradation increases linear with onset pressure. 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). As the average H factor at the mode onset for the discharges considered is often larger than 1, for β_N values

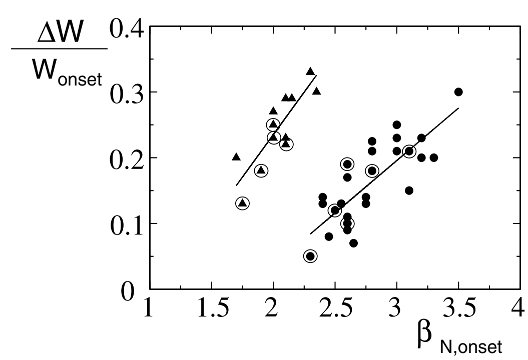

FIG. 1. Fractional confinement degradation due to a $(3, 2)$ NTM versus β_N at the mode onset for ASDEX Upgrade. The discharges included in this figure cover a wide range of plasma parameters ($B_t = 1.5$–2.5 T, $I_p = 0.8$–1.0 MA, safety factor: $q_{95} = 3.0$–4.3). Encircled symbols correspond to the same machine parameters: $B_t = 2.5$ T, $I_p = 1.0$ MA ($q_{95} = 4.3$).

 0031-9007/01/87(27)/275001(4)$15.00

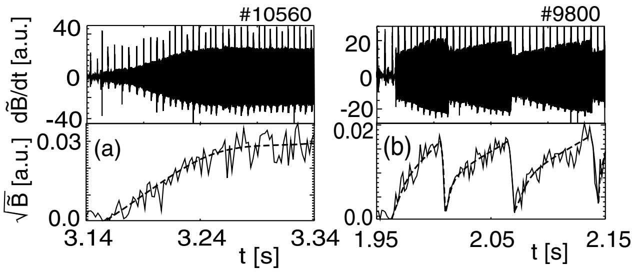

FIG. 2. Raw Mirnov signal ($d\tilde{B}/dt$) as well as the square root of the integrated signal ($\sqrt{\tilde{B}}$) for the $(3, 2)$ NTM at $\beta_N = 2.3$ for a low confinement discharge (a) and a high confinement discharge (b).

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 [11] 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. The raw Mirnov signal ($d\tilde{B}/dt$) as well as the square root of the integrated signal which is proportional to the island size are given for a high and a low confinement discharge at the same $\beta_N = 2.3$. In the low confinement case the mode amplitude smoothly grows until it saturates (Fig. 2a). The Mirnov signal in the high confinement case at the same β_N value looks different (Fig. 2b). Here the mode growth often is interrupted by sudden drops in amplitude. As already mentioned above, we call this state FIR-NTMs. As the NTM growth time is quite large (50–100 ms for ASDEX Upgrade), due to the frequent amplitude drops, the NTM cannot reach its saturated size. Thus the averaged mode amplitude shown in Fig. 2b is smaller by about a factor of 2 than that shown in Fig. 2a, although we have chosen a discharge with the same β_N value at mode onset.

In the following it will be investigated whether the reduced averaged island size is sufficient to explain the observed reduction in confinement degradation. 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 [12,13]. Assuming that the density and heating profiles do not change due to an island of width w (normalized to the minor radius a), one finds $\delta W/W = f(r_{\rm res})w/a$. $f_{\rm res}$ has been determined for typical ASDEX Upgrade density and temperature profiles as discussed in [7]. Using a high resolution ECE system, the location $r_{\rm res}/a$ of the rational $q = 1.5$ surface has been found in [14] to be 0.58 for $q_{95} = 4.5$. For different values of q_{95}, we assume the location of the resonant surface $r_{\rm res}/a$ to be $0.6(q_{95} = 4.4)$ and $0.65(q_{95} = 4.0)$, respectively, which is in agreement with soft x-ray measurements. The size of the magnetic islands has been determined using magnetic measurements, calibrated by the island width as obtained from ECE measurements in comparison to discharges with similar q_{95}. The confinement degradation resulting from

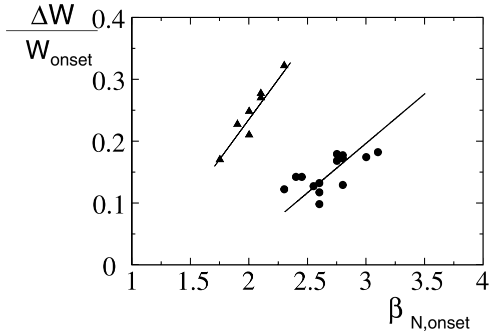

FIG. 3. Confinement degradation as estimated from the averaged NTM island size for the discharges with $q_{95} = 4-4.5$ from Fig. 1. For comparison the regression lines from Fig. 1 are added.

the measured island size calculated as discussed above 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 behavior 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 confinement. However, transitions between the low and high confinement regime within one discharge are possible as well. 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 2.25 s leads to more frequent amplitude drops and hence a smaller averaged island size.

III. 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 $(4, 3)$

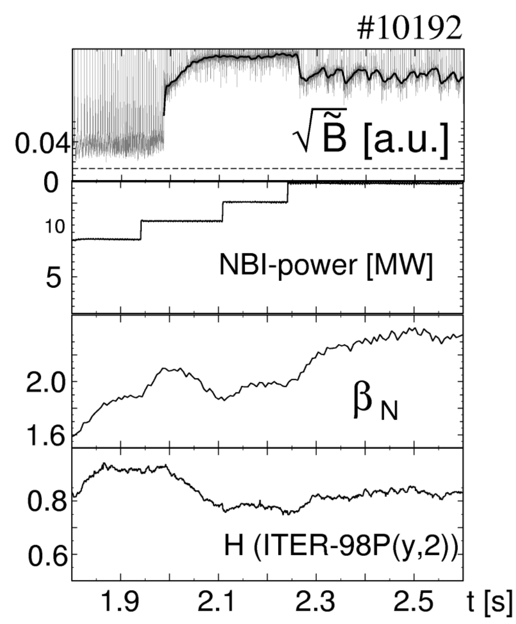

FIG. 4. Waveforms of the $(3, 2)$ mode amplitude ($\sqrt{\tilde{B}}$), neutral beam heating power, β_N, and H factor for a discharge with a transition between the low and high confinement regime due to a change in heating power.

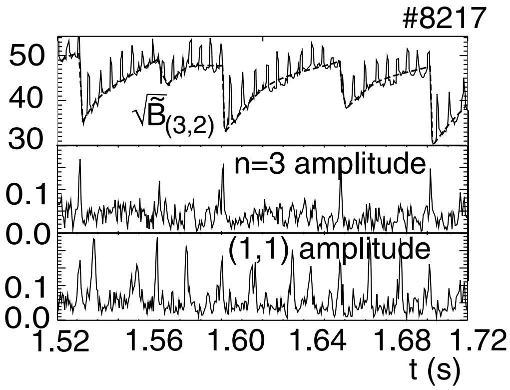

FIG. 5. (3, 2) mode amplitude ($\sqrt{\tilde{B}}$) together with the amplitude of the (4, 3) and (1, 1) mode activity. The (4, 3) mode bursts always coincide with (1, 1) activity and the amplitude drops of the (3, 2) NTM. The spikes on the (3, 2) signal are due to strong ELM activity.

mode, growing on a time scale of less than 1 μs [9]. This mode usually occurs in short bursts (on a time scale of 1 μs), 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 due to their fast growth ($\tau_{\text{growth}} <$ 300 μs) seem to be ideal modes, possibly driven by the pressure gradient at their corresponding rational surface. The occurrence of the $(m + 1, n + 1)$ modes always coincides with (1, 1) mode activity which is a necessary condition for the nonlinear coupling to the (m, n) NTM. Figure 7 (corresponding to Fig. 12 of [9]) illustrates that the reduction in NTM mode amplitude really requires the nonlinear coupling of phase locked modes. The occurrence of an (4, 3) alone does not seem to be sufficient for a reduction in NTM amplitude. Even a large (4, 3) amplitude just before 2.987 s does not reduce the (3, 2) amplitude. Only when the (3, 2) and (4, 3) modes have a common phase velocity, the NTM amplitude drops. The time in which the amplitude drop occurs is very short (about 500 μs), much shorter than the resistive time scale. If one assumes forced reconnection, however, the time could be sufficient for sto-

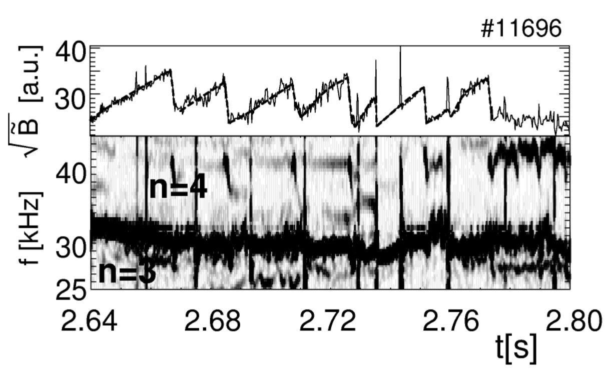

FIG. 6. Same as Fig. 5, but (4, 3) mode amplitude. The figure shows (5, 4) bursts reducing the amplitude of an (4, 3) NTM.

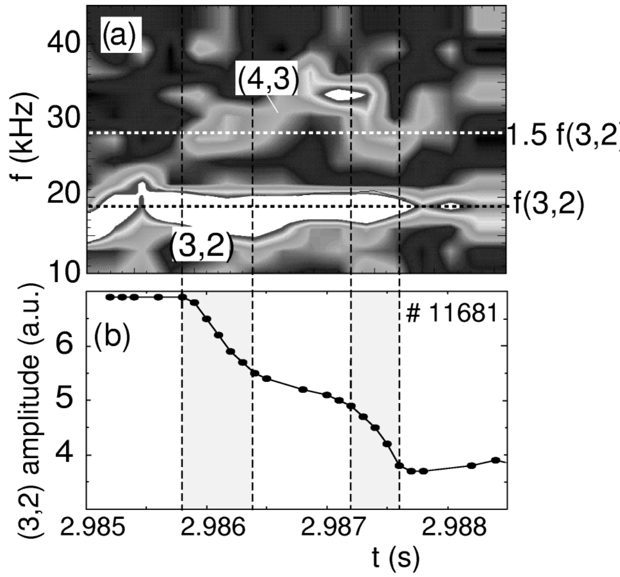

FIG. 7. (a) Frequency versus time of the signal of an ECE channel showing a (4, 3) mode burst together with a (3, 2) NTM. (b) (3, 2) island width from Mirnov measurements [9].

chastization [15] in the presence of two coupled modes of different helicity as argued in [9].

IV. Summary and conclusions.—A high confinement regime ($H \approx 1$) at high β_N values ($\beta_N \geq 2.3$) has been found on ASDEX Upgrade in spite of the presence of (3, 2) NTMs. The reason for the reduced confinement degradation caused by the NTM is frequent amplitude drops of the (m, n) NTM due to the nonlinear coupling to an $(m + 1, n + 1)$ 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 for a wide range of plasma parameters.

The transition to FIR-NTMs with the beneficial effect on energy confinement has been also found on JET. Figure 8 shows a similar behavior for JET as has been found for ASDEX Upgrade (see Fig. 1). The transition to the high

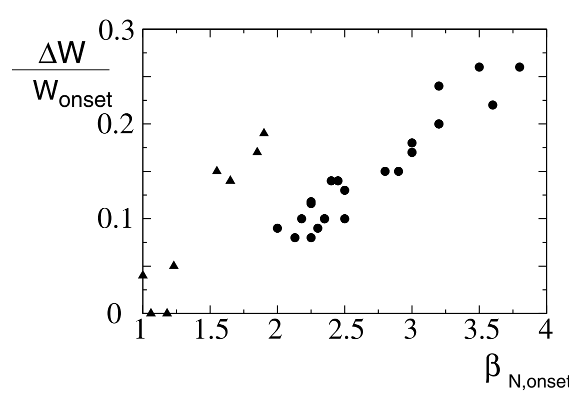

FIG. 8. Fractional confinement degradation due to a (3, 2) NTM versus β_N at the mode onset for JET. Machine parameters: $B_t = 1.0-2.7$ T, $I_p = 0.8-2.0$ MA, $q_{95} = 2.6-4.4$.

confinement regime at JET occurs, however, already at somewhat smaller β_N values ($\beta_N \approx 2.0$).

$(2,1)$ NTMs did not occur in the discharges considered on JET and ASDEX Upgrade. Their onset would have required even higher heating powers, and—at least on ASDEX Upgrade—they only occur at very low densities.

As the modes causing the amplitude drops seem to be MHD modes, their occurrence should only be determined by the current and pressure profiles. The similarity of these profiles between small and large tokamak experiments suggests that these should not be too different in a reactor scale experiment. The density profiles in H modes in all experiments seem to be very flat. The temperature profile has been found to be stiff for sufficient heat flux, the logarithmic temperature gradient probably limited by turbulence caused the ion temperature gradient driven modes [11]. Thus, a high confinement regime at $\beta_N > 2$ in spite of the onset of NTMs might also be possible for ITER and in a tokamak reactor.

In ITER the occurrence of $(2,1)$ NTMs might remain a problem. They did, however, not occur in the discharges considered on JET and ASDEX Upgrade. Their onset would have required even higher β values, and, at least on ASDEX Upgrade, lower densities. It is not clear yet if one has to expect $(2,1)$ NTMs on ITER-FEAT. At least according to the polarization current model (see, e.g., [16]) one would expect a strong stabilizing contribution due to the high normalized collisionality $\bar{\nu}_{ii} = \nu_{ii}/m\epsilon\omega_e^*$ (ν_{ii}: ion-ion collision frequency; m: poloidal mode number; ϵ: inverse aspect ratio; ω_e^*: electron diamagnetic drift frequency).

This work has partly been funded by EURATOM. The UKAEA author in addition was funded by the U.K. department of Trade and Industry. The authors would like to thank all contributors to the EFDA work program, especially those working in the JET-task force MHD.

[1] Z. Chang *et al.,* Phys. Rev. Lett. **74**, 4663 (1995).
[2] O. Sauter *et al.,* Phys. Plasmas **4**, 1654 (1997).
[3] H. Zohm *et al.,* Plasma Phys. Controlled Fusion **40**, B237 (1997).
[4] ITER-FEAT Outline Design Report, International Atomic Energy Agency, Vienna, 2001.
[5] O. Sauter *et al.,* Phys. Rev. Lett. (to be published).
[6] G. Gantenbein *et al.,* Phys. Rev. Lett. **85**, 1242 (2000).
[7] S. Günter *et al.,* Plasma Phys. Controlled Fusion **41**, 767 (1999).
[8] K. Lackner *et al.,* Plasma Phys. Controlled Fusion **36**, B79 (1994).
[9] A. Gude, S. Günter, M. Maraschek, H. Zohm, and ASDEX Upgrade Team, Nucl. Fusion (to be published).
[10] S. Günter *et al.,* Nucl. Fusion **38**, 1431 (1998).
[11] ITER Physics Basis, Nucl. Fusion **39**, 2204 (1999).
[12] Z. Chang and J. D. Callen, Nucl. Fusion **30**, 219 (1990).
[13] Z. Chang *et al.,* Nucl. Fusion **34**, 1309 (1994).
[14] J. Meskat *et al.,* "Analysis of the structure of neoclassical tearing modes in ASDEX Upgrade," Plasma Phys. Controlled Fusion (to be published).
[15] A. J. Lichtenberg *et al.,* Nucl. Fusion **32**, 495 (1992).
[16] H. Wilson *et al.,* Phys. Plasmas **3**, 248 (1996).