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ABSTRACT.

The plasma parameters required for the occurrence of (3,2) FIR-NTMs and thus good confinement properties at high normalised plasma pressure (β_N) are investigated. Both on ASDEX Upgrade and on JET it is found that, with remarkable consistency between the devices, for a variety of plasma parameters in conventional current profile scenarios, this regime establishes itself for discharges with sufficient high normalised plasma presure at mode onset $\beta_{N,onset} > 2.3$. An active triggering of this regime has been achieved by lowering the magnetic shear at the q = 4/3 rational surface. That way an ideal (4,3) MHD mode is being destabilised, forcing the required three wave coupling between the (3,2) NTM, (1,1) and (4,3) mode activity.

1. INTRODUCTION

Neoclassical tearing modes (NTMs) are magnetic islands driven unstable by the loss of boot-strap current inside the island in tokamak plasmas with monotonic current profiles. These modes are of major concern for a tokamak reactor as they are considered the most severe limitation to the maximum achievable normalised plasma pressure β_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, I_p: plasma current). In present day tokamak experiments NTMs of (m,n)=(3,2) helicity are often observed at β_N values in the range of those planned for the next step tokamak experiment ITER [1].

As NTMs are driven by the loss of bootstrap current inside magnetic islands [2, 3] their island width is expected to grow nearly proportional to the plasma pressure. Thus for β_N values as planned for ITER NTMs usually cause confinement degradations of about 20% to 30%. However recently a new regime of (3,2) NTMs, the Frequently Interrupted Regime (FIR), has been discovered [4, 5] in which the confinement degradation due to the NTMs is strongly reduced in discharges with sufficient high normalised plasma presure at mode onset ($\beta_{N,onset} > 2.3$). In this regime the growth of the NTMs is often interrupted by sudden drops in NTM amplitude. As the NTM growth time is much larger than the time between two subsequent amplitude drops, the NTMs cannot reach their saturated amplitude. Thus the time averaged NTM amplitude is significantly reduced resulting in weakened confinement reduction. The observed drops in NTM amplitude have been explained by non-linear coupling between the (3,2) NTM, (1,1) and (4,3) mode activity. It has been proven that the sudden drops in NTM amplitude only occur if the three modes are locked in phase [4]. Whereas besides the (3,2) NTM often (1,1) activity is present in the discharges, the (4,3) mode activity required for the three-wave coupling only occurs at sufficiently high β_N values. This mode often appears in very short bursts with a duration of about 1ms, the growth time of these mode bursts being less than 200 μs.

Both the high plasma pressure required for (4,3) mode activity as well as its small growth time suggest this mode being an ideal MHD mode which is close to marginal stability, driven unstable by the non-linear mode coupling. According to linear MHD stability calculations a large pressure gradient at low magnetic shear can drive low-n ballooning modes unstable [6]. Therefore a flattening of the magnetic shear close to the *q = 4/3* surface should destabilise an ideal (4,3) mode. It will be shown in this paper that via this mechanism one can not only destabilise ideal (4,3) modes but also trigger the transition of an (3,2) NTM into the Frequently Interrupted Regime.

Whereas in the discharges considered in this paper, the non-linear coupling between a (3,2) NTM, (4,3) and (1,1) mode activity results in a reduction of the NTM amplitude, it has been recently found that non-linear coupling of (3,2) NTMs to other MHD modes can have a similar effect. In [7] a reduction in the (3,2) NTM amplitude due to coupling to (4,3) and (7,5) modes has been shown. In this paper we first compare the plasma parameters required for the occurrence of FIR-NTMs as observed on ASDEX Upgrade and JET. After a discussion of the linear stability of the (4,3) mode we report on experiments to trigger the transition to (3,2) FIR-NTMs by localised Electron Cyclotron Current Drive (ECCD) on ASDEX Upgrade and by a more global reduction of magnetic shear in the plasma centre due to early central counter current drive by lower hybrid waves in JET.

2. COMPARISON OF PLASMA PARAMETERS REQUIRED FOR FIR-NTMS ON ASDEX UPGRADE AND JET

FIR-NTMs have been observed so far on ASDEX Upgrade as well as on JET. Whereas several examples of FIR-NTMs on ASDEX Upgrade have been given in Refs. [4, 5], Fig.1 shows an example on JET. It is seen that the (3,2) NTM amplitude suddenly decreases as soon as a (4,3) mode burst and a (1,1) mode activity are locked in phase. The occurrence of the (4,3) mode itself is not sufficient to cause a significant amplitude reduction here even if in addition (1,1) activity is present.

In Ref. [5] it has been reported that FIR-NTMs are widely observed if β_N exceeds a certain value. On ASDEX Upgrade at plasma pressures above β_N=2.3 (3,2) NTMs usually are FIR-NTMs causing relatively small confinement reduction. This is true for a wide range of plasma parameters. Only if the density profiles become very flat due to strong central electron heating [9] a larger total plasma pressure is required for the transition to FIR-NTMs.

On JET good confinement has been seen already for β_N above 1.9. In the JET discharges with β_N values below 2.3 shown in [5] however it is not (4,3) mode activity that causes the drops in NTM amplitude. In these discharges very small toroidal magnetic field strengths have been used (B_{tor} < 1.2T). To achieve β_N values below 2.3 therefore only moderate heating power (often below 6 MW) was required. This amount of heating power was just marginal to enter type I ELMy H mode. The corresponding discharges were therefore characterised by infrequent large ELMs. As seen in Fig.2, these strong ELMs were responsible for the drops in the (3,2) NTM amplitude.

Figure 3 shows the confinement reduction caused by (3,2) NTMs versus the β_N value at NTM onset. Discharges in which ELMs cause the drops in NTM amplitude and thus confinement improvement are highlighted. A comparison of the fractional confinement degradation caused by (3,2) NTMs on JET and ASDEX Upgrade shows very good agreement if the JET discharges discussed above are not included (see Fig.4). Below β_N= 2.3 NTMs are smoothly growing, causing a degradation in confinement proportional to the plasma pressure as their island size grows approximately linear with pressure. Above $\beta_N = 2.3$ the confinement reduction becomes much smaller as the plasma pressure is sufficient to destabilise the (4,3) modes that cause amplitude drops if coupled to the (3,2) and (1,1) mode activity. For even higher plasma pressures the confinement degradation again increases, but still remains much less compared to what would be expected for smoothly growing NTMs.

3. THE STABILITY OF IDEAL (4,3) MODES

From ideal MHD stability analyses it is well known that large pressure gradients at low magnetic shear can drive low-n ballooning modes, so-called infernal modes [6], unstable. Such modes are of special importance in advanced scenario discharges with non-monotonic current profiles. If the minimum q-value is close to low order rational surfaces, the large pressure gradients characteristic for internal transport barriers often drive ideal modes unstable, leading to termination of the improved confinement or even to disruptions, see e.g. [10].

Although ideal (4,3) modes are usually not observed in conventional monotonic current profile discharges, the magnetic shear around the $q = 4/3$ surface is often quite small as well. To in-vestigate the linear stability of the ideal (4,3) mode we used an equilibrium reconstruction of a conventional scenario ASDEX Upgrade discharge (#15863) and the linear MHD code CASTOR [11]. For the experimental plasma pressure and magnetic shear ($s = 0.7$) the mode is stable. If one artificially increases the plasma pressure at fixed magnetic shear the mode can be driven unstable if the pressure gradient is above twice the experimental one (see Fig.5). Lowering the magnetic shear destabilises the mode as well. Figure 6 shows a scan of magnetic shear at fixed pressure gradient. For low magnetic shear the (4,3) mode becomes unstable already for plasma pressures close to the experimental ones.

From these linear stability investigations one can conclude that it might be possible to destabilise ideal (4,3) modes at reasonable plasma pressure by lowering the magnetic shear. We have performed corresponding experiments on ASDEX Upgrade: In a discharge with quasistationary plasma conditions in which no MHD activity was present besides (1,1) modes and ELMs, we have driven current localised just outside the $q = 4/3$ radius by electron cyclotron current drive. Such a current drive should locally flatten the magnetic shear around the $q = 4/3$ surface if driven in the direction parallel to the plasma current. To find the right radial position we have chosen discharge conditions as used for the stabilisation of (3,2) neoclassical tearing modes, but slightly higher toroidal magnetic fields. As we know the exact radial position of the ECCD to be at the $q = 1.5$ surface when its stabilising influence on the NTM is maximum, a slight increase in the magnetic field shifts the location of the current drive inside the q = 1.5 radius. We have chosen a toroidal magnetic field leading to an ECCD deposition about 3cm inside the $q = 1.5$ radius. For current drive parallel to the plasma current, a (4,3) mode appears about 100 ms after switching on the external current drive, see Fig.7. This mode seems to be an ideal one as its growth time is quite small ($\tau_{growth} < 300\mu s$). The mode disappears after the external current drive is switched off.

4. TRIGGERING OF THE TRANSITION INTO THE FIR REGIME BY LOCALISED ECCD ON ASDEX UPGRADE

As reported above, the drops in the amplitude of a (3,2) NTM require a non-linear three-wave coupling to (1,1) and (4,3) modes. Whereas (1,1) mode activity is nearly always present for discharge conditions prone to NTMs, the (4,3) mode is usually linearly stable as shown above. Increasing the plasma pressure has a destabilising effect and thus makes a non-linear destabilisation easier. This might be the reason for the required high plasma pressures for FIR-NTMs. Since we have demonstrated above the destabilising effect of reduced magnetic shear onto the (4,3) mode, it should be possible to trigger the transition to FIR-NTMs already at lower plasma pressure. Using again electron cyclotron current drive just outside the $q = 4/3$ radius, we were able to prove this hypothesis.

Figure 8 shows time traces for two very similar discharges in which the external current is driven in co- and counter direction, respectively. A ramp in the toroidal magnetic field strength was applied to fine tune the location of the ECCD for maximum effect. For co-current drive we clearly find the transition into the FIR regime after switching on the ECCD whereas no effect is seen for counter current drive. When comparing co- and counter ECCD discharges one finds improved confinement if the NTM shows the FIR behaviour.

At about 2.7s again a smooth mode appears also for co-current drive. The reason for this back transition could either be the change in ECCD location or a decrease in density caused by the electron cyclotron heating. A reduction in particle confinement for strong electron heating has frequently been observed on ASDEX Upgrade [9]. A possible explanation of this phenomenon is destabilisation of trapped electron modes which could cause an enhancement in particle transport [12, 13]. In the discharge considered, the ECRH causes a drop in line averaged density from $5.9 \cdot 10^{19}$ m^{3} to $5.0 \cdot 10^{19}$ m^{-3}. This decrease in density results in a reduction of the bootstrap current at the $q = 1.5$ surface and thus the NTM drive.

To achieve a more stationary situation we fixed the toroidal field to an optimum value as found from the field ramp experiments above ($B_{tor} = 2.19$ T). In addition we also tried to keep a constant β value by a feedback control of the neutral beam heating power. That way a very clear FIR-NTM behaviour has been observed for more than a second (Fig.9) using co-ECCD. For counter ECCD the NTM shows some FIR characteristics before switching on the ECRH which disappears afterwards. During the ECCD phase the mode amplitude is smooth, but slowly decreases. This effect again might be caused by the increased particle transport and the resulting reduced bootstrap current density at the NTM rational surface.

5. HIGH CONFINEMENT AT LOW GLOBAL MAGNETIC SHEAR IN THE PLASMA CENTRE

Instead of a local flattening of the magnetic shear around the $q = 4/3$ surface as described above for ASDEX Upgrade, we reduced the magnetic shear in the plasma centre globally in JET. This has been done transiently by early Lower Hybrid Counter Current Drive (LHCD). Time traces of a corresponding discharge are shown in Fig.10. As seen in Fig.11, the (3,2) mode has a strong FIR character. Therefore, very good confinement (H_{98y} = 1.4), at high plasma pressure (β_N = 3.3) has been achieved. For these discharge conditions with very low central magnetic shear the confinement improvement is even larger than that already found with FIR-NTMs in usual discharges.

To prove if the FIR character of the NTM disappears if we increase the minimum q-value and thus reduce (1,1) activity, we raised the magnetic field from B_t = 1.2 T to 1.5 T. All other discharge parameters were kept the same. In these discharges no continuous (1,1) activity is observed. Most of the time one finds coexisting (3,2) and (4,3) mode activity of small amplitude. A coupling between these modes happens only occasionally. If the (4,3) and (3,2) modes are coupled in phase, also (1,1) activity is present, probably driven by non-linear mode coupling. During these periods the (3,2) NTM amplitude is further reduced.

Although the FIR character of the (3,2) NTM in these discharges is quite weak, their amplitude is small enough to allow very good confinement (β_N = 2.9, H_{98y} = 1.5). The reason for the small mode amplitude is not strongly related to the (4,3) mode activity. This can be proven by looking onto the mode amplitudes during the phase of small heating power. During this time the plasma pressure is small enough such that no (4,3) activity is present. In a discharge with conventional current profile, but otherwise the same discharge conditions as in the discharge considered in Fig.10 (Pulse No: 59096), the field perturbation caused by the (3,2) NTM is about $3 \cdot 10^{-4}$ T, for Pulse No: 59175 (with LHCD in the early phase) it is $1.7 \cdot 10^{-4}$ T. After increasing the magnetic field to 1.5 T (Pulse No: 59174), at same level of heating power the NTM amplitude is only about $5 \cdot 10^{-5}$ T. Obviously the change in the current profile as well as the resulting shift of the mode's rational surface towards the plasma centre reduce the drive of the NTM significantly.

SUMMARY AND DISCUSSION

In this paper it has been shown that (3,2) FIR-NTMs occur for sufficiently high plasma pressure ($\beta_{N,onset} > 2.3$) both on ASDEX Upgrade as well as on JET. This is true for a broad range of plasma parameters as long as conventional current profiles are considered. Drops in the amplitude of (3,2) NTMs for $\beta_{N,onset} < 2.3$ reported earlier [5] are caused by large infrequent type I ELMs in low heating power JET discharges.

Utilising the fact that three wave coupling between the (3,2) NTM, (1,1) and (4,3) mode activity has been found to be the reason for the drop in NTM amplitude, we were able to trigger the transition to FIR-NTMs. As besides the NTM also (1,1) activity is always present in the discharges considered, we concentrated on the stability of the (4,3) mode activity. From linear stability analysis we concluded that either a large pressure gradient or a low magnetic shear are required for destabilisation of ideal (4,3) modes. The requirement of sufficient large plasma pressure was in agreement with the experimental observation that FIR-NTMs only occur above a certain value of β_N. Utilising localised electron cyclotron current drive on ASDEX Upgrade we have proven that lowering the magnetic shear at the $q = 4/3$ rational surface destabilises ideal (4,3) modes. If the reason for the required high plasma pressures really was a sufficient drive of the ideal (4,3) mode, one should be able to trigger the transitions to FIR-NTMs by lowering the magnetic shear at the $q = 4/3$ surface as well. Corresponding experiments on ASDEX Upgrade have successfully demonstrated such a controlled transition to FIR-NTMs via a local flattening of the magnetic shear.

On JET a more global flattening of the central magnetic shear by early LHCD also resulted in strong FIR-NTMs. In addition, even at low heating power without (4,3) mode activity, we found in such discharges a somewhat smaller NTM amplitude compared to conventional current profile discharges. This was probably caused by the reduced drive of the (3,2) NTM due to the global change in the current profile. As at high plasma pressure in addition the amplitude drops caused by the three wave coupling reduce the time averaged NTM amplitude, we achieved nearly record values for JET discharges ($H_{98y} = 1.4$, $\beta_N = 3.3$) even at low triangularity ($\delta \approx 0.3$) in these discharges.

The very good agreement for the normalised plasma pressure required to enter FIR-NTMs on JET and ASDEX Upgrade together with the very weak dependence on other plasma parameters suggest that also in ITER FIR-NTMs should occur at sufficiently high plasma pressure. We have found $\beta_N = 2.3$ at NTM onset would be the corresponding critical value. For plasma pressures somewhat below this value the confinement degradation caused by (3,2) NTMs would be about 30% whereas right above this value it should be even below 10%. Although the ITER operation point is planned to be somewhat below this value, it might be possible to consider operation at a little higher normalised plasma pressure. Thus, (3,2) NTMs might not be a very serious problem for ITER. The experimental setup for NTM stabilisation by external electron cyclotron current drive should therefore give highest priority to the stabilisation of the potentially much more dangerous (2,1) NTMs.

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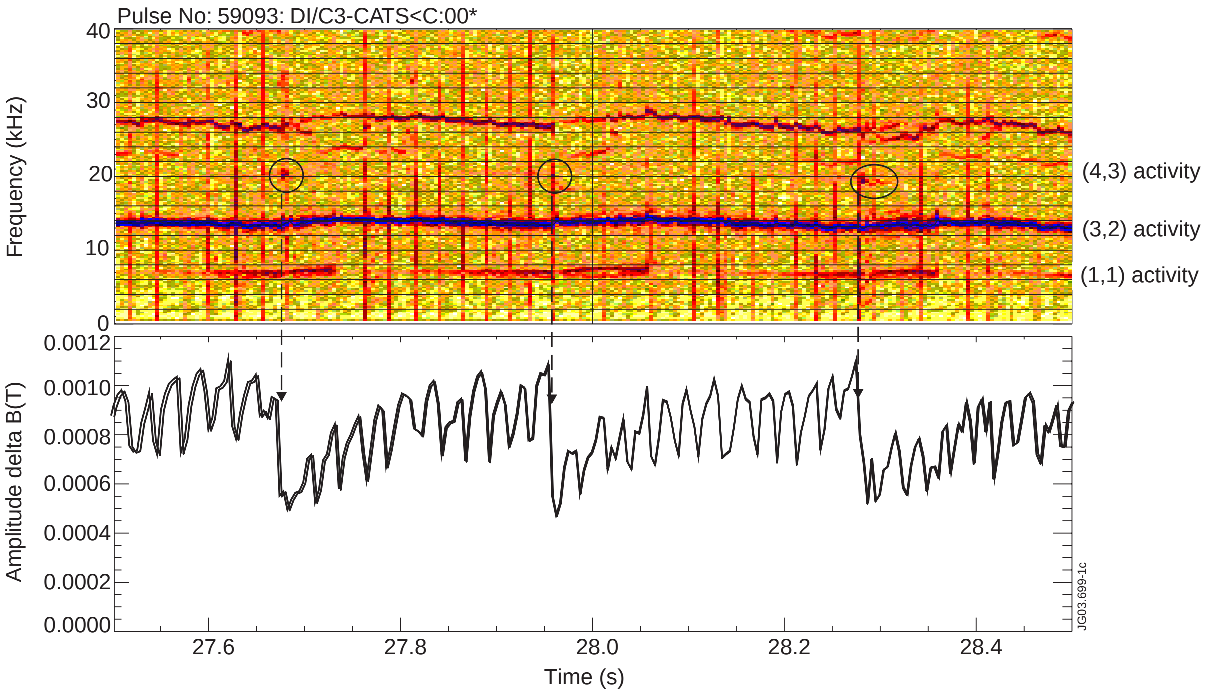


Figure 1: (a) Wavelet plot of the mode activity measured by the Mirnov coils for the JET Pulse No: 59093. (b) Amplitude of the (3,2) NTM. The NTM amplitude is suddenly reduced when the (4,3), (3,2) and (1,1) mode activity are locked in phase. If the (4,3) mode has a different frequency, no amplitude reduction occurs even if additionally (1,1) mode activity is observed. The small amplitude drops in between the big events are caused by ELMs.

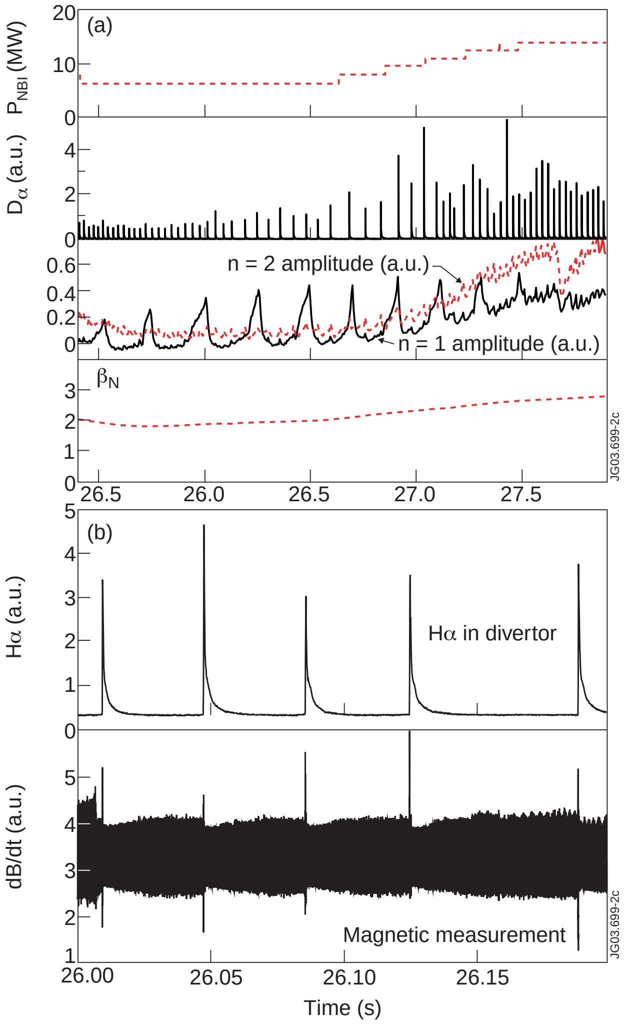


Figure 2: (a) Time traces of heating power, Dα signal, mode amplitudes and bN value for the JJET Pulse No: 59093. The heating power is just marginal to give rise to type I ELMs. As the frequency of these ELMs is nearly proportional to the heating power [8], the ELMs are infrequent and of large size. (b) (3,2) NTM amplitude for a short time interval (26-26.2 s). Each ELM slightly reduces the NTM amplitude resulting in a behaviour very similar to FIR-NTMs.

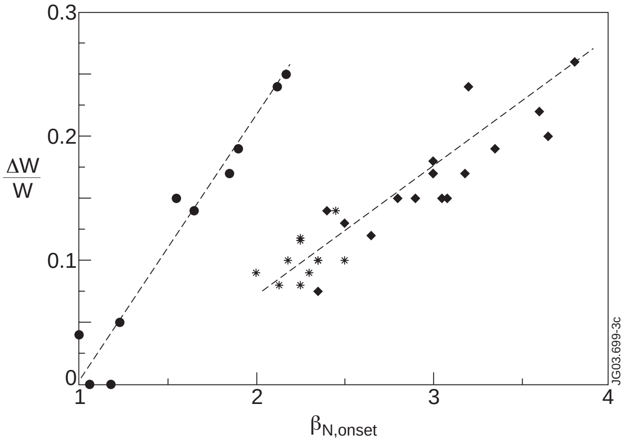


Figure 3: Relative confinement reduction (difference in plasma energy content at mode onset and after its saturation, normalised to the energy at NTM onset) due to (3,2) NTMs versus β_N at NTM onset for JET. Circles mark discharges with smootly growing NTMs, diamonds FIR-NTMs, and stars represent discharges in which the drops in NTM amplitude are caused by type I ELMs.

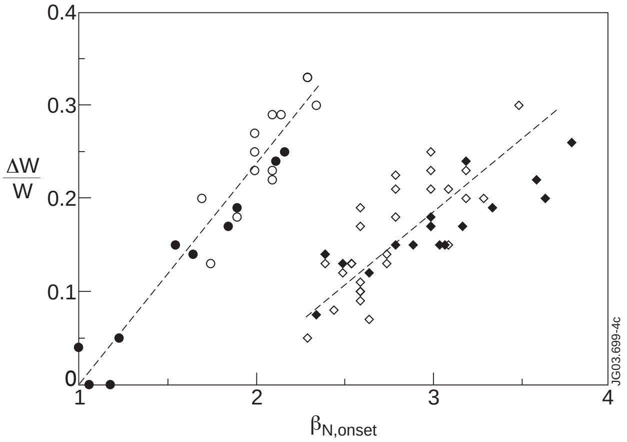


Figure 4: Comparison of reduction in energy confinement due to (3,2) NTMs on ASDEX Upgrade and JET. Full symbols as in Fig. 3, open symbols are ASDEX Upgrade results. Very good agreement is seen both in the relative confinement degradation as well as in the β_N value above which FIR-NTMs cause less energy losses. Discharges highlighted in Fig.3 are not included here as they only occur in the special case of very low heating powers and toroidal magnetic fields.

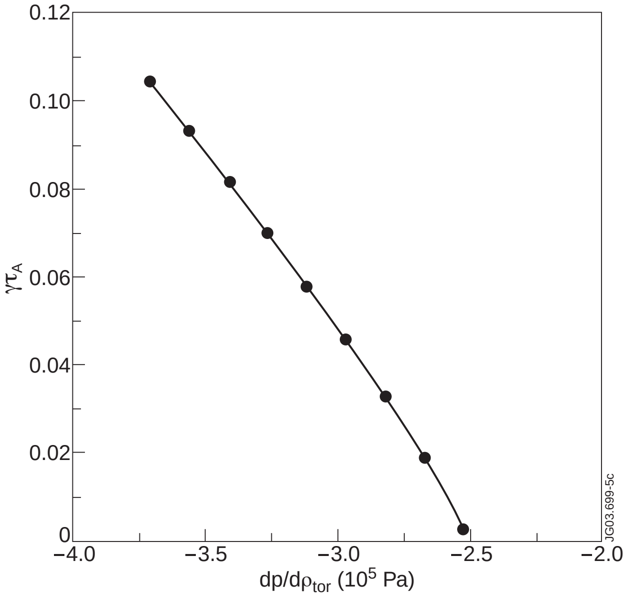


Figure 5: Growth rate of the (4,3) ideal mode versus pressure gradient at the (4,3) mode rational surface at constant magnetic shear (as found from the equilibrium reconstruction without external current drive, s = 0.8): The mode gets destabilised with increasing plasma pressure.

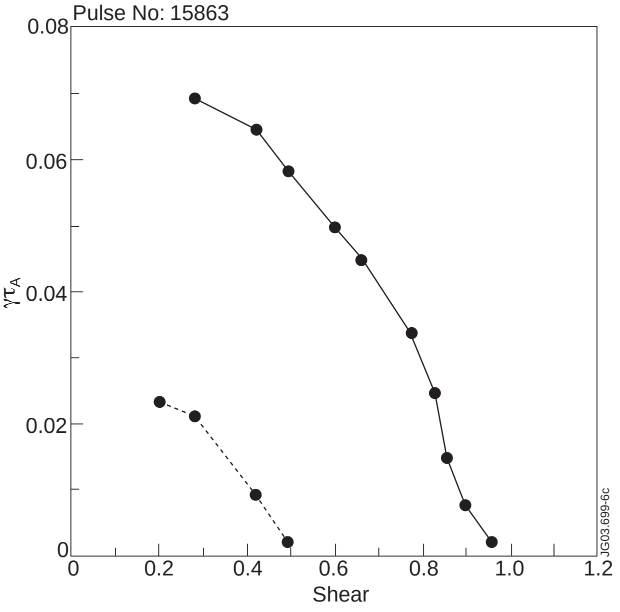
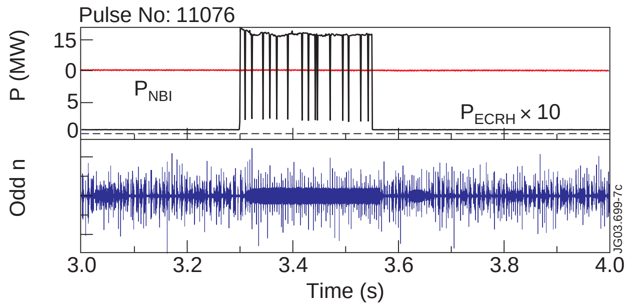


Figure 6: The growth rate of the (4,3) mode for two values of plasma pressure (dashed line =1.6, solid line: 2.5 times the experimental pressure gradient) as function of the magnetic shear. (Pulse No: 15863).



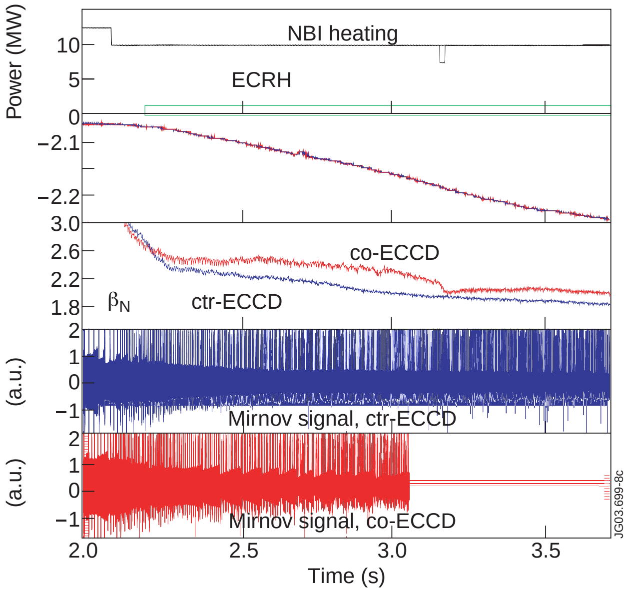
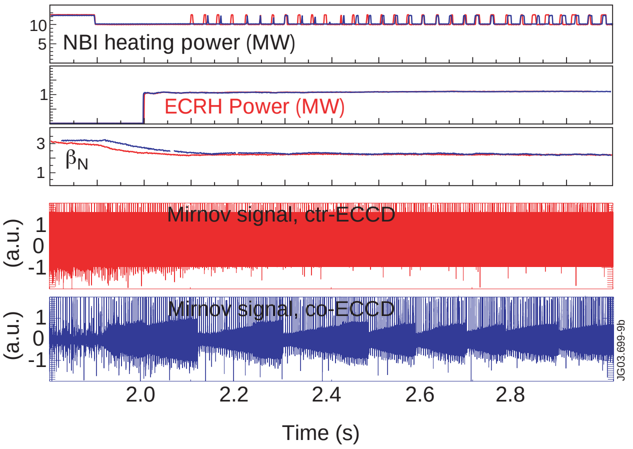


Figure 7: At constant NBI power about 1.6MW ECRHpower, driving current in co-direction, is switched on between 3.3 and 3.55s. The Mirnov signal for odd toroidal mode numbers shows the growth of a (4,3) mode after the ECRH is switched on. The mode decays after the ECRH power is switched off. The mode activity seen during the time without ECRH corresponds to (1,1) mode bursts.

Figure 8: Time traces of heating power, toroidal magnetic field, β_N, and Mirnov signals for two similar discharges, but with co- (Pulse No:17950) and counter-ECCD (Pulse No: 17049) respectively. A ramp in the toroidal magnetic field is performed to find the optimum location of the ECCD to trigger FIR-NTMs. A clear FIR behaviour is seen between 2.3 and 2.8 s in case of co-ECCD.



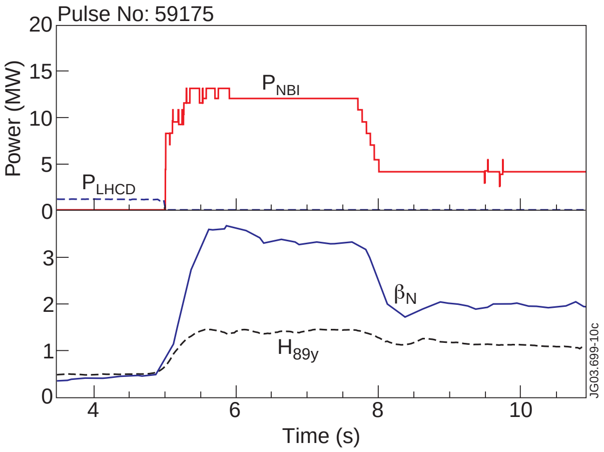


Figure 9: Time traces of heating power, β_N, and Mirnov signals for two discharges at constant magnetic field (B_{tor} = 2.19T). Again co-(Pulse No: 17955) and counter- (Pulse No: 17956) ECCD was applied. Very strong amplitude drops are found for co-ECCD.

Figure 10: Time traces of heating power, β_N, and H_{98y} for a JET discharge (Pulse No: 59175) in which lower hybrid counter current drive in the early phase of the discharge was used to increase the minimum q value and thus to reduce the magnetic shear in the plasma centre.

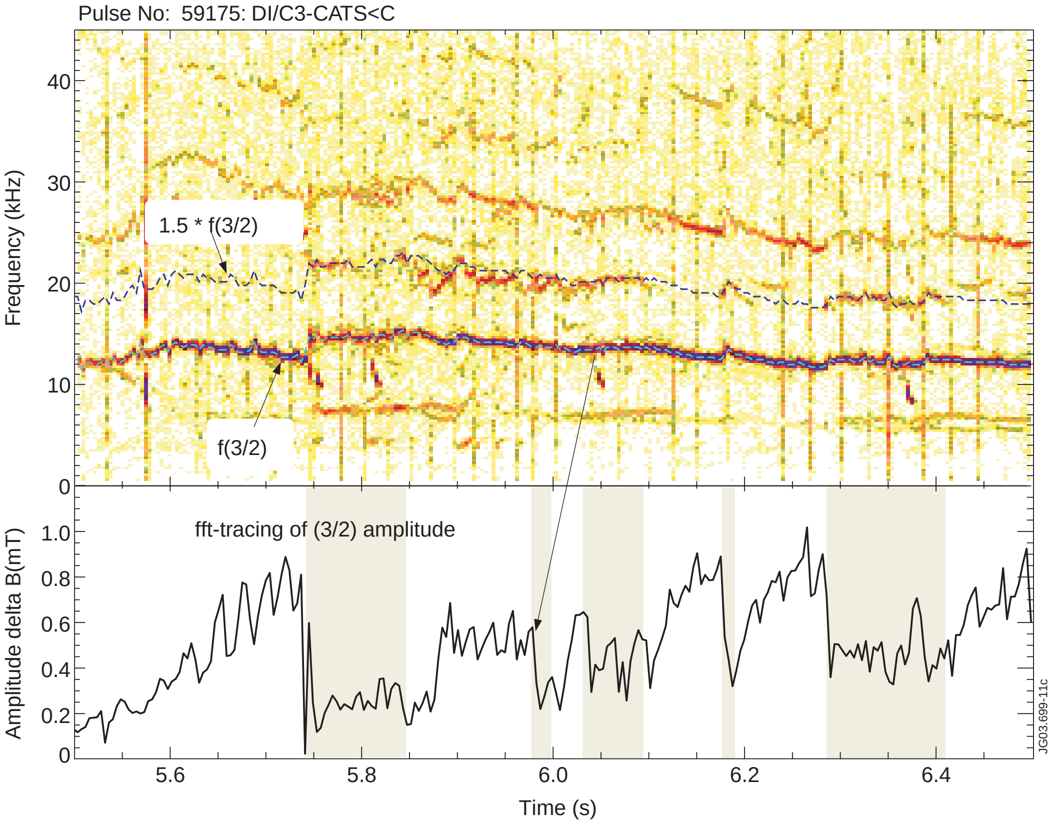


Figure 11: Wavelet plot of the mode amplitude as measured by the Mirnov coils (upper figure), and Amplitudes of the (3,2) mode activity (lower figure). The amplitude of the (3,2) NTM decreases if the (4,3) and the (3,2) modes are locked in phase (shaded areas). During these times a very pronounced (1,1) mode activity is seen. Often a short burst of (4,3) activity results in a increased rotation frequency of the (3,2) mode which additionally is expected to reduce the (3,2) mode amplitude.

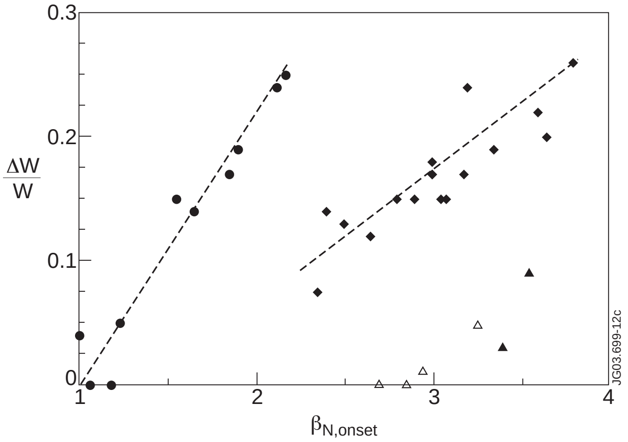


Figure 12: Same as Fig.3, but the discharges close to the H-mode threshold (marked there by stars) are not included. Instead the discharges with very small central magnetic shear are given (triangles). Full symbols correspond to discharges with strong FIR character. Discharges marked by open symbols are rather characterised by weak mode activity..