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Onset and control of Neo-classical Tearing Modes on JET

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1. INTRODUCTION

Neo-classical Tearing Modes (NTMs) are a critical issue for Next Step devices. They occur at $\beta_N > \sim 2$ in ELMy H-mode (the baseline scenario envisaged for ITER FDR). The modes occur above a critical β_N when an MHD perturbation, such as a sawtooth, triggers a seed island with large enough size. They degrade confinement (and thus fusion performance) and can lead to disruptions. Critical issues for Next Step devices are extrapolating onset criteria, which requires detailed understanding of the mechanisms involved, and developing control techniques, which are likely to be required. NTMs have been clearly identified on JET in previous work [1]. This paper reports on further experiments examining onset mechanisms, with fast magnetic and ECE diagnostic, improving onset criteria scaling data, and investigating control of the modes with Ion Cyclotron Current Drive (ICCD). Present studies focus more on the 3,2 mode, which occurs at lower β_N, than the more catastrophic 2,1 mode, and is therefore easier to study experimentally, and more likely to occur in Next Step devices.

2. ACTIVITY ACCOMPANYING NTM ONSET

A typical pulse (47296), is shown in Fig 1 where a 3,2 NTM is triggered at 26.7s. As the mode grows, we observe n=1 activity reducing substantially, with sawteeth becoming suppressed. Plasma rotation also slows. The mode leads to a degradation in confinement and consequent reduction or slower rise in β_N. Higher heating powers trigger a 2,1 tearing mode, observed at 28.6s, which leads to a much larger loss of confinement and transition back to L-mode. In other cases [1] 2,1 modes have led to current terminating disruptions. A higher frequency 4,3 mode is usually observed, which decays with 3,2 onset. The vertical lines on the spectrogram are ELMs, which do not affect the NTM evolution.

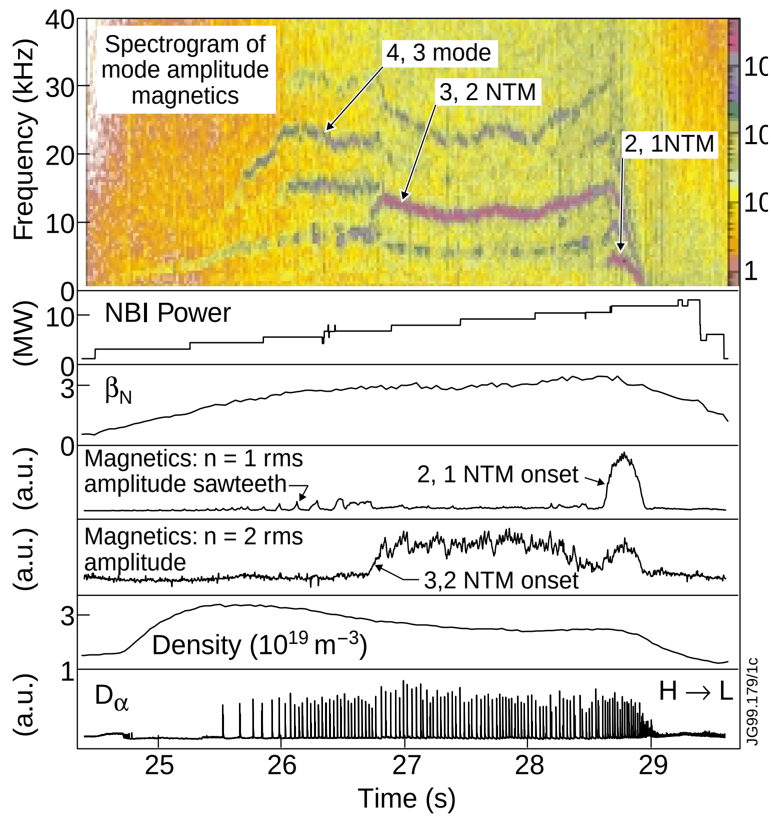

Figure 1: Typical example of an NTM experiment (pulse 47296) in which Neutral Beam heating power is steadily increased.

2.1 Correlation of NTM with sawteeth

A key aspect of the underlying theory is the requirement for seed perturbations. This is important to test: Fig 2 shows a clear correlation of NTM onset time (taken from spectrograms) with sawtooth events and peak n=1 sawtooth precursor amplitudes. We note that the onset correlates better with the n=1 peak than the crash itself (which do not always coincide). This establishes MHD activity, in these cases sawteeth, as a key part of the mechanism responsible for seeding the NTM. We examine the modes involved below.

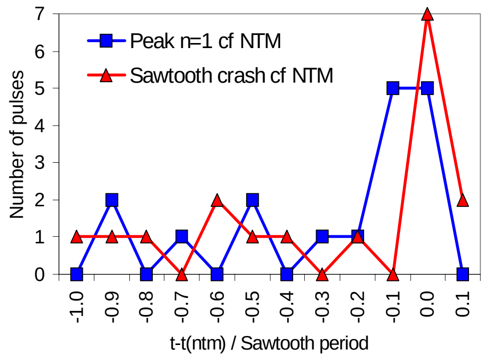

Figure 2: Correlation of NTM with sawtooth activity for 17 pulses, each normalised to sawtooth period.

2.2 Onset mechanisms and mode structure

Careful timing of fast data clearly identifies the 3,2 mode onset and accompanying mode numbers associated with the onset, as shown in Fig 3:

The 3,2 starts with frequency just higher than that of n=1 sawtooth precursors. ECE data locates it to a radius of ~3.55m on the outboard midplane, which is consistent with rotation profiles and q-profiles from EFIT. There is a strong kink-like component to the mode with flux surface displacements much greater on the magnetic axis side of the island than on the outside. Typical saturated island sizes are ~10cm at 1.7T, measured by the ECE diagnostic.

Prior to the appearance of the 3,2, a clear n=2 precursor is observed, which appears to be m=2. This 2,2 generally correlates with n=1 sawtooth activity, terminating exactly at sawtooth crashes. It has double the n=1 frequency, and so is identified as a harmonic of the sawtooth precursor. This 2,2 mode is also seen (more clearly) in more marginal pulses where the 2,2 activity is more prolonged and 3,2 onset has been delayed; here ECE data clearly locates the 2,2 activity to the centre of the plasma, within a minor radius of ~20cm. In these more marginal pulses it is possible to see two n=2 harmonics for a time. One is clearly m=2, the other is less distinct but with frequency ~70% of the 2,2 frequency (therefore further out in minor radius and estimated from rotation profiles to be close to q=1.5), indicating that seeding is taking place but that the resulting island size is not sufficient to lead to NTM growth. The 3,2 mode has a lower frequency than the 2,2, and appears to co-exist with it for a short time in some cases, indicating that locking between the resonant surfaces is not required to seed the NTM. However it seems clear (not least from the statistical analysis) that it is via toroidal coupling to this 2,2 sawtooth precursor, that the seed island for the NTM is induced.

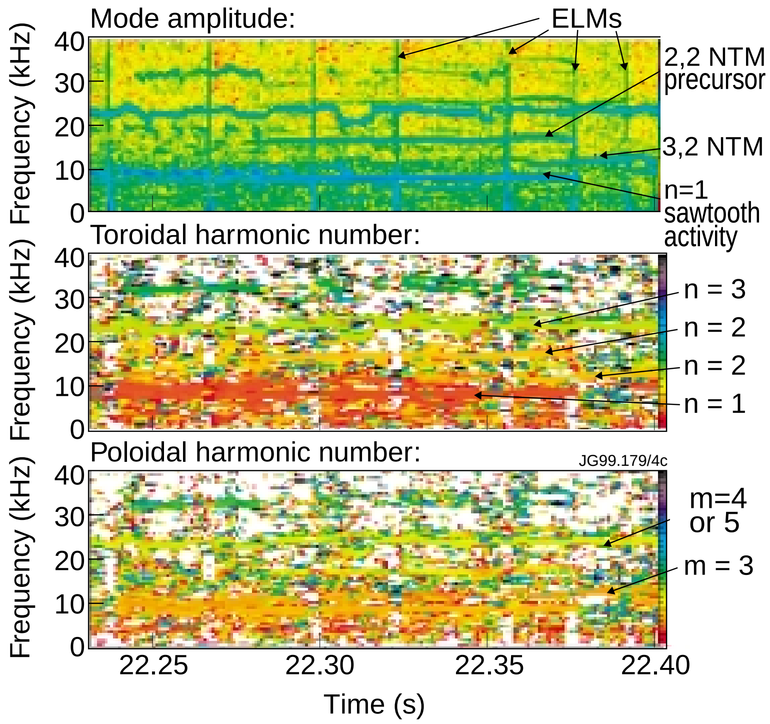

Figure 3: Spectrograms for onset of a 3/2 NTM (pulse 47285), where colour indicates mode amplitude, toroidal and poloidal harmonic numbers (top to bottom)

There is also strong 4,3 activity prior to the 3,2 mode, which somewhat degrades confinement, as can be seen by the slight reduction in the rate of increase of β_N in Fig 1 at ~26.3s. ECE identifies this as an island at R~3.38m. This mode occurs in nearly all pulses once intermediate β_Ns (~2) are reached, persisting until the 3,2 mode has saturated in amplitude, when the 4,3 then becomes stabilised. Like the 3,2, the onset of the 4,3 appears to correlate well with sawtooth activity. Unlike the 2,2 activity, once seeded, the 4,3 amplitude evolution does not correlate with sawtooth activity or other MHD, but remains steady until its decay. Thus this mode is likely to be another NTM. Other higher mode numbers (n=4, m less clear) are also sometimes seen early on, either persistently or more intermittently. Generally most of this activity dies away once the 3,2 NTM saturates in amplitude.

The regular appearance of 4,3 modes and possibility of other modes raises concerns about the viability of NTM stabilisation, which would be required if scaling of onset criteria point to lower NTM thresholds in β_N for Next Step devices. This is only a practical proposition if there are very few unstable modes (probably 1 or 2).

3. SCALING AND ISLAND EVOLUTION FITS

The new data obtained in this campaign approximately agrees with the scaling of previous JET data (ref [1], based on a wider range of experiment types), refining the error bars on the exponents in a dimensionless local parameter fit to the combined data:

$$\beta_N \text{ (3,2 NTM onset)} \propto \rho_{i*}^{\,0.64\pm0.17}(\nu_i/\varepsilon\omega_{e*})^{-0.10\pm0.04}.$$

where $\rho_{i*}=[(2k_Bm_iT_i)^{1/2}/eB_T]/a$, $\nu_i=5.09\times10^{-13}n_e/T_i(eV)^{3/2}$, and $\omega_{e*}=m(dP_e/dr)/r_s.e.n_eB_T$ in terms of the usual parameters at the q=1.5 surface (with poloidal mode number m=3). However, it should be noted that the new data is systematically approximately 15% higher in β_N than the previous data. This may be due to the much smaller steps used in the NBI ramp-ups of the new campaign, or to changes in the plasma configuration due to installation of a new divertor. However, if the previous data β_Ns are scaled up by 15%, this has little effect on the fitted powers, mainly reducing error bars - clearly this should be investigated further.

Two models have been developed to explain the role of a seed by adding stabilising terms to the island evolution equation, based on ion polarisation current [2] or perpendicular conductivity [3]: The island size evolution has been modelled for the JET data using both of these models. Fig 4, where beam power is stepped down to reduce β, shows that while stabilising terms are required to match island size evolution, either model is capable of explaining the data.

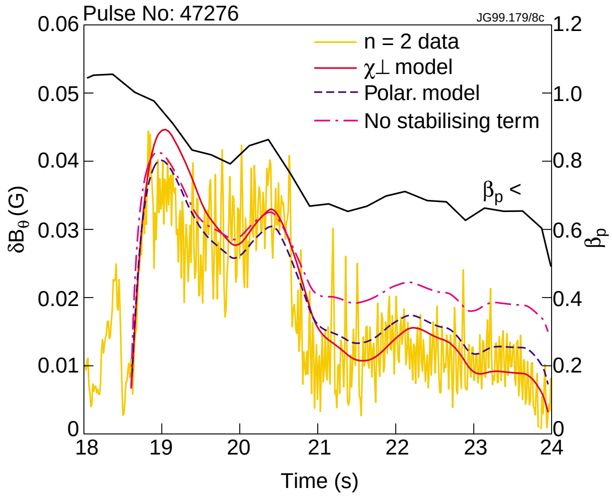

Figure 4: Time evolution of mode amplitude as β_p changes due to NBI step down. This is compared with predictions of the Rutherford island evolution equation using either ion polarisation or perpendicular transport ($\chi_\perp$) terms and with no stabilisation terms.

In practice, mode onset also depends on seed size, governed by the more complex physics of sawtooth amplitude, geometric coupling and dynamic shielding. Thus we need further information about seed size scaling. This approach is described in ref [4]. Onset seed island sizes are ~1-3cm on JET, but are too scattered to constrain the model well. Comparisons with other devices, to extend the data range and obtain predictions for Next Steps, are underway.

4. PRELIMINARY ICCD STABILISATION EXPERIMENTS

Calculations (using the 'FIDO' code [5]) indicate that a moderately localised current drive is possible with minority ion cyclotron current drive (Fig 5), which may assist NTM stabilisation through modification to Δ', or preferential 'O' point current drive. This was applied during NTMs, with deposition location scanned on the inboard side by means of a B_T ramp - see Fig 6. However, for the Hydrogen concentrations used, no effect was seen, probably due to insufficient current drive levels. Clearly, further detailed work including optimisation of the RF scenario (hydrogen minority concentration, etc.) is required.

Similar approaches using Lower Hybrid Current Drive on COMPASS-D have appeared to partially stabilise NTMs [6].

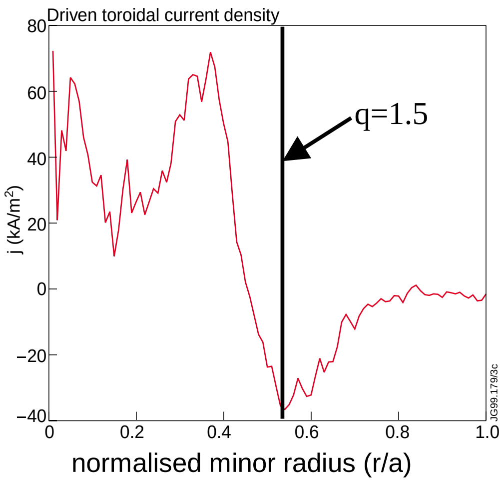

Figure 5: Monte Carlo simulation of ICCD deposition using 52MHz 2nd harmonic Hydrogen (at 8%), –90° phasing, as in experiments (ignoring electron back current) for pulse 47805 at 25.5s.

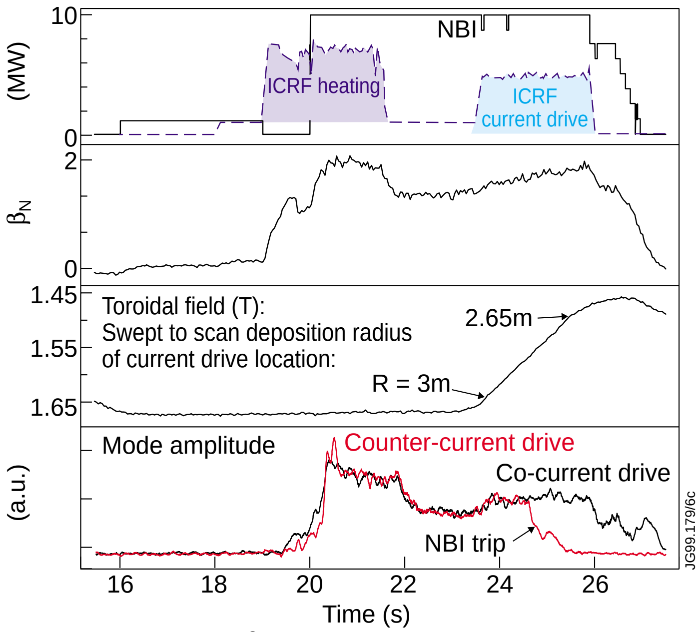

Figure 6: Heating, β_N and toroidal field for pulse 47805 (47803 was similar), with effect of ICCD on mode amplitude for 'co-' (47805, –90° phasing giving co- current drive near the plasma centre and counter- further out) and 'counter-' (47803, +90° phasing reversing the current drive) directions.

5. CONCLUSIONS AND FURTHER WORK

The onset of Neo-classical tearing modes has been examined in considerable detail, with fast data providing measurements of mode numbers and location. This has provided useful insight into the mechanisms involved. There is a clear correlation between NTM onset and sawtooth MHD. The 3,2 NTM appears to be triggered by a 2,2 harmonic of the sawtooth precursor, but locking between these harmonics is not required to induce the NTM. A 4,3 mode, also sawtooth triggered and likely to be an NTM, is seen reproducibly at lower β_N than the 3,2, but dying away as the 3,2 grows. This raises concerns for Next Step devices if mode control is required, which will be more difficult if several modes co-exist. Triangularity and elongation effects need investigation if the new RC-RTO-ITER is to adopt stronger shaping: very preliminary studies on JET showed a small fall in $\beta_{N-onset}$ as upper triangularity rose from .3 to .4, but a more complete study is necessary. The data from these experiments, including onset island size scalings, is being incorporated into new models being developed which incorporate seeding physics, to provide predictions for Next Step devices. Initial attempts with ICCD control failed to demonstrate an effect, although considerably more can be done to improve this scenario. Thus, recent progress in identifying the physics mechanisms, developing physics based fitting models and measuring onset criteria, provide optimism that this area is becoming well understood and Next Step behaviour will be predictable.

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