Neo-classical Tearing Mode Studies in JET

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Abstract. Studies of (3,2) and (2,1) Neo-classical Tearing Modes (NTMs) in JET are presented. The effects of plasma shape and edge safety factor (q_{95}) on the β-limits set by NTMs are addressed, as are results on the effect of ICRF heating. For the (2,1) NTMs initial comparisons with the β-limit thresholds from the DIII-D tokamak are presented.

1. Introduction

Neo-classical tearing modes (NTMs) are expected to limit the achievable fusion power in the ELMy H-mode regime for Next Step devices such as ITER. Previous studies [e.g. 1,2,3] have largely focused on the stability of the (3,2) NTMs (where the notation describes the poloidal and toroidal mode numbers, respectively). This mode is found to limit performance by causing a moderate degradation in energy confinement (~10 to 20%) and is found to have a threshold in normalised β, $\beta_n=2\mu_0<P>/<B>^2/(I(MA)/a(m)B_t(T))$, which scales approximately linearly with the normalised ion gyro-radius (ρ^*) for the present range of experimental parameters. Theoretical considerations suggest that this linear ρ^* scaling may weaken or reverse for sufficiently low ρ^* [4,5], though this has not been tested experimentally. While less studied, the (2,1) NTM is potentially more serious as it frequently leads to disruptions (or a termination of the discharge by the machine protection systems).

From a confinement viewpoint a way to improve performance is to increase plasma current. At constant toroidal field this can be achieved by lowering q_{95} or by increasing the plasma shaping (elongation and triangularity). Both of these methods of improving performance are being considered, or exploited, in the ITER-FEAT design and an issue is their effect on the β-limits set by NTMs; this issue is addressed in this paper. Another issue which is addressed is the effect on the NTM β-limits of the heating scheme and first results on β-limits in ICRF (Ion Cyclotron Resonance Frequency) heated discharges compared with solely NBI (Neutral Beam Injection) heated discharges are discussed. Finally initial results concerning the threshold for (2,1) modes in JET are discussed.

2. Effect of plasma shape on (3,2) NTM stability

A scan in plasma shape during 1999 examined the effect of increasing elongation (κ) and triangularity (δ) together, while year 2000 experiments have involved a scan in which it is largely the triangularity which is varied.

In these experiments solely NBI heating is used, and this is applied in progressive (~1MW) steps to slowly raise β, until a (3,2) NTM is destabilised. Since the density and temperatures tend to vary across these (3,2) shape scans it is necessary to correct for this variation to see the underlying dependence of the β_n-threshold on shape. One approach is to correct, using empirical scalings, to constant ρ* and ν*/εω*, which are the parameters used in Ref [4] (ρ* is the ion gyro-radius normalised to the minor radius, and the collisionality (ν*) is normalised by the inverse aspect ratio (ε) and electron diamagnetic frequency (ω*)). For JET the (3,2) β_n-threshold, for standard shape plasmas, scales as $\beta_n(3,2) \propto (\rho^*)^{0.7} (\nu^*/\varepsilon\omega^*)^{-0.11}$. Correcting the shape scan data in this manner and then making a linear fit to the κ and δ dependence of the (3,2) β_n-threshold shows that triangularity is stabilising and elongation is destabilising (Fig 1).

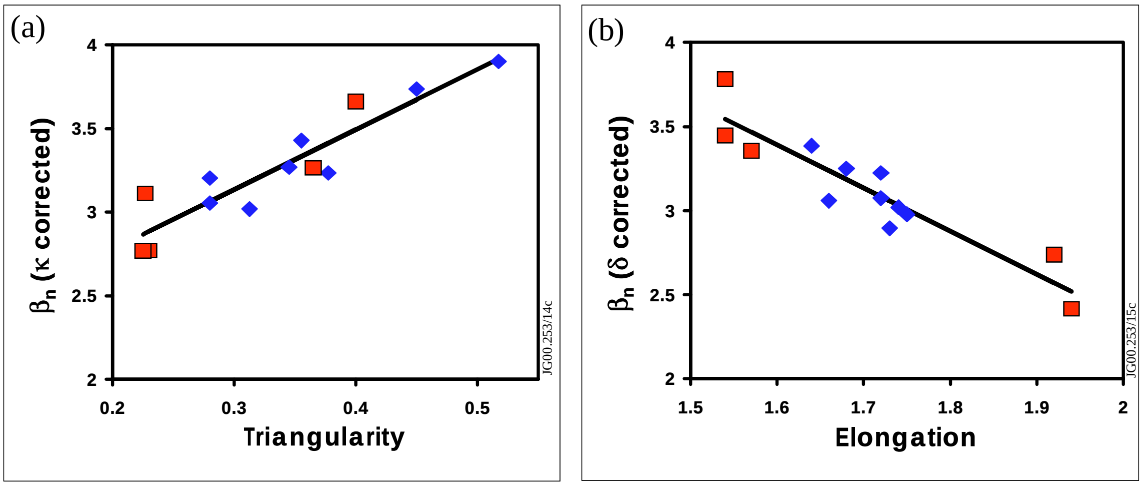

FIG 1 (3,2) β_n-threshold data corrected to $\rho^* = 8\times10^{-3}$, $\nu^*/\varepsilon\omega^* = 0.04$. (a) Triangularity dependence of the shape scan data corrected to $\kappa=1.7$ (b) Elongation dependence of shape scan data corrected to $\delta=0.3$. Red squares are from 1999 shape scan and blue diamonds from 2000 triangularity scan.

The choice of parameters to hold constant while examining the shape dependence of the NTM threshold is not well defined. In practice the objective of increasing the shaping is to increase the current at a given toroidal field and empirically it is reasonable to assume that the density is maintained constant relative to the Greenwald limit. Scaling the shape scan data to constant toroidal field and Greenwald fraction shows a rather weaker effect of increasing the triangularity.

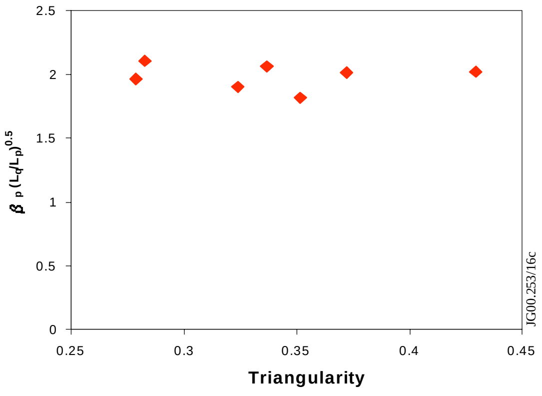

FIG 2 At constant ρ^*_θ the variation of the (3,2) NTM threshold with triangularity for κ~1.7, using local β_p, L_q and L_p at q=3/2.

While the above scalings give important information from the viewpoint of predicting the effect of plasma shape on operational limits, they do not directly address the underlying physics. Assuming the polarisation current sets the seed island threshold, then NTM growth is governed by [5]:-

$$\frac{\tau_r}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\left(L_q / L_p\right)\frac{\beta_P}{w}\left(1 - \frac{w_{pol}^2}{w^2}\right)$$

with, $w_{pol} \approx [g(\nu,\varepsilon)\ (L_q/L_p)\ \varepsilon]^{0.5}\ \rho_{\theta i}$. If we assume at onset that the seed island is a multiple of w_{pol}, $w_{seed}=Aw_{pol}$ (with $A>1$ for growth), then at NTM onset:-

$$(L_q / L_p)^{0.5} \beta_p = r_s \Delta' \rho_\theta^* \frac{A^3}{(1-A^2)} g(\nu,\varepsilon)^{1/2}$$

where ρ_θ^* is the poloidal ion gyro-radius, $\rho_{\theta i}$, normalised to the NTM minor radius, r_s. So the appropriate local parameters are $(L_q/L_p)^{0.5}\beta_p$,and ρ_θ^* assuming Δ' constant. At constant ρ_θ^* and $(\nu^*/\varepsilon\omega^*)$ the variation with triangularity of the threshold in $(L_q/L_p)^{0.5}\beta_p$ for (3,2) NTMs is weak, as shown in Fig 2. So triangularity has a modest effect on the underlying stability of the NTM, but this translates into improvements in the β_n-threshold due to profile changes.

3. Effect of q_{95} on NTM stability

As noted in the introduction the operating domain for ITER increases as the plasma current is increased at constant toroidal field (i.e. q_{95} is reduced). But an issue is how the NTM limit varies with q_{95}? Scans of the variation of the β_n-threshold with q_{95} have been performed for both (2,1) and (3,2) NTMs as shown in Fig 3.

It can be seen that there is a significant drop in the β_n-limit for $q_{95}<3$ for both the (2,1) and (3,2) NTMs. Also for $q_{95}<3$ locked modes and disruptions become significantly more likely when an NTM is destabilised. Similar results for the (3,2) NTM have been reported by ASDEX-U [6] and COMPASS-D [7]. The data in Fig 3 are the direct values obtained in the experimental scans. As discussed in Section 3 an empirically 'sensible' scaling is to hold the toroidal field and Greenwald density fraction constant; if this is done then there is quantitatively little difference to the results shown in Fig 3 (a similar conclusion arises from correction to constant ρ* and ν*/εω*). Thus the confinement benefits from higher current (lower q_{95}) can be eroded by the reduced NTM thresholds.

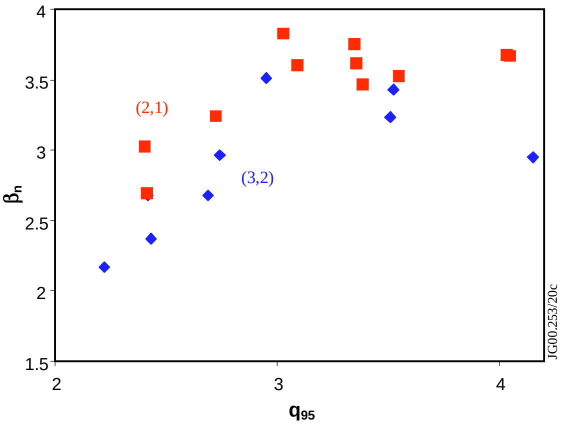

FIG 3 Showing how the β_n-limit for (2,1) and (3,2) NTMs varies with q_{95}.

4. Effect of ICRH vs NBI on NTM stability

A full scan of the effects of ICRH versus NBI heating remains to be completed. But initial results show interesting effects on NTM stability resulting from the larger sawteeth that centrally deposited ICRH can cause (Fig 4). The β_n-threshold for a (3,2) NTM in this case (~0.8) is very low. In local parameters the discharges with predominantly ICRF heating, and large sawteeth (central ΔSXR/SXR~40%) also have a much lower threshold, than NBI only heated discharges (Fig 5).

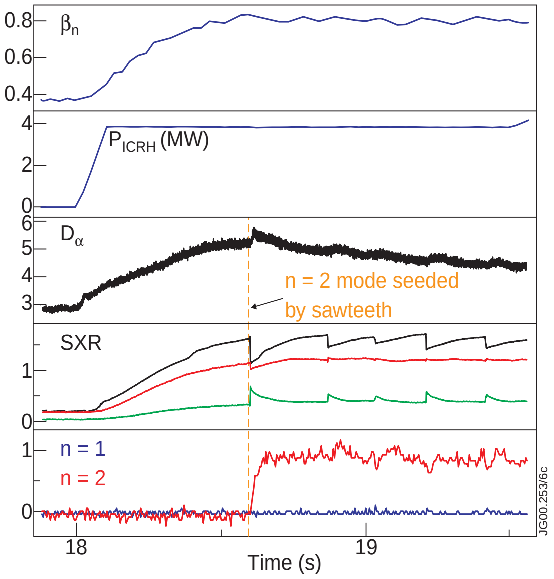

FIG 4 I_p=1.7MA, 2.7T ICRF only heated discharge (42MHz H-minority) in which a (3,2) NTM forms

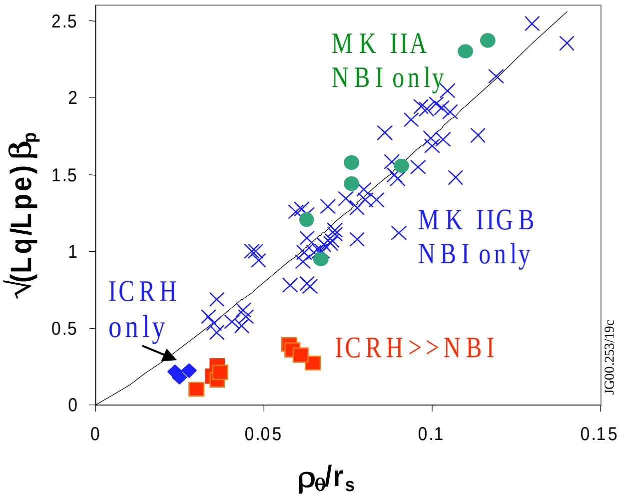

FIG 5 Comparison in local NTM stability parameters of the threshold for (3,2) NTMs in NBI only and predominantly ICRF heated discharges. Here β_p is the local value at the q=3/2 surface.

An interesting feature of these ICRH cases is that the island width tracks the diamagnetic-β with an apparent time delay of about 400ms. Calculations with the PION code [8] show this time delay is consistent with the time for the fast ions from the ICRF heating to thermalise, perhaps indicating that it is the thermal pressure which drives the NTM, though it should be noted on the same timescale that there is a transition to ELM-free H-mode and a sharp rise in density.

5. NTM studies for the m=2, n=1 mode

Recent experiments have extended the (2,1) NTM database on JET, which previously consisted of only a few pulses. A typical pulse is shown in Fig 6, where it can be seen that the formation of the (2,1) NTM is preceded by the occurrence of a (3,2) mode at lower β. In JET it is found (3,2) NTMs strongly suppress sawteeth, tending in general to preclude them as a seed for the (2,1) NTM. At q_{95}~3, with the available NBI heating power, it has only proved possible to form (2,1) NTMs for B_t<1.2T, which limits the range in ρ* that can be scanned; however, initial comparisons with DIII-D data show reasonable consistency in the results (Fig 7). The scalings are however somewhat different in JET and DIII-D - $\beta_p(local) \propto \rho_{*\theta}^{1.5}\nu_*^{0.02}$ in JET and $\beta_p(local) \propto \rho_{*\theta}^{1.02}\nu_*^{0.58}$ .in DIII-D.

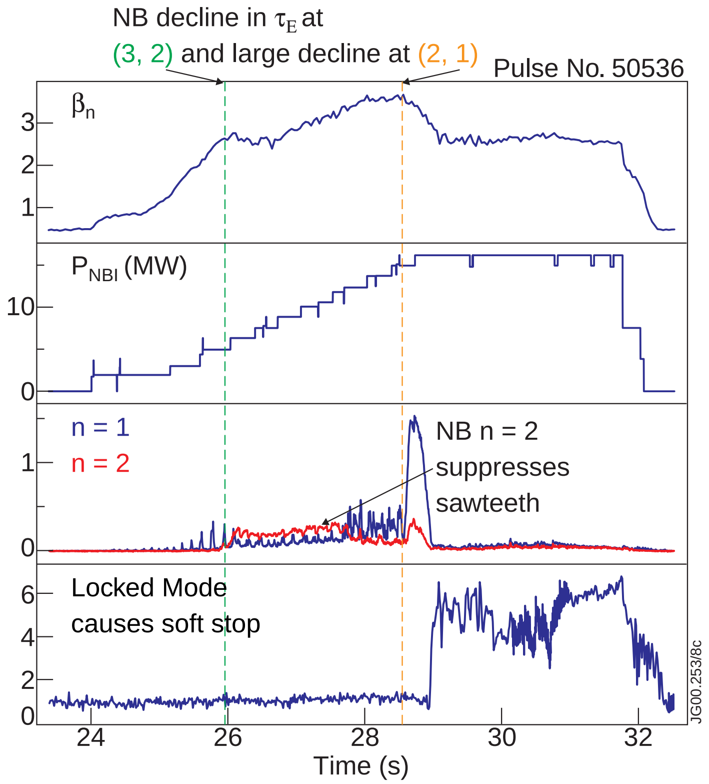

FIG 6 Typical 1T pulse in which a (2,1) NTM forms and grows rapidly into a locked mode.

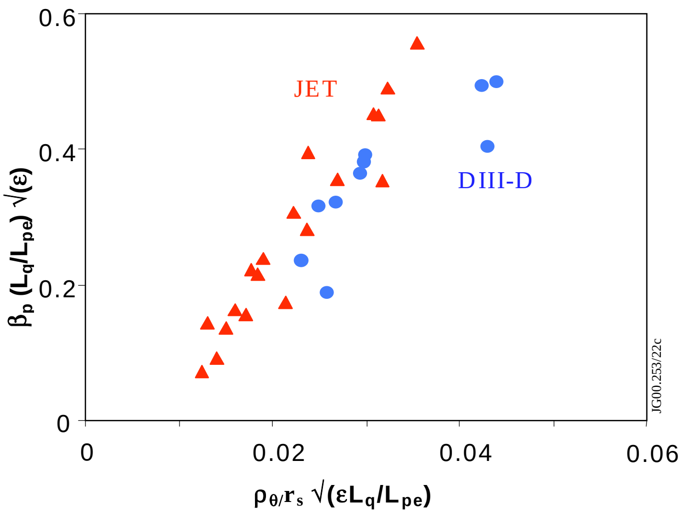

FIG 7 Onset of (2,1) mode in JET and DIII-D corrected to ($\nu^*/\varepsilon\omega^*$)=0.07

6. Summary

Many aspects of NTMs, which are important for ITER, have been studied on JET:-

- **Effect of plasma shape**. Increasing δ raises the β_n limit, while increasing κ lowers it at constant ρ^* and $\nu^*/\varepsilon\omega^*$; however in local parameters the effect is much weaker, indicating that the underlying change to NTM stability from changing the shaping is weak.
- **Effect of edge-q.** For q_{95}<3 the β_n-limit decreases, for both (2,1) and (3,2) NTMs, eroding the benefit of higher current operation, though there is a benefit from the increased density limit at higher current.
- **Effect of heating scheme**. ICRF heating studies indicate large sawteeth can more easily trigger (3,2) [and (2,1)] NTMs
- **(2,1) NTMs.** Systematic studies have just begun and further studies are needed to reconcile the cross machine scaling results.

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