Neoclassical tearing mode stability at low rotation and implications for ITER

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Abstract. The theoretical framework for dependence of Neoclassical Tearing Mode (NTM) stability on rotation is reviewed and tested against the latest developments in the experimental field. Theoretical models indicate a number of mechanisms through which rotation dependence is introduced, making this a critical parameters for extrapolation to ITER. Experimentally, a rotation dependence in NTM onset thresholds is identified for two types of NTM using a range of techniques on DIII-D and JET. Generally NTM thresholds are observed to fall significantly as rotation is reduced, and this is consistent with a number of mechanisms playing a role – such as decreases in magnetic shielding and changes to ion polarization current effects. For the most serious mode, the 2/1 NTM, β thresholds are observed to fall by a third as net momentum injection is removed from the plasma. Of theoretical interest is the observation that thresholds fall further as counter rotation and rotation shear is increased. In addition error fields are observed to lower thresholds, although on at least one device this does not act to induce locked modes, even at low plasma rotation. The form of behaviour suggests a significant role for the ion polarization current model, indicating that modest changes in island rotation could have strong effects on NTM stability thresholds. Further work is needed to quantify these effects better, and ascertain how they can be used to improve NTM stability.

1. Introduction - Issues and Impact of NTMs

A key issue for ITER is the extrapolation of the onset threshold and control requirements for the Neoclassical Tearing Mode (NTM) - the principal expected performance limit of both the ITER baseline and hybrid scenarios [1]. However, the behaviour of this instability remains challenging to understand, with many uncertainties in the theory governing behaviour, in particular to understand which theoretical models are dominant, and to quantify them. These difficulties are exacerbated in the prediction of ITER, which requires extrapolation in two key variables – ρ^* and rotation – that are fundamental to the behaviour of much of the underlying physics. Of concern is that ITER will operate at low ρ^*, where contributions from small island stabilisation effects will be reduced, and it will not benefit from the stabilising influence of high plasma rotation, driven by the strong neutral beam momentum injection used in most present devices.

The main elements of uncertainty come from the initial island triggering process (the ‘seeding’) and the NTM threshold physics. For example, if the seeding is due to magnetic coupling [2,3] then differential rotation between resonant surfaces would play a strong role in influencing NTM β threshold. But if islands appear due to a β related pole in delta prime [4], then mode thresholds would be less dependent on rotation and ρ^*. Variations in the underlying NTM drives can also contribute. For example, the commonly observed ρ^* scaling of NTM β thresholds [3, 5, 6, 7] arise from the mechanisms involved in stabilising the NTM at small island size [8, 9, 10]. But if these small island terms are dominated by ion polarisation current effects, then a strong dependence is also expected on island rotation in the ExB frame [11].

[*]*See appendix of M. L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu) IAEA*

In this paper we explore these issues, summarising in section 2 the status of the theoretical models, describing how the various ρ^* and rotation dependencies arise, and considering the implications for experimental behaviour. We then discuss the experimental observations in section 3, highlighting key recent results, in order to draw out the underlying physics mechanisms involved, and ascertain the implications for ITER. We present our conclusions in section 4.

2. Formalism

To understand how the various physical mechanisms combine to trigger an NTM, it is useful to consider the modified Rutherford equation, which governs the evolution of an island of full width, w and minor radius, r [12,13]:

$$\frac{\tau_r}{r}\frac{dw}{dt} = r(\Delta' - \alpha w) + r\beta_P\left[a_{bs}\left(\frac{0.65\,w}{w^2+w_d^2} + \frac{0.35\,w}{w^2+28\,w_b^2}\right) - \frac{a_{GGJ}}{\sqrt{w^2+0.2w_d^2}} - \frac{a_{pol}\;w}{w^4+w_b^4}\right] \qquad (1)$$

Here the NTM is driven by a helical hole in the bootstrap current [14] that develops about an island due to pressure flattening (the a_{bs} or 'bootstrap' term); this is dependent on the local poloidal β, β_p (with a small correction for field curvature [15], the a_{GGJ} term). Once triggered, islands rapidly grow (on a resistive timescale, τ_r) to a saturated size which to first order depends on the ratio of the bootstrap term to the classical tearing stability index (the $r(\Delta'-\alpha w)$ term, where the α introduces an island size dependence leading to saturation [16]), which by definition is negative at the onset of an NTM.

With just the above discussed terms, NTMs would grow from zero island widths in all discharges with positive shear at a rational q flux surface. However, the w_d, a_{pol}, and w_b terms act to make the NTM stable at small island size (and low β) leading to the requirement of a seeding event to induce a large enough island for bootstrap driven growth to take over. These small island terms are due respectively to the effects of ion polarisation currents (a_{pol} term) [8], finite transport over the island (w_d term) [9], and the loss of bootstrap as size approaches ion banana widths (w_b term) [10]. These govern both the threshold for the mode, and the requirements for its control. Most significantly they lead to a dependence of the NTM threshold β on normalised poloidal Larmor radius, ρ^*, which is expected to play a key role in the scaling of NTM physics towards ITER. They also lead to a metastability threshold for the mode – a β value below which the NTM is unconditionally stable, because the bootstrap drive is not strong enough to overcome stabilising Δ' and small island effects.

As an example, ion polarisation current effects can be characterised by [11],

$$a_{pol} \propto g(\nu,\varepsilon)\,(L_q/L_p)^2\,\rho_{i\theta}^2\;\;.\;\;\Omega(\Omega-\omega_i^*)/\omega_e^{*2} \qquad (2)$$

where 'g' is a function of normalised collisionality, $\nu=\nu_i/\varepsilon\omega_e^*$, with g=1 for ν<<1, and $g=\varepsilon^{-3/2}$ for ν>>1; ν_i is the ion collision frequency, ω_e^* (ω_i^*) is the electron (ion) diamagnetic frequency, and $\rho_{i\theta}$ is the poloidal ion Larmor radius (all quantities taken at the relevant resonant surface. This term also depends on the natural island propagation frequency (Ω) in the zero radial electric field frame of reference, which is hard to measure experimentally and hard to predict theoretically. Nevertheless, assuming the Ω term is constant and leads to a positive (stabilising) sign for a_{pol}, then folding Eq. (2) back into Eq. (1), neglecting w_d and w_b terms, and assuming a given 'seed' island size, $w=w_{seed}$, we can solve for marginal growth (dw/dt=0) to give a threshold for NTM onset in β_p, $\beta_{p\text{-}onset}$, which scales with ρ^*:

$$\sqrt{\frac{L_q}{L_p}}\,\beta_{p\text{-}onset} \propto -r_s\Delta' \, . \, \rho^*_{i\theta} \, . \, \frac{w_{seed}/w_{pol}}{[1-(w_{pol}/w_{seed})^2]} \, . \, g(\nu,\varepsilon) \qquad (3)$$

where $w_{pol}^2 = a_{pol} / (a_{bs}\, \varepsilon^{1/2}\, L_q/L_p)$ and $\rho_{i\theta}^* = \rho_{i\theta}/r_s$.

A key element this establishes is the link between the $\beta_{p\text{-}onset}$, and the seed island size at NTM onset. When w_{seed} is small, very high β_p is required for neoclassical growth, but as seed size increases the $\beta_{p\text{-}onset}$ falls, reaching a minimum at $w_{seed}=\sqrt{3}w_{pol}$.

A similar form can be obtained with the finite island transport model (w_d), as discussed in Refs [3] and [17], assuming a heat flux limited approach to allow for low collisionality [9], although in this case no rotation dependence is expected (with definitions as in [6]):

$$w_d = [\chi_\perp R_0 L_q / \mathrm{v}_e\, n]^{1/3} \qquad (4)$$

In some situations the distinction between the seeding and the NTM evolution can also become mixed – for example where high β leads to a pole in Δ', initiating *classical* island growth that is then driven further by the bootstrap term [18]. In these cases, the small island terms will still be important, in setting the degree to which β_N must rise in order to make Δ' sufficiently large to overcome the small island terms and trigger the tearing modes. This mechanism is thought to be significant where other seeding processes may be weak, such as in hybrid scenarios for the 2/1 NTM, where strong sawtoothing activity is avoided and coupling to other core activity will be weak due to geometric effects.

2.1. Role of rotation

Considering the above formalism we see rotation can enter into the behaviour in several ways:

1) Firstly there is an explicit dependence entering through the ion polarisation current term. This can have a strong effect, flipping the sign of the term to either drive or suppress tearing. But the significance of this effect also depends on how much the ion polarisation current mechanisms dominates over other small island size effects.
2) Then there is the issue of how the seed island is formed. In a magnetic coupling based model (eg toroidal [2] or three wave [19] coupling to core instabilities) the perturbation at the NTM resonant surface will be shielded out by differential rotation with respect to the applied perturbation (eg a sawtooth precursor).
3) In addition, the triggering instability itself may have a dependence on rotation, as is observed for the sawtooth instability [20, 21].
4) Changes in rotation can influence the Δ' directly due to changes in interaction between resonant surfaces [22] and rotation shear across the NTM resonant surface [23] – these effects will depend on differential rotation in the plasma.
5) Finally the interaction of a mode (particular if near the plasma edge, such as the 2/1 NTM) with the vessel wall may have a stabilising effect of the tearing mode.

These effects would also enter in different ways – dependent on absolute rotation, differential rotation, or rotation in a particular frame of reference. However, in most instances (except for the ion polarisation term) it can be seen that increased rotation would be expected to have a stabilising influence on the NTM. It is now useful to consider some recent experimental observations, in order to examine how the above formalisms may manifest themselves.

3. Experimental observations

3.1. Exploring the underlying physics of the modified Rutherford equation

A good extrapolation of NTM physics to ITER scales requires us to be able to identify and quantify the relevant physics terms. However, given the number of physics terms which remain relatively uncertain, isolating the necessary effects experimentally can be quite challenging and requires a number of techniques. The cleanest way to test elements in the modified Rutherford equations is by using controlled β rampdown experiments, comparing island evolution modelling based on Eq. (1) against experimental behaviour. This has been performed on a number of devices for the 3/2 NTM (for which steady and measurable island size behaviour is easy to obtain as β is ramped down), with steadily more sophisticated

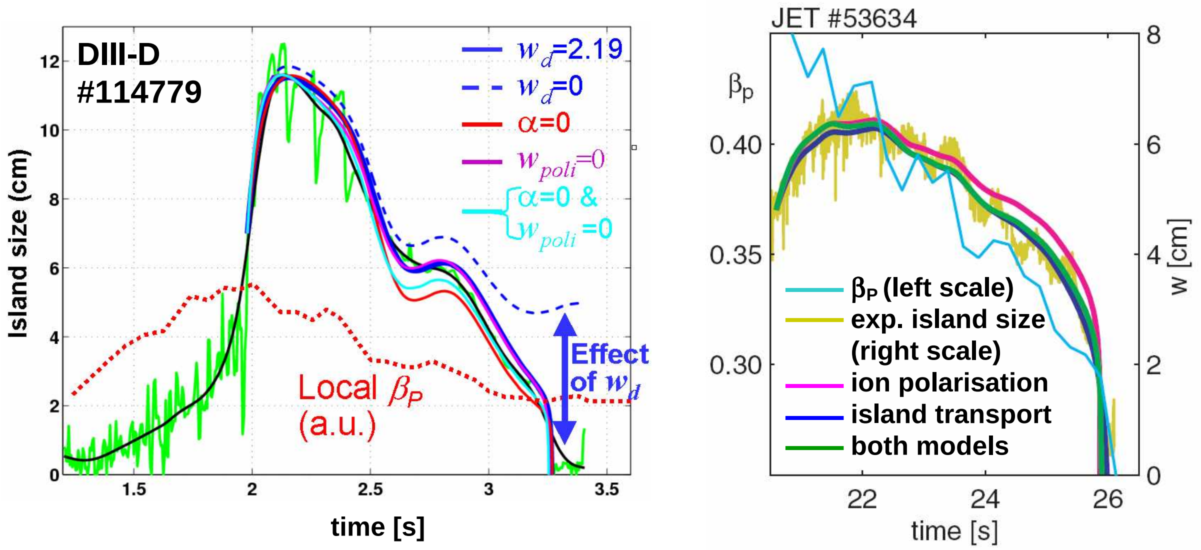

Fig 1: Experimental island evolution for DIII-D (left) and JET (right) in comparison to the modified Rutherford equation, based on a range of assumptions to test model dependency as described in text.

techniques [6, 24, 25, 26] – calculating more of the parameters based directly on the time evolving data, including more terms and using correctly motivated local parameters and full bootstrap current calculations. Examples for DIII-D and JET are shown in Fig. 1. The fit for DIII-D (left panel) shows the importance of including the small island terms to get a match to experimental data (green, or black for a smoothed version) at small island size. In the optimal fit (blue) we can sufficiently constrain parameters to obtain good estimates of $r\Delta'$=-2.9, $r\alpha$=10m^{-1} and w_d=2.19cm. The other curves show the effects of removing the ion banana term (w_{poli} which is w_b in Eq. 1) or the island size term, α. In the DIII-D fit, where ion polarisation currents were neglected, the island transport effects (w_d) were well constrained, with adjustments of a few percent leading to significantly worse fits. However, as we see in the right panel (this time taking a JET example), it is much harder to discriminate between the ion polarisation current (magenta) and finite island transport (blue) effects – either or both (green) can effectively give a fairly good model of the island evolution through the stabilisation point.

Thus we see that island evolution modelling has effectively reached its limit in being able to elucidate the underlying NTM physics. Good quantification of the major parameters can be obtained. But discrimination of the underlying physics models seems unlikely. We must therefore turn to other techniques. The key to this lies in exploiting the different parameter dependencies inherent in the models (Eq.'s 2 and 4). In particular the rotation dependence provides a key opportunity to discriminate between the models, and is an important parameter to explore experimentally, as ITER will have relatively little momentum injection.

3.2. 3/2 NTM rotation studies

Experiments exploring the rotation dependence have focussed on both the 3/2 NTM and 2/1 NTM – dependent on the tools and operational regimes most readily available. Turning first to the 3/2 NTM, which is easier to explore due to its more benign nature (it does not lock or cause disruptions, except at very low q_{95}), the JET tokamak has examined rotation dependence at mode onset. The first studies on these focussed on variation of momentum injection by substituting neutral beam injection (NBI) heating power with ion cyclotron resonant heating (ICRH). These yielded a clear result with 3/2 NTM thresholds falling dramatically as momentum injection was lowered (Fig. 2a). After correcting for the usual ρ^* dependence in the scaling a clear effect of rotation was still observed (Fig 2b).

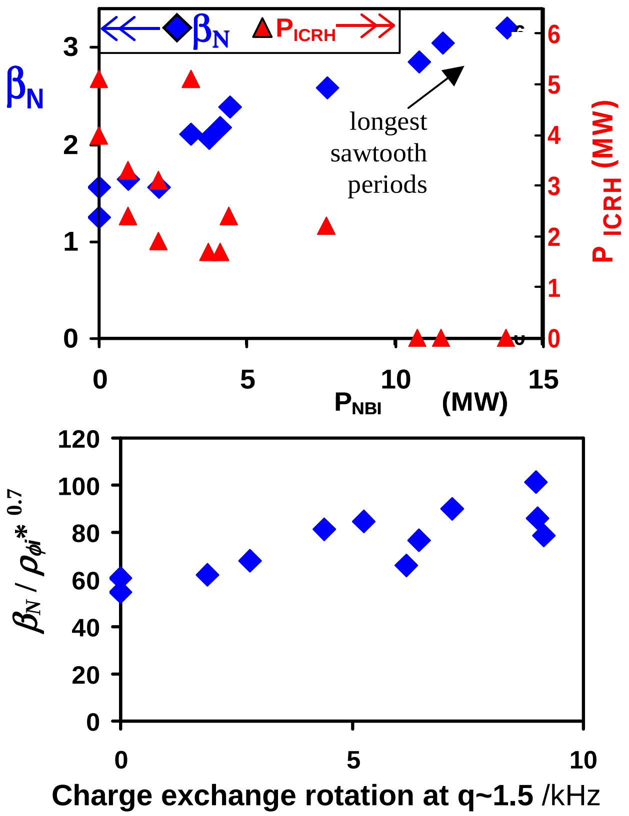

Fig 2: a) Upper panel – Change in 3/2 NTM threshold with NBI power (blue diamonds) and ICRH power levels (right scale, triangles). b) Lower panel - threshold variation relative to usual NTM scaling plotted vs rotation.

However, the use of ICRH raises some questions, as it introduces two additional considerations. Firstly ICRH is well known on JET to influence sawtooth period via a build up of sawtooth-stabilising populations of fast particles in the core, and this can in turn change the NTM thresholds [1,27]. Secondly the ICRH exhibits a different heating and fuelling profile to NBI. On the former point, this was addressed by adjusting the phasing of the ICRH scheme to '–90°' which acts to eject core fast particles. This succeeded in mitigating the stabilisation effect in terms of sawtooth period (Fig 3a), the parameter most linked with NTM threshold [1]. But there was still some variation in terms of amplitude of magnetic activity accompanying the sawteeth, although this was small compared to natural variation and somewhat outweighed by the trend to increasing magnetic amplitude as β_N was increased. However, the ICRH dominated discharges also had more peaked temperature

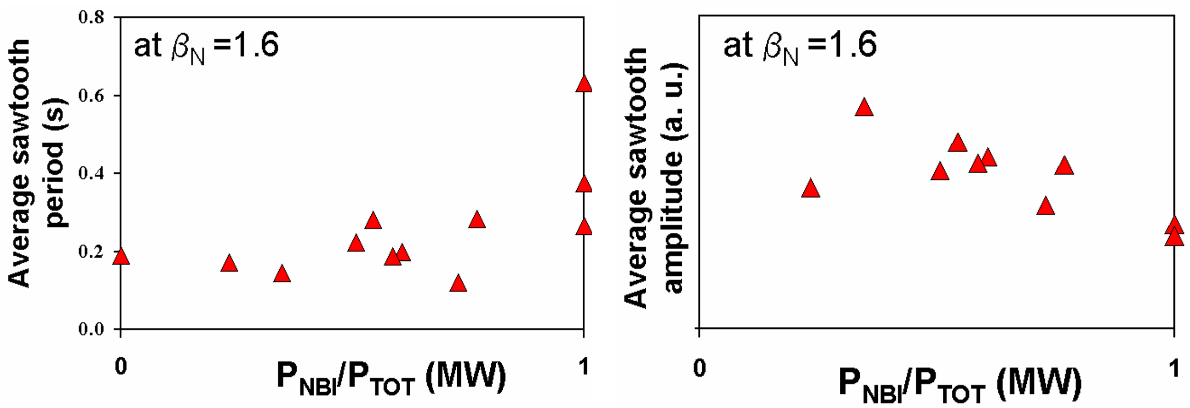

Fig 3:Variation in sawtooth parameters as discharges passes through β_N=1.6.

profiles. These concerns led to sufficient uncertainties to justify a further study to see if the apparently strong rotation effects were born out without this change in heating.

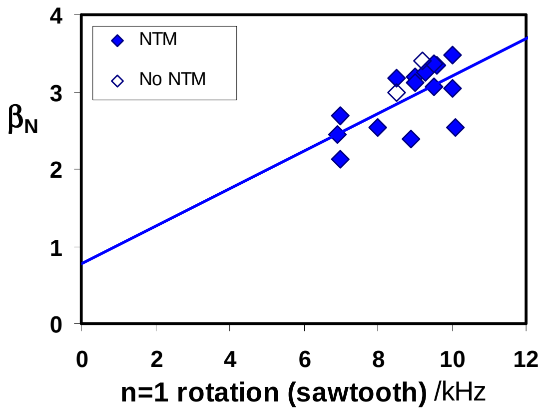

Fig 4: 3/2 NTM β_N thresholds on JET as NBI injector mix is changed to vary rotation.

A second series of experiments explored 3/2 NTM onset by changing the mix between different neutral beam injectors on JET. This exploited the fact that some NBI injectors inject in a more tangential direction than others, and so give more momentum to the plasma. A series of heating power ramp-ups was applied varying the mix of injectors. The results (Fig. 4 plotted against core plasma rotation taken from sawtooth MHD precursors) show a clear trend, with highest β_N (>2.7) thresholds all accessed only at high core rotation (>8.5kHz), However, NTMs can still occur at lower β_N values in this region. Careful analysis of data has yielded no particular differences in the phenomenology or parameters of these cases, and so the differences are attributed to the natural variation in NTM triggering.

These studies showed that rotation does indeed play a significant role in NTM onset, and that lower rotation is expected to lead to lower thresholds in devices with less momentum injection. Indeed, it is likely that for the 3/2 NTM on JET, which typically is associated with triggering related to sawtooth activity [1], rotation dependence originates with changes in the shielding between surfaces with different rotations. Thus while there are good indications of the role of at least one of the effects from discussion in section 2.1, the other elements remained unclear, and further studies were required.

3.3. More detailed investigation of rotation with 2/1 NTM studies

To progress further in understanding the underlying NTM physics, and also to address the mode of most serious concern for ITER, attention was turned to the 2/1 NTM. A first set of experiments was carried out on DIII-D and JET to explore the role of error fields. These act to brake the plasma magnetically at the resonant surface, potentially stopping rotation and driving tearing mode growth. Experimentally the surface of greatest concern for error fields is at q=2, where a tearing mode can substantially impact performance [28], while the poloidal mode number is low (m=2, making tearing relatively easy) and the surface is typically far out in minor radius (and so reasonably close to sources of error field which fall linearly towards the plasma core). The questions asked were: can this drive combine with NTM triggering processes to lead to lower thresholds for the mode? If so, then how does this act?

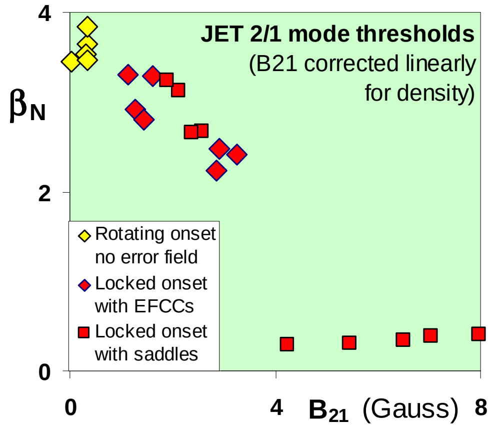

Fig 5: JET error field thresholds at various constant heating powers.

Experiments first utilised a series of β and error field ramps, raising one parameter, while the other was usually held constant. The results [29] showed a clear dependence, with 2/1 NTM thresholds lowered by the presence of error fields. However the most interesting aspect is in the detailed behaviour. In the JET cases (Fig. 5), any application of error field resulted in the mode being formed in a locked state as soon as it appeared. Thus these cases could be attributed to the 'usual' error field induced mode process, whereby the error field brakes the plasma and drives tearing directly. The interesting aspect for JET is that the plasma sensitivity to error fields has increased at medium to high β_N levels (>2), compared to that at low β_N values (<<1), as previously observed in high β_N RWM regimes [30]. In DIII-D a different behaviour is observed (Fig. 6). Here the thresholds are significantly lowered by error fields with the mode still born rotating.

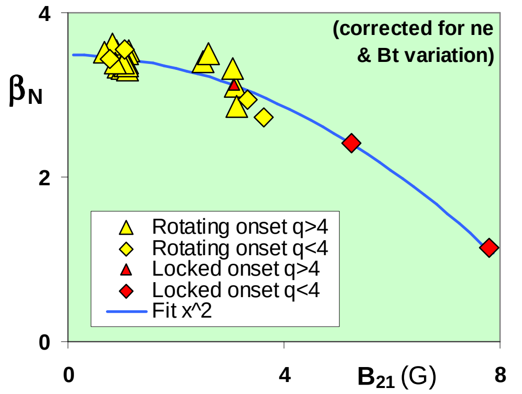

Fig 6: DIII-D 21 NTM β_N threshold as a function of error field applied.

The difference in the DIII-D behaviour is attributed to the harmonic spectrum which has much less m=1 field than JET, and so will brake the bulk plasma less, while applying a stronger q=2 resonant perturbation. However the DIII-D observations indicate a fundamentally different process to JET in which the initial seed island is not driven by the static error field but is responding to rotation changes. Considering the triggering process, we note that these 2/1 modes are not strongly associated with triggering MHD such as sawteeth or ELMs, but are instead more likely to be associated with changes to the classical tearing stability due to proximity to the ideal β_N limit [18]. Thus it is considered likely that the NTM onset is being influenced by changes in underlying NTM stability via the ion polarisation current term (or possibly wall effects). The first preliminary indication of this is shown in Fig 7, where a trend towards decreased mode rotation frequency in the CX frame is observed as error field is increased.

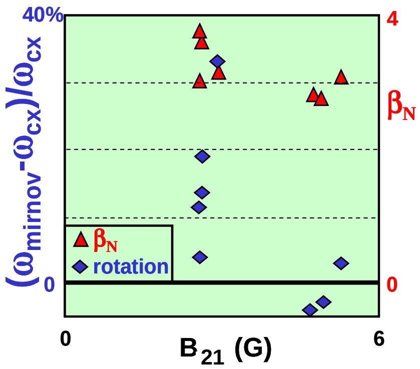

Fig 7: DIII-D mode rotation in CX frame (◆, left scale, taken as approximation for ExB rotation) for rotating mode cases of Fig 6 showing rotation trends towards zero as error field rises and NTM onset β_N falls (▲).

To explore these issues further, rotation was then varied directly on DIII-D using counter-beam injectors balanced with co- injectors to vary net momentum injection. The resulting scan (Fig. 8) yields a number of interesting observations. Of note for ITER is that without net momentum injection, 2/1 NTM thresholds fall by a third from β_N~3 to ~2. However, from the physics perspective, the interest lies in the detail. Firstly it is observed that with increasing torque in the counter direction (and also rotation – Fig. 9), NTM β_N thresholds do not rise, but actually fall further. In addition rotation shear across the core (Fig. 10) or in the edge region (not shown) correlate well with q=2 rotation. Thus the lowest β_N NTM thresholds do not occur at the lowest rotation or rotation shear, indicating that mode coupling type processes (to other instabilities or error fields) or Δ' variations due to rotation are not playing a role in NTM onset in this study, and that wall interactions (if present) must be weak.

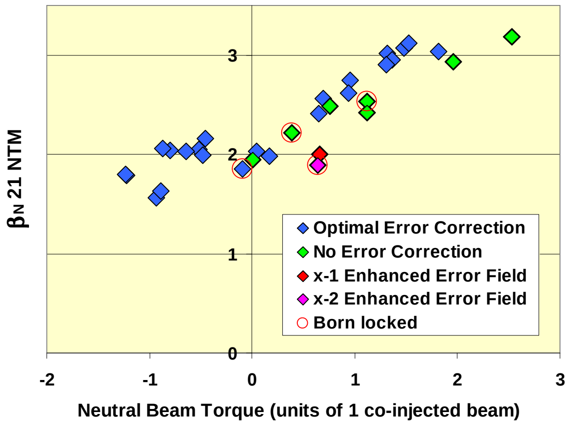

Fig 8: Variation in 2/1 NTM β_N threshold on DIII-D as neutral beam momentum is changed from net co to counter injection.

The role of error fields is explored further in Fig. 8, where error fields are progressively increased from optimal intrinsic error correction (blue) to no correction field (green) to enhanced error field (red, pink), although these fields were smaller than those applied in Fig 6. This shows only modest effect on NTM thresholds even when close to balanced injection, where the low natural plasma rotation would be expected to increase error field sensitivity. In addition, many of the modes are born rotating (e.g. Fig. 11) - again, even when beams are close to balanced injection. This confirms the conclusions from Fig. 6: that modest levels of error field do not act directly to stop plasma rotation and induce error field modes - their effect is more subtle, changing the NTM stability itself.

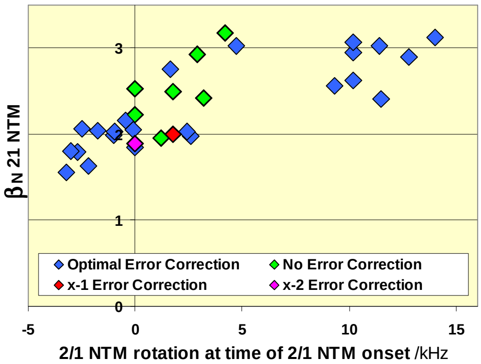

Fig 9: Variation in 2/1 NTM threshold vs mode frequency on DIII-D

For these discharges, well constrained reconstructions based on Motional Stark Effect current profile diagnostics confirm that current profiles do not change systematically as co- is substituted for counter-NBI. Thus having ruled out this and most aspects by which rotation may be influencing the NTM thresholds in these studies, this suggests that the rotation effect must principally be entering through the rotation dependence in the ion polarisation current terms. Rotation profiles from these experiments are now being explored in detail to test this hypothesis.

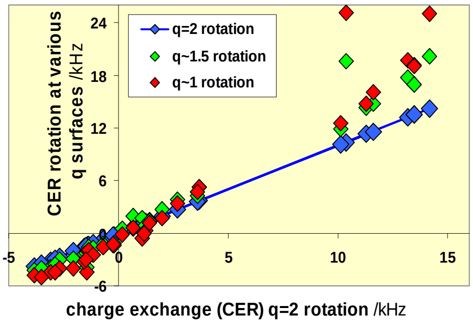

Fig 10: q~1, 1.5 and 2 rotation at times of 2/1 NTM onset on DIII-D (this is carbon rotation from charge exchange so has a small offset from actual resonant surface rotation).

4. Conclusions

In this paper we have explored the origins and manifestation of rotation dependence for the NTM, using experimental data to validate predicted behaviour, and discriminate between elements of the theory. We see that there are a significant number of ways in which rotation can enter into the NTM behaviour, and these would be expected to manifest differently in different situations. We have explored the application and limits of detailed numerical modelling for experimental interpretation, showing that while experiments can identify and quantify the role of small island effects, they cannot discriminate between different models for small island stabilisation, such as ion polarisation current or finite island transport effects.

Nevertheless, other aspects of NTM manifestation, and more imaginative experimental techniques, are beginning to identify the rotation mechanisms and consequences more specifically. For the 3/2 NTM, which is usually triggered by an additional instability, such as a

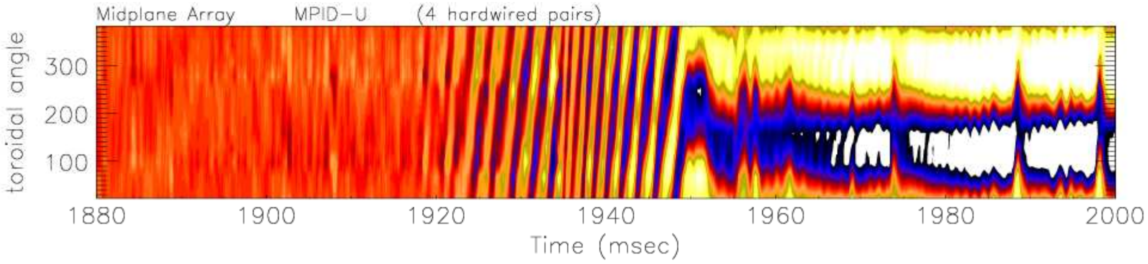

Fig 11: Onset of a slowly counter rotating NTM (430Hz) in DIII-D for shot 126689 with modest net counter injection (-0.45 units of beam out of 2.6 in total) and optimal error correction.

sawtooth, strong plasma rotation is thought to enter through shielding effects between triggering and triggered instability. Rotation thus plays an important role in keeping mode thresholds high. The study of the 2/1 NTM has revealed more subtle behaviour, with new results indicating that further effects such as the variations introduced through ion polarisation current effects (or possibly even new physics ingredients) play a major role. In addition the data raises serious concerns due to the low 2/1 NTM thresholds observed at low rotation.

These results point to two key conclusions. Firstly low rotation is seen to lead to lower NTM thresholds in all cases, compared to conventional co- NBI plasmas. Secondly the behaviour can be subtle and effects such as ion polarisation currents or error fields can have a strong influence on NTM thresholds. This leaves two principal tasks for the NTM community – to resolve which will be the important or dominant physical mechanisms governing NTM behaviour in ITER, and to quantify them.

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