

Neoclassical tearing mode stability at ITER-like parameters

R. J. Buttery¹, S. Coda², D. F Howell¹, A. Isayama³, R. J. La Haye⁴, D. Raju⁵, A. Sen⁵, E. Strait⁴, the DIII-D team⁴ and JET-EFDA contributors*.

¹EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB UK.

²Association EURATOM-Confédération Suisse, EPFL, CRPP, CH-1015 Lausanne, Switzerland.

³Japan Atomic Energy Agency, 801-1 Muko-yama, Naka, Ibaraki 311-0193, Japan.

⁴General Atomics, P.O.Box 85608, San Diego, CA 92186-5608, California, USA.

⁵Institute for Plasma Research, Bhat, Gandhinagar-382428, India.

Email contact of main author: richard.buttery@jet.efda.org

Abstract. New studies explore NTM scalings in the key parameters of extrapolation to ITER – rotation and ρ^* . Experiments show falls in both 3/2 and 2/1 NTM thresholds (denoting as *poloidal/toroidal* number) by about 1 unit in β_N as momentum injection is withdrawn. Behaviour provides insight into the underlying physics mechanisms governing NTM behaviour, suggesting possible roles for rotation shear and/or ion polarisation currents in governing tearing stability. A new cross-machine study explores ρ^* scaling for the performance limiting 2/1 NTM in the hybrid scenario, where high β_N access is a crucial requirement. Results raise questions, with a general fall in NTM β_N thresholds with ρ^* on two devices, but JET indicating improved stability. Possible origins of this discrepancy are discussed, together with overall implications for ITER and plans for further work.

1. Introduction – role of rotation and ρ^* in NTM scalings

Two crucial differences between ITER and most present devices are that it will not benefit from the stabilising effect of high plasma rotation driven by strong neutral beam momentum injection, and it will operate with considerably lower ρ^* . Theoretically, both of these differences are expected to lead to lower thresholds for Neoclassical Tearing Modes (NTMs). To understand this influence, it is instructive to explore the modified Rutherford equation for growth of an island of full width, w , using a simplified form to make the argument [1]:

$$\frac{\tau_r}{r} \frac{dw}{dt} = r\Delta' + r\beta_p \left[a_{bs} \frac{w}{w^2 + w_d^2} - \frac{a_{pol}}{w^3} \right] \quad (1)$$

Here an island is driven (on a resistive timescale, τ_r) to large amplitude by the helical hole it creates in the bootstrap current (a_{bs} term [2]), arising due to pressure flattening in the island itself. If unchecked, this effect would drive many islands to large size, overcoming their natural classical tearing stability ($r\Delta'$ term, which is typically negative). However, effects due to finite parallel thermal conductivity in the island (w_d term [3]) and also from ion polarisation currents (a_{pol} term [4]) act to give stability at small island size. Typically these effects scale with the ion banana width leading to a ρ^* dependence in the NTM stability.

The criteria for NTM onset depends not only on the balance between the physics mechanisms discussed above, but requires additional processes to either raise Δ' or induce a large enough initial ‘seed’ island to give positive growth. For baseline scenarios, where NTMs are often triggered by coupling to other MHD events (eg sawteeth), a linear ρ^* dependence is generally observed in the NTM β_N threshold [5 and references therein]. This is generally interpreted as the small island terms reducing with ρ^* , thereby lowering the β_p required for island growth (with a given seed size). These processes also provide many opportunities to introduce rotation dependence in the NTM onset. Reduced rotation shear across the plasma will increase coupling between a triggering instability and the NTM. The triggering instability itself may also depend on plasma rotation. Rotation shear at the NTM flux-surface may modify tearing

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stability, while the absolute rotation level will govern the stabilising effect of image currents in the vessel wall. Finally the threshold for NTM stability arising from ion polarisation currents is expected to be strongly modified by changes to rotation in the ExB frame. As the various effects depend on different measures of rotation or rotation shear, investigating this can help assess which physics processes are dominant. It is also important to understand the operational impact of the dependence for ITER. We explore rotation issues in section 2.

In contrast to baseline plasmas, in hybrid scenarios the principal limiting 2/1 NTM is hypothesised to be due to a positive pole (singularity) in Δ' as the ideal β limit is approached [6], explaining its growth from near zero amplitude. If true the ρ^* dependence of the NTM β threshold would be non-linear – close to the ideal limit at high ρ^* , but perhaps only falling slightly at lower ρ^* values. But if the usual NTM physics terms dominate (eg ELM triggering of NTMs, with threshold dictated by small island terms) then much lower limits might occur in ITER. Section 3 explores this issue; section 4 considers implications and further work. Plasmas used generally were close to the ITER shape (single null, similar elongations and triangularity) and q_{95} , although higher in ρ^* and rotation (except when beams were balanced).

2. Rotation dependence of NTM β threshold in JET and DIII-D

New experiments have been performed to explore rotation dependence by varying neutral beam (NB) momentum injection. Experiments on JET focused on the 3/2 NTM, for which the operational range in momentum input is widest. These studies followed previous work [7] substituting neutral beam injection for ion cyclotron heating (ICH) which indicated a strong trend, with β_N thresholds falling from ~ 3 to ~ 1.4 as momentum injection was removed. New fitting and correction for ρ^* variation (using an NBI-only fit [8]) yields the underlying rotation dependence at constant ρ^* as: $\beta_N = 2.03 + 0.10f_{core}$, where core rotation, f_{core} (kHz), was 10kHz in NB only plasmas (Fig.1). However, the use of ICH heating led to some changes in pressure profiles as well as a modest influence on sawteeth (though ICH was phased to avoid sawtooth stabilisation). Thus a new scan has been performed using NB only, by varying the mix between beams of different injection angles. Using this technique up to 40% variation in momentum injection and rotation can be achieved, resulting in a $\sim 30\%$ variation in NTM thresholds. Again, this data must be corrected for ρ^* dependence where, encouragingly, a two dimensional fit in rotation and ρ^* yields a $\rho^{*0.76}$ dependence, consistent with previous NTM database fits. This ρ^* dependence itself accounts for about half the rotation variation in the scan (higher ρ^* is accessed with more NB power and so increased rotation). The remaining rotation dependence (Fig.2) can then be parameterised as $\beta_N = 2.19 + 0.10f_{core}$, similar to that found in the ICH scan. Thus both scans appear consistent with momentum injection from the beams raising 3/2 NTM thresholds by about 1 unit in β_N .

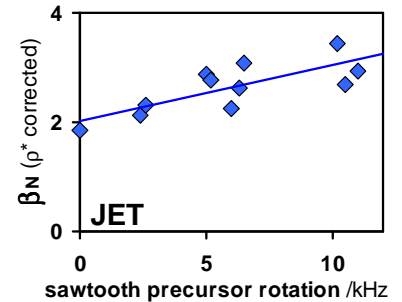


Fig.1: 3/2 NTM threshold variation in ICH:NBI scan.

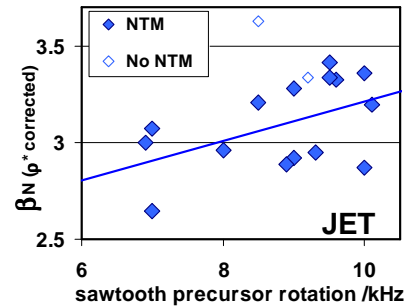


Fig.2: 3/2 NTM β_N threshold variation with NB momentum.

Turning to the 2/1 NTM, previous studies on JET and DIII-D had already indicated a possible rotation dependence through the influence of error fields in lowering 2/1 NTM thresholds [9]. New scans were launched using DIII-D's unique capability to mix co and counter beam injection in ITER relevant high β configurations and assess β limits. Beams were ramped to trigger the NTM at various rotations, with MSE EFITs indicating little current profile

variation due to the different beam mixes. This yielded a strong rotation effect on the 2/1 NTM with β_N thresholds falling by about 1 unit as co-injection momentum was withdrawn (Fig.3) and rotation reduced (Fig.4). Various levels of error field were also applied, ranging from optimal intrinsic error correction (blue) to no/reverse/2 x reverse correction (green/red/pink). Encouragingly, the effect of error fields is modest even at low plasma rotations, being similar in its influence to studies with purely co-NB plasmas [9]. Indeed, most modes are formed rotating (the non-circled points) indicating that even at low rotation the process is not one of error field penetration (which would drive locked modes). This suggests that there is not an enhanced sensitivity to error field modes at low rotation, as might be expected theoretically.

Of considerable interest is that thresholds do not rise (and perhaps fall further) as net counter-torque and counter-rotation increases. This is contrary to expectations if the wall were playing a strong role. Rotation shear between rational q surfaces also rises as counter injection is increased (Fig.5) suggesting core modes are not playing a role in the seeding (as this would raise thresholds with shear). Local rotation shear at $q=2$ (Fig.6) also increases roughly in proportion to rotation. However, while this might naively be expected to make tearing harder in both co and counter directions (effectively trying to shear the island structure, which would raise thresholds in both direction), recent theoretical work [10,11] predicts an effect on Δ' that depends on sign and magnitude of rotation shear, and so may explain the β_N scaling. DIII-D saturated 2/1 mode sizes also indicate a possible dependence on rotation shear, potentially confirming this role. Further analysis is exploring the issue in more detail, as well as other possibilities such as changes in ion polarisation currents due to variations in rotation in the ExB frame.

3. ρ^* dependence in hybrid scenario

In separate studies the β limit to the hybrid scenario, which originates from a 2/1 NTM, has been explored. This is key to the viability of the hybrid, which relies on access to high β_N . Data was taken from DIII-D, JT60-U and JET, with heating power, and so β_N , slowly ramped until a 2/1 NTM was encountered. Data was limited to $q_{95}=4-5$ and triangularity $\sim 0.3-0.5$, although elongations ranged $\sim 1.4-1.8$ and inverse aspect ratio $\sim 0.24-0.35$, with JT-60U at the low end of the latter two parameters. The results are plotted in Fig. 7. The 2/1 NTM unstable points

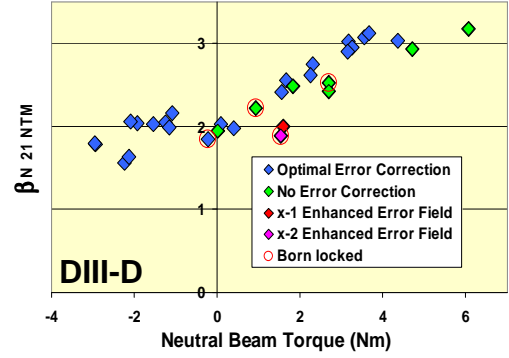


Fig 3: Variation of 2/1 NTM threshold as beam mix is varied from net co- (+ve x) to net counter- injection (-ve x).

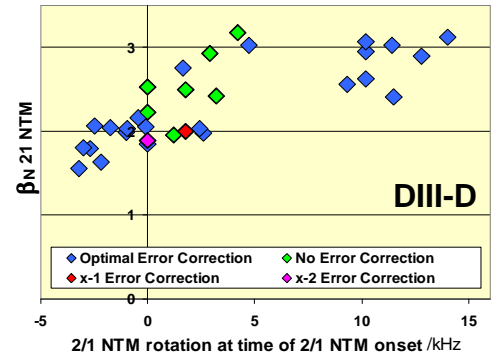


Fig 4: Variation in 2/1 NTM threshold vs mode frequency on DIII-D

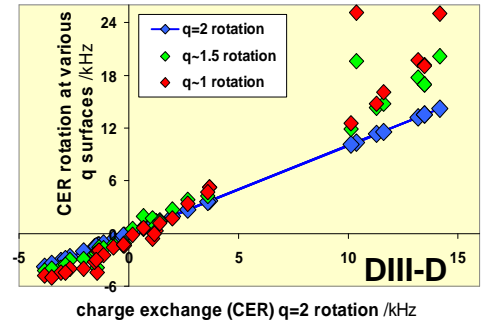


Fig 5: $q \sim 1, 1.5, 2$ carbon rotation (from charge exchange) at 2/1 NTM onset.

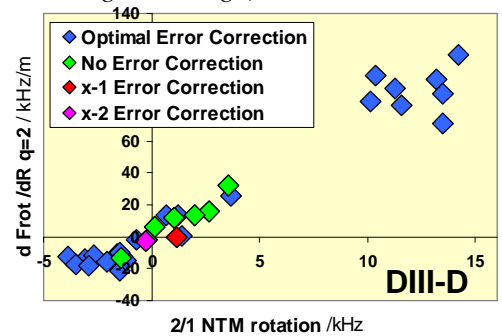


Fig 6: Toroidal rotation gradient at $q \sim 2$ (carbon) at 2/1 NTM onset.

indicate a ρ^* scaling, which possibly saturates in the DIII-D data, as β_N reaches the empirical ‘ $4l_i$ ’ estimate of the ideal β_N limit (at $\beta_N \sim 3.2$), corresponding to a pole in Δ' [6]. But for JET, no limiting instability was encountered, despite it accessing higher β_N than the other devices. The origins of this difference are now being explored, with attention focusing on three elements. Firstly, the non-thermal populations are significantly higher on JET than DIII-D – thermal β_N may be the governing physics parameter (though this does not seem consistent with the Δ' poles model). Variations in current profile and rotation are being explored. And it is possible that a higher magnetic Reynolds number on JET may change the seeding physics. The resolution of this issue is critical to extrapolating 2/1 NTM β limits for ITER hybrid regime.

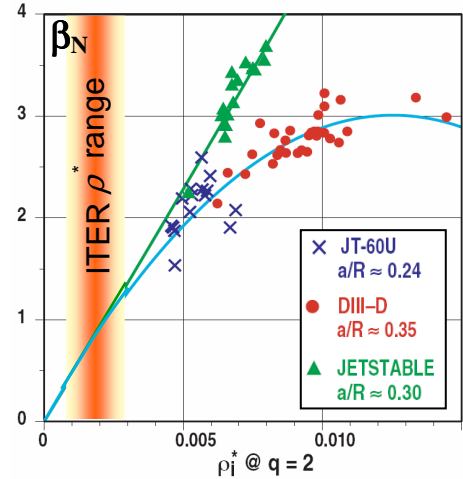


Fig 7: 2/1 NTM hybrid β_N limit (and JET stable points) cross machine scaling.

4. Discussion, implications and further work

Investigations of the most critical parameter scalings for NTM onset in ITER have been made. For the baseline scenario, rotation dependencies have identified a substantial lowering of 2/1 and 3/2 NTM thresholds by about 1 unit of β_N from ~ 3 to ~ 2 . This suggests that without significant momentum injection, NTM thresholds on ITER will be significantly lower than in present devices. Whether there is a further lowering of thresholds with ρ^* remains a key question, which depends on understanding better the triggering process and its likely scaling, particularly for the 2/1 NTM. For the hybrid scenario, for which high β_N access is crucial to performance, the 2/1 NTM β_N scaling remains uncertain, with conflicting evidence between the devices. For both regimes it remains possible that the 2/1 NTM is associated with proximity to ideal stability limits, and so remain limited to high β_N at ITER ρ^* s (provided large sawteeth are avoided), or is governed by NTM threshold physics which scales with ρ^* to give lower β_N thresholds for ITER.

These studies are helping to discriminate the underlying physics and identify which are the significant mechanisms. For the 3/2 mode it is likely that variations in shielding between triggering MHD and resonant surfaces accounts for the principal variation. For the 2/1 rotation dependence, the process is more subtle, and appears to depend on local properties at the $q=2$ surface. Further work is underway to analyse this, focusing on rotation shear (for Δ' influence) and ExB rotation (to identify ion polarisation current effects). The additional studies proposed in section 3 will also help understand the governing physics for the 2/1 hybrid NTM.

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