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Multimachine Extrapolation of Neoclassical Tearing Mode Physics to ITER

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ABSTRACT.
New data and inter-machine comparisons are presented exploring the role of rotation, ρ* and error fields in governing tearing mode β limits. It is found that conventional aspect ratio tokamak β_N limits due to 2/1 tearing modes fall from values in excess of 3 with the usual strong neutral beam torque injection, to ~2 in low torque plasmas for ITER-like baseline scenarios. The fractional rates of fall in β_N limits with rotation Mach number seem broadly consistent between tokamaks (including spherical tokamaks), and indeed also with onset thresholds for 3/2 NTMs in the conventional tokamak (all extrapolate to fall by about 1 unit in ≤N for complete withdrawal of co-injected torque). Analysis of the detailed behaviour suggests an action through changes to the rotation shear impacting the intrinsic stability of the tearing mode, and further, that this is not through so called NTM 'small island' effects, but is more likely due to modifications of the classical tearing stability parameter, Δ′. In addition, an enhanced error field effect has been observed at and below the ITER baseline β_N~1.9 (well below the ideal β limit, where such effects usually manifest), whereby modest levels of error field can assist 2/1 mode formation, particularly at low rotation or when the natural tearing instability β threshold is approached. Nevertheless, ITER baseline-like scenarios are found to be just stable, provided there is good error field correction. Turning to ρ* dependence, previous databases for the metastable threshold for the 3/2 NTM have been extended, with new data from JT-60U at low ρ* confirming that ITER will operate well above this threshold and so be susceptible to NTM triggering events. A new database constructed for the 2/1 NTM β_N limit in hybrid scenarios indicates ρ* effects can be dominated by variations from other parameters, such as q profile shape or fast particle content. These results are of high significance for the extrapolation to ITER, indicating that the expected trends of NTM theory do indeed manifest towards increased tearing mode susceptibility, but that ITER-like scenarios remain stable at the necessary operating points (e.g. in β_N). However they also show that the mechanisms by which the key parameters act to change the stability (e.g. through changes to Δ′) leave the door open for further control techniques through the manipulation of plasma profiles.

1. INTRODUCTION

If unmitigated, Neoclassical Tearing Modes (NTMs) act as the principal ≤ limit to ITER-like baseline and hybrid scenario H mode plasmas [1]. However, the extrapolation to ITER is subject to key uncertainties in the physics mechanisms, and in particular the role of three key parameters – rotation, error field, and ρ* (the local resonant flux surface value of ion poloidal Larmor radius, normalised to resonant surface radius). Addressing these issues is crucial because most present devices operate with high ρ* and rotation compared to ITER (parameters that are expected to help stabilise NTM physics), while the influence of error field effects in NTM relevant regimes remains relatively un-researched. New work is reported in this paper that explores for the first time, rotation scaling down towards ITER relevant levels, and compares trends between different devices and NTM types. The role of error fields in further influencing this behaviour is then examined. Finally, cross-machine databases for ρ* scaling have been extended towards ITER and into new plasma regimes.

To understand the critical questions, and to set a context for the ensuing results and their discussion, it is useful to briefly outline the main physics concepts governing NTM behaviour. The full formalism and references are provided in [2], from which we provide a simplified picture here. NTM behaviour can be described in terms of the growth rate of a magnetic island (size, w) due to various drives and sinks, via the modified Rutherford equation:

$$\frac{\tau_r}{r}\frac{dw}{dt} = t\,\Delta' + r\beta_p\, w \left(\frac{a_{bs}}{w^2 + w_d^2} - \frac{a_{pol}}{w^4 + w_b^4}\right) \qquad (1)$$

Here the island is driven by a helical hole it generates in the bootstrap current (abs term), overcoming the intrinsic classical tearing stability usually observed at low β_N (Δ' term, usually negative at low β_N). Further effects act to prevent island growth becoming ubiquitous, by stabilizing the mode for small island sizes – these are the terms in wd, representing the incomplete flattening of pressure gradients in small islands, and in apol, representing the generation of ion polarisation currents when islands are comparable to the ion banana width.

These simple mechanisms introduce the main effects that make extrapolation to ITER uncertain. Firstly the small island effects (when Δ' is negative) introduce the need for a triggering perturbation to drive formation of a large enough island for NTM growth. Both terms discussed act on the scale of the ion banana width, $\sqrt{\varepsilon}\,\rho_{\theta i}$, and so would seem to impart a strong (linear) ρ* dependence to the NTM physics. However, the translation of this into NTM onset threshold scaling is less clear theoretically, as this requires magnetic coupling to a second instability to drive the island up in size and overcome the NTM threshold physics - the size and coupling of this triggering instability might also vary with β, ρ* or magnetic Reynolds number. Alternately, if NTM onset arises from variations in underlying tearing stability (such as through Δ'), it is not clear that a strong ρ* dependence would emerge at all.

The other main element these terms introduce is a strong dependence on rotation. For example, if the seeding occurs by coupling to secondary instabilities, then differential rotation between the relevant surfaces plays a strong role in shielding out the perturbation and raising mode thresholds. Rotation may also govern the triggering instability (such as the sawtooth), or change the stability of the NTM itself – e.g. through interaction of the mode with the plasma wall or error fields, or through changes to the island structure (arising from sheared rotation) affecting its energetics (and– Δ') [3,4]. Finally the threshold physics from the ion polarisation current depends on how the island propagates relative to the ion fluid, potentially varying both its size and sign [5]. Related to these effects is the role of error fields – asymmetries in the magnetic field of a tokamak that naturally arise in its design and construction. These act to brake plasma rotation, and drive island formation. The fields are shielded out in most present devices by fast plasma rotation arising from strong torque injection. But in lower rotation devices thresholds are expected to fall [6] as the resonant surfaces can be stopped more easily.

Thus it is important to assess the role of these effects as we move towards ITER parameters. The form of the observed behaviours depends on, and so informs about, the mechanisms involved in the NTM physics and its extrapolation to ITER. The following sections now explore these issues in turn to look both at empirical trends and the underlying physics.

2. ROTATION

Experiments were undertaken to study rotation effects on a number of devices, deploying a variety of mechanisms to vary the plasma rotation. In each case heating power, and so plasma β, was usually steadily increased until a mode was encountered. Both 2/1 and 3/2 modes were studied; we commence with the 2/1 NTM as it has the most serious consequences, usually leading to large confinement falls, locked modes and disruptions.

For the 2/1 NTM, experiments were conducted on three devices; on DIII-D and JT-60U rotation was changed by varying the mix of co- to counter injecting neutral beams, while on NSTX magnetic braking with resonant fields was deployed. DIII-D utilized ITER baselinelike lower single null H mode scenarios with q = 1 activity (usually sawteeth) present, although with raised safety factor (q_{95}~4.4 compared to the ITER baseline value of ~3), in order to keep the mode rotating and enable its study. JT-60U plasmas had a slightly higher aspect ratio (~4 rather than 3) and lower elongation, although they were generally operated at similar q_{95} and triangularity to the DIII-D experiments. As is natural for a Spherical Tokamak (ST), NSTX operates with higher q_{95} and β_N, and much stronger shaping, but serves as an important check on the nature of the physics and trends.

The results, in Fig.1, show a pronounced dependence of the NTM β_N limit on rotation. To enable cross machine comparisons, we normalise rotation velocity to Alfvén velocity (characteristic for field line bending) to obtain the Mach number. Part of the DIII-D results were published earlier [2] but have since been extended in the counter direction, using reversed plasma current operation to clarify trends. Due to the differing geometry and stronger field curvature effects in the ST, the NSTX results might not necessarily align with conventional tokamak onset β_N, but here only a geometrical factor is used to allow for the larger ratio between volume average field β_N and standard β_N in the ST. A number of points emerge. The most important result is the fall of about a third in the β_N limit due to 2/1 tearing from the usual co-injection operation in DIII-D (right most triangles), to the low rotation plasmas with near balanced beam injection. The JT-60U data seems to confirm the low absolute value of 2/1 NTM β_N limit at low rotation. Interestingly, both DIII-D and JT-60U indicate the fall continues as rotation increases in the counter direction – rotation is not simply stabilising for tearing modes; a more subtle effect is at play (note the DIII-D Mach number is based on actual mode rotations, so is not simply explained by a diamagnetic offset due to island propagation in the fluid). Finally, at high rotation, NSTX data shows that a similar scale of effect to DIII-D (in terms of percentage change in – β limit per Mach number) occurs in the spherical tokamak. These data raise many physics questions, which are important to explore in order to understand the implications for extrapolation and control in ITER. Investigation utilising the complementary capabilities of different devices can assist here:

Exploring trends in local parameter for the DIII-D data (Fig.2) confirms that the threshold in terms of the NTM bootstrap drive [7] required to trigger the mode is significantly reduced at low rotation. However, the increased noise introduced in such calculations no longer resolves the trend so clearly within the low rotation region. Nevertheless, extended analysis of the local parameters indicates that the plasma profiles remain broadly constant over these shots, with core MHD and/or MSE indicating q=1 presence, and q=2 radii and kinetic profile parameters found to be similar. This therefore suggests that the continued fall in β_N thresholds as counter rotation increases in Fig.1 is a real effect in terms of tearing mode drives (rather than simply a consequence of profile variation), posing a challenge for theoretical interpretation – rotation is not simply stabilising to tearing; the sign also matters.

To resolve the underlying physics mechanisms, it is important to identify which measure of rotation (or rotation shear) governs behaviour. One possible explanation of the asymmetry in Fig.1, is that ion polarisation currents play a role (which depend on sign and size of island propagation relative to the E×B rotation). However, Ref. [2] found no corresponding trends in the relevant parameters [5,7] for this model for DIII-D, while NSTX similarly sees a lack of correlation in the relevant island propagation parameter (Fig.3). This suggests variation in ion polarisation currents (and the ion polarisation current mechanism itself) is not dominant in setting the 2/1 tearing onset β.

Further insight can be gained by exploring the form of the rotation effect. From the discussion in section 1, a rotation shear dependence would indicate a local effect directly influencing the island energetics and so its stability. Conversely, dependence on rotation value or rotation difference indicates a role involving other parts of the plasma or vessel and so additional physics mechanisms governing behaviour (coupling to other modes, the wall or error fields). However, in the D3D data there is a near monotonic relation between rotation and rotation shear. Thus an analysis only slightly favours rotation shear in terms of improved correlation of β_N or bootstrap drive with rotation measure.

However in NSTX much greater variation is achieved (e.g. Fig.4, where different trigger mechanisms are also distinguished), in part by the application of different types of error field (n=1 and n=3 which brake and resonate differently in the plasma) but also due to a naturally greater range of rotation profiles. As a result, a local parameter analysis can determine the critical rotation measure. Thus in Fig.5, it can be seen that for any single trigger mechanism, the correlation is poor with rotation (5a), but much better (5b) with the Alfvén normalised rotation shear quantity of ref [2] (note correlation coefficients, r^2, are given in the plots for each, and all, triggers).

Returning to the DIII-D data, it was already observed in Ref [2] (and further borne out by the extended data set here) that NTM β thresholds fell while rotation, rotation shear and differential rotation between resonant surfaces increased in the counter direction. This tended to rule out magnetic coupling to other parts of the plasma or vessel as playing a substantial role in 2/1 mode onset (such couplings would weaken as the magnitude of rotation differentials increased, and so raise thresholds). This in turn suggests that the rotation role arises from changes to the intrinsic island stability, a picture that is now consistent with the above NSTX-related deductions that rotation shear is the more likely governing parameter for the NTM threshold. Given the lack of other possibilities, it seems most likely that this effect is due to changes in the classical tearing stability, Δ' of an island arising from the rotation shear. This poses some concern, in that it suggests islands will be larger with less rotation shear, as well as having lower thresholds. It may go some way to explaining why 2/1 tearing modes have more severe effects and become disruptive when they lock. However, explaining the sign dependence in the onset data (the asymmetry about x = 0 in Fig.1) still remains challenging, with most theories to date [3, 4] expecting a symmetric effect.

It is interesting to see if the same trends apply to the 3/2 NTM, both to further test these physics mechanisms, and to understand the implications for this confinement reducing mode. Previous studies [8] had shown a fall of about 1 unit in 3/2 NTM β_N thresholds (after correcting for a ρ^* dependence) when beam heating was substituted by Ion Cyclotron Resonant Heating (ICRH) on JET. However, this change in heating led to changes in profile and sawtooth behaviour (which were triggering these 3/2 modes), and so the experiment has recently been repeated by simply varying neutral beam injection angle. The results (Fig.6) project out to the same dependence observed for the ICRH scan, showing that 3/2 NTM thresholds do fall as torque is withdrawn. However the mechanisms by which rotation acts are still open, with some element expected to be due to changes in the coupling between sawtooth and NTM resonant surfaces.

Is the underlying intrinsic tearing stability also changed, as for the 2/1 mode? To explore this question investigations of saturated 3/2 mode behaviour were undertaken on DIII-D, where it was observed (Fig.7) that switching from co-injected to balanced neutral beam torque led to a large rise in 3/2 mode amplitude as mode rotation and its shear fell. To explore this in more detail, further studies were performed utilising the DIII-D beam mix experiments of Fig.1, which usually produced a 3/2 mode before 2/1 onset. 3/2 mode amplitudes were measured and a variant of Eq.1 (neglecting small island terms, and setting $\dot{w} = 0$) was used to calculate Δ' values consistent with mode saturation. The results (Fig.8) show that the size of $r\Delta'$ value (which is stabilising, being the negative of the y-axis value plotted) falls as flow shear is reduced indicating decreased tearing stability. This shows that 3/2 tearing modes will (like the 2/1 mode) intrinsically be less stable and larger at lower rotation shear.

3. ERROR FIELDS

The role of error fields is important to assess at the low rotation values expected in ITER. Error fields have already been noted to influence 2/1 NTM thresholds at high plasma rotation [1]. This may be related to error field amplification effects [9], whereby the field couples to, and is amplified by, an external kink mode when β_N is close to the ideal β_N limit. However, although error fields are expected to have increased effects at lower plasma rotation, the action on the NTM is less clear, particularly as these modes can occur at lower β_N, well below the ideal limit.

Thus the DIII-D database of Fig.1 was extended with additional discharges in which error fields were ramped up at various constant β_N and torque values. A first scan was made using the ITER-like baseline scenario close to its standard operational β_N value (~1.9), with torque varied shot to shot. The results (Fig 9a, blue points) show a clear effect, with error field required to induce a mode falling as torque is reduced. Here error field is plotted as the vacuum calculated 2/1 component relative to optimal error correction vs torque, to reflect the underlying rotation drive (as rotation itself is perturbed by the error field). This shows plasmas with low positive torque (which have ITER-relevant rotations in Fig.1) to be just marginally stable in DIII-D. However, it should be noted that there is an additional residual error field present even with optimal correction, with density rampdown studies suggesting an effect from a mixture of field harmonics equivalent to a further 1.5G of 2/1 field. This suggests that with good error field correction, ITER should have some margin in stability, though further experiments are needed to ascertain how this threshold scales towards ITER parameters. These observations are surprising, as previous results in very low power plasmas [11] indicated that error field thresholds rose rapidly when torque was applied. Whilst, a decrease in error field locked mode thresholds with torque has recently been observed in plasmas that are closer to the ideal β_N, limit [12], we here see that for intermediate levels of β_N (in plasmas well below the ideal β_N limit) modest amounts of error field (1-4 Gauss) can readily trigger modes, even when significant torque is applied. This physics is investigated further by taking points at other ≤N values in co and counter rotating discharges and considering mode onsets: this wider data set, is shown in Fig 9b and added as red points with torque reversed in Fig 9a. This indicates that it is not merely rotation, or its magnitude, that governs behaviour, with a difference emerging between co and counter torque data (red cf blue in Fig 8), and a possible β_N dependence, with more error field needed at lower β_N, as also observed in [12]. Indeed it appears this effect might best be approximated by a scaling with proximity in β_N to the NTM limit itself. It is particularly interesting that at low levels, the error field often acts to trigger a rotating NTM (with lower β_N threshold) rather than a locked mode – these are not traditional error field penetrations; instead the error field is perturbing the underlying tearing mode stability, perhaps through reduced local flow shear. These effects are novel, meriting further investigation and theoretical consideration as to how proximity to an intrinsic tearing mode limit leads to enhanced error field interaction.

4. ρ* SCALING

A ρ* scaling associated with NTMs has been widely observed in many devices (see [1] for a review), and indeed, as mentioned in section 1, this falls in line with theoretical expectations. This would seem to indicate an adverse trend for ITER, but the data should be treated with caution. The ρ* scaling for mode onset arises from the small island terms that govern the seeding thresholds for the mode. Typically, to predict such a dependency, one must invoke the idea of a fixed seed size arising from some other (unmeasured) perturbation, independent of ρ* and β_N. In experimental measurements, the scaling for onset is equally dubious, with often a β versus ρ* scaling simply describing the operational space of that device (higher ρ* is usually accompanied by higher β) [13]. One might equally well observe that tokamaks of differing sizes appear to have similar ranges in the β_N onset of their NTMs.

Thus in exploring ρ^* dependence, it is important to distinguish two key elements. Firstly a ρ^* dependence of the metastable threshold for NTM stability (which more purely depends on the small island physics than the mode onset does) is important to quantify in order to understand whether ITER is in the metastable domain for NTMs, and how difficult it will be to completely remove the instability. Here previous crossmachine databases have been extended for the 3/2 NTM towards ITER's low ρ^* values with new data from JT-60U (Fig.10). These confirm a prediction of a very low metastable threshold for ITER, suggesting that, if they occur, small seed islands (comparable in physical width to those in present devices) will be able to grow to large 3/2 NTMs, and that complete removal of the modes will be challenging – although ITER's gyrotron systems are expected to achieve this [14]. Similar trends have now also been observed for the 2/1 NTM marginal β, although these data are being published separately, once a full cross-machine analysis is complete.

The second element where cross machine studies are important is in NTM onset scaling, in order to break β– ρ^* dependencies in a single device. Here a new database has been compiled for the most serious mode, the 2/1 NTM, for the hybrid scenario, which relies on high β_N access (Fig.11, where toroidal ρ^* is used for noise resilience). This reveals a surprising trend. Whilst there is an apparent ρ^* dependence in DIII-D and JT-60U data, the JET data shows higher 2/1 NTM β_N thresholds, and indeed NTM stable operation at the highest β_N, virtually at the calculated with-wall ideal kink β limit. The origins of these differences are being explored in terms of underlying plasma parameters. Within the JET data, NTM onsets were mainly observed at low collisionality (comparable to DIII-D NTM onset values). However high β_N JET stable cases are observed at both low and high collisionality, suggesting that additional q profile variation (used here to optimise confinement, but only possible at low collisionality) lowered the NTM thresholds (rather than the low collisionality itself). The role of q profile, and fast particle content (which is higher in JET) is being explored further, with new theories predicting a strongly stabilizing role for fast particles in the linear phase of the tearing mode [15], as well as a strong dependence on qmin when its value is close to unity [16]. Whilst the precise roles of the governing parameters remain to be elucidated, these results clearly show that ρ^* is not the only important parameter governing the 2/1 β_N limit, and that devices with lower ρ^* can have higher β_N access.

CONCLUSIONS

NTM threshold scaling towards ITER has been explored with new cross-machine studies to resolve the most critical parameter dependencies for extrapolation: rotation, ρ^* and error fields. These reveal a key effect of the 2/1 NTM onset threshold falling to lower β_N at low rotation values relevant to ITER, and an increase in error field sensitivity in this regime. However, the ITER baseline scenario remains NTM stable at the nominal operating β_N in DIII-D, provided good error field correction is deployed. The rotation dependence for the 2/1 mode (and to some degree the 3/2 mode) seems most consistent with an action of rotation shear on the intrinsic tearing stability, and the studies provide a rich and challenging data set to explore the underlying physics governing NTM behaviour. ρ* scaling of NTM metastable thresholds is confirmed as expected, though ρ* dependence of NTM onset is less established, with other parameters clearly playing a strong and even dominant role, so providing additional levers to control NTM behaviour. Further work is needed to resolve some key elements, such as error field threshold scaling at low rotation and intermediate β_N, as well as to better understand the governing parameters for the hybrid scenario β_N limit, including the role of rotation here also.

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REFERENCES:

[1]. Buttery, R.J., et al., "Cross-machine NTM physics studies and implications for ITER", Fusion Energy 2004 (Proc. 20th Int. Conf. Villamoura, 2003), paper EX/7-1.
[2]. Buttery, R.J., et al., Phys. Plas. **15** (2008) 056115.
[3]. Coelho, R. and Lazzaro, E., Phys. Plasmas **14** (2007) 012101.
[4]. Sen, A. et al., Proc. 32nd EPS Conf. ECA 29C (2005) P-2.046.
[5]. Wilson, H.R., et al., Phys. Plas. **3**, (1996) 248.
[6]. Fitzpatrick, R., Nucl. Fusion **33** (1993) 1049.
[7]. Sauter, O. et al., Phys. Plas. **6** (1999) 2834; and 9 (2002) 5140.
[8]. Buttery, R.J., et al., "Rotation and shape dependence of NTM thresholds on JET", Proc 31st EPS Conf. on Contr. Fus. and Plasma Phys. (2001, Funchal), ECA 25A (2001) 1813.
[9]. Boozer, A.H., Phys. Rev. Lett. **86** (2001) 5059.
[10]. Scoville, J.T., and LA Haye, R.J., Nucl. Fus. **43** (2003) 250.
[11]. Buttery, R.J. et al., Nucl. Fus. **40** (2000) 807.
[12]. Reimerdes, H.R. e al., paper EX/5-3Ra – this conference.
[13]. Buttery, R.J., et al., Nucl. Fus. **44** (2004) 678.
[14]. La Haye, R.J., et al., Nucl. Fus. **46** (2006) 451, and paper IT/P6-9 this conference.
[15]. Takahashi, R. et al., submitted to Phys. Rev. Lett.
[16]. Brennan, D.P., et al., Phys. Plas. **14** (2007) 056108.

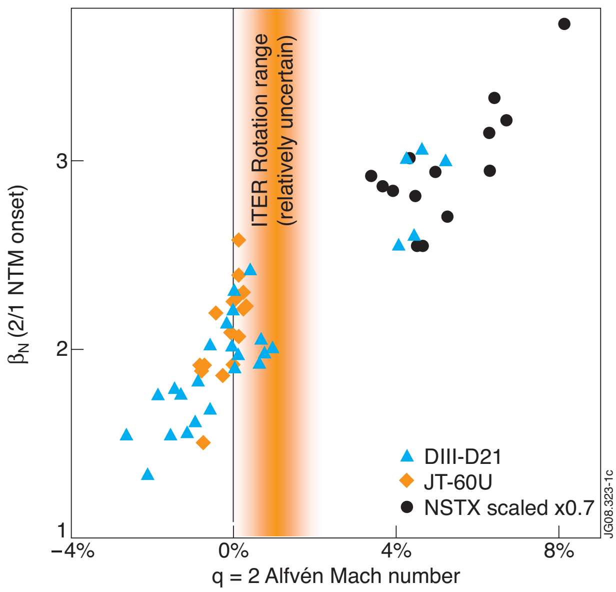


Figure 1: Rotation dependence of 2/1 NTM β_N limit.

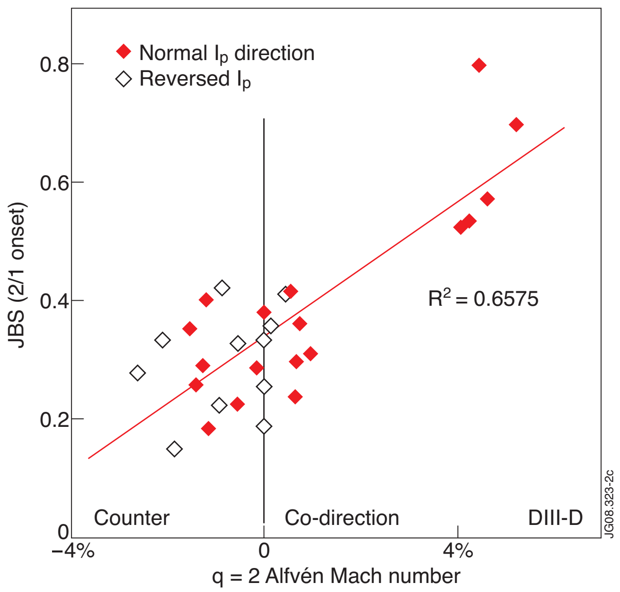


Figure 2: DIII-D data from Fig.1 plotted as local bootstrap drive [7] for the NTM.

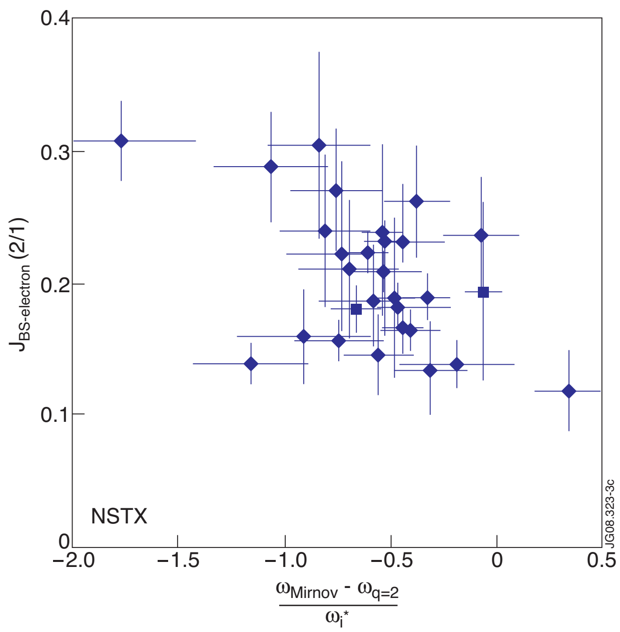


Figure 3: A lack of correlation is observed in 2/1 onset threshold (NTM bootstrap drive) and rotation parameters governing ion polarisation current effects in NSTX.

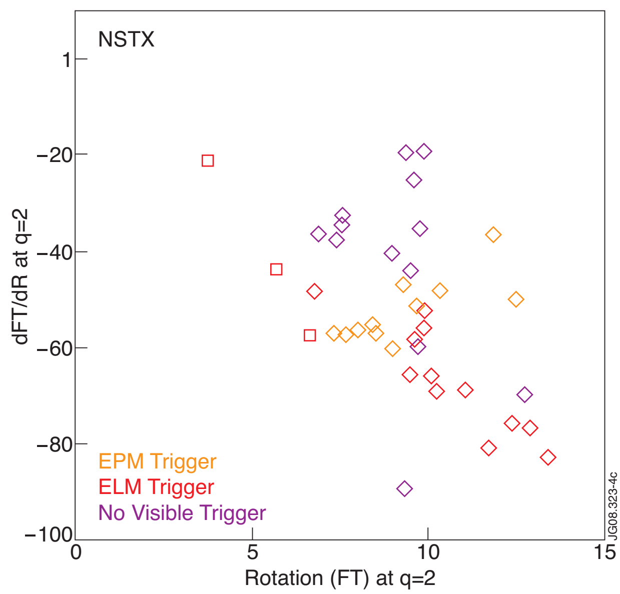


Figure 4: On NSTX rotation (FT) and rotation shear (dFT/dR) are decoupled at 2/1 NTM onset.

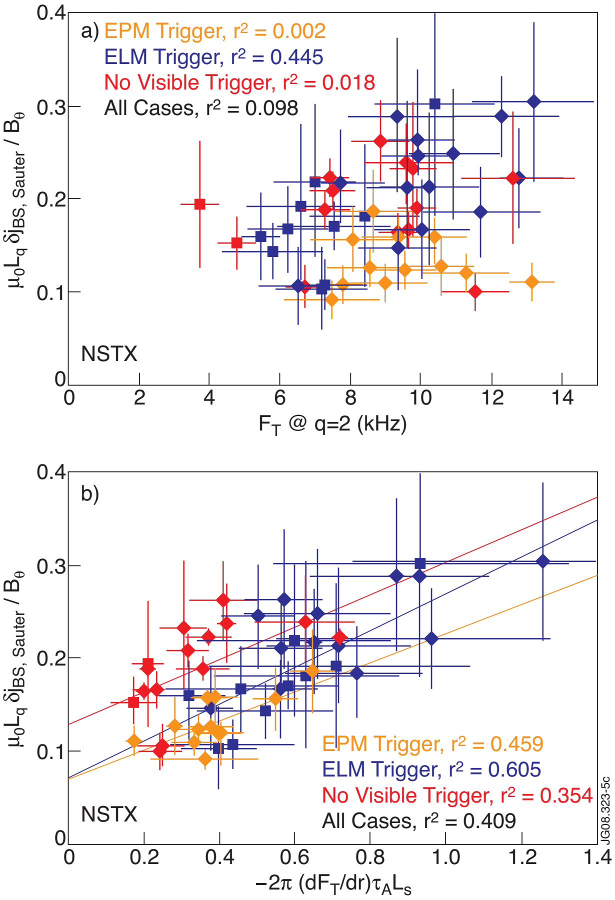


Figure 5: Bootstrap drive at 2/1 NTM onset versus (a) rotation, and (b) rotation shear in NSTX.

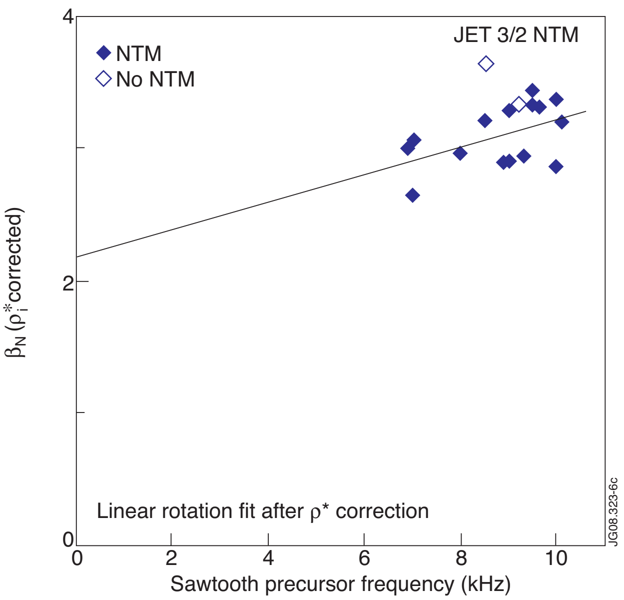


Figure 6: 3/2 NTM threshold and core rotation

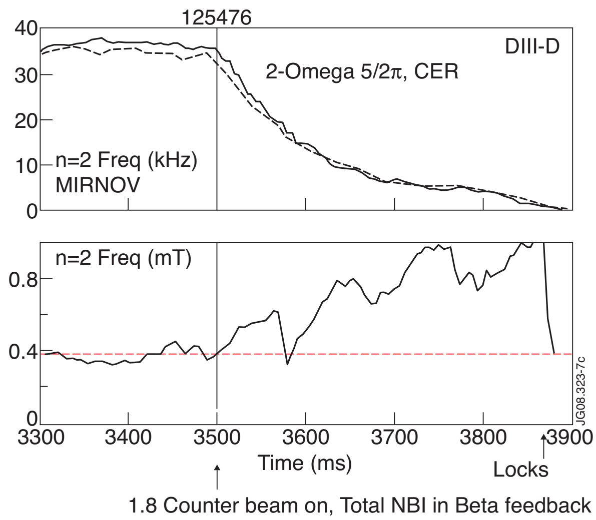


Figure 7: Rise in 3/2 NTM amplitude on DIII-D following a step from co to balanced beam injection.

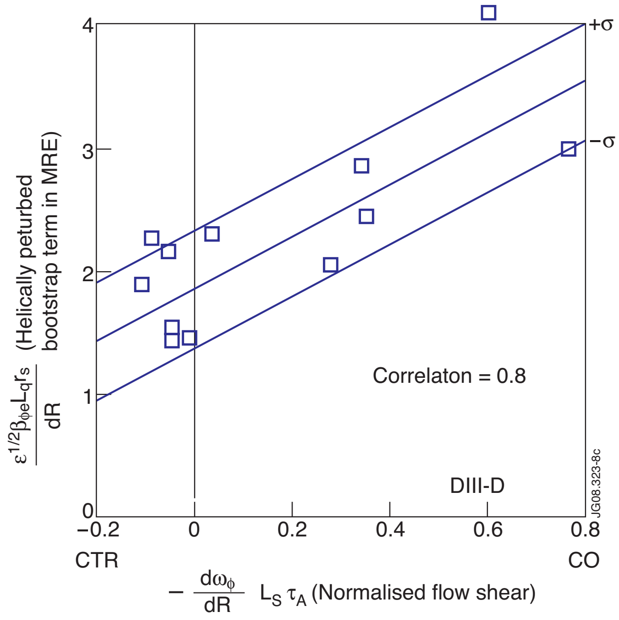
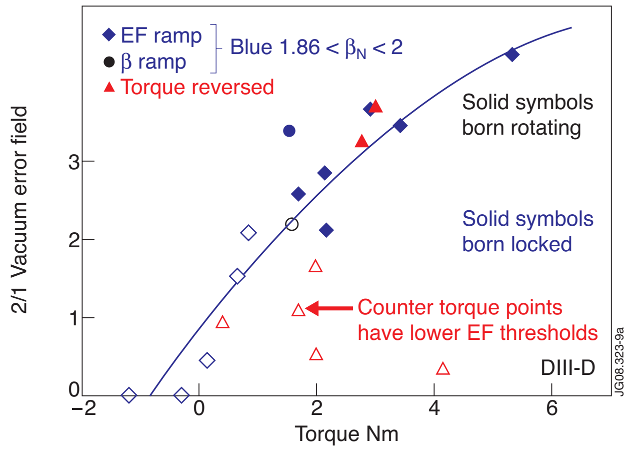


Figure 8: Calculating mode drives from island sizes (w) for DIII-D saturated 3/2 NTMs. From Eq. 1, y values above must be balanced by equal and opposite rΔ′ values.



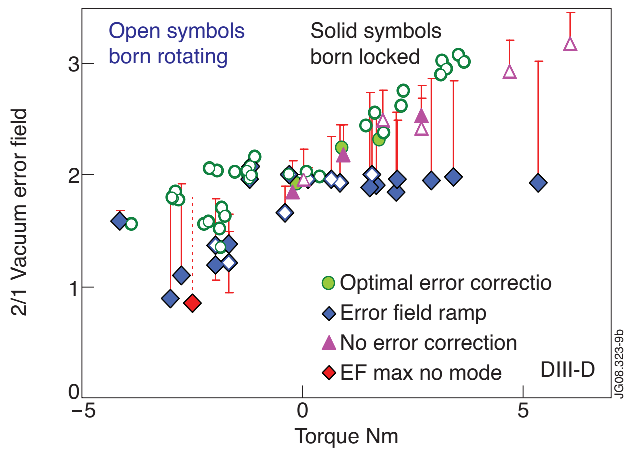


Figure 9: Variation in error field threshold for ITER like baseline plasmas plotted: (a) for shots with β_N~1.9 (blue) and other points with torque reversed (red). (b) for the wider data set plotted as red bars (1 unit=4Gauss) against torque and β_N.

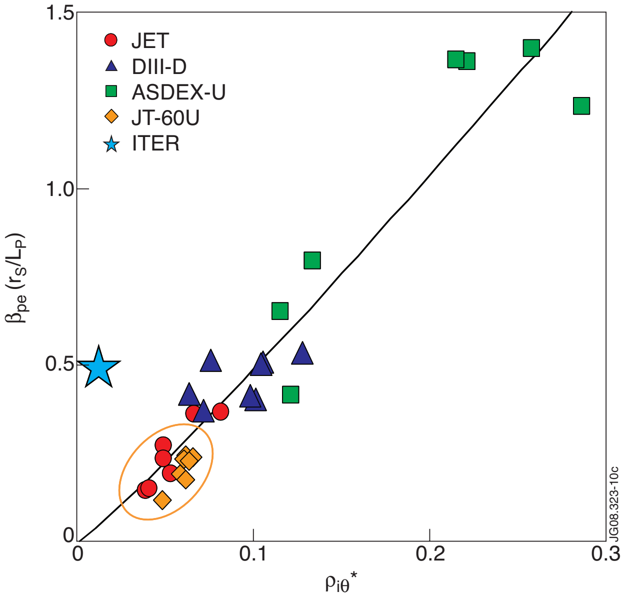


Figure 10: Cross-machine scaling of 3/2 NTM metastability threshold with ρ.*

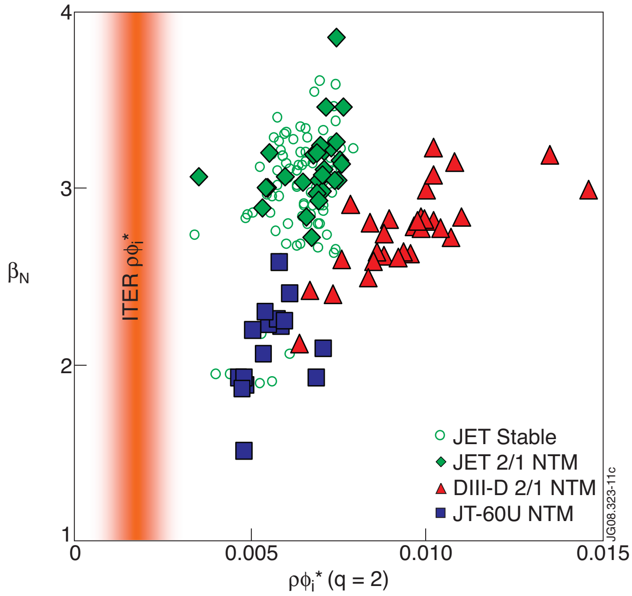


Figure 11: Comparison of 2/1 NTM limits for hybrid scenario between devices.