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ABSTRACT.

Cross machine identity experiments have been performed on JET, DIII-D and ASDEX Upgrade to measure the physics governing Neoclassical Tearing Mode (NTM) metastability and its scaling towards ITER. Results indicate ITER baseline scenarios will operate well above the b threshold for metastability of NTMs, and so be susceptible to NTM triggering events. Modelling techniques have been extended to use a fully time dependent treatment, with local parameters and a full bootstrap calculation in order to reproduce detailed island evolutions, responding to changes in profiles. Preliminary results indicate a weak scaling of scale length associated with small island size stabilisation effects, indicating that for complete removal of NTMs in ITER, ECCD systems will have to drive islands down to a few cm in size, similar to levels required for mode removal in present devices.

1. MOTIVATION

3/2 Neoclassical Tearing Modes (NTMs) remain a serious concern for the ITER baseline scenario, the ELMy H-mode. They can decrease confinement by 10-20% (and fusion power by 20-40%), with a progressively worsening effect as β is raised (although some recovery is possible at higher β_N due to ‘FIR’ interaction with other modes). A key question therefore is how the underlying physics governing NTM behaviour scales? In particular critical uncertainties remain in small island stabilisation terms. These controls not only the criteria for mode onset, but also the requirements for NTM control systems (for example ECCD in ITER), governing the degree of current drive required and the island sizes at which self-stabilisation occurs.

The evolution of an island of full width, w, can be described by the modified Rutherford equation [1,2]:

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

Here, r is radius of the resonant surface, tr is resistive diffusion time, and bp is local poloidal beta at the resonant surface. The $r(\Delta'\text{-}\alpha w)$ term represents classical tearing stability, with a coefficient a for its island size dependence [3]. The abs term is the bootstrap drive for the mode taken from Ref. [4] with a_{GGJ} the field curvature correction [5]. w_d, a_{pol}, and w_{poli} describe potentially stabilising small island size effects for finite transport over the island [6], ion polarisation current [7] and loss of bootstrap on ion banana orbit scales [8]. These lead to a metastable β threshold for the NTM and requirement for other seeding physics to trigger the mode. However, w_d and a_{pol} remain the subject of considerable debate about their underlying physics, which has proved difficult to resolve experimentally, making ITER extrapolation uncertain. Thus in this work we adopt a different approach of attempting to empirically measure these terms and their scalings towards ITER, as set out below.

2. EXPERIMENTS AND RESULTS

Cross machine ‘ITPA’ identity experiments have now been executed on JET, DIII-D and ASDEX Upgrade to address these questions, by using β ramp-down experiments in matched scenarios. At large island sizes, the island size is expected to track the β_p, as can be readily obtained by solving Eq. (1) for dw/dt=0 if w_d, a_{pol}·, and w_{poli} are neglected. However as β is reduced, island size falls, and small island terms start to drive the island sizes down more rapidly. This can be seen in Fig.1, where a clear ‘knee’ point is observed from which the island starts to decay -this is the ‘marginal β’ point and as described in more detail in Ref .[9].

Results measuring this marginal β from all three devices are shown in Fig.2, plotted in terms of local parameters related to the underlying NTM bootstrap drive (poloidal electron $\beta \times r/L_P$) against normalised ion poloidal Larmor radius, $\rho_{i\_pol}{}^{*}$. The β values have been corrected slightly for the observed collisionality dependence (which gives an average ~6% variation) using a regression fit to the data. This yields: $\beta_{Pe\text{-}marg} = 8.79\, \rho_{i\_pol}{}^{*\,1.15}\, \nu^{0.06}$, where n is the ion collisionality normalised to inverse aspect ratio multiplied by electron diamagnetic frequency. As can be seen in Fig.3, a good scan has been obtained in collisionality and $\rho_{i\_pol}{}^{*}$. The data indicates a clear trend with the marginal β falling with $\rho_{i\_pol}{}^{*}$, while collisionality dependence is weak. Also plotted in Fig.2 is the ITER operating point for ELMy H-mode baseline scenario 2. This indicates that ITER will operate well above the NTM metastability β threshold, and so susceptible to NTM triggering from events such as sawteeth, fishbones or other sources of tearing instability. Thus it will be important to consider control of NTM seeding instabilities in ITER.

3. MODELLING DISCHARGES WITH THE MODIFIED RUTHERFORD EQUATION

To quantify the underlying physics of the NTM and make more specific predictions for ITER, it is necessary to fit the island evolution equation (1) to the experimental behaviour. This can then yield an empirical measurement of the uncertain terms. However, in these b ramp-down discharges, we commonly find profiles evolving, particularly as the plasma transitions from Type I to Type III ELMs, and later to L-mode. Thus, to get good fits to the behaviour and clear measurements from the fitting, previous modelling techniques have been extended to use a fully time dependent treatment, local parameters at the NTM resonant surface, and full bootstrap calculation [4]. An example is shown in Fig.4, where we see a fixed profile approach cannot reproduce rises in the bootstrap drive (and mode amplitude) observed at ~3.7s, as a result of local density gradient increases when type III ELMs commence.

To measure the small island size terms Eq (1) is fitted to the experimental island size evolution taking a_{bs}, a_{GGJ}, w_{poli}, and τ_r from formulae in Refs [4,5,8]. Δ' is set to match the peak mode amplitude at high β; w_d or a_{pol} is set to ensure full stabilisation at the correct time; α is adjusted to match island sizes at intermediate points in the evolution. Island sizes are calculated from magnetics mapped to the resonant surface and calibrated against ECE (as in [10]). The roles of the various physics terms are highlighted in Fig.5, for a shot which has a large ramp in β, and no complicating 4/3 modes (which often cause 3/2 amplitude reductions). The best fit is shown in blue, with $r\Delta' = -2.9$, $r\alpha' = 10\text{m}^{-1}$ and

w_d = 2.19cm. The other curves show the effects of removing various terms relative to this fit. Most notable is that a small island size term (here w_d) is essential to get a stabilisation. This term is well constrained with changes of a few percent leading to significantly different times for the final stabilisation. In addition, it is clear that without the a parameter intermediate island sizes cannot be reproduced. The Poli term has little effect on the best fit beyond changing the level of wd required to match the stabilisation point. This fitting procedure has now been executed for a set of DIII-D discharges, with the preliminary resulting $\rho_{i\_pol}{}^*$ dependence of w_d, plotted in Fig.6, being fairly weak.

CONCLUSIONS, IMPLICATIONS AND NEXT STEPS

Identity experiments have measured the 3/2 NTM marginal β and its scaling on JET, DIII-D, and ASDEX Upgrade. These clearly indicate that ITER will operate well above the metastability threshold for these modes, and so be susceptible to them. New modelling techniques have been developed to accurately reproduce island evolutions, based on a new time dependent and local parameter treatment. Preliminary indications suggest a weak dependence for small island stabilisation scale lengths. If this is borne out by the full data from all three devices, then this would suggest that to remove 3/2 NTMs in ITER, current drive systems would have to drive island sizes down to levels similar to those required on present devices. It should be noted, however, that it may be tolerable for ITER to operate with continuously ECCD-suppressed low amplitude NTMs. Nevertheless, even in this case the role of the small island size terms remain important to quantify, in order to understand the requirements for these systems. Next steps are to: (i) correct for variations in resonant surface radius in the island size measurement; (ii) extend fits to JET and ASDEX Upgrade data; (iii) finalise ITER extrapolations for marginal beta and island sizes.

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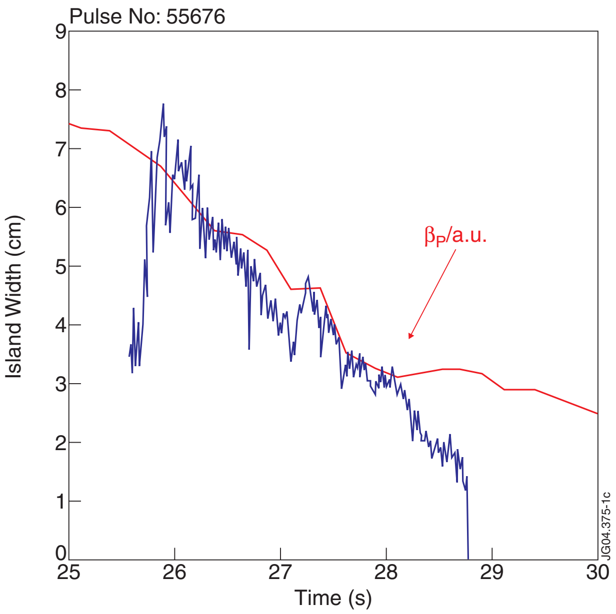

Figure 1: *Decoupling of island width from β.*

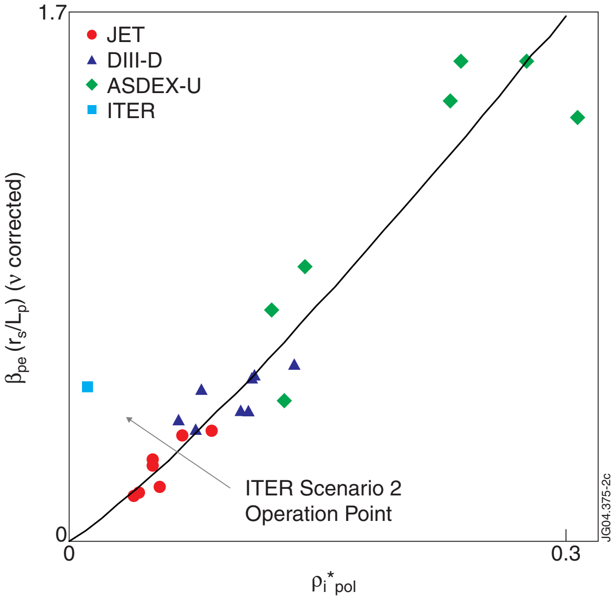

Figure 2: *3/2 NTM metastability threshold scaling.*

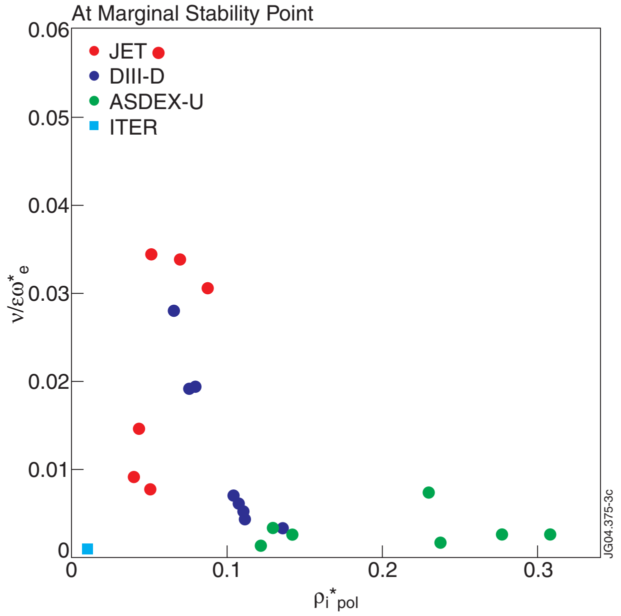

Figure 3: Range of parameters explored at marginal β point.

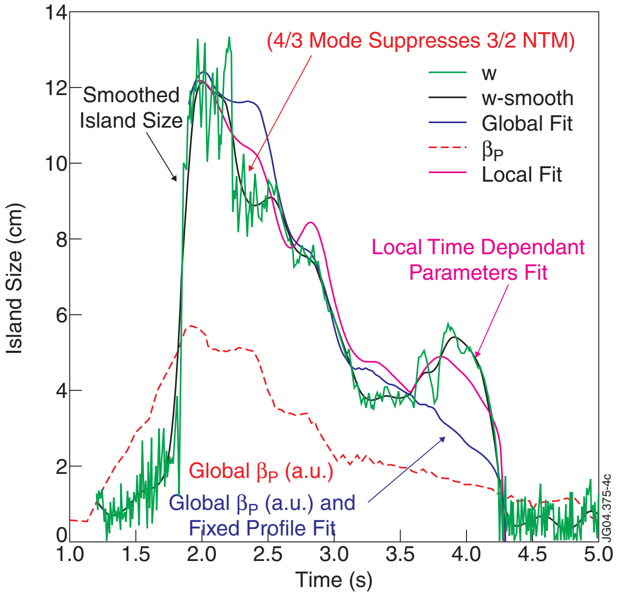

Figure 4: Comparison of different techniques for fitting island evolution for DIII-D Pulse No: 111270.

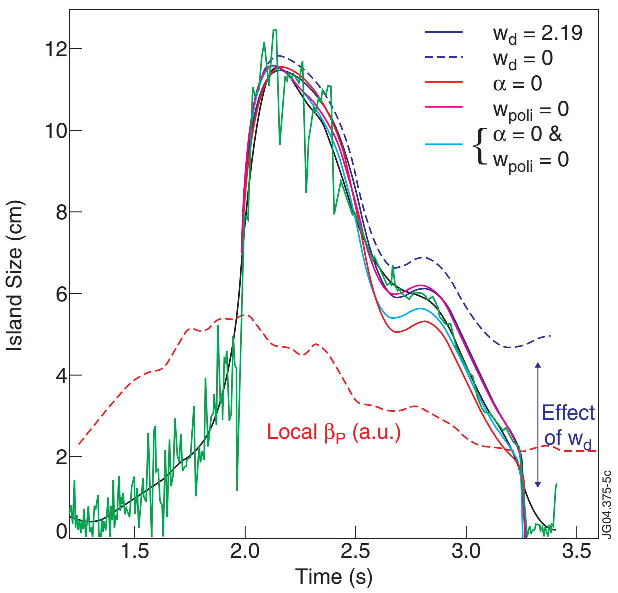

Figure 5: Role of terms in island evolution fitting for DIII-D Pulse No: 114779, as described in text.

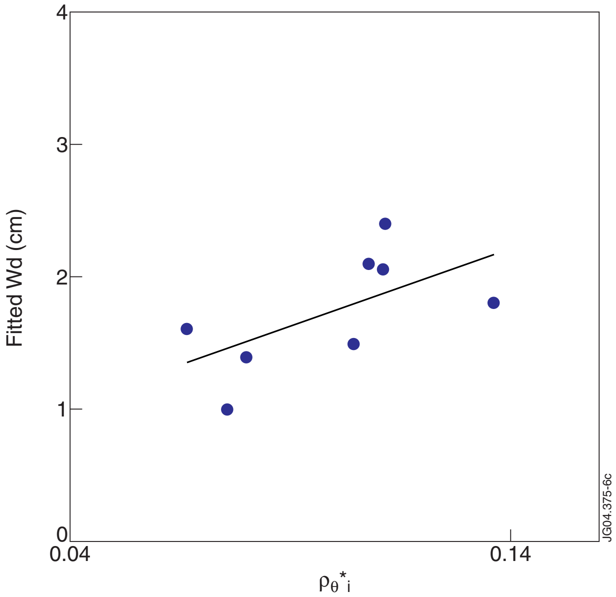

Figure 6: ρ* dependence of w_d term (DIII-D).