Interplay of Error Field and Neoclassical Tearing Mode drives and rotation for the 2/1 mode on JET and DIII-D

R. J. Buttery[1], R. J. La Haye[2], T. C. Hender[1], D. F. Howell[1], J. T. Scoville[2], JET-EFDA contributors[*] and the DIII-D team[2].

[1]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK.
[2]General Atomics, San Diego, CA, USA.

Abstract. Complementary studies are reported from the DIII-D and JET tokamaks, exploring the role of error fields in the triggering of 2/1 tearing modes at high β. In all cases a strong lowering of β_N thresholds (~20 to 60%) is observed even when modest levels of error field (~2-4G) are applied. On JET, the effect appears to be a manifestation of increasing error field sensitivity at high β_N, leading to strong coupling and directly inducing locked modes. Conversely on DIII-D rotating modes are observed indicating error fields may be changing the underlying metastability of the NTM. The role of sideband harmonics is also important in determining the degree and location of magnetic braking.

Introduction

2/1 tearing modes pose a concern for the performance of baseline and hybrid scenarios in next step fusion devices such as ITER, potentially causing serious reductions in confinement or termination [1]. Previous studies have focussed on two aspects that lead to such modes: with low momentum injection (such as during scenario formation prior to main heating) intrinsic non-axisymmetric ‘error’ fields can resonate with the plasma, stopping its rotation and driving island growth [2,3]. Conversely, at high performance, holes in the pressure gradient driven ‘bootstrap’ current, associated with small magnetic islands, can drive such islands to large size ‘neoclassical’ tearing modes (NTMs) [4,5]. Although earlier work had found a lowering of error field thresholds close to ideal stability limits [6], the different physical mechanisms for the two types of tearing instability might be assumed to imply that they could be treated separately. For example, even modest levels of momentum injection can dramatically raise low β error field thresholds [7]. However, new evidence suggests that two types of tearing mode drive can also combine to lower thresholds for mode triggering. This interplay is interesting as a mechanism to explore the basic underlying physics of the instability triggering. It is also important to understand in terms of potential limits to fusion power.

Experiments

To provide a good comparison of results between JET and DIII-D, experiments used matched shape lower single null divertor (SND) plasmas [8]. The regime used was that of previous NTM identity studies on JET and DIII-D [8], where the neoclassical nature of the 2/1 mode was clearly established, with visible island structures and β dependent size. The JET studies reported here are all performed at 0.94MA, 0.98T, q_{95}=3.4, which gives optimal scope to vary heating power while obtaining 2/1 NTMs reliably, and avoiding density limits and neutral beam shine-through problems. On DIII-D a match to JET q_{95} was extended to higher q_{95}, to take advantage of additional parasitic opportunities to explore the effects in more detail.

Experiments were performed on JET using the Error Field Correction Coils (EFCCs) [9], as well as taking data from previous experiments with the internal saddle coils [10], while DIII-D employed the ‘C’ (Correction) coils. On DIII-D, β ramps were usually applied at constant levels of error field until a mode was triggered. This enabled a refined scan at low levels of error field (without mode locking and disruption), parasitic to other 2/1 NTM studies. On JET this approach sometimes led to mode formation as the error field was switched on and stepped up, and so instead error field ramps were usually applied at constant heating power.

A typical discharge with the EFCCs on JET is shown in Fig 1. Heating is ramped to reliably

[*]see appendix: J. Pamela et al., Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004).

trigger a 3/2 NTM (blue trace) before raising further to leave the plasma sub-critical to the 2/1 NTM. EFCC are then ramped. These brake the rotation and somewhat degrade confinement. As the rotation falls below half of its original value, a locked plasma response is observed (at 30s). This causes a large fall in β_N and density before a real time system detects the mode and shuts down the heating. The mode then decays away. In most discharges a 3/2 NTM is triggered before the 2/1 NTM, so cases where the 3/2 NTM is not present are discarded, as this will change the overall rotation and profile behaviour. DIII-D cases without 3/2 modes sometimes appeared with 2/1 NTM onset β_N thresholds below trend.

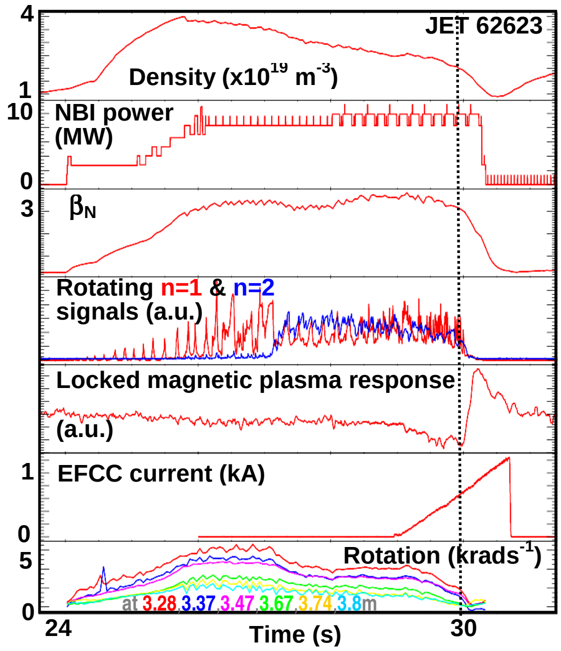

Fig 1: Typical experiment on JET.

As the intrinsic error field on DIII-D is only well measured for double null divertor (DND) shapes [11], values for the SND shape had to be based on these. Calculations for the C-coil 2/1 harmonic component show this introduces a 15% discrepancy, and so a systematic error of this order is expected in the total applied error field on DIII-D. Field harmonics are calculated using a non-Jacobian treatment. This enables the optimum fit for DIII-D intrinsic error field sources and their q_{95} dependence (which have only been obtained in the non-Jacobian form [11]) to be employed, providing the most accurate available method for representing how the intrinsic error and C coil fields (which partially oppose and cancel) combine. While not a fully quantatively precise approach, this enables a consistent comparison between the devices. Only 2/1 harmonics are considered (using a straight field line weighted calculation) to avoid further uncertainties in the intrinsic error and how sidebands couple in (discussed later). For JET the same treatment is applied, although here the intrinsic error is a much smaller fraction of the total, and is measured empirically in terms of equivalent applied error field required to cancel the offset in error field thresholds that the intrinsic error introduces. This amounts to 0.4 Gauss of 2/1 field [7].

The JET results are shown in Fig 2, superposed on previous low β_N studies [7]. In these cases, the modes always form locked when any level of error field is applied, beyond the intrinsic error. Here the mode onset process for JET appears to be that of 'classic' error field penetration (discussed further below), with the locked mode forming as the rotation reaches zero.

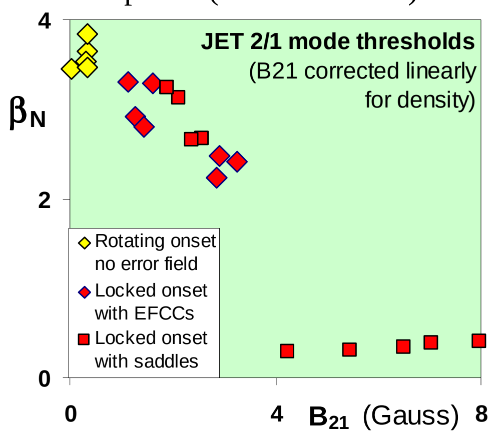

Fig 2: JET error field thresholds at various constant heating powers.

Thus in Fig 2 we correct for slight variations in plasma parameters using a simple linear density dependence for B_{21} as found for error field threshold scalings [12]. The key difference between the low and high β_N scans lies in the rotation dependence. At low β_N, the threshold was observed to rise rapidly as plasma rotation increased with neutral beam torque. By contrast, as high β_N are approached there appears to be an increased error field sensitivity [13] giving rise to enhanced braking, despite the higher torque. It is interesting to note that 2/1 mode β_N thresholds are strongly affected, even with levels of error field substantially lower than those expected to trigger error field modes in Ohmic plasmas.

The main results for DIII-D are shown in Fig 3 indicating a marked fall in the 2/1 NTM β_N threshold as error field rises. This is best approximated by a quadratic relation, β_N=3.48–0.04B_{21}^2, indicating that it may be the torque applied (proportional to B_{21}^2) at the q=2 surface that is key parameter in lowering β_N thresholds. (Previous studies [6] also show error field thresholds at low β_N rising as NBI power increases). Of particular note here is the large number of discharges where the initial mode forms rotating (yellow symbols). This indicates a different mechanism to 'classic' error field penetration [3] where the resonant response to the error field induces a drag, eventually stopping plasma rotation, and allowing the error field to directly drive island growth. In the DIII-D cases, the initial island cannot be dominantly driven by the error field because it forms rotating. This suggests a more subtle effect with the error field influencing the mechanisms that govern NTM metastability. For this reason, we correct for scatter in the DIII-D data using scalings based on NTM physics. A best fit to this data (after eliminating error field dependence) yields $\beta_N \propto n^{0.57\pm0.20}\ B_T^{-0.77\pm0.13}$. This is consistent within error bars with fits to previous DIII-D 2/1 NTM onset campaigns [8], which indicate a scaling $\beta_N \propto n^{0.70\pm0.07}\ B_T^{-0.96\pm0.17}$, originating from the underlying ρ^* and collisionality dependence in the NTM physics. A further fit to the q_{95} dependence (compare triangles and diamonds in Fig 3) yields a zero q_{95} exponent within error bars, although a degeneracy between toroidal field and q_{95} in the new data prevents this being well constrained. However, fixing density and B_T exponents to values fitted for the previous campaign (which did not suffer this degeneracy), establishes the dependence as $\beta_N \propto q_{95}^{-0.03\pm0.13}$ - much weaker than for the 3/2 NTM (~$q_{95}^{0.5}$).

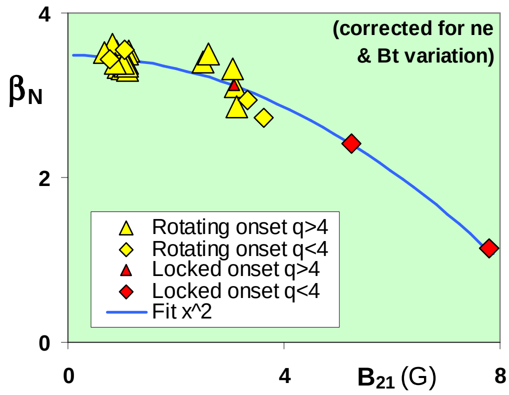

Fig 3: DIII-D 2/1 NTM β_N threshold as a function of error field applied.

The key question must be how is the error field changing the terms that govern NTM metastability? The most obvious means is via changes to the q=2 rotation. If the change occurs in the zero radial electric field frame of reference then, rather than just braking the plasma in lab frame, this would alter the ion polarisation current term that governs NTM metastability in the modified Rutherford equation for island evolution [14]. Lowering this rotation, will proportionately lower the NTM threshold, while reversing its sign will help drive island formation (although stabilising effects from incomplete flattening of the island due to transport will still play some role). A preliminary analysis (Fig 4, where error field, B_{pen} now also includes contributions from sideband harmonics [11]), based purely on toroidal rotation indicates a promising trend with higher error fields associated with lower rotation in the zero electric field frame, and lower 2/1 NTM β_N thresholds. This may also explain the difference with JET where the initial mode rotation without error field is ~90% higher than the toroidal rotation - much greater than the ~35% seen on DIII-D. Thus it is possible that the rotation on JET is too fast to lower thresholds by this mechanism, and so becomes reliant on a conventional locked mode

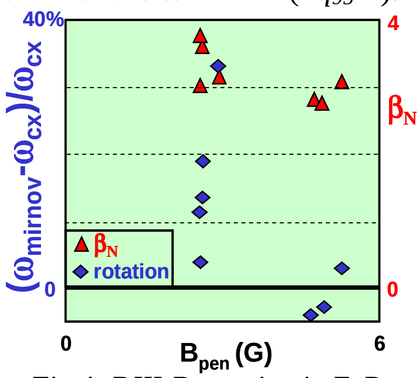

Fig 4: DIII-D rotation in ExB frame falls as error field rises and rotating 2/1 NTM threshold falls.

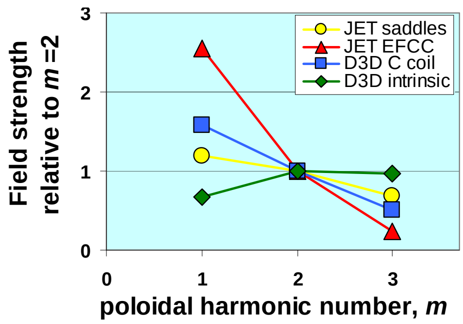

Fig 5: Error field spectra on JET and DIII-D.

mechanism, bifurcating to a locked state when braking halves initial rotation. Work is now underway to refine these calculations to include poloidal rotation and pressure gradient terms.

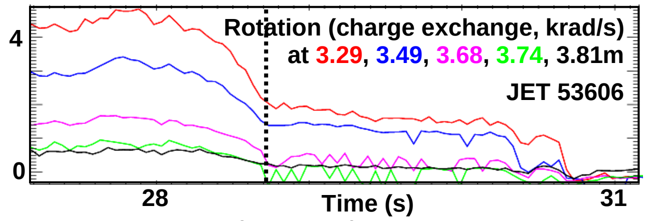

Fig 6: Locking of q=2 surface (3.71m, 28.7s) by JET saddle coils while core plasma still rotates.

A further explanation of the difference between DIII-D and JET may lie in the spectra of error field applied. The DIII-D studies are dominated by the intrinsic error, with varying low levels of correction from the C-Coil. As shown in Fig 5, the intrinsic error field has very little m=1 component, and so will have maximum effect at q=2 while less overall braking on the plasma from sideband harmonics. This contrasts with studies with EFCCs where the strong 1/1 fields exhibit a noticeable drag across the whole plasma, even at lower field levels. Conversely, when the saddle coils were applied at high β_N (green points in Fig 2, yellow in Fig 5), it is found (Fig 6) that while the plasma is stopped at q=2 (with locked modes which also sometimes unlock when saddle fields are switched into error field correction), the core plasma rotation is maintained. Thus it is the combination of error field spectra and rotation effects which explain this interplay of 2/1 mode drives at high β_N.

Conclusions

A marked effect of error fields lowering the β_N limit due to 2/1 NTMs has been observed, even when the fields are applied at levels considerably lower than Ohmic error field thresholds on present devices. The way in which this is manifested appears to depend on both the sideband harmonics and plasma rotation. Data from DIII-D suggest evidence for the error fields changing the plasma rotation to alter underlying NTM physics terms and directly trigger an NTM. Conversely on JET the rotation in the ExB frame of reference appears too fast for this effect, and the usual locked mode penetration is observed, although with increased error field sensitivity overcoming the strong momentum injection from neutral beams. In addition the data confirm present onset scalings and additionally indicate a very weak or zero q_{95} dependence of the 2/1 NTM onset threshold, while the absence of a 3/2 NTM prior to the 2/1 NTM can sometimes lead to slightly lower onset β_N for the 2/1 NTM. These results motivate further work to explore error field sensitivity and scaling (towards ITER parameters) in the intermediate β_N regime.

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