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The Impact of 3-D Fields on Tearing Mode Stability of H-modes

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New processes have been identified in the interaction of 3-D fields with tearing mode stability that raise concern for H-modes at modest β_N. These arise from the plasma response at the tearing resonant surface, which is expected to depend on plasma rotation and underlying tearing stability [1]. This leads to additional sensitivities to those previously identified at low density [2] or high β_N (where ideal MHD responses amplify the applied fields) [3]. In particular, the field threshold to induce modes falls to zero as natural tearing β_N limits are approached, and plasma responses are further enhanced at low rotation. Typical field thresholds to induce modes in torque-free β_N~1.5 H-modes are well below those in Ohmic plasmas, or even plasmas above the no-wall ideal kink β_N limit, and scale differently to Ohmic regimes. Comprehensive scans have been executed on DIII-D and NSTX to explore the underlying physics, probe and distinguish between the ideal and resistive responses, and determine the principle scalings to next step devices.

Underlying tearing stability and plasma rotation play critical roles in the criterion for 3-D fields to induce a mode. Although rotation helps shield the field, a residual tearing response and associated braking torque can overcome this, leading to widespread tearing; the nature of this response and the degree of rotation set the threshold for mode formation. To explore this, and discriminate from changes in the ideal plasma response, new studies on DIII-D scanned magnetic probing response and field threshold with rotation and β_N. As low rotation leads to lower tearing β limits [4], this has helped decouple tearing and ideal responses. Fig. 1 shows two key effects: for a given level of beam driven torque, the required field to induce a mode falls to zero as the NTM β_N limit is approached (in relaxed plasmas that are well below ideal β_N limits); and for a given β_N, the field threshold falls with beam injected torque and plasma rotation (which remains parallel to I_P). The behavior suggests the 3-D field interaction becomes strongly enhanced when in proximity to tearing instability. This interpretation is confirmed by magnetic probing prior to mode onset (Fig. 2), with plasma response increasing substantially with β_N, thus less applied field is needed to cause braking. At constant β_N, the response also rises as rotation falls, particularly evident at low β_N in Fig. 2. This shows that the easier destabilization of modes at low rotation, is not just because the plasma has less inertia or a lower torque balance, but because the plasma responds more strongly with less rotation – a different and additional mechanism to ideal responses that amplify fields at high β_N [2].

An important further aspect is the interaction with the Neoclassical Tearing Mode (NTM). In most cases in H-mode plasmas, the tearing mode forms rotating, and so cannot be being driven directly by the 3-D field. Rather the NTM stability must be changing, most likely through rotation braking [4]. This aspect was explored on NSTX, utilizing its capability to deploy n=1 and n=3 fields, and decouple rotation from rotation shear. Various mixes of field were applied during β ramps to access the 2/1 NTM. The clearest effect on rotating mode threshold is a trend of bootstrap drive (related to β, but captures more NTM physics) with rotation shear (Fig. 3), confirming previous observations in NTM β limit scaling on NSTX [5], but accessed here through 3-D field braking. Exploring the interaction in more depth (Fig. 4), both resonant (n=1) and non-resonant (n=3) fields have progressive and similar magnitude effects in braking the plasma and leading to modes (though the balance between rotation and rotation shear braking varies with n=1:n=3 field mix). This indicates that the influence on stability is most likely through the braking, rather than a resonant interaction of the field directly with the mode (though braking may be partly a resonant effect). Further, there appears to be a critical ~50% level of braking beyond which modes form locked, with braking response on the approach to this initially weak (and modes forming close to their natural β limit) and then rising rapidly (and modes triggered with less bootstrap drive). This provides a basis for a unifying criteria for the critical field to trigger a mode, akin to (but effectively an extension of) the original Fitzpatrick model [1]. Simply put, once enough field is applied to achieve substantial braking then a mode will result – the exact nature of the mode or onset mechanism is secondary. However, the amount of field required to achieve such braking will depend on proximity to the tearing β limit and rotation.

On this basis, new scalings for error field sensitivity of H-modes are required and have been obtained. n=1 field thresholds for modes were measured as a function of main plasma parameters in constant β_N=1.8 torque-free H-modes, using balanced beam injection on DIII-D. As in [2] rotation is treated as a hidden self-generated parameter, its value implicitly assumed to vary as part of the scaling (though adding torque would be a method to raise thresholds), and a dimensional constraint can be invoked to deduce machine size scaling. While density scaling is stronger and more favorable for next step devices than previous Ohmic scalings, the toroidal field is worse (Fig. 5), and generally thresholds are a factor ~6 below Ohmic predictions. These results have far-reaching implications, suggesting that tearing mode stability needs to be considered in assessing magnetic field symmetry requirements (or the impact of 3-D field control systems) and operating points of future devices, and that it is vital to make such assessments at relevant torques or plasma rotations. Modeling of these recent results is underway with the MARS and NIMROD codes to test this understanding and confirm that the scale of effects matches current theoretical models.

References: ***note order changed…***

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FIGURES:

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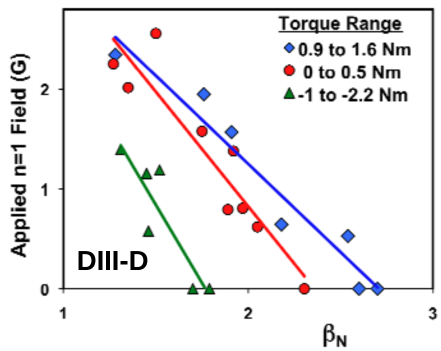

Fig 1: n=1 3-D field required to trigger 2/1 tearing modes vs β_N & torque.

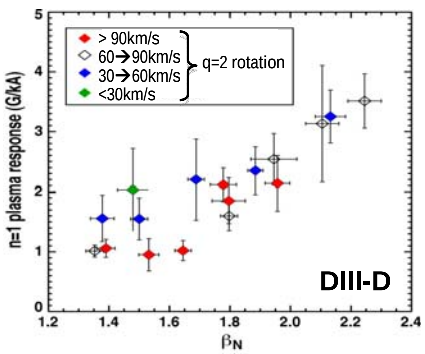

Fig 2: Plasma response to 10Hz n=1 field prior to mode onset.

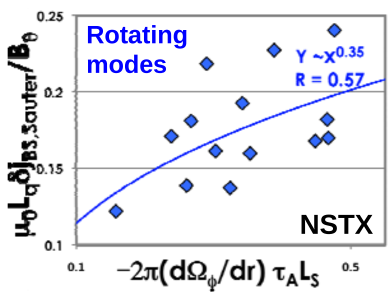

Fig 3: Bootstrap drive vs rotation shear normalized to Alfven inverse time and magnetic shear for rotating mode onset.

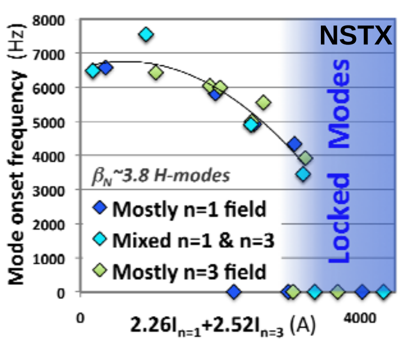

Fig 4: Incidence of modes with various forms and levels of magnetic braking.

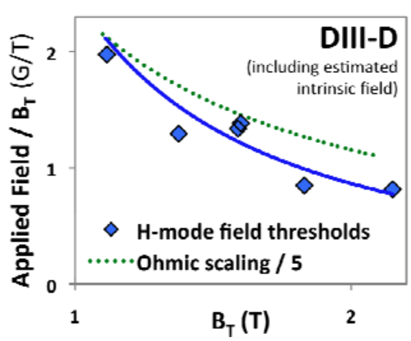

Fig 5: Toroidal field scaling of mode threshold.

Paper Title

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Abstract Text. Enter the abstract in one continuous paragraph (maximum of about 2400 characters). Do not use mathematical characters or expressions, Greek or other symbols, and superscripts or subscripts. The size of the text box cannot be exceeded.

New processes have been identified in the interaction of 3-D fields with tearing mode stability in tokamaks that raise concern for H-modes at modest values of normalized beta. These arise from the plasma response at the tearing resonant surface, which is expected to depend on plasma rotation and underlying tearing stability. In experiments on DIII-D and NSTX, response and sensitivity to 3-D field is found to be influenced by proximity to natural tearing stability beta limits, in addition to effects previously observed at high normalized beta or low density described by a kink-like plasma response. An increasing response develops as normalized beta rises, even from very modest values ~1-2, with required fields to induce modes falling to zero as tearing limits are approached. This response is further enhanced at low rotation and torque, with field thresholds to induce modes in torque free H modes at normalized beta of 1.5 being well below those in Ohmic plasmas, or even plasmas above the no-wall ideal kink beta limit, where an enhanced response is expected. Both resonant (n=1) and non-resonant (n=3) types of field are observed to lead to modes with similar levels of applied field. An interaction with neoclassical tearing mode physics is identified, with the neoclassical modes frequently being triggered during the braking phase prior to locked mode onset. A unifying criterion between locked and rotating mode onset mechanisms is proposed, to predict mode thresholds based on torque balance considerations, and this is compared to data. On this basis, the first threshold scalings with main parameters in torque free H modes have been measured, identifying a more favorable density scaling but worse toroidal field scaling, and much lower thresholds in general compared to the previous Ohmic scalings on which ITER is based. The results highlight fascinating new mechanisms and questions in the underlying physics, suggesting a re-evaluation of the performance and operating techniques for next step plasma regimes should be considered. Modeling of these recent results is underway with the MARS and NIMROD codes to test this understanding and confirm that the scale of effects matches current theoretical models.

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