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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. Response and sensitivity to 3-D field is found to be influenced by proximity to natural tearing stability β limits, in contrast with previously observed effects at high β_N or low density, described by a kink-like plasma response [1,2]. An increasing response develops as β_N 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 β_N~1.5 well below those in Ohmic plasmas, or even plasmas above the no-wall ideal kink β_N limit, where an enhanced response is expected [1]. An interaction with neoclassical tearing mode physics is identified, and a unifying criterion between locked and rotating mode onset mechanisms is proposed and compared to data. On this basis, the first threshold scalings with main plasma parameters in torque free H modes have been measured, identifying a more unfavorable toroidal field scaling than for Ohmic regimes [3]. 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.

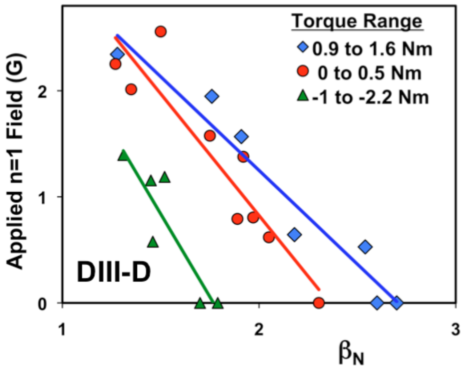

Fig 1: n=1 3-D field required to trigger 2/1 tearing modes vs β_N & torque.

Plasma rotation plays a critical role in shielding out 3-D fields and setting criteria for mode onset. While such fields mainly limit low density (where the plasma is easily stopped) or high β_N (where a kink is driven, amplifying the field) in present devices, next step devices, with relatively low injected torques, may be far more susceptible. There may also be an interaction with neoclassical tearing modes (NTMs), which are known to be more unstable at low rotation. These elements are highlighted by new scans on DIII-D exploring error field sensitivity up to the 2/1 NTM β_N limit as a function of applied torque. Fig. 1 shows two key effects: for a given level of 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); also, for a given β_N, the field threshold falls with injected torque and plasma rotation (which remains in the direction of I_P but is lowest in the negative torque cases). As changes in the β_N limit for such discharges have previously been linked to underlying tearing stability changes and Δ' [4], this behavior suggests the 3-D field interaction itself becomes strongly enhanced in proximity to tearing instability. This interpretation is confirmed by magnetic probing earlier in these discharges (Fig. 2); plasma response to applied field increased substantially with β_N, thus requiring less applied field to cause braking. Careful examination also indicates the response rises at low rotation. This is particularly evident at low β_N and

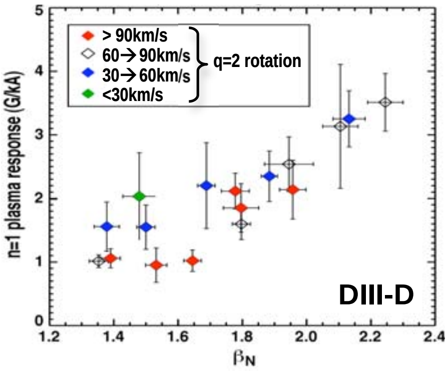

Fig 2: Plasma response to 10Hz n=1 field prior to mode onset.

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 – a different mechanism to recent ideal MHD models of the 3-D field interaction [1,2].

An important further aspect is interaction with the NTM. In most cases in H mode, the 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 effects. Various mixes of 3-D field were applied during β ramps to access the 2/1 NTM. The clearest effect on rotating mode threshold appears to be a trend with rotation shear (Fig. 3), confirming an action of the 3d fields on NTM stability that is similar to effects previously observed in NTM β limit scaling on NSTX [5], but accessed here through the 3-D field braking the plasma. Exploring the interaction in more depth (Fig. 4), both resonant (n=1) and non-resonant (n=3) fields are found to have a similar progressive effect on plasma rotation (and rotation shear) and in triggering the modes. These observations indicate the influence on stability is most likely to be through braking, rather than a resonant interaction at the mode's rational surface. Further, there appears to be a critical ~50% level of braking for modes to form locked, with braking rising increasingly rapidly on the approach to this. This provides a basis for a unifying criteria for the critical field to trigger a mode, much akin to the original Fitzpatrick model [6]. 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 second order.

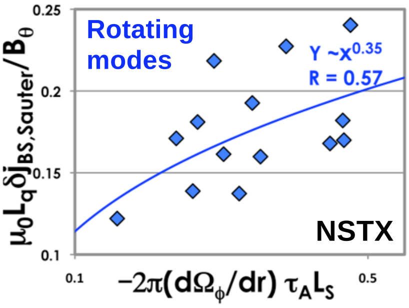

Fig 3: Bootstrap drive vs rotation shear for rotating onset modes.

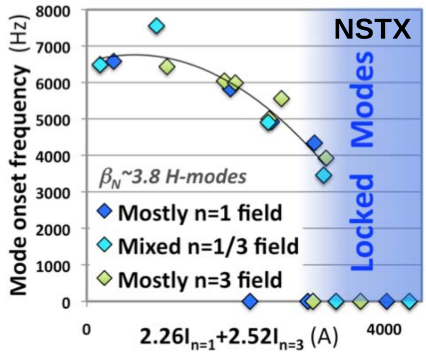

Fig 4: Incidence of modes with various forms and levels of magnetic braking.

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 [3] rotation is treated as a hidden self-generated parameter, its value implicitly assumed to vary (though adding torque would be a method to raise thresholds), and a dimensional constraint is invoked to deduce machine size scaling. While density scaling is slightly stronger and more favorable for next step devices than previous Ohmic scalings, the main difference is with toroidal field (Fig. 5), where the normalized field threshold falls much more strongly than Ohmic scalings, with roughly double the exponent. 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 is underway to explore the physics of this plasma response.

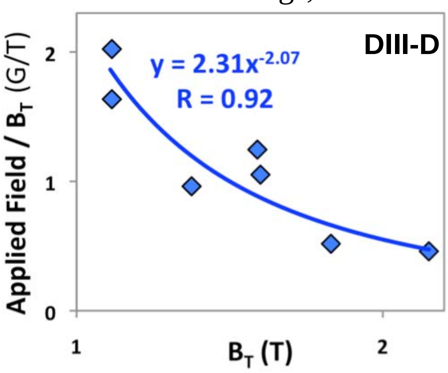

Fig 5: Toroidal field scaling of mode threshold.

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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. 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 contrast with 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, in particular identifying a more unfavorable toroidal field scaling than that previously observed for Ohmic regimes, 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 is underway with a number of codes to explore the issues of plasma response and its dependencies on underlying tearing stability and rotation.

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