Exploration of the means for real-time probing of m/n=2/1 tearing mode stability evolution in the ITER baseline scenario in DIII-D

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1. Introduction

Experiments in DIII-D are developing the basis to sense decreasing tearing stability as a discharge evolves, i.e. before a tearing mode goes unstable with subsequent mode locking, loss of H-mode and disruption. Disruption avoidance is desirable so the mitigation system does not have to be used. The approach to tearing instability is thus needed to predict and interrupt the chain of events that would lead to the need for mitigation.

2. DIII-D ITER Baseline Scenario (IBS) Discharges at Low Torque

Of particular interest is the m/n=2/1 tearing mode in the q_{95}=3.1, β_N=1.8 ITER baseline scenario [1,2]. A modest neutral beam torque was chosen (~1.3 Nm or twice the ITER equivalent) to have a naturally *stable* tearing frequency around 2 kHz. This frequency is just within the capability of both the internal I-coil currents for n=1 magnetic probing and of modulation of electron cyclotron resonant heating (ECRH) at q=2 for probing. The discharges have early turn-on of continuous co to I_p electron cyclotron current drive (ECCD) to the end of I_p flattop applied at q=3/2 with the intent to preemptively stabilize this mode which otherwise could grow and lock at low torque. The interval probed is in I_p flattop with β_N constant from 3 to 5 sec (absent a 2/1 mode) with a q=2 resistive diffusion time τ_R of ~2000 msec, m/n=1/1 sawteeth "crashes" every ~160 msec and edge localized modes (ELMs) every ~ 30 msec. The external C-coil was used for n=1 error field correction with the I-coil run in a dual mode: n=3 DC bias to help keep density down for ECRH (but still allowing ELMs) and n=1 AC for frequency sweeps for resonant magnetic field probing.

3. Passive Probing Methods That Do Not Destabilize

(3.i.) A rotating n=1 field from the n=1 phasing of three quartets of individual "I-coils" was applied. The frequency is repeatedly stepped across the anticipated m/n=2/1 natural mode frequency with the n=1 magnetic plasma response monitored; a larger response is expected at frequency resonance as the tearing mode is closer to being excited [3]. However, coupling to drive n=1 kink modes (even though $\beta_N/4l_i$~0.5 is low) may also be picked up [4-5].

Disadvantages are that wall shielding greatly reduces the applied perturbation and makes detection of the plasma response challenging. Further, switching power amplifiers (SPAs) are limited in current at higher frequency. An example of two consecutive staircase sweeps (one every 250 msec) in the plasma in which the *onset* of the 2/1 tearing mode occurs at the very end of the second sweep is shown in Figure 1. Peaks are increasing in amplitude as the discharge leads up to 2/1 mode onset. As each peak in the response is only captured by one frequency step, the steps are too big. If as much as 0.2 kHz off, the product of the differential rotation $\delta\,\Omega$ and the reconnection time τ_{rec} can be large, i.e., ~10 >>1 for a Sweet-Parker time of 8 msec. While intervals with sawteeth crashes (ST) may facilitate the frequency sweep of the resonance, smaller steps are needed for better resolution.

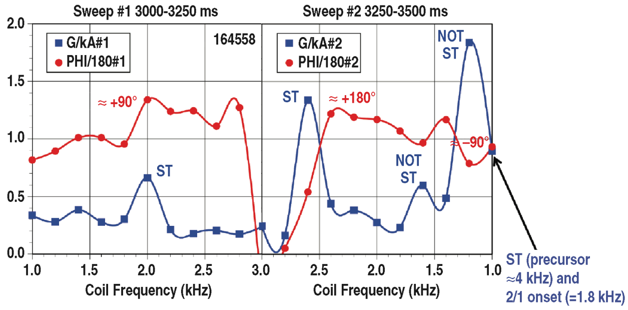

Fig. 1. Cross-correlation of n=1 magnetic response (measured by outboard midplane Mirnov array) at I-coil frequency in slowing rotation plasma indicates stability evolving. Each step is 0.2 kHz for 22 msec. Normalized by auto-correlation of I-coil current to account for decreasing SPA current (~1/f above 1 kHz).

(3.ii.) ECRH near the natural stable mode frequency was modulated to stimulate tearing modes for getting a response. The advantages are no direct change in equilibrium current density (as by ECCD), and that any response on magnetics is due to the plasma only. ECRH causes T_e (and hence p_e) to oscillate in a flux tube [6]. Force balance requires a perturbation to perpendicular current density which requires a perturbation to the parallel current density. This will couple to the (stable) tearing mode. One expects that the toroidal and poloidal location of the ECRH absorption "spot" and not the phase of the ECRH power will determine the phase of the stable mode. A technical difficulty with the plasma control system (PCS) commanding a variable frequency sweep of the gyrotron power on/off required switching to fixed frequency modulation with the plasma rotation swept down by torque adjustment. An example of a measurable resonant response is shown in Figure 2 as the plasma rotation crosses the ECRH modulation frequency and is further "swept" by the

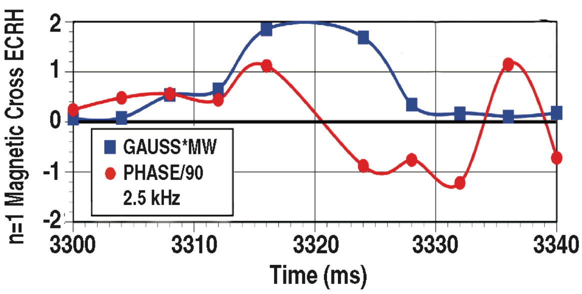

Fig. 2. Cross-correlation of n=1 magnetic response with ECRH power. ECRH modulation at fixed frequency of 2.5 kHz close to the slowly falling proxy tearing mode frequency that is further made transient by a sawtooth crash.

momentum pulse coming out of the core after a sawtooth crash. A 180-degree phase change is seen between the two sides of the peak.

4. Active Probing Methods That Are Intended to Destabilize

(4.i.) CW counter-ECCD at q=2 was *pulsed* to try to destabilize the mode and observe decay-rates to assess the distance to the stability boundary. One looks for the onset of the n=1 mode, its detection by the PCS, a command to turn off the ECCD pulse, and a subsequent mode decay from the magnetics. The decay rate should become slower as stability evolves closer to marginality. However, the counter-ECCD failed to destabilize the mode. Figure 3 shows an example of the counter-ECCD as well as the relative current drive and alignment for the data; substantial ECCD is analyzed to be driven close enough to q=2 for destabilization to be expected [7]. A figure of merit is Y~-1 with X~0 for good effect. In practice, pulses are either too short and/or too weak for destabilization. The inability of short ECCD pulses to destabilize the 2/1 mode obviates this technique in these IBS plasmas unless more gyrotron power is available for destabilization.

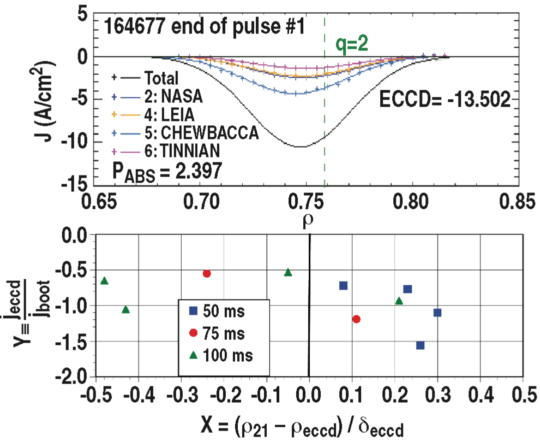

Fig. 3. a) Example of counter-ECCD aligned to q=2 (from MSE-EFIT and TORAY-GA) from 4 gyrotrons. b) EC current drive relative to local bootstrap current density (from analysis code ONETWO) versus relative alignment factor at end of pulses of different duration. Here δ_{eccd} is the full width half maximum of the ECCD.

(4.ii.) β_N was raised by either ramps or in small steps to increase the destabilizing bootstrap current. One looks for the onset of the n=1 mode, its detection by the PCS, a command to reduce the neutral beam heating power back down to lower β_N, and a mode decay from the magnetics. Here, a mode was readily destabilized and at the earliest mode detection the neutral beam injection power and thus β_N were dropped. However, the mode always locked to the resistive (vacuum vessel) wall as the energy confinement time τ_E of ~150 msec (scale for reducing β_N and thus, mode amplitude squared) exceeded the time to lock to the wall (~40 msec). Thus no decay rate could be measured before prompt wall-locking. As seen in Figure 4, there is little difference between the initial β_N (before the increase) and the β_N at mode onset; rather than a beta limit, the stability can be interpreted as metastability in which "seeding" by sawteeth or ELMs exceeds a critical size to grow. Decreasing the underlying

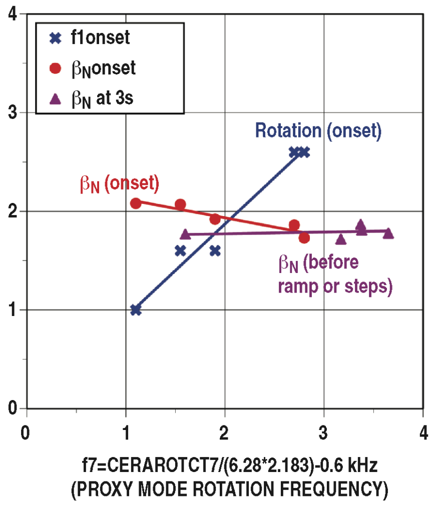

Fig. 4. β_N before ramp or steps *and* at onset of 2/1 tearing mode versus proxy rotation (from CER) at onset. Note that the mode rotation at onset correlates well with the proxy rotation from chord closest to q=2.

classical stability and/or increasing the β_N and thus the helically perturbed bootstrap current both make the critical island smaller, reducing the necessary seeding [8].

5. Conclusions and Future Work

Follow-up work on passive probing in the 2017 DIII-D campaign may include: (1) applying I-coil sweeps with smaller frequency steps for better resolution as well as making use of the new "Super SPA" power supply for more AC current at the ~2 kHz needed, and (2) modulated ECRH frequency sweeps are now checked out and ready in the PCS for application to "constant" natural mode rotation. The inability of short pulses of counter-ECCD to destabilize the mode for evaluation and the prompt locking of the destabilized mode by small beta step-ups makes the passive probing by coils or ECRH the more feasible approaches for application.

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