Magnetic Island Evolution Due to ELM-NTM Coupling in DIII-D

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High performance hybrid discharges with more than 50% noninductively driven plasma current have been realized in ASDEX-U, JET, JT-60U, and DIII-D [1] tokamaks. Although counter-intuitive, the greatest hybrid performance has been found for discharges with multiple core MHD instabilities. Of particular interest has been the observation of sawteeth stability resulting from m/n=3/2 neoclassical tearing modes (NTM) coupling with edge localized modes (ELMs). This coupling causes repeated Alfvénic current profile flattening that corresponds to 3/2 island shrinkage [2]. With each ELM-NTM coupling event, poloidal flux is pumped from the core to the edge across the 3/2 rational surface maintaining the minimum safety factor (q_{min}) above unity [2]. This magnetic flux-pumping is determined by taking an ensemble average of motional Stark effect (MSE) pitch angles 5 ms before, and 5 ms after a series of ELM events. These measurements are then used to directly calculate the change in q-profile using Ampere's law [3]. In this work we will show that 2/1 neoclassical tearing modes (NTMs) also couple with ELMs and produce stronger flux-pumping than 3/2 modes. This work details ELM-NTM coupling and discusses the possibility of improved overall hybrid performance from the presence of a 2/1 mode.

A characteristic of hybrids is the occurrence of stationary plasma conditions for times longer than the current relaxation time. In hybrids where 2/1 NTMs are accidentally triggered and permitted to saturate, it has been found that the current profile and other plasma parameters remain stationary, albeit at lower beta and with poorer energy confinement. Furthermore, sawteeth do not appear in these discharges.

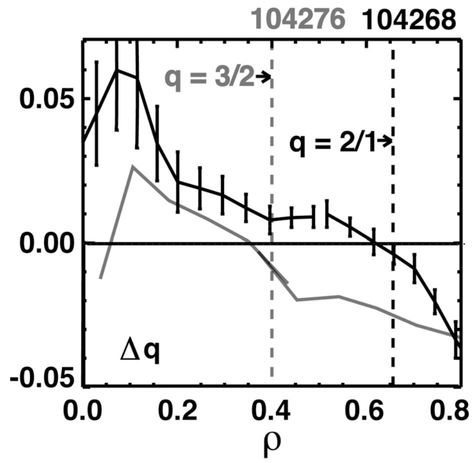

Fig. 1. Change in the safety factor profile measured through direct MSE analysis using Ampere's law and ensemble averaged over 44 ELM events. ρ is the normalized minor radius.

Magnetic flux-pumping analysis shows larger periodic changes in the q-profile for hybrids that develop 2/1 NTMs. Figure 1 shows on average a change in the q_{min} per ELM of just under 0.06, which is more than twice that measured in previous 3/2-hybrid work. This stronger 2/1 flux-pumping should mean that 2/1-hybrids can operate without sawteeth at higher plasma current, or with less frequent ELMing, since a more rapid drop in q_{min} will be countered by a greater flattening of the overall current profile per event. Also, the change in q shows a zero crossing at the 2/1 rational surface.

The n=1 magnetic probe signal shown in Fig. 2 is for a hybrid discharge where a 2/1 NTM was deliberately destabilized by a rapid increase in neutral beam heating. Once the NTM appeared, active suppression of the mode was applied using electron cyclotron current drive (ECCD) focused at the 2/1 rational surface [4]. At ~5700 ms the 2/1 mode NTM is completely suppressed, and sawteeth appear for the first time in the discharge. This is a nearly identical finding as in the 3/2 suppressed case [5]. During the period where the mode is partially suppressed (4500-5500 ms) flux-pumping profiles were present. This suggests that 2/1-flux-pumping maintains sawteeth stability.

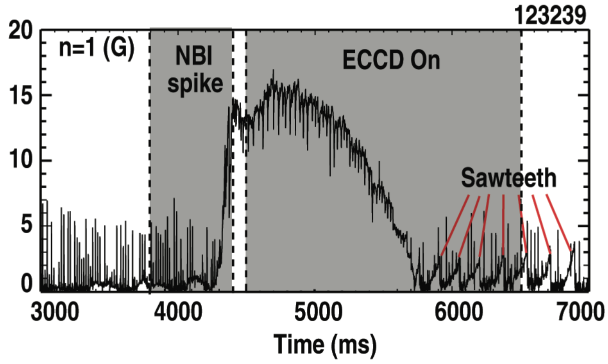

Fig. 2. The amplitude of an n=1 tearing mode followed by sawteeth after complete NTM suppression.

Achieving higher normalized fusion performance in the 2/1-hybrid will require a significant improvement in energy confinement. The island width of 3/2-hybrid NTMs is 6 to 8 cm and according to the belt model [6] degrades energy confinement by 8.3%. A similar sized 2/1 NTM results in considerably larger confinement degradation because of a cubic relationship with the rational surface minor radius. For this reason a 2/1 NTM must be partially suppressed to less than 3 cm wide. However, for low plasma rotation machines like ITER, permissible island widths will likely depend upon the threshold for mode locking [7].

ELM-NTM coupling can be considered in two distinct phases, an Alfvénic timescale drop in the island size followed by a resistive recovery to the original saturated island width. In studying the evolution of the ELM-NTM coupling, saturated 2/1 NTMs were considered. The radial proximity of these modes to the Mirnov magnetic probes produces the largest poloidal magnetic field fluctuation amplitudes, and hence results in the greatest signal-to-noise for studying mode width evolution. Electron cyclotron emission (ECE) radiometry temperature fluctuation, and MSE density fluctuation data were also considered and agree well with probe measurements.

To examine the recovery phase of the ELM-NTM coupling, the simplest form of the modified Rutherford equation [8] (MRE) containing neoclassical effects is taken as,

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \frac{\varepsilon^{1/2} L_q \beta_p}{L_p w} \quad , \qquad L_q = \frac{q}{(dq/dr)} \quad , \qquad \text{and} \qquad L_p = -\frac{p}{(dp/dr)} \quad , \tag{1}$$

where τ_R is the time constant for resistive diffusion within the island region, r is the minor radius of the rational surface, ε is the local inverse aspect ratio at r, β_p is the ratio of kinetic pressure to poloidal magnetic pressure, and Δ' is the classical stability index. By applying an impulse perturbation to the MRE and expanding, an accurate description of the ELM-NTM coupling resistive recovery phase is obtained. The relatively fast impulse at an ELM and the relatively long τ_R in the MRE, suggests an ideal coupling of the NTM to the ELM, which is a peeling/ballooning mode; this could result in a transient negative “pole” in the Δ' term [9]. The evolution of the island width w is taken as,

$$w = w_{sat} - \delta_0 e^{-t/\tau_{relax}} \quad , \qquad \text{and} \qquad \tau_{relax} = \frac{w_{sat}^2 L_p \tau_R}{r^2 \varepsilon^{1/2} L_q \beta_p} \quad , \tag{2}$$

where w_{sat} is the saturated island width, δ_0 is the downward going impulse perturbation, t is time, and τ_{relax} is a time constant describing the relaxation of the island back to a saturated size.

Figure 3 shows excellent agreement between the measured island width and the analytical description of the recovery given by Eq. (2). The relaxation time constant for this discharge is calculated to be 11.3 ms. The drop (δ_o) is not analytically determined and was taken from the local minimum of the measured values for each of the coupling events.

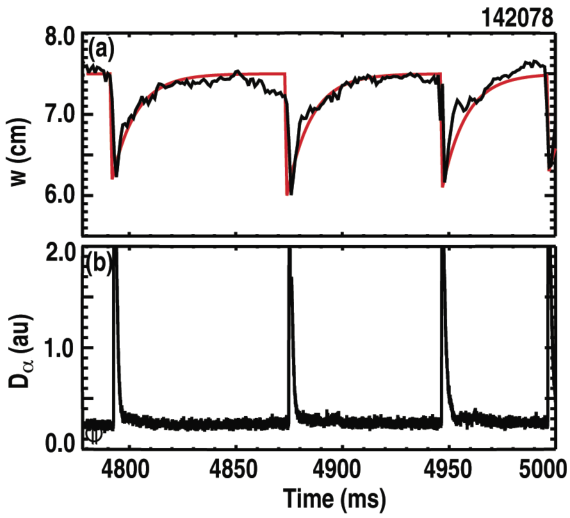

Fig. 3. For ELM-TM coupling events, (a) (black) measured island width (red) analytical expression for the recovery given by Eq. (2). (b) Filterscope measurement of ELM induced D_α emissions.

An empirical analysis shows that the drop in island width increases with the size of the ELM. Identical discharges containing roughly the same size 2/1 islands were considered. By changing the plasma shape, the size and period of the ELMs were varied. Here ELM size is characterized by the loss of plasma stored energy W resulting from each event. The stored energy was measured using a diamagnetic loop located outside the machine vacuum vessel. Figure 4 shows a clear upward trend between the fractional stored energy loss $\Delta W/W$ of the ELM and the fractional drop in the island width $\Delta w/w$. Each point plotted corresponds to a single ELM event. $\Delta W/W$ is calculated by subtracting the W after an ELM from W before the ELM and then dividing by the W before the ELM. An identical procedure is followed for calculating $\Delta w/w$. An alternative ELM size measurement was made using infra-red television camera (IRTV) measurements of the divertor heat flux, and showed good agreement with the diamagnetic loop measurements.

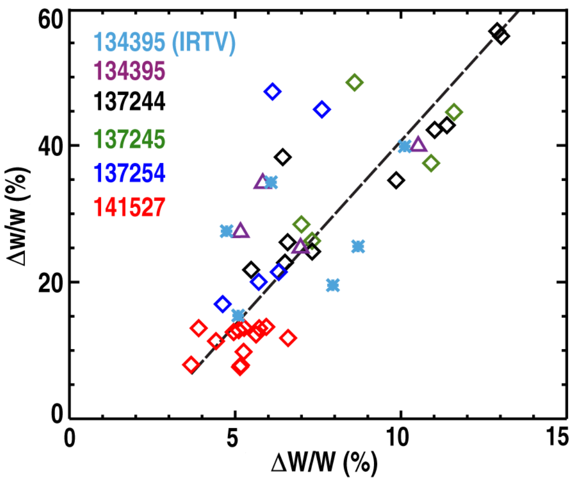

Fig. 4. Fractional drop in the magnetic island width vs. the fractional drop in ELM stored energy measured by diamagnetic loop and IRTV divertor heat flux camera.

Proximity may partly explain this stronger ELM-NTM coupling with larger ELM size. ELM size is related to the radial depth of the most unstable mode [10]. Specifically, the dominant lower order mode numbers of the ELM are located deeper in the plasma and result in greater energy expulsion. Because of their greater depth, larger ELMs also have a greater proximity to core tearing modes improving their interaction. This finding parallels the previously mentioned result that 2/1 NTMs exhibit stronger flux-pumping than 3/2 modes, as 2/1 NTMs are located closer to the ELMing pedestal region.

These findings suggest that a 2/1 hybrid-like discharge may outperform existing 3/2 hybrid discharges. Partial suppression of a 2/1 island should produce a dual effect of improving energy confinement while simultaneously allowing the inherently stronger 2/1 flux-pumping to sustain a flatter current profile without sawteeth.

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