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# Fishbone-like Instability at the Edge of ELM-free Quiescent H-modes in DIII-D

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**Abstract**. Quiescent H-modes (QH-mode) are characterized by edge MHD activity known as the Edge Harmonic Oscillations (EHO). This paper reports the observation of EHOs in the form of chirping modes that resemble fishbone activity.

QH-modes are high confinement plasmas with an edge transport barrier but no Edge Localized Modes (ELMs). This mode of operation, observed in DIII-D [1], ASDEX-Upgrade [2], JT-60U [3] and JET [4] plasmas, is of interest for future nuclear fusion experiments, due to the absence of ELMs in steady state conditions. Unlike ELM-free plasmas [5] where the edge pedestal density increases leading to large ELMs, QH-modes have controlled edge densities and constant radiated power (Fig. 1). Long-lived QH-modes are observed in DIII-D plasmas with durations > 4 s (or 30 $\tau_E$), limited only by hardware constraints [1]. Initially

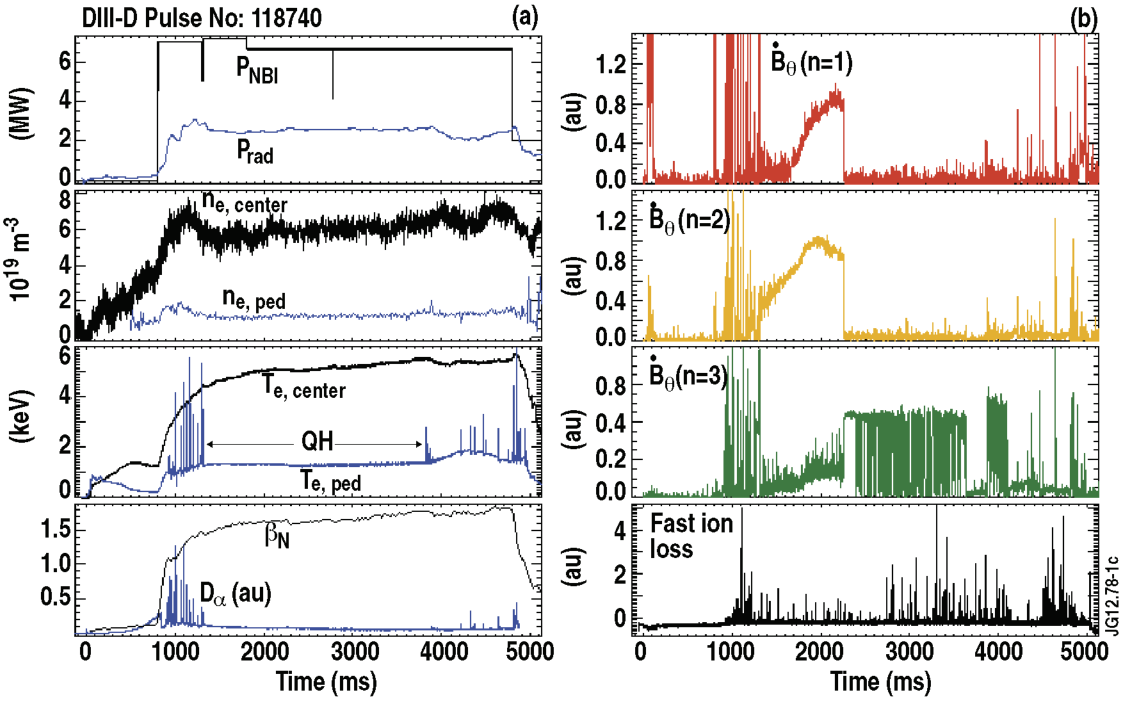

Fig. 1. Time traces from a QH-mode pulse (single upper null, $I_p$ = 1.3 MA, $B_T$ = 2 T, $\langle\delta\rangle = 0.45$, $\kappa = 1.86$, $q_{95}$=4.18, counter NBI). (a) NBI power and total radiated power, chord averaged radial density and density at the top of the pedestal, electron temperature at the centre and top of pedestal, normalized $\beta$ and divertor $D_\alpha$. (b) Magnetic probe signals showing MHD activity with toroidal mode numbers $n$=1–3; signal from beam ion loss detector.

obtained with strong counter-current Neutral Beam Injection (NBI), recent DIII-D experiments have demonstrated that QH-modes can also be obtained with co-injection [6] and in low torque plasmas with balanced NBI [7].

QH-modes are characterized by the EHO, edge MHD activity usually reported as continuous, saturated, coherent modes with low toroidal mode numbers, most dominantly *n*=1–3 [8]. The term EHO has also been applied to a variety of edge MHD activity that appear to delay ELMs by enhancing transport at the top of the pedestal. In some QH DIII-D pulses the continuous coherent modes are substituted by broadband activity [6], while in others reported here, the EHO appears in the form of repetitive bursts resembling fishbone activity.

An experiment performed in 2004 to study the influence of the plasma current in QH-mode stability [9] showed that the EHO was suppressed when the current was ramped-down. This indicated that the EHO behaved as an external kink (or peeling-mode), an interpretation consistent with edge-stability modeling that showed the EHO occurs near the external kink/peeling stability boundary [9,10]. The figures shown here are from the reference pulse for the current ramp down experiments, using dominant counter-NBI. The EHO is initially a continuous mode with dominant toroidal mode number *n*=2, then changes to an *n*=3 bursting mode (Fig. 2), with durations of 10–15 ms and a repetition frequency of ~55 Hz. This sudden change in mode number is not understood. The *n*=3 bursts with decreasing frequency are in anti-phase with *n*=5 bursts that increase in frequency. This may indicate that the *n*=3 and *n*=5 modes are localized on opposite sides of the radial electric field well observed in QH

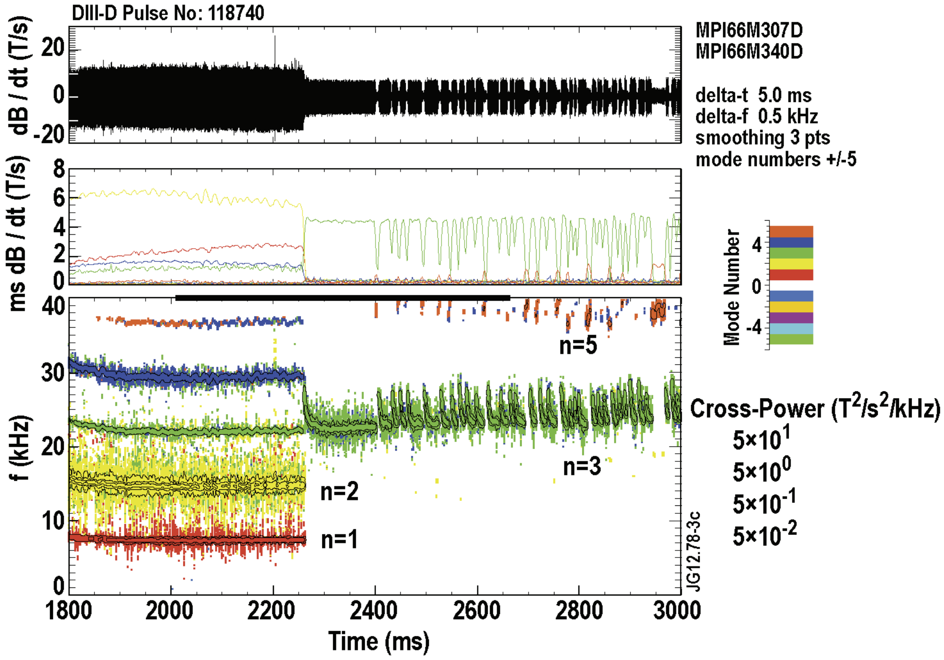

Fig. 2. (a) Magnetic field fluctuations measured on the outboard midplane; (b) amplitude for toroidal mode numbers *n*=1–5 (positive *n* means mode propagation in the direction opposite to $I_p$); (c) spectrogram showing the EHO, initially as a continuous mode with dominant *n*=2, then changing into *n*=3 chirping modes interspaced with *n*=5 bursts.

discharges just inside of the separatrix [11]. Like the continuous EHO, electron cyclotron emission data confirms that both the $n$=3 and the $n$=5 bursts are edge modes, localized within the edge pedestal, in the last 1–2 cm from the separatrix. Both the continuous and bursting MHD modes are effective at maintaining the QH-mode by keeping the edge pressure low. When the $n$=3 bursts are suppressed, for instance by ramping-down the current, the density and pressure at the top of the pedestal starts to increase as observed in ELM-free plasmas.

The chirping nature of the bursts suggests the modes could be driven by NBI fast ions similar to the internal $n$=1 fishbone bursts [12]. The pulse described here has a high fast ion pressure in the plasma core and at the top of the ion temperature pedestal (at $\psi$=0.89) the electron and the beam fast ion pressures are comparable ($P_{\text{beam}}$ = 2.45 kPa, $P_{\text{e}}$ = 3.56 kPa), although at the top of the outer electron pressure pedestal (at $\psi$=0.96), the fast ion pressure is one order of magnitude smaller (Fig. 3). For the $n$=3 bursts, the mode frequency in the plasma frame decreases from ~$n$x11 kHz to $n$x9 kHz. As observed with typical internal fishbones, the mode fundamental frequency is close to the precession frequency of the fast ions. For full energy beam ions that pass near the outer pedestal on trapped orbits, the precession frequency is about 9 kHz for deeply trapped ions and 15 kHz for barely trapped. Losses of NBI fast ions, measured in the midplane, are often observed in QH-modes, associated with the EHO [13] and higher frequency broadband fluctuations [8]. In the example shown here, fast ion losses although observed are not significant and neither the $n$=3 nor the $n$=5 bursts are clearly correlated with the losses. Improved fast ion diagnostics are planned

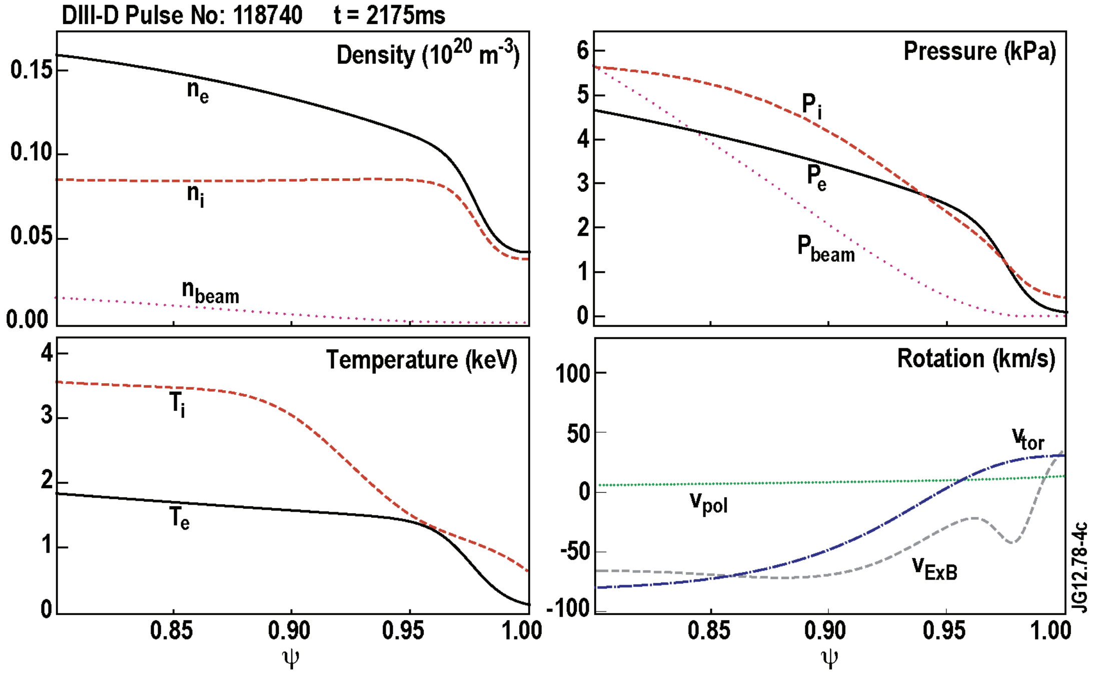

Fig. 3. Plasma profiles near the edge: (a) densities $n_{\text{e}}$, $n_{\text{i}}$ and $n_{\text{beam}}$; (b) temperatures $T_{\text{e}}$ and $T_{\text{i}}$; (c) pressures $P_{\text{e}}$, $P_{\text{i}}$ and $P_{\text{beam}}$; (d) rotation velocities $v_{\text{toroidal}}$, $v_{\text{poloidal}}$ and $v_{\text{ExB}}$. (Electron density and temperature from Thompson scattering laser data; $T_{\text{i}}$ and rotation from charge exchange recombination data. Positive rotation is in the direction of $I_{\text{p}}$, i.e. counter to NBI.)

The EHO has been previously interpreted as a low-n external kink (peeling) mode destabilized by a combination of edge pressure, current and rotational shear [10]. This interpretation is applicable to both bursts and continuous EHOs, as both lie in the same region of the edge stability diagram close to the external kink boundary. However the bursts draw attention to the possible relevance of fast ions in the edge stability of these plasmas, where the external kink (similarly to the internal kink) might have a branch that becomes unstable due to the resonant interaction of the MHD mode with a fast ion population [14]. To test this hypothesis, modeling of external kink stability including kinetic effects as well as the already demonstrated important flow effects [10] will need to be performed. Here we draw attention to possible similarities with observations in JET DT hot-ion H-mode discharges, where bursts of the $n$=1 outer mode, an edge MHD mode interpreted as an external kink, were triggered at a critical alpha particle density as indicated by the ion-cyclotron emission diagnostic [15].

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