Bifurcation of Quiescent H-mode to a Wide Pedestal Regime in DIII-D and Advances in the Understanding of Edge Harmonic Oscillations

EX-D

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In a recent discovery, the Quiescent H-mode (QH-mode) regime in DIII-D has been found to bifurcate into a new state at low torque in double-null shaped plasmas, characterized by increased pedestal height, width and global confinement [1, 2]. This provides an alternate path for achieving high performance ELM-stable operation at low torque, in addition to the conventional QH-mode operation sustained at low-torque with applied 3D fields [3]. Measurements and simulation indicate that in the wide pedestal state, the decreased ExB shear destabilizes broadband turbulence, which relaxes edge pressure gradients, improves peeling-ballooning stability and enables a wider and thus higher pedestal and enhanced confinement. In parallel, new experimental study and modeling [4] of low, experimentally-relevant toroidal mode number (n≤5) Edge Harmonic Oscillation (EHO), which regulates the standard QH edge, validate the proposed importance of rotational shear in exciting the EHO. The ability to accurately simulate the EHO and maintain high performance QH-mode at low torque is an essential requirement for projecting QH-mode operation to ITER.

The wide pedestal QH-mode regime has been sustained at net zero NBI torque and ITER relevant edge parameters for 12 τ_E and with 40% improvement in global confinement over the standard QH-mode [Fig. 1]. The transition to the wider pedestal appears as a bifurcation in the pedestal transport as the injected torque is ramped down in QH-mode plasmas using a balanced double null shape. The bifurcation is characterized by a sudden cessation of the coherent EHO and the onset of broadband edge MHD mode accompanied with a lower edge ExB shear. Increased edge turbulence reduces the pedestal gradient, which further improves the already high edge stability, raising the pedestal width and pressure [Fig. 2] while still remaining below the ELM instability threshold. The wide pedestal state has been sustained without ELMs for both co- and counter-I_p torque over the range +1 to -2 Nm, with reactor-relevant parameters of β_N=1.5-2.3, H_{98y2}=1.2-1.6 and pedestal ν_e^*=0.2-0.4.

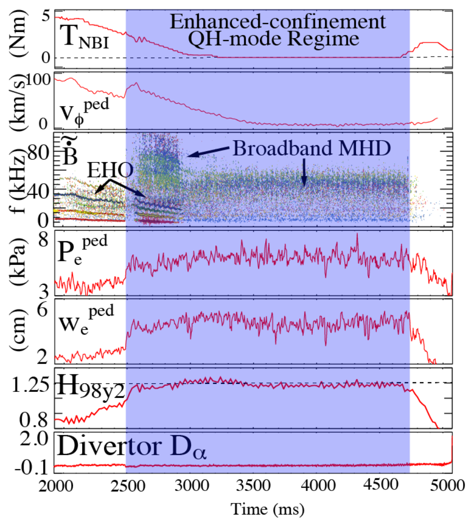

Figure 1: Time evolution of injected torque (T_{NBI}), toroidal rotation at pedestal top ($V\phi^{ped}$), MHD activities, pedestal height (Pe^{ped}) and width (We^{ped}), global confinement (H_{98y2}), and Dα signal in shot 163518.

The bifurcation in the pedestal transport occurs as the ExB rotation shear in the pedestal is reduced. Combining multiple diagnostics reveals two branches of the broadband fluctuation that regulates the wide pedestal QH edge: (1) a low-k, low-frequency ($k_\theta\rho_s$≲0.05, 10-100 kHz) ion-directed branch that extends over the whole pedestal and peaks near the separatrix, and (2) an intermediate-k (0.7<$k_\theta\rho_s$<1.2) electron-directed branch that is localized near the

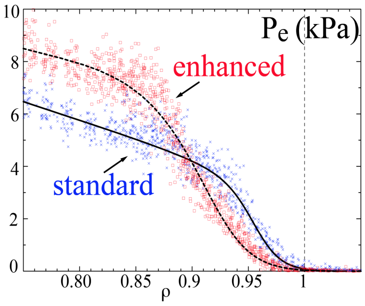

Figure 2: Pedestal pressure before (t=2350ms) and after (t=4300ms) the transition in discharge 163518

pedestal top. The increased edge turbulence-driven transport ($\rho \gtrsim 0.9$) reduces the pressure gradient below the kinetic ballooning mode stability limit, which is usually assumed to set pedestal gradients for standard H- and QH-mode regimes in the EPED model. This raises peeling-ballooning thresholds over EPED projections, as stability drives and sinks integrate over a larger volume [Fig. 2]. Meanwhile, inside of the pedestal ($0.8 \lesssim \rho \lesssim 0.9$) lower transport is observed due to turbulence suppression by the locally increased ExB rotation shear, similar to NTV-aided QH-mode with low NBI torque [3]). The higher pedestal and improved outer-core ($0.8 \lesssim \rho \lesssim 0.9$) transport synergistically boost the plasma confinement factor H_{98y2} by up to 45% over the standard QH regime.

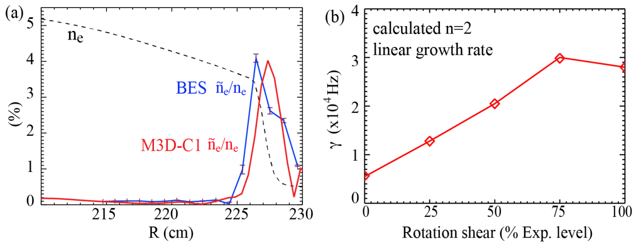

Figure 3: (a) The radial mode structure comparison between M3D-C1 modeling and BES measurements. (b) The calculated linear growth rate of n=2, the dominant EHO component observed in the experiment, increases with rotational shear.

A key advance has also been made in the validation of the rotational shear as additional drive of the EHO. EHO is thought to be a low-n kink/peeling mode driven by edge current and rotation shear. While the current drive mechanism has been demonstrated in previous current ramp experiments, the rotation drive is actively being studying. The low-n ($n \leq 5$) EHO has been modeled for the first time using the 3D resistive MHD code M3D-C1, which allows a direct comparison with experiments [4]. The calculated linear eigenmode structure matches closely the EHO characteristics from external magnetics data and internal measurements from the ECE, BES, ECE-I and MIR diagnostics [Fig. 3a]. Numerical investigations indicate that the low-n EHO-like solutions are destabilized by the rotation shear [Fig. 3b] while high-n modes are stabilized, independent of the rotation direction. The least stable mode at the experimental rotation level agrees with the detected dominant EHO component. The modeling results are consistent with the theoretical picture of the EHO being destabilized by rotation shear, explaining the disappearance of the EHO (and recurrence of ELMs) often observed at low torque, its occasional recurrence and eventual disappearance in the wide pedestal QH regime (for example, from 2590-2840ms in Fig. 1). Torque scan experiments at fixed collisionality find the EHO ceases at the same edge rotation and rotation shear level regardless of the torque ramp rate, supporting this hypothesis. The limitations in NBI torque in standard QH-mode can be overcome by applying 3D fields to drive NTV torques in the pedestal [3].

To conclude, a new demonstration of high QH-mode performance at low torque and a more rigorous understanding of the mechanisms regulating the pedestal to improve confinement and stability have strengthened the physics basis for achieving high performance, ELM-stable discharges in future burning plasmas with low torque and collisionality.

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