Wide Pedestal Quiescent H-mode Plasmas in DIII-D Tokamak

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Quiescent H-mode (QH-mode) is a naturally ELM-stable high performance operation mode which has been obtained in DIII-D, ASDEX Upgrade, JET, and JT-60U [1 and references within]. The additional transport to maintain constant density and radiation is provided by the benign coherent edge harmonic oscillations mode (EHO) [2] which is thought to be a kink/peeling mode [3]. A new QH-mode regime with enhanced pedestal has been discovered in DIII-D at reactor-relevant low torque and collisionality [4]. The regime was originally found in conventional QH-mode when the counter-Ip neutral beam torque drops to ~2Nm in double null plasma shapes. It is referred to as 'wide-pedestal QH-mode' because the pedestal width exceeds the EPED kinetic ballooning mode (KBM) limit [5]. Across the transition from QH to wide-pedestal QH, the pedestal electron pressure generally increases by 60% and widens by 50% and the plasma confinement (ITER Hy_{98y2}) rises by 40%. The onset of broadband edge MHD modes and micro-turbulence accompanied with a lower ExB shear in this region is a common feature of the wide-pedestal QH, instead of EHO. It is conjectured that the increased transport provided by these edge modes reduces the pedestal gradients resulting in a higher pedestal while still remaining below the ELM-limit. Since its discovery, several experiments have been conducted in DIII-D to explore its operational space with emphasis on parameters that are practical for the utilization of wide-pedestal QH-mode in other present-day devices, and for its application to ITER and burning plasmas.

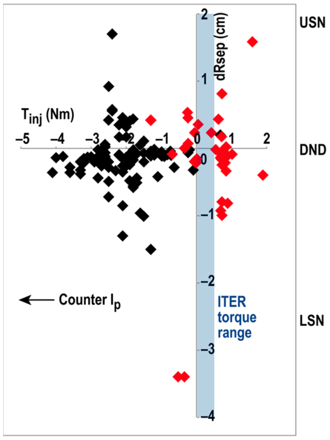

Figure 1: Operating space of wide-pedestal QH-mode (black: access; red: sustain)

The neutral beamline configuration in DIII-D allows (a) independent variation of the input NBI torque and power and (b) a range of net-torque from co- to ctr-Ip direction using a combination of co- and counter-NBI. The wide-pedestal QH regime was originally discovered in conventional QH plasmas when the net counter-NBI torque was reduced to a level of ~2Nm. To date, this regime has been accessed with NBI torque ranging from 4.1Nm conter- to 0.7Nm co-current, and has been sustained over even broader range from 4.1Nm-ctr to 1.9Nm-co (Fig. 1). Note that there were no 3D magnetic fields applied in these experiments except that for error field correction (EFC). The operating torque range for wide-pedestal QH exceeds the scaled DIII-D torque range that is equivalent to the anticipated torque range in ITER using the scaling in Ref. 6.

If wide-pedestal QH-mode is to be used in future devices, we need also to demonstrate zero torque startup. Wide-pedestal QH with net zero torque throughout the whole discharge has been attained on DIII-D [7]. As illustrated in Fig. 2(#174658, red), the initial formation phase has only net-0.04Nm co-NBI while the sustainment phase has only net-0.06Nm ctr-NBI. Note results presented in this paper all have plasma current and toroidal magnetic field in the same direction (clockwise). The small finite non-zero torque resulted from the uncertainty associated with the beam output even though it was commanded to net zero torque. These discharges are stationary for more than 20τ_E (limited only by NBI duration) with reactor-relevant plasma conditions (β_N=1.75, H_{98y2}=1.25, $\nu_{*,ped}$=0.3-0.4) in DN shape. With similar input power, the pedestal height and width of wide-pedestal QH, accessed with zero torque (red), reached similar values as those accessed during a ramping down of the torque (black). Although zero torque operation of wide-pedestal QH does not require 3D fields application (except for EFC) (e.g., #163518), these zero torque start-up discharges benefit from neoclassical toroidal viscosity (NTV) torque generated by applied 3D fields. The NTV torque provides enough toroidal rotation to avoid locking at low torque, for example, in #174658, the external coils are switched on shortly after the transition from L-mode to wide-pedestal QH-mode, the edge of plasma remains ctr-rotating even at zero NBI torque. The good wall condition (low collisionality), good EFC, and excellent edge stability limit from high shaping (high triangularity) also contribute to the success of access wide-pedestal QH-mode with zero torque.

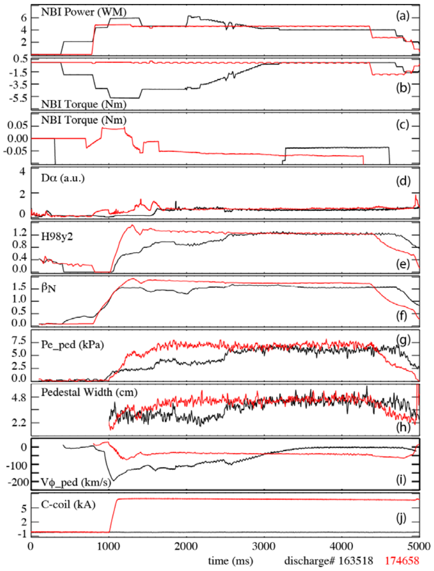

Figure 2: Time trace of (a) NBI power, (b) and (c) NBI torque, (d) Dα signal, (e) H98y2, (f) β_N, pedestal electron (g) pressure and (h) width, (i) pedestal rotation velocity, (j) c-coil current in wide-pedestal QH discharges: #163518 (black) accessed with torque ramp down and #174658 (red) with zero torque start-up

The wide-pedestal QH-mode was originally discovered in balanced double null (DN) shape, with dRsep~0 (dRsep is the radial distance between the flux surfaces connected to the upper and lower x-point at the outer midplane). The same torque ramp experiments conducted in upper single null (USN) shape with dRsep ~ +2cm resulted in loss of coherent EHO and occurrences of ELMs at low torque [8]. New experiments have been carried out to explore the operating space in terms of plasma shape, especially towards more ITER-relevant lower single null (LSN) shape. Wide-pedestal transition has now been seen in a range of plasma shapes including USN, DN and LSN, in terms of dRsep, ranging from -1.5cm to +1.6cm. Furthermore, the wide-pedestal QH-mode has been sustained in a wider range of dRsep, from -3.4cm (LSN) to +1.6cm (USN) as illustrated in Fig. 1. For the LSN shape with dRsep= -3.4cm, the average triangularity δ_{avg} is ~0.44 similar to the ITER target δ_{avg}.

No power limit was observed in the conventional QH-mode with coherent EHO such that the plasma remains ELM-stable until the input power reaches the core beta limit [2]. Previously, ELMs were observed in those discovery experiments of wide-pedestal QH-mode when the input power was increased by ~35% [4]. No ELM occurs in the new experiments with higher power but lower density than those original discovery experiments. This suggests that the return of ELMs in those previous experiments might be associated with the higher density rather than the higher power, similar to the conventional QH-mode where the pedestal pressure increases with density and ELMs appear at high density. New NBI power scan experiments at moderate density are conducted and the stationary wide-pedestal QH-mode is produced over the entire power range studied (3.9-5.5MW). The highest NBI power in these experiments is limited because the total torque is kept near zero while there is only one beamline directed opposite to the other three.

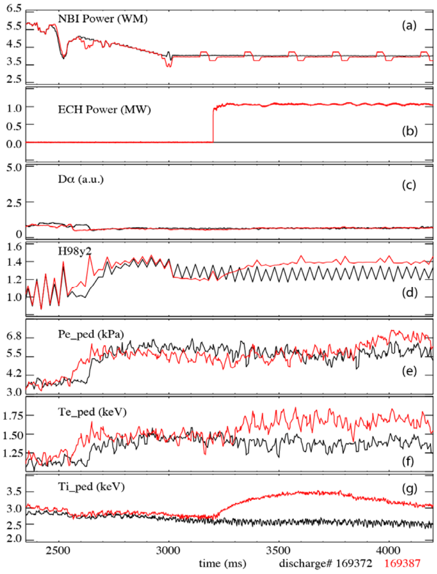

Figure 3: Time trace of (a) NBI torque, (b) ECH power, (c) Dα signal, (d) H98y2, pedestal (e) electron pressure, (f) electron temperature and (g) ion temperature in discharge #169372 (black) and 169387 (red)

Unlike other H-mode plasmas on DIII-D which suffer reduced confinement and performance at low torque and rotation, wide-pedestal QH favors low torque similar to the conventional QH-mode. In the highest power case mentioned in the previous paragraph, β_N reaches 2.3 and H98y2 reaches 1.6 simultaneously. Another interesting observation is that the H98y2 scaling increases with power while the global energy confinement time τ_E in wide-pedestal QH is independent of input power.

Using RF heating is another way to operate at low torque thus we also start to investigate the compatibility of wide-pedestal QH with ECH injection. In contrast to most H-mode and conventional QH-mode on DIII-D where confinement generally degrades with ECH, additional confinement improvements in both core and pedestal with ECH injection have been observed in some wide-pedestal QH-mode discharges. An example is shown in Fig. 3 where 1MW ECH is injected into the core (deposited around $\rho \sim 0.25$) of a wide-pedestal QH-mode (#169387) which has 4MW NBI power. Both the pedestal pressure and global confinement factor (H_{98y2}) grow higher compared to early in the discharge or a similar discharge (#169372) without ECH injection. The pressure increase is mostly from the temperature raise which is seen in both electron and ion channels. The discharge remains ELM-stable and has little change in rotation with ECH injection. Increased E×B shear just inside the pedestal combining with core profile stiffness is thought to improve confinement with ECH.

The role of edge magnetic and density fluctuations in forming the wide pedestal is being studied. The broadband MHD is composed of two counter-propagating low-*k* branches [8] while the intermediate-*k* density turbulence propagates in the electron-direction (lab frame) and oscillates periodically [9]. A flat spot is observed in the pedestal profiles of wide-pedestal QH-mode, especially that of the electron temperature. The location of the flat spot is close to the location of the peaking of the amplitudes of some of these edge modes (Fig. 4). Linear and non-linear simulations are carried out to investigate these modes.

Low torque (low rotation) operation has been very challenging where RMP-ELM suppression is lost and plasmas often suffer confinement degradation and/or lock modes. Wide-pedestal QH-mode might be a solution for this. We are working on understanding the physics for its low rotation access and further extending it to lower q_{95} (so far it has been obtained $4.7<q_{95}<7.5$ and 3.8 transiently) and in condition with plasma current and toroidal magnetic field in opposite directions.

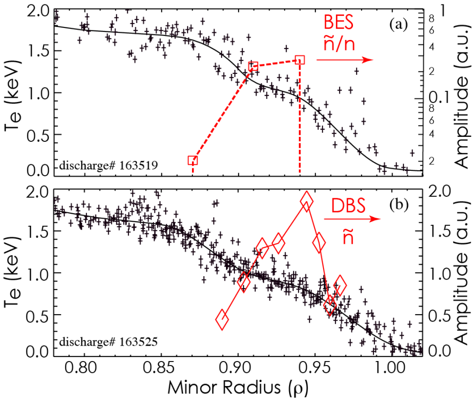

Figure 4: Electron temperature profiles and density fluctuations of (a) low-k (lab frame) electron-directed MHD meassured by BES and (b) (lab frame) electron-directed intermediate-k turbulence measured by DBS in discharge 163519 and 163525

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