High β, High Confinement, Stationary ELM-free Operation at Low Plasma Rotation

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Experiments on the DIII-D tokamak have achieved for the first-time stationary edge localized mode (ELM)-free plasmas with simultaneous high β, high confinement, and low plasma rotation [1]. These experiments successfully combine the physics of quiescent H-mode (QH-mode), for constant density operation without ELMs at the maximum possible stable pedestal pressure, with the physics of 3D magnetic fields to tailor the rotation profile to achieve large $E \times B$ shear near the edge even with no net injected neutral beam torque and overall low levels of rotation.

H-mode confinement is necessary to achieve fusion performance goals in future burning plasma devices such as ITER. However, the pulsed heat loads from ELMs in standard H-mode would rapidly erode divertor tiles in ITER or DEMO. QH-mode offers a potential solution by operating without ELMs with constant density and radiated power, and at H-mode confinement levels (ITER $H_{98y2}>1$). QH-mode has been seen in a number of devices (DIII-D, JET, JT-60U, ASDEX-U) and over a wide range of input power essentially going from the L-H power threshold up to the core β limit. Key to QH-mode operation is the edge harmonic oscillation (EHO), a benign, edge localized, electromagnetic oscillation that replaces the role of ELMs for edge particle transport [2]. Theory [3] identifies the EHO as a nonlinearly saturated kink-peeling mode, destabilized by rotational shear before the edge reaches the zero-rotation stability boundary. As the instability grows, its drag against the nearby resistive wall increases, thus reducing the edge rotational shear. This feedback loop allows the instability to saturate and reach a steady state condition known as the EHO, without large transient events.

The rotational shear effect is predicted to be independent of the direction of the plasma rotation, and indeed QH-mode has been accessed both with large co-I_p and large counter-I_p neutral beam injection (NBI) torque, as long as the pedestal velocity shear exceeds a minimum value [4]. More recent experiments [1] indicate that the important quantity in maintaining a QH-mode edge is the shear in $\omega_E = E_r/RB_\theta$ (the toroidal component of the $E \times B$ drift), rather than the shear in the measured rotation of the carbon impurity ions (commonly assumed as a proxy for the fluid rotation).

With only NBI to generate the pedestal velocity shear, QH-mode access would be precluded in future burning plasma devices, which are likely to use only small co-I_p NBI torque or no NBI. For example, the expected NBI torque in ITER is equivalent on DIII-D to a very small NBI torque, <1 Nm, according to the equivalence criterion in [1]. Furthermore, NBI may not be used in a DEMO reactor, because the large ports for NBI subtract outboard area that is very valuable for tritium breeding, and because the NBI ducts and sources significantly extend the tritium containment boundary and its cost.

Non-resonant magnetic fields (NRMFs) offer an alternate means of driving rotation without NBI torque. According to neoclassical theory, confirmed in DIII-D experiments [5], NRMFs applied to a plasma with initial velocity near zero can accelerate the rotation in the counter-I_p direction. This NRMF-driven counter torque can maintain larger edge counter-rotation for a given NBI torque, and extend QH-mode duration down to lower NBI torque than is possible without NRMF, as shown in Fig. 1. In these discharges the NRMF is an n=3 field applied with the I-coil, a double-row set of non-axisymmetric coils internal to the vessel. Further experiments have shown that a larger counter torque can be driven by the n=3 field from the DIII-D C-coil, a single-row set of non-axisymmetric coils external to the vessel.

In general, no adverse impact of the NRMF on the global energy confinement is observed, other than a transient dip often observed at the time of the field application. Figure 2 shows a set of discharges, all without core MHD modes, and all with applied NRMF. Virtually all such QH-mode discharges show an improvement in confinement at low NBI torque and rotation, independent of the NBI torque ramp rate and even accounting for differences in the beam absorption between co- and ctr-NBI. This result is somewhat surprising, because the confinement quality of other H-mode plasmas in DIII-D is generally reduced with lower NBI torque and rotation. For example, the confinement quality H_{98y2} in advanced inductive scenario plasmas is reduced from >1.5 to approximately 1.0 as the NBI torque is reduced from all co-NBI sources toward balanced injection, with no obvious evolution in the q-profile. [6].

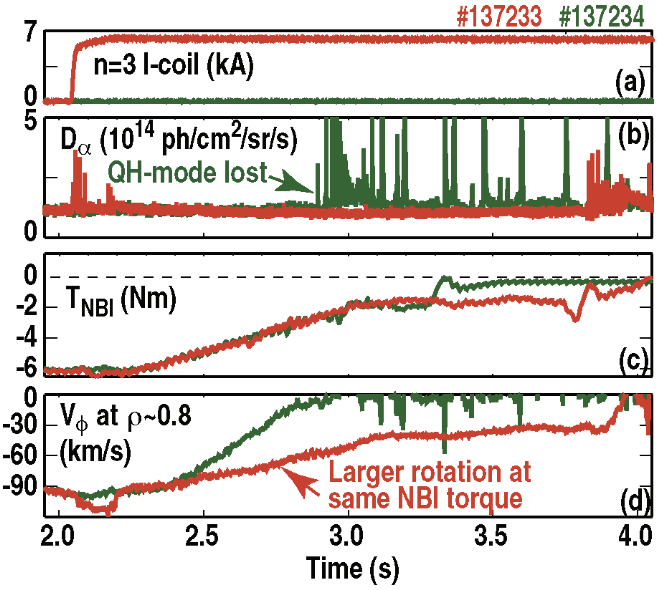

Fig. 1. Comparison of time traces for discharges with (red traces) and without (green traces) n=3 NRMF. An NBI torque ramp-down is used to investigate minimum torque and rotation requirements for QH-mode operation. Edge rotation and QH-mode are maintained at lower NBI torque with the n=3 NRMF (red).

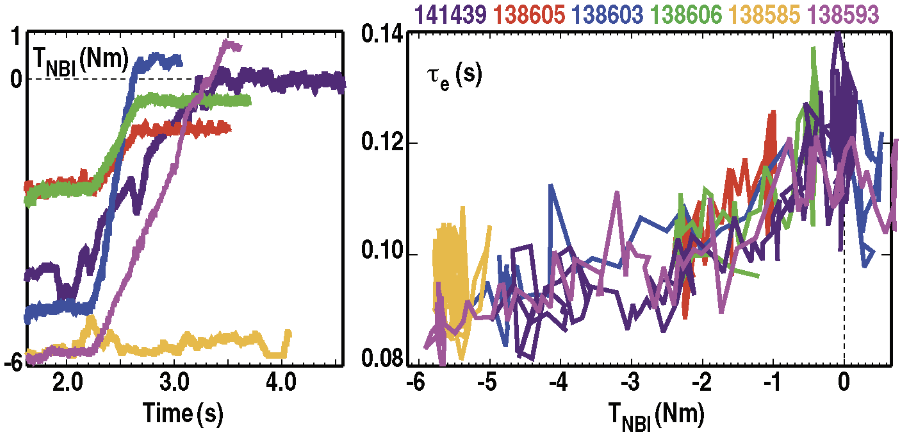

Fig. 2. (a) Time histories of the injected neutral beam torque and (b) plot of the energy confinement time vs the neutral beam torque for a set of discharges with NRMF applied. The confinement increases with decreasing NBI torque. All discharges are MHD quiet, except for the EHO that characterizes QH-mode.

Reduced density fluctuations at ρ≥0.8 have been observed to correlate with the improved confinement observed in low-rotation QH-modes [1]. Owing to differences in the NBI and NRMF torque profiles, the edge $E \times B$ shearing rate at ρ≥0.8 actually increases at reduced rotation and NBI torque. The measured shearing rate is comparable to TGLF calculated linear turbulence growth rates, therefore the observed improved confinement is consistent with the paradigm of sheared flow stabilization of turbulence [7].

There are several identifiable requirements that should be satisfied in ITER in order to access QH-mode. For example, the plasma edge should operate on the kink-peeling boundary of pedestal stability, and the edge rotation shear should exceed the minimum required for QH-mode. The EPED1 model [3] can be used to predict edge pedestal height and width for various assumed pedestal density. Calculations (Fig. 20 in Ref. 8) show that the ITER edge will be on the kink-peeling stability boundary for any foreseeable value of the density, and therefore ITER's pedestal will be in the QH-mode parameter range of collisionality and beta. With regards to the edge rotation shear requirement, recent DIII-D experiments have demonstrated QH-mode plasma operation with large edge counter-rotation even with NBI torque levels from zero-net up to exceeding the ITER equivalent co-I_p NBI torque on DIII-D. These plasmas use n=3 NRMFs applied by the external coil set (C-coil), i.e. a coil similar to the ITER error field correction coil (EFCC). The neoclassical counter-I_p torque from the applied NRMFs provides both the edge rotation shear necessary for QH-mode, and a stabilizing effect against locked modes. One such discharge is shown in Fig. 3. The plasma has an ITER-similar lower single-null cross section shape, ITER-relevant value of β_N~2.0, ν^*_{ped}~0.05, and β_T^{ped}~1%, and shows excellent confinement quality H_{98y2}=1.3 even though the core toroidal rotation is near zero.

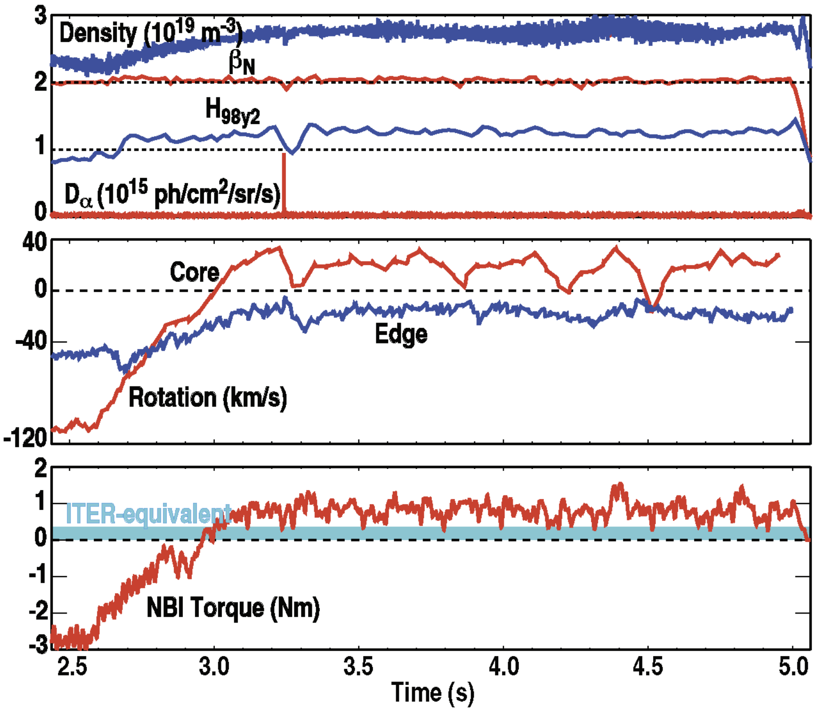

Fig. 3. Time histories of plasma parameters for discharge 149220, demonstrating ELM-free QH-mode operation sustained for >10 energy confinement times with constant density, excellent energy confinement quality, and counter-I_p edge rotation with co-I_p NBI torque exceeding the ITER equivalent level on DIII-D (3.3≤t≤5 s). The C-coil NRMF is applied until t=4.9 s.

Experiments have also begun the development of QH-mode plasmas operating with lower q_{95}, for higher values of the normalized fusion performance $G=\beta_N H_{89}/q_{95}^2$ [8]. Using the C-coil to apply NRMFs, QH-mode at the value of G=0.4, which is the desired value for Q=10 operation in ITER, has been obtained (Fig. 14 in Ref. 8). In this case the NBI torque is still slightly in the counter-I_p direction, i.e. outside the ITER-equivalent range. However, in another case, QH-mode with G≤0.4 was obtained transiently with small co-I_p NBI torque (duration ~τ_L). Upcoming experiments are planned to continue developing this high performance QH-mode target as an operating mode for ITER, including developing a plasma formation approach consistent with ITER-similar constraints.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698, DE-AC02-09CH11466, DE-AC52-07NA27344, and DE-FG02-04ER54761.

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