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# Reactor-relevant Quiescent H-mode Operation Using Torque from Non-axisymmetric, Non-resonant Magnetic Fields

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The promise of quiescent H-mode (QH-mode) as a viable operating regime for future burning plasma devices including ITER has been enhanced considerably in recent DIII-D experiments that extended the envelope of QH-mode operation to include co-$I_p$ neutral beam torque at reactor relevant levels. Exploration of the new operating space has shown these plasmas to have excellent confinement quality and to reach normalized fusion performance consistent with that needed for $Q$=10 operation in ITER. These results were achieved by utilizing the torque due to neoclassical toroidal viscosity (NTV) [1] produced by non-axisymmetric, non-resonant external magnetic fields to maintain strong edge counter-$I_p$ rotation even when the neutral beam injection (NBI) torque is co-$I_p$. Through this technique, we have provided a first demonstration of stationary, QH-mode plasmas without edge localized modes (ELMs) with NBI torque at the equivalent level and in the direction expected in ITER. In addition, QH-mode plasmas have simultaneously demonstrated the reactor requirements of stationary, constant density operation without ELMs at the maximum possible stable pedestal pressure and with particle transport rapid enough for helium exhaust [2]. Using $n$=3 non-resonant magnetic fields (NRMF), recent experiments have achieved long duration QH-modes with NBI torque from counter-$I_p$ up to co-$I_p$ values of 1-1.3 Nm. Scaling from ITER, this co-$I_p$ torque is 3 to 4 times the NBI torque that ITER will have [1]. The example in Fig. 1 illustrates that the discharge remains in QH-mode with a co-$I_p$ torque slightly greater than the ITER value. These experiments utilized an ITER-relevant lower single-null plasma shape, exhibited excellent confinement quality $H_{98y2}$=1.3 and were done with ITER-relevant values of $\nu^*_{\mathrm{ped}}$~0.1 and $\beta_T^{\mathrm{ped}}$~1%. In preliminary experiments using $n$=3 fields only from a coil outside the toroidal coil, QH-mode plasmas with low $q_{95}$=3.4 have reached normalized fusion gain values of $G=\beta_N H_{89}/q_{95}^2$=0.4, which is the desired value for ITER.

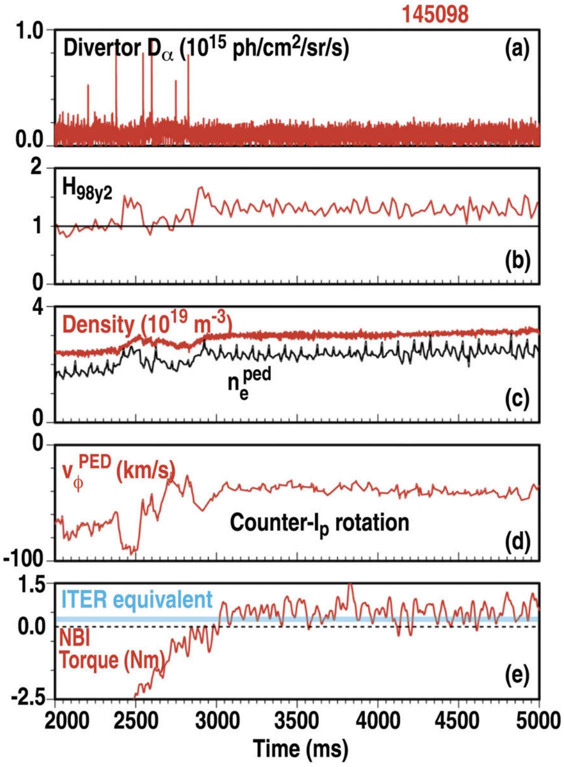

Fig. 1. Shot showing QH-mode operation without ELMs for 2 s with constant density, good energy confinement and counter-$I_p$ pedestal rotation with co-$I_p$ NBI torque somewhat above the ITER equivalent level produced using counter-$I_p$ torque from NRMF. NRMF is on throughout time shown.

QH-mode is a robust operating mode which was first discovered in DIII-D and has subsequently been investigated on ASDEX-U, JET and JT-60U. The key to QH-mode operation is the presence of an edge electromagnetic mode, the edge harmonic oscillation (EHO), which provides the extra transport to allow the edge plasma to reach a transport equilibrium with edge pressure gradient and current density just below the ELM limit [3]. Experimental results are consistent with the theoretical prediction that the EHO is a kink-peeling mode that is destabilized by edge rotational shear at edge conditions near but below the ELM limit [3]. Even though QH-mode is easier to create with counter-$I_p$ NBI, a successful prediction of this theory is that QH-mode operation is possible with either sign of the NBI torque, provided the torque is large enough to produce sufficient edge rotational shear [3]. At the relatively low co-$I_p$ NBI torque of 1 Nm, the edge rotational shear with NBI alone is insufficient to maintain the EHO. By adding a counter-$I_p$ torque from the NRMF, the results in Fig. 1 illustrate that we can maintain counter-$I_p$ edge rotation even when the NBI torque is co-$I_p$. A more dramatic illustration of the effect of the NRMF is shown in Fig. 2, which demonstrates that in these cases the NRMF allows counter-$I_p$ rotation across most of the plasma and, more importantly, creates a significant shear in the edge rotation.

Scans of the NBI torque in the steady portion the discharge [cf. Fig. 1(e)] showed that QH-mode could be sustained for a continuous torque range from counter-$I_p$ up to co-$I_p$ torques of 1-1.3 Nm for the particular plasma and NRMF configuration in this experiment. The behavior of the rotation after the shot passed the torque limit is consistent with the previously identified local peak in the NTV torque at slightly counter-$I_p$ rotation [4]. Previous work on the magnitude of the NTV torque also agrees with theory [1].

DIII-D is equipped with two non-axisymmetric coil sets which were used in these experiments to both create the $n$=3 NRMF and correct intrinsic $n$=1 error fields. One coil set ($I$-coil) is located inside the vacuum vessel and the other ($C$-coil) is located outside the toroidal coils. Consistent with theoretical predictions that the $C$-coil should produce greater NTV torque, our best shots to date used the $C$-coil to produce only $n$=3 NRMF; this was supplemented by additional $n$=3 NRMF from the $I$-coil whose magnitude was constrained by the need to also do $n$=1 error field correction. The plasmas in Figs. 1 and 2 used this configuration. Plasmas which use only the $C$-coil for the $n$=3 NRMF were also investigated, since it would be easier in future devices to engineer coils for NRMF if they were located outside the toroidal coil. Preliminary experiments in this configuration have achieved QH-mode at zero net NBI torque. This coil configuration was also utilized to investigate low $q_{95}$=3.4 discharges, which reached a fusion gain of $G$=0.4. For these cases, $q_{95}$ was decreased by ramping down the toroidal field during the shot. The fusion gain and torque limits for this NRMF coil configuration remain to be determined.

Peeling-ballooning mode stability analysis of previous QH-mode discharges indicate that they operate very close to the peeling stability boundary [2,3]. Our recent shots with NRMF also operate along this boundary [1,4]. Utilizing the EPED1 model, peeling-ballooning stability calculations for ITER indicate that the H-mode pedestal in ITER will also operate along this boundary at the pedestal densities needed to produce significant fusion power [4]. Accordingly, both the recent experimental results and this theoretical prediction indicate that QH-mode with NTV torque from NRMF is an attractive potential operating mode for future burning plasma devices including ITER.

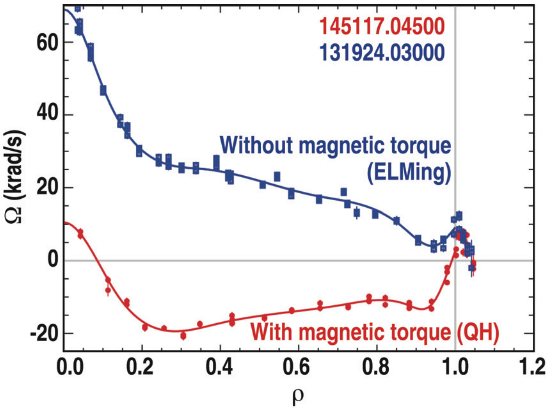

Fig. 2. Radial profiles of the $C^{+6}$ angular rotation speed $\Omega = V\varphi/R$ for two different discharges, a QH-mode one with and an ELMing H-mode one without magnetic torque from NRMF. The comparison is made under steady conditions with approximately the same co-$I_p$ NBI torque of 1.5 Nm.

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