Transport in the DIII-D Steady-State Hybrid Regime as the Torque is Decreased and Electron Heating Increased

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DIII-D steady-state hybrid plasmas are high-performance H-mode discharges with $\beta_N \leq 3.7$ and $H_{98y,2} > 1$, an anomalously broad current profile with no sawteeth, and a benign n=2 or n=3 neoclassical tearing mode [1, 2]. Fully non-inductive hybrids are driven by ∼45% bootstrap current, ∼35% neutral beam driven current, and ∼20% electron cyclotron current drive (ECCD). The high levels of neutral beam injection (NBI) used for current drive in this scenario result in plasmas with high levels of net injected torque that are mainly ion heated. Future fusion reactors will operate at low net injected torque/rotation [3] and in dominantly electron-heated regimes with equilibrated electron and ion temperatures [4, 5]. Thus, efforts have begun to extend the steady-state hybrid regime to reactor-relevant conditions by lowering the net injected torque and increasing the electron heating. This paper discusses the transport increases observed in the steady-state hybrid regime as the torque is lowered and the electron heating increased.

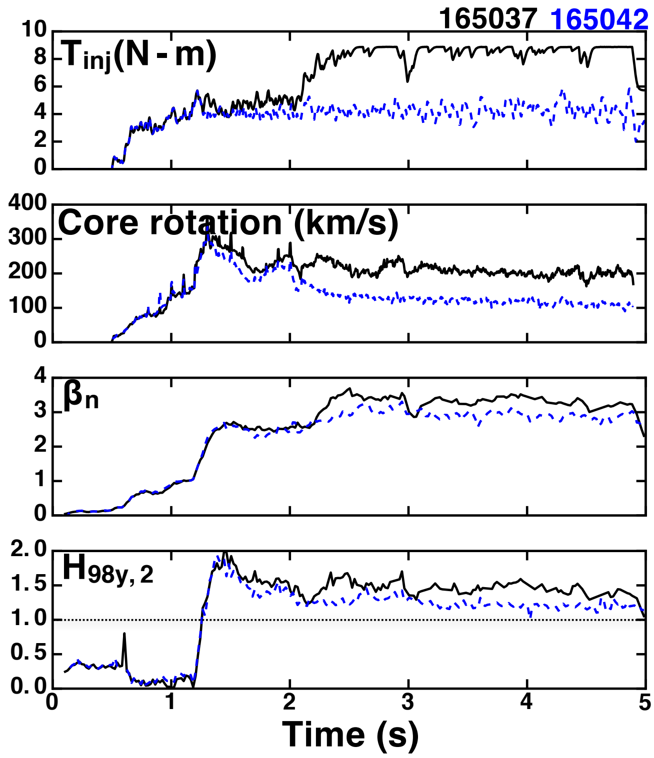

Figure 1: Comparison of net injected torque (a), core rotation (b), β_N (c), and $H_{98y,2}$ (d) for two hybrid discharges at high torque (black solid) and low torque (blue dashed.)

As the net injected torque/rotation is lowered in the hybrid regime, the confinement decreases. The torque is varied by using a combination of co- and counter-NBI, as illustrated in Fig. 1. The torque is lowered from 8.5 N-m to 4 N-m at fixed injected power ($P_{inj} = 11$ MW and $P_{ECCD} = 3.2$ MW that is deposited at $\rho = 0.15$) in otherwise similar plasmas: $I_p = 0.98$ MA,

$B_T = 1.98$ T, $q_{min} = 1.1$, $q_{95} = 5.9$, and diverted in the double-null shape biased upwards. The reduction in net injected torque changes the core toroidal rotation from 200 to 100 km/s during the high-β phase. As the torque is lowered, the global performance decreases with β_N changing from 3.2 to 2.8 and $H_{98y,2}$ from 1.5 to 1.3.

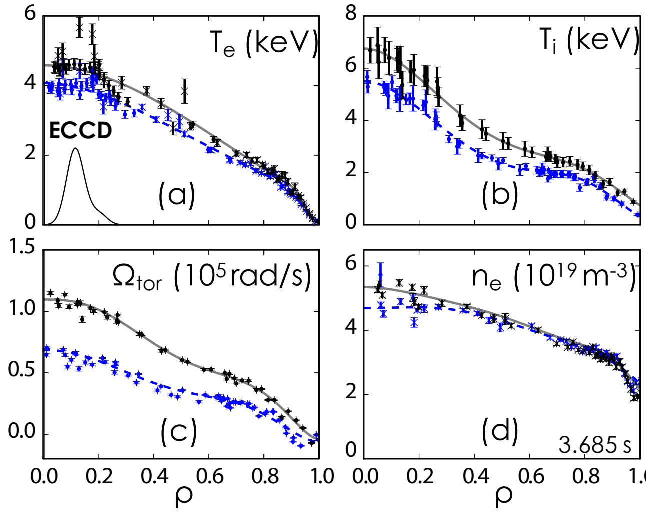

Figure 2: Radial profiles for hybrids at high torque (black solid) and low torque (blue dashed): (a) electron temperature, ion temperature, toroidal rotation and (d) electron density.

The profiles for these two discharges at a representative time during the high-β phase are shown in Fig 2. The electron temperature (T_e) profiles deviate at $\rho = 0.8$, with the lower torque discharge achieving ~10% lower core T_e than the high torque discharge. The low torque ion temperature (T_i) profile is at least $\sim$ 20% lower across the plasma profile compared to the high torque case. A flat spot in the T_i radial profile is observed in both profiles from $\rho = 0.6 - 0.8$, but the flat spot becomes more appreciable at lower torque. The electron density (n_e) profiles are similar in these discharges outside of $\rho \geq 0.4$, but the low torque plasma has lower on-axis n_e. The toroidal rotation (Ω_{tor}) decreases across the whole plasma at low torque; in particular, the on-axis toroidal rotation drops by almost 50%. The $3/2$ tearing mode is located at $\rho = 0.3 - 0.35$ for all discharges discussed here.

The local response to changes in net injected torque are not the same for all transport channels. The local radial transport analysis for these discharges was conducted with TRANSP [6], where an ad-hoc fast-ion diffusion was applied to match the TRANSP predicted neutron rate with the measured experimental neutron rate. The time-averaged electron heat diffusivity (χ_e), ion heat diffusivity, (χ_i) and momentum diffusivity (χ_{mom}) is shown for these discharges in Fig 3, averaged during the high-β phase. At low torque, χ_e is $\sim 2\times$ higher across the plasma than at high torque. At both torques, χ_i peaks at $\rho \approx 0.7$, but the peaking is six times higher at low torque; this is reflected in the increased flattening of T_i at this radius. The momentum diffusivity increases slightly as the torque is lowered. The increase in transport, particularly in the thermal ion channel, is expected at lower torque as the shear in the ExB flow is reduced by $30 - 50\%$ from $\rho = 0.2 - 0.9$ compared to the higher torque case. This reduction is expected to increase drift-wave turbulence levels, which are known to increase energy and particle transport rates.

The effects of electron heating were investigated in the steady-state hybrid regime by comparing a NBI-only hybrid with a NBI+ECCD-heated hybrid. These discharges both had 11 MW of co-current NBI and the latter also had 2.6 MW of ECCD injected at $\rho = 0.15$; otherwise, these discharges are similar to the high torque case discussed above. Both discharges achieved similar performance with $\beta_N = 3.2$ and $H_{98y,2} = 1.4$. The profiles for these two discharges are shown in Fig 4. The ion profiles (T_i and Ω_{tor}) are similar between these two discharges, with small differences due to the use of β_N beam feedback control. The NBI+ECCD-heated discharges has higher T_e inside of $\rho = 0.8$ than the NBI-only discharge, achieving 25% higher T_e on-axis. This increases the on-axis T_e/T_i from 0.6 in the NBI-only hybrid to 0.7 in the NBI+ECCD hybrid. In contrast, n_e is similar between these discharges up to $\rho = 0.2$, but the NBI+ECCD-heated discharge experiences n_e pumpout on-axis that decreases the on-axis density.

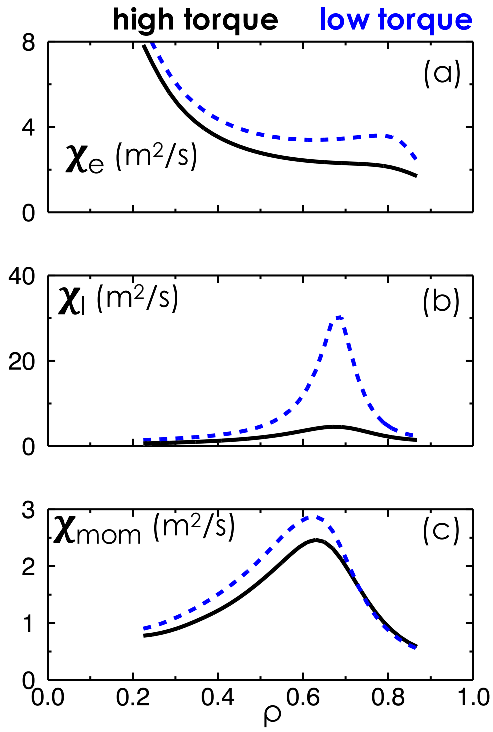

Figure 3: Radial profiles of the (a) electron and (b) ion heat diffusivities, and (c) momentum diffusivity for the high torque (black solid) and low torque (blue dashed) hybrids averaged during the high-β phase.

The local transport response to electron heating is not unlike the response to lower rotation. The time-averaged χ_e and χ_i are shown for these discharges in Fig. 5, averaged during the high-β phase, where the transport analysis conducted in a similar manner to the torque scan described previously. The NBI+ECCD-heated discharge has higher χ_e across the entire plasma compared to the NBI-only hybrid. Similarly, the NBI+ECCD-heated hybrid also has higher χ_i than the NBI-only discharge; in particular, the peak at $\rho = 0.7$ increases by $\sim 2\times$. The

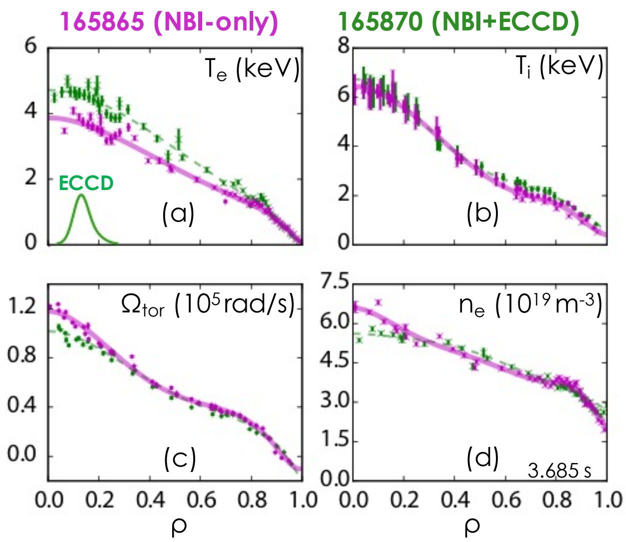

Figure 4: Radial profiles for NBI-only (pink solid) and NBI+ECCD (green dashed) hybrids: (a) electron temperature, ion temperature, toroidal rotation and (d) electron density.

increase in heat transport as T_e/T_i increases has been observed before on DIII-D [7] and is attributed to the dependence of the ion temperature gradient instability on T_e/T_i.

TGYRO [8] transport simulations using TGLF+NEO [9, 10] have been conducted for both the torque and electron heating scan in the steady-state hybrid scenario. As the torque is lowered, TGLF predicts that both the ion and electron heat turbulent fluxes become more low-k dominated, consistent with expectations that ExB shear is stabilizing to low-k turbulence. As the electron heating is increased, TGLF predicts that the electron heat turbulence flux becomes more high-k dominated, consistent with experimental turbulence measurements from beam emission spectroscopy [11].

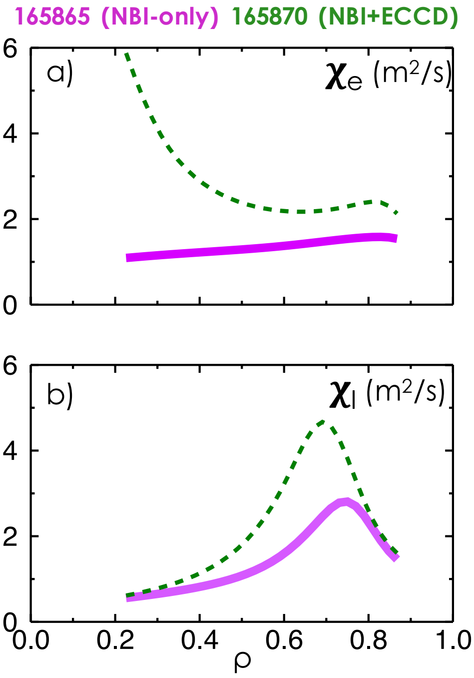

Figure 5: Radial profiles of the (a) electron and (b) ion heat diffusivities for the NBI-only (pink solid) and NBI+ECCD (green dashed) hybrids averaged during the high-β phase.

The steady-state hybrid scenario has been extended to lower torque and increased electron heating. As the torque was halved, an increase in the heat transport was observed due to a decrease in ExB shear. As T_e/T_i was increased, the heat transport increased due to an increase in high-k electron heat turbulence. The effect of electron heating on confinement at low torque in steady-state hybrids is a subject of future investigation. However, in the DIII-D ITER baseline scenario, the transport increase observed with decreased torque and increased T_e/T_i did not add linearly [12].

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