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Physics Advances in the ITER Hybrid Scenario on DIII-D* EX-C

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Experiments on the DIII-D tokamak have developed a long duration, high performance plasma discharge that is an attractive operating scenario for ITER [1,2]. Distinct from the Advanced Tokamak regime, this “hybrid scenario” regime is inductively driven, with bootstrap current fractions of 35%-50% and a fully penetrated current profile with q_0~1. Compared to standard H-mode discharges, the hybrid discharge has a broader current profile that is less susceptible to the onset of m/n=2/1 NTM (allowing higher β operation) and theoretically lower turbulent growth rate characteristics (allowing higher confinement).

Hybrid discharges on DIII-D have remarkably good transport properties. Figure 1 shows the experimental ion and electron thermal diffusivities (χ_i and χ_e) for a hybrid discharge with q_{95}=3.1, β_N=2.65, and H_{89P}=2.6. This plasma was sustained for ≈5 current relaxation times with a normalized fusion performance, given by $\beta_N H_{89P}/q_{95}^2$=0.7, that is 70% above the value of this parameter projected for Q_{fus}=10 operation in ITER. While the magnitudes of both χ_i and χ_e are relatively small in Fig. 1, electron heat conduction clearly dominates the energy loss process. This is consistent with nonlinear GYRO simulations that show the ETG mode and TEM cause the majority of transport, although these modes are predicted to be linearly stable in the core. The ion thermal diffusivity is found to be remarkably close to the neoclassical value across the plasma cross-section, which is not completely understood since the GKS gyrokinetic stability code predicts that the T_i profile is marginally unstable to the ITG mode outside of ρ=0.52. For plasmas with higher edge safety factor, the measured χ_i is found to increase above the neoclassical value, especially in the outer regions of the plasma, but electron heat conduction still dominates. Other transport studies on DIII-D have measured for the first time the $\rho*$ scaling of heat transport in hybrid plasmas with the other dimensionless parameters kept constant. For with q_{95}>4, a factor of 1.6 scan in $\rho*$ determined that the effective thermal diffusivity has a scaling close to gyroBohm-like in the core (although more Bohm-like near the edge).

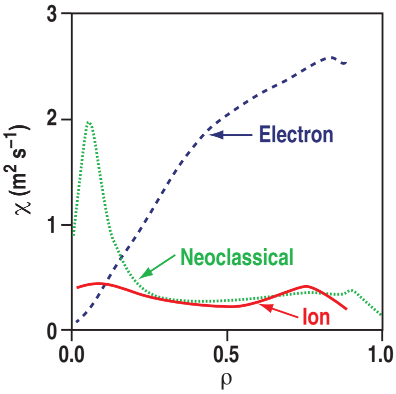

Fig. 1. Radial profiles of electron (dashed line), ion (solid line), and neoclassical (dotted line) thermal diffusivities for hybrid discharge on DIII-D with dominant 4/3 NTM.

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Other experiments on DIII-D applied 3rd harmonic electron cyclotron heating to hybrid plasmas with $T_i>T_e$ and found a decrease in toroidal rotation and confinement quality. This result is similar to observations in standard H-mode plasmas with $T_i>T_e$, where the electron heating is predicted to have a destabilizing effect on the ITG mode. In addition, a radiative divertor has been successfully applied to the hybrid scenario using argon injection, with good core confinement and high levels of radiation (P_{rad}/P_{input}=60%) simultaneously achieved. High impurity enrichment ($\eta_{Ar}>30$) in the divertor has been demonstrated.

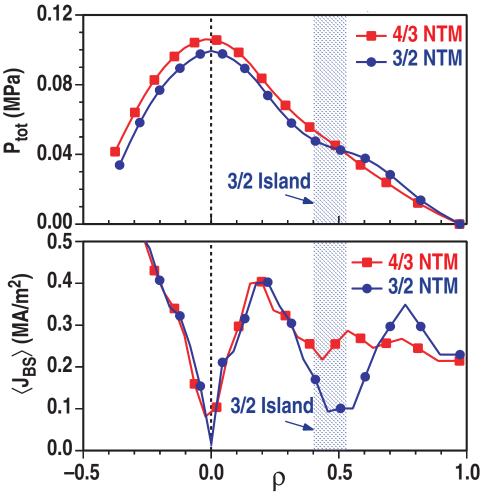

Fig. 2. Direct analysis of motional Stark effect signals without equilibrium reconstruction [3] for hybrid discharges with a dominant 4/3 NTM (red) or 3/2 NTM (blue) showing (a) total pressure profile, and (b) bootstrap current density profile.

Hybrid scenario discharges on DIII-D can have either a dominant m/n=3/2 NTM or a dominant m/n=4/3 NTM, depending upon initial conditions, with the latter having typically 15% higher H_{89P}-factors (maximum 30% higher). One reason for the lower confinement in 3/2 NTM hybrid plasmas is the flattening of the pressure profile near the q=1.5 surface, as seen in Fig. 2. This figure shows the first direct measurement of the "missing" equilibrium bootstrap current near the 3/2 NTM location; the drop in the pressure-driven current density is much less for the 4/3 NTM case. The second reason for improved confinement in 4/3 NTM hybrid discharges is a greater E×B velocity shear owing to higher toroidal rotation (resulting from smaller island drag effects). While several realizations of the hybrid scenario have been reported on other tokamaks [4-6], the dominant 4/3 NTM hybrid scenario appears to be unique to DIII-D.

The 3/2 NTM has the beneficial effect in hybrid plasmas of broadening the current profile and maintaining $q_0 \geq 1$ (without sawteeth for $q_{95}>4$ and with very small sawteeth for $q_{95} \leq 4$). Three possible mechanisms have been identified to explain this effect. The first is based on the observed coupling between the 3/2 NTM and ELMs, which can lead to poloidal flux pumping. Direct analysis of the motional Stark effect signals shows that during the ELM event, some of the ohmic current is quickly displaced (≤1 ms) to larger radius, which raises q_0 by ≈0.03. The second is counter current drive near the axis by the 2/2 component of the NTM. Calculation of the linear mode structure with both PEST3 and NIMROD show that the relative amplitude of the 2/2 component becomes large as q_0 approaches 1. While the directly driven counter current is small, mode conversion at the Alfvén wave resonance layer near the axis between the NTM eigenmode and a large $k_\perp$, small $k_\parallel$ kinetic Alfvén wave should result in additional counter current drive from electron Landau damping of the KAW. Finally, either the NTM itself or the mode converted KAW can cause scattering and radial transport of fast ions, which reduces the co-NBCD at the axis. Although there are no large changes in fast ion confinement when the NTM appears, even a small redistribution of the fast ions would be sufficient to produce the anomalously high value of q_0.

The elimination of sawteeth by the 3/2 NTM allows β_N to be increased to just below the ideal no-wall stability limit ($\approx 4l_i$). Recent experiments on DIII-D have pushed the hybrid scenario to even higher β_N by using co-ECCD at the q=2 location to completely suppress the 2/1 NTM; in these cases, a 2/1 NTM develops shortly after the ECCD is turned off with β_N at or above the $4l_i$ limit.

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