Full-f Neoclassical Simulations Toward a Predictive Model for H-mode Pedestal Ion Energy, Particle and Momentum Transport

EX-D

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The transport leading to the ion temperature (T_i), flow (v_ϕ, v_θ) and effective nuclear charge (Z_{eff}) profiles in the H-mode pedestal is shown to be predominately determined by kinetic neoclassical and neutral physics on DIII-D and NSTX. The characteristic intrinsic co-I_p toroidal flow, negative radial electric field (E_r) well, impurity density pinch, and weak T_i gradient scale lengths observed in low-collisionallity pedestals are quantitatively reproduced using XGC0 [1], a full-f multi-species (D^+, C^{6+}, e^-) flux-driven neoclassical transport simulation with self-consistent neutral recycling and model-based anomalous transport. Figure 1 demonstrates the quantitative agreement between the predicted and measured intrinsic flows in the pedestal of a zero-torque ECH-heated H-mode discharge on DIII-D. Flows at the outboard midplane predicted by XGC0 (red lines) are in good agreement with the measured D^+ and C^{6+} flows (black points) for $\psi_N > 0.9$ where the momentum generated by turbulent stress is small. The predicted non-zero flux-surface averaged intrinsic flow (blue lines) is consistent with the observation of intrinsic co-I_p torque in the H-mode edge in many tokamak devices.

Ion orbit loss of high-energy counter-I_p ions is balanced by a pinch of colder ions; thus, the net neoclassical particle transport in the H-mode pedestal is very small while the neoclassical energy and momentum transport is large. The E_r root solution that balances ion orbit loss against the neoclassical pinch is in excellent agreement with the measured negative E_r well inside the separatrix. The enhanced loss of high-energy counter-I_p ions results in non-Maxwellian enegy distributions with the tail skewed toward co-I_p, driving net intrinsic co-I_p flow and T_i anisotropy ($T_\theta \neq T_\phi$). Figure 2 demonstrates the quantitative agreement between the predicted carbon T_i profiles for a 9 MW NBI heated discharge on DIII-D from XGC0 (solid lines) and the profiles measured with orthogonal charge-exchange spectroscopy views (data points) [2]. The simulation reproduces the observed anisotropy and the increase in T_i in the scrape-off layer (SOL) due to the large radial excursions of high-energy trapped orbits at the outboard midplane.

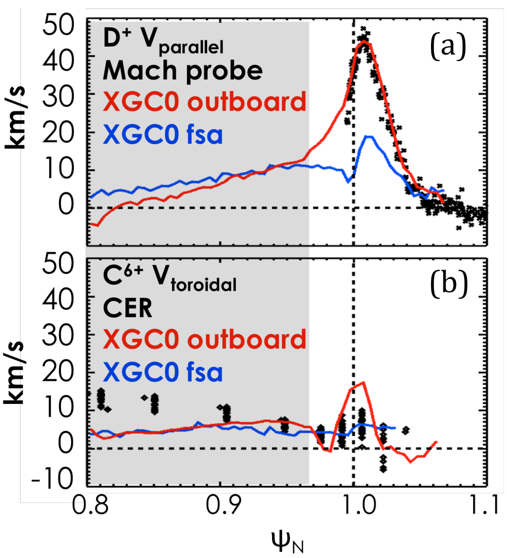

Figure 1 Predicted intrinsic flows at outboard midplane for an ECH-heated discharge using XGC0 (red lines) compared to measured (a) D^+ parallel flow and (b) C^{6+} toroidal flow (black points). Blue lines are predicted flux-surface averaged flows. Ion transport is predominately anomalous in gray region, neoclassical in white region.

XGC0 simulations demonstrate that the net particle transport and electron thermal transport in the pedestal is dictated by turbulent or mode-driven transport (anomalous) while the ion thermal and momentum transport are predominately neoclassical, especially at low-collisionality. This insight resolves the physics behind the separation in energy, momentum and particle transport rates observed in the tokamak edge following the L-H transition, an ELM, or the transition to a stationary H-mode regime without large ELMs. For example, the onset of the edge harmonic oscillation (EHO) in QH-mode on DIII-D increases the particle transport, while the corresponding increase in the anomalous energy transport has a negligible impact on the total energy transport [3].

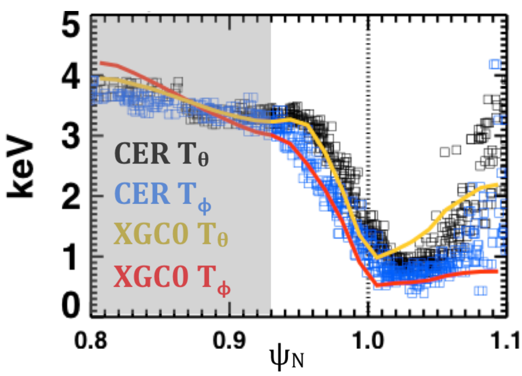

Figure 2 Comparison of C^{6+} T_i profiles at outboard midplane predicted from XGC0 (solid lines) to the measured profiles (data points) in a QH-mode pedestal. Ion transport is predominately anomalous in gray region, neoclassical in white region.

Ion thermal transport is neoclassical across the entire plasma radius on NSTX and a double barrier in the thermal ion transport has been observed to form when sufficient rotational shear is generated via transient edge rotation braking from an ELM or non-axisymmetric magnetic perturbation (EPH-mode) [4]. The dramatic improvement in thermal confinement is accompanied by modest changes in the particle transport and measured turbulence amplitude. XGC0 simulations demonstrate that parallel rotation shear gradients on the order of an ion orbit width enhance the confinement of ions in the tail of the energy distribution and reduce the neoclassical ion thermal transport. The intrinsic rotation driven by kinetic effects across the thermal barrier and changes in the nature of the turbulence reinforce the rotation shear and resolves how a transient increase in the edge flow shear leads to a stationary state with a double transport barrier in the thermal transport and a single barrier in the particle transport.

The neoclassical origin of E_r and the intrinsic flows results in a predictable connection between the E × B flow shear and plasma geometry that can be leveraged to control the requirements for the L-H transition. For example, the flow shear increases as R_X is moved outward to a low-triangularity shape. Quantitative agreement between the dependence of the L-H transition on R_X on NSTX and the predictions from XGC0 provide supporting evidence that neoclassical transport plays a significant role in the formation and sustainment of the H-mode transport barrier [5].

XGC0 leverages recent advances in high-performance computing to quantify the contribution of neoclassical transport, including the significant finite-orbit-width effects, on H-mode pedestal transport. Quantitative agreement with the measured T_i, flow, E_r and Z_{eff} profiles for a wide range of H-mode conditions on DIII-D and NSTX, the dependence of the L-H transition on magnetic geometry and the observed separation of pedestal particle and energy transport provide confidence that full-f neoclassical transport calculations with self-consistent neutral recycling represents a crucial step toward a predictive model for the H-mode pedestal transport and provide a tool for inferring the global ion pedestal parameters based on limited edge diagnostic coverage.

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