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Several aspects of neoclassical dynamics are believed to be important in explaining enhanced edge flows, current, and confinement in tokamaks. For example, substantial ion flow in the tokamak boundary region – the pedestal and scrape-off layer (SOL) – and their spatial variation can be important for stabilization of instabilities, interpreting temporal fluctuation spectra, and also for radial transport of plasma, especially its toroidal momentum. In these studies, the δf code NEO [1] is used to study the neoclassical transport for parameters relevant in the plasma edge and outer core. Extensions of these studies further into the tokamak boundary region are explored via comparisons with COGENT [2], a full f Eulerian code describing both closed and open field-line regions, and UEDGE [3], a 2D fluid code with a neoclassical transport model for both closed and open field lines allowing general collisionality.

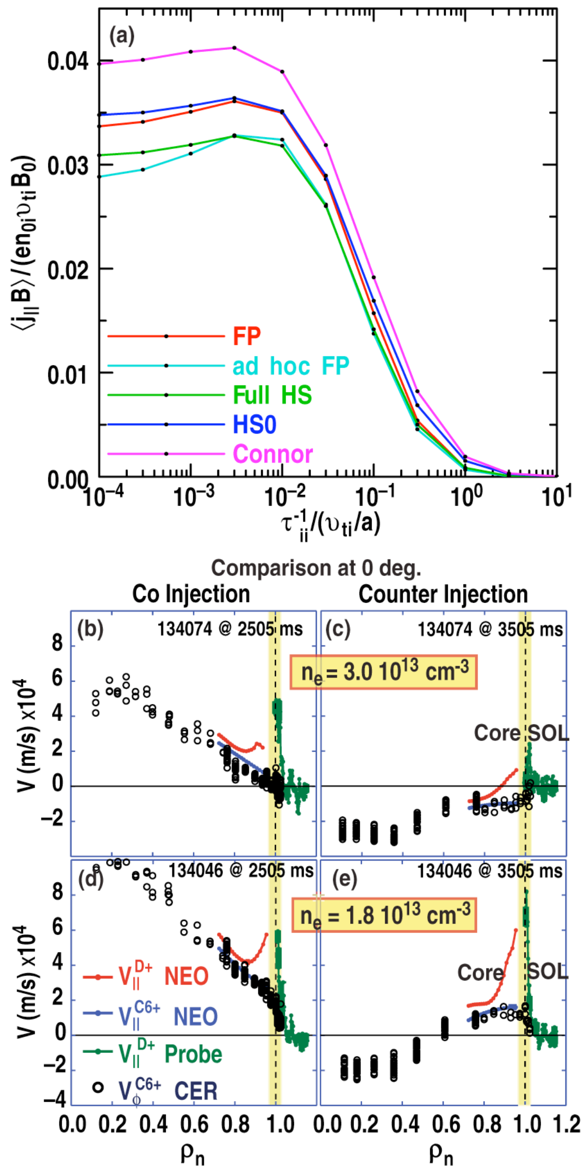

Fig. 1. (a) NEO calculation of the bootstrap current versus collision rate for a pure plasma comparing results from various model collision operators (test particle with ad hoc-field particle operator, full Hirshman-Sigmar operator, zeroth-order Hirshman-Sigmar operator, and Connor model) with results from the full Fokker-Planck collision operator (FP). (b-e) Velocity comparison of the CER toroidal carbon measurement (open circles), NEO parallel carbon calculations (blue lines), NEO parallel deuterium calculations (red lines), and Mach-probe parallel deuterium measurements (green lines) for (a,c) co- and (b,d) counter-NBI injected phases.

The NEO code has been developed as a practical predictive tool for high-accuracy neoclassical calculations. NEO was developed to improve the local neoclassical physics of NCLASS [4], mainly by using a direct kinetic approach, rather than a fluid moment-approach, and including toroidal rotation and general geometry. While existing neoclassical codes use model collision operators, NEO includes the full linearized Fokker-Planck collision operator [5], and no approximations beyond the drift-ordering are used. For implementation of the operator, novel numerical algorithms based on a spectral expansion scheme in velocity space have been developed, which are designed for high-accuracy treatment of the disparate velocity scales that arise in the case of multi-species plasmas. Using NEO, extensive comparisons of neoclassical transport levels predicted by the exact collision operator and those from various commonly used model operators have been made to assess the physical accuracy and limitations of the latter over a range of collisionality regimes [Fig. 1(a)]. In general, the error in the model collision operators is 20–30% for the ion energy flux, 10–15% for the electron energy flux and ambipolar particle flux, and 5–10% for the bootstrap current. Comparisons between NEO and NCLASS find that NEO provides a 30% correction to NCLASS for the neoclassical flows for typical DIII-D plasmas.

Comparisons have been made between the NEO neoclassical simulations and experimental measurements of the deuterium parallel velocity profiles in the edge for DIII-D L-mode discharges [6]. Figure 1(b-e) shows that the NEO calculations trend to agreement with the measurements upon approach to the last closed flux surface. Specifically, the deuterium velocity, which follows the carbon velocity in the core measurements, rapidly rises toward the edge. This indicates that deviations between the deuterium and carbon flows in the edge can be explained by neoclassical physics.

While NEO is limited to the closed magnetic field line region, extensions of these studies including the transition from the pedestal to the scrape-off-layer region are explored using COGENT. COGENT is a 4D continuum gyrokinetic code which describes both closed and open field-line regions. The code is distinguished by a fourth-order finite-volume (conservative) discretization independent of grid choice, hence providing no loss of accuracy order in going to non-uniform grid. This exploits arbitrary mapped multiblock grid technology (nearly field-aligned on blocks) to handle the complexity of divertor geometry without loss of accuracy. With COGENT, the generation of intrinsic plasma flows due to neoclassical particle losses in the tokamak edge, e.g. from thermal ion orbit losses and X-point losses, are investigated.

Simulations in the open field-line region will also be performed with the multi-species fluid transport code UEDGE. UEDGE has previously been used to compute the electrostatic potential in the pedestal and SOL regions, showing a deep negative radial electric field well associated with the H-mode in tokamaks [7]. However, these simulations could not adequately differentiate the parallel flow for the deuterium and carbon species. A recent upgrade to the parallel velocity and current equations includes the full neoclassical viscous terms arising from gradients in velocity and heat-flux moments with coefficients that account for the collisionality regime [8]. This model includes Coriolis and centrifugal force effects as well as neutral charge-exchange friction with neutrals. Comparisons with the results of NEO and COGENT will give a clear picture of the adequacy of this generalized fluid transport model with the more detailed and computationally intensive kinetic models in the long mean-free path regime, as well as provide a target for the kinetic codes in the collisional regime.

While most NEO work focuses on the local neoclassical transport dynamics, non-local effects due to finite-orbit-width may be important in the plasma edge. These effects were previously studied with neoclassical simulations which purport to compute the total distribution, f, more accurately than in the standard local $O(\rho_*)$ ordering by retaining some nonlinear terms related to finite-orbit width, while simultaneously reusing some form of the linearized collision operator. However, here we show that non-local corrections to the distribution function are not generally valid if the nonlinear correction to the collision operator is ignored [9].

Finally, the success of the NEO spectral discretization scheme has motivated the development of a prototype linear gyrokinetic stability code using an analogous discretization scheme. We believe the NEO-type spectral discretization approach has the potential to be optimal for the collisional edge region, in contrast to the GYRO discretization scheme which is optimal in the collisionless limit.

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