Edge Gyrokinetic Theory and Continuum Simulations[1]

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Abstract. Understanding the structure of the edge transport barrier in high-performance (H-mode) discharges requires a kinetic description of the plasmas because the radial width of the pedestal observed in experiments is comparable to the radial width of individual ion drift orbits (leading to a large distortion of the local distribution function from a Maxwellian), and because the ion and electron mean-free-paths are long compared to the connection length for the hot plasma at the top of the edge pedestal (violating the assumptions underlying collisional fluid models). A gyrokinetic formulation (2v) is a reasonable approximation for edge plasmas because it is believed that pedestal physics is likely dominated by phenomena having low frequencies compared to the ion gyrofrequency. But previous gyrokinetic theories and codes do not apply to edge plasmas because they cannot treat fully nonlinear electromagnetic perturbations with multi-scale-length structures in space-time for full divertor geometry.

We report on the development and application of TEMPEST, a fully nonlinear (full-f) gyrokinetic code, to simulate H-mode edge plasmas. This 5-dimensional $(\psi, \theta, \zeta, E_0, \mu)$ continuum code represents velocity space via a grid in equilibrium energy (E_0) and magnetic moment (μ) variables, and configuration space via a grid in poloidal magnetic flux (ψ), poloidal angle (θ) and toroidal angle (ζ). The geometry can be a circular annulus or that of a diverted tokamak and so includes boundary conditions for both closed magnetic flux surfaces and open field lines. The same set of gyrokinetic equations are discretized for both geometries. The equations are solved via a Method-of-Lines approach and an implicit backward-differencing scheme using a Newton-Krylov iteration to advance the system in time. The spatial derivatives are discretized with finite differences while a high-order finite volume method is used in velocity space (E_0, μ). A fourth-order upwinding algorithm is used for parallel streaming, and a fifth-order WENO scheme is used for particle cross-field drifts. Boundary conditions at conducting material surfaces are implemented on the plasma side of the sheath. The code includes kinetic or Boltzmann electrons. A nonlinear Fokker-Planck collision operator (CQL) from the STELLA code has been extracted and integrated into TEMPEST using the same implicit Newton-Krylov solver. The gyrokinetic Poisson equation is solved self-consistently with the gyrokinetic equations as a differential-algebraic system involving a nonlinear system solve via a Newton-Krylov iteration using a multigrid preconditioned conjugate gradient (PCG) solver for the Poisson equation.

The following results are presented from the application of TEMPEST, (1) As a test of the interaction of collisions and parallel streaming, TEMPEST is compared with published analytic and numerical results for endloss of particles confined by combined electrostatic and magnetic wells. Good agreement is found over a wide range of collisionality, confining potential, and mirror ratio; and the required velocity space resolution is modest. (2) In a large-aspect-ratio circular geometry, excellent agreement is found for a neoclassical transport with parallel ion flow without radial electric field; (3) The full-f 4D (2d2v) TEMPEST gyrokinetic continuum code produces frequency, collisionless damping of GAM and zonal flow with fully nonlinear Boltzmann electrons for the inverse aspect ratio ϵ-scan and the tokamak safety factor q-scan in homogeneous plasmas. The TEMPEST simulations have demonstrated an enhanced collisionless Landau damping due to the FOW effect, $k_\psi \rho_i q$. The enhancement is not monotonic as q increases, and especially strong in the range of $1.5 < q < 4$, which is qualitative consistent with BES GAM amplitude measurements The TEMPEST simulation shows that GAM exists in edge plasma pedestal for steep density and temperature gradients, and an initial GAM relaxes to the standard neoclassical residual, rather than Rosenbluth-Hinton residual due to the presence of ion-ion collisions. (4) In divertor geometry, it is found that the endloss of particles and energy induces parallel flow stronger than the core neoclassical predictions in the SOL.

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