A Fully Implicit Particle-in-Cell Method for Gyrokinetic Electromagnetic Modes

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It is widely recognized that magnetic instabilities and fluctuations play an important role in the dynamics and transport of magnetically confined plasmas. For example, microinstabilities driving turbulence are known to change character from electrostatic to electromagnetic as β, the ratio of plasma pressure to magnetic pressure, is increased. Above a critical β value, a new branch of electromagnetic modes called kinetic ballooning modes (KBM) dominate both the ion temperature gradient (ITG) and trapped electron mode (TEM) instabilities [1]. Magnetic instabilities and fluctuations can induce reconnection of the magnetic field into "tearing" modes, and electromagnetically "ballooned" modes can exist at the outboard side of a toroidal plasma. These instabilities and fluctuations must be understood for the successful operation of a magnetic fusion device but have been difficult to study in particle-in-cell codes.

When the characteristic frequencies of the studied phenomena are smaller than the gyrofrequency, it is desirable to employ gyrokinetic or drift kinetic models, which analytically remove time scales associated with gyromotion. These models, however, suffer from well-known numerical problems. The $v_{\parallel}$ formulation with explicit time discretization suffers from a severe time step constraint [2], and the $p_{\parallel}$ formulation is limited to simulations at low β regimes or at short wavelengths due to an inexact cancellation of two large, non-physical terms appearing in Ampere's law that emerge from the choice of coordinates [3].

In this talk, we describe our implementation of a fully-implicit time integration scheme based on the work of G. Chen and L. Chacón [4-6] for a gyrokinetic ion, drift kinetic electron electromagnetic model employing the $v_{\parallel}$ formulation in the full volume fusion plasma code XGC-1 [7]. By choosing the $v_{\parallel}$ formulation, we avoid introducing non-physical terms in Ampere's law, while the implicit discretization eliminates the previous time stepping difficulties. Each time step of the implicit scheme, however, requires the solution of a large system of nonlinear equations. This can be made practical by formulating the system in terms of the field equation residuals, requiring far less solver memory than formulating in terms of the full particle system. Preconditioned iterative schemes including Picard, Anderson mixing, and Jacobian-free Newton-Krylov are then explored to solve the resulting system of equations. The preconditioner is derived from an electron fluid model, which accurately captures the fast time scale physics in the kinetic model. We will present our efforts to optimize the preconditioner in addition to numerical results validating the scheme.

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