COMMUNICATIONS IN COMPUTATIONAL PHYSICS
Vol. 5, No. 1, pp. 183-194

Commun. Comput. Phys.
January 2009

Full Torus Electromagnetic Gyrokinetic Particle Simulations with Kinetic Electrons

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Received 27 December 2007; Accepted (in revised version) 20 May 2008

Available online 15 July 2008

Abstract. The full torus electromagnetic gyrokinetic particle simulations using the hybrid model with kinetic electrons in the presence of magnetic shear is presented. The fluid-kinetic electron hybrid model employed in this paper improves numerical properties by removing the tearing mode, meanwhile, preserves both linear and nonlinear wave-particle resonances of electrons with Alfven wave and ion acoustic wave.

PACS: 52.20.Gz, 52.35.Ra, 52.65.Cc

Key words: Gyrokinetic particle simulation, plasma turbulence, electromagnetic gyrokinetic theory.

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1 Introduction

Anomalous particle and heat transport in magnetized fusion plasma in the electrostatic limits have been studied extensively by three dimensional gyrokinetic turbulence simulations [1, 2]. The ion heat transport driven by ion temperature gradient mode (ITG) [3] and regulation by the zonal flows is well understood [2, 4]. The electron heat transport can be related to trapped electron modes (TEM) [5–7], effective perpendicular transport induced by stochastic magnetic field lines [8, 9], or possibly by electron temperature gradient mode (ETG) [10–12]. On the other hand, in the presence of magnetic perturbations, there exist new branches of modes, for example, toroidicity induced Alfven eigenmodes (TAEs) [13, 14], Alfvenic ion temperature gradient (AITG) modes [15, 16], and kinetic ballooning modes (KBM) [17], that can play important roles in plasma instabilities and transport.

To predict the particle and heat transport level reliably for the next generation burning plasma experiments, for example for the International Thermonuclear Experimental

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Reactor (ITER), it is important to include the electromagnetic effects self-consistently into the gyrokinetic simulation. However, in electromagnetic gyrokinetic particle-in-cell (PIC) simulations [18, 19], freely streaming electrons above the local Alfven speed greatly enhance particle noise inherent to the electromagnetic gyrokinetic PIC method [20, 21]. A fluid-kinetic hybrid electron model [22–25] has been proposed to circumvent these difficulties. The hybrid model solves for the adiabatic response in the lowest order as massless electron fluid equations and solves the resonant interaction in the higher order kinetic equations, based on an expansion of the electron response using a small parameter of the square-root of the electron-ion mass ratio

$$\delta_m = (m_e/m_i)^{1/2}$$

(m_e and m_i are the electron and the ion mass respectively), while preserving the linear and the nonlinear wave-particle interactions (note, however, that we did not conduct nonlinear simulation in this paper).

The motivation for the development of the hybrid model is to remove the well known numerical difficulty [20, 21] of resolving the electron response to the tearing parity near mode rational surfaces in the presence of magnetic shear. The hybrid model is free from this difficulty by removing the tearing mode physics in our simulations, while the full kinetic model [20, 21] can suffer from the difficulty since the tearing mode is retained. The hybrid model makes approximations at the electron gyroradius scales and removes the $k_\parallel = 0$ component of the inductive parallel electric field (here, $k_\parallel$ is the wave vector parallel to the equilibrium magnetic field), that is the collisionless tearing mode. However, the hybrid model treats rigorously all other $k_\parallel = 0$ modes, including electrostatic fields, magnetic field perturbations, zonal flows and zonal fields, and all the ideal and resistive MHD modes. The hybrid model is optimal for simulation of drift and Alfvenic turbulence on the ion gyroradius scales. The hybrid model does not treat the tearing physics in exchange for better numerical properties when simulating drift-Alfvenic turbulence.

Based on the mathematical derivation by [23, 25] presented a toroidal version of the fluid-kinetic hybrid electron model for treating electron dynamics in electromagnetic gyrokinetic particle simulations. However, the major focus of the numerical calculations in [25] was the examination of the shear Alfven wave dynamics in global tokamak plasmas with only the fluid hierarchy of the hybrid model (which constructed a closed set of physics discussion employing the lowest order fluid electrons). On the other hand, global toroidal gyrokinetic particle simulations with kinetic electrons using the electrostatic version of the hybrid model were reported [7,26]. In this paper, the full torus electromagnetic gyrokinetic particle simulations using the hybrid model with kinetic electrons in the presence of magnetic shear are presented. The fluid-kinetic electron hybrid model employed in this paper improves numerical properties by removing the tearing mode. The hybrid model preserves both linear and nonlinear wave-particle resonances of electrons with Alfven wave and ion acoustic wave (note that we do not perform nonlinear simulations in this paper).