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Electromagnetic High Frequency Gyrokinetic Particle-in-Cell Simulation

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Abstract. Using the gyrocenter-gauge kinetic theory, an electromagnetic version of the high frequency gyrokinetic numerical algorithm for particle-in-cell simulation has been developed. The new algorithm, being an alternative to a direct Lorentz-force simulation, offers an efficient way to simulate the dynamics of plasma heating and current drive with radio frequency waves. Gyrokinetic formalism enables separation of gyrocenter and gyrophase motions of a particle in a strong magnetic field. From this point of view, a particle may be viewed as a combination of a slow gyrocenter and a quickly changing Kruskal ring. In this approach, the nonlinear dynamics of high frequency waves is described by the evolution of Kruskal rings based on first principles physics. The efficiency of the algorithm is due to the fact that the simulation particles are advanced along the slow gyrocenter orbits, while the Kruskal rings capture fast gyrophase physics. Moreover, the gyrokinetic formalism allows separation of the cold response from kinetic effects in the current, which allows one to use much smaller number of particles than what is required by a direct Lorentz-force simulation. Also, the new algorithm offers the possibility to have particle refinement together with mesh refinement, when necessary. To illustrate the new algorithm, a simulation of the electromagnetic low-hybrid wave propagating in inhomogeneous magnetic field is presented.

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1 Introduction

The gyrokinetic theory [1–3] is normally known as a tool for description of the low frequency dynamics of plasmas in a strong magnetic field. Changing variables to a gyrocenter coordinate system in the original Vlasov and Maxwell's equations, the gyrokinetic

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formalism yields a system of gyrophase-independent equations, which describe slow (alternatively, low frequency with $\omega \ll \Omega$, where Ω is the cyclotron frequency) phenomena in plasmas. However, the physics associated with the omitted fast gyrophase part may be important. Particularly, in fusion plasmas, radio frequency (rf) waves in both ion and electron cyclotron frequency ranges are used for plasma heating and current drive. In this paper we present a computational algorithm, which is an alternative to direct Lorentz-force simulation and which allows one to numerically study an arbitrary frequency dynamics of plasmas within the gyrokinetic framework. This paper addresses electromagnetic version of the algorithm developed in the previous work by Kolesnikov *et al.* [4,5].

The high frequency gyrokinetic approach we discuss in this paper is based on the gyrocenter-gauge kinetic theory, developed by Qin *et al.* [6–8] in the limit of particle gyroradius much smaller than the scale length of the ambient magnetic field, $\rho/L_B \ll 1$ (in the case of strongly magnetized plasmas). The gyrokinetic formalism transforms the Vlasov-Maxwell system in 6D particle coordinate system $z=(\boldsymbol{x},\boldsymbol{v})$ to a new 6D gyrocenter system $\boldsymbol{Z}=(\boldsymbol{X},U,\mu,\xi)$. Here, $\boldsymbol{X}$ and U are the location and parallel velocity of the particle gyrocenter, μ is the magnetic moment and ξ is the gyrophase angle. While $F(\boldsymbol{x},\boldsymbol{v},t)$ is the distribution function in the old particle coordinates, $F(\boldsymbol{Z},t)$ is the distribution function in the new coordinates, where the parallel (gyrocenter) and the perpendicular (gyrophase) dynamics are decoupled, such that

$$F(\boldsymbol{Z},t)=\langle F(\boldsymbol{Z},t)\rangle. \tag{1.1}$$

Here, the notation for a gyrophase-averaged quantity is introduced by

$$\langle a\rangle \doteq (2\pi)^{-1}\int a d\xi.$$

All the fast gyrophase dynamics is completely captured by, so called, gauge function $S(\boldsymbol{Z},t)$. Similar approach was used by Lee *et al.* [9] and Park *et al.* [10] for treatment of arbitrary frequency dynamics.

An algorithm based on gyrokinetics may prove useful if we need to add an arbitrary frequency dynamics, like rf waves, into existing sophisticated gyrokinetic particle codes [11] developed to study low frequency turbulence phenomena in general geometry. Also, the new algorithm may be much more computationally effective than the direct Lorentz-force integration. There are several reasons for this. First, the motion of gyrocenters is slow; larger time step may be used for simulation of their dynamics, thus saving some computing time. Second, cold response may be separated from the kinetic effects in the expression for the current, which will allow to reduce the total number of particles required in the simulation. Third, the algorithm allows adaptive particle refinement together with mesh refinement, a feature important for the systems with different spatial scales. This paper will address these issues in more detail.

We believe that our new approach may be especially useful for computational study of the dynamics of propagation, conversion and absorption of radio frequency waves