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Vlasov-Fokker-Planck Simulations for High-Power Laser-Plasma Interactions

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Abstract. A review is presented on our recent Vlasov-Fokker-Planck (VFP) simulation code development and applications for high-power laser-plasma interactions. Numerical schemes are described for solving the kinetic VFP equation with both electron-electron and electron-ion collisions in one-spatial and two-velocity (1D2V) coordinates. They are based on the positive and flux conservation method and the finite volume method, and these two methods can insure the particle number conservation. Our simulation code can deal with problems in high-power laser/beam-plasma interactions, where highly non-Maxwellian electron distribution functions usually develop and the widely-used perturbation theories with the weak anisotropy assumption of the electron distribution function are no longer in point. We present some new results on three typical problems: firstly the plasma current generation in strong direct current electric fields beyond Spitzer-Härm's transport theory, secondly the inverse bremsstrahlung absorption at high laser intensity beyond Langdon's theory, and thirdly the heat transport with steep temperature and/or density gradients in laser-produced plasma. Finally, numerical parameters, performance, the particle number conservation, and the energy conservation in these simulations are provided.

AMS subject classifications: 82D10, 82C31, 78M12, 80A20

Key words: Vlasov-Fokker-Planck equation, electric conductivity, inverse bremsstrahlung, nonlocal heat transport, positive and flux conservation method, finite volume method.

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1 Introduction

In the area of high-power laser-plasma interactions, non-Maxwellian electron distribution functions (EDFs) extensively exist in many important processes, such as the generation of plasma current under a strong direct current (DC) electric field, the inverse bremsstrahlung (IB) absorption in an intense laser field, and the nonlocal electron heat transport due to a steep temperature gradient. The well-known transport theory by Spitzer and Härm [1] can be used to calculate the generated plasma current as well as the electron heat flux, and Langdon's IB operator [2] can handle the IB absorption consistently with the evolution of EDF. However, these models are based on the linear perturbation theory with the weak anisotropy assumption of EDF. Therefore, Spitzer-Härm's theory is valid only under a weak DC electric field and a small temperature gradient, and Langdon's operator is valid only at a low laser intensity with a high plasma temperature. In order to describe the nonlinear processes with highly non-Maxwellian EDFs occurring in high-power laser-plasma interactions, a full solution of the kinetic equation such as the Vlasov-Fokker-Planck (VFP) equation without perturbation approximations is necessary.

In this paper, we apply our developed VFP simulation code to study plasma kinetics in a strong DC electric field, an intense laser field, or under a steep temperature gradient. In Section 2, we present the numerical scheme for solving the VFP equation with highly non-Maxwellian EDFs. We update the configuration space part of the VFP equation by the positive and flux conservation method [3,4], and the velocity space part by the finite volume method [5], which extends the finite difference method [6]. Then we apply our simulation code to three typical problems with highly non-Maxwellian EDFs developed. We investigate the plasma current generation in a strong DC electric field in Section 3.1, the nonlinear IB absorption with a wide plasma temperature range at the high laser intensity in Section 3.2, and the nonlocal heat transport with a steep temperature gradient in Section 3.3. In Section 3.4, numerical parameters, performance, the particle number conservation, and the energy conservation are revealed. Finally, a summary is given in Section 4.

2 Vlasov-Fokker-Planck equation and numerical schemes

2.1 Master equation

In the kinetic theory, the plasma is usually described by the particle distribution functions $f^a(\mathbf{x},\mathbf{v},t)$, which can be considered as the possibility to find particle a in the 6-dimension phase space between $(\mathbf{x},\mathbf{v}) \to (\mathbf{x}+d\mathbf{x},\mathbf{v}+d\mathbf{v})$ at time t. Since most plasma properties are determined by electrons, we just consider the time evolution of the EDF in this paper. In an unmagnetized fully ionized plasma, the time evolution of the EDF can be described