SIMULATION OF THE COLLISIONAL PLASMA KINETICS UNDER THE ACTION OF LASER AND PARTICLE BEAMS

M.G. Cadjan, M.F. Ivanov

High Energy Density Research Center, Russian Academy of Science
127412, Izhorskaya 13/19, Moscow, Russia

The processes of laser and particle beam interaction with plasma are determined by both the collective kinetic effects and Coulomb collisions. The problem is that the Fokker-Planck equation for the collisional plasma dynamics is very difficult as regards either analytic or direct numerical investigation. An effective approach to overcome these difficulties is the method of stochastic differential equations [1].

In the present work we derived the nonliner Langevin equation for particle motion in collisional plasma. This equation allows to incorporate the collisional processes into the well-known PIC codes in a simple and effective way. It is known that the equation of Fokker-Planck and Langevin equation are the alternative methods for the description of Markovian diffusion process $\mathbf{v}(t)$. Thus, the starting point of our work is the stochastic equivalence of these methods, i.e. we are looking for the nonlinear Langevin equation: $d\mathrm{v}_i/dt \ = F_i(\mathbf{v}) + D_{ik}(\mathbf{v})\xi_k$, which describe the particle motion in collisional plasma. Here F_i, D_{ik} are the deterministic functions and $\vec{\xi}(t)$ is the random white noise with the following characteristics: $< \vec{\xi}(t) > = \ 0, < \xi_i(t) \ \xi_k(t+\tau) > = \ \delta_{ik} \ \delta(\tau)$. So, our purpose is to derive this equation and to generalize the well known PIC-method for the case of collisional plasma.

The Langevin approach can be simply applied when the integral of collision can be written as a function of velocity. But, as for the description of Coulomb collisions by the Landau integral of collisions, the kinetic equation for the f_α has an integral dependence on the f_β (where f_α and f_β are the distribution function of particles of species α and β respectively). This method is applied directly for the diffusion model of collision integral [3,4], and for the case when the collisions between the electrons and relatively cold ions are dominant [2]. For the general case the "quasi-Maxwellian" model [4] was constructed and corresponding Langevin equation was derived:

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \mathbf{F}_L + \mathbf{F}_{\mathrm{fr}} + \sqrt{G}\,\xi - \left(\sqrt{H} - \sqrt{G}\right)\frac{\left[\tilde{\mathbf{v}} \times [\tilde{\mathbf{v}} \times \tilde{\xi}]\right]}{\tilde{\mathbf{v}}^2}, \tag{1}$$

where

$$\mathbf{F}_{\mathrm{fr}} = -\sum_\gamma \frac{m_\gamma + m}{m_\gamma V_{T_\gamma}^2} G_\gamma \mathbf{v}_\gamma + \chi \Delta \mathbf{F}\,, \tag{2}$$

$$\Delta \mathbf{F} = (\sqrt{HG} - H)\frac{\tilde{\mathbf{v}}}{\tilde{\mathrm{v}}^2} + \frac{1}{2}\sum_\gamma \frac{1}{\tilde{\mathrm{v}}_\gamma}\left\{G'_\gamma \mathbf{v}_\gamma + \left(G'_\gamma - H'_\gamma\right)\frac{[\tilde{\mathbf{v}} \times [\tilde{\mathbf{v}} \times \tilde{\mathbf{v}}_\gamma]]}{\tilde{\mathrm{v}}^2}\right\}\,, \tag{3}$$

$$H_\gamma = \frac{n_\gamma L^{\alpha\gamma}}{4\pi}\frac{\Phi_\gamma - \Psi_\gamma}{\xi_\gamma}\,, \qquad G_\gamma = 2\frac{n_\gamma L^{\alpha\gamma}}{4\pi}\frac{\Psi_\gamma}{\xi_\gamma}\,, \tag{4}$$

$$H'_\gamma = \frac{n_\gamma L^{\alpha\gamma}}{4\pi}\frac{3\Psi_\gamma - \Phi_\gamma}{V_{T_\gamma}\xi_\gamma^2}\,, \qquad G'_\gamma = 2\frac{n_\gamma L^{\alpha\gamma}}{4\pi}\frac{\Phi_\gamma - (2\xi_\gamma^2 + 3)\Psi_\gamma}{V_{T_\gamma}\xi_\gamma^2}\,.$$

Here $H = \sum_\gamma H_\gamma(\xi_\gamma)$, $G = \sum_\gamma G_\gamma(\xi_\gamma)$, $\Phi(\xi) = \int_0^\xi dx e^{-x^2}/\sqrt{\pi}$ is the error function, and $\Psi(\xi) = -\frac{1}{2}d(\Phi/\xi)/d\xi$ is the Chandrasekhar function, $\tilde{\mathbf{v}} = \mathbf{v} - \mathbf{u}_{ion}$, $\xi_\gamma = |\mathbf{v} - \mathbf{u}_\gamma(\mathbf{x}, t)|/V_{T_\gamma}$, and $\mathbf{u}_\gamma$ is the average velocity of the species γ. The parameter χ depends on the definition of stochastic integral.

The derived equation is satisfactory for many problem of interest, and becomes "exact" (i.e., it is equivalent stochastically to the description of collision by Landau operator) in the number of limits [4]. Using the derived equations numerical algorithm was developed and tested.

With the use of the developed approach the problem of the short laser pulses interaction with overdense plasmas was considered. Using the simulation of laser-plasma interaction in collisionless regime, the authors of the paper [5] studied the influence of the sheath on the absorption and showed that the value of absorption coefficient from the simulation using the realistic reflection condition (when the particles are reflected by the longitudinal field of the double layer existing at the plasma boundary) can be greater than the linear theory prediction by up to 50%. The problem under consideration is formulated as follows: the immobile ions of plasma fill the half-space $x \geq X_i$, i.e., the density of ions component is equal to n for $x \geq X_i$ and is zero for $x < X_i$. The laser light propagates along the $x-$axis and have the main frequency ω_o, where $\omega_o < \omega_{pe}$. The simulation parameters is chosen close to the described in Reference [5].

Using the developed approach we calculated the absorption coefficient in both collisional and collisionless regimes [4]. (The laser light wavelength is $\lambda = 0.35 mkm$, the charge of ions is $Z = 3$ and the electron concentration is $n_e = 25n_{cr}$, where n_{cr} is the critical density for the incident wave.) The result of absorption coefficient simulation in a wide range of plasmas parameters (temperature and plasma frequency) is shown in Fig.1. The bold curve separates the region of plasma parameters (large temperatures and densities) where the spatial dispersion is large enough and the value of η_{ab} is greater than the linear theory prediction. For the case of strongly nonlinear regime of laser-plasma interaction the strong longitudinal electric field at the plasma boundary is observed. The generation of a high frequency radiation as well as the formation heated electrons is investigated [2].

The simulation results of electron beam stopping in plasma is shown in Fig.2. The initial plasma temperature is $100eV$; the electrons beam velocity corresponds to $10keV$, the ratio of beam and background densities is $1/10$.

We conclude by mentioning that the developed approach is applicable to various problems for collisional plasma simulations.

References

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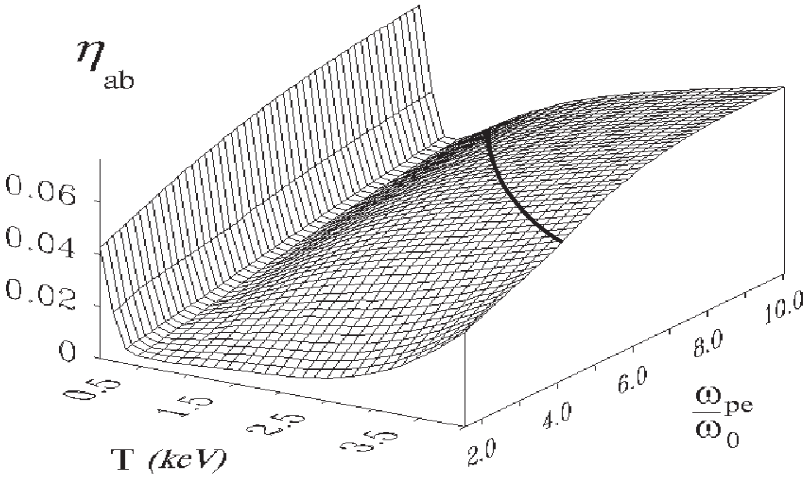

Figure 1. Absorption coefficient η_{ab} as a function of plasmas parameters: T is the plasmas temperature (in keV), ω_{pe} and ω_0 are the plasma frequency and the frequency of laser light.

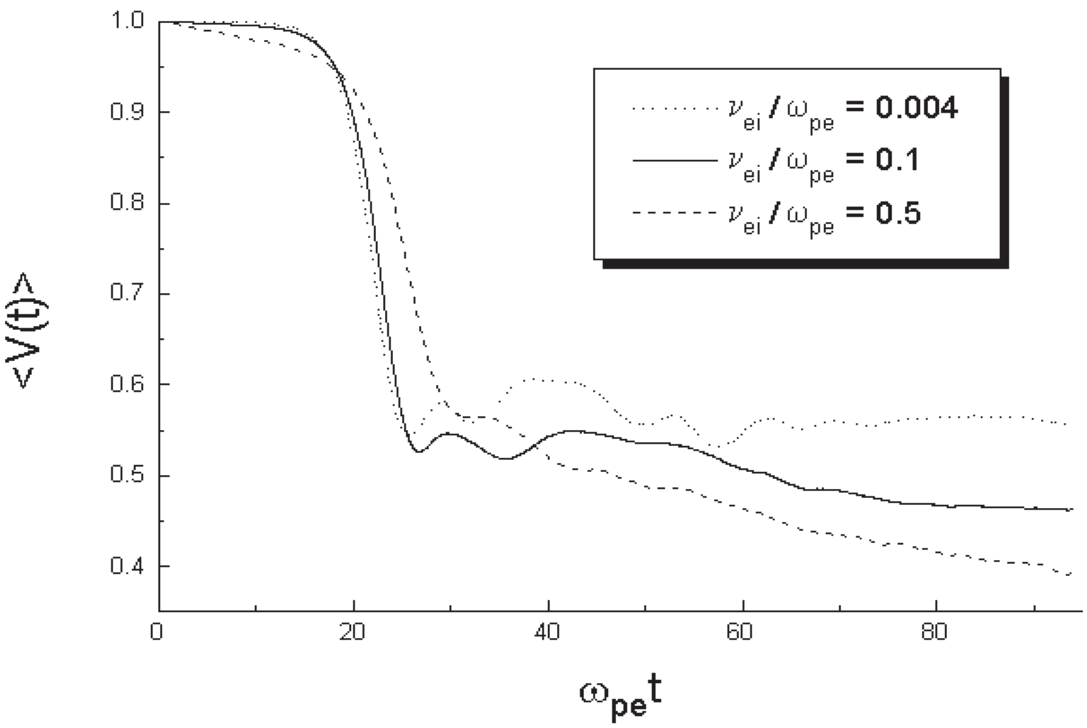

Figure 2. The dependence of averaged velocity of electron beam $< V(t)/V(0) >$ as a function of time ($N_{beam}/N_0 = 0.1, E_0 = 10keV, T_0 = 100eV$).