1D PIC simulation study of nonlinear beam plasma interaction

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Abstract

Since the early days of plasma simulation studies, superthermal electrons having energies much greater than the injected beam electrons have been widespreadly observed. The origin of such superthermal tail in the electron velocity distribution is generally believed due to the second order Fermi acceleration, i.e., the acceleration due to turbulence. In this paper, generation of superthermal electrons is studied by using a 1D PIC simulation code.

Key words: beam plasma interaction; Langmuir turbulence; energetic particle

In various plasma environments, energetic particles are ubiquitously observed featuring superthermal tail distribution. The physical origin of the superthermal electron generation is now widely believed to be due to some sort of nonlinear interaction between the particle and the wave turbulence, i.e., the second-order Fermi acceleration.

This problem has been addressed by many authors. For instance, attempts combining strong-turbulence (i.e., Zhakarov) equation for the waves and weak-turbulence diffusion equation for the particles were employed to explain the superthermal electrons. Recently, it has been suggested in a series of study [1–3] that the self-consistent kinetic description of superthermal electron distribution is possible. By solving the set of weak turbulence equations including effects of spontaneous single-particle fluctuations via the so-called "plasma parameter" $g = 1/n_e\lambda_D^3$ [where $\lambda_D = (\epsilon_0 T_e/n_e e^2)^{1/2}$ is the Debye length, n_e is the background electron density, T_e is the electron temperature, and e is the unit charge], Yoon *et al.* showed that the g parameter plays a pivotal role in superthermal electron generation. To confirm this theoretical analysis, we have carried out a particle simulation experiment.

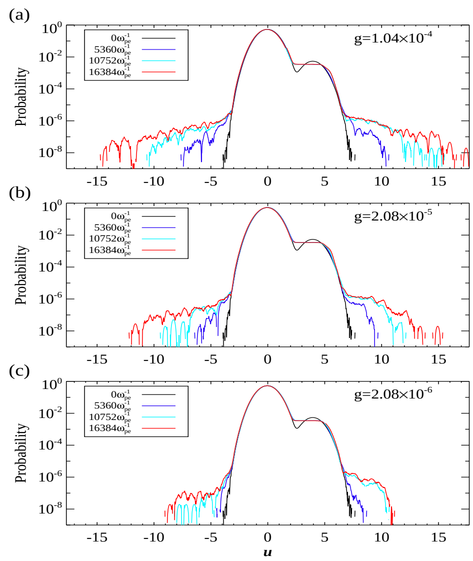

Fig. 1. Time evolution of the electron velocity distribution of (a) $g = 1.04 \times 10^{-4}$, (b) $g = 2.08 \times 10^{-5}$, and (c) $g = 2.08 \times 10^{-6}$.

Simulation study on the beam plasma interaction has also a long history. In early days, Dawson and Shanny studied long time behavior of distribution

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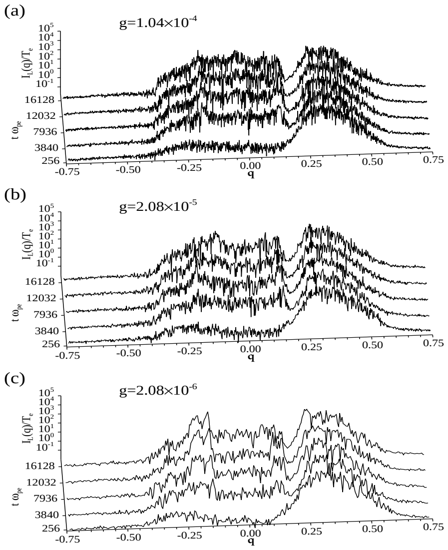

Fig. 2. Evolution of the Langmuir mode spectral wave energy density ($I_L(q)$) when (a) $g = 1.04\times10^{-4}$, (b) $g = 2.08\times10^{-5}$, and (c) $g = 2.08 \times 10^{-6}$.

and observed particles with energies much greater than the injected energy [4].

We have employed a one-dimensional electrostatic code KEMPO1 [5]. The number of grids used is 4096 and the time steps are taken to be 65,536 (2^{16}). we set 48,000 background and 480 beam electrons per cell, so that the total number of electrons in our system reaches near 200 million. We take the inverse of the number of pseudo-particles in a cube within λ_D as the g value. Since the discrete particle effect which is one of the inherent characteristics of a PIC code is closely related to the thermal fluctuations, our g value may closely resemble the g parameter defined in Ref. [1].

We normalize each physical quantity in accordance with Ref. [1]. For example, the normalized velocity u and wave number q are defined by $u = v/v_e$ and $q = kv_e/\omega_{pe}$ respectively. The time scale is normalized by ω_{pe}^{-1}. All energy-related values such as energy density ρ_E and the Langmuir wave intensity I_L are normalized by the electron temperature T_e.

The beam density (n_b) is 1% of the background electron density n_e, the beam drift velocity V_0 is set to be $4.0v_e$, and $v_b = v_e$, where the electron and beam thermal velocity v_e and v_b are defined by $v_e = (2T_e/m_e)^{1/2}$ and $v_b = (2T_b/m_e)^{1/2}$. The electron plasma frequency $\omega_{pe} = (n_e e^2/\epsilon_0 m_e)^{1/2}$ is fixed at 0.125, which means n_e is constant for all systems. We vary v_e as $\sqrt{2}\omega_{pe}/5^{1/3}$ for $g = 1.04 \times 10^{-4}$, $\sqrt{2}\omega_{pe}$ for $g = 2.08 \times 10^{-5}$, and $\sqrt{2}\omega_{pe} \times 10^{1/3}$ for $g = 2.08 \times 10^{-6}$ to control the plasma parameter $g = 1/n_e\lambda_D^3$, where the electron Debye length $\lambda_D = v_e/\sqrt{2}\omega_{pe}$. To avoid a numerical instability induced by grids [6], we controlled v_e carefully so that Δx always remains very close to λ_D. Finally, the ion temperature is set to be one third of the electron temperature.

The difference in electron distribution for different g values has been of our central interests. Figure 1 shows the time evolution of the electron velocity distribution up to $16384\omega_{pe}^{-1}$ for each g value. All distributions are smoothed by the Savitzky-Golay method [7]. Notice significant generations of the superthermal tail when $g = 1.04 \times 10^{-4}$ in Fig. 1-(a). When $g = 2.08 \times 10^{-5}$, one can observe the overall decrease of particle distribution at the tail as in Fig. 1-(b). Electrons with $|u| \geq 15$ are hardly found unlike the $g = 1.04 \times 10^{-4}$ case. This trend becomes more evident in the case of $g = 2.08 \times 10^{-6}$ (Fig. 1-(c)), where no electron with $|u| \geq 11$ is shown.

Fig.2 shows the time evolution of the Langmuir spectrum. Initially most of energy in the Langmuir mode ($0.25 \leq q < 0.45$), but with time, the energy is transferred to the backscattered ($-0.35 \leq q < -0.15$) and condensate ($-0.12 < q < 0.12$) modes.

In conclusion, we have confirmed the result of the previous weak turbulence theory given in Ref. [1–3] by using PIC simulation that superthermal electron can be generated in relation with the plasma parameter g, which describes the discrete particle effect.

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References

[1] P.H. Yoon et al., Phy. Rev. Lett. 95 (2005) 215003.

[2] P.H. Yoon et al., J. Geophys. Res. 111 (2006) A09106.

[3] T. Rhee et al., J. Geophys. Res. 111 (2006) A09107.

[4] J.M. Dawson, R. Shanny, Phys. Fluid 11 (1968) 1506.

[5] H. Matsumoto, Y. Omura, Computer Space Plasma Physics, Terra Sci. Pub., Tokyo, 1993, p. 21.

[6] C.K. Birdsall, A.B. Langdon, Plasma Physics via Computer Simulation, McGraw-Hill, New York, 1985.

[7] A. Savitzky, M. Golay, Analytical Chemistry 36 (1964) 1627.