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ANOMALOUS ELECTRON DIFFUSION ACROSS A MAGNETIC FIELD IN A BEAM-PLASMA SYSTEM

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The diffusion of electrons across a magnetic field in the presence of a beam-plasma instability has been studied by means of two-dimensional numerical simulations. It is found that the beam electrons can diffuse much faster across the magnetic field than the thermal electrons. This can be explained by the fact that the electrons in the beam are in resonance with the waves excited by the beam-plasma instability so that they experience a nearly d.c. electric field, causing large $cE \times B/B^2$ excursions.

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Beam-plasma interaction has been studied for more than three decades both experimentally and theoretically. The linear theory of the beam-plasma interaction is well-known.¹ In the *nonlinear regime*, quasilinear and single wave nonlinear theory are well understood.^{2,3} Numerous numerical simulations have been performed for strongly nonlinear plasma turbulence under various initial and boundary conditions.⁴ Experimentally, beam-plasma interaction has been used for plasma production and heating,⁵ radiation generation,⁶ current drive,⁴ and active space experiments.⁷

Here we report on the results of two-dimensional numerical simulations of beam-plasma instability in a magnetic field. While a great deal of work has been carried out to investigate plasma diffusion in velocity space, little work has been done for a study of spatial diffusion of electrons in the presence of beam-plasma instability.

Figure 1 shows a sketch of a two-dimensional electrostatic simulation model used for this simulation. Beam electrons are streaming along a uniform magnetic field $\mathbf{B}_0 = (0, B_{0y}, B_{0z})$ in a uniform ambient plasma. The code is two-dimensional so that only two-dimensional perturbations $\mathbf{k} = (k_x, k_y, 0)$ are considered in the model. The beam electrons are localized across the magnetic field with its width δ being a small fraction of the size of the ambient plasma, L_x . Note that in this model, beam electrons are assumed to be neutralized initially so that no appreciable electrostatic field exists due to charge non-neutrality associated with beam injection. This is a reasonable assumption when the beam density is a small fraction of the ambient density.⁴ Typical parameters for the simulations are the following: size of the two-dimensional grid, $L_x \times L_y = 64\Delta \times 256\Delta$, $\delta = 8\Delta$, $\omega_{ce}/\omega_{pe} = 0.5$ and 1 where Δ is the grid size, ω_{ce} and ω_{pe} are the electron gyro and electron plasma frequencies, mass ratio $m_i/m_e = 100$, beam velocity $V_0/V_e = 10, 20$ where V_e is the thermal velocity of the ambient electrons. θ in Fig. 1 is the parameter which characterizes the angle of wave propagation with respect to magnetic field. $\theta = 30^\circ, 45^\circ$, and 60° are chosen. Typically, four simulation particles

per grid are used for the ambient and beam particles. The ratio of the beam density n_b to the ambient density n_e is $n_b/n_e = 1/3$ and $1/4$.

Figures 2 and 3 show results of a simulation using $\omega_{ce}/\omega_{pe} = 0.5$, $V_0/V_e = 20$, and $\theta = 45^\circ$ at $\omega_{pe}t = 25$ (Fig. 2) and 70 (Fig. 3). Shown in the figures are locations of the beam electrons (a), the ambient electrons whose initial positions overlap with the positions of the beam electrons (b), phase space, $(y - V_y)$ (c), and the electrostatic potential contours (d). At an early phase of the instability at $\omega_{pe}t = 25$ shown in Fig. 2, a small amplitude modulation in the beam location is seen while no such modulation is visible in the location of the ambient electrons. A phase space plot in $(y - V_y)$ also indicates a presence of a small perturbation associated with the beam-plasma instability. Potential contours shown in Fig. 2(d) clearly indicate the wave fronts aligned in the y -direction suggesting that the unstable waves propagate in that direction. The amplitude of the potential is still small at this stage, $|e\phi|/T_e \lesssim 0.05$.

At $\omega_{pe}t = 70$, shown in Fig. 3, the instability grows to large amplitude and the spatial diffusion across the magnetic field for the beam electrons far exceeds that for the ambient electrons as shown in Fig. 3(a) and (b). Trapped beam electrons and the familiar vortex structure are seen in the phase space shown in Fig. 3(b). While most of the trapped particles are beam electrons, some of the ambient electrons are accelerated by the waves thereby becoming trapped electrons.⁸ The amplitude of the electrostatic potential shown in Fig. 3(d) reaches $|e\phi|/T_e \lesssim 0.1$ with distinct two-dimensional spatial structures determined by the width of the beam across magnetic field and by the most unstable mode along magnetic field whose parallel wave number is given by $k_{\parallel} = \omega_{pe}/V_0$.

The diffusion coefficient of the beam and ambient electrons can be studied quantitatively from Fig. 4 in which $\langle(\Delta X)^2\rangle \equiv \sum_{i=1}^N [X_i(t) - X_i(0)]^2/N$. The displacement square of the electrons from the initial positions across the magnetic field is shown for both beam and ambient electrons. It is clear

that the beam electrons undergo a displacement square much larger than the ambient electrons in agreement with the instantaneous snapshots of their locations shown in Fig. 2(a) and (b). A low frequency oscillatory motion in $\langle (\Delta X)^2 \rangle$ is clearly visible in Fig. 4 whose frequency is $\omega/\omega_{pe} \approx 0.25$. This frequency is close to the most unstable mode for an oblique propagation in the beam-plasma system.⁸

The diffusion coefficient may be estimated in the following manner. Since the beam electrons are resonant with the waves, they experience a nearly d.c. electric field. Ambient electrons are not in resonance with the wave so that their net displacement due to $c\mathbf{E} \times \mathbf{B}/B^2$ results in an oscillatory motion, which tends to cancel out and leave a small net displacement. The diffusion coefficient for the beam electrons can then be given by

$$D_x = \frac{\langle (\Delta X)^2 \rangle}{2\tau_c} = \frac{c^2 E_y^2 B_z^2}{2B^4} \tau_c = \frac{1}{2} \frac{E_y^2}{8\pi n T_e} \frac{\omega_{pe}^2}{\omega_{ce}^2} V_e^2 \tau_c, \quad (1)$$

where ρ_e is the ambient electron gyroradius, τ_c is the decorrelation time, and $B_z^2/B^2 = 1/2$ in this simulation. For a short time, $\langle (\Delta X)^2 \rangle$ should increase as $V_d^2 t^2$ and the drift speed V_d is given by

$$V_d^2 = \frac{1}{2} \frac{E_y^2}{8\pi n T_e} \frac{\omega_{pe}^2}{\omega_{ce}^2} V_e^2, \quad (2)$$

so that $\langle (\Delta X)^2 \rangle \simeq 0.1(\omega_{pe} t)^2$, where $E_y^2/8\pi n T_e = 0.1$ from the simulation and $\omega_{pe}/\omega_{ce} = 2$ are used. The value of $\langle (\Delta X)^2 \rangle$ in Fig. 4 agrees with the above estimate for a short time, $\omega_{pe} t \lesssim 50$ where $\langle (\Delta X)^2 \rangle$ increases as t^2 . For a longer time, $\omega_{pe} t \gtrsim 50$, $\langle (\Delta X)^2 \rangle$ increases more or less linearly with t , giving the measured diffusion coefficient

$$D_x \approx 0.25 \Delta^3 \omega_{pe}. \quad (3)$$

After the saturation of the instability, $\omega_{pe} t > 50$, the level of fluctuations decreases and settles near $E_y^2/8\pi n T_e \approx 10^{-2}$ in the simulation. The decorrelation time τ_c after saturation may be determined from the motion of trapped

electrons, which is a complex nonlinear function of the wave amplitude. Here we simply use the linear growth rate to see if it gives a reasonable estimate. The linear growth rate γ for a cold, infinite beam is estimated from $\gamma/k_{\parallel}V_o \approx (k_{\parallel}/k)\sqrt{3}(n_b/n_o)^{1/3}/2^{4/3} \approx 0.2$ and $\rho_e = V_e/\omega_{ce} = 2\Delta$. The measured growth rate in the simulation for a finite width beam is smaller, $\gamma/\omega_{pe} \approx 0.1$, so that $D_x \approx 0.2\Delta^2\omega_{pe}$ which is in good agreement with the measurement shown in Fig. 4. The measured growth rate is smaller than that predicted by linear theory for an infinite beam because the beam width is smaller than the parallel wavelength.⁸

Equation (1) suggests that the beam diffusion coefficient is proportional to B^{-2} provided other parameters remain the same. This has been tested by another simulation where the magnetic field is increased by a factor of 2 so that $\omega_{ce}/\omega_{pe} = 1$ while all the other simulation parameters are kept the same as in the first case. Figure 5 shows the displacement of the beam and ambient electrons for this case. The general behavior remains the same as in Fig. 4 in which the linear phase is followed by the nonlinear phase with a slower diffusion process. The magnitude of the diffusion and, hence, the displacement is almost a factor of four smaller than the previous case, confirming the prediction from Eq. (1).

In conclusion, we have shown that beam electrons injected into a plasma may be subjected to rapid diffusion across the magnetic field because of the inherent beam-plasma instability. The expression of the diffusion is obtained and checked by numerical simulations.

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Figures

FIG. 1. A sketch of the two-dimensional simulation model. A localized electron beam is streaming along the magnetic field $\mathbf{B}_0 = (0, B_{0y}, B_{0z})$. The ambient electrons are uniformly distributed in the $(x - y)$ plane.

FIG. 2. Results of the simulation at $\omega_{pe}t = 25$. Positions of the beam electrons (a), positions of the ambient electrons which are located at the same positions to the beam electrons (b), phase-space $(y - V_y)$ (c), and the electrostatic potential contours, $-0.051 \lesssim e\phi/T_e \lesssim 0.054$ (d).

FIG. 3. Results of the simulation at $\omega_{pe}t = 70$. Positions of the beam electrons (a), and of the ambient electrons (b), phase space $(y - V_y)$ (c), and the electrostatic potential contours, $-0.1 \lesssim e\phi/T_e \lesssim 0.089$ (d).

FIG. 4. Displacements of the beam and ambient electrons across the magnetic field. $\omega_{pe} = 2\omega_{ce}$.

FIG. 5. Displacements of the beam and ambient electrons across the magnetic field. $\omega_{pe} = \omega_{ce}$.

Fig. 2

Fig. 3

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Fig. 4

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Fig. 5

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