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Nonlinear growthrate of a phase-space electron hole

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In many collisionless plasmas, BGK-like islands in phase-space (x, v) with a local deficit of particles, called as a phase-space holes (PS holes), form spontaneously in a range of velocities where ion and electron distribution function have velocity gradients of opposite signs. In this paper we investigate the nonlinear growth-rate of electron PS holes in a 1D electron-ion plasma with periodic boundary conditions. Growth and acceleration of a hole are closely linked to the equilibrium velocity gradient via the Liouville conservation of phase-space density.

Model

The model we adopt is the collisionless Vlasov-Poisson system, with two species (electrons e and positively-charged ions i). In space x , the box size is set to a fixed length L , with periodic boundary conditions.

The initial velocity distributions are shifted, such that there is an initial current, weak enough to avoid linearly triggering current-driven ion-acoustic waves. This is shown schematically in Fig. 1. These two Gaussian distributions, before including a hole, are noted as $f_{0,i}$ and $f_{0,e}$. The key point in the present study is that, for each simulation, the initial condition includes a single electron PS hole with prescribed dimensions and shape, which satisfy a non-linear dispersion relation [1, 2]. Because of this initial hole, $f_e(x, v, t = 0) \neq f_{0,e}(v)$ (the difference is the hole, $\delta f_e = f_e - f_{0,e}$). Fig. 1 includes a schematics of an initial prescribed hole and its evolution at some later time. This setup is similar to the one investigated in [3], but a crucial improvement is

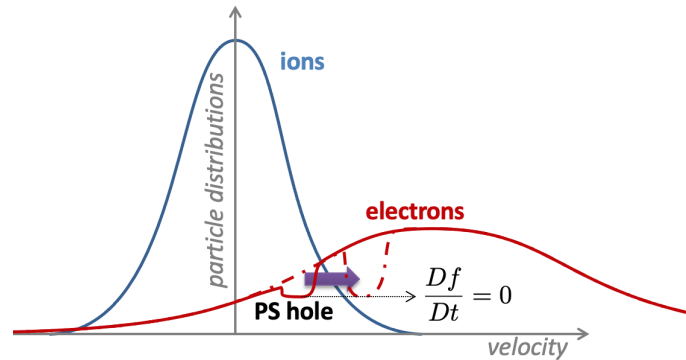


Figure 1: Schematics of the initial velocity distributions of ions and electrons, with an initial electron PS hole, and its evolution (represented by a purple arrow) to a later time.

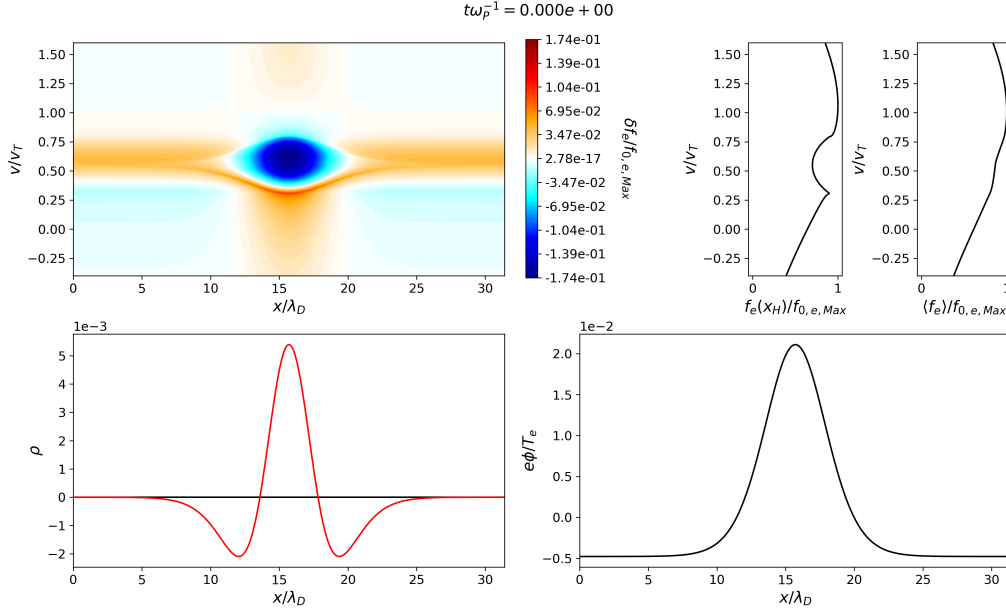


Figure 2: Prescribed electron distribution at $t = 0$. Top left: perturbed electron distribution function ($\delta f_e = f_e - f_{0,e}$). Top right: velocity distribution sliced at a x value corresponding to the O point of the PS hole ($f_e(x_H)$), and x -averaged velocity distribution ($\langle f_e \rangle$). Bottom left: charge density. Bottom right: electric potential.

that here the PS hole has been much more carefully crafted to produce as few secondary structures as possible. Fig. 2 shows precisely an example of initial distribution function. Note how the spatial profile of the electric potential features an anti-well which traps electrons.

The system is solved numerically using the semi-Lagrangian code COBBLES [4].

Theory of nonlinear growth of PS hole

Analytical theories have been developed [5, 6], based on a simple model of "box hole" of width $\Delta x \times \Delta v$, and assuming constant equilibrium velocity gradients in the velocity region spanned by the hole. These theories provide analytical estimates of the nonlinear growth-rate of an isolated electron PS hole, which may be summarized in a simplified version as

$$\frac{\gamma}{\omega_{p,i}} \approx -2 \frac{\Delta v}{\Delta x} \frac{A}{\lambda^{-2} + 4B} \frac{\partial_v f_{0,e}|_{v_h} \partial_v f_{0,i}|_{v_h}}{\partial_v f_{0,i}|_{v_h}^2} \quad (1)$$

where $v_h(t)$ is the center velocity of the hole, A and B are two constants, and λ is the screening length which can be obtained from the linear dispersion relation. Note that this formula predicts subcritical instabilities, by a mechanism reviewed in our recent tutorial [7].

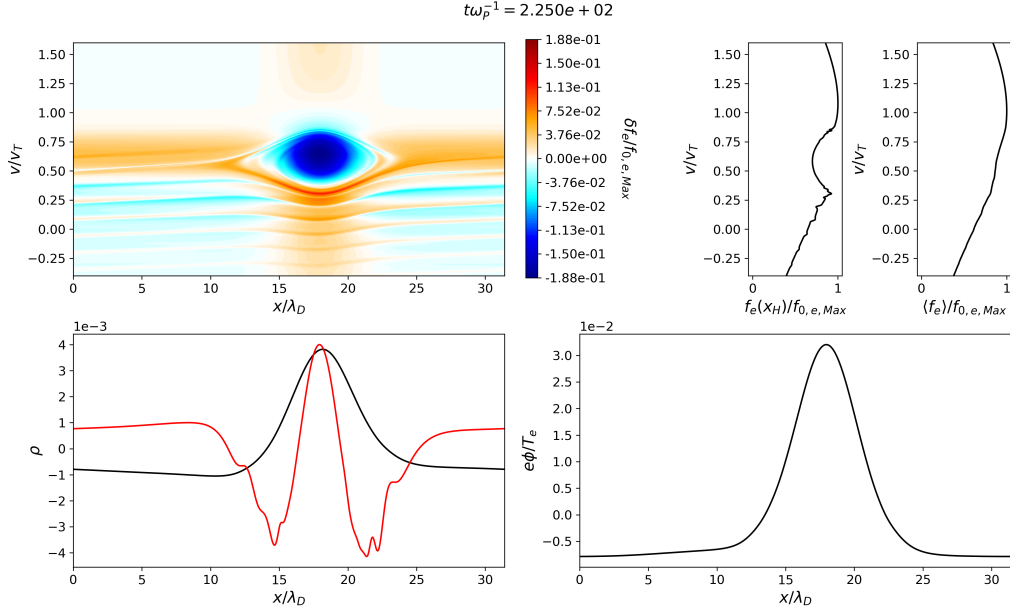


Figure 3: Prescribed electron distribution at $t = 225\omega_{c,i}^{-1}$. Same legend as for Fig. 2.

Note that the main dependency is the triple product $\Delta v \partial_v f_{0,e} \partial_v f_{0,i}$ which is very similar to the triple product $\Delta v \gamma_L \gamma_d$ found in the nonlinear growth-rate calculated for energetic particle-driven modes [8] based on the Berk-Breizman model [9], since in the latter context γ_L plays the role of $\partial_v f_{0,e}|_{v_h}$, and γ_d plays the role of $\partial_v f_{0,i}|_{v_h}$.

The goal here is to compare the nonlinear growth-rate measured in our numerical simulations with the expression Eq. eq:dupreetheory.

Results

Fig. 3 shows the self-consistent evolution of the initial prescribed hole, as obtained in our numerical simulation. Note that the hole is mainly accelerating, and only slightly changing in shape.

By tracking the hole, and measuring its depth at all times, we measure an instantaneous nonlinear growthrate of the PS hole. Fig. 4 shows the measured nonlinear growthrate against the local electron velocity slope ($\partial_v f_{0,e}|_{v_h}$). Except for the last two points to the right, which are outside the range of validity of theory because of secondary structures, we observe good agreement with the theoretical relationship between the growthrate and electron slope, Eq. (1).

In future work, we will analyse the impact of the velocity slope of ions, the impact of the amplitude of the potential anti-well, and the impact of structures on velocity-space transport,

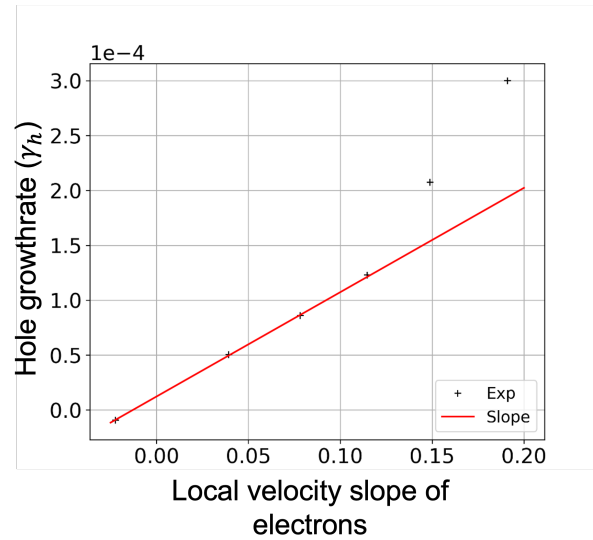


Figure 4: Nonlinear growthrate of an isolated electron phase-space hole, against the local electron velocity slope.

especially in the presence of strong turbulent fluctuations [10].

We further plan to conduct a similar analysis for the nonlinear growth of a PS hole in trapped-particle driven drift-wave turbulence, based on a gyro-bounce-averaged model [11, 12].

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