Phase-space electron-hole dynamics in 1D-1V kinetic plasma

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The dynamics of electron-holes in plasmas constitute a foundational topic in plasma physics, owing to their pivotal role in turbulence, transport, and the redistribution of energy and momentum in both natural and laboratory environments. Electron-holes are typically described as localized depressions in the electron distribution function, in other words, negative perturbations in phase-space density, that evolve into self-consistent, coherent structures. These entities can propagate over extended regions of plasma while retaining stability over significant timescales.

Their nonlinear interaction with the equilibrium plasma can give rise to rich dynamical behaviours, including acceleration and deceleration, variation in amplitude and spatial extent, subcritical triggering of instabilities [1], and interactions among structures, as observed in both experiments [2, 3] and simulations [4–6]. Electron-holes have been shown to impact particle transport [7, 8], modify the saturation amplitudes [9], drive anomalous resistivity [10], shift the mode frequency [7], and contribute to amplitude oscillations or chaotic dynamics [11], as well as interact with zonal flows [12].

Understanding electron-hole dynamics is not solely of theoretical interest, but it plays a critical role in a variety of physical contexts, including space and astrophysical plasmas [13, 14], the Earth's magnetosphere [15–17], and regions of magnetic reconnection [18, 19]. In laboratory settings, electron-holes are relevant to energetic particle dynamics in magnetic confinement devices [20], collision-less shock formation [21], and drift-wave turbulence [22], all of which influence transport, energy dissipation, and confinement stability. Despite their importance, key elements, such as the conditions for growth, mechanisms of acceleration, and the quantitative effects of turbulence, remain inadequately understood.

Electron-hole stability in phase space is a delicate balance between the electromagnetic interactions of the plasma and the momentum associated with the hole. By the latter half of the 20th century, observations in stellar [16], laboratory [23], and numerical settings [6, 24, 25] had confirmed a variety of hole behaviours, including growth, acceleration, decay, and coalescence. Analytical [26–29] and numerical [30, 31] efforts in the early 1980s laid the foundation for the modelling of electron-hole acceleration and growth-rates. However, limitations on computational resources constrained their ability to explore complex behaviours.

More recently, advances in spacecraft diagnostics [17] and computing capabilities have enabled detailed investigation of electron-hole dynamics through high-resolution kinetic simulations [32–37], thereby expanding the accessible parameter space.

This study builds on this foundation by employing the Vlasov-Maxwell solver COBBLES (COnservative Berk–Breizman semi-Lagrangian Extended Solver) [38] to investigate single electron-hole dynamics in 1D1V phase space. Through systematic variation of a key parameter, such as the electric potential, we aim to identify the dominant mechanisms governing hole acceleration and growth.

In this context, we focus on how variations in the electric potential amplitude ϕ_0 influence electron-hole behaviour, particularly through their effect on the equilibrium gradients. The dynamics of electron-holes are strongly influenced by the shape of the equilibrium electron and ion distribution functions. However, changing ϕ_0 also modifies the hole's velocity width, with $\Delta v_h \sim \sqrt{\phi_0}$. Consequently, a given electron-hole will experience different gradients of the equilibrium distributions across its width in the velocity direction. To account for this, we introduce the effective electron equilibrium gradient, denoted $\partial_v f_{eq,eff}$. This is defined as the characteristic gradient $f'e,h$ experienced by the hole, weighted by its velocity width. In practice, we approximate it as $\partial_v f_{eq,eff} \sim \partial_v f_{e,0}\sqrt{\phi_0}$ [37].

To investigate the influence of electric potential amplitude on the growth rate of electron-hole phasetrophy, we conducted nine numerical simulations. These were performed at a fixed relative hole velocity $\delta v_h = 0.45 v_T$ and electron drift velocity $v_d = 1.00 v_T$, while varying the potential amplitude over the range $\phi_0 e/T_e = [5\times10^{-3}, 1\times10^{-1}]$.

Two distinct regimes are present in figure 1: For $\phi_0 < 4\times10^{-2} T_e/e$, the growth-rate scales as $\gamma_h \sim \phi_0^{1.3}$, and for higher amplitudes, it scales as $\gamma_h \sim \phi_0^{0.8}$. Additionally, we observe a discrepancy between the two methods used to compute γ_h, from phasetrophy growth-and from acceleration, for large ϕ_0, since to calculate it, one assumes a constant equilibrium gradient across the velocity interval Δv_h, which becomes invalid at higher ϕ_0. However, at low ϕ_0, the two growth-rate estimates agree well, supporting the assumption of a nearly uniform gradient across the electron-hole width.

Figure 1 also shows the effective gradient $\partial_v f_{eq,eff}$ normalized to match the simulation data. For large ϕ_0, the effective gradient closely follows the numerical growth-rate, both qualitatively and quantitatively. In contrast, notable discrepancies appear in the low-amplitude regime. These observations suggest that for small electron-holes, where the gradient does not vary significantly across Δv_h, the local gradient $\partial_v f_{e,0}$ is sufficient to describe the dynamics. For larger holes,

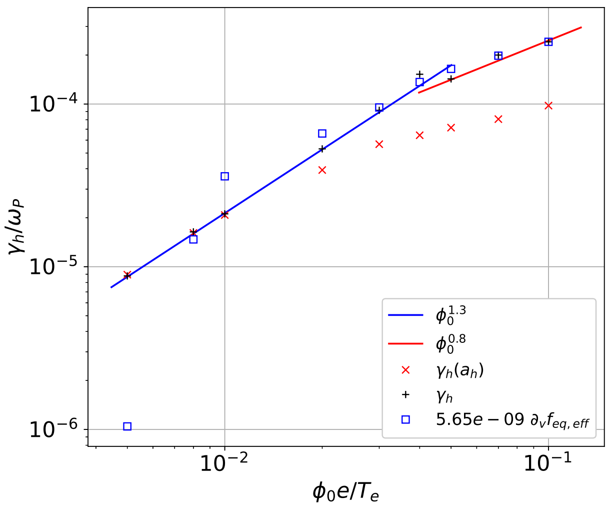

Figure 1: Electron-hole phasetrophy growth-rate as a function of the initial electric potential amplitude. Black crosses are numerical simulation results. $\gamma_h(a_h)$ the growth-rate estimated from acceleration. Solid red and blue lines correspond to power law fits. And blue squares are the normalized effective gradient $\partial_v f_{eq,eff}$.

however, this is not enough and one needs to consider variations on the equilibrium gradients across the electron-hole through means of an effective gradient.

In conclusion, we have measured and observed the effects of electron-holes dynamics, such as acceleration and growth of the structure, in phase-space through numerical simulations. In particular, we have found that considering the different gradients of the distribution functions over the hole's width through the effective gradient can more accurately match the observed growth-rate for large electron-holes. However, further work is required to improve the understanding of electron-hole dynamics in phase-space.

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