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Communications in Nonlinear Science and Numerical Simulation
Communications in Nonlinear Science and Numerical Simulation 13 (2008) 215–220
www.elsevier.com/locate/cnsns

Decay instability of electron acoustic waves

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Available online 18 April 2007

Abstract

Eulerian and particle in cell (PIC) simulations are used to investigate the decay instability of electron acoustic waves (EAWs). An EAW is a nonlinear wave with a carefully tailored trapped particle population, that can be excited by a relatively low driver amplitude, if the driver is applied resonantly over many trapping periods. The excited EAW rings at nearly constant amplitude long after the driver is turned off, provided the EAW has the longest wavelength that fits in the plasma. Otherwise, the EAW decays to a longer wavelength EAW, through a vortex-like trapped particle population merging.

PACS: 52.65.Ff; 52.65.Rr; 52.35.Fp; 52.35.Mw; 52.35.Sb

Keywords: Vlasov; Eaw; Decay; Trapping

1. Introduction

In 1991, Hollway and Dorning [1] noted that certain nonlinear wave structures can exist in a plasma even at low amplitude. They called these waves electron acoustic waves (EAW) since the dispersion relation is of the acoustic form (i.e. $\omega = 1.31kv_{\text{th}}$ for small k). Here, ω is the angular frequency of the wave, k the wave number, and v_{th} the thermal velocity of the plasma electrons. Within linear theory, an EAW would be heavily Landau damped, since the wave phase velocity is comparable to the electron thermal velocity [2]. However, the EAW is a Bernstein–Green–Kruskal nonlinear mode (BGK mode) [3] with electrons trapped in the wave troughs. Because of the trapped electrons, the distribution of electron velocities is effectively flat at the wave phase velocity, and this turns off Landau damping.

As shown by the authors in [4], the EAWs can be launched by a small amplitude driver if the driver is applied resonantly over many trapping periods. The driver continuously replenishes the energy removed by Landau damping, so the trapped particle distribution (and the EAW) is eventually produced. This result

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1007-5704/$ - see front matter
doi:10.1016/j.cnsns.2007.04.012

was demonstrated using a particle in cell (PIC) simulation. For the case where the wavelength is the longest wavelength that fits in the plasma, the launched EAW persists at nearly constant amplitude long after the driver is turned off. However, when the driven EAW does not have the longest wavelength, the EAW decays to a longer wavelength EAW. In phase space, the trapped particles for an EAW appear to be a vortex structure, and the decay to longer wavelength involves a merger of the vortices [5–9]. In this sense the decay process can be thought as an example of inverse cascade.

In this paper, we first describe the excitation and decay of EAWs in a plasma with periodic boundary conditions. In this case, waves travel only in one direction as they would in an infinite length plasma (or a toroidal plasma). We then discuss the excitation and decay of EAWs in a plasma with particle and wave reflection at each end. In this case the EAWs are standing waves. In both cases, resonant excitation and decay to longer wavelength are observed.

2. Particle in cell simulation for a plasma with periodic boundary conditions

We scale time by the inverse plasma frequency ω_p^{-1}, where $\omega_p = \sqrt{4\pi ne^2/m}$ and n is the electron density. Length is scaled by the Debye length $\lambda_D = v_{th}/\omega_p$. With these choices, velocity is scaled by the electron thermal velocity $\lambda_D\omega_p = v_{th}$ and electric field by $\sqrt{4\pi nmv_{th}^2}$.

The PIC simulation follows the electron dynamics in the x-direction (the ions are considered motionless), which is the direction of wave propagation. The electron phase space domain for the simulation is $D = [0, L_x] \times [-v_{max}, v_{max}]$, where $v_{max} = 5$. For an initial set of simulations, we choose $L_x = 2\pi/k = 20$, but in later simulations the plasma length is increased to $L_x = 40$ and $L_x = 80$. This increase in length allows for decay to longer wavelength EAWs. The time step is $\Delta t = 0.1$. The simulations follow the evolution of $N \sim 5 \times 10^6$–10^7 electrons for many plasma periods ($t_{max} = 4000$). The initial electron velocity distribution is taken to be Maxwellian. Periodic boundary conditions in physical space are imposed, and Poisson's equation is solved using a standard fast fourier transform (FFT) routine.

The external driver electric field is taken to be of the form $E_D(x,t) = E_D^{max}\{1 + [(t-\tau)/\Delta\tau]^n\}^{-1}\sin(kx - \omega t)$, where $E_D^{max} = 0.01$, $\tau = 1200$, $\Delta\tau = 600$, $n = 10$, and $k = \pi/10$. The plasma response is studied as a function of the driver frequency ω, or equivalently, phase velocity $v_\phi = \omega/k = 10\omega/\pi$. An abrupt turn on (or off) of the driver field would excite Langmuir waves as well as EAWs, complicating the analysis. Thus, the driver is turned on and off adiabatically. The driver amplitude is near E_D^{max} (within a factor of two) for several trapping periods [10] ($t_{off} - t_{on} \simeq 1200 \simeq 11\tau_D$), and is near zero again by $t_{off} = 2000$. Here, the trapping period associated with the maximum driver field is $\tau_D = 2\pi/\sqrt{kE_D^{max}} = 112$.

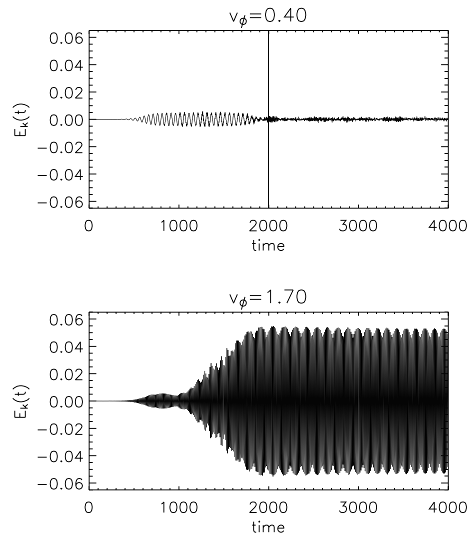

Fig. 1. Plasma response for two different values of the driver phase velocity: $v_\phi = 0.4$ (at the top) and $v_\phi = 1.70$ (at the bottom).