Electron Acoustic Waves in Pure Ion Plasmas

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Abstract.
Electron Acoustic Waves (EAWs) are the low frequency branch of electrostatic plasma waves. These waves exist in neutralized plasmas, pure electron plasmas and pure ion plasmas. At small amplitude, EAWs have a phase velocity $v_{ph} \simeq 1.4\bar{v}$ and their frequencies are in agreement with theory. At moderate amplitudes, waves can be excited over a broad range of frequencies and their phase velocity is in the range of $1.4\bar{v} \leq v_{ph} \leq 2.1\bar{v}$. This frequency variability comes from the plasma adjusting its velocity distribution so as to make the plasma mode resonant with the drive frequency. These plasma waves can also be excited with a chirped frequency drive resulting in extreme modification of the particle distribution, giving almost undamped waves with $(\gamma/\omega \sim 10^{-5})$.

Keywords: non-neutral plasma, plasma wave, Trivelpiece-Gould wave, EAW
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INTRODUCTION

The near-linear Electron Acoustic Wave (EAW) has a phase velocity $v_{ph} \simeq 1.4\bar{v}$ and its frequency has a strong temperature dependence $f_{\mathrm{EAW}} \propto T^{1/2}$. These waves have been studied theoretically [1] and numerically [2]; they have been observed in experiments with pure electron plasmas [3] and in laser produced plasmas [4, 5]. Linear Landau damping suggests that waves with such slow phase velocity are strongly damped. At finite amplitudes, however, trapping of particles near the phase velocity flattens the distribution function, resulting in weakly damped waves.

We observe that at small amplitude, the EAW dispersion relation is correctly described by the Holloway and Dorning approach. In contrast, at larger amplitude, we observe that we can excite EAW-type plasma waves over a continuous range of frequencies encompassing the small amplitude EAW and the small amplitude Trivelpiece-Gould (TG) plasma wave. Under these conditions, these plasma waves can not be uniquely named.

With a chirped frequency drive [6], these waves can also be excited over a continuum of frequencies. These chirp driven waves were initially described as BGK type plasma waves by Fajan's group at Berkeley. Vlasov-Poisson simulations [7] have also investigated the highly non-linear amplitude regime, suggesting that EAW-like modes with strong harmonic content, called KEEN waves, can be excited over a wide range of frequencies.

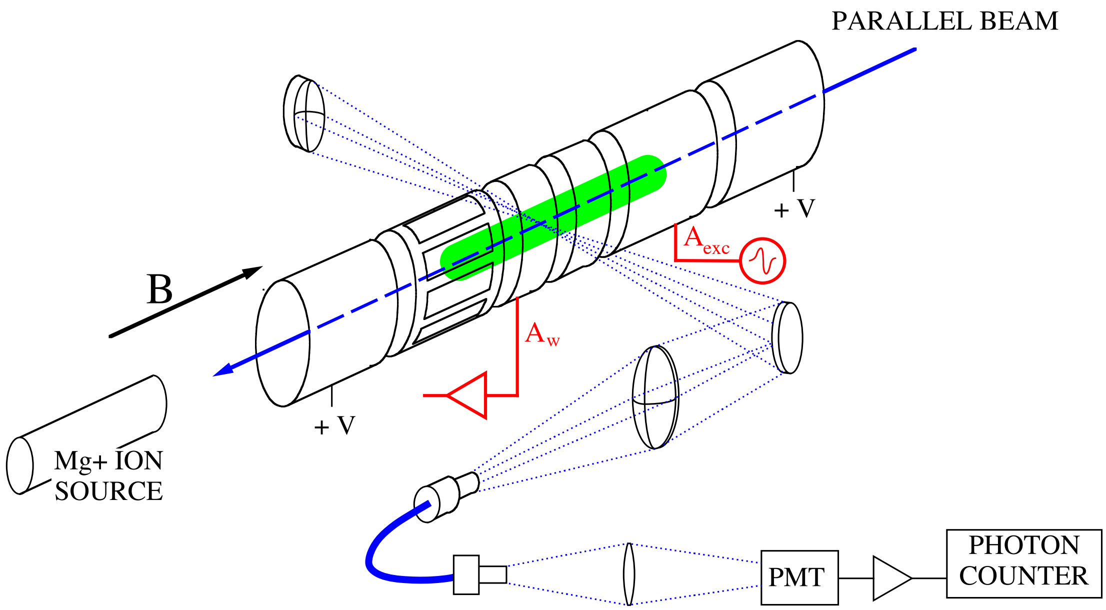

FIGURE 1. Experimental set-up.

APPARATUS

Figure 1 shows the electrode arrangement of our Penning-Malmberg trap with uniform axial magnetic field $B = 3$ Tesla. The trap conducting electrodes have a wall radius $R_w = 2.86$ cm and are contained in ultrahigh vacuum at $P \approx 10^{-10}$ Torr. The ion density is $n \sim 1.5 \times 10^7$ cm^{-3} over a radius $R_p \approx 0.45$ cm with a plasma length $L_p \simeq 9$ cm. The ions are held in steady state for days with a weak "rotating wall" electric field applied to the sectored electrode. The rotating wall is turned off about 100 ms before the wave measurement and turned back on about 200 ms later. The plasma density and temperature are measured with laser induced fluorescence. The temperature is controlled over 0.3 eV $\leq T \leq$ 1.5 eV.

We excite standing EAW and TG by applying a 3–100 cycle burst to the end electgrode at a frequency $f_{\rm exc}$ and amplitude $A_{\rm exc}$. To excite TG waves, 3–10 cycles are generally sufficient; in contrast, EAWs require a much longer drive to excite a wave lasting thousands of cycles. The amplitude of the burst is rounded to avoid exciting spurious TG modes from the harmonic content of the burst while driving an EAW. We excite the longest possible wavelength $(m_z = 1)$, that is $\lambda \approx 2L_p$, the lowest radial mode $(m_r = 1)$ and only consider azimuthally symmetric modes $(m_\theta = 0)$ since excitation and detection electrodes are both azimuthally symmetric. These waves are standing and reflect thousands of times at the plasma ends.

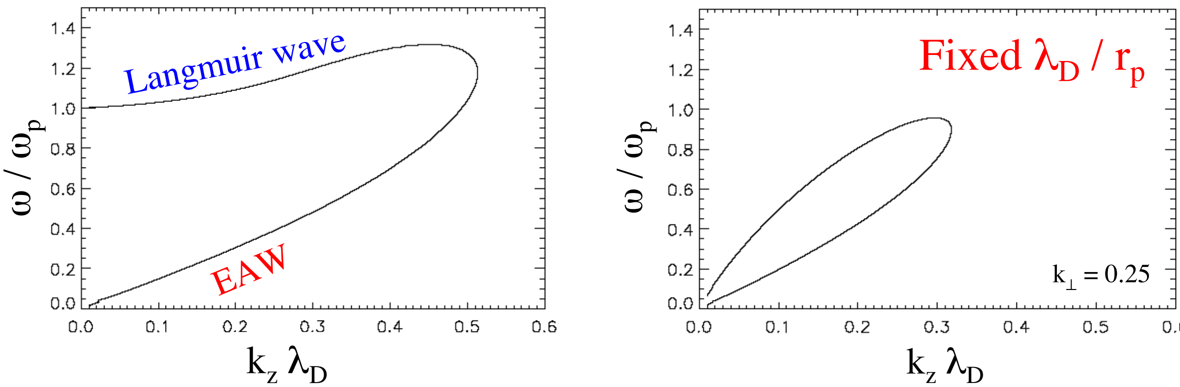

FIGURE 2. (a) Plasma wave dispersion relation in infinite plasma. (b) Plasma wave dispersion in non-neutral finite radial size plasma.

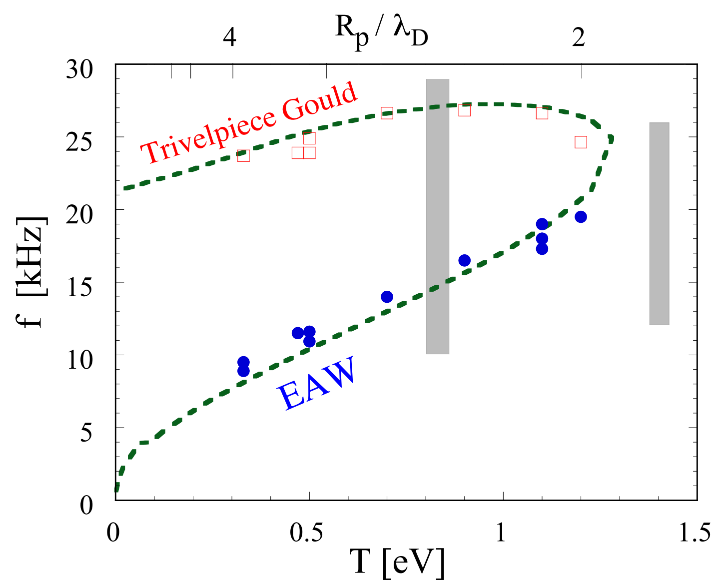

FIGURE 3. Measured plasma wave dispersion relation for fixed length with $m_z = 1$.

DISPERSION RELATION

The predicted dispersion relation of plasma waves in an infinite homogeneous plasma is shown in Fig. 2a. The upper branch is the traditional Langmuir wave starting at the plasma frequency for $k_z\lambda_D = 0$. The lower branch (EAW) first introduced by Holloway and Dorning[1] has an acoustic dispersion relation for small $k_z\lambda_D$ with a low phase velocity $\mathrm{v_{ph}} \simeq 1.4\bar{\mathrm{v}}$, where $\bar{\mathrm{v}} = (T/m)^{1/2}$. Their analysis considers a flattened particle distribution at $\mathrm{v_{ph}}$ eliminating the otherwise strong Landau damping.

In a trapped non-neutral plasma with a finite radial size, the perpendicular wave number is set by the radial plasma size. The fast plasma wave (TG) also has an acoustic dispersion relation and has $\omega < \omega_p$ since the radial wall short-circuits part of the electric field of the wave. In contrast, the EAW branch is essentially the same in a trapped

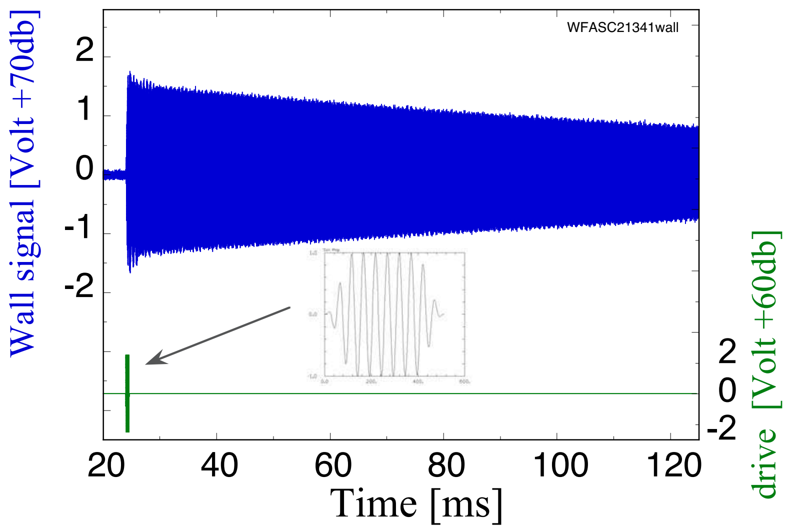

FIGURE 4. Trivelpiece-Gould wave driving burst and received wall signal.

plasma as in an unbounded plasma, as shown in Fig. 2b. For the data presented in this paper, the plasma length determines $k_z \approx m_z\pi/L_p$, where m_z is the axial mode number; $m_z = 1$ consists of half a wavelength in the trapped plasma. The plasma radius determines $k_\perp = \frac{1}{r_p}(\frac{2}{\ln(r_w/r_p)})^{1/2}$. This dispersion relation for $m_z = 1$ and variable plasma temperature results in the dashed line in Fig. 3.

When the amplitude is turned down sufficiently ($A_{\text{exc}} \sim 50$ mV), the waves are observed at only one frequency, plotted in Fig. 3 as dots (EAW) and squares (TG wave) for different temperatures. At small amplitude, these measurements are well described by the near-linear theory of Refs. [1, 2]. At temperatures above 1.3 eV, no waves are observed at comparably low excitation amplitude.

However, at larger amplitude the waves are excited over a range of frequencies and furthermore they ring at frequencies different than f_{EAW} or f_{exc} because the excitation has significantly modified the particle distribution function. The gray bar at $T = 0.8$ eV shows the range of frequencies over which a 100 cycle burst with $A_{\text{exc}} = 300$ mV resulted in a wave $f_w = f_{\text{exc}}$ ringing for hundreds of cycles. This means that at $T = 0.8$ eV a wave can be excited at "any frequency" within the vertical extent of the gray bar. Similarly, plasma waves at $T = 1.4$ eV are excited with $A_{\text{exc}} = 200$ mV for 100 cycles, past the "end of the thumb" as shown by the gray bar where no near-linear solution exists.

The drive modifies the particle distribution until the distribution becomes resonant with the drive. Wave names in these continuous regimes are ill-defined, since wave names are given for well characterized distributions such as Maxwellian or near-Maxwellian and beams.

Figure 4 shows a driving burst, consisting of 10 cycles at 21.5 kHz, applied to the excitation electrode, and the TG wave detected on a separate electrode. The received wall signal grows smoothly during the burst. Figure 5 shows a driving burst consisting of 100 cycles at 10.7 kHz with ramped amplitude to avoid exciting a TG wave. The

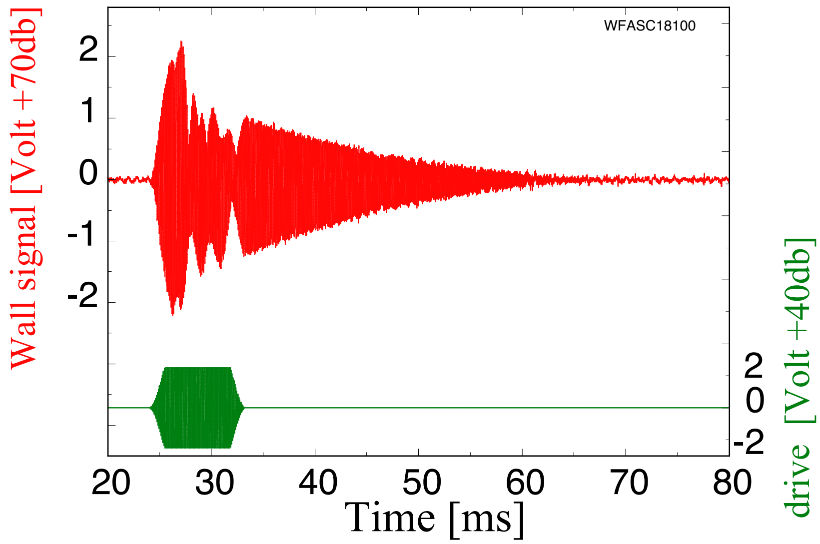

FIGURE 5. EAW driving burst and received wall signal.

EAW signal received on the wall A_w is "erratic" during the exciting burst reflecting the complicated process by which the particle distribution forms a plateau. If the driving burst is terminated after about 20 cycles, when A_w is the largest, the plasma oscillations damp within one or two wave cycles, presumably because the plateau was not formed yet. The fully-developed EAWs are observed to damp exponentially with $30 < \gamma < 3000 s^{-1}$; this is about $10\times$ faster than TG waves of comparable amplitude.

CHIRP DRIVE, EXTREME MODIFICATION OF $F(\mathrm{v})$

Similar plasma modes can also be excited to very large amplitude by a down-chirped frequency drive [6]. Here the chirped frequency creates extreme modification of $F(\mathrm{v})$, and can be tailored to support a mode at almost any frequency. We measure the parallel particle velocity distribution with a laser beam aligned along the magnetic field. Figure 6 shows an example of extreme modification of $F(\mathrm{v})$ from an amplitude-rounded ($A_{\mathrm{exc}} \approx 800$ mV) burst of 14.5 cycles total chirped from $20 \rightarrow 9$ kHz, corresponding to phase velocity $\mathrm{v}_{\mathrm{ph1}}$ and $\mathrm{v}_{\mathrm{ph2}}$ in Fig. 6. The glitch just to the left of $\mathrm{v} = 0$ and the 10% left-right sensitivity differences are laser-cooling artifacts. Here, the original Maxwellian distribution has been essentially split into two counter-propagating distributions, each supporting an EAW-like wave on the "inside" of $F(\mathrm{v})$. This wave rings at $f_w = 9.9$ kHz, with an amplitude giving $\delta n/n \sim 0.3$, with very weak damping $\gamma \approx 0.5$ sec^{-1}, $\gamma/\omega \sim 10^{-5}$. Similar frequency sweeping of phase space structures has been studied theoretically and numerically [8, 9], and driven phase space "holes" have been numerically explored [9, 10] as an explanation for observations of almost-undamped plasma waves in trapped systems [11].

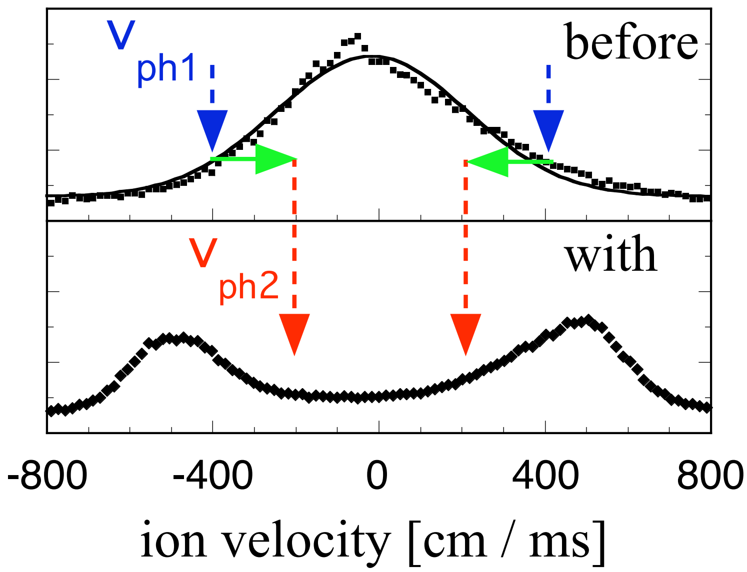

FIGURE 6. Particle distribution before wave and with plasma wave excited by a chirp sweeping from v_{ph1} down to v_{ph2}.

DISCUSSION

We have observed new, near-linear plasma waves with a phase velocity slow enough to be located in the bulk of the particle velocity distribution. At small amplitude, the experimentally observed standing wave in a magnesium ion plasma confirms the EAW theory concept of Holloway and Dorning, that is a local flattening of the particle distribution around the phase velocity suppressing Landau damping. At moderate and large amplitude, the wave can be excited at the small amplitude theory frequency, but also over a wide continuum range of frequencies. Here the wave driver modifies the particle velocity distribution until the distribution becomes resonant with the driver.

ACKNOWLEDGMENTS

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