Electron Acoustic Waves in Pure Ion Plasmas

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Overview

• We observe “Electron” Acoustic Waves (EAW) in magnesium ion plasmas. Measure wave dispersion relation.

• We measure the particle distribution function $f(v_z, z = \text{center})$ coherently with the wave

• A non-resonant drive modifies the particle distribution $f(v_z)$ so as to make the mode resonant with the drive.
Electron Acoustic Wave: the mis-named wave

- EAWs are a low frequency branch of standard electrostatic plasma waves.

- EAWs are non-linear plasma waves that exist at moderately small amplitude.

- Observed in: Laser plasmas
  Pure electron plasmas
  Pure ion plasmas
Other Work on Electron Acoustics Waves

- Theory: neutralized plasmas
  Holloway and Dorning 1991

- Theory and numerical: non-neutral plasmas
  Valentini, O’Neil, and Dubin 2006

- Experiments: laser plasmas
  Montgomery et al 2001
  Sircombe, Arber, and Dendy 2006

- Experiments: pure electron plasmas
  Kabantsev, Driscoll 2006

- Experiments: pure electron plasma mode driven by frequency chirp
  Fajan’s group 2003
Electron Acoustic Waves are plasma waves with a slow phase velocity 

\[ \omega \approx 1.3 \ k \bar{v} \]

This wave is nonlinear so as to flatten the particle distribution to avoid strong Landau damping.
Infinite homogenous plasma  (Dorning et al.)

\[ 0 = \varepsilon(k, \omega) = 1 - \frac{\omega_p^2}{k^2} \int dv \frac{k \frac{\partial f_0}{\partial v}}{kv - \omega} \]

Trapping “flattens” the distribution in the resonant region (BGK)

\[ 0 \approx 1 - \frac{\omega_p^2}{k^2} \ P \int dv \frac{k \frac{\partial f_0}{\partial v}}{kv - \omega} \]

“Thumb diagram”
Dispersion Relation

Infinite size plasma (homogenous)

\[ \frac{\omega}{\omega_p} = \frac{k_z \lambda_D}{\lambda_D} \]

Langmuir wave

EAW

Trapped NNP (long column finite radial size)

\[ \frac{\omega}{\omega_p} = \frac{k_z \lambda_D}{r_p} \]

Fixed \( \lambda_D / r_p \)

\( k_z = 0.25 \)

Experiment:
fixed \( k_z \)

vary \( T \) and measure \( f \)

\[ f \text{ [kHz]} \]

\[ T \text{ [eV]} \]
Penning-Malmberg Trap
Density and Temperature Profile

\[
\text{Mg}^+ \quad 0.05 \text{eV} < T < 5 \text{ eV} \quad r_p \sim 0.5 \text{ cm}
\]

\[
B = 3T \quad n \approx 1.5 \times 10^7 \text{ cm}^{-3} \quad L_p \sim 10\text{ cm}
\]
Measured Wave Dispersion

\(R_p/\lambda_D < 2\)
Received Wall Signal

The plasma response grows smoothly during the drive.

- Trivelpiece Gould mode
- 10 cycles
- 21.5 kHz
Received Wall Signal

Electron Acoustic Wave

During the drive the plasma response is erratic.

Plateau formation

100 cycles
10.7 kHz
Fit Multiple Sin-waves to Wall Signal

The fit consists of two harmonics and the fundamental sin-wave, resulting in a precise description of the wall signal.
Wave-coherent distribution function

Record the Time of Arrival of the Photons

Photon accumulation in 8 separate phase-bins
The coherent distribution function shows oscillations $\delta v$ of the entire distribution.

These measurements are done in only one position (plasma center, $z\sim0$)

$f = 21.5$ kHz
$T = 0.77$ eV
The coherent distribution function shows:

- oscillating $\Delta v$ plateau at $v_{\text{phase}}$
- $\delta v_0$ wiggle at $v=0$

These measurements are done in only one position (plasma center, $z=0$)
Distribution Function versus Phase

\[ f(v_z) \]

Trivelpiece Gould mode

\[ \text{wave phase} \]

\[ T = 0.77 \text{eV} \]

21341-21541
Distribution Function versus Phase

$f(v_z)$

Electron Acoustic Wave

[Graph showing distribution function with labeled axis and peak at 10.7 kHz, wave phase, and temperature 0.3 eV]

$n\text{PhoB1}$
Distribution Function versus Phase

\[ f(v_z) \]

Electron Acoustic Wave

\[ n \text{pmnB1} \]

Relative velocity [m/s]

\[ T = 0.3 \text{eV} \]

18055-18305
This measurement is done in only one position (plasma center)
Distribution Function versus Phase

Shows:
- trapped particle island of half-width $\Delta v$
- $\delta v_0$ wiggle at $v=0$

This measurement is done in only one position (plasma center)
- Two independent waves
- Collisions remove discontinuities
Island Width $\Delta v$ vs Particle Sloshing $\delta v_0$

Trapping in each traveling wave gives $\Delta v$

The sum of the two waves gives sloshing $\delta v_0$

Linear theory gives:

$$\Delta v = \left( 2 \delta v_0 v_{ph} \right)^{1/2}$$
Large amplitude drives are resonant over a wide range of frequencies.
The plasma responds to a non-resonant drive by re-arranging $f(v)$ such as to make the mode resonant.
$f(v)$ evolves to become resonant with drive!

Non-resonant drive modifies the particle distribution $f(v_z)$ to make the plasma mode resonant with the drive.
The coherent response gives a precise measure of the phase velocity. For a fixed frequency drive with 100 cycles at $f = 18$ kHz, the phase velocity is $v_{\text{phase}}$. The graph shows the coherent response in A.U. as a function of $v / v_{\text{th}}$, where $v_{\text{th}} = 2646. \text{ m/s}$ and $T = 1.75 \text{ eV}$. The coherent response is crucial for understanding the phase velocity in this context.
When the Frequency Changes \( k_z \) does not change

\[
k_z = \frac{\pi}{L_p}
\]

Plasma mode excited over a wide range of phase velocity:

\[
1.4 \, v_{th} < v_{phase} < 2.1 \, v_{th}
\]
When the particle distribution is modified, plasma modes can be excited over a continuum range, and also past the theoretical thumb.
Chirped Drive

The frequency is chirped down from 21kHz to 10 kHz

Damping rate $\frac{\gamma}{\omega} \sim 1 \times 10^{-5}$
Summary

• Standing “Electron” Acoustic Waves (EAWs) and Trivelpiece Gould waves are excited in pure ion plasma. Measured dispersion relation agrees with Dorning’s theory.

• We observe:
  - Particle sloshing in the trough of the wave
  - Non-linear wave trapping.
  - Close agreement with 2 independent waves + collisions model

• Surprisingly: Non-resonant wave drive modifies the particles distribution $f(v)$ to make the drive resonant. Effectively excites plasma mode at any frequency over a continuous range.