Stimulated Brillouin Scattering from a Two-Ion Plasma

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SBS from Fast and Slow Waves in Two-Ion Plasmas

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A plasma consisting of electrons and two types of ion supports two types of ion-sound wave (fast and slow). The density perturbations associated with these waves scatter incident laser radiation independently. We derive the equations governing SBS from the fast and slow waves. We compare the temporal growth rates of the two instabilities and the dependence of these growth rates on plasma parameters. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460.

Outline

- **We will discuss:**
  - **the need for a multi-ion SBS analysis**
  - **the canonical form of the SBS equations and the associated formula for the SBS growth rate**
  - **the dimensionless electron- and ion-fluid equations used to analyze sound waves**
  - **the dispersion equations for fast and slow sound waves**
  - **the growth rates of fast- and slow-wave SBS and their dependence on plasma composition**

Analysis of multi-ion SBS is necessary

- ICF experiments involve multi-ion plasmas.
- Vu[1] and Williams[2] have studied sound waves in two-ion plasmas.
- The Landau damping rates of the fast and slow waves differ and depend sensitively on the plasma parameters.
- Either wave can dominate the plasma response to the PM force.

[1] H. X. Vu *et al*., Phys. Plasmas 1, 3542 (1994).
[2] E. A. Williams *et al*., Phys. Plasmas 2, 129 (1995).

SBS in a one-ion plasma is well understood

- SBS is the decay of a pump light wave (0) into a Stokes light wave (1) and a sound wave (2).
- The SBS equations are

$$D_1(\omega-\omega_0, k-k_0)A_1^* = C_1 N_2 A_0^*$$

$$D_2(\omega, k)N_2 = C_2 A_0 A_1^*$$

where

$$A_1 = v_1/v_{te}, \quad N_2 = n_e/n_0 - 1,$$

$$D_1(\omega, k) = \omega^2 - \omega_{pe}^2 - c^2 k^2, \; C_1 = \omega_{pe}^2$$

- In a one-ion plasma with $T_i = 0$ and $k\lambda_{de} << 1$

$$D_2(\omega, k) = \omega^2 - c_{se}^2 k^2, C_2 = c_{se}^2 k^2$$

- Routine analysis shows that the temporal growth rate

$$\gamma_0^2 = \frac{C_1 C_2 |A_0|^2}{|\partial D_1/\partial\omega_1|(\partial D_2/\partial\omega_2)}.$$

Dimensionless variables facilitate the sound-wave analysis

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- Let $x/\lambda_{de} \rightarrow x$, $\omega_{pr} t \rightarrow t$, where ω_{pr} is the reference ion-plasma frequency, $e\phi/T_e \rightarrow \phi$, $n_e/n_{e0} \rightarrow n_e$, $n_i/n_{i0} \rightarrow n_i$, and $u_i/c_{sr} \rightarrow u_i$, where c_{sr} is the reference ion-sound speed.

- The linearized Poisson and fluid equations are

$$\partial^2_{xx}\phi = n_e - \sum_i \alpha_i n_i$$

$$n_e = \phi - p$$

$$\partial_t n_i = -\partial_x u_i$$

$$\partial_t u_i = -\beta_i \partial_x \phi - v_i^2 \partial_x n_i$$

where $\alpha_i = Z_i n_{i0}/n_{e0}$, $\beta_i = Z_i m_r/Z_r m_i$ and $v_i^2 = 3v_{ti}^2/c_{sr}^2$, $p = v_\perp^2/2v_{te}^2$.

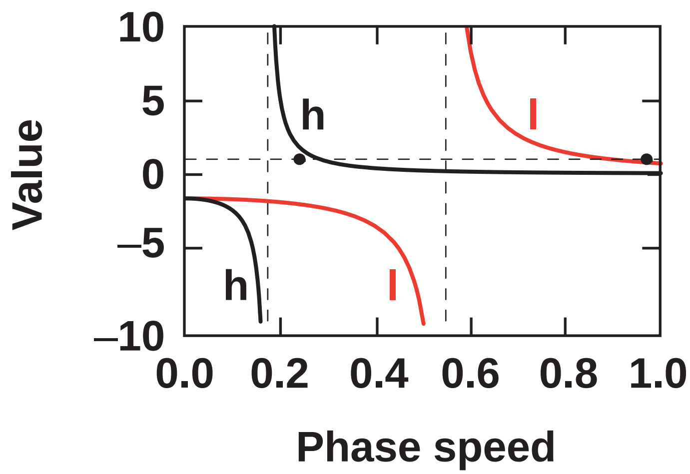
Sound-wave properties can be determined graphically

- In a two-ion plasma the dispersion equation is

$$1+k^2 = \frac{\gamma_l k^2}{\omega^2 - v_l^2 k^2} + \frac{\gamma_h k^2}{\omega^2 - v_h^2 k^2},$$

where $\gamma_i = \alpha_i \beta_i$.

- The natural frequencies can be determined graphically.



- Fast-wave: $v_l + \gamma_l/(1+k^2) < \omega_f/k$.
- Slow-wave: $v_h < \omega_s/k < v_h + \gamma_h/(1+k^2)$.

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In SBS the sound wave is driven by the PM force

- Driven oscillations of the electron density obey

$$\left(1+k^2-\frac{\gamma_l k^2}{\omega^2-v_l^2 k^2}-\frac{\gamma_h k^2}{\omega^2-v_h^2 k^2}\right)\bar{n}_e=\bar{p}.$$

- This equation can be rewritten as

$$\left(\omega^2-\omega_f^2\right)\left(\omega^2-\omega_s^2\right)\bar{n}_e=\frac{\left(\omega^2-v_l^2 k^2\right)\left(\omega^2-v_h^2 k^2\right)}{1+k^2}\,\bar{p}.$$

The SBS growth rate can be determined analytically

- The temporal growth rate for fast-wave SBS satisfies

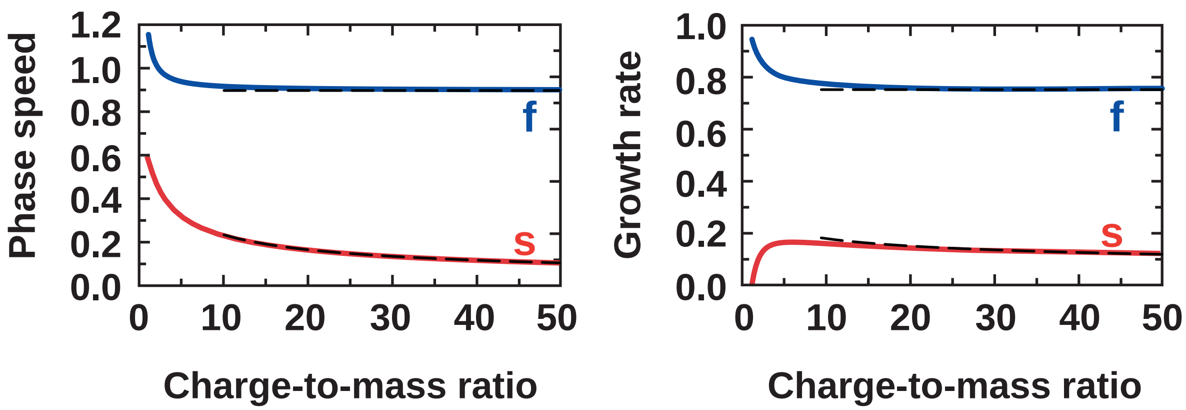
$$\gamma_f^2 = \frac{\gamma_0^2\left(v_f^2 - v_l^2\right)\left(v_f^2 - v_h^2\right)}{v_f\left(v_f^2 - v_s^2\right)\left(1 + k^2\right)},$$

where γ_0 is the growth rate in a plasma of reference ions.

- For slow-wave SBS let $f \leftrightarrow s$.

Increasing m_h hinders slow-wave SBS

- Suppose $Z_l n_l / n_{e0} = Z_h n_h / n_{e0} = 0.5$ and $M = Z_l m_h / Z_h m_l \rightarrow \infty$.

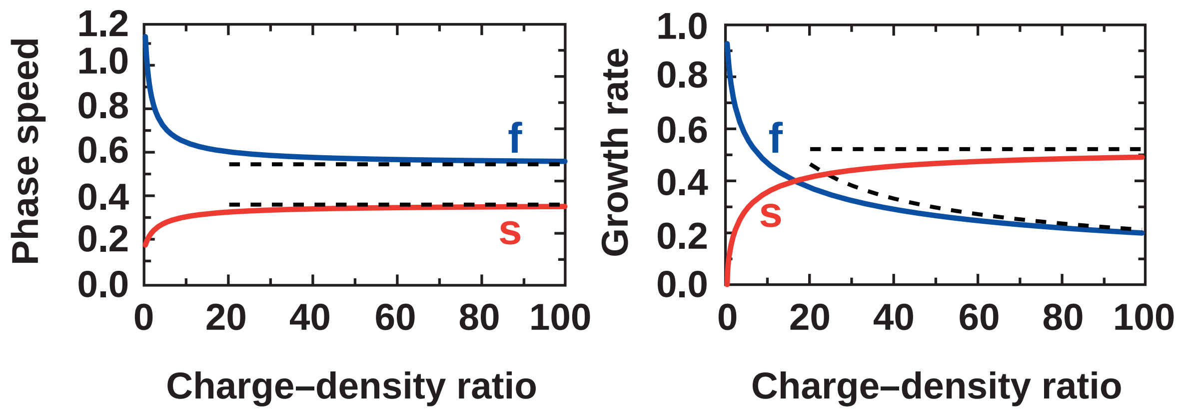


$n_e = 1.1 \times 10^{20}$ cm^{-3}
$T_e = 5.0$ keV
$T_l = T_h = 0.5$ keV
$\lambda_0 = 1.0$ μm

- $\omega_f / k \rightarrow v_l + \gamma_l / (1 + k^2)$. γ_f is decreased slightly.
- $\omega_s / k \rightarrow v_h \propto M^{-1/2}$. $\gamma_s \rightarrow 0$ as $M^{-1/4}$ because the response time of the slow wave increases.

Decreasing n_l suppresses fast-wave SBS

- Suppose that $Z_l m_l / Z_h m_l = 10$ and $N = Z_h n_h / Z_l n_l \to \infty$.



$n_e = 1.1 \times 10^{20}$ cm^{-3}
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- $\omega_s/k \to v_h + \gamma_h \big/ \left(1 + k^2\right)$ and γ_s increases.
- $\omega_f/k \to v_l$. $\gamma_f \to 0$ as $N^{-1/2}$ because the density perturbation that mediates SBS is suppresed when ω_f/k . v_l.

Summary

Analytic formulas for the growth rates of fast- and slow-wave SBS were derived

- These formulas allow the dependence of the growth rates on plasma parameters to be determined easily.
- The growth rate of fast-wave SBS is lower than the growth rate of SBS in a light-ion plasma.
- If Landau damping suppresses fast-wave SBS, slow-wave SBS can still grow with an appreciable growth rate.