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STUDY OF ION ACOUSTIC SHOCK WAVE INSTABILITIES IN ION BEAM DRIVEN COLLISIONLESS MAGNETIZED NEGATIVE ION PLASMAS

Physics

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ABSTRACT

The fluid theory analysis of the ion-acoustic shock wave instabilities in magnetized negative ion plasma containing electrons, positive ions (Cs+) and negative ions (SF6¯) is presented. Two unstable wave modes are found, one is fast Cs+ mode and other is slow SF6¯. The unstable wave frequencies and growth rates of these modes increase with the negative ion concentration i.e., when E(n_{SF6}/n^{+}_{Cs})>0.9 and for the ratio Te/Ti equal to 4. Numerical calculations of phase velocities of both the modes were carried out for typical parameters values of an experiment. It was observed that phase velocity of fast mode (Cs+) grows faster than that of a slow mode (SF6¯).

INTRODUCTION

Recently, there has been growing interest in the study of shock waves [1-9] in collisional and collision less plasmas. The conditions under which large density pulses might develop into sharp fronts or shocks were investigated in a Q machine by Andersen et al. [1] Under normal conditions, Te = Ti, Landau damping prevented the formation of a shockwave, but when the ratio Te/Ti is made about 3 or 4 and the concentration of negative ions is increased, shockwave formation can be observed in the plasma. However, negative ion plasmas produced by electron attachment to SF6¯ was first reported by Wong et al. [2]. Hershkowitz and Interator [3] made important improvements to the concept introduced by Wong et al.[2] and used their device to study beam plasma interactions in positive ion negative ion plasma [4]. A detailed study of various ion sources was presented by Sheehan and Rynn [5] and Sheehan et al [6] who later showed that such sources could be used to study plasmas with adjustable levels of strong turbulence. Experiments on ion acoustic shocks formed in collisionless plasma with negative ions have also been performed by Takeuchi et al.[7] under conditions substantially different from those of the present experiments. The theory of shock formation in fluid plasma has also been discussed by Montgomery [8]. In the present work the ion beam driven ion acoustic shock wave instabilities are studied by increasing the ratio Te/Ti to 4 and increasing the concentration of negative ions in the plasma. The instability analysis of ion acoustic shock waves is carried out in collisionless magnetized negative ion plasma. The plasma and beam responses are obtained using fluid treatment. We obtain the phase velocities and growth rates for both the unstable modes in the presence and absence of negative ions using first-order perturbation theory.

INSTABILITY ANALYSIS

We consider a magnetized collisionless plasma cylinder containing electrons, positive ions and negative ions. The positive ions are Cs+ ions and negative ions are SF6¯. The equilibrium densities of electrons, positive and negative ions, respectively as $n_{0e}=(1-\varepsilon)n_{0p}$ $n_{0+}=n_{0p}$ immersed in a static magnetic field ˆsBzP, where $\varepsilon(=n_{SF_6^-}/n_{Cs}^{+})$

is the relative ion density of negative ions and n_{0p} is the plasma density. The charge, mass and temperature of three species are ($-e, m_e, T_e$), (e, m_+, T_i) and (e, m_-, T_-), respectively. The plasma is collisionless. An ion beam with velocity $v_{0b}z$ mass m_b, density n_{0b} and radius $r_b(\cong a_1)$ propagates through the plasma along the magnetic field. The beam plasma system prior to the perturbation is quasi-neutral, such that $-n_{0e}+n_{0+}-n_{0-}+n_{0b}$ is approximately zero, since we $n_{0p} \square n_{0b}$ have taken . There is no electric field present in the equilibrium and plasma is partially uniform. The equilibrium is perturbed by an electrostatic perturbation to potential

$$\phi_1 = \phi\ (r)\exp\left[-i(\omega t - \vec{k}.\vec{r})\right] \tag{1}$$

The equations of motion and continuity for all the three species can be written as:

$$m_e\left[\frac{\partial \vec{v}_e}{\partial t} + \left(\vec{v}_e.\nabla\right)\vec{v}_e\right] = -e\vec{E} - \frac{e}{c}\left(\vec{v}_e \times \vec{B}_s\right) - T_e\frac{\nabla n}{n_{0e}} \tag{2}$$

$$m_+\left[\frac{\partial \vec{v}_+}{\partial t} + \left(\vec{v}_+.\nabla\right)\vec{v}_+\right] = -e\vec{E} - \frac{e}{c}\left(\vec{v}_+ \times \vec{B}_s\right) - T_+\frac{\nabla n_+}{n_{0+}} \tag{3}$$

$$m_-\left[\frac{\partial \vec{v}_-}{\partial t} + \left(\vec{v}_-.\nabla\right)\vec{v}_-\right] = -e\vec{E} - \frac{e}{c}\left(\vec{v}_- \times \vec{B}_s\right) - T_-\frac{\nabla n_-}{n_{0-}} \tag{4}$$

$$\frac{\partial n_e}{\partial t} + \nabla.\left(n_e\vec{v}_e\right) = 0 \tag{5}$$

$$\frac{\partial n_+}{\partial t} + \nabla.\left(n_+\vec{v}_+\right) = 0 \tag{6}$$

$$\frac{\partial n_-}{\partial t} + \nabla.\left(n_-\vec{v}_-\right) = 0 \tag{7}$$

On linearization equations (2), (3) and (4), we get perturbed electron density, positive & negative ion perturbed densities and beam perturbation as

$$n_{1e} = n_{0p}\frac{e\phi_1}{T_e} \tag{8}$$

$$n_{1+} = \frac{n_{0p}e}{m_+}\left(\frac{\nabla_\perp^2\phi_1}{\omega_{c+}^2} + \frac{k_z^2\phi_1}{\omega^2}\right) \tag{9}$$

$$n_{1-} = -\frac{n_{0p}\varepsilon e}{m_-}\left(\frac{\nabla_\perp^2\phi_1}{\omega_{c-}^2} + \frac{k_z^2\phi_1}{\omega^2}\right) \tag{10}$$

$$n_{1b} = \frac{n_{0b}ek_z^2\phi_1}{m_b\left(\omega - k_z v_{0b}\right)^2}, \tag{11}$$

where $c_+(=T_+/m_+)^{1/2}$ & $c_-(=T_-/m_-)^{1/2}$ are the thermal velocities of positive & negative ions and $\omega_{c+}(=eB_s/m_+c)$ & $\omega_{c-}(=eB_s/m_-c)$ are the cyclotron frequencies of positive & negative ions respectively. Using Eqs. (8), (9), (10) and (11) in the Poisson equation $\nabla^2\phi_1 = 4\pi e\left(n_{1e} - n_{1+} + n_{1-} - n_{1b}\right)$ we obtain a second degree differential equation, on solving which we get

$$1-\frac{1}{(1-\varepsilon)}\frac{\omega_{p-}^2}{\omega^2}\frac{k_z^2}{p_n^2\alpha_1}-\frac{\omega_{p+}^2}{\omega^2}\frac{k_z^2}{p_n^2}\frac{1}{(1-\varepsilon)\;\alpha_1}+\frac{1}{(1-\varepsilon)}\frac{\omega_{p-}^2}{\omega_{c-}^2\alpha_1} \quad (12)$$

$$+\frac{1}{(1-\varepsilon)}\frac{\omega_{p+}^2}{\omega_{c+}^2\alpha_1}=\frac{\omega_{pb}^2}{(1-\varepsilon)}\frac{k_z^2}{(\omega-k_z v_{0b})^2\,p_n^2\alpha_1}$$

where $\alpha_1 = \frac{\omega_{pe}^2}{v_{te}^2 p_n^2}+\frac{1}{(1-\varepsilon)}\frac{k^2}{p_n^2} \;\square\; \frac{4\pi\;\; n_{0p}e^2}{m\; v_{te}^2 p_n^2} \;\square\; \frac{\omega_{pi}^2}{c_s^2 p_n^2}$

$c_s^2 = T_e / m_i$ and $\omega_{pi}^2 = \frac{4\pi\;\; n_{0p}e^2}{m_i} = \omega_{p+}^2$

$\omega_{p-}^2 = \frac{4\pi n_{0p}\varepsilon e^2}{m_-}$ and $\omega_{p+}^2 = \frac{4\pi n_{0p}e^2}{m_+}$

Neglecting negative ions, Eq. (12) can be written as

$$\left(\omega^2-b_1^2\right)\left(\omega-k_z v_{0b}\right)^2=\frac{\omega_{pb}^2\omega^2k^2}{\alpha_1 p_n^2\alpha_2} \quad \text{where } b_1^2=k^2c_s^2\frac{1}{\alpha_2}$$

$$\omega^2=b_1^2=\frac{k^2c_s^2}{\left[1+\frac{p_n^2\;\;c_s^2\omega_{p+}^2}{\omega_{c+}^2\omega_{pi}^2}\right]} \qquad \alpha_2=1+\frac{\omega_{p+}^2}{\omega_{c+}^2}\frac{p_n^2\;\;c_s^2}{\omega_{pi}^2}.$$

Which gives the growth rate and phase velocity of unstable mode for positive ions as

$$\gamma = I_m\delta = \left[\frac{b_1}{2}\frac{\omega_{pb}^2k^2}{\alpha_1\alpha_2 p_n^2}\right]^{1/3}\frac{\sqrt{3}}{2} \qquad (13)$$

$$v^{posi}_{\;\;ph}(\varepsilon)=\omega/k = \frac{c_s}{\left(1+\frac{p_n^2\;\;c_s^2}{\omega_{c+}^2}\right)^{1/2}}. \qquad (14)$$

Similarly, in the absence of positive ions, the growth rate for negative ion mode can be written as

$$\gamma = I_m\delta = \left[\frac{c_1}{2}\frac{\omega_{pb}^2\;\;k^2}{(1-\varepsilon)\alpha_1\alpha_3 p_n^2}\right]^{1/3}\frac{\sqrt{3}}{2} \qquad (15)$$

$$v^{n}_{\;ph}(\varepsilon)=\omega/k = \frac{c_s}{(1-\varepsilon)^{1/2}}\frac{(m_i/m_-)^{1/2}}{\left(1+\frac{1}{(1-\varepsilon)}\frac{p_n^2\;\;c_s^2}{\omega_{c-}^2}\frac{\omega_{p-}^2}{\omega_{pi}^2}\right)^{1/2}}. \qquad (16)$$

RESULTS AND DISCUSSIONS

In our calculations, we used the typical experimental parameters shown in table I.

TABLE – 1

Mode No.	np0~ ni0 (cm3)		Te (eV)	Ti (eV)	Bs (gauss)	Eb	Plasma radius
1	1011	0-0.95	0.2	0.08	6x103	10	2

Based on typical experimental parameters, the growth rates and phase velocities of the unstable mode (in the presence of negative ions) are evaluated using eqs. (15) & (16). The growth rate and phase velocity of the unstable mode (in the presence of negative ions) increase with the increase in density of negative ions. Our model is valid in the limit when wavelength of the ion-acoustic wave is large than the Debye length (Dell>>). Our observations are also qualitatively similar to the experimental observations of Takeuchi et al. [7].

As the negative ion concentration becomes quite appreciable (e> 0.5), the phase velocity of the unstable mode increases.

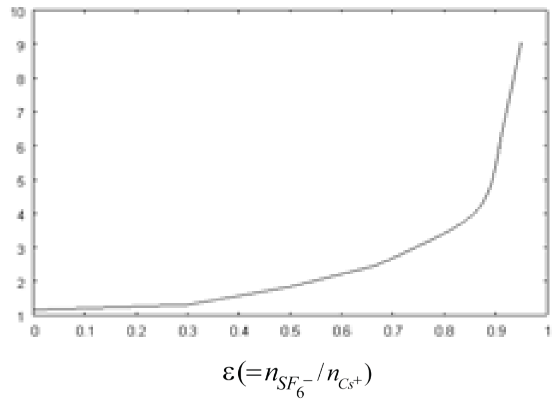

Fig. 1: Growth rate of unstable negative ion mode with relative density of negative ion concentrations.

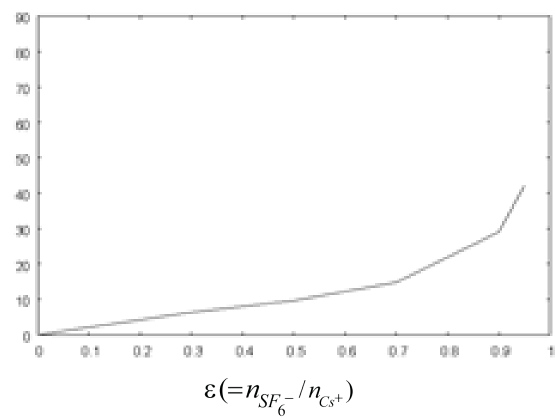

Fig. 2: Phase velocity of unstable negative ion mode with relative density of negative ion concentrations.

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