EXPERIMENTAL EVIDENCES OF MODULATIONAL INSTABILITY OF LANGMUIR WAVES EXCITED BY AN ELECTRON BEAM IN A PLASMA

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1 - INTRODUCTION

It is well known that the interaction of an electron beam, characterized by beam velocity v_b, beam density n_b, with a higher density ambient plasma, n_0, excites Langmuir waves, with unstable wave number given by $k_0 = \omega_{pe}/v_b$, where ω_{pe} is the ambient plasma frequency. For a cold beam, in the limit $n_b/n_0 \ll 1$, the instability is due to a feedback mechanism involving bunching of the electrons leading to a growth in the space charge density (hydrodynamic regime). A thermal spread in the velocities of the beam particles (kinetic regime) tends to suppress the hydrodynamic instability. This has an important implication even when the velocity spread is initially small because the development of the instability itself causes the velocity spread to increase. The condition for neglecting the beam thermal spread, Δv, is $(n_b/n_0)^{1/3} \geq (\Delta v)/v_b$. [1,2]

It was shown previously[3] that when the energy of the waves in resonance with the beam, W_r, normalized by the plasma thermal energy n_0T_e, where T_e is the electron plasma temperature, becomes greater than $(k_0\lambda_D)^2$, λ_D is the Debye length, these waves become unstable due to modulational instability (MI). These instabilities act to transfer the field energy from waves resonant with the beam to waves with shorter wavelengths which are not resonant. When the MI energy transfer rate exceeds the rate at which field energy is generated by the beam, the beam instability will be stabilized.

This paper reports results obtained in a beam plasma interaction experiment. In our experiment, typically, $(\Delta v)/v_b \approx 0.2$, $n_b/n_0 \approx 10^{-3}$, so that $(n_b/n_0)^{1/3} \leq (\Delta v)/v_b$ and the wave energy growth and saturation are governed by kinetic effects.[1] The estimation of the maximum wave energy due to the warm beam quasi-linear diffusion process gives $W_r \geq (k_0\lambda_D)^2$, indicating that the modulational instability can be the responsible mechanism for the suppression of the beam plasma instability observed in the experiment.

2 - EXPERIMENTAL PROCEDURE

Experiments were carried out in a double plasma device with multipole surface magnetic confinement. A discharge plasma is created by accelerating primary electrons produced by tungsten, oxyde coated, hot cathod filaments in argon or helium gases. The inner diameter (plasma diameter) of the device is 0.60 m and its total length is 1.20 m. The chamber is divided into a source chamber ($l_s = 0.30$ m) and a target chamber ($l_t = 0.90$ m) by a triple grid (source, control and target grids). The whole chamber is filled with gas ($p \leq 5 \times 10^{-5}$ mbar) and a discharge plasma is created in the source chamber region. The inner side of the metallic cylinder of the source chamber is connected to the source grid so that when the source grid is negatively biased with respect to the target chamber a dc electron beam is generated, which flows towards the target chamber. This electron beam propagates into the target chamber and ionizes the gas, thus creating a plasma in that chamber with the parameters given in Table 1.

Table 1 - Experimental parameters

Plasma density	$n_0 \simeq 10^{14} - 10^{15}\,\mathrm{m}^{-3}$
Plasma electron temperature	$T_e \simeq 2\,\mathrm{eV}$
Natural plasma density fluctuations	$(\delta n_0)/n_0 \leq 10^{-2}$
Beam energy	$E_b \leq 250\,\mathrm{eV}$
Beam plasma density ratio	$n_b/n_0 < 5 \times 10^{-3}$
Electron neutral collision frequency	$\nu_{en} \simeq 5 \times 10^5\,/\mathrm{s}$
Electron ion temperature ratio	$T_e/T_i \simeq 10$
Beam thermal spread	$(\Delta v)/v_b \simeq 0.2$
Beam radius	$r_b \simeq 0.30\,\mathrm{m}$

Electron plasma density and temperature measurements were performed using cylindrical Langmuir probes, calibrated for the density measurements by detecting the cutt-off frequency of a low amplitude electromagnetic wave (EMW), launched into the plasma. Plasma electric field oscillation measurements were performed with movable cylindrical probes at the floating potential connected to a spectrum analyser or to an oscilloscope. The beam electron and accelerated plasma electron energy distribution functions were investigated with an electrostatic multigrid energy analyser using the method of retarding potential.

Experiments were carried out in argon or helium gases at filling pressure of $p \leq 5 \times 10^{-5}$ mbar. At this range of pressure the electron neutral collision frequency, ν_{en}, is enough smaller than the beam plasma instability growth rate, γ_{pb}, which allows the excitation of the Langmuir wave by the beam plasma instability.

3 - DISCUSSION OF EXPERIMENTAL RESULTS

The dynamics of the electron beam plasma interaction is shown in Figures 1 and 2 for $n_0 \simeq 2 \times 10^{14}\,\mathrm{m}^{-3}$, $E_b \simeq 100\,\mathrm{eV}$, $n_b/n_0 \simeq 2 \times 10^{-4}$ for argon and helium respectively. These figures show the electron beam energy distribution function at different positions across the system. In the beam quasi-linear relaxation theory the diffusion of the beam particles in the field of oscillations excited by them leads to the establishment of a "plateau" on the velocity (or energy) distribution function at characteristic distances given by[4]

$$l_{QL} \simeq \frac{v_g}{\gamma_{bp}} \simeq 3\frac{v_{te}}{v_b}\frac{v_{te}}{\omega_{pe}}\frac{n_0}{n_b}\left(\frac{\Delta v}{v_b}\right)^2 \Lambda\,, \tag{1}$$

where Λ is the logarithm of the ratio of the final to the thermal noise which is of the order of magnitude of the Coulomb logarithm. We assume that the unstable mode wavenumber is k_0 and since it is a plasma wave, the wave group velocity is $v_g = 3v_{te}^2/v_b$, where v_{te} is the plasma thermal velocity. The retardation of the beam electrons by the electrical field of the plasma waves causes the widening of the warm electron energy distribution to energies smaller than E_b and a reduction of the beam plasma instability growth rate. This process will be over when the energy of the waves reaches the value of [4]

$$W_s \simeq \frac{1}{15}\frac{n_b}{n_0}\left(\frac{v_b}{v_{te}}\right)^4, \qquad (2)$$

where W_s is the saturation energy wave of the beam plasma instability normalized by n_0T_e. This high value for W_r can be explained when we consider the effects of oscillation pileup in the development of beam instability.[5] However, when the energy of the oscillation reachs the threshold of the MI, the character of the beam plasma interaction changes. The MI takes place when its growth rate, $\gamma_{MI} = \omega_{pe}(m_eW_0/m_i)^{1/2}$ is larger or of the same order of γ_{bp}. W_0 is the pump wave energy normalized by n_0T_e. Using $W_0 \simeq W_s$, we obtain $\gamma_{MI} \simeq \gamma_{bp}$ for $(\Delta v)/v_b \geq 0.7$ for argon and $(\Delta v)/v_b \geq 0.4$ for helium, which are satisfied at positions $x \simeq 0.40\,\mathrm{m}$ and $x \simeq 0.20\,\mathrm{m}$, respectively. This ion mass ratio dependence appears clearly in Figure 3 that shows the space evolution of the unstable wave amplitude observed in the experiment.

Modulational instability generates the formation of cavities which means density wells filled with the Langmuir waves. The wave number of these waves is determined by the intensity of the pumping wave by $(k\lambda_D)^2 \sim W_0 \sim 1.2$. The Langmuir waves created by MI are immediately absorbed by the electrons. The formation of the cavity is accompanied by the appearance of the radiation at the second harmonics and by the acceleration of the bulk electrons due to the absoption of the trapped waves. These effects can also be observed in Figures 1-3.

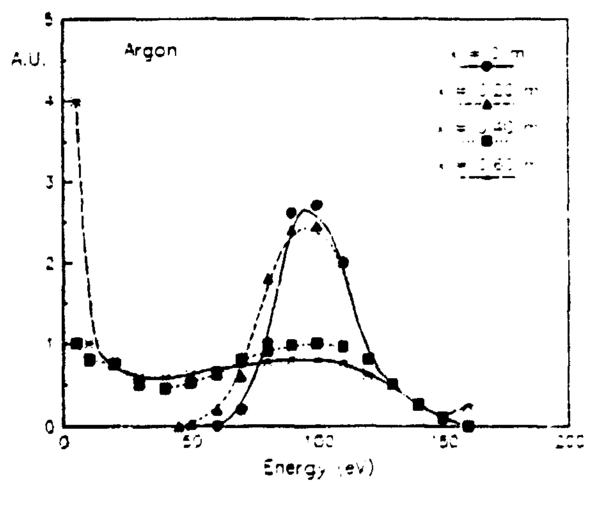

Fig. 1 Electron beam energy distribution function at different positions across the system for argon.

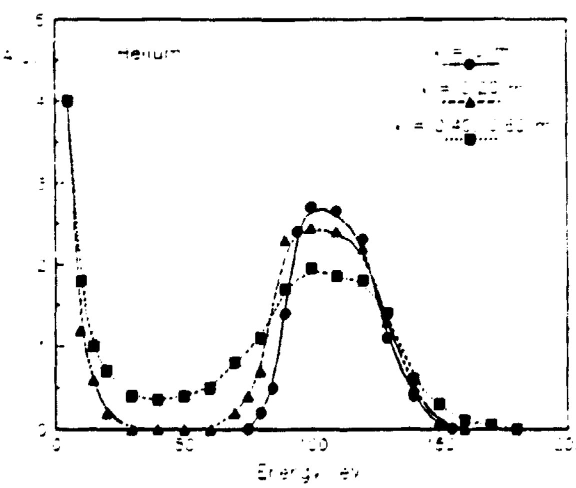

Fig. 2 Electron beam energy distribution function at different positions across the system for helium.