EXPERIMENTAL STUDY OF ELECTRON BEAM RELAXATION IN THE VICINITY OF THE THRESHOLD FOR MODULATIONAL INSTABILITY EXCITEMENT

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The interaction of a weak non-relativistic electron beam with an unmagnetized collisionless plasma is one of the most interesting features of modern plasma physics. Electron plasma waves (Langmuir waves) are excited as the electron beam transfers energy to the plasma [1,2]. Depending on the beam energy, the amplitude of excited waves can be high enough to become unstable to modulational instability which characterizes the so-called strong Langmuir turbulence [3,4]. In such regime, these waves are trapped by density cavities that occur spontaneously in the plasma as a result of the instability and, in turn, the trapped waves steeps the density cavity even more and the process continues as the waves collapse to smaller and smaller spatial lengths while its amplitude increases [5]. At collapse burn out stage where the cavity is small enough, the Langmuir wave energy is released to plasma electrons through Landau damping and the excess density variations are released as ion-sound waves [4-7].

This experimental work shall focus on the development of a beam-plasma system into Langmuir turbulence regime and its influence on the properties of plasma. On the other hand, the investigation of the macroscopic characteristics of the system gives information about the development of turbulence process.

Experiments were carried out in a double QUIescent Plasma (PQUI) device with multipole surface magnetic confinement with 0.60 m of inner diameter and 1.20 m of total length [8,9]. The device is divided by grids into a source ($l_s = 0.30$ m) and a target plasma ($l_t = 0.90$ m) electrically insulated. A DC plasma discharge is created independently in both chambers by accelerating primary electrons produced by tungsten hot cathode filaments uniformly placed near the inner wall of the vessel. An electron beam with energy $50 \leq W_b \leq 400$ eV and initial spread of about $\Delta W_b / W_b \approx 0.15$ is created biasing the source chamber negatively with respect to the grounded target chamber.

In this investigation, the experiments were carried out in argon gas at filling pressure range of $10^{-4} \leq p \leq 10^{-3}$ mbar; plasma density range of $10^8 \leq n_0 \leq 10^{10}$ cm^{-3}; beam to plasma

density ratio range of $5.0 \times 10^{-5} \leq n_b / n_0 \leq 5.0 \times 10^{-3}$; electron-neutral collision frequency $\nu_{en} / \omega_{pe} \leq 10^{-4}$; electron to ion temperature ratio of about $T_e / T_i \leq 15$; ion-neutral collision frequency $\nu_{in} / \omega_{pi} < 5.0 \times 10^{-3}$; and beam radius $r_b \approx 25$ cm.

The electron density and temperature measurements were performed using a single cylindrical Langmuir probe calibrated for density measurements by detecting the cut-off frequency of an electromagnetic wave launched into the plasma. The same probe operating at ion saturation current regime was used for ion-sound oscillation measurements. The Langmuir wave intensity was measured by an insulated dipole probe connected to spectrum analyser. The electron energy distribution function was measured by an electrostatic multigrid energy analyzer using the retarding potential method.

We obtained the threshold conditions for the transition from the quasi-linear beam-plasma interaction into strong turbulence regime. The results are shown in Figure, in a plane of the parameters W_b / T_e and n_b / n_0. The upper black circles correspond to the conditions where we observe the saturation of Langmuir wave amplitude and lower red triangles correspond to the conditions for the appearance of ion sound oscillations. The line is the theoretical threshold for modulational instability excitement in a beam plasma system, $(n_b / n_0)_{th} \sim (T_e / W_b)_{th}^3$ [4].

Under modulational instability threshold (low beam energy case), the Langmuir wave energy saturates due to complete relaxation of the beam, i.e., the position of saturation of the wave energy corresponds to the position where quasi-linear plateau is formed at the beam energy distribution function (known as "beam relaxation length"). At sufficient intense beam energy (above threshold conditions), the non-linear instability transports the plasma waves to shorter wavelength scales where the resonant interaction between beam and waves does not occur and, consequently, the beam can propagate over distances beyond the position of wave saturation. Figure 2 shows the measured beam relaxation length as a function of beam to plasma density ratio for two different electron beam energies, $W_b / T_e = 50$ and $W_b / T_e = 200$. The relaxation length L is normalized to wavelength, $L_{norm} = L / (v_b / \omega_p)$, and solid line corresponds to the dependence $L_{QL} \propto (n_b / n_0)^{-1}$ predicted by quasi-linear beam plasma theory.

We observe that for low beam energy, the experimental data presents good agreement with quasi-linear theoretical curve. For $n_b / n_0 = 4.5 \times 10^{-4}$ and $W_b / T_e = 40$, the relaxation length corresponds to position where Langmuir wave saturates, $L_{norm} \approx 150$ as expected. For high beam energy, the measured relaxation lengths are higher than quasi-linear ones as

predicted by turbulence theory. For $n_b/n_0 = 4.5$ x 10^{-4} and $W_b/T_e = 130$ the wave saturation occurs at normalized position *120* while total beam relaxation is observed at $L_{norm} > 140$. We also observe the appearance of a high frequency Langmuir wave ($f > f_p$) with wavenumber k_0 r_{De} of the order of 0.3. This high frequency waves only appear in turbulent regime and in the position where the beam excited wave ($f \approx f_p$) has saturated as shown in Figure 3.

The space profile of Langmuir wave amplitude shown in Figure 3 (curve a) presents different regions. Region labeled by 1 shows the quasi-linear growth of Langmuir wave ($\gamma_1 =$ 1.1 x 10^{-3} ω_p). Region 2 corresponds to the beginning of stabilization of electron beam-plasma instability ($\gamma_2 = 4.3$ x 10^{-4} ω_p. Damping of Langmuir waves (region 3) coincide with the effective absorption of high frequency waves. The dissipation velocity of pumping wave energy is determined by an effective frequency collision (ν_{eff}). From the balance energy equation, $\nu_{eff} E_0^2 / 8\pi = \Gamma_k W$, where Γ_k is the Landau damping rate and W is the energy of high frequency oscillations, we obtain $\nu_{eff} = 10^{-3} \omega_p$, which agrees with the one obtained from region 2 of Figure 3, through $\nu_{eff} = \gamma_1 - \gamma_2$.

Ion sound waves with characteristic wavenumber corresponding to the final size of collapsing cavities are also observed in the turbulent regime as pointed out by Figure 1 [4,6]. The scenario of strong Langmuir turbulence is completed by the appearance of bulk accelerated electrons [10].

Acknowledgement

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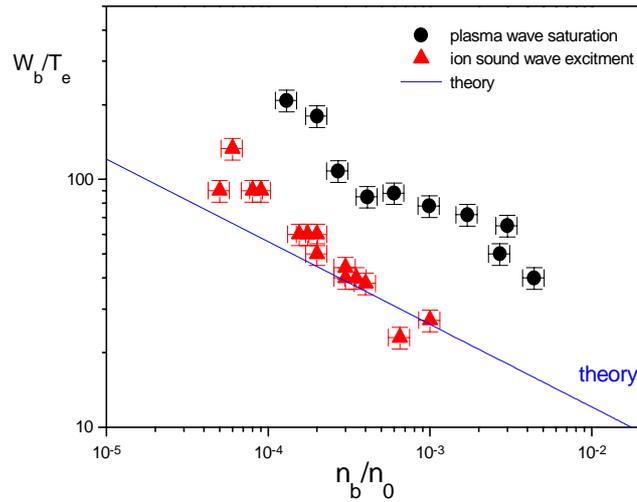
Fig. 1. Threshold conditions for transition from quasi-linear electron-plasma interaction to strong turbulence regime in a plane of the parameters W_b / T_e and n_b / n_0.
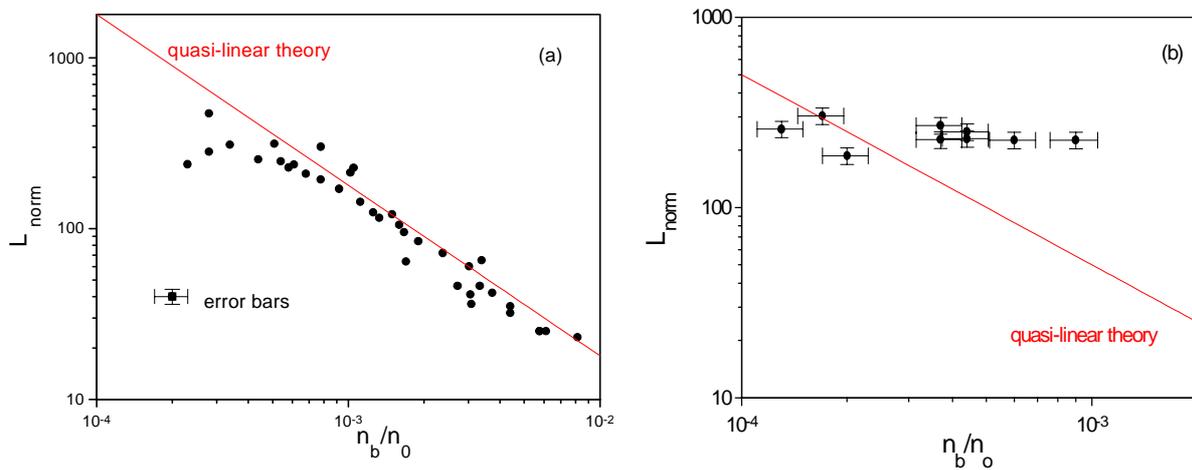
Fig. 2. Normalized beam relaxation length L_{norm} as a function of beam to plasma density ratio n_b/n_0 for beam energy: a) $W_b / T_e = 50$ and b) $W_b / T_e = 200$
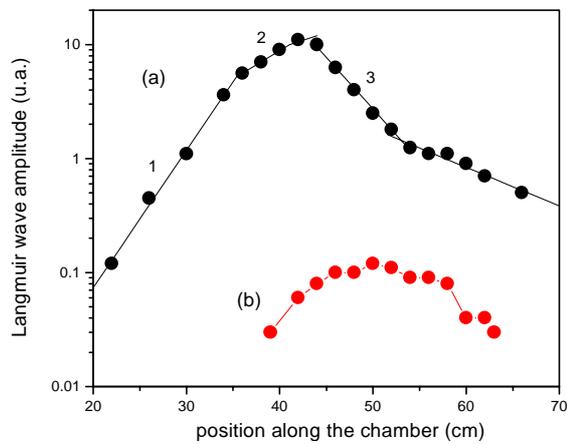
Fig. 3. Space profile of Langmuir wave amplitude for $n_b/n_0 = 4.5 \times 10^{-4}$ and $W_b / T_e = 130$. a) $f = 410$ MHz (plasma frequency) and b) $f = 490$ MHz (high frequency).