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Manifestation of wave collapse in developed strong Langmuir turbulence in a magnetic field

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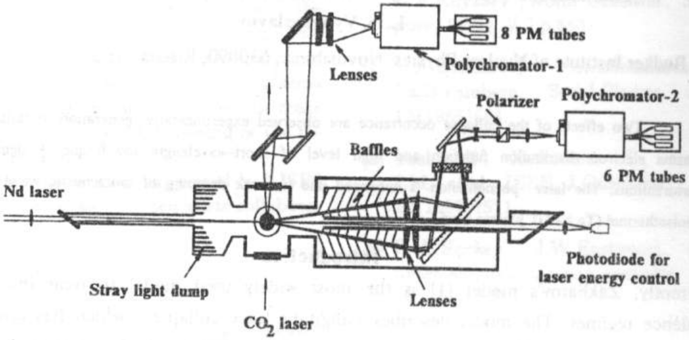
Two effects of the collapse occurrence are observed experimentally: generation of tails of plasma electron distribution function and high level of short-wavelength low-frequency density perturbations. The later phenomenon is enhanced due to weak damping of ion-acoustic waves in nonisothermal (Te >>Ti) plasma used.

Introduction

Currently, Zakharov's model [1] is the most widely used model to treat the strong turbulence regimes. The model describes Langmuir wave collapse , which has also been found in experiments. However, this model, in its original form, does not include the resonant wave-particle interaction. Therefore, difficulties arise in determining the time- and space-averaged statistical characteristics of the steady state turbulence since, in this regime, heated plasma electrons can change the collapse dynamics . In addition, there are other important factors that need to be taken into account to construct a realistic picture: the presence of a magnetic field in the plasma, plasma non-isothermality and electron-ion collisions. It is also difficult to take into account all these factors in numerical calculations because of the fact that full-scale kinetic simulations are still far beyond the capabilities of modern computers. Experiments on the observation of spectra of Langmuir turbulence driven by a relativistic electron beam have been carried out under the conditions included all the above mentioned aspects. The obtained spectra are found strongly unstable relative to the low frequency modulational instability [2] that shows the fulfillment of the strong turbulence regime. In the present paper, two experimental signatures of the collapse occurrence are found in this case. The short wavelength ion-acoustic turbulence and the superthermal electrons are observed in the same region of the momentum space during the beam-plasma interaction.

Experimental setup

The experiments were carried out on the GOL-M device. The preliminary hydrogen plasma (n_e=1.5 · 10^{15} cm^{-3}, T_{eo}=1 eV, D=6 cm, L=250 cm, magnetic field in homogeneous part is B_o=2.5 T, in the mirrors B_m=4.5 T) was created by a discharge. The beam with the energy of electrons E=700 keV was injected into the plasma through one of the mirrors. The beam parameters were: the maximum current I_b=2÷3 kA, the diameter d_b=2 cm, the duration of the beam τ_b=200 ns. In the experiments, the Thomson scattering technique was used for studying a non-Maxwellian electron distribution function (Fig.1). Two simultaneously operating systems were employed for the observation of light



Fgure 1. Collection system for light scattered at 90 and 8 degrees

scattered at the angles 90^o and 8^o, respectively. It is known, that the spectral density of scattered radiation is higher at the small scattering angles. Thus, the registration of light scattered at an angle of 8^o was employed for studying the superthermal "tails" of the electron distribution function. The temperature and density of the bulk of plasma electrons were measured simultaneously by a 90^o system. This system allows to measure an electron temperature with the range of 5—150 eV, where the upper value is limited by the plasma background light during the REB injection. The Nd-glass laser was used as a source of the probe beam with the following parameters: The pulse energy: up to 40 J / 15 J (at wavelength 1060 nm / 530 nm); pulse duration: 8 — 10 ns, beam divergence: $2 \cdot 10^{-4}$ rad. The stray light occurred due to the scattering of the laser radiation on the elements of construction and, predominantly, on the low-temperature bulk of plasma electrons, was suppressed in a 8^o system by the high-contrast interference filters (purchased from Barr Associates, Inc.) with the bandwidth adjusted to the positions of corresponding receiving channel of the polychromator-2.

The spectra of low frequency ion-acoustic fluctuations were studied with the same experiments by the collective laser scattering with a pulse CO_2 laser as a source of light ($Q = 10$ J, $\tau = 10^{-6}$s). The detailed description of this technique can be found elsewhere [3, 4]. In the presented experiments, the scattered radiation was detected at the angles $\theta = 6°$, 11° and 16° to the direction of the laser beam propagation

Experimental results

Due to collisional damping of Langmuir oscillations, the plasma electron temperature has increased up to 30÷50 eV during first 40 ns after start of the REB injection [2]. Thus, the nonisothermality condition ($T_e >> T_i$) was fulfilled practically during all the time of the REB interaction with a plasma. The first measurements at 50 — 100 ns from the beginning of the REB pulse give clear signals in four receiving channels. When processing the signals, it was assumed that the distribution function has the power law: $f(E_e) \propto E_e^{-\alpha}$ for the energies $E_e > 300$ eV (approximately 10 T_e). The scattered spectrum was calculated numerically for the given index of a power α, and its convolution with the instrumental functions of the channels was found. The value of α=2.5 provides the best fitting to the experimental data. The shape of the distribution function is given in Figure 2. The spectrum of the ion-acoustic oscillation is also shown in the figure. It is seen that both non-Maxwellian and superthermal ion-acoustic oscillations are positioned in the same region of the momentum space. The estimated total level of low-frequency turbulence is 2% $n_e T_e$.

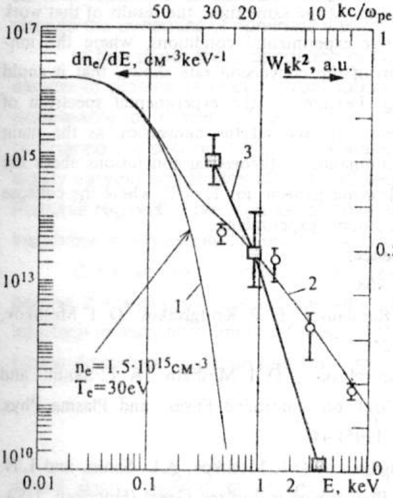


Figure 2. Distribution function of plasma electrons and spectrum of ion-acoustic turbulence during the REB injection, 1) Maxwellian bulk, 2) high energy electron tail, 3) ion-acoustic waves

Discussion and conclusion

The intense short wavelength ion-acoustic oscillations that appear in strong Langmuir turbulence case and do not associated with the return current instability [3,4] is the main signature of the collapse occurrence. In an isothermal non-magnetized plasma, the collapse is a sole mechanism to shift the waves into the short wavelength region, where they could transfer their energy to small fraction of the plasma electrons. In case of $T_e >> T_i$ the short wavelength ion-acoustic oscillations produced by the collapse can switch on two other processes of the energy transfer through the turbulence. First, it is conversion on the ion acoustic oscillations [6, 7] — the nonlinear transfer of the Langmuir waves from the pumping region directly to the damping region. Second, in a magnetoactive plasma (when the magnetic addition to the dispersion of the Langmuir waves exceeds greatly the thermal addition) it is the resonant scattering of the electron plasma waves, excited by REB, along the lines of constant frequency in a momentum space. Both these processes as well as the collapse lead to a "tail" formation, i.e. to the heating of a small fraction of plasma electrons. It is evident, that the heating of a non-Maxwellian part of the electron distribution function is connected with the Landau damping of slow Langmuir waves (real or virtual, as it is in case of the conversion). The question is how to determine the main mechanism of transferring energy of turbulent oscillations towards the short wavelength side of the spectrum. It is unlikely that the fastest mechanism among those above mentioned, the resonant scattering of Langmuir waves on the ion-acoustic oscillations, provides the required energy flow. As it was proved earlier [2], the energy is pumped into the oscillations, propagating at not too oblique angles according to the REB direction ($\theta < 30^{o}$). The dispersion permits interaction of these waves only with the ion-acoustic waves with $k < 8\,\omega_{pe}/c$, which intensity is low [4, 5]. Besides the dispersion limits also the deceleration of Langmuir waves by rather high phase velocity, which corresponds to the energy of associated resonant electrons about 10 keV. This value is much higher than that observed experimentally. The conversion rate can be estimated after the work [6], without regard to magnetic field, because for $k > 8\,\omega_{pe}/c$ the thermal addition in the dispersion exceeds the magnetic one. At the same time, the results of that work should be considered with care referring to our experimental conditions, where the ion-acoustic turbulence is not weak. The estimation of the conversion rate shows, that it could provide the energy balance with the pumping. Features of the experimental spectrum of Langmuir turbulence [2] do not count, however, in favor of the conversion as the main mechanism of the energy transfer. The final examination of theoretical conclusions about the dominant role of the conversion in the energy flow mechanism for $T_e >> T_i$, where the collapse acts only as the catalyst, is still requires some additional experiments.

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