Study of the ion acoustic turbulence of a plasma in an intense electromagnetic wave by means of the scattering of a CO_2 laser beam

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The scattering of a CO_2 laser beam has been used to determine the spatial-temporal spectrum and the integrated energy density of the ion acoustic waves excited in a plasma by an intense electromagnetic wave.

Pertinent questions in a study of the strong Langmuir turbulence, which is produced in a collisionless plasma by intense electromagnetic radiation, are the questions of the excitation of ion acoustic waves and the effect of these (possibly intense) waves on the dissipation of plasma-wave energy.[1]

In an effort to resolve these questions, we have carried out an experimental study of the ion acoustic waves excited in a plasma by an electromagnetic wave, using the scattering of a CO_2 laser beam as a diagnostic method. This contactless method yields the most comprehensive information[2] on the amplitude and spectrum of the ion sound. Under these experimental conditions the scattering parameter was $\alpha = (k_s r_D)^{-1} > 30$ (k_s is the wave vector of the ion sound, and r_D is the Debye length), which corresponds at $k_0 r_D \simeq 3$ (k_0 is the wave vector of the laser beam) to small-angle scattering by collective oscillations of the plasma.

The parameters of the experimental apparatus are described in detail in Refs. 3–5. A plasma of density $N_e \simeq 2 \times 10^{13}$ cm^{-3}, with an electron temperature $T_e \sim 10$ eV and an ion temperature $T_i \sim 1$ eV, is produced in helium at a pressure of 10^{-2} Torr in a chamber 20 cm in diameter and 150 cm long. Electromagnetic radiation in the 8-mm range is focused by a quasioptical system of mirrors and lenses ($v_\sim / v_{Te} \simeq 0.2$, where $v_\sim$ is the electron oscillation velocity, and v_{Te} is the thermal velocity) into the central part of the plasma column, which is immersed in a weak magnetic field ($H_0 \simeq 100$ Oe). The electric vector of the pump wave is directed parallel to the axis of the chamber and to the external magnetic field.

Earlier experiments in this device had shown that the application of an intense electromagnetic wave to a plasma with a density near the critical density gives rise to a Langmuir turbulence in the plasma with a high energy density[3] $W_e \simeq 10^{-1} N_e T_e$. The onset of this turbulence is accompanied by the production of epithermal accelerated electrons,[4] a "brightening" of the plasma,[5] and other effects.

For the probing of the turbulent plasma region we use a hybrid CO_2 laser[6] that operates on one longitudinal mode and one transverse mode of the optical resonator. The laser power is 10–25 kW at a pulse length $\tau_p \simeq 5$ μs. The laser beam diameter in

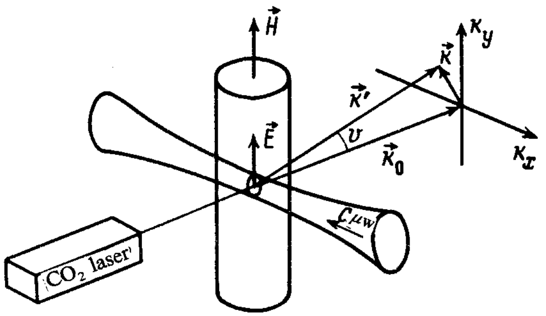

FIG. 1. The experimental geometry.

the plasma is $\simeq 1.2$ cm. The laser beam is produced with a spatial spectrum that converges slightly toward the analysis plane (Fig. 1), which lies 160 cm from the axis of the chamber, where there is a photodetector with dimensions of 1×1 cm. This optical arrangement makes it possible to achieve a resolution $\Delta k_x = \Delta k_y \simeq 4.6$ cm^{-1} in terms of the wave vectors of the ion sound. The k_x and k_y spectra of the fluctuations are analyzed by moving the photodetector along the x and y coordinates, respectively, in the analysis plane (Fig. 1).

The light scattered in the plasma is recorded by homodyne detection with a quadratic semiconductor photodetector, in which the scattered light is mixed with part of the probing beam, used as a reference signal. As a result, a beat signal at the frequency of the plasma density fluctuations is produced at the photodetector output. These fluctuations are analyzed in real time by an S4-47 spectrum analyzer. In one measurement cycle, the analyzer scans a band of 10 MHz with a central frequency that can be varied from 5 to 50 MHz. The sensitivity of the receiving apparatus at a frequency resolution $\Delta f \simeq 0.3$ MHz is $\simeq 10^{-12}$ W. The minimum fluctuation density that can be detected in the instrumental band of frequencies and wave vectors in the geometry in Fig. 1 is $\delta N_e \simeq 2\times 10^7$ cm^{-3}.

In the laser-scattering experiments we observed a temporal correlation between the onset of the beat signal from the photodetector and the onset of the signal of

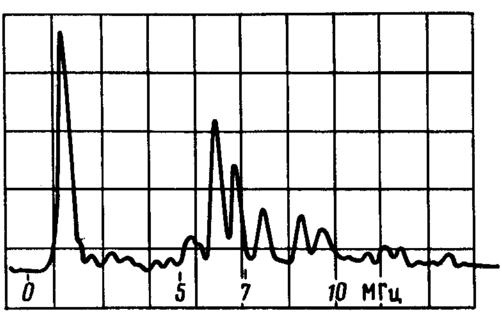

FIG. 2. Spectrogram of the beat signal.

epithermal accelerated electrons from the collector at the end of the chamber. These electrons were evidence of a resonant interaction of the pump wave with the plasma.

The frequency spectrum of the beat signal from the photodetector over one operating cycle of the apparatus (Fig. 2) is a set of narrow peaks with a width near the instrumental width, covering a broad frequency band. Figures 3a and 3b show frequency spectra averaged over a large number of operating cycles: a k_x spectrum for $k_y = 26\ \mathrm{cm}^{-1}$ and a k_y spectrum for $k_x = 0$, respectively. The intensities here are expressed in terms of the density modulation depth in the receiver passband[7]: Δf, Δk_x, Δk_y.

Analysis of the results reveals that the application of a pump wave to a plasma with a density near the critical density generates an ion acoustic turbulence with a broad k_x and k_y spectrum, with a maximum intensity in the direction along the electric field of the pump wave. As k_y is increased from a value on the order of 20 cm^{-1}, the intensity decays, and the spectrum shifts toward higher frequencies. A similar behavior is observed as a function of $|k_x|$, so that we can estimate the average perturbation propagation velocity (Figs. 3a and 3b). This velocity is approximately equal to the ion acoustic velocity in a helium plasma, $v_s \simeq 1.3 \times 10^6$ cm/s for $T_e \simeq 7$ eV.

By integrating the quadratic density perturbation over the frequency-spatial spectrum of the waves, we can find the energy density in the ion acoustic waves. The energy density in the ion sound divided by the thermal energy of the plasma is $W_s/N_e T_e = (\delta N_e/N_e)^2 \sim 4 \times 10^{-8}$. This is a lower estimate of the energy density, because of the nonlocal nature of the measurement method, which gives us an average over a plasma volume $\sim 1\ \mathrm{cm}^3$. If the ion acoustic waves are excited in a thin plasma slab (the

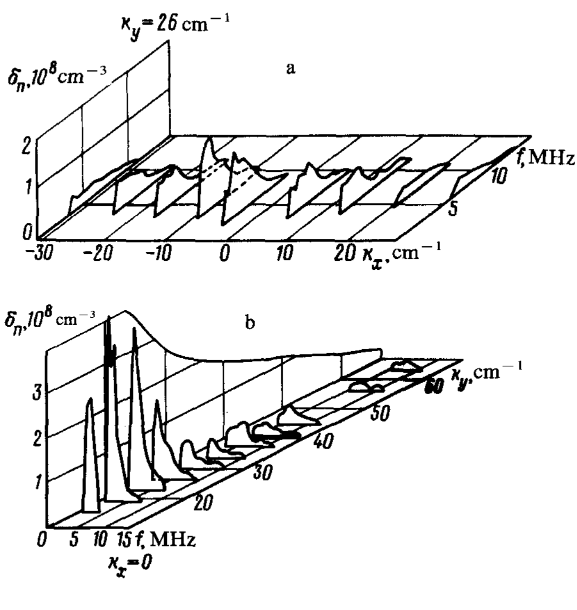

FIG. 3. Spatial-temporal spectrum of the ion acoustic waves.

broadening of the k_x spectrum may be due to this factor) with a thickness on the order of the skin thickness, the intensity of the ion sound integrated over the spectrum corresponds to $(\delta N_e/N_e)^2 \sim 10^{-7}$.

In summary, these results show that the application of intense electromagnetic radiation to a plasma results in the excitation of long ion acoustic waves ($\lambda_s \sim 10^3 r_D$) near the point of the plasma resonance. The energy density of these waves is well below the energy density of the plasma waves. The ion acoustic waves observed experimentally may be excited either directly, as a result of the incipient modulational instability, or as a result of secondary effects associated with the acceleration of electrons by the plasma waves and the generation of currents in the plasma.

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