Effective collision rate in a plasma with strong Langmuir turbulence

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The absorption of a test electromagnetic wave in a plasma, in which strong Langmuir turbulence has been excited by an electron beam, has been measured. The conditions for the transition of the turbulence to a saturation state have been found. The anisotropic properties of the turbulence have been determined.

It has been shown[1,2] experimentally that the turbulent state of a plasma excited by an electron beam or an electromagnetic field is an ensemble of collapsing Langmuir cavities, as predicted by theory of strong Langmuir turbulence.[3]

The density (i.e., concentration of volume) of the cavities themselves determines the intensity of the strong Langmuir turbulence and is an important characteristic for the anomalous effects which stem from this turbulence, such as the anomalous conductivity and the anomalous absorption. As we know, the dissipative properties of the medium can be expressed in terms of an effective collision rate ν_{eff}, which can be measured. The intensity of the turbulence process can thus be estimated indirectly.

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In this letter we are reporting the first attempt to work through measurements of ν_{eff} to study the intensity of strong Langmuir turbulence as a function of the pump level during excitation by an electron beam. We have found the conditions under which the strong turbulence reaches a state of saturation, and we have determined the anisotropic properties of this turbulence.

The rate ν_{eff} was determined from the damping of a test electromagnetic wave in a turbulent plasma transparent to this wave: $\omega > \omega_{pe}$. The measurements were carried out by measuring the Q of a resonator filled with plasma[4] (Fig. 1).

Specifically, this resonator was part of a metal vacuum chamber of the apparatus, with a radius of 3.5 cm. The resonator was bounded at one end by a grid anode, in front of a thermionic cathode which was used to produce the plasma and to inject an electron beam into the plasma. The resonator was bounded at its other end by a diaphragm with a coupling aperture, behind which there were wave mode converters for exciting a resonator mode (H_{11q} or E_{11q}). The resonator was 120 cm long.

The plasma in the apparatus was produced by a beam-plasma discharge in argon at a pressure of 2×10^{-4} Torr. The plasma density was distributed essentially uniformly along the resonator axis during the decay stage. The radial profile of the plasma density could be described approximately by a Bessel function $J_0(r/R)$.

A strong Langmuir turbulence was excited as an electron beam passed through the plasma in a current channel with a radius $a_j = 1.5$ cm. The energy of the beam electrons was varied over the range $eU_0 = 200$–2000 eV. As has been shown previous-

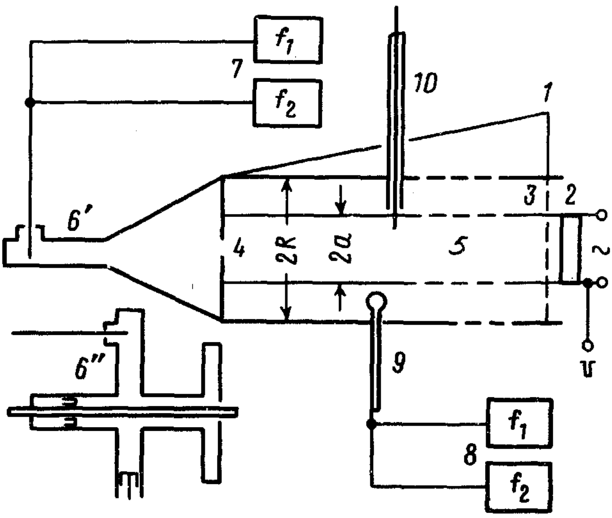

FIG. 1. Experimental apparatus. 1—Cylindrical resonator; 2—thermionic cathode; 3—grid anode; 4—coupling aperture; 5—region of turbulent plasma in the electron-beam channel; 6′—H_{11} wave converter; 6″—E_{01} wave converter; 7—microwave sources of test waves at two frequencies; 8—microwave detectors of the test waves; 9—loop antenna; 10—Langmuir probe.

ly,[1] a strong Langmuir turbulence arises in a plasma when a threshold condition $n_b/n_0 > 1.7\times10^2\,(T_e/m_e v_0^2)^2$, is satisfied, where n_b is the beam density, n_0 is the plasma density, and v_0 is the velocity of the beam particles as they enter the plasma. The plasma density at the resonator axis during the experiment was $n_0 = 1.8\times10^{11}$ cm^{-3}. The electron temperature was $T_e \simeq 1.0$ eV. The resonator frequency, $f = 6$ GHz ($\lambda = 5$ cm), was chosen such that the plasma would be transparent. The lower level of the diagnostic signal, $\sim 10^{-3}$ W, was chosen as low was possible, well below the thresholds for any of the nonlinear processes associated with the application of the microwave radiation to the plasma.

The effective collision rate $\nu_{\rm eff}$ was determined from the expression[4]

$$\nu_{eff} = \frac{2\pi}{C_{f_j}}\,\frac{n_c}{n_0}\,\frac{(R/a_j)^2}{1-a_j^2/2R^2}\,(\Delta f - \Delta f_0), \tag{1}$$

where C_{F_j} is a shape coefficient reflecting the particular way in which the plasma films the resonator cross section, $n_c = m_e\omega^2/4\pi e^2$ is the cutoff plasma density for the signal frequency $f=\omega/2\pi$, and Δf and Δf_0 are the half-widths of the resonance curves in a plasma with a strong Langmuir turbulence and in a quiet plasma, respectively, under otherwise equal conditions. The H_{11q} mode is a transverse mode with respect to the beam propagation direction for arbitrary q, so it is transverse with respect to the field of the primary Langmuir wave. At $n_0 = 1.8\times10^{11}$ cm^{-3}, the index of the E_{01q} mode is approximately $q \simeq 30$; this mode can thus be thought of in practice as a longitudinal mode, since the energy determined for the longitudinal component of the electric field, concentrated in the turbulence zone, is five times the energy for its transverse component.

In the experiments it was established that the effective collision rate increases with increasing density and energy of the beam electrons. It had been shown previously[1] that a Langmuir (plasma-wave) pump is characterized by the parameter $\delta = 6\times10^{-3}(n_b/n_0)/(T_e/m_e v_0^2)^2$, which determines the transition of the beam-plasma system to a state of strong Langmuir turbulence (under the condition $\delta > 1$). It was found that the average density of the Langmuir field is essentially proportional to δ.

The measured dependence of $\nu_{\rm eff}$ on the pump level is thus plotted as dimensionless quantities, $\nu_{\rm eff}/\omega_{pi} = F(\delta)$ (Fig. 2), where ω_{pi} is the ion plasma (Langmuir) frequency. Curve 1 corresponds to the H_{11q} mode. The ratio $\nu_{\rm eff}/\omega_{pi}$ increases essentially linearly with δ, i.e., with increasing level of the Langmuir pump, up to a value $\delta_{\rm sat} \simeq 120$ at which saturation sets in.

Curve 2 in Fig. 2 corresponds to the $E_{01,30}$ mode. Again in this case we see a linear increase in $\nu_{\rm eff}/\omega_{pi}$ with the pump, up to the saturation stage, which begins at the same $\delta_{\rm sat}$ as for curve 1. The saturation value of $\nu_{\rm eff}/\omega_{pi}$, however, is larger by a factor of about 3 in this case.

We turn now to a discussion of the results. The absorption of an electromagnetic wave, characterized by an effective collision rate, is associated with the excitation of small-scale density fluctuations in the plasma. Consequently, the electric field, which

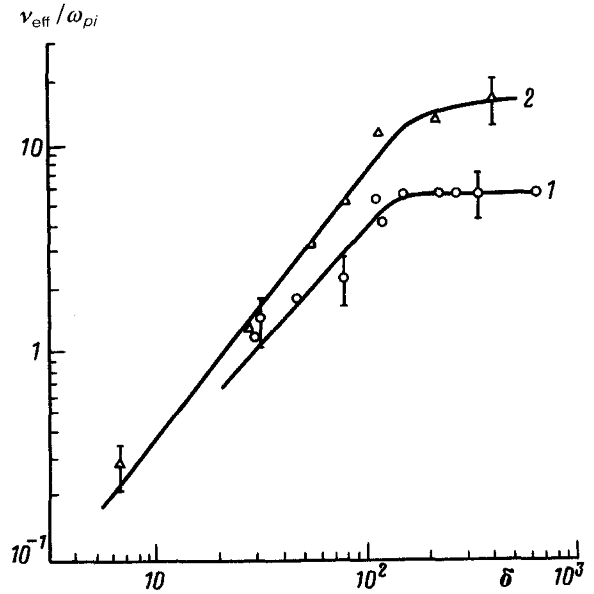

FIG. 2. Ratio of the effective collision rate to the ion plasma frequency, $\nu_{\rm eff}/\omega_{pi}$, versus the parameter δ, which represents the pumping by the electron beam. 1—Measurements at the $H_{11,42}$ resonant mode; 2—measurements at the $E_{01,30}$ resonant mode.

is uniform with respect to fluctuations, is modulated with a length scale which corresponds to an effective removal of energy from the wave by the electrons. The ion acoustic waves[1,2] with the characteristic values $k_s r_{De} \sim 1$, which we have observed previously under conditions of strong Langmuir turbulence, may have been small-scale fluctuations of this sort. According to the theory for the anomalous absorption of electromagnetic radiation by ion acoustic fluctuations,[5,6] the effective collision rate can be described by the approximation

$$\nu_{eff} \simeq \omega_{pe} \frac{W_s}{n_0 T_e} \overline{\cos^2\theta} \exp(-\omega^2/2\omega_{pe}^2). \tag{2}$$

Here W_s is the average energy density of the ion sound, and $\overline{\cos^2\theta}$ is the square of the cosine of the angle between the polarization vector of the electromagnetic wave and the wave vector of the ion acoustic fluctuations, averaged over the angular distribution. Expression (2) assumes (first) that $W_s/n_0T_e \ll 1$, (second) that the distribution of the plasma electrons is not greatly different from Maxwellian, and (third) that the absorption is caused primarily by ion acoustic waves with a characteristic wave number $\sim r_{De}^{-1}$ and a spectral width $\Delta k \leqslant r_{De}^{-1}$.

This expression can be compared with experimental data for values of W_s/n_0T_e, which are not too large and which correspond to relatively small values of δ. In making such a comparison we must bear in mind that the short-wavelength sound which is involved here has extremely short decay lengths, on the order of the length of the waves themselves in the final stage of the collapse ($l_s \simeq 30 r_{De}$). This sound is thus concentrated primarily near a cavity within a distance on the order of the size of the cavity. The density of acoustic energy, averaged over volume, is thus found from $W_s/n_0T_e \simeq (W_s/n_0T_e)_{\max} \cdot N_k V_s$, where N_k is the spatial density of cavities on the final stage of collapse, $V_s \simeq l_s^3 \simeq 3\times 10^4 r_{De}^3$ is the volume occupied by the sound waves, and $(W_s/n_0T_e)_{\max}$ is the maximum energy of the perturbation of the plasma density near a cavity. This maximum energy is, in order of magnitude, $k_s^4 r_{De}^4 \sim 1$. Expression (2) can thus be rewritten as

$$\nu_{eff}/\omega_{pe} \simeq 3 \cdot 10^4 r_{De}^3 N_k \overline{\cos^2\theta} \exp(-\omega^2/2\omega_{pe}^2). \quad (3)$$

Assuming that the sound is distributed isotropically if δ is not too large, i.e., assuming $\overline{\cos^2\theta} = 1/3$, and having data for $\delta = 7$ which point to a value[1] $N_k \simeq 20\ \text{cm}^{-3}$, we find $\nu_{\text{eff}}/\omega_{pi} \simeq 0.2$. This result agrees satisfactorily with the experimental data. In addition, the proportionality[1] $N_k \propto \delta$ means that expression (3) gives a correct description of ν_{eff} as a function of δ at $\delta < \delta_{\text{sat}}$.

With regard to the anisotropy of ν_{eff} at $\delta > \delta_{\text{sat}}$, we note that the role of the acoustic perturbations is being played in this case by small-scale density variations associated with the cavities in the final stage. These cavities lie close together, at separations on the order of their size (there is a close packing of cavities in a regime of ultrastrong turbulence). We would expect $W_L/n_0T_e \sim (W_L/n_0T_e)_{\max} \sim 1$ in this state. Under the assumption that the distribution of the wave number associated with this small-scale structure is ellipsoidal with an eccentricity $k_{\parallel}/k_{\perp} \simeq 3$, and under the further assumption that all the cavities are oriented along the beam trajectory,[7] we find that the particular anisotropy in the absorption of the longitudinal and transverse modes, which is associated with the value of the $\overline{\cos^2\theta}$, is $\nu_{\text{eff}\parallel}/\nu_{\text{eff}\perp} \simeq 2$, again in satisfactory agreement with experiment.

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