Experimental observation of enhanced scattering of electromagnetic waves by a plasma in the presence of a singular point

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Enhanced scattering of electromagnetic waves by spontaneous plasma fluctuations, an effect connected with linear transformation, has been observed in experiment.

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Scattering of electromagnetic waves by collective fluctuations is a potentially valuable method of plasma diagnostics. It is not extensively used, however, because of the low intensity of the scattered signal and because of the absence of radiation sources that make it possible to observe fluctuations with wavelengths of the order of the Debye radius. It was shown theoretically long ago[1] (see also[2]) that these difficulties can be overcome to a considerable degree by choosing the experimental conditions such that the hybrid resonance condition is satisfied for the probing wave in the investigated plasma volume. In this case the incident wave is linearly transformed into a slow plasma wave, and it is the latter which is scattered by the fluctuations. The scattered wave is transformed back into an electromagnetic mode that is radiated out of the plasma. Owing to the increase of the amplitudes of the incident and scattered waves near the transformation point, the intensity of the scattered signal increases by several orders of magnitude, and the slowing down of the wave makes the scattering sensitive to small-scale fluctuations. This effect was first observed in[3]. However, the high plasma turbulence level did not make it possible to interpret uniquely the experimental results. The later experiments were performed with ion-sound oscillations artificially introduced into the plasma.[4] The purpose of the present study was to observe experimentally enhanced scattering in a relatively quiescent plasma, and to compare in detail the results with the theory. The experiments were performed with the linear installation of[5] (Fig. 1), in the frequency range $\sqrt{\omega_{He}\omega_{Hi}} < \omega_0 < \omega_{He}$. The plasma was produced in a vessel placed in a uniform (~ 3 kOe) magnetic field and was maintained by absorption of 3-cm waveguide power. The working gas was argon at pressures 5×10^{-4} to 5×10^{-2} Torr. The probing wave ($\lambda_0 = 12.5$ cm, $f_0 = 2.4$ GHz) was fed to the plasma through a waveguide. The scattered signal was registered with an S4-27 spectrum analyzer.

Under the experimental conditions the plasma was not uniform in either the radial or the longitudinal direction. When the concentration on the tube axis at the location of the waveguide junction exceeded the critical value n_c for the frequency f_0, the so-called oblique Langmuir wave (the Trivelpiece-Gould mode) was excited in the plasma. The shape of the surface $n = n_c$, which bounds the transparency region of this wave, and the pattern of its propagation in a two-dimensionally inhomogeneous plasma waveguide are shown in Fig. 1. The linear transformation takes place in the vicinity of the singular point (focus).[5,6]

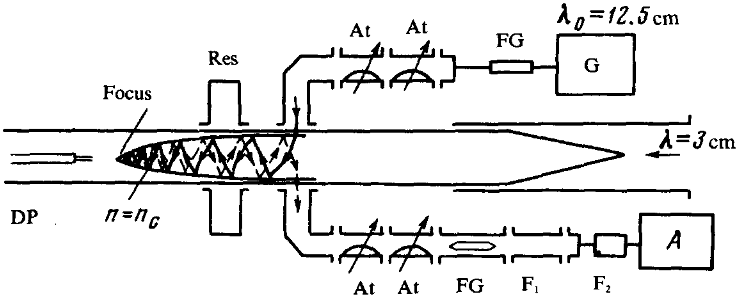

FIG. 1. Experimental setup: G—generator, FG—ferrite gate, At—attenuator, F1—filter for the suppression of the signal at the frequency f_0, F2—filter for the suppression of the 3-cm power signal, A—spectrum analyzer, Res—resonator, DP—double probe.

Inasmuch as $T_e \gg T_i$ under the experimental conditions, the wave with longitudinal (relative to the magnetic field) deceleration could be scattered by ion-sound fluctuations propagating along the magnetic field. A theoretical calculation for actual experimental conditions leads to the following expression for the ratio of the spectral density of the power p_s of the scattered signal to the incident power P_0:

$$\frac{P_s}{P_0}\left(\frac{1}{\text{Hz}}\right) = \frac{16}{3}\pi\left(\frac{2\pi}{\omega_{pi}}\right) n_c\, a\, r_e^2 \left(\frac{X_0}{b}\right)\left(\frac{X_0}{r_D}\right)^3 \rho(\Omega)\,\frac{S(\Omega)}{S_T(\Omega)}\,\kappa^2, \tag{1}$$

$$\rho(\Omega) = \frac{a y^3}{1 + a y^3}\, e^{-\gamma y}\,\frac{y}{x}\ ; \quad y = \frac{x}{\sqrt{1 - x^2}}; \quad x = \frac{\Omega}{\omega_{pi}},$$

where ω_{pi} is the ion plasma frequency, a and b are the longitudinal and radial scales of plasma in homogeneity, respectively, $\lambda\!\!\!^{-}_0=c/\omega_0$, r_D is the Debye radius, $\Omega=\omega-\omega_0$, $\alpha=\frac{3}{8}(b/r_D)$, $\gamma=(\nu/\omega_0)(a/r_d)$, ν is the frequency of the collisions of the electrons with the neutral atoms, κ is the ratio of the probing power that reaches the focus to the incident power P_0 (the coupling coefficient) $S(\Omega)$ is the spectral density of the ion-sound oscillations in the plasma, and $S_T(\Omega)$ is the analogous quantity for an equilibrium plasma.

According to (1) the scattering gain can amount to $\sim(\lambda\!\!\!^{-}_0/r_D)^3\approx 10^8$ times.

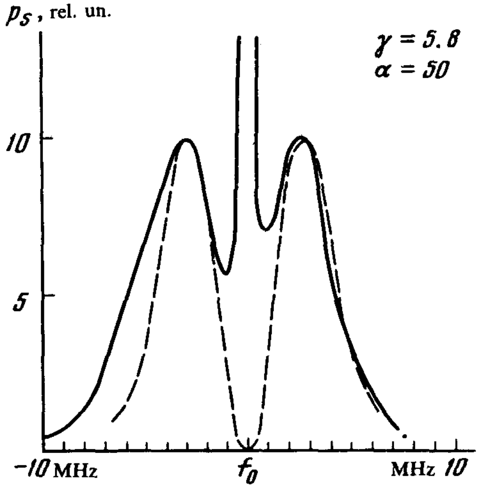

FIG. 2. Scattering spectrum: solid curve—experiment $H\sim 3000$ Oe, $P_0=1.6\times10^{-2}$ W, $p=1.8\times10^{-2}$ Torr. Dashed line—theoretical curve when expression (1) is used with $\alpha=50$, $\gamma=5.8$.

We registered in the experiment scattered-signal spectra whose shapes agreed sufficiently well with expression (1) at $S(\Omega)/S_T=\text{const}$ (Fig. 2). A comparison of the shapes of the spectra with (1) yields for the parameters α and γ the values $\alpha=45\pm7$; $\gamma=7\pm2$. According to probe measurements $a=2.5$ to 3.5 cm, $b=0.4$ to 0.7 cm, $T_e=1.9$ to 2.3 eV, and correspondingly $\alpha=47\pm9$; $\gamma=11\pm6$. The measured value of p_s/P_0 at the maximum of the spectrum was $(7\pm2)\times10^{-12}$ Hz^{-1}. From formula (1) at $S(\Omega)/(S_T)\kappa^2=1$ we get for this ratio a value 3×10^{-12} Hz^{-1}.

When the incident power changes from 10^{-3} to 10^{-1} W the shape of the spectrum and the ratio p_s/P_0 remained unchanged. Further increase of $P_0(P_0>2\times10^{-1}$ W) led to a jumplike increase of the scattered signal by approximately 100 times, an increase accompanied by a radical change in the form of the spectrum (Fig. 3). These phenomena are apparently due to development of parametric instability.

To establish the connection between the observed enhanced scattering and the presence of a focus, measurements were made at a concentration n under the waveguide, lower than the critial n_c, and also at $n>n_c$, but with a uniform distribution of the concentration along the system axes. In neither case was a scattered signal registered.

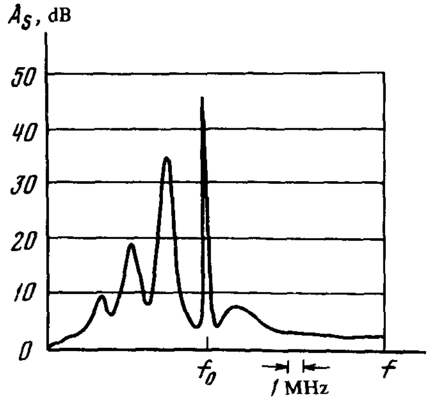

FIG. 3. Scattering spectrum upon development of parametric instability: $H \sim 3000$ Oe, $p = 1.6 \times 10^{-2}$ Torr, $P_0 \sim 2 \times 10^{-1}$ W.

The results allow us to conclude that in this experiment, we actually observed enhanced scattering of electromagnetic waves by ion-sound oscillations, with a level close to thermal, in the presence of a singular point. The use of this effect is particularly promising in the investigation of parametric turbulence.

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