Resonant lowering of the threshold for a parametric instability of an inhomogeneous plasma in a frequency-modulated pump field

V. I. Arkhipenko and L. V. Simonchik
Institute of Molecular and Atomic Physics, Belarus Academy of Sciences, Minsk, Belarus

V. N. Budnikov, E. Z. Gusakov, N. M. Kaganskaya, and V. L. Selenin
A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences,
194021 St. Petersburg, Russia

(Submitted 3 November 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 12, 829–833 (25 December 1994)

A resonant lowering of the threshold for the onset of a parametric instability of an inhomogeneous plasma has been observed. The effect is resonant in terms of the rate of the frequency modulation of the pump wave. The physical reason for the effect has been determined: a suppression of convective losses when the velocity of the decay point is equal to the group velocity of one of the waves. © *1994 American Institute of Physics.*

It is generally believed[1,2] that a spatial variation of a plasma has a stabilizing effect on parametric instabilities in the plasma. The decay condition

$$k_0(x)=k_1(x)+k_2(x), \tag{1}$$

imposed on the projections of the pump wave vector $\mathbf{k}_0$ and the wave vectors of the excited waves, k_1 and k_2, does not hold everywhere. It generally holds near isolated points $x=x_d$. The convective transport of energy of the excited waves out of the narrow interaction region, with a width

$$|x-x_d|\simeq l=\left|\frac{d}{dx}(k_0-k_1-k_2)\right|^{-1/2},$$

not only raises the instability threshold in this case but also changes the nature of the instability, reducing it to a spatial amplification with a growth rate

$$S=\exp\left(\frac{\pi\gamma^2 l^2}{|v_1 v_2|}\right). \tag{2}$$

Here γ is the instability growth rate in a homogeneous plasma, and v_1 and v_2 are the projections of the group velocities of the excited waves onto the direction of the variation.

According to Ref. 3, a time variation of a plasma also has a stabilizing effect on parametric instabilities, leading to a frequency detuning of the three-wave resonance:

$$\omega_0(t)=\omega_1(t)+\omega_2(t). \tag{3}$$

In addition, for the parametric decay $t \to l + s$, an instability may also be promoted if the plasma is both spatially inhomogeneous and time-varying, as was shown in Ref. 4. Decay conditions (1) and (3) for the three interacting waves can be satisfied near a moving point $x_d(t)$ at which there is a convective amplification characterized by a growth rate

$$S = \exp\left(\frac{\pi\gamma^2 l^2}{|v_1 - v_d||v_2 - v_d|}\right), \tag{4}$$

where $v_d = (dx/dt)\ d$ is the velocity of the decay point. As the velocity of the decay point approaches the group velocity of one of the waves, the growth rate of the parametric amplification of plasma noise [see (4)] may increase sharply, and the threshold for the parametric instability may correspondingly decrease. The physical reason for this effect is a suppression of the convective losses of one of the waves as the difference between its group velocity and the velocity of the decay point decreases. According to Ref. 4, when the length scale of the inhomogeneity and the time scale of the time variation of the plasma satisfy certain relations, so that the equality $v_2 = v_d$ holds, there can be a substantial modification of the spectra of the noise pumped parametrically in the plasma. This effect could in principle be exploited for a selective excitation of plasma waves.

Experimentally, a selective parametric excitation of plasma noise by the effect predicted in Ref. 4 has not been observed. Nor is there any observational evidence for the effect itself—the resonant lowering of the threshold for the onset of a parametric instability in an inhomogeneous, time-varying plasma. The apparent reason for this situation is that there are difficulties in controlling the parameters of an inhomogeneous, time-varying problem and in studying nonlinear parametric processes in such a plasma.

We believe that a resonant lowering of a threshold for a parametric instability and a selective excitation of plasma noise can also occur in a steady-state inhomogeneous plasma subjected to a time-varying pump wave, specifically, a frequency-modulated pump wave $\omega_0 = \omega_0(t)$. The coordinate of the decay point in this case will also depend on the time $[x_d = x_d(t)]$, but this dependence can easily be controlled by varying the rate at which the pump oscillator is swept.

In this letter we are reporting the first observation of a resonant lowering of the threshold for a parametric instability of an inhomogeneous, magnetized plasma—a lowering which is resonant in terms of the rate at which the frequency of the pump wave is swept. The experiment was carried out on a linear plasma device.[5] A plasma which was inhomogeneous in both radial and axial directions $[n_e = n_e(r,t)]$ was produced in a tube 2 cm in diameter and 1 m long filled with argon to a pressure of 2×10^{-2} torr and immersed in a magnetic field of 3 kG. The maximum electron density was $n_e \simeq 10^{12}$ cm^{-3}, and the electron temperature was $T_e \simeq 2$ eV. An oblique pump plasma wave (or Langmuir wave) with a power $P_0 < 100$ mW was excited in the plasma by means of a waveguide launching device. The pump frequency was modulated linearly:

$$f = f_0 - \frac{t}{\tau}\Delta f, \tag{5}$$

where $f_0 = 2650$ MHz, $\Delta f \leqslant 350$ MHz, and $\tau \geqslant 1$ μs is the modulation period. The return path of the frequency of the sweep generator was suppressed to a level of -20 dB by means of a modulator.

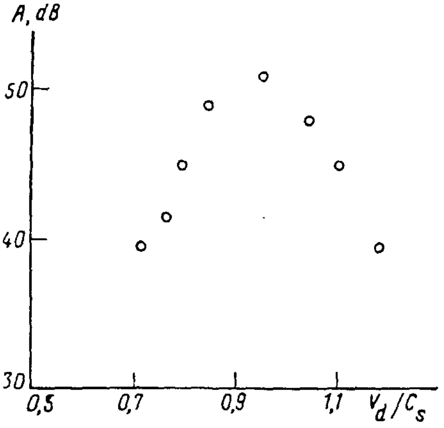

FIG. 1. Scattered signal versus the velocity of the decay point.

At the axis of the tube, where the plasma density is at the critical value ($n=n_c=\pi f^2 m_e/e^2$), the conditions for a hybrid resonance for the pump wave are satisfied. In the case of a monochromatic pump ($\Delta f=0$) a convective parametric backscattering instability has been observed in this region.[5] This instability is described by the growth rate in (2) at $P_0<20$ mW. As a result of this instability, an ion acoustic wave is excited in the plasma. It propagates opposite the gradient of the plasma density. Measurements of the scattering spectra of the pump wave in the heterodyne and homodyne regimes, which are customarily carried out in order to study parametric instabilities, are impossible to carry out in the case of a frequency-modulated pump. In the present experiments, the parametric excitation of ion acoustic waves was studied by the intensified-scattering method used in Ref. 5. For this purpose, an oblique plasma wave of low power ($P_i<5$ MW) at a frequency $f_i=2250$ MHz was excited in the plasma by the waveguide device mentioned above. The point of the hybrid resonance for this wave was in a region of the plasma where the density was higher than that of the corresponding region for the pump wave, because of the condition $f_i<f_0+\Delta f$. The probe wave slowed down near this point and could be scattered by the acoustic waves excited parametrically. We studied the scattering spectrum observed in a waveguide as a function of the sweep rate, the power, and the modulation amplitude of the pump wave.

The results show that the frequency modulation of the pump wave makes it possible to lower the threshold for detection of the parametrically excited ion acoustic wave by a factor of 1.5 under optimum conditions ($\Delta f=350$ MHz, $\tau=5.3$ μs). The spectrum of the scattering of a probe wave in this case is a line 1 MHz wide with a redshift of 2 MHz. The amplitude (A) of the scattered signal and thus that of the ion acoustic wave fall off sharply at a deviation from the optimum velocity as small as 20%. Figure 1 shows the behavior of this amplitude as a function of the calculated velocity of the decay point, v_d, divided by the ion acoustic velocity $c_s=\sqrt{T_e/M_{\text{Ar}}}$. The velocity of the decay point was varied by varying the modulation period τ; it was found from the expression

$$v_d=\frac{2a}{\tau}\frac{\Delta f}{f_0}, \tag{6}$$

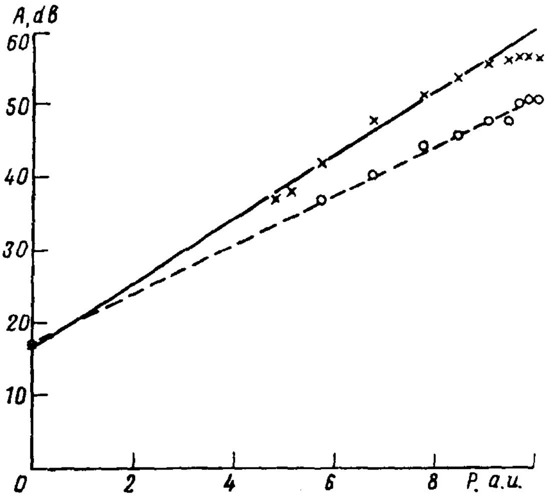

FIG. 2. Scattered signal versus the pump power. × —Resonant sweep rate (τ=5.2 μs, Δf=350 MHz); O—disrupted resonance (τ=4.4 μs, Δf=350 MHz).

which is valid in the case of a linear frequency modulation. In these calculations we used the experimental values of the longitudinal length scale of the plasma inhomogeneity ($a=4$ cm) along with $T_e=2$ eV, $\Delta f=350$ MHz, and $f_0=2400$ MHz. The coincidence of the maximum of the $A(v_d)$ dependence with the point $v_d=c_s$, on the one hand, and the sharp decrease in it when the sweep rate deviates from the optimum value, on the other, confirm that there is a resonance mechanism for the lowering of the threshold for the parametric instability, as discussed above.

The amplitude of the ion acoustic wave is an approximately exponential function of the pump power (Fig. 2). The curve is steepest for resonant frequency modulation (the crosses); the curve is more gently sloping when there is a deviation from resonance (the circles). This result is in qualitative agreement with a prediction of expression (4). An extrapolation of the two $A(P_0)$ curves to $P_0=0$ yields approximately the same values for $A(0)$, so we can say that the parametric amplification of the ion acoustic noise occurs from approximately the same level. The gain values $A(P)/A(0)$ observed experimentally reach $S_1\simeq 10^4$. The level of the ion acoustic wave excited in the process corresponds to a strong parametric reflection of the pump, which is apparently linked with the saturation of the $A(P)$ curve at high pump power levels.

A Decrease in the pump modulation amplitude at a fixed resonant sweep rate and at a fixed power level lowers the level of the ion acoustic wave. The $A(\Delta f)$ curve (Fig. 3) turns out to be approximately exponential. This behavior agrees with the idea that convective losses do not occur at $v_d=c_s$. This behavior is apparently linked with a decrease in the duration of the interaction of the ion acoustic wave with the pump. An extrapolation of the $A(\Delta f)$ curve to $\Delta f=0$ yields an independent estimate of the gain in the case of a resonant sweep: $S_2=A(350\text{ MHz})/A(0)\simeq 2\times 10^3$. The result that this gain satisfies $S_2<S_1$ can be explained on the basis of the lower pump power in this experiment.

We believe that these experimental results confirm the hypothesis that there can be a resonant lowering of the threshold for a parametric instability of an inhomogeneous plasma during frequency modulation of the pump wave.

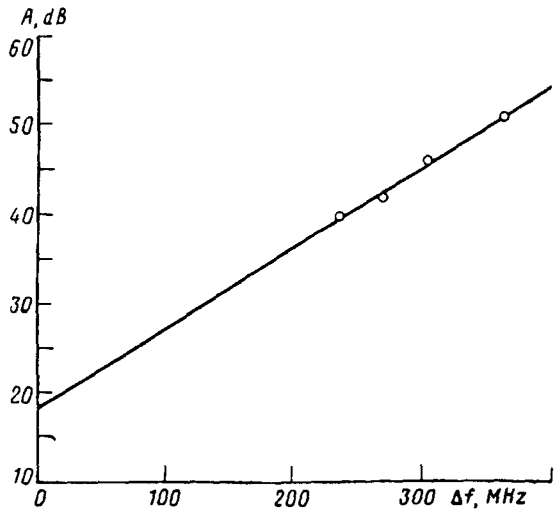

FIG. 3. Scattering signal versus the size of the sweep interval.

This study was supported by a grant from the International Science Foundation (R34000) and also, in part, by the Fund for Fundamental Research of the Republic of Belarus (Grant F7-082).

[1] A. D. Piliya, *Proc. of the X. Conf. on Phenomena in Ionized Gases* (1971), p. 320.
[2] M. N. Rosenbluth, Phys. Rev. Lett. **29**, 565 (1972).
[3] L. M. Gorbunov and A. N. Starodub, Pis'ma Zh. Tekh. Fiz. **3**, 820 (1977) [Sov. Tech. Phys. Lett. **3**, 332 (1977)].
[4] A. A. Andreev and V. I. Fedorov, Fiz. Plazmy **5**, 1058 (1979) [Sov. J. Plasma Phys. **5**, 593 (1979)].
[5] V. I. Arkhipenko *et al.*, Fiz. Plazmy **13**, 693 (1987) [Sov. J. Plasma Phys. **13**, 398 (1987)].

Translated by D. Parsons