Ionizational self-ducting of whistlers in a plasma

I. A. Vdovichenko, G. A. Markov, V. A. Mironov, and A. M. Sergeev
Institute of Applied Physics, Academy of Sciences of the USSR

(Submitted 24 June 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 5, 216–219 (10 September 1986)

A self-ducting of whistlers in a plasma has been observed. It is a consequence of an additional ionization of the gas caused by the field of the electromagnetic wave.

The mutual localization of an rf field and a plasma is an attractive possibility for solving problems of directed transport of electromagnetic energy by charged particles, developing nonlinear radiators and waveguide systems, etc. Problems of this type arise in studies of a variety of physical problems, ranging from the production of a fusion plasma to active experiments in the earth's ionosphere. In the present letter we report an experimental observation of a self-ducting of whistlers caused by an additional ionization of the plasma by the rf field of the electromagnetic wave.

The experiments are carried in a discharge chamber 150 cm long and 20 cm in diameter, in which a push-pull oscillator ($W_b = 360$ W, $\omega_b = 10^8$ s^{-1}) generates a quasihomogeneous background plasma with an electron density $N_b \gtrsim 2 \times 10^{10}$ cm^{-3}. The pressure of the working gas (air) is $p = (6–7) \times 10^{-3}$ torr, and the electron mean free path is $l_e \simeq 4$ cm. The longitudinal magnetic field $H = 160$ Oe corresponds to the

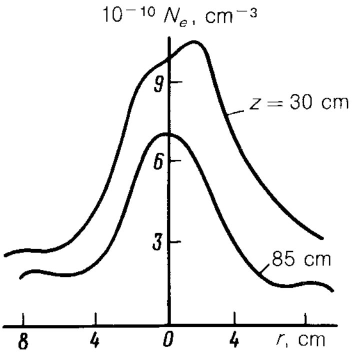

FIG. 1.

condition $\omega_{\text{pb}} = (4\pi N_{\text{b}}e^2/m)^{1/2} > \omega_H = eH/mc$. The observations consist of measuring the field of 2 helical-coil antenna (6 cm) which is coaxial with the discharge chamber and connected to the output of a GST-2 oscillator ($W_0 \lesssim 25$ W, $\omega_0 = 10^9$ s^{-1}).

At low levels of the power supplied to the antenna ($W_0 \lesssim 0.1$W), a well-defined resonant cone is observed in the background.[1] The vortex angle of this cone (2θ) is determined by the relation tan $\theta \simeq \omega_0/\omega_H$. Outside this resonant cone, the distribution of the rf potential decays rapidly with distance from the source.

As the power is raised ($W_0 \gtrsim 5$ W), the spatial distributions of the plasma density (N) and of the rf field change substantially. A narrow plasma filament forms in the discharge chamber, spanning the entire apparatus in the longitudinal direction. Figure 1 shows radial profiles $N(r)$ constructed from the saturation ion current drawn by a fixed Langmuir probe for two distances z from the source at $W_0 = 10$ W.

Direct measurements of the difference between the phases of the oscillations along the plasma filament reveal that a wave with a length $\lambda_{\parallel} \simeq 20$ cm is propagating along the direction of the magnetic field. This length increases slightly with distance from the antenna. The observed slowing of the wave $n_{\parallel} \simeq 10$, agrees with the slowing of a longitudinal whistler in the plasma of density $N \simeq 7 \times 10^{10}$ cm^{-3}, which is approximately the electron density in the filament. Figure 2 shows radial profiles of the z

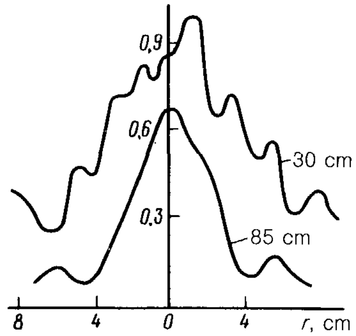

FIG. 2.

component of the rf electric field under conditions similar to those in Fig. 1. It follows from the results of these measurements that the waveguiding structure forms at a distance $z = 2$–3 from the source as a result of a "deexcitation" of small-scale field perturbations associated with the plasma waves. We wish to call attention to the fact that the phases of the oscillations of the field E_z, which is propagating along the filament, are shifted in the side lobes by π with respect to the oscillations at the axis. This circumstance is evidence that the field which is confined in the waveguide is rotational, and it represents a substantial difference between the picture described here and the self-ducting of oblique plasma waves which has been studied previously.[2]

How can this experiment be interpreted? An additional ionization of the gas in the discharge is caused by the near field and wave field of the antenna. At a low source power, there is no emission of a whistler, and the sole reason the plasma density exceeds the background is the heating of electrons in the electrostatic rf field, which is concentrated in the region $z \ll \lambda_{\parallel \mathrm{b}} = 2\pi c(\omega_H/\omega_0 - 1)^{1/2}/\omega_{\mathrm{pb}}$, near the antenna. The longitudinal scale length for the decay (by a factor of e) in the density is $L_{\parallel} \simeq 50$ cm. When the filament is excited, the plasma density along the axis of the filament varies more smoothly, changing by 20–30% over a distance of 50 cm. This result suggests that the additional ionization of the gas in the filament is caused primarily by the field of the electromagnetic wave which is propagating from the rf source.

To construct a self-consistent spatial distribution of the wave field[1)] in the discharge, we consider a model of a radially symmetric plasma filament which is uniform along the z axis. A whistler with an electric field $\mathbf{E} = \frac{1}{2}[\mathscr{E}(r)\exp(i\omega_0 t - ihz) + \mathrm{c.c.}]$ is travelling along this filament. Ignoring the excitation of plasma waves, we can easily find a relationship between the longitudinal component $\mathscr{E}_z$ and the radial component $\mathscr{E}_r$, which are responsible for the ionization of the gas, and the azimuthal projection of the amplitude $\mathscr{E}_\varphi$:

$$\mathscr{E}_z = -\frac{1}{\sqrt{u}hv_r}\frac{d}{dr}(rv\mathscr{E}_\varphi), \qquad \mathscr{E}_r = \frac{hu\dfrac{d\mathscr{E}_r}{dr} + \sqrt{u}v\mathscr{E}_\varphi k_0^2}{h^2u - 2k_0^2v} \tag{1}$$

Here $k_0 = \omega_0/c, u = \omega_H^2/\omega_0^2$, and $v = \omega_{\mathrm{p}}^2/\omega_0^2 = \omega_{\mathrm{pb}}^2/\omega_0^2(1+n)$, where $n = N - N_{\mathrm{b}}/N_{\mathrm{b}}$. For simplicity, we assume that the plasma density distribution $N(r)$ is "smeared" by the transverse diffusion of charged particles and is wider than the radial structure of the wave field. After the obvious modification of expressions (1), we then find the following equation for the azimuthal component:

$$\frac{a^2\mathscr{E}_\varphi}{dr^2} + \frac{1}{r}\frac{d\mathscr{E}_\varphi}{dr} - \frac{\mathscr{E}_\varphi}{r^2} - \frac{\mathscr{E}_\varphi}{u}\,\frac{h^2u - 2k_0^2h^2uv - k_0^4v^2u}{h^2u - 2k_0^2v} = 0. \tag{2}$$

Equation 2 should be used along with the diffusion equation for the electron density; the electron balance is maintained by ionization and attachment. Using the model function $\nu_i = \alpha(|\mathscr{E}_z|^2 + 1/u|\mathscr{E}_r|^2)$ for the rate of electron impact ionization of the air molecules, we find

$$D_\perp\left(\frac{d^2n}{dr^2} + \frac{1}{r}\frac{dn}{dr}\right) - \nu_a n + \alpha(1+n)(|\mathscr{E}_z|^2 + \frac{1}{u}|\mathscr{E}_r|^2) = 0, \tag{3}$$

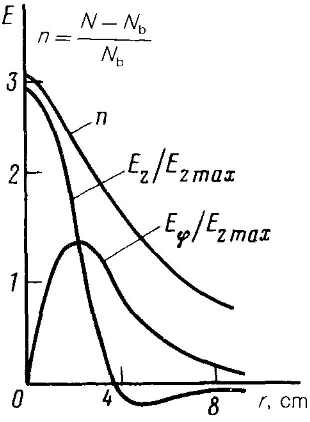

FIG. 3.

where the transverse diffusion coefficient $D_\perp$ and the electron attachment rate ν_a are assumed independent of the amplitude of the rf field. Figure 3 shows localized distributions $\mathscr{E}_\varphi(r)$, $\mathscr{E}_z(r)$, and $n(r)$ found through a numerical integration of systems (2)–(3). The obvious qualitative agreement of the results, which extends to the "subtle" change in the sign of the longitudinal component of the amplitude at the periphery of the duct, suggests that an ionizational self-ducting of a whistler is being observed in these experiments. We wish to stress that the phenomenon observed here is a consequence of an increase in the electron density in an intense rf field, in contrast with the results of Refs. 4 and 5 on the self-focusing of whistlers accompanied by a reduction of the plasma density. In this sense, the phenomenon observed here is qualitatively reminiscent of the self-effect of electromagnetic waves during the heating of a semiconductor plasma.[6]

The case in which the transverse refractive index for the wave becomes infinite in Eq. (2), at $N = N^* = h^2uc^2m/8\pi e^2$, corresponds to a leakage of whistler energy into plasma waves.[7] If, as in our case, the maximum density of the filament satisfies $N < N^*$, the coefficient for the excitation of short-wave perturbations is quite low:

$$T \sim \exp\left(-\frac{\pi\omega_p L_\perp}{c} \left[\frac{\omega_H(\omega_H - 2\omega)^-}{\omega(\omega_H - \omega)} \right]^{1/2} \right) \ll 1$$

($L_\perp$ is the transverse dimension of the filament). An estimate shows that the corresponding decay rate for the spatial decay of the whistler amplitude in the longitudinal direction is $10^{-3} - 10^{-5}$ cm^{-1}. The decrease in the field amplitude due to the interaction with plasma waves should lead to a decrease in the charged-particle density and an increase in the length of the electromagnetic wave, $\lambda_\parallel$. It may be that this effect contributes to the observed increase in $\lambda_\parallel$ along the apparatus. A more important cause of the longitudinal nonuniformity of the filament, however, is the influence of the near field of the source on the plasma density.

In view of all of these results, we can thus assert that this experiment has revealed a self-ducting of a whistler due to a heating of electrons in the field of the wave. An increase in the temperature leads to an additional ionization of the gas and to the formation of a plasma filament, which confines and directs the radiation which produces it.

---

(1) The problem of the field structure of a whistler of finite amplitude was first examined in the quasioptical approximation in Ref. 3.

[1] R. K. Fisher and R. W. Gold, Phys. Rev. Lett. **22**, 1093 (1969).

[2] G. A. Markov, V. A. Mironov, and A. M. Sergeev, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 672 (1979) [JETP Lett. **29**, 617 (1979)].

[3] A. G. Litvak, Zh. Eksp. Teor. Fiz. **57**, 629 (1969) [Sov. Phys. JETP **30**, 344 (1970)].

[4] R. L. Stenzel, Phys. Fluids **19**, 857 (1976).

[5] A. A. Balmashnov, Phys. Lett. **79A**, 402 (1980).

[6] Z. K. Yankauskas, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 189 (1984) [JETP Lett. **39**, 223 (1984)].

[7] V. I. Karpman and P. N. Kaufman, Zh. Eksp. Teor. Fiz. **83**, 149 (1982) [Sov. Phys. JETP **56**, 80 (1982)].

Translated by Dave Parsons