Self-channeling of plasma waves in a magnetic field

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The effect of nonlinear self-channeling of plasma waves in the lower-hybrid frequency range which leads to the formation of a sharply-localized plasma region and a strong high-frequency field is identified experimentally.

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In this work we report the results of the direct observation of a self-interacting of plasma waves in the frequency range $\omega_{H_i} < \omega < \omega_{H_e}$ ($\omega_{H_{e,i}}$ are the electron and ion cyclotron frequencies, respectively). We found that a stationary isolated plasma waveguide which captures the lower-hybrid waves that produce it is formed under the effect of radiation. Moreover, the plasma is localized in a strong-field region, which significantly differentiates the observed effect from the self-focusing of electromagnetic waves studied earlier in an isotropic plasma.(1)

The plasma was generated by means of a high-frequency (HF) induction coil placed at the front end of a glass cylinder and coaxially with it. Parameters of the experimental setup were as follows: cylinder diameter—20 and 120 cm, respectively, induction coil diameter and length—10 and 7 cm, respectively. HF field frequency—50 MHz, gas pressure (air or helium)—3×10^{-2}–5×10^{-3} tor. To determine the parameters of the plasma and HF potential we used movable probes and the measurements were carried out by means of spectral analyzers and oscillographs.

When the power applied to the HF source was $W\sim 10$ W the plasma was focused near the induction coil, the discharge luminescence being uniform throughout the cylinder cross section. Application of a longitudinal constant magnetic field $H_0 = 500$ Gauss leads to compression of the plasma into a narrow pinch with a diameter considerably smaller than that of the induction coil and a length limited by the dimensions of the system. Moreover, characteristic conical surface is observed visually in the region of the induction coil (Fig. 1). The experimental data (Figs. 2a and b) show that the plasma density N and HF potential amplitude ϕ are practically invariant along the pinch and both decrease rapidly from the center of the cross section. Measurements of the phase difference of oscillations at various points showed that a wave propagates along the system axis whose length λ decreases with reduced plasma density. At $W = 12$ W and air pressure $p = 10^{-2}$ tor, the HF field maximum at a distance $L = 60$ cm from the induction coil is ~ 2 V/cm, $N\approx 5\times10^{7}$ cm^{-3}, electron temperature $T_e\approx 10$ eV and $\lambda\approx 12$ cm. Thus, the structure under study forms a plasma-waveguide channel that is considerably detached from the walls, which contains both the plasma and strong HF field.

Before we proceed with interpretation of results, it should be pointed out that the measured value of wavelength is considerably smaller than that of the electromagnetic waves-whistlers observed experimentally

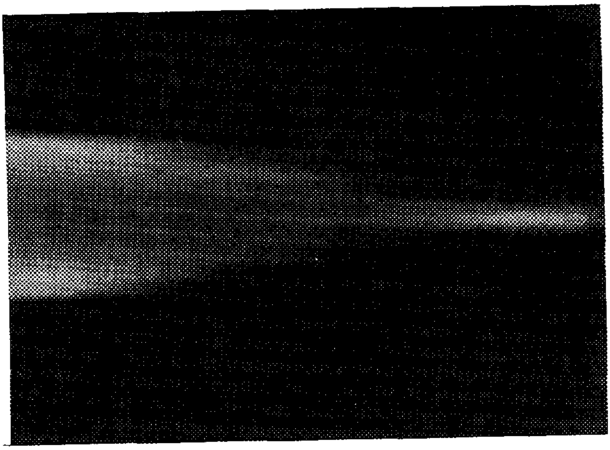

FIG. 1. Structure of discharge luminescence.

$$\left(\lambda_b = c/f\left(1 + \frac{\omega_p^2}{\omega_{H_e}\omega_{H_i}}\right)^{1/2} \approx 6\ \mathrm{m}\right).$$

Thus, the observed picture is definitely associated with excitation of the plasma (lower-hybrid) waves in a plasma with a concentration above the critical $N_{er} = mf^2\pi/e^2$. The same is also shown by the characteristic distribution of plasma luminance (Fig. 1) near the source which repeats the spatial structure of the HF potential.[2]

Thus, the physical picture of the subject phenomenon is as follows. Induction-coil-excited lower-hybrid waves propagate along the resonant conical surfaces from the source coils. The focal growth of the HF field promotes increased ionization and the predominantly longitudinal (along the magnetic field) transfer leads to formation of a plasma waveguide that channels the plasma waves which form the channel. At low power levels ($W \approx 10$ W) the axial plasma density slightly exceeds the critical $N_{\rm cr} \approx 3 \times 10^7$ cm^{-3}, and near the walls $N \ll N_{\rm cr}$ and, therefore, the self-consistent distribution of the plasma and field is detached from the walls. As the applied power increases the plasma density in the pinch increases as also does its diameter. At $W \sim 100$ W the electron density everywhere in the cylinder exceeds the critical and the role of the walls as regards field localization becomes significant.

The distinctive feature of the observed phenomenon is the concurrent stationary localization of the plasma and high-frequency field. To interpret self-channeling of the plasma waves, we shall consider a simple model of an axisymmetric formation which is uniform along a magnetic field. In this case the wave field potential Φ and plasma electron density N are clearly $\Phi = \psi(r)\exp(i\omega t - ikz)$ and $N = N(r)$, respectively, where τ is the distance from the channel axis $z \| \mathbf{H}_0$, and $k = 2\pi/\lambda$. The HF field ionizes the gas and, therefore, the plasma density depends on the intensity of the wave propagating in the plasma. Particle diffusion in the channel cross section must be taken into the consideration as a result of sharp localization of the plasma region; this

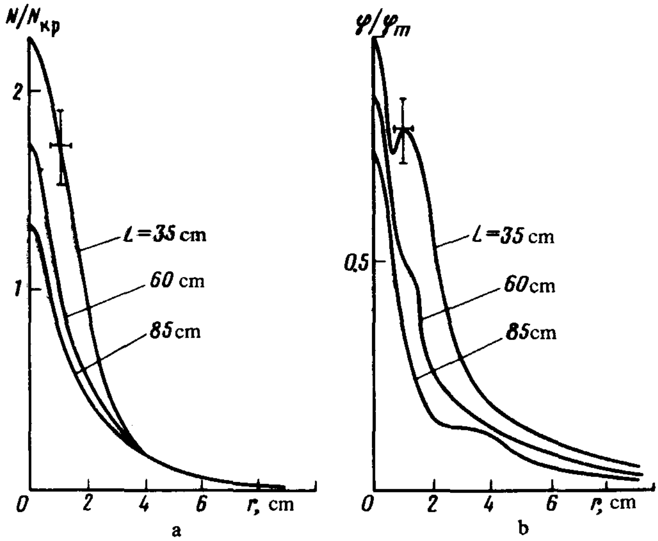

FIG. 2. Radial distribution of plasma density (a) and HF potential (b).

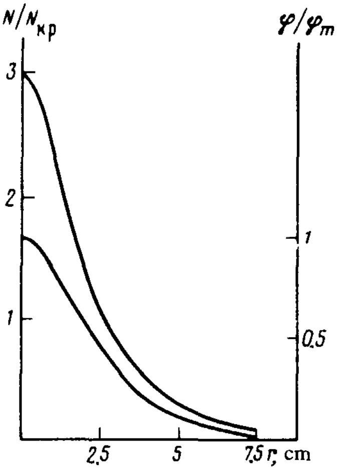

FIG. 3.

leads to a substantially nonlocal dependence of electron density on the HF potential amplitude

$$\frac{d^2N}{dr^2} + \frac{1}{r}\,\frac{dN}{dr} + [\alpha(k\psi)^{2\beta} - \nu_a]\frac{N}{D_\perp} = 0\ . \qquad (1)$$

The term $\alpha(k\psi)^{2\beta}$ in Eq. (1) approximates the frequency of molecular ionization by the electron shock ($\beta > 1$), ν_a is the frequency of electron attachment to electronegative molecules of the air,[1] and $D_\perp$ is the coefficient of ambipolar diffusion across the magnetic field. The potential of a lower-hybrid wave, propagating in a plasma with a distribution given by Eq. (1), satisfies the Poisson equation

$$\frac{d^2\psi}{dr^2} + \frac{1}{r}\frac{d\psi}{dr} - k^2\left(1 - \frac{N}{N_{cr}}\right)\psi = 0 . \qquad (2)$$

Equations (1) and (2) assume spatially-localized solutions,$^{2)}$ for which $N > N_{cr}$ near the axis and $N < N_{cr}$ in the peripheral region, a fact which determines exponential field decay. Rapid decrease of density occurs due to attachment (or longitudinal transfer in helium). Similar solutions correspond to the possibility of existence of a self-sustaining plasma-waveguide channel that is detached from the cylinder walls. Figure 3 shows distributions of the plasma density and HF potential obtained as a result of numerical calculation of Eqs. (1) and (2) for $\beta = 2$, $D_\perp / \nu_a = 6.3$ cm^2 and $\lambda = 12$ cm, which agree well with those measured experimentally (Figs. 2a and b).

HF energy dissipation is accompanied by a reduction in the wave amplitude as it propagates in the channel. This somewhat modifies the transverse structure described by Eq. (2) and, in particular, leads to a decrease in the plasma density at the axis of a system from the wave source along the magnetic field, a fact which stands in agreement with the experimental data obtained.

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1)Estimates show that a longitudinal transfer of electrons is immaterial for a plasma pinch obtained experimentally in air. This factor is, nevertheless, important for a helium plasma. It leads to the same result as the attachment and, thereby, it explains a structural similarity of channels in two different gases.

2)The possibility of formulation of localized solutions in the case of ionization nonlinearity was noted for the electromagnetic waves (whistlers) and plasma waves in Refs. 3 and 4.

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