Demonstration of the self-focusing of plasma waves

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The nonlinear effects which accompany the propagation of high-amplitude waves in various media are presently being studied in several college courses: optics,[1,2] the theory of wave processes,[3] and plasma physics,[4,5] among others. No laboratory apparatus has been available, however, for a graphic demonstration of the self-effects of wave fields.

One extremely interesting nonlinear effect, important in many applications, is the self-focusing of electromagnetic waves which was predicted by G. A. Askaryan back in 1962. This self-focusing results from changes induced in the optical properties of a medium by a sufficiently intense wave field which produces a kind of a lens in the medium. A simple and reliable apparatus has now been developed at Gor'kiĭ State University to demonstrate the self-focusing and self-channeling of plasma waves in a magnetic field.[6-8] Underlying the operation of this apparatus is the circumstance that if the *rf* input power is low, $W < 100$ W (if the degree of ionization is low, $n_e/N_0 \lesssim 10^{-5}$), and if the electron mean free path is short in comparison with the characteristic dimensions of the field inhomogeneity, then the structure of a discharge in the lower-hybrid frequency range reproduces the structure of the wave fields which create and sustain the discharge. The apparatus is shown schematically in Fig. 1.

A quartz or glass discharge tube (1) 6–10 cm in diameter and 100–150 cm long is placed in a longitudinal magnetic field $B \sim 500$–1000 G, produced by a solenoid consisting of several (four or five) coils ($\Delta B/B \lesssim 0.1$). The tube is pumped down to $p \sim 10^{-2}$ torr and can be sealed off. A discharge is ignited in the low-density air by means of an external spiral inductor (2), which is the plate load of a push-pull oscillator (3) using GU-33V vacuum tubes (Fig. 2). The oscillation frequency is $f = 60$ MHz, and the supply power is $W \lesssim 100$ W. The inductor has five turns and a total length $l \sim 5$–10 cm. Commercial GST-2 oscillators ($f \sim 180$ MHz, $W \sim 25$ W) could also be used as the rf source. A glass tube (4 mm in diameter and $L \sim 50$ cm long) is inserted into the discharge tube through a soft vacuum seal at its end. A coaxial rod antenna (4) can be pushed through this inner tube for a diagnostic study of the rf fields in the discharge. The antenna is a length of RK-50-1 coaxial cable, with the central conductor extending 1 cm from its end. A rubber tube can be used as the vacuum seal if there is continuous vacuum pumping. The rf signal from the antenna output is fed to one input of an S7-8 oscillscope; the second input receives a reference signal from a corresponding antenna near the inductor. Comparison of the phases of the oscillations at various points in the discharge reveals the wavelength in the plasma.

Figure 3a is a general view of a discharge ignited and sustained by oblique plasma waves. The dark vertical bands are left by the shadow cast by the magnet coils. We might note that the diameter of the plasma column is much smaller than that of the discharge tube. Figure 3b is an enlarged photograph of the discharge region near the inductor. We can clearly see a resonant conical surface with base at the inductor and a narrow plasma filament extending out from the vertex of the column in the direction along the magnetic field. Measurements with a movable rod antenna and a high-speed oscilloscope triggered by a signal from the inductor easily show that slow waves travel along this filament and that their wavelength λ is approximately equal to twice the length of the inductor ($\lambda_\parallel \sim 2l$). The retardation is $\lambda_0/\lambda_\parallel = c/f\lambda_\parallel \sim 10^2$. Over the given frequency range ($\omega_{Bi}, \omega_{Pi} \ll \omega \ll \omega_{Pe}, \omega_{Be}$ where $\omega_{Be,i}$ are the electron and ion gyrofrequencies, and $\omega_{Pe,i}$ are the electron and ion plasma frequencies), the only waves which could have such a retardation are electrostatic oblique plasma waves (lower-hybrid waves).[9] We recall that such waves propagate only in a dense plasma, with an electron density n_e higher than the critical value[4,9] ($n_{cr} = m\omega^2/4\pi e^2$). Such waves are frequently called "internal plasma waves." The relationship between the transverse ($k_\Delta = 2\pi/\lambda_\perp$) and longitudinal ($k_\parallel = 2\pi/\lambda_\parallel$) wave numbers for these waves depends on the electron density: $k_\perp \approx k_\parallel\sqrt{n_e/n_{cr}}$ ($\omega_{Pe} \ll \omega_{Be}$). Under these experimental conditions, the relation is determined by the rf power. By moving the rod antenna through the discharge tube one can show that the amplitude of the

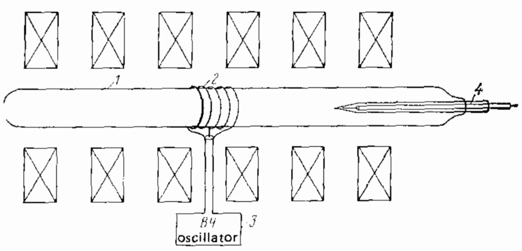

FIG. 1. Sealed-off version of the apparatus for demonstrating the self-focusing of plasma waves.

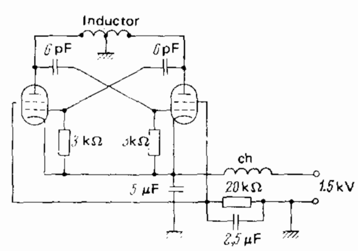

FIG. 2. Circuit of the rf oscillator which excites the plasma waves.

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FIG. 3. Structure of the discharge excited as a result of the self-channeling of oblique plasma waves.

longitudinal component of the electric field of the wave traveling along the filament has a maximum at the axis of the filament and falls off monotonically toward the tube wall. It can be concluded from these results that the discharge structure which has been demonstrated results from a self-channeling of ionizing plasma waves, which form and maintain a self-consistent plasma distribution in the form of a self-localized plasma-wave channel stretched out along the magnetic field from the focus of the resonant surface. That this assertion is correct is shown clearly by the following facts: As the rf power is raised, the plasma density increases, as can be seen from the brightening of the optical emission from the discharge. As a result, in accordance with the theory,[9,10] the vertex angle of the resonant cone decreases, the focus moves away from the source, and the length of the plasma-wave channel increases. At high values of the rf power, $W \gtrsim 50$ W ($P \lesssim 2 \cdot 10^{-2}$ torr, $B \gtrsim 600$ G), this apparatus makes it possible to observe a stratification of the discharge, which demonstrates higher-order wave modes in the self-localized plasma waveguide. When the second symmetric mode is excited (for example), we find a cylindrical halo around the central plasma filament, while the excitation of asymmetric modes gives rise to plasma sidebands at the corresponding field antinodes. When the magnetic field is turned off, the discharge converts into a diffuse ellipsoid centered on the source, and the signal from the movable antenna fades sharply.

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