Self-focusing of Gaussian helicon beams in a magnetized solid-state plasma

Z. K. Yankauskas

Vil'nyus Civil Engineering Institute

(Submitted 27 October 1983; resubmitted 13 January 1984)

Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 5, 189–190 (10 March 1984)

There is an effective mechanism for the self-focusing of Gaussian helicon beams in the *rf* range in a magnetized solid-state plasma.

The numerous experiments on the self-focusing of electromagnetic waves have been restricted to frequencies in the optical range, since it is virtually impossible to reach the critical power level at lower frequencies in the nonlinear dielectrics available. In this letter we report an experimental and theoretical study of an effective mechanism for the self-focusing of helicon beams in a magnetized semiconductor plasma at frequencies in the *rf* range (~ 100 MHz) at a current density $\gtrsim 0.5$ A/mm^2 in the channel.

The existence of slightly divergent Gaussian helicon beams in a magnetized solid-state plasma was demonstrated theoretically and verified experimentally in Ref. 1. The divergence angle of such beams is smaller than that of Gaussian beams in free space. Further experiments with *n*-InSb have shown that at a current density ~ 0.5 A/mm^2 a significant amount of heat is evolved in the wave channel, the carrier density increases, and there is a self-focusing of the beam, accompanied by a sharp decrease in the divergence angle.

We first offer a mathematical proof and then look at the experimental results.

According to Ref. 1, each field component of a Gaussian helicon beam satisfies a scalar equation (for simplicity, damping is ignored)

$$\frac{\partial^2}{\partial z^2}\nabla^2\varphi - k_\varphi^4\varphi = 0, \qquad k_\varphi = \frac{4\pi N_\varphi e\omega}{H_0 c}, \tag{1}$$

where N_φ and e are the density and charge of the electrons, ω is the frequency, and H_0 is the static magnetic field along the z axis; here $N_\varphi = f(|\varphi|^2)$.

Heating causes the electron density N_φ in the waveguide channel to become higher than the density outside the channel, N_0. Correspondingly, we have

$$k_\varphi > k_0, \quad k_\varphi^2 = \frac{4\pi N_\varphi e\omega}{H_0 c}, \qquad k_0^2 = \frac{4\pi N_0 e\omega}{H_0 c}. \tag{2}$$

Writing φ in the form $\varphi = U\exp - ikz$, we find from (1) the standard self-focusing equation for determining the radial profile $U(r)$:

$$\frac{\partial^2 U}{\partial r^2} + \frac{1}{r}\frac{\partial U}{\partial r} + \frac{k_\varphi^4(U^2) - k^4}{k^2}U = 0. \tag{3}$$

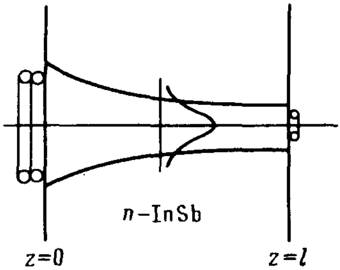

FIG. 1. Experimental arrangement.

We find the critical beam diameter from

$$d_h = \frac{2\pi k_0}{\sqrt{k_\varphi^4 - k_0^4}} . \tag{4}$$

We recall that for the self-focusing of an ordinary electromagnetic wave we would have the equation $u'' + (1/r)u' + (k_\varphi^2 - k^2)u = 0$, instead of (3), and the critical diameter d_e would be

$$d_e = \frac{2\pi}{\sqrt{k_\varphi^2 - k_0^2}} . \tag{5}$$

Consequently, the self-focusing of the helicon beam is more effective if $k_\varphi \gg k_0$, since

$$d_h \approx \frac{2\pi k_0}{k_\varphi^2} << d_e \approx \frac{2\pi}{k_\varphi} .$$

A convenient method for exciting and detecting channeled waves in a solid-state plasma was proposed and implemented a long time ago.[2] The experimental arrangment is shown in Fig. 1.

A plane excitation coil is applied to the surface of a semi-conductor (InSb) plate at $z = 0$. Also shown in Fig. 1 is the profile of the Gaussian beam, $U(r)$. At the opposite surface of the plate, at $z = l$, there is a pickup turn of much smaller diameter; by moving this pickup we can record the radial profile $U(r)$ at both $z = 0$ and $z = l$. At a low beam intensity, diffraction causes a broadening of the beam. With increasing intensity, the diffraction angle decreases, and at a current density ~ 0.5 A/mm^2 in the channel there is a contraction of the original $U(r)$ profile: The width decreases by a factor of several units. We attribute this contraction of the channeled beam to self-focusing. Evidence of an increase in the carrier density in the channel comes from the fact that the phase velocity is lower than that for a plane helicon. The radial temperature profiles at $z = 0$ and $z = l$, measured with point thermocouples, essentially reproduce the $U(r)$ profile.

Here are the parameters from one of the many experiments that have been carried out at room temperature: n-InSb, $N_0 = 1.8 \times 10^{22}$ m^{-3}, $f = 300$ MHz, $B_0 = 1.2$ T, helicon wavelength $\lambda = 6$ mm, beam diameter of 4 mm at the entrance, beam diameter of 1 mm at the exit at a current density ~ 0.5 A/mm^2, channel-sample temperature drop ~ 80 °C, thermal conductivity of the crystal ~ 50 W/(m·deg), $l = 2$ cm.

[1]Yu. K. Pozhela, R. B. Tolutis, and Z. K. Yankaukas, Fiz. Tekh. Poluprovodn. **17**, 1689 (1983) [Sov. Phys. Semicond., to be published].
[2]Z. K. Yankauskas, Fiz. Tverd. Tela (Leningrad) **12**, 2835 (1970).

Translated by Dave Parsons
Edited by S. J. Amoretty