

# WHISTLER WAVE DUCTING ALONG DENSITY ENHANCEMENTS CAUSED BY HEATING OF ELECTRONS IN A LABORATORY PLASMA

A.V. Kostrov, A.V. Kudrin, L.E. Kurina, G.A. Luchinin,  
A.A. Shaikin and **T.M. Zaboronkova**

*Institute of Applied Physics, Russian Academy of Sciences  
46 Ul'yanov st., Nizhny Novgorod 603600, Russia*

## Abstract

We have established that a thermal-diffusion-driven redistribution of plasma, caused by the electron heating in a quasi-static field of a current loop of rather large radius, leads to formation of the duct with enhanced density. Based on experimental data and the results of theoretical calculations it is shown that this duct can sustain whistler modes that are excited by a magnetic-type antenna immersed in it.

## 1. Introduction

It is thought that the electron heating caused by the antenna near-zone field in a magnetoplasma gives normally rise to a density depression aligned with an external static magnetic field [1]. In this paper, we demonstrate that the thermal effects due to the electron heating in the vicinity of a large current loop can be responsible for the formation of a magnetic-field-aligned density enhancement which conveys whistler-mode waves launched by a small magnetic-type antenna that is immersed in this enhancement.

## 2. Experimental results

Our experiments were carried out in a vacuum chamber of length 150 cm and diameter 80 cm. An argon plasma was created at pressure  $p = 5 \times 10^{-3}$  Torr by a rf pulsed discharge in the uniform static magnetic field  $B_0 = (90 \pm 5)$  Gs. This plasma had the form of a quasiuniform column of length 80 cm and diameter 40 cm. The external static magnetic field was created by three coaxial coils displaced at distance 10 cm from each other. Under the conditions of the experiment, the electron temperature  $T_e$  and the ion temperature  $T_i$  coincided and came to  $T_e = T_i = 0.5$  eV. Two loops with their planes perpendicular to the external magnetic-field direction were placed on the axis of the plasma column. The loop with a larger radius ( $b_1 = 6$  cm) was used to create a density duct, while the other loop with smaller radius ( $b_2 = 2.5$  cm) launched whistler-frequency electromagnetic waves into this duct. After switching off the pulse source creating the background plasma, during the decay stage of the plasma with density  $N_e = (5 \pm 0.5) \times 10^{11}$  cm $^{-3}$  (characteristic decay time was  $\tau_N = 2$  msec), an impulse signal with fixed frequency 60 MHz, power  $P = 100$  W and length up to  $\tau_1 = 1.2$  msec was applied to the first large loop of radius  $b_1$ . The second antenna a radius  $b_2$  was fed continuously by a signal of power  $P < 0.5$  W. The frequency  $f$  of this signal could change from 17 MHz to 150 MHz. The plasma diagnostics consisted of a 34.9 GHz microwave interferometer for radially averaged density measurements and of movable double and resonance microwave probes for local density measurements. The spatial distribution of excited electromagnetic fields was detected with a movable frame antenna of radius  $\sim 0.3$  cm. The surfaces of emitting and receiving antennas were covered with a dielectric shell to eliminate the ion-sheath effect on the impedances of these antennas. To obtain the spatial amplitude and phase distributions of electromagnetic waves excited in the plasma, interferometer techniques were used [2].

Under the experimental conditions the power level fed to the loop with radius  $b_1$  was

high enough to cause the ohmic heating by its quasistatic field of the plasma electrons up to temperature  $T_e \simeq 1.5$  eV. Because this loop was large enough to be somewhat greater than the characteristic transverse scale  $L_\perp$  of the electron heat conduction in the unperturbed plasma ( $L_\perp/b_1 \approx 0.5$ ), a field-aligned duct with enhanced density formed. It was aligned with the loop axis and surrounded by a low-density annular layer whose radial position was determined by the loop radius. This plasma density perturbation spanned the entire chamber in the longitudinal direction. The perturbed plasma density profiles  $N_e(\rho)$  measured at the same time are shown in Fig. 1a, b for distances  $z = 50$  cm and 70 cm from the loop. Some nonsimmetry in the distribution of the plasma over the radial coordinate is explained by the fact that the loop axis made some small angle with the external static magnetic-field direction. Results of phase measurements made on axis  $\rho = 0$  are shown in Fig. 2a, b for the two values of the frequency of the launched wave:  $f_1 = 50$  MHz and  $f_2 = 100$  MHz. As is clear from Fig. 2a, b, the wavelength of the wave propagating in the perturbed plasma is  $\lambda_w = 13$  cm for the frequency  $f_1$ , and  $\lambda_w = 6.6$  cm for the frequency  $f_2$ . Fig. 3a shows the dependence of the magnitude of the field component  $H_z$  on the radial coordinate  $\rho$  at distance  $z = 70$  cm for frequency  $f_2 = 100$  MHz.

### 3. Theoretical analysis

Recall that in the whistler frequency range

$$\omega_{LH} \ll \omega < \omega_H \ll \omega_p \quad (1)$$

( $\omega_{LH}$  is the lower hybrid frequency,  $\omega_H$  and  $\omega_p$  are the cyclotron and plasma frequency of electrons) the dielectric tensor of a cold collisionless magnetized ( $\mathbf{B}_0 \parallel \mathbf{z}_0$ ) plasma is given by the general tensor  $\hat{\epsilon}$  [3]. In the frequency range (1), only the extraordinary wave is propagating and its refractive index can be approximately described by

$$q_k^2(p, v) = p^2 \left( \frac{u}{2} - 1 \right) - v + (-1)^k \frac{pu}{2} \sqrt{p^2 - 4 \frac{v}{u}}, \quad (2)$$

where  $v = \omega_p^2/\omega^2$ ,  $u = \omega_H^2/\omega^2$ ,  $k=1,2$ , and quantities  $q$  and  $p$  denote the components of the wave vector ( $\mathbf{k} = \mathbf{k}_\perp + k_\parallel \mathbf{z}^0$ ) normalized to  $k_0 = \frac{\omega}{c}$ , i. e. its longitudinal,  $p = \frac{k_\parallel}{k_0}$ , and transverse,  $q = \frac{k_\perp}{k_0}$ , components. The branch  $q_1$  corresponds to the whistler wave, and the branch  $q_2$  to quasioleostatic waves. It follows from the analysis of the form of the whistler-mode refractive index surfaces for different plasma densities that a duct with enhanced density can support and guide slightly leaky whistler modes when the following condition is satisfied:

$$\mathcal{P}^* < p' < \tilde{\mathcal{P}}, \quad (3)$$

In the preceding,  $\mathcal{P}^* = \max\{\tilde{\mathcal{P}}_c, \mathcal{P}_0\}$ ;  $p' = \text{Re}p$ ,  $\tilde{\mathcal{P}}_c = \sqrt{\frac{4\tilde{v}}{u}}$ ; and  $\mathcal{P}_0 = \sqrt{\frac{v_0}{u^{1/2} - 1}}$  and  $\tilde{\mathcal{P}} = \sqrt{\frac{\tilde{v}}{u^{1/2} - 1}}$  are the normalized longitudinal whistler propagation constants in a uniform plasma with the densities  $N_0$  ( $v(\rho) = v_0$ ) and  $\tilde{N}$  ( $v(\rho) = \tilde{v}$ ), respectively. We assume that  $\tilde{N} > N_0$ .

More specific assertions can be drawn based on the results of rigorous theoretical calculations. We note that in our case linear theory is sufficient to describe the ducting of whistlers,

since the creation of the nonuniform plasma-density profile is not associated with the propagation of whistler waves, which have a rather small amplitude, but is a result of the nonlinear interaction of the strong quasistatic loop field with the plasma. Let us limit ourselves to the simplest model of the plasma density profile:

$$\begin{aligned} N_e &= \tilde{N}, & v(\rho) &= \tilde{v} & \text{for } \rho < a, \\ N_e &= N_0, & v(\rho) &= v_0 & \text{for } \rho > a. \end{aligned} \quad (4)$$

From the condition of continuity of the tangential field components at  $\rho = a$  we can obtain the following dispersion equation for the guided by a cylindrical density duct [3,4]. As is known, the dimensionless propagation constants  $p$  of waveguide modes are roots of the dispersion relation (6) which in the general case can be investigated only numerically. For the numerical calculations we chosen the following values of parameters:  $B_0 = 95$  Gs ( $\omega_H = 1.7 \times 10^9$  s<sup>-1</sup>),  $N_0 = 2.7 \times 10^{11}$  cm<sup>-3</sup> ( $\omega_p = 3.8 \times 10^{10}$  s<sup>-1</sup>),  $\tilde{N} = 4.5 \times 10^{11}$  cm<sup>-3</sup> ( $\omega_p = 3.8 \times 10^{10}$  s<sup>-1</sup>),  $a = 3$  cm (for  $z = 50$  cm) and  $a = 4$  cm (for  $z = 70$  cm), which correspond to the conditions of our laboratory experiments (see Fig. 1a, b). The numerical results are presented in Table 1. Also, for the subsequent comparison, results of measurements of the propagation constant  $p_w$  and the wavelength  $\lambda_w$  in the duct are given in Table 1. From this we can conclude that a good agreement is observed between the experimental values  $\lambda_w$  and the theoretical values  $\lambda_T$  of the whistler wavelength.

$f$ , MHz	$a$ , cm	$p = p' - ip''$	$\lambda_T = \frac{2\pi}{k_0 p'}, cm$	$p_w = \frac{2\pi}{k_0 \lambda_w}$	$\lambda_w, cm$
50	3	$47.204 - i8.160 \times 10^{-2}$	12.7	46.2	13
100	4	$45.397 - i9.680 \times 10^{-2}$	6.6	45.5	6.6

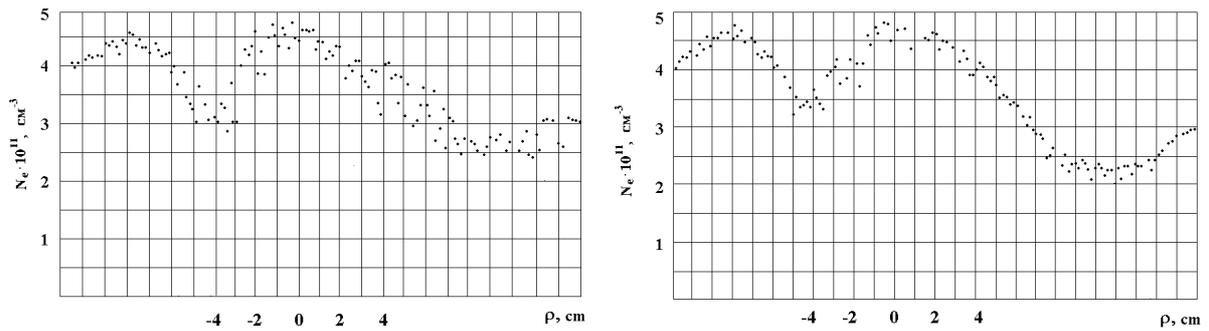
**Table 1.**

To explain the formation of the plasma density profile shown in Fig. 1, we have solved numerically the equations governing the thermal diffusion of plasma together with the electron heat conduction equation, specifying the heating source by a modal function appropriate to the experimental conditions. The density profiles are found to be in agreement with those observed in the experiment (see Fig. 1). The behavior of the magnitude of the longitudinal field component  $H_z$  versus  $\rho$  in the fundamental mode at frequency  $f_2 = 100$  MHz is shown in Fig. 3b for the duct with the model density profile  $N(\rho)$  given by (5), with  $a = 4$  cm. A comparison of the results of theoretical calculations of the field distribution in the duct with the experimental data (Fig. 3a) indicates a good agreement between them.

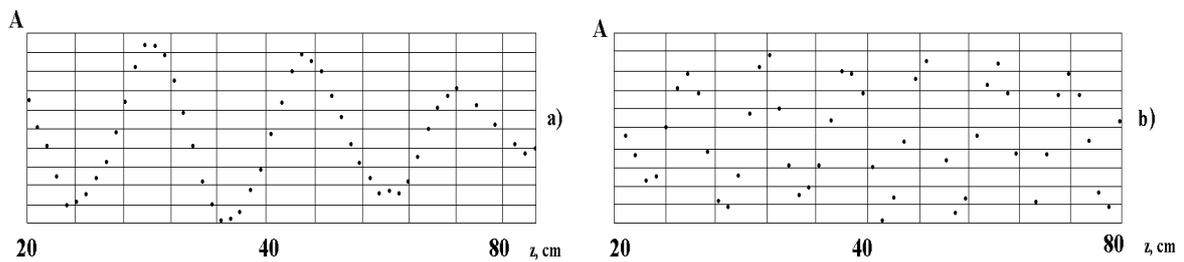
#### 4. Conclusions

The results presented show that due to the electron heating in the vicinity of a large current loop with its radius comparable to the transverse scale of the electron heat conduction, a magnetic-field-aligned duct with enhanced plasma density on its axis can form in a magnetoplasma. Based on the results of the theoretical calculations and experimental data, one may conclude that the creating duct is capable of guiding the slightly-leaky whistler modes that can be excited by a magnetic-type antenna immersed in this duct.

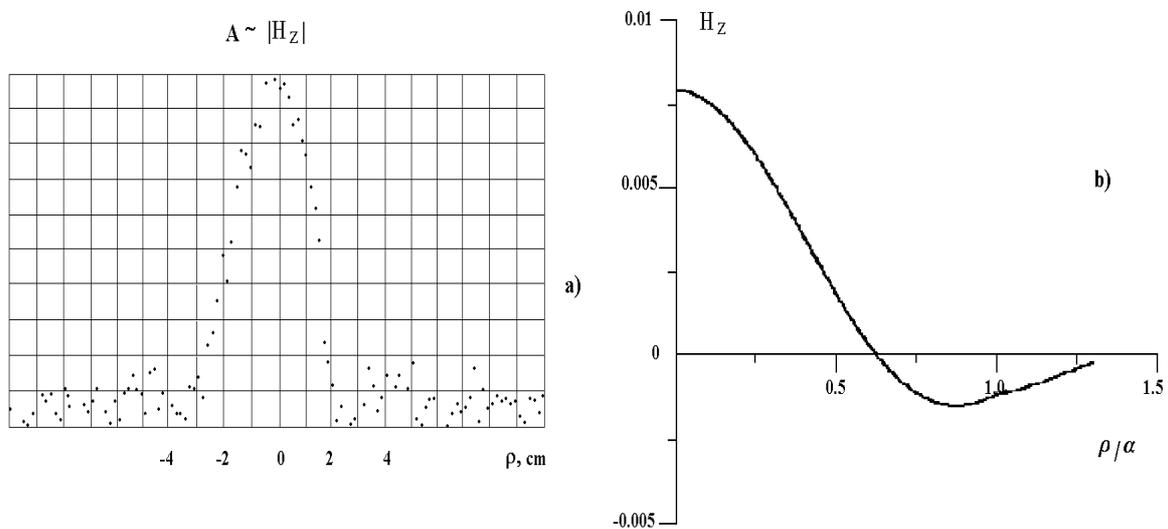
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**Figure 1.** Spatial distribution of the plasma density perturbation  $N_e(\rho)$   
a)  $z = 50$  cm, b)  $z = 70$  cm.



**Figure 2.** Results of the phase measurements in the duct ( $\rho = 0$ ).  
a)  $f_1 = 50$  MHz, b)  $f_2 = 100$  MHz.



**Figure 3.** Spatial distribution of the field component  $H_z(\rho)$  in the duct.  
(a) experimental result, (b) theoretical calculation.

## References

- [1] Egorov S.V., Kostrov A.V. and Tronin A.V.: JETP Lett. **47**, 102–106 (1988)
- [2] Stenzel R.L.: Rev. Sci. Instrum., **47**, 91 (1976)
- [3] Zaboronkova T.M., Kudrin A.V. and Markov G.A.: Plasma Physics Rep. **19**, 397–403 (1993)
- [4] Zaboronkova T.M., Kostrov A.V., Kudrin A.V., Tikhonov A.V., Tronin A.V. and Shaikin, A.I.: Sov. Phys. JETP **75**, 625–632 (1992)