Low-frequency waves produced by a package of laser plasma clouds in a magnetized background

V N Tishchenko1, A G Berezutsky1, E L Boyarintsev1, Yu P Zakharov1, I B Miroshnichenko 1,2, V G Posukh1, A G Ponomarenko1, A A Chibranov1,2 and I F Shaikhislamov1

1Institute of Laser Physics SB RAS, Akademika Lavrentieva Avenue, 15B, Novosibirsk, Russia
2Novosibirsk State Technical University, Karl Marx Avenue, 20, Novosibirsk, Russia
E-mail: tVN25@ngs.ru

Abstract. It was shown for the first time that in a laboratory experiment a train of laser plasma clouds makes it possible to increase the length of the whistler waves generated in the power tube of a magnetized medium. The intensity of waves is orders of magnitude higher than the level achieved by known methods.

1. Introduction
In laboratory experiments and simulations, it was shown that a packet of laser plasma clouds forms Alfven and slow magnetosonic waves in a magnetized medium (hereinafter referred to as the background). Such waves transfer 50% of the clouds energy in the power tube in the form of a stream of compressed, rotating plasma [1, 2]. High efficiency energy injection is achieved by fulfilling a set of dimensionless conditions (“resonance”) relating the parameters of clouds and background. The large length of the flows is the result of the mechanism of merging of waves (MMW) generated by individual clouds. Previously, MMW was proposed by the authors for gases, where periodic packets generated infra- and ultrasound.

The present work shows for the first time the possibility of pumping whistlers created by a packet of laser plasma clouds into the power tube of a magnetic field in the background. The record intensity, characterized by the ratio of the amplitude of the magnetic field of the whistlers to the external field $B_W \sim 0.1$ ÷ $0.2$, is achieved when the clouds “resonate” with the background, when only the whistlers are excited. With the simultaneous generation of whistlers and the Alfven wave, the $B_W$ value decreases by factor of $\sim 5$, which is associated with an additional channel for the removal of clouds energy [3, 4, 5]. The amplitude of whistlers excited by exposure to laboratory plasma with modulated radio emission is much lower [6, 7].

2. The theoretical basis of the experiment
Whistlers are formed at the stage of explosive expansion of laser plasma clouds as a result of interaction with the magnetic field and background plasma by the Lorentz force. In this case, torsion deformation of the magnetic field lines occurs, the electrons acquire azimuthal rotation around the axis of symmetry passing through the center of the cloud and oriented along the unperturbed magnetic field $B_0$ of the background. Whistlers contain azimuthal $B_\phi$ and radial
$B_r$ magnetic field components, an electric field, and a longitudinal current. The hodogram of $B_x$ and $B_y$ corresponds to the right-handed polarization of the magnetic field vector. The whistler propagates along $B_0$ with a speed that is approximately equal to the group velocity $V_g/c = 2Ω/(1 - Ω^2)/[2Ω + Ω^2/(1 - Ω)^2]$, where $c = 3 \cdot 10^{10}$ cm/s is the speed of light in vacuum, $Ω = f/f_{ce}$ is the ratio of the whistler frequency to the cyclotron frequency of the electrons, $f_{ce} = eB_0/cm_e \approx 2.8 \cdot 10^6 B_0$, $Ω_{pe} = f_{pe}/f_{ce}$, $f_{pe} = 9 \cdot 10^3 \cdot √n_0$ is the plasma frequency of the electrons, $n_0$ cm$^{-3}$ is the background plasma density. The experimentally measured velocity of low-frequency whistlers $V_g \sim (4/6) \cdot 10^7$ cm/s depends on $n_0$ and $B_0$. Whistlers correspond to the frequency range of $F_1 < f < F_2 \ll f_{pe}$ [7], where $F_1 = (f_{ci} \cdot f_{ce})^{1/2} = 6.54 \cdot 10^4 B_0 \cdot √Z_0/m_0$, $F_2 = f_{ce}$, $f_{ci} = 1.53 \cdot 10^4 \cdot Z_0 \cdot B_0/m_0$ is the cyclotron frequency of the background ions. A laser plasma clouds creates only whistlers if the ratio of the ion-plasma length to the dynamic radius $R_d$ of the cloud is:

$$L_{pi} = c/(2π f_{pi} R_d) = 3.61 \cdot 10^4 Z_0^{-1} \sqrt{m_0/n_0} \cdot B_0^3 (1 + β_0)/Q > 0.6$$

$$R_d = (8π \cdot Q/B_0^3 (1 + β_0))^{1/3} \approx 630(Q/B_0^3 (1 + β_0))^{1/3}, f_{pi} = 210 \cdot Z_0 \cdot √n_0/m_0, β_0 \sim 0.1 ± 1$$

$R_d$ is the ratio of the background plasma pressure to pressure $B_0$. When values of $L_{pi}$ are 0.05 – 0.25, the Alfven wave is formed [1, 2]. If $L_{pi}$ is 0.25 – 0.4, form the Alfven wave and weak whistlers [3, 4, 5].

From the mention above relations, the laser plasma clouds with energy $Q \sim 20$ J used in the experiment create a whistler in the background with heavy ions, for example argon, with magnetic fields $B_0 = 50 – 200$ G in the range of plasma density $n_0 \approx (1/5) \cdot 10^{12}$ cm$^{-3}$. The whistler frequency is close to $F_1/5$ and, when using two consecutive clouds, it decreases by about two times. Clouds are created at a fixed point upon irradiation of a point target with two laser pulses with delay $τ$, which can be estimated from the characteristic time of clouds expansion $τ = R_d/V_0 \sim 5/7$ µs, where $V_0 \sim 1.5 \cdot 10^7$ cm/s is the initial thermal expansion velocity of the laser plasma. In the experiment, when the delay time $τ$ of the laser pulses is varied, the following whistler generation modes are possible: at $τ ≫ τ_d$, two successive whistlers; $τ \ll τ_d$ the length is approximately the same as from one cloud; at $τ = τ_d$, the length of the whistler wave increases by a factor of 2. From the calculations it follows that the train of periodic clouds generates a single whistler wave, the length of which linearly depends on the number of clouds used. The whistler group velocity $V_g \approx (3/6) \cdot 10^7$ is much higher than the Alfven wave velocity. One of the main characteristics of the interaction of plasma clouds with the background is that the Alfven Mach number under the experimental conditions is anomalously large: $M_A = V_0/C_A \approx 10$.

3. Experiment setup

The experimental design at the KI-1 facility is shown in figure 1. In a cylindrical vacuum chamber (length 5 m, diameter 1.2 m, pressure $2 \cdot 10^{-6}$ torr), an axial magnetic field $B_0 \sim 50–200$ G and a longitudinal stream of argon plasma (background) were created with speed $1.2 \cdot 10^6$ cm/s, temperature $T_0 \sim 10$ eV, $β_0 \sim 0.5$. The radiation from CO$_2$ lasers created one or two clouds with energies $Q \sim 20$ J upon irradiation of a polyethylene target (diameter $25$ mm) located on the camera axis. Each laser pulse was previously divided into two equal parts in energy, which allowed the formation of a plasma expansion, which ensured the azimuthal symmetry of the whistler. The sensors measured the plasma concentration, longitudinal current, electric field, and magnetic field components azimuthal $B_φ$, radial $B_r$, and longitudinal $B_z$. We varied $B_0$, $n_0$, and the corresponding $L_{pi}$ values, as well as the delay of the second pulse relative to the first laser pulse.
Figure 1. The experimental setup of KI-1 facility. 1 - vacuum chamber, 2 - background plasma flow created by the $\theta$-pinch (3), 4 - solenoid creating an external magnetic field parallel to the axis of the chamber, 5 - emission of a CO$_2$ laser, 6 - target, 7 - focusing lenses, 8 - measuring probes placed in various sections of the chamber, 9 - a flow of plasma clouds.

4. Experimental results

Figures 2 and 3 show the azimuthal magnetic fields of whistlers generated by one and two clouds of laser plasma in a magnetized background, in which the ion-inertial length $L_{pi} = 1.3$. The hodograms characterizing the polarization of the magnetic field vector are presented in the insets. Hereinafter, the time $t = 0$ corresponds to the moment of irradiation of the target with the first laser pulse, $Z$ is the distance from the target to the sensors. As can be seen from the hodogram, the magnetic field vector has the right-handed polarization, which is one of the properties of whistler waves. As can be seen from figure 4, the spectrum of whistlers created by two clouds of laser plasma is shifted to the region of lower frequencies in comparison with the spectrum of whistlers from a single cloud. An increase in the number of clouds, as follows from the calculations, is accompanied by a decrease in the frequency of the resulting wave. The amplitude of the whistler depends on $L_{pi}$. Thus, when changing the magnetic field by 2 times, the value of $L_{pi}$ being fixed, the maximum value of $B_\phi$ practically does not change. With a decrease to $L_{pi} \sim 0.5$, due to an increase in the background plasma concentration, $B_W$ decreases by factor of 4, which is consistent with experiments [3, 4, 5], where a single cloud of laser plasma generated, simultaneously with the whistlers, an Alfvén wave in helium and hydrogen plasma at $L_{pi} \sim 0.25 \div 0.38$.

Figure 2. The time variation of $B_\phi$ for whistlers created by one plasma cloud.

Figure 3. The time variation of $B_\phi$ for whistlers created by two plasma clouds.
5. Conclusion
The clouds of laser plasma, resonantly interacting with magnetized background plasma, generate intense whistlers in the power tube, the length of which linearly depends on the number of clouds. The amplitude of the whistlers reaches record values of $\sim 0.2$ relative to the external field.

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