Controlling the type and intensity of low-frequency waves generated by laser plasma clots in a force tube of magnetized plasma

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Abstract In this work, we study the influence of the parameters of a magnetized background plasma on the intensity of whistler waves generated by periodic laser plasma bunches in a magnetic field tube. It is shown that at $0.3 < L_{pi} > 0.4$ Alfvén waves and whistlers are generated. In the region $L_{pi} > 0.5$, intense whistlers with an amplitude of $δB_{max}/B_0 ≈ 0.24$ are generated.

1. Introduction

Numerous works have been devoted to the interaction of laser radiation with matter, which is associated with a wide field of application - material processing, aerospace applications, special tasks, communications, as well as the emergence of a number of new directions in physics, chemistry, biology, instrument making, medicine, military technology, and sciences about life, etc. Through research on the interaction of laser radiation with matter, back in the late 60s, it became possible to generate laser plasma, which is a tool for laboratory modeling of nonstationary processes in space plasma. Laser plasma can act as a source of generation of artificial wave disturbances in the near-Earth plasma, which is an extremely urgent problem. Its solution is necessary both for the development of the problems of active experiments aimed at obtaining knowledge about the structure of the ionosphere, and for applications, most of which are related to the exploration of outer space.

In ILP SB RAS [1-2] it was shown for the first time that periodic plasma bunches created by repetitively pulsed laser radiation at a certain ratio between the energy and the pulse repetition rate generate a single wave in the surrounding gas, for example, an infrasonic wave. The effect of combining shock waves created by individual optical breakdowns of a gas into a single wave was called the wave merging mechanism (WMM). The length of a single wave linearly depends on the number of bunches in the packet, which makes it possible to form weakly damped energy flows with relatively low energy consumption. The method allows you to control the type, frequency and intensity of the generated waves. В настоящей работе представлены экспериментальные результаты резонансного взаимодействия сгустков лазерной плазмы с замагниченной плазмой фона для генерации альфвеновских и вистлерных волн.
This paper presents the experimental results of the resonant interaction of laser plasma bunches with a magnetized background plasma for the generation of Alfvén and whistler waves.

2. Wave merging mechanism

The wave merging mechanism (WMM) has been experimentally confirmed for gases, plasma with a magnetic field and under the action of a laser plasma source located in a magnetic field [3-8]. The essence of the mechanism is as follows. Periodic shock waves are created in a continuous medium, the initial velocity of which is greater than the speed of sound \( C_0 \). If the main criterion of the WMM is met, the waves from the individual bunches are combined and create a single low-frequency wave, the length of which is linearly dependent on the number of laser pulses.

The results of numerical simulations [4,6,9] showed that the MOV is effective for the formation of low-frequency Alfvén, magnetosonic and whistler waves in a magnetized plasma, the length of which linearly depends on the number of pulses and energy consumption for their creation. For single optical breakdowns, the wavelength weakly depends on the pulse energy \( \sim Q^{1/3} \).

The main criterion for the WMM is the dimensionless pulsation frequency of repetitively pulsed laser radiation for combining waves, lying in the range:

\[
0.1 < \omega = \frac{f \cdot R_d}{C_A} < 0.4
\]

where \( C_A \) is the Alfvén velocity; \( R_d \) is dynamic radius (radius at which the pressure of the bunch is comparable to the pressure of the surrounding gas) \( R_d = (Q/p_0)^{1/3} \), \( Q \) is the energy of the bunch; \( f \) is the laser pulse repetition rate. At frequencies \( \omega < 0.1 \), the bunches create a sequence of short noninteracting Alfvén waves. At large values of \( \omega > 0.4 \), the wavelength decreases.

High efficiency of conversion of the source energy into a wave is achievable if additional conditions are met, depending on the properties of the surrounding background:

\[ \alpha = \frac{R_l}{L_{pi}} > 5, \]

where \( R_l \) is the Larmor radius.

2. The Larmor radius is approximately equal to the radius of deceleration by the magnetic field \( R_L = r_l / R_d \sim 1 \). If these conditions are violated, the AQW is not formed or its amplitude is extremely small and unstable.

3. Plasma \( \beta \) is a parameter characterizing the ratio of the thermal pressure of the background plasma to the pressure of the external magnetic field [9]:

\[ \beta = \frac{8 \pi k ((1 + Z_\infty)n_0)T_0}{B_0^2} < 1. \]

4. The ratio of the ion - inertial length to the dynamic radius of the plasma bunch:

\[ L_{pi} = l_{pi} \frac{cm}{R_d \frac{cm}} = \frac{c/\omega}{R_d} \sim 0.1 - 0.3, \]

The results of numerical modeling and experimental data [4, 6-9] showed that when the criteria of the WMM and the value of the dimensionless parameter \( L_{pi} \) <0.3 are met, Alfvén and magnetosonic waves are generated with a maximum amplitude at \( L_{pi} \sim 0.1 \), and when \( L_{pi} > 0.4 \), whistler waves are generated in the plasma. Intensity of which is characterized by the azimuthal component of the magnetic field \( B_\phi \).

The purpose of this work is to experimentally verify the generation of whistlers by laser plasma bunches. By varying the range of the dimensionless parameter \( L_{pi} \), it is supposed to check the modes of wave generation: 0.1 <\( L_{pi} < 0.3 \) bunches generate Alfvén and magnetosonic waves, and at 0.3 <\( L_{pi} > 0.4 \) - Alfvén waves and whistlers. Whistlers are generated in the region \( L_{pi} > 0.4 \).
3. Experimental setup

The experiments were carried out at the KI-1 facility of the Institute of Laser Physics of the Siberian Branch of the Russian Academy of Sciences. The experimental scheme is shown in Figure 1. A high-vacuum (p = 10^{-6} Torr) chamber with a diameter of 1.2 m and a length of 5 m was filled with plasma generated by a θ-pinches, the concentration varied in the range n_0 = 10^{12} \div 4 \cdot 10^{13} \text{ cm}^{-3}. The plasma temperature, determined from the current-voltage characteristics of the probes, is approximately T \sim 10 \text{ eV}. In experiments with an argon background Ar+, the typical velocity of plasma motion along the chamber axis is 10–20 km / s. A laser plasma bunches was generated by irradiating a polyethylene target with CO_2 laser pulses (spot area S = 2.5 cm²). A target in the form of a plate, the plane of which is perpendicular to the magnetic field, is located on the axis of the camera. Pulses with an energy of Q \sim 200 J and a duration of \sim 1 \mu s sequentially created on the target bunches of laser plasma with an energy of Q \sim 25 J, an initial expansion velocity of 100 km / s. From measurements of the shape of the plasma glow at different times, it follows that the dynamics of the bunch expansion is close to spherical, which is necessary from the conditions for the manifestation of the WMM and the generation of quasi-stationary Alfvén and other types of waves localized in the flux tube. An external magnetic field is B_0 = 100 \div 300 \text{ G}, along the chamber axis, is created by a source that supplies current to the solenoid, covering the entire outer surface of the chamber.

An array of eight sensors (Langmuir probes, magnetic probes and Rogowski belt) made it possible to measure the plasma concentration n, the components of the magnetic fields B_φ, B_r, B_z, the electric field and the longitudinal current J_z in various sections of the chamber at a distance of z \sim 3 m from the target and r \sim 30 cm radially from the camera axis. The spatial resolution of the measurements is 1 cm, the temporal resolution is approximately 10 ns, the frequency band of the magnetic probes is 20 MHz.

The characteristic spatial scale of the problem is the dynamic radius R_d, which is the distance from the target at which the energy density of the laser plasma is compared with the background energy density. The main dimensionless parameters of the problem are the Alfvén-Mach number (M_A) and the dimensionless parameter L_{pi} is the ratio of the ion-inertial length to the dynamic radius R_d and the magnetization of the ions R_L is the ratio of the gyroradius of the laser plasma ions to the dynamic radius R_d. Thermal beta background in these experiments was relatively low \beta <1. To obtain data on the effect of the ion-inertial length, in our experiments, helium and ten times heavier gas, argon, were used as the background plasma.

**Figure 1.** Schematic of the experiment on the generation of whistlers at the KI-1 facility. 1- Vacuum chamber. 2- plasma flux created by the θ-pinches (3). 4- turns of the solenoid, which creates an external magnetic field, axial to the axis of the chamber. 5- CO_2 laser radiation. 6- target. 7- focusing lenses. 8- measuring probes located in different sections of the chamber. 9- laser plasma bunches.
Table 1 shows the dimensionless parameters of the experiment.

| Table 1. Experimental parameters | Helium | Argon |
|----------------------------------|--------|-------|
| $B_0$                            | 100 G  | 100 G |
| $R_d$                            | ~70 cm | 70÷80 cm |
| $M_A$                            | 1÷3,5  | 3,5÷10 |
| $L_{pi}=c/R_d\omega_{pi}$        | 0,3÷0,6| 0,6÷1,7 |
| $\beta$                          | 0,08÷0,8| 0,08÷0,8 |
| $\varepsilon_b=R_l/R_d$          | ~0,5   | ~0,4÷0,5 |

In terms of dimensional experimental parameters, the optimal conditions approximately correspond to the magnetic field $B_0 \sim 100$−$200$ G, the background plasma from argon ions at a temperature of $\sim 10$ eV, and the energy of laser bunches $Q = 25$ J at an initial expansion velocity of 150 km / s. The main difference between these experiments is the use of a background plasma of Ar and He, which, in comparison with experiments where a hydrogen plasma was used [7, 10], makes it possible to significantly increase the ion-inertial length.

4. Results

Figure 2 shows typical plasma concentration computed from measurements with Langmuir probes. Zero instant of time corresponds to the arrival of the laser pulse on the target. Up to this point, the signal indicates the background plasma concentration. The figure illustrates two cases - background plasma from He and Ar. The average velocity of the background plasma, measured by the time-of-flight method, was approximately $V_{He} = 24$ km/s and $V_{Ar} = 12$ km/s. To achieve lower background plasma concentrations $n_0 = (1 \div 2) \cdot 10^{12}$ cm$^{-3}$ and, accordingly, a higher $L_{pi}$ value, laser plasma was created at the stage of lowering the background plasma flux concentration, as can be seen from the figures.

![Figure 2. Plasma concentration $n_0(t)$ (helium on the left, argon on the right). The target is irradiated with a laser pulse at a background plasma concentration of $n \sim 1.6 \cdot 10^{12}$ cm$^{-3}$. External magnetic field $B_0 = 100$ G.](image)

An important result of the experiments was the registration of the characteristic properties of whistlers: an azimuthal magnetic disturbance of right-handed circular polarization propagating at high speeds ($V_w > 300$ km / s). Figure 3 shows typical oscillograms of the azimuthal component of the magnetic field $B_\phi(t)$. Registration of signals by magnetic probes at distances $z = 140$ cm showed that magnetic disturbances have right-hand circular polarization and a characteristic decreasing frequency from $10^4$ Hz at the beginning of the packet to $2 \cdot 10^3$ Hz at the end.
Figure 3. Azimuthal magnetic field $B_\phi(t)$ (left - background helium plasma ($L_{pi} = 0.45$), right - argon plasma ($L_{pi} = 0.6$)). The inset shows the hodograph of the magnetic field. Distance $z = 140$ cm from the target. External magnetic field $B_0 = 100$ G.

To illustrate the transient regime, when the parameter of ion-inertial length lies in the range $0.3 < L_{pi} < 0.4$, Figure 4 shows the case when, in addition to whistlers, an Alfvén wave propagates in a medium \cite{10}. The disturbance was registered at a distance $z = 90$ cm from the target. The inset shows the hodograph of the magnetic field. At a concentration of hydrogen plasma $n_0 = 5 \cdot 10^{12}$ cm$^{-3}$, a whistler propagates in the medium at a speed of $V_w = 220$ km / s, and an Alfvén wave ($C_A = 70$ km / s). The dot on the graph shows the arrival time of the Alfvén wave at the probe.

This is also confirmed by the hodograph of the magnetic field, which has right-handed circular polarization, which is typical for whistlers. At the moment of time $t = 12$ $\mu$s, the polarization is transformed into a left-handed one, which is associated with the arrival of an Alfvén wave.

Figure 4. Derivative of the azimuthal magnetic field generated by one plasma bunch. External magnetic $B_0 = 175$ G. The inset shows the hodograph of the magnetic field. The dot on the graphs shows the arrival time ($t = 12$ $\mu$s) of the Alfvén wave.

Thus, when the parameter $L_{pi}$ lies in the range $0.3 < L_{pi} < 0.4$, the regime of generation of whistler and Alfvén waves is observed in a plasma with a magnetic field. The amplitude of the whistlers $B_{\text{pw}} =$
8 G, the Alfvén wave $B_\text{eq} = 12$ G. In this case, the amplitude of the waves can be increased when switching from the mode of generating several types of waves to the mode of generating only whistlers or Alfvén and magnetosonic waves.

5. Summary

In this work, we investigated the influence of the parameters of the magnetized background plasma on the intensity of whistler waves generated by periodic bunches of laser plasma in the magnetized background plasma. Experimentally, at the KI-1 facility, the range of values of the dimensionless parameter $L_{\pi i}$ was confirmed, at which three modes of wave generation are observed. In the range $0.1 < L_{\pi i} < 0.3$, bunches generate Alfvén and magnetosonic waves [8], and at $0.3 < L_{\pi i} < 0.4$ - Alfvén and whistler waves. In the region $L_{\pi i} > 0.5$, intense whistlers with $\delta B_{\text{max}} / B_0 = 0.24$.

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