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Generation of torsional Alfvén and slow magnetosonic waves by periodic bunches of laser plasma in a magnetised background*

A.G. Berezutsky, V.N. Tishchenko, Yu.P. Zakharov, I.B. Miroshnichenko, I.F. Shaikhislamov

Abstract. **Using numerical simulation, the influence of parameters of a magnetised background plasma on the intensity of quasi-stationary Alfvén and slow magnetosonic waves produced by periodic bunches of a laser plasma in a magnetic field tube is investigated. It is shown that in a weak magnetic field, the waves propagate together, carrying a flow of rotating plasma, and in a strong field, the bunches form simultaneously two types of waves propagating with different velocities.**

Keywords: *shock-wave merging, laser plasma bunches, Alfvén torsional wave, slow magnetosonic wave, numerical simulation.*

1. Introduction

In Refs [1 – 3], the generation of quasi-stationary waves (QSWs), Alfvén torsional waves (ATWs) and slow magnetosonic waves (SMSWs) by periodic bunches of laser plasma in a magnetic field tube, was first discovered. QSWs contain extended plasma flows that carry longitudinal (SMSW) and azimuthal (ATW) momenta. In Refs [1 – 3] criteria were also proposed that provide injecting up to half a bunch energy into the magnetic field tube. The large QSW length provides weak attenuation, which is important when solving the problem of energy transfer over a long distance. While the effects of injection of single plasma bunches are investigated using the well-known experimental 'Krot' [4] and LAPD setups [5, 6], at the KI-1 facility (Institute of Laser Physics, Siberian Branch of the Russian Academy of Sciences) the study of QSW generation using a train of high-power laser pulses (~200 J) was started. The developed criteria allow both numerical and natural laboratory modelling of the QSW formation in space using the plasma bunches of arbitrary nature. An example of using these criteria in planning experiments is given in [7, 8].

In this paper, we study the influence of the properties of a magnetised plasma (hereinafter referred to as background) on the longitudinal and azimuthal momenta carried by the SMSW and ATW. The background is characterised by the ratio of the plasma thermal pressure to the background magnetic field pressure $\beta = 8\pi p_0/B_0^2$. The value of β varied in the range from 10^{-3} to 1, which corresponds to conditions in space. The study was conducted using calculations on a supercomputer, since on experimental facilities it is problematic to ensure optimal conditions for the generation of QSWs in such a wide range of β. Thus, in Ref. [7], β was varied in a narrow range (0.1 – 0.5).

In calculations on a supercomputer, we used a three-fluid magnetohydrodynamic (MHD) model [1], axially symmetric with respect to the external magnetic field. The spherical geometry of the expansion of a bunch allowed high-efficiency generation of ATWs and SMSWs, which possessed axial symmetry and propagated along the axis of the magnetic flux tube. It was established that the QSW length is proportional to the number of bunches, and its radius depends on the energy of a single bunch, $R_\mathrm{d} = (Q/p_0)^{1/3}$, and the total background pressure $p_0 = B^2/(8\pi) + nT$.

2. Mechanism of wave merging

The wave merging (WM) mechanism was studied in detail in Refs [1 – 3]. Its essence is as follows. At a certain repetition rate of plasma bunches, depending on their energy and environmental properties, the partially merging waves form a single low-frequency wave, the spatial length of which linearly depends on the number of bunches and on the total energy expenditure for their generation. In a plasma with a magnetic field for efficient generation of QSWs the source parameters must meet the criteria for WM, which allow finding the efficient regime of generation depending on the properties of the ambient background. The criteria were obtained by the authors in calculations and confirmed in experiments on the KI-1 facility [7, 8].

The main WM criterion is the closeness of the dimensionless repetition rate of plasma bunches $\omega \approx fR_\mathrm{d}/C_\mathrm{i} \approx \omega_\mathrm{r}$ to the 'resonant' frequency ω_r, which depends on the type of excited waves. Here f is the physical repetition rate of the bunches, C_i is the velocity of sound in air, and for plasma with a magnetic field it is the velocity of ATWs, which is significantly higher than that of SMSWs under the ionospheric conditions. In a neutral gas and in the case of spherically symmetric plasma expansion, $\omega_\mathrm{r} \sim 5$ [9]. In a plasma with a magnetic field, where ATWs and SMSWs are localised in the magnetic field tube, $\omega_\mathrm{r} \sim 0.3$. When $\omega \ll \omega_\mathrm{r}$, the source forms separate bursts of wave disturbances, and at $\omega \gg \omega_\mathrm{r}$, the bursts merge into a single disturbance of the type of a single powerful explosion. For the formation of extended low-frequency wave disturbances, the frequencies should be chosen in the range $\omega \sim$ 0.25 – 0.5. The QSW contains a constant component of plasma

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A.G. Berezutsky, V.N. Tishchenko, Yu.P. Zakharov, I.B. Miroshnichenko, I.F. Shaikhislamov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: a.berezuckiy@yandex.ru

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and magnetic field perturbations, as well as a variable component having the frequency equal to the repetition rate of bunches.

For the formation of high-intensity ATWs, the main criterion is supplemented with the following requirements:

1. The ratio α of the Larmor radius of the source ion to the ion-plasma length should be such that $\alpha \geqslant M_a m_2 z_1/(m_1 z_2) \geqslant 5$, where M_a is the ratio of the initial plasma expansion velocity to the ATW velocity. The ATW amplitude increases with increasing α. Here m_1, z_1, m_2, z_2 are the mass and charge of the background ions and the source, respectively.

2. The ratio of the Larmor radius of the ions to the dynamic radius of an individual bunch is $R_L = r_L/R_d = 0.3-2$, where the ATW parameters weakly depend on R_L.

3. The ratio of the thermal pressure of the background plasma to the external magnetic field pressure is $\beta < 1$.

4. The ion-plasma length of the background plasma is $L_{pi} = l_{pi}/R_d < 0.3$, where $l_{pi} = c/\omega_{pi}$; c is the velocity of light; and ω_{pi} is the ion plasma frequency.

The following parameters were used in the calculations: $\omega = 0.4$, $L_{pi} = 0.1$, $M_a = 1$, $\alpha \sim 103$, $m_2 = 207$, $z_2 = 2$, $m_1 = 1$, and $z_1 = 1$.

3. Results

The effect of the background on the ATW azimuthal momentum density P_φ and the SMSW longitudinal momentum density P_z, produced by a sequence of 50 plasma bunches at a fixed point in space is illustrated in Fig. 1. The maximum values of P_z and P_φ, achieved at a distance R from the axis of symmetry of the waves, equal to zero and 0.15, are shown. ATWs and SMSWs have cylindrical symmetry and propagate in a magnetic flux tube with velocities depending on the ratio β of the background plasma pressure to the magnetic field pressure. The SMSW and ATW velocities are related by the formula $V_m/C_a = 1/\sqrt{1 + 2/(\gamma_0\beta)}$, where $\gamma_0 = 1.6$ is the adiabatic index of the background plasma. The ATW carries the angular momentum of the rotating background plasma, the longitudinal current, and the azimuthal magnetic and radial electric fields. The localisation of ATWs on the scale of $\sim R_d/2$ is achieved as a result of the balance of forces acting on ions, i.e., the centrifugal force and the force of the radial electric field. The SMSW carries a flow of compressed background plasma, electric and magnetic field perturbations. The azimuthal currents displace the magnetic field from the SMSW. As a result, the sum of the magnetic field pressure and the pressure of plasma compressed in the SMSW is equal to the total background pressure, which causes the localisation of the SMSW in the magnetic field tube.

In the region $\beta > 1$, the velocities of ATWs and SMSWs are close to each other, the waves are overlapped in space (Fig. 1b) and form a single flow of rotating plasma, which, as seen from Fig. 2, transfers mainly the azimuthal momentum I_φ. In strong magnetic fields ($\beta \ll 0.1$), as follows from the calculations, the pressure at the leading edge of the SMSW is much higher than the background plasma pressure, which causes the supersonic propagation of the SMSW. Thus, in the range of $\beta = 10^{-2}-10^{-3}$, the calculated value of the SMSW velocity is by 3–5 times smaller than the ATW velocity and is about 10 times higher than the theoretical value of the QSW velocity $V_m = C_a/\sqrt{1 + 2/(\gamma_0\beta)}$, which corresponds to weak magnetosonic waves.

Figure 2 shows the effect of β on the longitudinal (I_z) and azimuthal (I_φ) momenta contained in the volume of the SMSW and ATW. In the region $\beta > 1$, the velocities of the ATW and the SMSW are close to each other. Due to this fact, the bunches form a single flow of rotating plasma that transfers mainly the azimuthal momentum. When $\beta \ll 0.1$, two

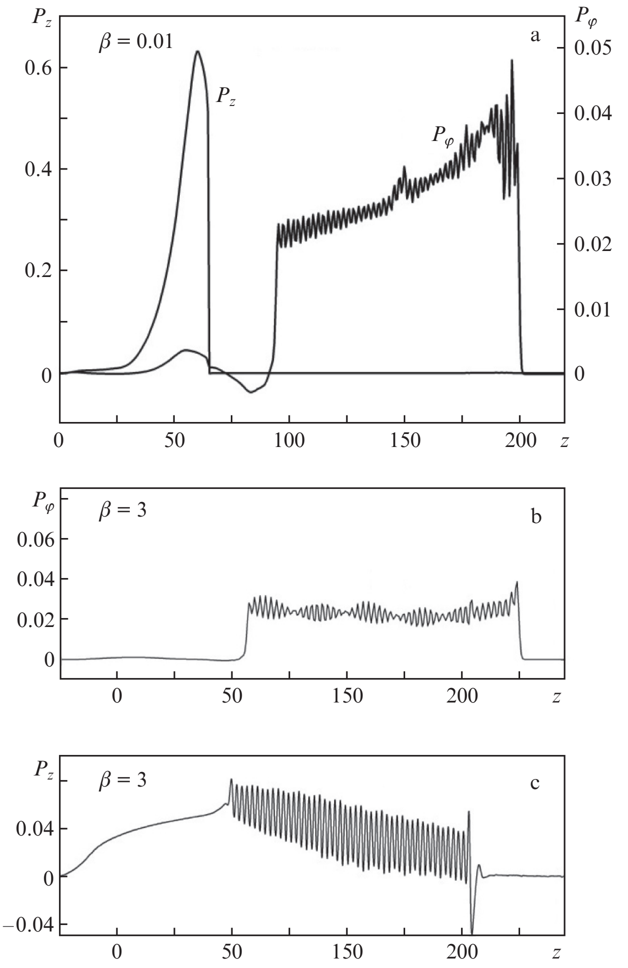

Figure 1. Distribution of the density of the SMSW longitudinal momentum P_z and the ATW azimuthal momentum P_φ along the magnetic flux tube for the moment of time $t = 200$; bunches act at the point $z = 0$ for t varying from 0 to 125.

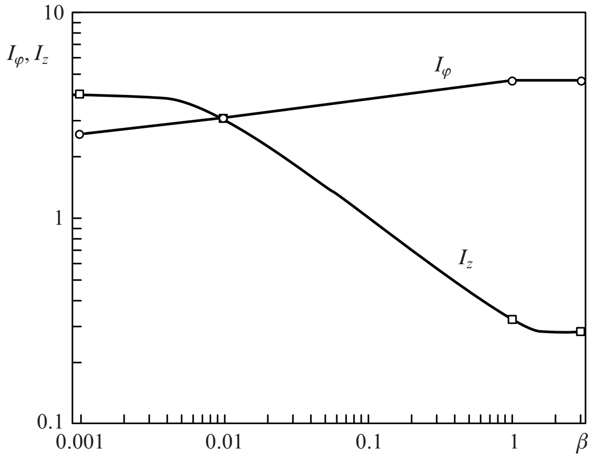

Figure 2. Dependences of the SMSW longitudinal momentum I_z and the ATW azimuthal momentum I_φ on the value of β.

separate plasma flows propagate in the magnetic field tube, namely, the rotating one in the ATW and the compressed one in the SMSW. The bulk integral momenta of the fluxes are approximately equal. As it can be seen from Fig. 3, in a wide range of β from 0.001 to 1, the pulses are localised in the magnetic field tube with a radius of $\sim R_d$.

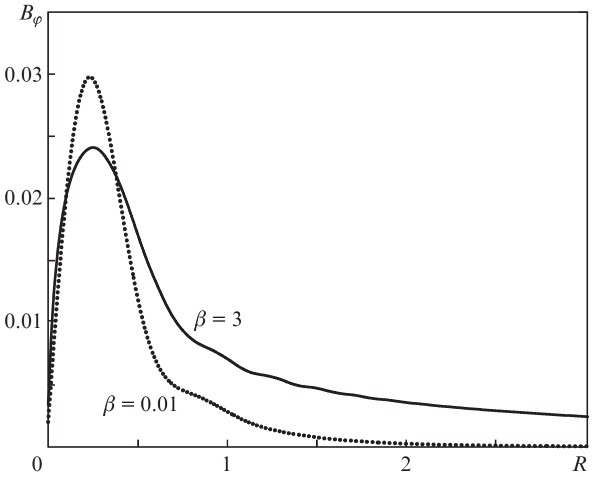

Figure 3. Radial distribution of the azimuthal component of the magnetic field in the ATW for different values of β.

4. Conclusions

We established that quasi-stationary waves generated by a train of laser plasma bunches in a magnetic field tube transfer extended plasma flows carrying longitudinal and azimuthal momenta. In strong magnetic fields ($\beta \ll 0.1$), the flows are separated in space, which is due to the difference in the propagation velocities of the ATW and the SMSW. In weak fields ($\beta \sim 1$), wave disturbances of the ATW and SMSW type propagate together, resulting in a single flow of rotating plasma with predominance of the azimuthal momentum. In a wide range of β values, wave disturbances and plasma flows are localised in a magnetic flux tube on the R_d scale.

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