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GENERATION OF ALFVÉN WAVES IN MAGNETIZED PLASMA BY LASER PLASMA BUNCHES AT MACH NUMBERS MUCH LESS THAN UNITY

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Abstract. In this paper, we examine a torsional Alfvén wave produced by periodic plasma bunches in a magnetized plasma flux tube. A new effect has been revealed: the wave is generated not only during the action of bunches, but also for a long time after the termination, which makes it possible to increase the wavelength by several times. We have determined the conditions under which the wave contains η~40 % of the total bunch energy. The wave radius depends on the energy of one bunch; and the length, on their number. The optimum number of bunches is 15. Simultaneously with the Alfvén wave, a bunch plasma jet (η~35 %) and a slow magnetosonic wave (η~10 %) propagate in the flux tube. Similarity parameters scale the results to laboratory and near-Earth magnetized plasma.

Keywords: plasma bunches, magnetic field, Alfvén wave, numerical simulation.

INTRODUCTION

Laboratory experiments and calculations have revealed an effect of resonant interaction of periodic laser plasma bunches with gases and magnetized plasma [Tishchenko et al., 2004, 2016; Tishchenko, Shaikhislamov, 2014; Berezutsky et al., 2019]. The bunches act at a fixed point of an unlimited space; in a magnetized plasma (hereinafter referred to as the background), waves propagate along a flux tube in opposite directions relative to the zone of their generation. Experiments with two laser facilities have shown the possiblity of scaling by the bunch energy. When resonance conditions (hereinafter referred to as criteria) are met, a train of bunches forms a single low-frequency wave containing n~50 % of the bunch energy. The uniqueness of the method is as follows: in gases, point pulsating plasma generates an infrasound; in a magnetized plasma, bunches create a wave and a jet of large-scale, long-range plasma jet of bunches in a narrow magnetic flux tube; their length linearly depends on the number of bunches, and the radius depends on the energy of one bunch, which gives rise to intense powerful flows. According to the criteria, quasistationary waves of the following types are formed in the background: a torsional Alfvén wave (TAW) transfers the angular momentum of the azimuthally rotating background plasma, magnetic and electric fields; a quasistationary slow magnetosonic wave (SMW), longitudinal momentum and thermal energy of compressed background plasma; whistlers, electromagnetic emission. Waves of each type represent a single wave, and, if the resonance criteria are violated, a packet of weak waves propagates in the flux tube.

The advantage of the method compared to the well-known methods of Alfvén wave generation consists not only in the long length of TAW, but also in the high intensity that is many times higher than the level achieved by traditional methods. TAW intensities can be compared with the data obtained by other authors, using the ratio, presented in the papers, of the wave magnetic field to the magnetic field of the background B_A whose square characterizes the relative energy density in the wave. In methods that use RF radiation, frame antennas, and heating facilities, the relative magnetic field $B_A<10^{-2}$ [Markov et al., 2001; Gigliotti et al., 2009; Aidakina et al., 2015]. A large value of B_A~0.3 is achieved in explosive-type processes in a wave generation zone, for example, at the shock wave front during the interaction of the solar wind with Earth's magnetosphere [Hull et al., 2012], as well as in laboratory experiments during expansion of a laser plasma bunch in which the pressure is much greater than the background pressure [Vshivkov et al., 1989; Gorbachev et al., 1993; Niemann et al., 2013]. Yet at a distance comparable to the wavelength, B_A decreases several times. In TAW, B_A~0.2 does not change when propagating over a long distance. The use of single bunches for generating low-frequency waves is limited by the weak dependence of the wavelength on the bunch energy $\lambda \sim Q^{1/3}$.

TAW and SMW generated by plasma bunches whose initial velocity of expansion V_1 corresponds to the Alfvén Mach number (one of the criteria) have previously been studied: $M_A=V_1/C_A\sim 1$, where C_A is the velocity of Alfvén waves in the background (see, e.g., [Tishchenko et al., 2016; Berezutsky et al., 2019]). This mode is of interest for the simultaneous formation of

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TAW, SMW, whistlers, and jet. Nonetheless, in a highly rarefied medium, for example, in the ionosphere — magnetosphere, where C_A~500÷1000 km/s, the condition M_A~1 is difficult to fulfill for laser bunches or explosive plasma generators with a chemical energy source [Adushkin et al., 1993], where the velocity may be as high as V_1~100 km/s.

In this paper, the generation of TAW by bunches whose velocity corresponds to M_A<<1 has been examined for the first time. We have revealed a new effect: prolonged generation of TAW after termination of action of bunches, which makes it possible to increase the energy and wavelength several times compared to M_A~1.

FORMULATION OF THE PROBLEM

The purpose of the work is to search for conditions under which the maximum efficiency of converting the bunch energy into an extended torsional Alfvén wave generated by a train of periodic bunches in a magnetized quasineutral plasma flux tube is achieved. In the calculations, we vary the criteria that most strongly affect the length and intensity of TAW — the Alfvén Mach number, the repetition rate of bunches, and their number.

The experimental study of TAW is limited to the number of plasma bunches available in existing facilities: two consecutive bunches in KI-1 [Tishchenko et al., 2016; Berezutsky et al., 2019], one in LAPD [Niemann et al., 2013], and one in KROT [Aidakina et al., 2015]. In KI-1 and LAPD, bunches are formed when a target is exposed to powerful ~ 200 J laser pulses; the target with a radius of ~1 cm is located on the axis of a vacuum chamber filled with background plasma; and in KROT, with an electric discharge. Generation of quasistationary waves and their propagation over a long distance can be studied only through calculations on powerful supercomputers. Results of calculations of the effect of the Mach number and the bunch repetition rate on TAW can be verified only with KI-1 (two bunches); justification for the planned experiment is given below.

Wave formation diagram. In an unlimited homogeneous completely ionized background at the point $r=z=0$, point spherical plasma bunches are created one by one; the initial pressure in them is much greater than the total plasma and magnetic field pressure. TAW results from the interaction of expanding bunches with the background. Simultaneously with TAW, a bunch plasma flow and a single slow magnetosonic wave are pumped into the flux tube from the zone of action of bunches. The waves and the flow propagate in the magnetic flux tube symmetrically with respect to z=0. The main properties of the waves are as follows. TAW contains an azimuthal magnetic field B_φ and a rotating plasma background, field-aligned current, and an electric field balancing the centrifugal force of ions rotating around the wave symmetry axis on which the current is maximum and B_φ=0. In SMW, plasma of the background is compressed, the azimuthal current displaces the magnetic field; as a result, the total pressure in the wave is equal to pressure of the background, and the radius of SMW as it propagates over a long distance remaines unchanged. Depending on M_A values and the ratio of plasma pressure to the magnetic field of the background (criterion β), the waves propagate either separately in the sequence: TAW, SMW, jet (β~M_A<1); or in the sequence: jet, TAW, SMW (β<1, M_A>1); or the waves and the jet are combined in space (β~1, M_A~1). There also may be other combinations of the wave and jet propagation sequence. Depending on the repetition rate of the bunches, their energy, and background properties, the train of bunches forms a single TAW, a single SMW, and a plasma jet, or a packet of noninteracting waves and an explosive jet at the frequency of the bunches.

The calculations used the MHD model in cylindrical coordinates with axial symmetry, considering ions of bunches, background ions, and electrons common to them as separate liquids. Equations for pulses contain the Lorentz force, which provides interaction between the liquids. The equations are supplemented with Faraday's law of induction, in which the electric field is found from the electron liquid motion equation, assuming that electrons have a small mass and neglecting the Hall term. Magnetic induction was calculated using a vector potential, which numerically provided zero divergence. The convective part of the equations was solved by the donor cell method. To increase the order of approximation in space, we used the method of staggered grids; in time, the predictor-corrector scheme. The time step was selected automatically during the calculation, in accordance with the Courant—Friedrichs—Lewy condition. The spatial size of the cells was assumed to be much smaller than the initial radius of bunch. The external boundaries of the problem were set open: along the magnetic field, the Z boundary was at a great distance — hundreds of transverse sizes of waves, which eliminated wave reflection; the radius of the computational domain was assumed to be several times smaller, with boundary conditions corresponding to transparency for disturbances generated near the zone of action of the bunches. The large size of the computational domain, the small step in space and time define the great memory for the problem, whereas the computational time of one option in the parallel computation mode was over ~24 hrs. When taking into account the Hall term describing generation of whistlers, the computation time increases manifold. It follows from calculations and experiments that bunches create whistlers in the range of parameters M_A≥1 and at an ion-plasma length greater than L_{pi}~0.5 (see below), which is not considered in this paper. Physical or computation instabilities were not observed in the entire range of initial data assumed close to meeting the criteria. The model was verified by the following methods: comparing with experimental data from KI-1 and LAPD, energy conservation in the computational domain, and varying the grid spacing.

The model equations, initial data, and calculation results we use are presented in dimensionless form. Velocities were normalized to the velocity of Alfvén waves in the background $C_A\left[\text{cm/s}\right]=B_0\left[\Gamma\text{c}\right]/\left(4\pi n_0 m_0\right)^{12}=$

$$=2.18\cdot10^{11}B_0/\left(n_0\left[\text{cm}^{-3}\right]m_0\left[\text{a.m.u.}\right]\right)^{1/2},$$

where m_0, n_0 is the ionic mass and the plasma concentration of the background; B_0 is the magnetic field of the background. Spatial variables were normalized to the dynamic radius $R_\mathrm{d}[\mathrm{cm}] = \left(8\pi Q / B_0^2(1+\beta)\right)^{1/3} \approx$ $\approx 630\left(Q[\mathrm{J}] / B_0^2[\mathrm{G}](1+\beta)\right)^{1/3}$, whose value was close to the diameter of the waves and the zone of displacement of the magnetic field as a result of the expansion of bunch with energy Q in the background. The time was normalized to $t_0=R_\mathrm{d}/C_\mathrm{A}$; the concentration of ions of bunches, background, and electrons, to n_0; magnetic fields, to B_0.

The initial data corresponded to the values of dimensionless criteria, some of which were assumed to be constant, whereas others were varied. The following criteria whose values are close to optimal are fixed in the calculations.

The ratio of plasma pressure of the background to the magnetic field pressure in the calculations is taken to be equal to

$$\beta = 8\pi k(1+Z_0)n_0T_0 / B_0^2 = \\ = 4\cdot 10^{-11}(1+Z_0)n_0\left[\mathrm{cm}^{-3}\right]T_0[\mathrm{eV}] / B_0^2 = 0.001. \quad (1)$$

Here Z_0=1 and T_0 is the plasma charge and temperature in the background.

The normalized ion-plasma length of the background is

$$L_\mathrm{pi} = c / \left(\omega_\mathrm{pi} R_\mathrm{d}\right) = \\ = 3.66\cdot 10^4 Z_0^{-1}\sqrt{m_0 / n_0}\sqrt[3]{B_0^2(1+\beta)/Q} = 0.1. \quad (2)$$

Here ω_pi is the ion-plasma frequency in the background.

We vary the following criteria, they are also initial data.

1. The Alfvén Mach number

$$M_\mathrm{A} = V_1/C_\mathrm{A} \sim 0.1 \div 1. \quad (3)$$

2. The dimensionless repetition rate of bunches

$$\omega \approx f R_\mathrm{d} / C_\mathrm{A} \approx 0.1 \div 0.4, \quad (4)$$

where f [Hz] is the dimensional repetition rate of bunches. At M_A~1, the frequency range ω≈0.3÷0.4 is optimal for generating an extended TAW, concurrently with which SMW and a plasma jet of bunches are formed. In $\omega \ll 0.2$, the train of bunches generates a sequence of noninteracting Alfvén waves. At $\omega \gg 0.3$, the TAW length is short. We show below that at M_A~0.2 the frequencies ω≈0.2÷0.3 are optimal, which is important for creating extended TAW.

3. We varied the number of bunches N=1÷30 to determine the limit value of N and, thereby, the TAW length.

4. Due the change in M_A, the criterion α is also varied, the condition α>5 corresponds to the generation of intense TAW

$$\alpha \approx M_\mathrm{A}\frac{m_1 z_0}{m_0 z_1} > 5. \quad (5)$$

From the condition α>5 and calculations (see below) it follows that at M_A~0.2 TAW is generated by bunches with the ionic mass m_1>100; in the background, the ionic mass is limited to m_0<15. We utilize the following values in the calculations: m_1=207, m_0=2, 4, 14, 28; charges of ions of bunches and the background $Z_0=Z_1$=1.

If the criteria are not fulfilled, the energy is diverted in all directions as a sequence of noninteracting disturbances of the background. A small part of the bunch energy is pumped into the flux tube.

Calculation results

Structure of TAW is shown in Figure 1. A sequence of point bunches with a repetition period $T_\mathrm{S}=1/\omega$ is absorbed at the point $r=z=0$.

At $M_\mathrm{A} \ll 1$, TAW consists of two parts (see Figure 1, *b*): the front part L_1~$C_\mathrm{A}(N–1)T_\mathrm{S}$ is formed during action of bunches; the length depends on the number of bunches N and the period of their repetition T_S; the part L_2~N corresponds to generation after termination of action of the bunches. Here C_A=1 is the dimensionless Alfvén wave velocity. At M_A~1 and more, TAW contains only L_1, and its efficiency is several times lower than that at M_A~0.2 since the bunch energy is spent not only on exciting TAW, but also on generating SMW and a plasma jet of bunches.

Figure 2 shows the effect of M_A on the length of a wave produced by one bunch.

Distribution of the azimuthal magnetic field B_φ is given for t=100. At a low velocity of bunch expansion M_A=0.2, the bunch energy is extracted mainly by the Alfvén wave. A plasma cloud performs several radial pulsations accompanied by generation of five peaks (see Figure 2, *a*) and subsequent smooth attenuation of B_φ.

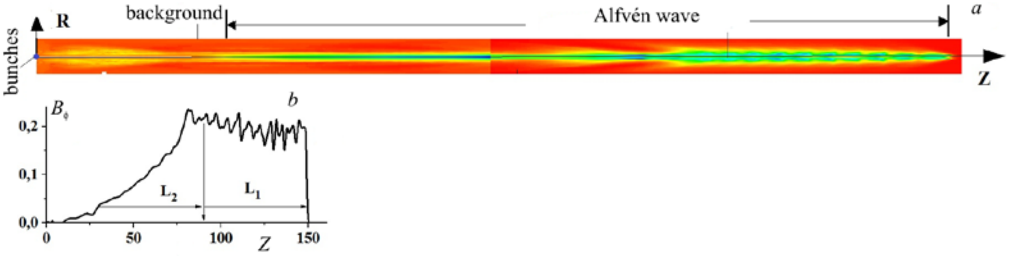

Figure 1. Distribution of a relative magnetic field B_φ in TAW generated by ten bunches with a repetition period T_S=3. The Z-axis is parallel to the magnetic field of the background. The wave is symmetrical with respect to the point Z=0, its shape is cylindrical. Designations are as follows: *a* is $B_\varphi(Z, R)$, t=120, bunches are active during the period $t_\mathrm{b}=(N–1)T_\mathrm{S}$~27; *b* is the distribu-

tion of $B_\varphi(Z)$ in TAW at R~0.15, where B_φ is maximum; T_S=6, t_b=54, t=150.

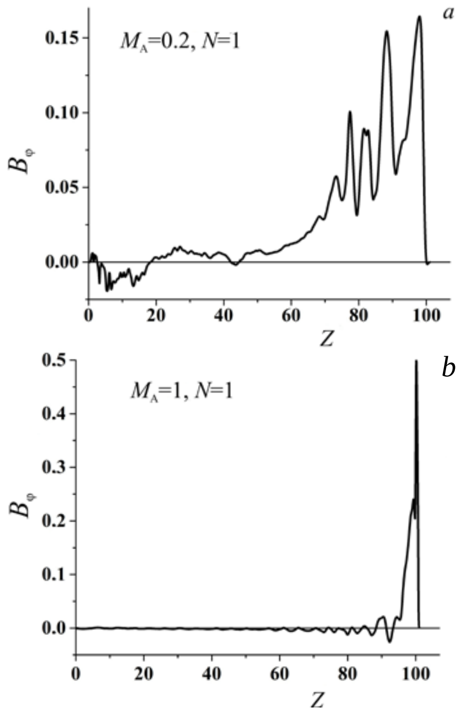

Figure 2. Distribution of the azimuthal magnetic field in a torsional Alfvén wave generated by one bunch at M_A=0.2 (*a*) and M_A=1 (*b*)

The roughly estimated duration τ~2/M_A=10 of periods of radial expansion and subsequent collapse of plasma to the point z=r= 0 is close to the calculated value. At M_A=1, an Alfvén wave is formed at the stage of initial expansion and subsequent collapse of the bunch, during which the average pressure in the cloud decreases to the background level due to the rapid extraction of cloud energy by the jet, TAW, and SMW to the flux tube. As a result, the wave contains a leading peak τ~2 and attenuation that lasts for ~3. Thus, a bunch with a low velocity of plasma expansion can increase the Alfvén wave length several times. As follows from the calculations, the efficiency of converting the bunch energy to TAW is maximum: η~0.4 at M_A≈0.2.

The dependence of TAW length on M_A, as well as the efficiency of generation of TAW, SMW, and plasma jet are plotted in Figure 3. It can be seen that of the greatest interest in the region of M_A~0.2 achievable in low-temperature (~100 eV) plasma bunches is the generation of TAW whose length and efficiency are much greater than those of SMW. The jet also has high efficiency of ~40 %, but its length is short compared to that of TAW.

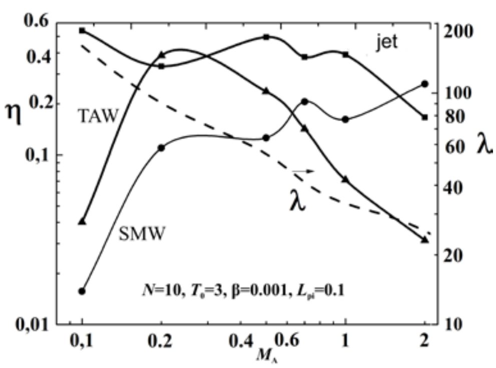

Figure 3. Alfvén Mach number as a function of TAW length λ and efficiency η of TAW, SMW, and jet. Parameters T_S=3, N=10, L_{pi}=0.1, β=0.001, M_1=207, m_0=2, Z_1=Z_0=1

Figure 4 shows the effect of the number of bunches N on distribution of the azimuthal magnetic field $B_\varphi(Z)$ in TAW at a distance R~0.15 from the axis of wave symmetry, where $B_\varphi(Z, R)$ is maximum. The characteristic TAW radius is ~ 0.5.

During action of bunches, the front part of TAW is generated, which is indicated on the plots by the area between the vertical arrow and the leading front of TAW. Figure 4, *a* indicates that at small values of N and T_S the main part of TAW (the area to the left of the vertical arrow) is formed after termination of action of bunches at the stage of radial collapse of the plasma cloud of the bunches. The characteristic length of TAW L~50. The possibility of increasing the length due to the number of bunches is illustrated in Figure 4, *b*. Yet at N>15, B_φ and the efficiency ~B_φ^2 of TAW generation decreases, and the length of the back part of the wave weakly depends on N, starting from N>20. So, at N=30 B_φ is about two times less than that at N=10. Figure 5 shows the dependence of the efficiency of wave and jet generation on the number of bunches. As an optimal value, we can take N~15 when the maximum efficiency is achieved and L~120.

The effect of the bunch repetition period on TAW length and wave generation efficiency is shown in Figure 6. Here M_A=0.2, N=10, α=5.18, L_{pi}=0.1, β=0.001, M_1=207, Z_1=2, m_0=4, Z_0=1.

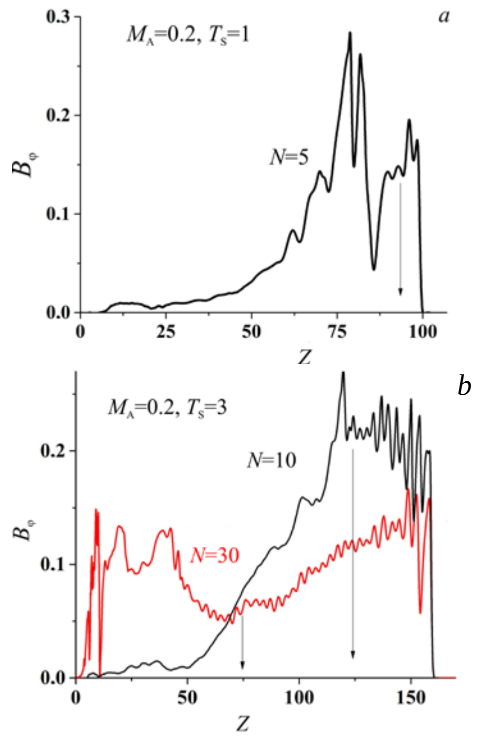

Figure 4. Distribution of azimuthal magnetic field B_φ in TAW: N=5, T_S=1 (*a*); N=10 and N=30, T_S=3, M_A=0.2, α=5.18, L_{pi}=0.1, β=0.001, M_1=207, Z_1=2, m_0=4, Z_0=1 (*b*)

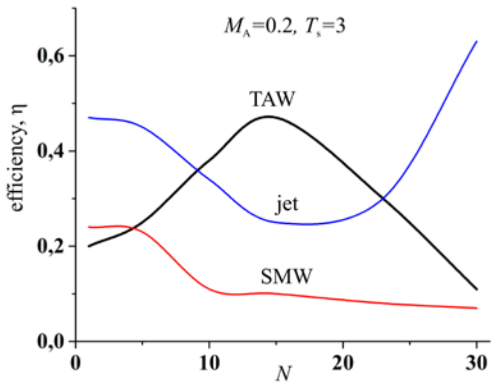

Figure 5. Wave and jet generation efficiency as a function of the number of bunches. The repetition period T_S=3. M_A=0.2, α=5.18, L_{pi}=0.1, β=0.001, M_1=207, Z_1=2, m_0=4, Z_0=1

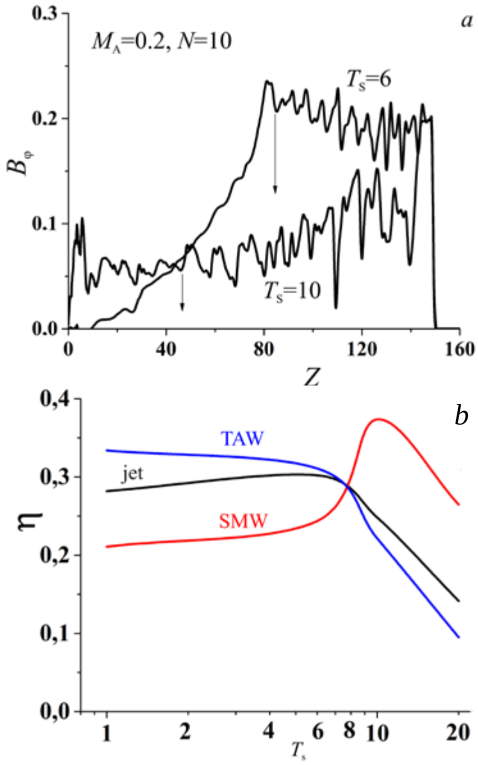

Figure 6. Magnetic field of TAW generated by ten bunches at T_S=6 and T_S=10 (*a*); wave and jet generation efficiency as a function of the bunch repetition period (*b*)

The optimal value for TAW generation is T_S~5÷6 when the efficiency is close to the maximum, and the wavelength is ~120, which is about twice the length of TAW generated at M_A~1. The values of T_S~10÷15 and M_A~0.2 are of interest for the formation of SMW containing ~35 % of the bunch energy.

The wave efficiency, length, and structure depend not only on M_A, T_S, and *N*, but also on other criteria such as β and α. The parameter β has a weak effect in a wide range at β<1; and α, at α>5. Thus, Figure 7 shows an Alfvén wave generated at β=0.1. Parameters are the same as in Figure 6, *a* (T_S=6), where β=0.001. When β>2, $B_φ$ and the efficiency of generation of Alfvén and slow magnetosonic waves decrease several times. The effect of the criterion α on $B_φ$ is demonstrated in Figure 8. In the

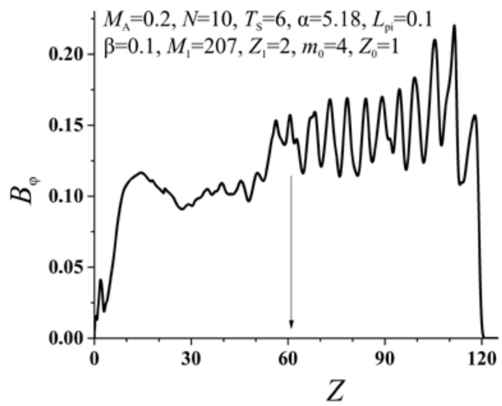

Figure 7. Magnetic field of TAW generated at β=0.1. Parameters are given in the Figure

background with M_A=0.2 and heavy ions, the parameter α<1, $B_φ$ decreases approximately ten times compared to $B_φ$ shown in Figure 8, *b*, where M_A=1 and α=7.4.

Criteria of quasistationary wave generation

We can distinguish two main approaches to the use of the criteria.

1. Energy and expansion velocity of plasma of bunches are given, it is necessary to determine the range of values of plasma concentration, ionic mass, and magnetic field of the background at which bunches generate intense quasistationary waves and a bunch plasma jet.
2. The inverse problem is to determine parameters of bunches depending on the parameters of the background.

Consider the former case in relation to setting up an experiment with KI-1 to test its capability of generating Alfvén waves created by laser plasma bunches with a

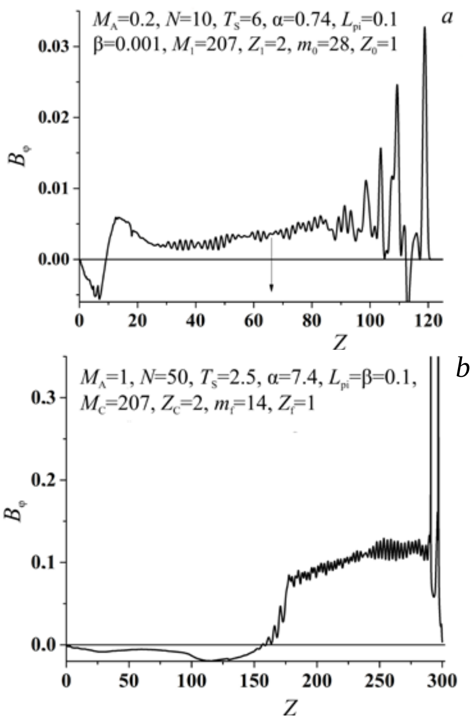

Figure 8. Magnetic field of TAW generated when the criterion α is violated M_A=0.2 (*a*); magnetic field of TAW generated when the criterion α is fulfilled. M_A=1 (*b*)

Mach number M_A=0.2÷0.3. The waves are generated by successive bombardment of a 2.5 cm plate, located on the axis of a cylindrical vacuum chamber (pressure of ~10^{-6} Torr, 5 m length, radius of the chamber R_K=60 cm), by two microsecond pulses of CO_2 lasers with an energy of ~200 J, which sequentially produced two spherical plasma bunches with an energy of ~25 J each. The shape of the bunches is close to spherical, the initial pressure is much greater than the total plasma pressure and the magnetic field of the background. The following values of the background parameters can be achieved: magnetic field up to B_0<500 G, plasma concentration n_0~10^{12}÷$3\cdot10^3$ cm^{-3}, ionic mass of bunches m_0=1÷40 (atomic hydrogen and argon), ion charge of the background Z_0=1.

Using the criteria, we estimate the ionic mass of bunches, as well as the magnetic field and concentration of the background, at which bunches with M_A~0.2÷0.3 effectively generate an Alfvén wave in the experiment. The following parameters are specified for the bunches: energy Q~25 J, velocity V_1=100 km/s, charge Z_1=2; for the background: ion charge Z_0=1. Two bunches create a single Alfvén wave (TAW) if criteria (2), (3–5) are fulfilled at a time.

The minimum value of the magnetic field is limited by the condition of weak influence of chamber walls on wave formation and propagation, which is achieved if the wave radius is equal to ~(0.5÷1)R_d, less than the radius of the chamber R_c=60 cm. Assuming R_d=50 cm and β=0.01÷0.1, the minimum value of the magnetic field of the background B_0 is found from the dynamic radius expression

$$B_0 = \frac{1.58\cdot10^4}{R_K^{3/2}}\sqrt{\frac{Q}{1+\beta}} \approx 226\text{ G.} \tag{6}$$

Expression (5) for the criterion α yields a minimum value of the ionic mass of bunches at which they generate an Alfvén wave:

$$m_1 = \frac{\alpha z_1 m_0}{M_A z_0} = \frac{\alpha\cdot2\cdot1}{M_A\cdot1} = \frac{2\alpha}{M_A} > 50, \tag{7}$$

where α>5 is the wave generation condition. The maximum ionic mass of the background m_0~4 (helium) is restricted to the limit ionic mass of bunches m_1=207 (lead), which can be used in the experiment. Further, we take m_0=1 in the estimates. From Formula (2) for L_{pi} follows an expression for the concentration of the background

$$n_0 = \frac{1.34\cdot10^9 m_0 B_0^{4/3}(1+\beta)^{2/3}}{Z_0^2 L_{pi}^2 Q^{2/3}} = \frac{1.34\cdot10^9\cdot1\cdot B_0^{4/3}\cdot1}{1\cdot L_{pi}^2\cdot8.64}. \tag{8}$$

Formula (3) for M_A gives another expression for the concentration of the background

$$n_0 = 4.75\cdot10^{22}/m_0\left[M_A B_0/V_0\right]^2. \tag{9}$$

The range of n_0 and B_0 values, where wave generation should be expected, is displayed in Figure 9 as a colored area. The group of dashed lines corresponds to optimal values of the ion-plasma length L_{pi}; solid lines

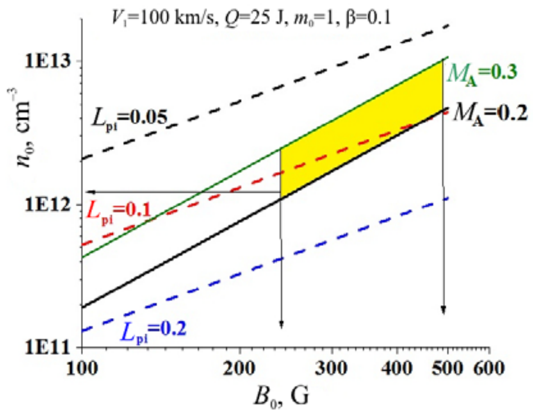

Figure 9. Concentration of the background as a function of magnetic field. The area where TAW generation is expected in the experiment with KI-1 is highlighted in yellow

are calculated for M_A=0.2 and 0.3, between which the efficiency of Alfvén wave generation is maximum. The vertical left arrow bounds a minimum value of the magnetic field B_0~220 G, at which chamber walls do not affect the wave. The right arrow bounds the operating range of B_0 in the facility. The horizontal arrow indicates the range of values n_0>10^{12}÷$3\cdot10^{12}$ cm^{-3}, which may vary in experiments.

Expression (4) allows us to estimate the laser pulse repetition period at which two bunches generate one wave

$$T_S \approx 1/f \approx M_A R_d/\omega V_1 \approx 5\div10\text{ ms.}$$

Here we take M_A≈ω≈0.2÷0.3, R_d~50 cm, V_1~10^7 cm/s. Alfvén waves are expected to be generated at the following parameters: background — plasma concentration n_0~10^{12}÷10^{13} cm^{-3}, magnetic field B_0~200÷500 G, ionic mass m_0=1; bunches — energy Q~20÷25 J.

CONCLUSIONS

Thus, a limiting length and efficiency of ~40 % of TAW generation can be achieved with a train of ~15 laser plasma bunches with a Mach number M_A~0.2÷0.3, and an ionic mass of ~207 (Pb^+); ionic mass of the background is less than 15. The azimuthal magnetic field in TAW may be as great as ~0.15÷0.2 of the magnetic field in the background. The bunch repetition period and the TAW length are ~2÷3 times longer than those at M_A~1. The long length of TAW is achieved due to prolonged generation after termination of action of bunches. In the background with ions m_0>15, quasistationary Alfvén and slow magnetosonic waves are generated by bunches with M_A~1. In the entire range of M_A~0.1÷2, a bunch plasma jet is formed, localized, like waves, in a magnetic flux tube whose radius depends on the energy of one bunch. The calculation results can be verified in the KI-1 facility.

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