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Generation of laser plasma bunches with a high efficiency of energy concentration for laboratory simulation of collisionless shock waves in magnetised cosmic plasma

Yu.P. Zakharov, A.G. Ponomarenko, V.N. Tishchenko, V.M. Antonov, A.V. Melekhov, V.G. Posukh, P.A. Prokopov, V.A. Terekhin

Abstract. **We present the results of first experiments on the formation of collisionless shock waves (CSWs) in background plasma by injecting laser plasma bunches transverse to the magnetic field (as a piston) with a maximum energy up to 100 J per unit of solid angle and with a high enough degree of ion magnetisation. With this aim in view, on a unique KI-1 facility at the Institute of Laser Physics, Siberian Branch of the Russian Academy of Sciences (ILP), a plastic (polyethylene) target irradiated by a CO_2 laser in the most energy-efficient regime (near the plasma formation threshold) and a highly ionised hydrogen plasma with a high concentration in a large volume (not less than 1 m^3) have been employed. As a result of model experiments performed on the basis of a model of collisionless interaction of plasma flows, developed at the VNIIEF and being adequate to the problem under consideration, not only an intensive, background-induced, deceleration of a super-Alfven laser plasma flow, but also the formation in that flow of a strong perturbation having the properties of a subcritical CSW and propagating transverse to the magnetic field, have been first registered in the laboratory conditions.**

Keywords: *highly efficient generation of laser plasma, background plasma in a magnetic field, collisionless interaction model of super-Alfven flows, Larmor radius of ions, diamagnetic cavity, collisionless shock waves, laboratory astrophysics.*

1. Introduction

From the very beginning of the development of a new direction of fundamental research named 'laboratory astrophysics' in the mid-1990s [1, 2] (or even from the end of the 1980s [3]), which arose at the interface of the programmes related to super-powerful lasers, laser fusion and plasma astrophysics [3], and up to date [4], one of the main objectives of this research consists in laboratory simulation of cosmic collisionless shock waves (CSWs) with different Alfven–Mach numbers M_A up to $M_A \geqslant (m_i/m_e)^{1/2}$ (m_i and m_e are the masses of ions and electrons). To this end, various experiments with laser plasma (LP) are being conducted in the framework of HEDP (high energy density physics) programmes, including those on high-power laser facilities, both with the magnetic field B_0 (e.g., VULCAN [5]) and without it (Omega [6] and other facilities). Typically, the initial velocity V_0 of the LP front amounts to about 1000 km s^{-1}. Currently, many new processes of collisionless interaction of plasma flows and formation of corresponding CSWs have been revealed, which is primarily stipulated by the Weibel instability [6] (without an external field B_0) being fundamentally important for the astrophysical CSWs and acceleration of particles on them, for example, after supernova explosions. However, most cosmophysical explosive phenomena (such as ejections from the Sun or active experiments in the ionosphere) are characterised by the moderate initial numbers $M_{A0} \leqslant 10$ (in terms of V_0) and a significant role that the magnetic field B_0 may supposedly play in a variety of tasks related to the CSWs.

Despite a considerable interest in the laboratory simulation of such magnetised CSWs, from the beginning of the study and application of LP in the experiments [7] until now, this CSW type has never been obtained in the laboratory conditions. Currently, focused studies on this subject are only conducted on the KI-1 laser facility at the ILP [8, 9] and on the largest LAPD plasma facility in the United States, having a length of ~20 m [10–13]. In Russia, these experiments are performed at the ILP in the framework of cooperation with the VNIIEF where a model of collisionless interaction of a spherical plasma cloud with background plasma (BP) was first developed [14], and also at the Los Alamos laboratory (the US) where appropriate calculations for a hybrid model [15, 16] and additional experiments on the Trident CO_2 laser having a pulse energy of several kilojoules are performed [17].

In this paper, based on the experiments on generating the LP bunches and studying the regimes of their intensive interaction with a magnetised BP, a model CSW on a full characteristic scale of ~1 m is for the first time obtained.

2. Setting up the experiments on modelling the magnetised CSW on the KI-1 laser facility at the ILP. Requirements of similarity criteria

Setting up the experiments of the 'CSW' series [12, 13] on the KL-1 facility is based on the analysis of the so-called magnetic laminar mechanism (MLM) of interaction of the LP cloud with BP according to a model developed at the VNIIEF [14]. This model is based on evaluation in the form of a simple relation $E^*_{max} \approx \delta E_0$ (for $\delta < 1$) of the efficiency criterion δ of transfer of the cloud energy (E_0) to the background (E^*) by means of the MLM. Here, the parameter $\delta = R^{*2}/(R_L R^*_L)$ is determined by the Larmor radii R_L and R^*_L of the LP and BP ions, respectively, which are calculated by the velocity V_0,

Yu.P. Zakharov, A.G. Ponomarenko, V.N. Tishchenko, V.M. Antonov, A.V. Melekhov, V.G. Posukh, P.A. Prokopov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia, e-mail: ki1z@mail.ru;
V.A. Terekhin Russian Federal Nuclear Center 'All-Russian Research Institute of Experimental Physics (VNIIEF)', prosp. Mira 37, 607190 Sarov, Nizhnii Novgorod region, Russia

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while the scale $R^* = [3N_0/(4\pi n^*)]^{1/3}$ defines the maximum radius of the diamagnetic cavity of a spherical cloud of LP in BP with a concentration n^* (at $M_{A0} > 1$, i.e. in the case of possible CSW formation). The BP ions are accelerated along the vortex electric field $E_\varphi \propto V_0B_0/c$ arising at the expense of the magnetic field displacement on the cavity boundary, while the LP ions are slowed down due to their Larmor rotation in the direction opposite to $\boldsymbol{E}_\varphi$. As a result, a strong interaction arises between the LP and BP ions, being strong enough for CSW generation. The main necessary condition to ensure this effect (obtained in the MLM model and hybrid calculations performed at the VNIIEF [14]) is that the parameter δ should exceed unity, which can be only achieved at the expense of a sufficiently high energy $E_0 = 0.3(N_0m_i/Z)V_0^2$ of the spherical LP cloud, more precisely, at the expense of a large total number N_0 of the cloud's electrons, since it is desirable to use rather small V_0. Here Z is the charge of LP ions, the velocity V_0 of which cannot be less than $\sim$100 km s^{-1} due to the LP generation conditions [8]); therefore, the Larmor radii of ions also cannot be less than certain values.

The analysis [8, 9] has shown that, in the case of experiments conducted within a 'conventional' laboratory range of parameters being typical for large plasma facilities (with magnetic fields of kilogauss order and BP concentration $n^* \approx 3\times10^{13}$ cm^{-3} in a volume of no less than 1 m^3), in order to achieve $\delta \geqslant 1$ with $M_{A0} \geqslant 10$ we have to generate a spherical LP cloud with the energy of $E_0 \geqslant 1$ kJ. We should note that a semi-qualitative physical model of MLM interaction was considered in the United States as early as in 1960s [18, 19]; however, this model did not gain further development, and so it is at the VNIIEF that the MLM model has been completed [14].

The first experimental confirmations of the MLM efficiency have been obtained on the KI-1 facility [20] for small values $\delta \approx 0.3$ and $R^* \approx 20$ cm at the energy of $E_0 \approx 45$ J of a quasi-spherical LP cloud. As a result, a solitary magnetoacoustic wave has been formed across the field $\boldsymbol{B}_0$ in the proton BP with $n^* \approx (2-3)\times10^{13}$ cm^{-3} at the distances of 30–40 cm along the radius from the chamber centre where the target was placed. The LP generation was conducted by means of bilateral irradiation of a caprolon fibre-target with a diameter of 0.27 mm by means of the beams of pulsed microsecond radiation from the 'LUI 2m' CO_2-laser with the main peak duration of $\tau \sim 100$ ns, peak energy of 1 kJ, and the beam diameter of 4 mm in the target area [21]. It was assumed that the axially symmetric LP clouds thus generated could efficiently exclude the magnetic field B_0 to ensure the MLM implementation without the parasitic polarisation effects and a drift of the asymmetrically expanding LP bunches transverse to the field $\boldsymbol{B}_0$. This was implemented (originally in a vacuum magnetic field [22]), and the experimental data on the MLM, being in good agreement with the results of calculations, have been first obtained [23].

3. Possibilities and features of high-efficient LP generation with a large effective number of particles ($\sim 10^{19}$) on a planar plastic target for CSW formation

For further development of the programme of forming a magnetised CSW, the experience of recent experiments on modelling the super-compression of the Earth magnetosphere [24–26] has been used, in which the LP bunches expanding from the planar or convex plastic targets with a large focal spot diameter of radiation D (10–30 mm) near the plasma formation threshold, where the conversion efficiency of the laser pulse energy Q into the plasma kinetic energy E_k can reach its maximum [8] (up to $\sim$50% [27]), have been successfully applied. A factor of significant expansion of the LP bunches is fundamentally important for these targets – this enables the bunches, in spite of spherically asymmetric nature of their expansion, interact effectively with homogeneous [24] and dipole [25] magnetic fields in vacuum, similarly to the case of a spherically symmetric LP cloud. This LP expansion regime provides a diamagnetic current needed to displace the field B_0, while the criterion of efficiency is the total values of the number of electrons N_{0e} in LP and the efficient energy E_{0e} into full solid angle. Namely these criteria characterise the advantage, which is gained by directional expansion of the bunches from planar targets, since the available kinetic energy E_k of a bunch and the total number of electrons N_e can be concentrated along these directions by means of, for example, 'stretching' of the required size of R^* along the normal to the target in order to increase the parameter δ and thus to satisfy the conditions of CSW formation ($\delta \geqslant 1$). In the case of the KI-1 facility, this allowed us to implement the experiment on CSW generation with location of a planar target at the edge of the BP column having a diameter of no less than 80 cm, i.e. almost near the KI-1 chamber wall (the camera has a diameter of 1.2 m and a length of 5 m). A BP source of the θ-pinch type was attached to one of the camera end faces, with a corresponding realignment of the system of two laser beams on the target [9].

Recent results [28, 29] obtained in generation of such LP bunches (with a solid angle of expansion $\Delta\Omega \approx 1$ srad, Fig. 1) from a quasi-planar polyethylene target [13, 30] with the focusing spot diameter $D \approx 3-4$ cm demonstrate that it is possible to provide an effective energy $E_{0e} \approx E_k(4\pi/\Delta\Omega)$ up to $\sim$1000 J and an effective number of electrons $N_{0e} \geqslant 10^{19}$, which are required for the CSW. This method offers a real opportunity to attain $\delta \geqslant 1$ at the expense of a sufficiently large (no less than 45 cm) size of R^* calculated according to the formula for R^*, with N_0 replaced by N_{0e} at $n^* \approx 3\times10^{13}$ cm^{-3} in the preferred direction normally to the target (Fig. 2). In the

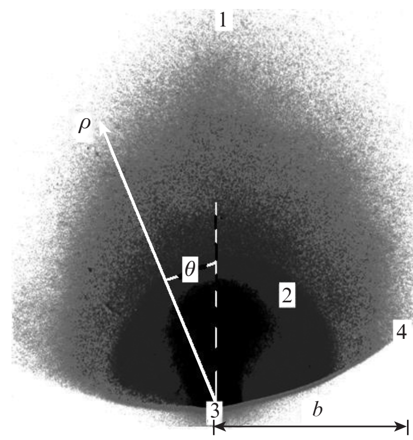

Figure 1. Shape of the LP bunch recorded by the image converter tube (ICT) on 13.03.12 at $t^* = 2.1$ μs (frame 77, exposure time 100 ns): point 1 is the glowing leading edge of the fast LP fraction at a distance of $a = \rho_0 = 41$ cm from the target located at point 3; point 2 is the second LP bunch; point 4 is the edge of the ICT screen at a distance of $b = 20$ cm horizontally from the vertical x axis.

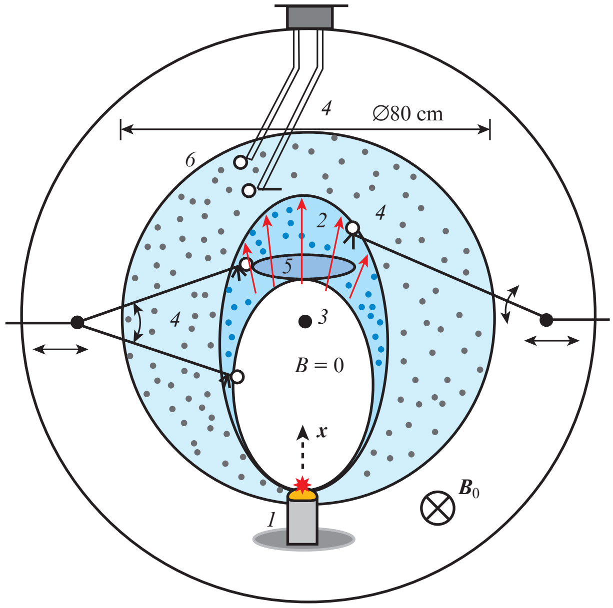

Figure 2. Schematic of the 'CSW' experiment on the KI-1 facility in the cross section of its camera (diameter of 120 cm) with a magnetic field $\boldsymbol{B}_0$:
(*1*) target on the insulator; (*2*) LP front; (*3*) central z axis of the camera, coinciding with the θ-pinch axis; (*4*) elements of different probe diagnostics; (*5*) region of LP and BP interaction; (*6*) boundary of the BP column with a diameter of 80 cm; $\boldsymbol{x}$ is the normal to the target in the diamagnetic LP cavity area ($B = 0$).

course of the research, the important general characteristics of such LP bunches have also been established [29].

Until now, different approaches have been used to interpret the data on the formation of angular distributions of the expansion of LP bunches from a planar target at the moderate flows $q \leqslant 10^{11}$ W cm^{-2} (Fig. 1); however, the Anisimov model [31, 32] is, apparently, the most well-grounded among them. This model of 3D self-similar expansion of a semi-ellipsoidal cloud of vapours has been designed for the tasks of ablation and deposition of films, but, according to numerous experiments with LP [33–35], it describes well the parameters and geometry of the inertial stage of LP expansion after completion of its formation by a laser pulse. The LP characteristics on the expansion stage of interest are mainly determined by the initial shape of the LP bunch at the time moment $t_0 \approx \tau$, when the bunch expanding at a velocity greater than the ion sound velocity C_s reaches the size of $x_0 \approx C_s\tau$ along the x axis normally to the target (Figs 1, 2). Herewith, the bunch has the characteristic radius $z_0 \approx D/2$ along the axes z and y. Then, knowing the value of $\alpha = x_0/z_0$, we can calculate the asymptotic coefficient $\beta \equiv K_z = x_\infty/z_\infty \geqslant 1$, which determines the ratio of the semi-axes a and b of the expanding LP ellipsoid on the inertial stage, and can be approximated by the relation $\beta \approx 1.1/\alpha^{1/2}$ [35]. Proceeding from the values of τ, initial temperature of electrons $T_{e0} \sim 70$ eV [30] and $D/2 \approx 1.3$ cm, we find $\alpha \approx 0.44$, which corresponds to the value of $\beta \approx 1.7$ that is close enough to the experimentally recorded ratio of semi-axes $a/b \approx 2.05$ (Figs 1, 3).

The glow boundary shape of the LP bunch (Fig. 1) gives us the experimental dependence $\rho(\theta)$ (Fig. 3), which corresponds to the calculated ellipsoidal dependence for $\beta^2 \approx 4.2$ (the estimation is performed according to Fig. 1) and the major semi-axis $a = \rho_0$ at $\theta = 0$:

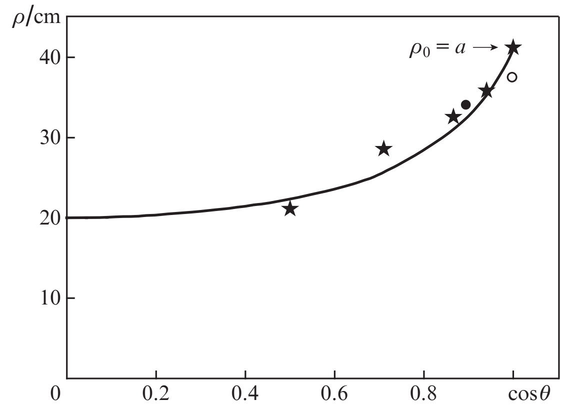

Figure 3. Position of the LP boundary calculated according to (1) (solid curve) and experimental data on the position of the front area of the LP maximum velocity (★), taken from Fig. 1, and also the values ρ recalculated to the time moment t^*, proceeding from the time moments TA1 (○) and TA2 (●) (see Fig. 4 below).

$$\rho_0 \sqrt{1/(\beta^2 \sin^2\theta + \cos^2\theta)} \equiv \rho_0 F(\theta). \qquad (1)$$

Formula (1) can be used to calculate the LP expansion energy per unit of solid angle ($\mathrm{d}E/\mathrm{d}\Omega$). From here, in the case under consideration it is possible to obtain the kinetic energy of the LP bunch consisting of protons and C^{3+}, C^{4+} ions and formed by the first laser radiation peak: the energy E_{k1} constitutes 40%–45% of the total energy $Q_1 \approx 150$–200 J of that peak [28, 29].

Calculation of the kinetic energy and other LP parameters has been carried out on the basis of the data taken from Fig. 4 and obtained by means of thin Langmuir probes [36–39] with allowance for the average ratio $\langle m_i/Z \rangle \approx 2.5$ amu, measured by a mass analyser for the caprolon and polyethylene targets [8, 36], and also using a new method of processing the current–voltage characteristics (CVC) of the thin probes with a radius of 10 μm (of the order of LP Debye radius) for rapid assessment of $\langle m_i/Z \rangle$ ([40], see also formula (A2)). As a result, the data for a probe located at a distance $R_{p1} = 40$ cm from the target (Fig. 4) give the effective energy $E_{0e}^{(1)}$ greater than

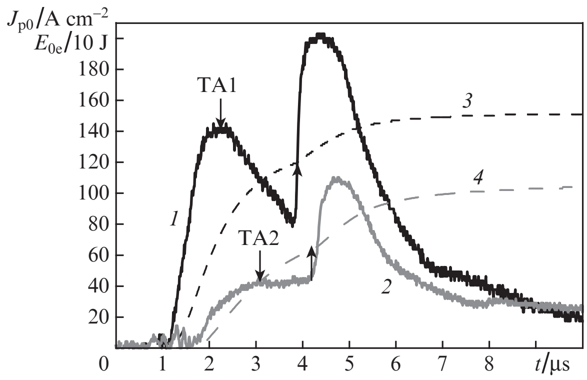

Figure 4. Dynamics of the probe ion current density $J_{p0}(t)$ at $R_{p1} = 40$ cm [$\theta = 0$; (*1*)] and $R_{p2} = 50$ cm [$\theta = 28°$; (*2*)], and also the effective energies $E_{0e}^{(1)}$ (*3*) and $E_{0e}^{(2)}$ (*4*) of LP bunches, calculated with respect to J_{p0}. The first of these bunches acquires its full energy at the time moments marked by the arrows pointing upwards. The arrows pointing down correspond to the time moments TA1 and TA2 when the maximum flows arrive to the probe.

1000 J and effective number of electrons $N_{0e}^{(1)}$ up to 2×10^{19}. For these parameters, the diamagnetic cavity in LP can reach the assumed scale of $R^* \approx 50$ cm, which is certainly sufficient for intensive interaction by the MLM at $\delta \geqslant 1$.

4. Main results on plasma interaction and CSW formation, and their discussion

The large-size diamagnetic cavity ($R^* \approx 50$ cm along and across the normal to the target) needed for CSW formation was obtained (Figs 5 and 6) in the expansion of LP bunches with the Alfven–Mach numbers $M_{A0} = V_0/C_A \approx 6$ (where $C_A = B_0/(4\pi n^* m_i^*)^{1/2}$) in the course of 'CSW' experiments (the concentration of hydrogen BP $n^* \approx (3-4)\times10^{13}$ cm^{-3} at the electron temperature of $T_e^* \approx 10$ eV) [12, 13]. Figure 7 presents the results of these experiments for different conditions, in particular, for the case of 'free' (i.e. in the absence of the magnetic field B_0) LP expansion into vacuum [curve (*1*)] and into the non-magnetised BP [curve (*2*)]. Dynamics of the current

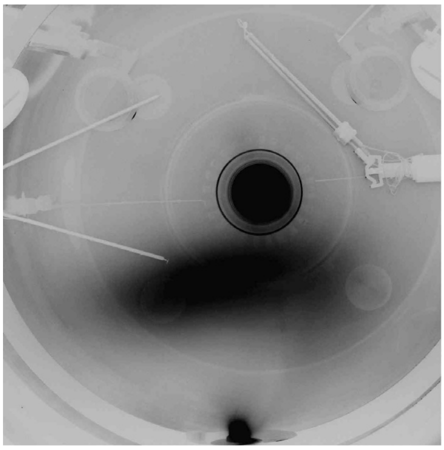

Figure 5. Time-integrated photograph of the interaction region of the laser plasma and magnetised background plasma. Below one can see the target glow, at the centre – a glow of the output θ-pinch, and below it – a glow of the region located near the edge of the diamagnetic cavity. At the top of the left and right, the lenses and turning mirrors designated for the target irradiation are seen.

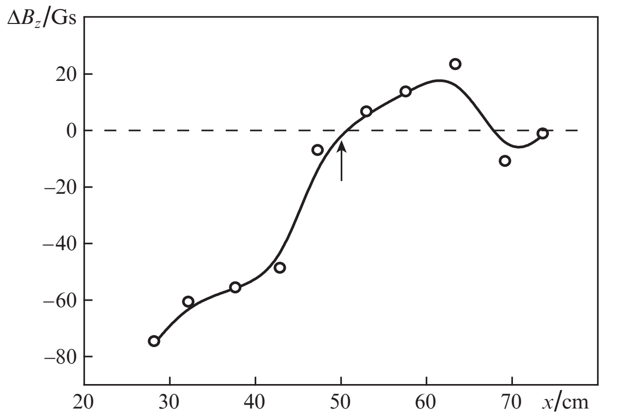

Figure 6. Radial structure of the diamagnetic cavity at the time moment $t = 6$ µs, which corresponds to the maximum cavity size, i.e. the region with $\Delta B_z < 0$. The boundary near the calculated value $R^* \approx 50$ cm is shown by the arrow. The initial field constitutes $B^* \approx 80$ Gs in the hydrogen BP at a concentration $n^* \approx 3\times10^{13}$ cm^{-3}.

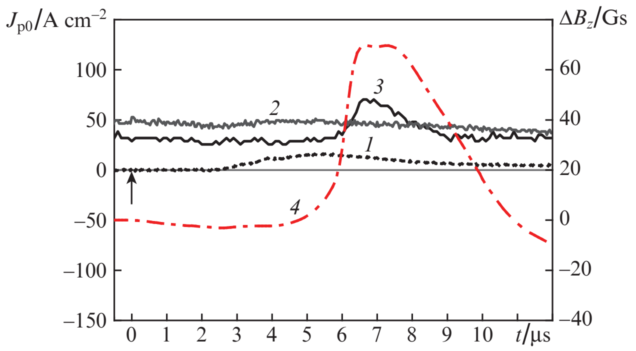

Figure 7. Dynamics of the ion current density J_{p0} at a distance $x = 75$ cm from the target: only LP in vacuum without magnetic field (*1*), LP in BP without magnetic field (*2*), LP and BP with magnetic field (*3*). Curve (*4*) is the magnetic field perturbation ΔB_z in the latter case. The arrow marks the time moment of triggering the laser.

$J_{p0}(t)$ being collected by a thin cylindrical electrode of the Langmuir probe (see Appendix) shows that the behaviour of the total plasma concentration $n(t)$ (i.e. of the sum of LP and BP concentrations) is close to that obtained in the calculations [20, 41]. In contrast to the rather smooth curves (*1*) and (*2*), considerable jumps of the concentration [curve (*3*)] and magnetic field [curve (*4*)], with a steep leading edge ($\Delta t \leqslant 0.5$ µs) and noticeable deceleration of LP in propagation along the x axis, are observed in the magnetised BP at a distance $x = 75$ cm (Fig. 8). We should note that the external magnetic field $B_0 = 110$ Gs is displaced by a diamagnetic background and reduced down to $B^* \approx 80$ Gs.

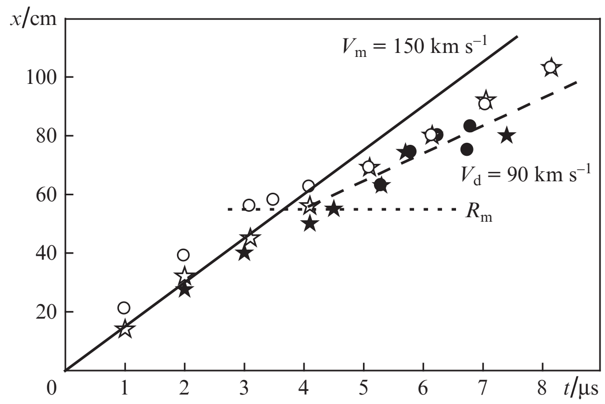

Figure 8. Joint $R-t$ motion diagram of maxima of the total concentration n_{max} (★, ☆) and magnetic field B_{max} (●, ○) during the interaction of LP with magnetised BP. The data of laboratory modelling (black dots) and related hybrid calculations (empty circles) obtained by the model [41]. The solid and dashed lines are the linear approximations; V_m is the velocity of the LP region with a maximum concentration, V_d is the average velocity of both maxima beyond the calculated radius R_m of gas-dynamic deceleration (~60 cm).

As a result, in the process of LP expansion with a velocity $V_0 \approx 200$ km s^{-1} (the calculated Larmor radii of LP and BP ions are $R_L \approx 62.5$ cm and 25 cm, respectively; and $\delta \approx 1.5$), a strong BP disturbance along the normal to the target and outside the cavity, propagating at the distances up to 80 cm with a velocity of $V_d \approx 75$ km s^{-1}, which exceeds the velocity C_f of the fast magnetic sound (Figs 7 and 8), was for the first time observed. The recorded considerable jumps of the concentration n^* and magnetic field B, having the leading edge length of $\Delta \approx \Delta t V_d \approx 3-4$ cm (of the order of c/ω_{pi}, where ω_{pi} is the ion plasma frequency) correspond to a subcritical magnetosonic CSW, possibly in a specific form (the so-called solitary shock [42]) due to the obvious absence of a stationary state behind the CSW front as a consequence of spherical geometry of the problem and comparable scales of c/ω_{pi} and R^*. Indeed, in addition to a small width of the leading edge and the presence of compression shocks in n^* and B (by ~2 and 1.65–1.85 times, respectively), approximately corresponding to the Rankine–Hugoniot relation [16, 43], analysis of the electron branch of the CVC has revealed a noticeable heating of BP electrons (from 7 to 11 eV), which is close to relevant calculations, while the data on the ionic branch of the probe's CVC [40] at the peak of these compression shocks are in satisfactorily agreement with the original ionic composition of BP with $\langle m_i^* \rangle \approx 1$ amu.

Thus, judging from a set of characteristics, the LP-induced strong BP perturbation represents a CSW produced for the first time in laboratory conditions by the bunches of exploding plasma (in our case – a subcritical magnetoacoustic CSW propagating perpendicularly to $\boldsymbol{B}_0$) with a Mach number M_f up to ~1.7–1.8. This Mach number represents a ratio of the perturbation front velocity $V_{df} \approx 80$ km s^{-1} and the fast magnetic sound velocity $C_f \approx 44$ km s^{-1}. The critical Mach number M_{f1} for a CSW propagating across the magnetic field in BP at $\beta^* = 8\pi n^* k_B T_e^*/B^{*2} \approx 1.3$ amounts to ~2.2 [44]. We are currently exploring the opportunities for conducting experiments on the KI-1 facility on modelling the supercritical CSW with $M_f > M_{f1}$, in particular, on modelling the effects of super-compression of the Earth magnetosphere [25, 26].

Note that the recorded deceleration (plasma velocity is reduced twice) of the LP peak with the highest concentration near the expected cavity boundary with $R^* \approx 50$ cm (at the gas-dynamic deceleration radius $R_m = [3N_0(m_i/Z)/(4\pi n^* m_i^*/Z^*)]^{1/3} \approx 60$ cm) is actually collisionless. The conventional ionic ($H^+ \rightarrow H^{*+}$) Coulomb collisions have the free path length $\lambda_{i-i}^* \approx 300$ cm, while the ion–electron collisions give $\lambda_{i-e}^* = 3 m_e m_i V_m V_{te}^3 \times (16\pi^{1/2} \Lambda e^4 Z^2 n_e)^{-1} \approx 6\times10^7 A_Z V T_e^{3/2}/(Z^2 n_e) \approx 10^3$ cm. Here $\Lambda \approx 10$ is the Coulomb logarithm; V is the velocity in cm s^{-1}; T_e is the temperature in eV; n_e is the concentration in cm^{-3}; A_Z is the atomic weight; and V_{te} is the average thermal velocity of electrons [9]. As a consequence, all the collision lengths exceed significantly the radius R_m and the value Δ, even for the H^+ ions at a velocity $V_m \approx 1.5\times10^7$ cm s^{-1} of the LP peak with the highest LP concentration.

Also note that none of the experiments on CSW generation, recently conducted in the USA [10, 11, 15, 17], has not given positive results. This is mainly due to the lack of the facilities with large vacuum chambers and dense enough BP capable of producing a large-scale diamagnetic cavity with $R^* \sim 1$ m. It seems that even if the lasers with the energy of several kilojoules were put into operation at LAPD in the near future, it is unlikely to expect a significant progress in addressing the issues under consideration if the results of simulating the collisionless interaction by the MLM, obtained at the VNIIEF [4] were not taken into account. This also follows from a large series of calculations on the CSW formation by the MLM and detailed analysis of their results in the report [16], where the required parameters of an experiment on the LAPD facility have been found: $E_0 \approx 50-100$ J, $V_0 \approx 250-500$ km s^{-1} (ions H^+, C^{4+}), $B_0 \approx 500-700$ Gs, and $n^* \approx 2\times10^{13}$ cm^{-3} (H^+ or He^+) in a BP column of ~50 cm diameter. These parameters and the criterion $\delta \approx 1$ at $R^* \approx 16$ cm can be attained on the LAPD facility in 2016, after putting into effect the Raptor laser and modernisation of the BP source with a large-diameter LaB6 cathode. However, in this case the Alfven–Mach number would be $M_{A0} \leqslant 2$, which is apparently insufficient for the CSW formation.

In conclusion of the discussion on the observed strong collisionless interaction between the substantially super-Alfven LP flow ($M_{A0} \approx 7$) and the magnetised BP, we should first and foremost remind that no processes of this type of interaction, with the Alfven–Mach numbers of $M_{A0} \geqslant 4-5$, have been found either experimentally or theoretically, apart from the MLM itself and Weibel instability [6] which, however, can be realised in the form of CSW at $\Delta \geqslant 100\ c/\omega_{pi}$.

As earlier [20], we are able to confirm the MLM efficiency in the case in question by means of a method of comparing the experimental data with the corresponding calculations performed in accordance with the hybrid model [41] developed by V.A. Vshivkov and G.I. Dudnikova purposely for the analysis of experimental results derived on the KI-1 facility at the Institute of Theoretical and Applied Mechanics, SB RAS. This model, along with a similar model [14] developed at the VNIIEF for an axisymmetric spherical cloud, does not contain in their equations any other interaction effects apart from the generation of laminar and radial vortex electric fields, the latter providing the interaction by the MLM. The diagrams of deceleration in the regions with a maximum concentration (Fig. 8), which have been derived experimentally (points 1, 2) and by means of calculations (points 3 and 4 with the same parameters and ionic LP composition of H^+, C^{2+}, and C^{3+}), show that these major interaction characteristics are well described by the MLM. Of course, the scope of magnetohydrodynamic description of electrons in the hybrid model, as applied to the study on CSW, is very limited; nonetheless, in some cases [16] such a description turns out efficient enough, while a good agreement between the experimental data and the calculations of this type in the case of generating electron whistlers (in the course of LP expansion in BP with $M_{A0} \leqslant 2$) [41] indicates a possibilityof using the hybrid models in describing the positive dispersion (on the scale of $\sim c/\omega_{pi}$) of this branch of a fast magnetoacoustic wave in quasi-parallel directions.

5. Conclusions

In the present work, theoretical basis and main results of a first successful 'CSW' experiment on the CSW generation by laser plasma in magnetised background plasma are presented. The classical approach is based on the MLM action ensuring a collisionless interaction of interpenetrating Alfven flows of the laser and background plasma in a transverse magnetic field.

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Appendix. Peculiarities of the methods of plasma diagnostics by thin Langmuir probes in the interpenetrating flows of laser and background plasma

In the simplest limiting regime of the so-called orbital motion (OM) of particles in the conditions of their collisionless collection by a small probe with a radius r_p being much less than the Debye radius h, a theory of ionic 'saturation' current I_i, which has been developed by Langmuir for spherical and cylindrical probes, gives the following generalised expression for a cylinder of a length l_p located transverse to the flow velocity $\boldsymbol{V}$ [39]:

$$I_\text{i}^\text{L} \approx 2r_\text{p} l_\text{p} e n_\text{e}\left[\frac{2}{m_\text{i}}(eZU + E_\text{i} + fT_\text{i})\right]^{1/2} \quad \text{for } eZU + E_\text{i} > T_\text{i}, \tag{A1}$$

where $E_\text{i} = m_\text{i}V^2/2$, T_i, Z and m_i are the energy, temperature, charge, and mass of ions; and the factor $f \leqslant 1$ is a function of ZU (where U is the voltage on the probe relative to the plasma), V and T_i/T_e. Further theoretical studies and numerical calculations performed by Laframboise [39] have shown that this expression may be valid up to the values $\xi_\text{p} = r_\text{p}/h \approx 1-3$.

Proven in a variety of experimental conditions, expression (A1) for the current provides an exceptional opportunity [37, 38] to use such probes in studying the interpenetrating plasma flows by 'separate' registration of the dynamics of a pulsed ion flow $J_\text{i} = en_\text{e}V = I_\text{i}^\text{L}/(2r_\text{p}l_\text{p})$ (at $E_\text{i} \gg eZU$ as in LP) and a slow evolution of concentration of the background medium surrounding the probe, based on the dependence $n_\text{e} \propto I_\text{i}^\text{L}$ at $eZU \gg E_\text{i}, T_\text{i}$ up to the concentration values of $\sim 10^{14}$ cm^{-3}, which is determined regardless of T_e (A1) according to the OM model in the experiments with a fast LP flow. In this sense, an important advantage of thin (with a diameter of $\sim$20 μm) tungstic cylindrical probes is the possibility of cleaning their surface at the expense of manufacturing a probe in the form of a loop heated by the current up to a temperature of 1000–1200 °C. This ensures equality of the physical collecting surface area of the probe and its geometrical surface area, and also the opportunity of applying a high enough voltage of $|U| \approx 50-150$ V without the 'breakdown' danger (in the case of 'separate' recording of the laser and background plasma). Under these conditions, an additional advantage of such probes arises, namely the possibility of evaluation by formula (A1) of ionic composition $\langle m_\text{i}/Z\rangle$ of the main component of background plasma, and, more importantly – of laser plasma, by means of a new method [40] of ion-brancg CVC processing (A2) using the expressions for a plasma flow moving with a velocity V:

$$\frac{A_Z}{Z} = e\left[J_\text{i}^2\Big/\frac{\partial J_\text{i}^2}{\partial U} - (\varphi_\text{p} - \varphi_\text{s})\right]\Big/E_\text{i}(V). \tag{A2}$$

Here A_Z is taken in amu; φ_p and φ_s are the probe and plasma potentials in volts; and $E_\text{i} = m_\text{p}V^2/2$ is the proton kinetic energy in electron volts.

To measure the magnetic field perturbations, the induction magnetic probes [37, 38] have been applied in the form of miniature coils (with a few turns) no larger than 1 cm, shielded from the interferences caused by the jumps of plasma potential up to 500 V by means of an insulated grounded titanium foil with cuts or by a thin-walled nickel tube with open ends.

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