

Laser plasma simulations of the generation processes of Alfven and collisionless shock waves in space plasma

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Abstract. Generation of Alfven waves propagating along external magnetic field B_0 and Collisionless Shock Waves propagating across B_0 are studied in experiments with laser-produced plasma and magnetized background plasma. The collisionless interaction of interpenetrating plasma flows takes place through a so-called Magnetic Laminar Mechanism (MLM) or Larmor Coupling. At the edge of diamagnetic cavity LP-ions produce induction electric field E_ϕ which accelerates BP-ions while LP-ions rotate in opposite direction. The ions movement generates sheared azimuthal magnetic field B_ϕ which could launches torsional Alfven wave. In previous experiments at KI-1 large scale facility a generation of strong perturbations propagating across B_0 with magnetosonic speed has been studied at a moderate value of interaction parameter $\delta \sim 0.3$. In the present work we report on experiments at conditions of $\delta \sim 1 \div 2$ and large Alfven-Mach number $M_A \sim 10$ in which strong transverse perturbations traveling at a scale of ~ 1 m in background plasma at a density of $\sim 3 \cdot 10^{13} \text{ cm}^{-3}$ is observed. At the same conditions but smaller $M_A \sim 2$ a generation, the structure and dynamic of Alfven wave with wavelength ~ 0.5 m propagating along fields $B_0 \sim 100 \div 500$ G for a distance of ~ 2.5 m is studied.

1. Introduction

With the aim to simulate processes in space plasmas we consider in this paper two different types of disturbances produced by explosive Laser-produced Plasma (LP) expanding in a magnetized Background Plasma (BP).

The first one is torsional Alfven Waves (AW), transverse MHD plasma perturbations propagating along field lines of the external magnetic field B_0 . In laboratory it was generated by injecting laser-produced plasma along (and quasi-parallel) the lines of B_0 in a presence of magnetized background plasma. The plasmas are sufficiently collisionless and interaction takes place due to a so-called magnetic laminar mechanism (MLM) or Larmor Coupling [1, 2, 3]. As a result of this interaction the net azimuthal ion current generates sheared azimuthal magnetic field B_ϕ [1] which could generate AW, propagating along B_0 . In experiment besides B_ϕ a related parallel current J_z was directly measured as well. It is believed that such disturbances can propagate in the magnetic flux tubes at the Sun chromosphere and transfer energy to the Corona.



The second type of perturbation is the collisionless shock wave (CSW) [4, 5, 6]. It is generated by the injection of LP in magnetized BP across B_0 . CSW propagates across the lines of external magnetic field; the registration is made by jump of magnetic field and of BP concentration. The plasma also is in collisionless mode, generation of disturbances is produced by MLM. Similar processes may occur in the solar Corona during a Coronal Mass Ejection.

2. Magnetic laminar mechanism

Magnetic laminar mechanism (MLM) or Larmor Coupling of LP with magnetized BP effectively operates in collisionless regime at high Alfvén-Mach numbers $M_A \geq 5$. LP, propagating with velocity V_0 , forms a so-called magnetic cavity (area of displaced external magnetic field), the curl electric field E_ϕ is generated at its boundary. BP-ions accelerate along to this field, while at the same time ions of LP are decelerated in their Larmor rotation (opposite to E_ϕ). Conditions at which a strong coupling between BP-ions and LP-ions results due to such mechanism were established by for the first time in [1]. Its effectiveness depends mainly on a so-called MLM-parameter $\delta = R_*^2 / R_L R_{L*} \geq 1$, where

$R_* = (3N_e / 4\pi m_*)^{1/3}$ – the radius of diamagnetic cavity (N_e – total number of electrons, n_* – concentration of BP-ions), R_L , R_{L*} – Larmor radii of LP-ions and BP-ions respectively. The effective deceleration of LP takes place at a scale of R^* , which is comparable to gas-dynamic scale of $R_m = (3N_e m_i Z_{i*} / 4\pi m_* m_{i*} Z_i)^{1/3}$, and its kinetic energy transferred to BP proportionally to parameter δ (here m_i , m_{i*} – ion mass of LP and BP respectively, Z_i , Z_{i*} – ion charge of LP and BP respectively).

But indeed, the physical processes of electromagnetic fields, responsible for the MLM-interaction, can act in the range up to $M_A \sim 1$ and moreover, could supply some kind of collisionless interaction along the B_0 -field, namely important for the AW experiment – opportunity to launch a torsional Alfvén Wave (AW) by azimuthal B_ϕ magnetic field, generated inside of spherical LP at early stage of its expansion. Such fields of the level $B_\phi / B_0 \sim 1$ were revealed during the first hybrid simulations [1] of MLM-interaction and later their probable consequences in a form of electron whistler [7] or AW [4, 12] were discovered. Usually, the generation [8] of such B_ϕ -fields are treated on the base of Hall term $K = [\text{rot} B \times B] / n$ in the equation for $\partial B_\phi / \partial t \propto -(C / 4\pi e) \text{rot} K$. Thus the value of B_ϕ can be estimated (for the time $\partial t \sim R_b / V_0$ at the characteristic scale $\sim C / \omega_{pi}$, where R_b – deceleration radius of LP in vacuum magnetic field, definition presented in table 1) as $B_\phi / B_0 \sim R_b / R_L \sim (\delta \cdot m_i Z_{i*} / Z_i m_{i*})^{1/2}$.

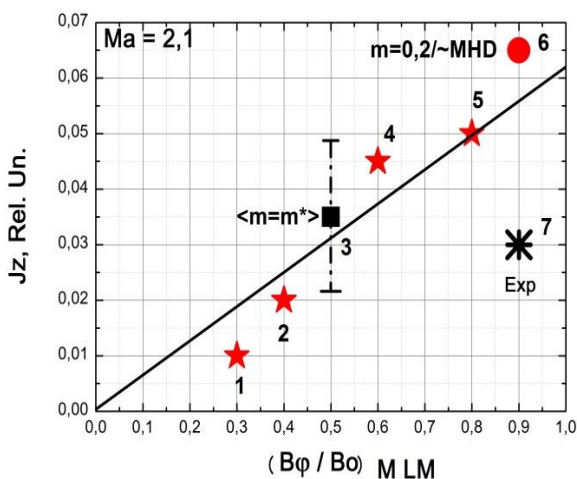


Figure 1. Linear relation between dimensionless J_z current (generated at the same time as AW) and the initial value of azimuthal B_ϕ / B_0 -field of MLM-model (1) for a set of 3-Fluids simulations:

- 1 – Run III – $\delta = 0,08$ and $m_i Z_{i*} / m_{i*} Z_i = 16$;
 - 2 – Run V – $\delta = 1,3$ and $m_i Z_{i*} / m_{i*} Z_i = 2$;
 - 3 – Run IVa – $\delta = 4,3$ for the special case of equal $m_i Z_{i*} / m_{i*} Z_i = 1,4$ with a low limit value J_z ;
 - 4 – Run I – $\delta = 4$ and $m_i Z_{i*} / m_{i*} Z_i = 1,5$;
 - 5 – Run II – $\delta = 3,5$ and $m_i Z_{i*} / m_{i*} Z_i = 3$;
 - 6 – Run “MHD” with $m_i = 0,2$ a.m.u.
- and experimental point 7 (with maximum level 1000 A, re-calculated to dimensionless J_z).

The same result could be obtain more exactly with taking into account the main equation of MLM-model, with a calculated maximal velocity $V_{\phi*} = 0.5 \omega_{ci*} R_* \sin \theta$ of BP-ions [9], accelerated by curl electric field during magnetic field exclusion by LP, in dependence upon polar angle θ (where ω_{ci*} – cyclotron frequency of BP-ions). As a result, a frozen to BP initial field B_0 will be torque at most

extent near “equator” ($\theta = 90^\circ$), while a pole, and the incline (or B_ϕ -field) of its field line could occur. So a resulting B_ϕ -field in a MLM-model will be:

$$B_\phi/B_0 = 0.5[\delta_0(m_i/m_{i*})(Z_{i*}/Z_i)]^{1/2} \sin \theta \cos \theta \quad (1)$$

with the maximal value at $\theta = \pm 45^\circ$ as was obtained by hybrid simulations [4]. At the figure 1, a successful comparison of such dependence (1) with the results of 3-fluids MHD-model of ILP [10] is presented in a variable values of initial B_ϕ/B_0 (estimated by MLM-model) and the calculated total current J_Z (in dimensionless units) of AW along to magnetic field B_0 . This 3-fluids MHD model simulates plasma as 3 fluid: LP-fluid, BP-fluid and overall electron fluid.

3. Experiment set up and results on Alfvén waves

Laboratory experiments are carried out at KI-1 facility [11]. The scheme of experiment is presented on figure 2. Large scale high-vacuum chamber 5 m long, 1.2 m in diameter kept a vacuum of $\sim 10^{-6}$ Torr can be filled by means of θ -pinch with the background plasma (H^+ or He^+). LP-clouds can be generated by two independent microsecond-pulse CO_2 -laser systems with similar parameters of radiation focused on a flat (or convex) target of polyethylene (focal size of laser spot $\varnothing 2.5$ cm). An external magnetic field up to 500 G is created by quasi-stationary current in a solenoid covering the entire outer surface of the vacuum chamber. Diagnostics of plasma is performed using double Langmuir probes P1 (with magnetic probes Mz, Mf), P0 (with magnetic probes Br, Bz, Bf), and a pair of probes IK1, IK2 with the corresponding three-component magnetic probes RM1 (L, T, H), RM2 (L, T, H). For direct detection of current J_Z , related to AW [12, 13, 14], Rogowski coil (PR) 5 cm in diameter was used. It was electrostatically shielded from the interference with potential of the plasma (as magnetic probes). Miniature collectors of direct ion-flux KB1 and KB2 are mainly used for recording such streams along the axis Z, and KB3 as a symmetrical double electrode is used for evaluation of current J_i and plasma electrons temperature T_e .

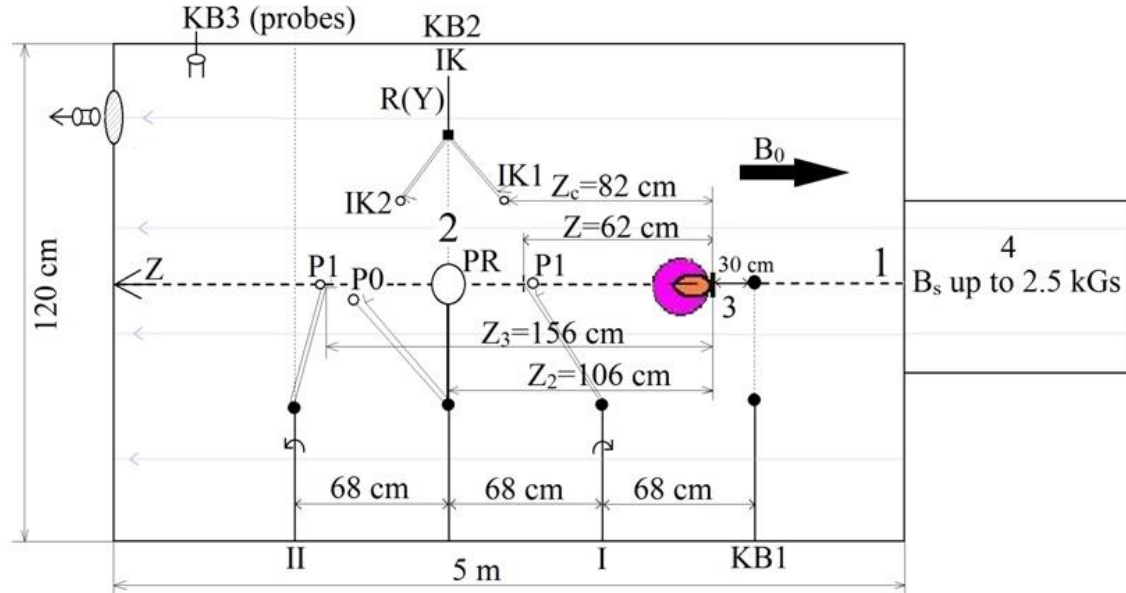


Figure 2. Experimental scheme of Alfvén wave experiment at KI-1 facility of ILP [2].

In this experiment a cylindrical coordinate system is used with the Z axis along the axis of symmetry of the vacuum chamber and magnetic field lines. The angular coordinate is ϕ , and the radial is r . The basic parameters and criteria of similarity of modelling experiment are presented in table 1.

The injection of LP was made along B_0 (Z axis). The propagation of AW is also recorded along Z axis by magnetic probes and Rogowski coil, arranged at different distances from the laser target.

Using BP magnetized by external magnetic field in the range 100-500 Gs we observed propagation of plasma perturbations in a magnetic flux tube. Diameter of this tube is $\sim 15\div 20$ cm, length is ~ 2.5 m along the chamber axis.

The propagation velocity of LP in the absence of the external magnetic field and the BP is about 200 km/s, while the speed of BP is order of magnitude smaller $\sim 20\div 30$ km/s. However, in a vacuum magnetic field LP front was found to move at a speed of about 90 km/s, and in magnetized BP $\sim 60\div 80$ km/s. LP-ions are slowing down at a time when magnetic cavity forms, so their speed is smaller than in absence of magnetic field. In the last case detailed comparison revealed that we observe in fact perturbation of BP rather than LP ions.

Table 1. List of experimental parameters

Dimensional parameters	AW experiment	CSW experiment
Concentration of H^+/He^+ background, n_*	$0,5\div 3,5 \cdot 10^{13} \text{ cm}^{-3}$	$\sim 3 \cdot 10^{13} \text{ cm}^{-3}$
Ion-skin scale (background)		$C/\omega_{pi} \sim 5 \text{ cm}$
External magnetic field (in background)	$B_0 = 100 \div 500 \text{ Gs}$	$B_0 = 110 \text{ Gs}$ (80 Gs)
Initial velocity of the front of LP-cloud (velocity of n_{\max} , maximum of concentration)	$V_0 \approx 200 \text{ km/s}$ ($V_M \approx 150 \text{ km/s}$)	
Effective energy of LP-cloud $E_0 = E_k \cdot 4\pi/\Delta\Omega$ (with E_k – kinetic energy, $\Delta\Omega$ – angle of LP expansion) with N_0 – effective number of electrons	$E_0 = 30 \text{ J}$, with $N_0 \sim 10^{18}$	$E_0 \sim 1000 \text{ J}$, with $N_0 \sim 10^{19}$
Deceleration radius of LP by magnetic field B_0 (radius of magnetic cavity in vacuum)	$R_b = (3E_0/B_0^2)^{1/3} \sim 30 \text{ cm}$ with $B_0 = 175 \text{ Gs}$	
Temperature of BP-electrons	$T_{e*} \sim 10 \text{ eV}$	$T_{e*} \approx 7\div 11 \text{ eV}$
Mean free path of LP-ions in background with initial speed V_0 (or at the lower speed V_R , relative to the background)	$\lambda_{ii*} \sim 200 \text{ cm}$, ion-ion Coulomb collisions (to $\leq 20 \text{ cm}$ with $V_R \approx 60 \text{ km/s}$ in H^+ background)	$\lambda_{i-i*} \sim 300 \text{ cm}$, ion-ion Coulomb collisions, λ_{i-e} , ion-electron Coulomb collisions
Alfven speed. Alfven wavelength (on Z-axis)	$C_A = 70 \text{ km/s}$, $\lambda_{AB} \sim 50 \text{ cm}$ ($B_0 = 175 \text{ Gs}$, H^+ background, $n^* = 3 \cdot 10^{13} \text{ cm}^{-3}$)	
Size of background along Z-axis and along r-axis	$\sim 100\div 200 \text{ cm}$ and 20 cm	
Dimensionless similarity criteria	AW experiment	CSW experiment
Alfven-Mach number	$M_A = V_M/C_A \sim 2$	$M_A = V_M/C_A \sim 7$
Larmor radius	$R_L = V_0 m_i C / e Z_i B_0$	
Magnetization of LP-ions with charge-mass composition $m_i/Z_i = 2,5$	$\varepsilon_b = R_L/R_b = 0,7 (\leq 1)$, with $R_L = 21 \text{ cm}$	
Radius of magnetic cavity of LP in background	$R^* \approx (3N_0/4\pi n^*)^{1/3} \approx 20 \text{ cm}$	$R^* \approx (3N_0/4\pi n^*)^{1/3} \approx 50 \text{ cm}$
MLM-parameter	$\delta = R^{*2}/R_L R_L^* \sim 3$	$\delta = R^{*2}/R_L R_L^* \geq 1$
Plasmas beta	$\beta = 8\pi n k T_{e*}/B_0^2 \sim 0,5$	$\beta = 8\pi n k T_{e*}/B_0^2 \sim 1$
Knudsen number	$Kn_i = \lambda_{ii*}/R_B \sim 10$ (with initial speed V_0 , but up to ≤ 1 with real speed $V_R \approx 60 \text{ km/s}$ relative to the background)	

Besides characteristic features of the AW, a high-frequency whistler precursor was registered as well like in our previous work [7]. The measurement of transverse component of the magnetic field has shown that the first disturbance has a right-hand circular polarization that corresponds to electron whistlers, after which the polarization direction is changed with the arrival of AW. The speed of whistler is about 300 km/s. Direct signals from magnetic probes Bf and Br, which corresponds to the derivatives of variations of magnetic field, are presented on figure 3. High-frequency precursor is more clearly visible on this figure. Right-hand circular polarization of transverse component of

magnetic field can be seen on figure 4. The polarization changes its direction at the moment 11.5 μ s, which corresponds to the arrival of AW.

The main result of this experiment is registration of evidence of AW, namely the transverse component of magnetic field B_ϕ and longitudinal current J_z , which are correlated in time. Results of measurement of two magnetic probes and the Rogowski coil arranged at distance 82, 130 and 106 cm from the laser target, respectively, are presented on figure 5.

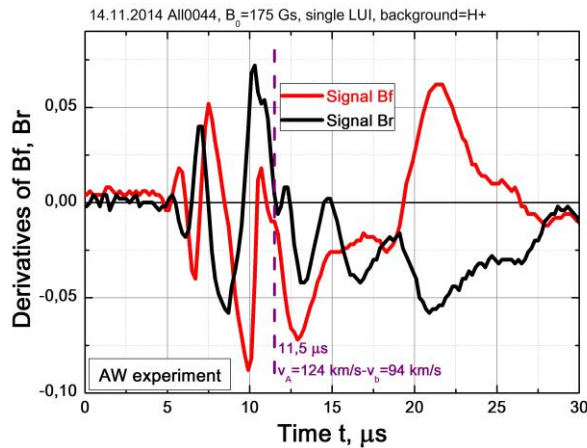


Figure 3. Derivatives of the variations of transverse B_ϕ , B_r components of magnetic field. Dash line represents the moment of change of polarization and arrival of AW.

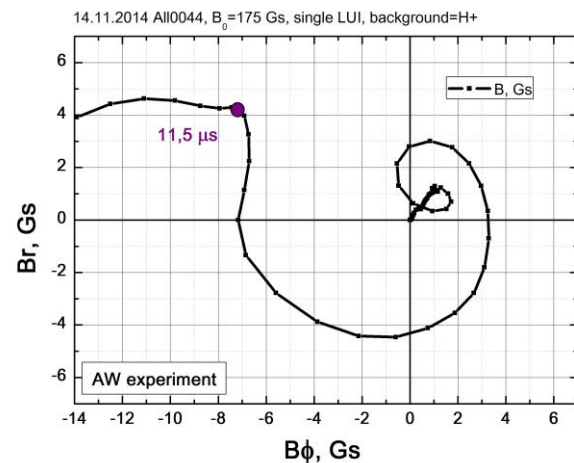


Figure 4. Hodograph of transverse component of the magnetic field variations. The circular polarization changes its direction at the moment 11.5 μ s.

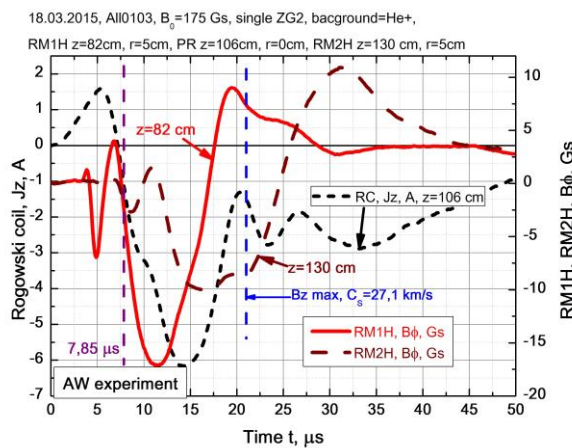


Figure 5. Perturbations of magnetic field B_ϕ at a distance 82 cm and 130 cm from the target and $r=5$ cm, detected by probes RM1H and RM2H. Longitudinal current J_z at a distance 106 cm from the target and $r=0$, detected by Rogowski coil. First vertical dash line at the moment 7.85 μ s represents the arrival of AW. Second one corresponds to maximum of magnetic field displacement, which is caused by slow magnetosonic wave.

It can be seen that the maxima of the perturbations are consistently propagating along the axis of the chamber. Time correlation between peaks of B_ϕ and J_z is confirmed by measurement of magnetic probes and Rogowski coil at the same distance from the target. The speed of AW, measured as the ratio of the distance from the target to the probe at the time of arrival of disturbance front, is 105 km/s. Taking into account the own speed of the background (30 km/s), the experimentally measured value of speed of AW is equal 75 km/s. Estimated value of the Alfvén speed will be

$C_A = B_0 (4\pi n_* m_{i*})^{-1/2} = 2.2 \cdot 10^{11} B_0 (n_* m_{i*} [a.m.u.])^{-1/2} = 8.6 \cdot 10^6 \text{ cm/s}$, with $B_0=175$ Gs – external magnetic field, $n_*=5 \cdot 10^{12} \text{ cm}^{-3}$ – concentration of BP, $m_{i*}=4$ a.m.u. – mass of BP-ions, which is close to the experimental value.

4. Experiment set up and results on collisionless shock waves

The scheme of experiment is presented in figure 6 [6]. In this case we use Cartesian coordinate system with X-axis directed along the CSW propagation and Z-axis along the applied magnetic field. The main difference from the previous experiment is that the LP is injected across $B_0 = 100$ Gs. Detailed experimental parameters are given in table 1.

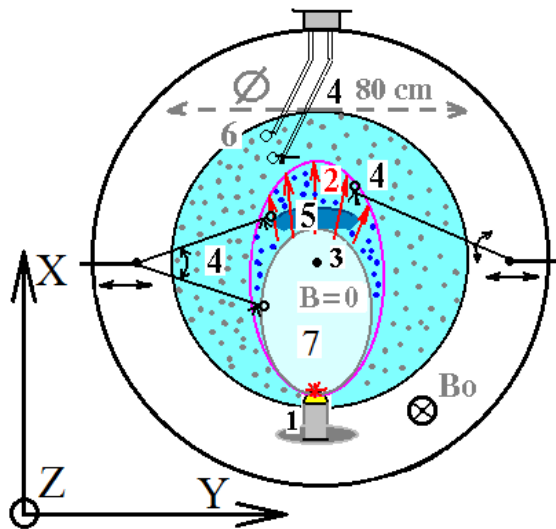


Figure 6. Experimental scheme of stand KI-1 for collisionless shock waves experiment.

- 1 – Laser target;
- 2 – Front of LP;
- 3 – Central axis Z of the chamber;
- 4 – Diagnostic probes;
- 5 – Area of interaction between LP and BP;
- 6 – The boundary of BP;
- 7 – $B=0$ – magnetic cavity (area of displaced magnetic field).

The CSW was detected by jump of magnetic field and BP density. Measurements of magnetic probe showed that near (~ 5 – 10 cm) the target displacement of magnetic field is almost complete; the boundary of magnetic cavity is located at the distance of ~ 50 cm.

To confirm that generation of the CSW is precisely due to MLM, measurements in absence of an external magnetic field were carried out. They show only a small jump of density in vacuum, while LP injection in un-magnetized BP doesn't produce density perturbation at all. When an external magnetic field is on, the strong jump of concentration of the BP caused by the expansion of LP can be observed (figure 7). An external magnetic field of 110 Gs is partially displaced by BP to a level of ~ 80 Gs. Therefore, at a time of arrival of the disturbance the probe shows a jump of magnetic field with a value of ~ 35 Gs. Both perturbations have sharp front with duration about ~ 0.5 μ s.

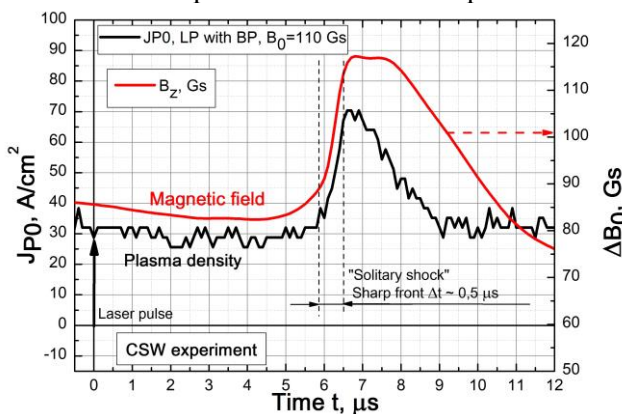


Figure 7. Plasma density and magnetic field jumps, corresponding to the CSW.

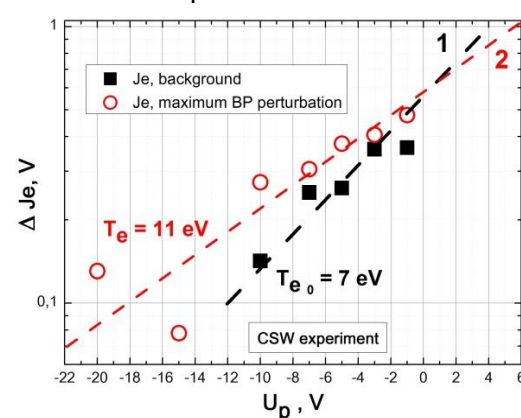


Figure 8. I-V characteristics of P0 probe for unperturbed BP (black line 1, black squares) and maximum of BP perturbation (red line 2, red circles).

Initial speed of the front of LP-cloud is about ~ 150 km/s. The front of density and magnetic field jumps move along the X-axis at a speed equal to a half of that value 75 km/s as determined from R-t diagram at a distance of about 50 cm near the expected boundary of the magnetic cavity. This velocity

corresponds to their magnetosonic Mach number $M_s \approx 1,5 \div 2$ and according to the theory of MHD-shocks [15] we could expect n_* , B_z -jumps like registered ones (figure 7) and the electron heating in a factor $\approx 1,7$ also closed to measured one $\approx 1,5$ (figure 8). Temperature measurements based on I-V characteristics of thin cylindrical probe P0 placed at the distance 75 cm from the target are presented on figure 8. Electron temperature of unperturbed BP (black line 1, black squares) is 7 eV; at the maximum of BP perturbation (red dash line 2, red circles) is 11 eV.

5. Conclusion

Conducted modelling experiments on collisionless interaction of laser-produced plasma with magnetized background plasma produced new data on basic plasma processes of wave's generation. The propagation speed of one type of measured perturbations was found to be close to the calculated value of Alfvén speed. We believe that they are generated by MLM or Larmor Coupling through formation of azimuthal B_ϕ fields at the edge of diamagnetic cavity.

High-frequency whistler precursor with right-handed circular polarizations, moving ahead of AW with the speed ~ 300 km/s, was observed as well. Both of these perturbations are not accompanied by significant variations of plasma concentration.

In another experiment strong perturbations resembling collisionless shock waves propagating across the external magnetic field at a speed of about 75 km/s have been observed. Registration was carried out by jumps of plasma density and magnetic field. Once again, obtained data confirm that these perturbations are generated by the same MLM or Larmor Coupling.

6. Acknowledgments

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7. References

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