Generation of Collisionless Shocks by Laser-Plasma Piston in Magnetised Background: Experiment “BUW”

Zakharov Yu.P.[1], Ponomarenko A.G.[1], Terekhin V.A.[2], Antonov V.M.[1], Boyarintsev E.L.[1], Melekhov A.V.[1], Posukh V.G.[1], Shaikhislamov I.F.[1]

[1]Institute of Laser Physics (ILP) SB RAS, Novosibirsk, Av. Lavrentyeva13/3,
630090, Russia, ki1z@mail.ru
[2]All-Russian Scientific Research Institute for Experimental Physics (VNIIEF), Sarov, Av. Mira 37,
607188, Russia

Theoretical basis and main results of the first successful large-scale, Laser-Plasma experiment “BUW”, on generation of Collisionless Shock Wave in magnetised Background Plasma, are presented. Our classic approach is based on the action of so called Magnetic Laminar Mechanism (or Larmor coupling) for collisionless interaction between interpenetrating super-Alfvenic plasma flows of Laser-Plasma and Background in transverse magnetic field.

Keywords: laser, plasma, shock wave, magnetic field, collisionless interaction

1 INTRODUCTION

At present (and in the past, in the 60-80s) a lot of experiments with Laser-Plasmas (LP) are conducted to generate and study [1] a Collisionless Shock Wave (CSW) under different conditions of two principle schemes: at presence of external magnetic field B_0 [2-7] and without it [9]. In the latter case, a great successes were achieved recently in simulations of astrophysical CSW at extreme Alfven-Mach numbers $M_A \geq 100$ (due to development of Weibel instability [9]), in spite of some unclear role of ion-electron collisions [10]. But in the former classic case, with a B-field, imbedded into Background Plasma (BP), the experimental progress was not so evident up to now, in spite of using [6] high-power lasers, like a Trident (in LANL, USA). Here we present shortly a basics of model [11] developed by VNIIEF for CSW-problem and extended data [12] of the first successful large-scale, LP-experiment “BUW”, performed at the KI-1 laser facility [4] of ILP.

2 COLLISIONLESS COUPLING OF MAGNETISED PLASMAS AT KI-1

Magnetic Laminar Mechanism (MLM or Larmor coupling [8]) of interaction LP with BP at high $M_A \geq 10$ is based on the action of curl electric field E_φ, arising due to exclusion of B-field by diamagnetic LP (expanding with front velocity V_0). Along to this field E_φ ($\sim V_0B_0/C$), the BP-ions are accelerated initially, while LP-ions could be decelerated during their Larmor rotation (opposite to E_φ). As a result, strong enough coupling between LP and BP should occur for CSW, under necessary conditions that were established by VNIIEF in their MLM-model [11]. One of them is a value of MLM-parameter δ that should be large enough $\delta = R_*^2/R_LR_L^* \geq 1$, for the given radius of diamagnetic cavity $R_* = (3N_e/4\pi n_*)^{1/3}$ [8] for spherical LP. Here N_e is the total number of LP electrons, n_* is the density of BP electrons, while the Larmor radii of LP-ions (R_L) and BP-ions (R_L^*), both are determined by V_0. As a result, deceleration of LP at the R_*-scale, comparable with gas-dynamic one $R_m = (3N_emz_*/4\pi n_*m_*z)^{1/3}$, could occur and the kinetic energy W_* transferred to BP could achieve a level of initial LP energy $E_k = 0{,}3(N_em/z)*V_0^2$, like $W_* \sim \delta*E_k$ (for $\delta \leq 1$). First experimental evidence [2] of MLM-interaction was obtained at the KI-1 facility under conditions of rather small values of both $\delta \sim 0{,}3$ and scale $R_* \approx 20$ cm (for energy $E_k \sim 40$ J of quasi-spherical LP), resulting in a weak magnetosonic wave in BP, at radii r ~ 30-40 cm from the center of KI-1 chamber.

3 KI-1 Up-GRADE TO STUDY SHOCK’ GENERATION BY LASER PLASMA

Recent achievements [13] of ILP in the field of LP-blob’ creation (into total expansion angle $\Delta\Omega \sim 1$ sr, see *Fig. 1*) from quasi-plane [14] polyethylene target ∅3÷4 cm, can supply its effective energy $E_0 = E_k(4\pi/\Delta\Omega)$ up to

~1000 J and effective number $N_{e0} \geq 10^{19}$. Such method gives a real opportunity to achieve in a "BUW" experiment (*Fig. 2*) the level of $\delta \geq 1$ at the expense of really large scale $R_* \sim 50$ cm into the chosen direction X (for LP-ions H^+, C^{+3} and C^{+4} with $V_0 \approx 200$ km/s).

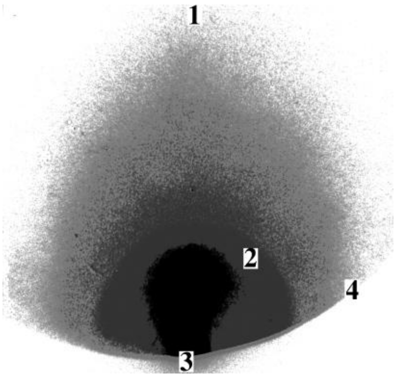

Fig.1: Shape of high-energy Laser-Plasma in vacuum at time t ≈ 2,1 μs (after laser); 1 – fast front at distance X = 41 cm; 2 – second LP-maximum; 3 – C_2H_2 target; 4 – line of blocked field view of GOI (with exposition time 100 ns).

It became possible to use such large R_* of cavity due to record diameter D = 120 cm (and length 5 m) of KI-1 chamber (with the target near its wall [4], *Fig.2*), filled by highly-ionized H^+-BP of diameter ∅90 cm generated by θ-pinch attached at the end of chamber.

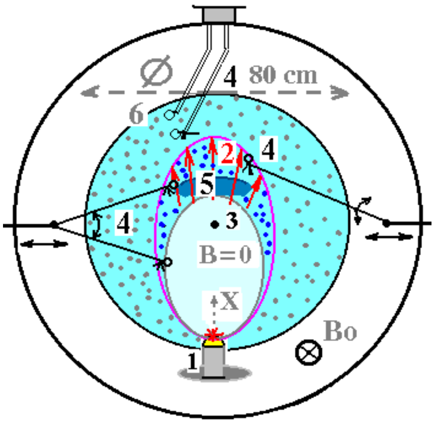

Fig.2: Principle scheme of "BUW" experiment at KI-1 facility of ILP with a chamber D=120 cm; 1 - target at support, 2 - Laser Plasma (LP) front, 3 - central Z-axis of chamber coinciding with axis of θ-pinch, 4 - various probe' diagnostics, 5 - interaction region of two plasmas (LP+BP), (X - target normal; B = 0 in diamagnetic cavity), 6 - boundary of Background Plasma (BP).

In *Fig. 3*, a profile of diamagnetic cavity ($\Delta B_z < 0$) with a boundary near theoretical size $R_* \approx 50$ cm is presented for the case of LP with effective energy $E_0 \approx 500 \div 700$ J.

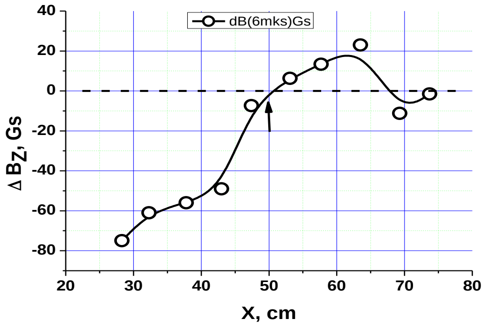

Fig.3: Profile of LP' diamagnetic cavity in magnetized plasma background with initial field B_* = 80 G and density $n_* \approx 3{*}10^{13}$cm^{-3} (t = 6 μs).

4 STRONG DISTURBANCE in "BUW", DISCUSSION and CONCLUSIONS

In *Fig. 4* the typical data of "BUW" experiment are presented for various conditions, in particular, for the cases of "free" LP expansion without magnetic field B_0 both in high-vacuum (*curve 1*) and unmagnetized BP (*curve 2*). The dynamics of current $J_{P0}(V)$ collected by thin cylindrical electrode of Langmuir probe (10 μm ~Debye) gives us near exact behaviour of total plasma density n via the relation for density of ion current J_i(A/cm^2) = 80*J_{P0}(V). So, in comparison with rather smooth curves *1,2* for given probe at distance X = 75 cm, its J_p - signal *3* in magnetized BP reveals a strong disturbances of n and B-field (*curve 4*), with sharp fronts (τ ≤ 0,5 μs) and significant deceleration during expansion along to X-axis. Note, that external (vacuum) magnetic field B_0 = 110 G was decreased by (also) diamagnetic BP down to $B_* \approx 80$ G.

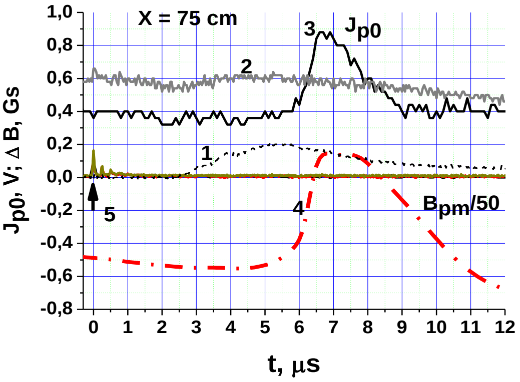

Fig.4: Dynamics of plasma ion current J_{P0} by Langmuir probe (∝fast flow=nV or density n) and magnetic field B at distance X = 75 cm; 5 – laser. All data were obtained at initial vacuum 3 μTorr in a chamber before formation of any plasmas.

As a result, under conditions of CO_2-laser energy ~300 J (~ one-half in 100 ns peak + μs-tail), BP' density $n_* \sim 3*10^{13}$ cm^{-3} (and temperature ~10 eV), we observed (*Fig. 4 and 5*) for the first time (along to target normal X and outside of cavity), the formation of strong BP' disturbance, propagating with super-magnetosonic velocity $V_d \approx 75$ km/s up to the distance ≥ 80 cm.

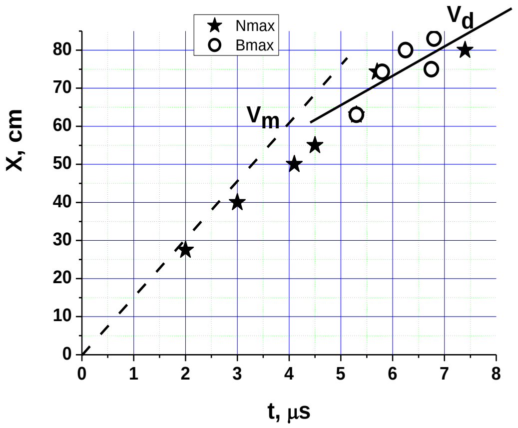

Fig.5: Joint R-t diagram of the motion of maxima n and B; V_m *–initial velocity of LP maximum;* V_d*– averaging disturbances velocity.*

The registered near 30% jumps of both n_* and B with a front width $\Delta \approx \tau^* V_d \approx 3\div4$ cm (~ C/ω_{pi}) correspond to expected ones [1] for magnetosonic Collisionless Shock Wave in a specific "Solitary" form [1]. The observed two-fold deceleration (*Fig. 5*) of LP' density maximum, near the expected scales of cavity $R_* \approx 50$ cm (and gas-dynamic radius $R_m \approx$ 60 cm) is collision-free. Usual ion-ion ($H^+ \rightarrow H_*^+$) Coulomb collisions [9] give a mean free path $\lambda_{i\text{-}i*} \approx$ 300 cm, while [4, 10] a perhaps more frequent ion-electron ones led to $\lambda_{i\text{-}e*}$ (cm) $= 3m_e m V_m V_{te}^3/16\pi^{1/2}\Lambda e^4 Z^2 n_e \approx 6*10^7 A_Z V(cm/s) T_e^{3/2}(eV)/Z^2 n_e(cm^{-3}) \sim 10^3$ cm So, we have enough large $\lambda >> R_m$ ($>>>\Delta$), even in the worst case of H^+ LP-ion with $A_z = 1$ a.e.m., $V_m \approx 1{,}5*10^7$ cm/s (and Z = 1). Therefore, in conclusion we can generalize, that as result of large-scale and strong enough collisionless MLM-interaction of Laser and Background Plasmas, we could generate for the first time in laboratory an explosive-type magnetized Collisionless Shock with a sharp ion-scale front jumps. For the velocity of fast magnetosonic wave ≈50 km/s, we had a magnetosonic Mach number ≈1,5 of generated disturbances (for the initial Alfven-Mach number of LP near $M_{A0} \approx 7$). Their data show, that a required shock jump-conditions [1] are satisfied and some distinct electron heating behind a front appears (from the slope of I_e–V_p characteristics of our double and asymmetrical probe). Note, that none of others recent similar LP-experiments [5-7] for CSW generation at USA facilities have not any positive results in this field up to now, mainly because of deficit of necessary experimental volume space to supply a large R_*. Moreover, as well as a lack of independent and both high-power sources of Laser and Background Plasmas.

Acknowledgements

This work has been supported by the Program (N 01201374303) for Basic Researches of ILP Siberian Branch of Russian Academy of Sciences.

REFERENCES

[1] Balogh A. and Treumann R. A., *Physics of Collisionless Shocks: space plasma shock waves* (Report No. 12 of Intern. Space Science Inst.), Springer (2013) 494 p.

[2] Antonov V M, Bashurin V P, Golubev A I, Zakharov Yu P, et al, J Appl Mech Tech Phys 26 (1986) 757-765.

[3] Kasenjar S, Hausmann M, Keskinen M, et al, Phys Fluids 29 (1986) 2007-2012.

[4] Zakharov Yu P, IEEE Trans: Plasma Sc, 31 (2003) 1243-1251.

[5] Constantin C, Gekelman W, Pribyl P, et al, Astrophys Space Sci, 322 (2009) 155-159.

[6] Schaefer D B, Everson E T, Winske D, et al, Phys Plasmas, 19 (2012) 070702.

[7] Schaefer D B, et al, Ibid, 20 (2013) 012108 and 21 (2014) 056312.

[8] Wright T P, Phys Fluids, 14 (1971) 1905-1910 /Longmire C.L., RAND RM-3386-PR (1963).

[9] Park H-S, Ryutov D D, Ross J S, et al, High Energy Density Phys, 8 (2012) 38-45.

[10] Zakharov Yu P, Ibid, 8 (2012) 329-330.

[11] Bashurin V P, Golubev A I, Terekhin V A, J Appl Mech Tech Phys 24 (1984) 614-622.

[12] Zakharov Yu P, et al, In: Techn Digest 6th Intern Symp "Modern Problem of Laser Physics" (25-31 Aug 2013) 193-194 / See: mplp.laser.nsc.ru

[13] Zakharov Yu P, Antonov V M, Boyarintsev E L, et al, Ibid, 191-192.

[14] Mora P, Phys Fluids 25 (1982) 1051-1056.