Generation of quasi-perpendicular Collisionless Shocks by Laser-Produced Plasma to simulate the effects of super-compression of the Earth's magnetosphere

Yu P Zakharov¹, A G Ponomarenko¹, V A Terekhin², A I Golubev², V M Antonov¹, E L Boyarintsev¹, K V Vchivkov¹, A V Melekhov¹, V G Posukh¹, P A Prokopov¹

¹Institute of Laser Physics (ILP), Siberian Branch of Russian Academy of Sciences (SB RAS), Novosibirsk, Av. Lavrentyeva 13/3, 630090, Russia.
²All-Russian Research Institute of Experimental Physics (VNIIEF), Sarov, Av. Mira 37, 607188, Russia.

E-mail: ki1z@mail.ru

Abstract. Giant plasma releases of so called Coronal Mass Ejections (CME, with kinetic energy up to \(E_k \sim 10^{36}\) erg) from the surface of the Sun and their potential catastrophic impact onto Earth's magnetosphere, with the probable opportunity to compress it in 2, 3 or more times [1, 2], represent one of the most important problem in the geophysical and historical bi-evolutional investigations of the past and present of the Earth. It was supposed that the re-connection of dipole magnetic field at magnetopause could play [2] an exclusive role in its inward shift, but from the more general point of view (to perform laboratory simulation [3-6] of magnetopause dynamics), a more important and common features of CME propagation in Solar Wind plasma are the formation of collisionless Quasi-Perpendicular Shocks (Q-PS) ahead of Super-Alfvenic CME. It is provided by the almost radial (along to \(R\)) motion of CME from the Sun, while the Interplanetary Magnetic Field \(B_0\) has an angle \(\theta \sim 45^\circ\) (relative to \(R\)) near the Earth orbit. Up to date, in spite of intensive development of laser energetics and energy of Laser-produced Plasma (LP), such Q-PS never were generated by LP [7], excluding recent experiment [8] at KI-1 facility of ILP. In the given work, a first results of our study were presented together with relevant calculations by hybrid code and the basic physics of VNIIEF-model [9] for the collisionless Magnetic Laminar Mechanism (MLM) of interaction between a spherical LP and magnetized Background Plasma (BP). A special analysis was done on the conditions and data of the formation of whistler precursor in front of revealed oblique (Q-PS) shocks as well as on the first data of dipole's field compression by BP and Shocks.

1. Introduction.

Recent numerical MHD-simulations of NASA [1, 2] show that due to the action (in ancient times) of CME (with the Super-High effective energy up to \(E_0 \sim 10^{37}\) ergs), a very strong compression of the Earth' magnetopause could occur, from its usual size \(R_{mp} \approx 10R_E\) (Earth' radius) up to extreme value \(R_{mp}^* \leq 1.5R_E\) (!). Therefore a real opportunity could appear for direct contact [2] of interplanetary and Solar energetic plasmas with the ionosphere’ and even upper atmosphere’ media. As a result, a lot of various chemical reactions and even possible origin of prebiotic life chemistry [1] could take place there, as a basic phenomenon of new scenario for the origin of life at the Earth. Some parts of these
effects we could successfully studied in our recent experiment HERMEX [5] at KI-1 facility of ILP, with a blobs of Laser Plasma (LP) and flow of Background Plasma (BP, near impulsive magnetic dipole $\mu$), to simulate an effect of two-fold compression of laboratory model of Magnetopause (MP). But this simulation was done in a rather simple way – without essential interaction effects between LP and BP, since both of them were directed to dipole along to small uniform magnetic field $B_0$ (it was $\perp \mu$). Here we present a first results of new simulative experiment MPS (Magnetopause & Shock), in which we try realize for the first time an important part of CME phenomena – a strong forward disturbance of BP in a form of Collisionless Shock Wave (CSW), namely Quasi-Perpendicular Shock (Q-PS), most typical one for the CME case near the Earth. Q-P case means angle $\geq 45^0$ between shock normal $\mathbf{k}$ and $B_0$ ($\| \mathbf{Z}$, horizontal central axis of facility chamber). At Figure 1 and Table, a general scheme and the parameters (with a relevant similarity criteria) of simulative experiment MPS at laser facility KI-1 (Kosmicheskie Issledovaniya-1) are presented.

**Figure 1.** Scheme of MPS experiment in the horizontal (ZY) plane of KI-1 facility of ILP: 1 – Laser polyethylene target (spot $\varnothing \sim 2.5$ cm); 2 – focusing mirrors for CO$_2$-laser (up to 500 J); 3 – dipole; 4, 5, 6 – sets of magnetic and Langmuir probes; 7 – wall of high-vacuum chamber (5 m long and $\varnothing 1.2$ m, pressure $\sim 3 \times 10^6$ Torr); 5 (is $P_1$ probe), 6 (LP). LP (Laser Plasma) – blob near target (1); CSW: Shock, generated near central part of BP (Background Plasma, flowing from the right), with maximal density up to $5 \times 10^{13}$ cm$^{-3}$ ($H^+$) in $\varnothing \sim 70 \pm 80$ cm, $\mu$ is a dipole up to $10^6$ G*cm$^3$.

2. MLM-processes for Collisionless Shock generation by Laser Plasma Piston.

A basic physical background to generate CSW by LP at KI-1, was a so a called Magnetic Laminar Mechanism (MLM), studied for the first time theoretically at VNIEF [9] and experimentally, for the first time at KI-1 [10]. Today only unique experimental features of KI-1 facility give a real opportunity to generate both PerPendicular (P-P) Shock [11] and Q-P one (Figure 2a) in laboratory, first of all, due to unique method [12] of producing Laser Plasma Blob with effective kinetic energy up to $E_0 \sim 1000$ J. Namely such large values of $E_0$ and effective number electrons $N_{el} \geq 10^{19}$ in LP are need to supply effective MLM-interaction of LP with BP and generate CSW in it at the need angle up to $\theta \approx 45^0$ due to the enough large value of MLM-parameter $\delta_0 \approx 1.5$ [9], determined as $\delta_0 = R^2 / R_L^2$. Here $R = (3N_{el}/4\pi n_e)^{1/3}$ is maximal size of diamagnetic cavity of LP in BP [9] and $R_L$ are Larmor radii of both LP$^+$ and BP$^+$ ions (both determined by $V_0$ and $B_0$). So, the effective MLM-interaction for CSW generation could be [9] at angles $\theta_m \geq 90^0 - \arcsin(2\delta_0/3)$, that means essential effect not only near “equator” (where $\theta = 90^0$) of expanding LP-sphere (where initial $B_0$-field directed from its pole to
pole). Since for our case of high Alfven-Mach number (M_0 ≥ 4, see Table), only MLM could supply enough [13] transfer LP energy E_k to kinetic energy E_v of BP (as E_v = δ_v E_k) for the CSW generation, we need to realize δ_v ≥ 1. For this case also the angle θ_a could reach a need value ~ 45° to generate a Q-P Shock. However, in the MPS we have used (Figure 1) not a spherical LP [10], but an expanding (within volume angle ΔΩ ~ 1 sr) LP-blob [6, 12], directed at the angle θ ~ 45° relative to B_0. For this and other cases we can use the relation for effective energy of LP-blob, as E_v ~ 4πE_k/ΔΩ up to 1 kJ.

| Parameters / Criteria                                      | Notations                                                                 | Values                      |
|-------------------------------------------------------------|---------------------------------------------------------------------------|-----------------------------|
| Density of Background Plasma - BP (its diameter Ω)          | n_v (Ω)                                                                  | (1-2) -10^{13} cm^{-3} (Ω ~ 70-80 cm) |
| Parallel (to B_0) velocity of BP (and its ions)             | V_v (H^+)                                                                | 50-60 km/s (H^+)            |
| Size of Magnetopause (MP) around dipole in the BP            | R_{mp} = (μ_0^2 / 4πn_v m_v V_v^2)^{1/6}                                 | ~ 25 cm                    |
| Magnetic moment of dipole and radius R_d                    | μ                                                                         | up to 10^6 G·cm^{-3}, R_d = 3.5 cm |
| Uniform magnetic field in chamber (along to V_v of BP)      | B_0                                                                      | 80 G                       |
| Kinetic energy of Laser Plasma-LP (Effective Energy)        | E_k (E_0)                                                                | ~ 60 J (700 J)              |
| Expansion velocity of LP (and its solid angle <ΔΩ>)         | V_0 (of front)                                                           | Up to 200 km/s (<ΔΩ ~ 1Sr) |
| Distance between a dipole center and point of LP             | R_0                                                                      | 103 cm                     |
| Size of MP in the stream of LP (in vacuum)                  | R_m = 0.75R_0/k^{1/6}                                                   | ~ 15 cm                    |
| Hall parameter D for MP in plasmas of BP and LP             | D = R_0/(C_0/ω)                                                          | D_1 ~ 3 and D_2 ~ 1        |
| Alfven-Mach number for LP in BP with Alfven C_A*           | M_A* ≈ V_0/C_A*                                                          | ~ 5-6 ~ 10                 |
| Energetic criterion LP (H^+ /C^+ ions, <s/mz > ≈ 2.5a.e.m.) | K = 3E_0R_0^2/μ_0^2                                                      | ~ 2*10^7 ~ 2*10^8          |
| Ratio of velocities of LP to BP                             | V_k/V_0                                                                  | ~ 4 (~10)                  |
| Ratio of the initial MP-size to its compressed one          | ξ = R_m/R_m^*                                                            | ~ 2 (HERMEX, 2013- without Shock!) |

For Giant CME(E_0 ≥ 10^{44} erg) impact onto Earth’ MP: M_A*~50 ≥ 10, V_0/V_1 ∼ 7 (10), K ~ 10^{12} >> 10, D_v ∼ D_v ~ 1000 >> 10 and ξ ~ 2 (while even up to ξ ~ 6 for Super CME with E_0 ~ 10^{37} erg)

For the main goal of whole experiment – maximal compression [5] of Magnetosphere Model (MM), we could expect that kJ-LP from its distance R_v ~ 100 cm (to dipole) with the energetic criterion K = 3E_0R_0^2/μ_0^2 ~ 10^8 should compress MM up to new size R_m = 0.75R_0/k^{1/6} ≈ 15 cm (from the initial R_v ≈ 25 cm). Such near 2-fold compression will be comparable with the data of previous HERMEX, but due to presence of Q-P Shock we could expect some additional effects [1, 2]. Note that up to now none of both shocks (P-P or Q-P) had not reliably observed in LAPD experiments of California University [14].

3. Data on Q-P Shock generation in MPS and its numerical simulations by Hybrid model.

At Figure 2 a main data on the Q-P Shock (a) generation are presented with the important feature of such shock [15], as a whistler precursor (curves 2, 3 ~ c B/εt – signal of probes with area 1 cm²), ahead front (curve 1) of density jump.

**Figure 2. a – Data of MPS on Q-P Shock generation by LP at distance R ~ 77 cm: 1– density; 2– magnetic B_x-field; 3– B_y-field (vector summ). b – Data of 2D-PIC simulation (spherical LP expansion into direction 45°) for close conditions and in the same notations (1,2,3).**

4– density (zoom in 5 times) of LP C^+ ions (H^+ ions stay at 65-70 cm).
The data of Figure 3 present another important feature, a joint and coincidental R-t diagram of MPS-experiment and its simulation by the model «Clouds03» (of Dudnikova and Vshivkov [16]), that early also was applied successfully for the analysis of data KI-1 on perpendicular Shock generation [12].

In spite of rather similar general MHD-features of colisionalless interaction between LP and BP, in MPS and its PIC-simulation (Figure 3), the details of magnetic structures in front of BP-density jump are very different. At Figure 2a, such MPS-structure reveals a typical for whistlers [17] phase shifted two oscillating B-components (2 and 3), really ahead of BP-jump (1), while a simulative data (Figure 2b) have a monotone character (2,3), very probably correlated with a dynamics of heavy LP-ions (4). The reason of absence a whistler precursor (Figure 2a) in MPS-simulation (Figure 2b), may be a zero electron mass [15] in the used «light» version of hybrid code [16]. In the control runs without heavy LP-ions (and similar R-t diagram), a whistler-type precursor also was absent at super-Alfvenic fronts.

4. Preliminary data of MPS experiment on the compressions of dipole magnetic field \( B_{d} \).

At the Figure 4 a joint data of Magnetic Probes (MP-3,4,5) and Langmuir one (1,2) near the dipole in a flow of BP (1) with the Q-P Shock (2) are presented. In the case of the compression-type both MP-signals, a cumulative effect of BP with QPS leads to the two-fold increasing of the total \( B_{d} \)-field jump (up to \( \Delta B_{d} \approx 180 \) G, in comparison with the BP-alone). This \( \Delta B_{d} \)-value is not so much in a sense of probable inward shift of MP (around ~30 % only), but it allows us to do a comparison with some MP-model predictions and to plan the development of MPS-experiment. In particular, to test a most simple and general MP-model for \( \Delta B_{d} \)-jump, based on the well known solution for the dipole field inside of super-conductive sphere [18], such as additional magnetic field \( B_{s} \) parallel to dipole \( \mu \). For the radius \( R_{s} \) of sphere and radius \( R_{d} \) of dipole (its super-conductive sheath) solution has a form: \( B_{s}(r) = \mu*[(1/r^{2} + K/R_{s}^{3})/(1-R_{d}^{3}/R_{s}^{3})] \), where \( K \) is a geometric factor: \( K = 2 \) for the whole sphere and \( K \approx 1 \) for its one half, as a model of MP front end. So for the given MPS-case (Figure 4), from the maximal value \( \Delta B_{d} \approx 180 \) G ~ \( B_{d} \), one could estimates a probable MP-size as \( R_{s} \approx 17-18 \) cm.

**Figure 4.** Joint data of Langmuir (1, 2) and magnetic (3-5) probes [19] near dipole (point 5 at Figure 1) in MPS1 experiment: 1 – initial part of Langmuir data is a flow of Background Plasma (BP); 2 – Shock-type disturbance of BP caused by Laser Plasma (LP) injected at the time \( t = 0 \); 3 – initial part of Magnetic Probe (MP) data caused by BP; 4 and 5 are disturbances of dipole magnetic field \( B_{d} \), registered by two orthogonal coils of MP (B2 and B3) at the distances more close to dipole surface (than Langmuir one). Sensitivity of Langmuir probe (P1) for its 1 V, gives BP-density \( (H^{+}) \approx 5*10^{13} \) cm\(^{-3}\), while 1 V of B2-jump corresponds to 75 G and B3-jump to 50 G.
5. Conclusions.
In the given paper a first data of new type, combined and complicated simulative experiment MPS with a laser-produced plasma, magnetized background and compact impulsive magnetic dipole, at KI-1 facility of ILP are presented. Two most important and fundamental results were obtained for the first time. Due to very high effective energy of laser plasma (up to $E_0 \sim kJ$) and density of background (up to $3 \div 5 \times 10^{13}$ cm$^{-3}$) at scale $\sim 1$ m, a collisionless Quasi-Perpendicular Shock was generated by laser plasma piston for the first time, with a typical whistler precursor (Figure 2a). At presence of such shock in a flow of background, a strong additional compression of magnetic field near dipole was revealed for the first time (Figure 4), as an important effect for the laboratory simulation of extreme super-compression of the Earth' magnetosphere [1, 2]. Future development of MPS experiment could allow to simulate also a collisionless Bow Shock [20, 21] in front of region of compressed dipole magnetic field and its probable interaction with a generated Quasi-Perpendicular Shocks.

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