Laser-plasma experiments to study super high-energy phenomena during extreme compression of the Earth's magnetosphere by Coronal Mass Ejections *

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Abstract. Problem of the global and even catastrophic modification of the Earth's magnetosphere (into Artificial one) by impulsive and huge plasma ejecta, was proposed for the first time during our study of possible after-effects of high-energy explosions against asteroids at near-Earth space. Later, a similar problem of extreme compression of the Earth's magnetopause from its usual $R_{mp} \approx 10R_E$ up to new stand-off distance $R_m^* \sim 3R_E$, by plasma of giant Coronal Mass Ejections (CME, with effective energy $E_0 \sim 10^{28}$ J), was considered for its simulations by Laser-Produced Plasma (LPP) at KI-1 facility of ILP, that were done initially without "Solar Wind" (in AMEX experiment). Here we present the first results of the "full" laboratory simulations of the CME-problem with the up-stream impact of LPP (with $E_0 \sim 1$ kJ) onto classical terrella-model of "stationary" magnetopause (with $R_{mp} \approx 17$ cm), formed near compact dipole in a flow of background H^+-plasma, imitated Solar Wind. As a result, we have observed for the first time a two-fold compression of magnetopause size, accompanied by very strong and near expected value of dipole magnetic field's compression up to the factor $7 \div 8 \approx (R_{mp}/R_m^*)^3$ inside of magnetopause. Our data allow to predict a global CME-effect at $E_0 \sim 10^{29}$J.

1. KI-1 Program and basic researches of Plasma-Dipole interaction for laboratory simulations

More than 50 years ago in many plasma laboratories had started various experiments with magnetic dipoles to create a model of the Earth's magnetosphere, so called "terrella". But up to now, none of them has not well confirmed possibilities to reproduce in a full measure (and to study) a whole physical processes [1], even in more simple case of front MagnetoPause (MP) with the main Chapman-Ferraro current system, which forms a magnetic cavity around dipole in Solar Wind (SW) . Moreover, in the past were absent a technical opportunities to simulate a non-stationary phenomena in MP-region, caused by strong shock-disturbances of SW, most powerful of which are a natural giant Coronal Mass Ejections (CME) from the Sun [2,3] as well as a artificial anti-asteroid explosions at near-Earth space [4]. Namely for simulation of both given cases of the global SW-disturbances, a general scientific Program was formulated near 40 years ago [5] during creation of the facility [6,15] "Kosmic Investigations - 1" (KI-1) of ILP, based on the using of high-power CO_2-lasers for generation of Laser-Produced Plasma (LPP) to imitate CME (and its shocks) or space explosions. From the very beginning of the realisation of KI-1 Program a study of the basic collisionless interaction processes between LPP and magnetic fields (or magnetized Background Plasma - BP), including dipole one, became the main goal of all investigations [6]. As a result, at their final stage a new and very

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important PIC-modeling [7], experimental [8] and theoretical [7,9] data on the Plasma-Dipole (PD) interaction was obtained, for the conditions required to simulate MP structure correctly. According to this data, the observed "anomalous" penetration of plasma (up to $R_n \sim$ Stoermer radius [8,10]) inside of classical MHD-scale of the MP at R_m and opposite outward shift of cavity boundary up to R_x are caused mainly by Hall-effects according to new model [7,9] at presence of observed Large Larmor Flute Instability [11-13]. Both non-MHD "R_n" and "R_x-effects" are determined by the low-value D <1, as shown for latter one at figure 1, where $D = R_m/\Lambda_i$ is a general physical criterion of the problem [14] for ion inertia scale $\Lambda_i = C/\omega_{pi}$. So, for the correct simulation of magnetic cavity boundary ($\gamma \approx 1$) we need to supply D ≥1, while to get a plasma front R_n rather close to R_m one needs a value D ≥ 2÷3 [7,9].

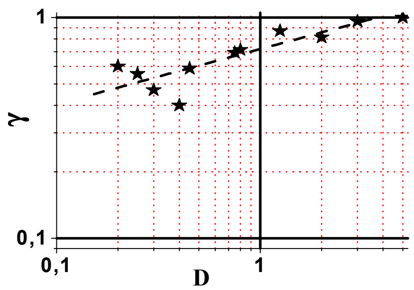

Figure 1. Combined data (*) of experiments and 3D/PIC-simulations of ILP [7-9] (with another calculation data by the same PIC-code [12] of Kyushu University) on the stand-off size R_x of magnetic cavity around dipole, in comparison with its Hall-MHD model [9] – dashed line. Here 3D-model dimensionless dependence (for D ≤1), like $\gamma = (R_x/R_m)^{-1} \approx \alpha D^{1/4}$, is determined by the main criterion D [14]. We had used the data of quasi-stationary overflowing of dipole by plasma stream (with MP at $R_m = R_{mp}$) and dipole in a flow of exploding plasmas, when $R_m = R_m^*$.

In a review papers [1,9] a lot of KI-1 experimental data on mainly steady (and some LPP) plasma overflowing of various dipoles μ are presented for regimes of different D up to D ≈ 5, when a both BP' front and MP-position are very close to MHD scale $R_{mp} = (\mu^2/4\pi n_* m_* V_*^2)^{1/6}$, determined by density n_*, ion mass m_* and velocity V_* of SW. For the case of exploding plasmas, a very useful approximation $R_m^* \approx 0{,}75 R_0/æ^{1/6}$ for MHD MP-position was suggested [4,11], based on the value of another, energetic criterion $æ = 3E_0R_0^3/\mu^2$ of problem, for the distance R_0 between a dipole and point of plasma ejection. Given relation for R_m^* was tested in comparison with a simple MHD-model [4,11] and 3D/PIC-simulations [11-13] of PD-interaction in vacuum as well as was verified in a series [11-13] of Artificial Magnetosphere Experiments (AMEX) with LPP in a wide range of 20 ≤ æ ≤ 5000.

2. A "full" simulative HERMEX experiment at KI-1 with Background and Laser Plasmas

The characteristics of new simulative scheme HERMEX (HERmean Magnetosphere EXperiment) shown at figure 2, are most suitable to study the non-stationary CME-related processes in the Mercury, more simple magnetosphere: without ionosphere and almost non-conducting planetary surface, that means a small influence of the additional current systems, like a field-aligned (Birkeland or FAC) one. This new scheme is similar to our previous one [15], when during a KEVL [11] experiment with high-density BP, the surface of dipole (with small moment $\mu \sim 10^5$ G*cm^3) had been hit by LPP blob. Here,

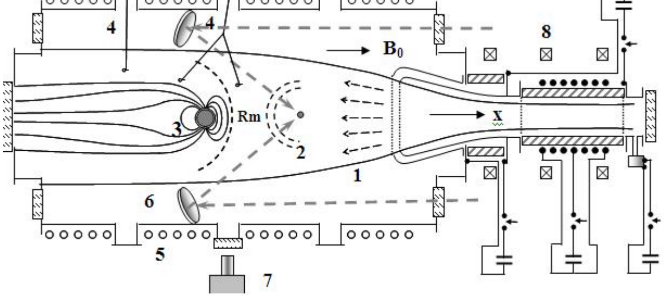

Figure 2. Experimental scheme of **HERMEX** with Background Plasma (**1**) and Laser-Produced Plasma (**2**) at distance R_0 = 46 cm from dipole (**3**), in high-vacuum chamber (∅ 120 cm), supplied by: Langmuir and magnetic probes (**4**), coil system(**5**) for uniform magnetic field B_0, focusing elements (**6**) for CO_2-Laser beams (2*100J / 100 ns), Gated Optical Imager-GOI/100 ns (**7**) and θ-pinch (**8**) to generate flow of Background Plasma.

we had used a new compact dipole with the moment up to 10^6 G*cm^3, which allows to supply all nessessary conditions (see Table) to simulate magnetopause of the Earth and its super-compression due to using of enhanced effective LPP-energy, i.e. $E_0=(dE_0/d\Omega)*4\pi$ (and effective number $N_{e0}\sim 10^{19}$ for electrons), while $E_k=(dE_0/d\Omega)*<\Omega>$. Laser spot was ~ 3 cm^2 at polyethylene target of convex form.

Parameters	**Notations**	**Values**
Density of Background Plasma - BP (its diameter)	n_* (∅)	$1.5\cdot10^{13}$ см$^{-3}$(∅ ~70-80 cm)
Velocity of BP (and ions)	V_* (H^+)	50-60 km/s (H^+)
Size of MagnetoPause (MP) in the BP	R_{mp}	17-18 cm
Magnetic moment of dipole and radius R_d	µ	$5*10^5$ G*cm^3, R_d = 2,7 cm
Uniform magnetic field in chamber (along to V_* of BP)	B_0	20 G
Kinetic energy of Laser Plasma-LPP (Effective Energy)	E_k (E_0)	~ 60 J (700 J)
Expansion velocity of LPP (and its solid angle <Ω>)	V_0 (of front)	≈ 210 km/s (<Ω> ~1 Sr)
Size of MP in the stream of LPP (in vacuum)	R_m^*	8 cm
Hall parameter D for plasmas BP and LPP	$D = R_m/(C/\omega_{pi})$	$D_*\approx 3$ and $D\approx 1{,}5$
Alfven-Mach number for LPP	$M_{a0} = V_0/C_{A*}$	~ 20 >> 1
Energetic criterion LPP (H^+/C^{+4} ions,<m/z>≈2.5a.e.m.)	$æ = 3E_0R_0^3/\mu^2$	~ 10^4 >> 1
Ratio of velocities of LPP to BP	V_0/V_*	~ 4 (~10)
Ratio of the initial MP-size to its compressed one	$\nu = R_{mp}/R_m^*$	~ 2
For the case of CME impact onto Earth' MP: M_{ao}~70 >>1, V_0/V_* ~7(~10), ν ~ 2÷3; æ ~10^{23} >>1, D_*~D~1000		

3. Electromagnetic Global Effect of CME and main results of HERMEX experiment

The fast and global changes ΔB of geomagnetic field (SSC) during MP-compression by CMEs, probably are the most dangerous of their after-effects [2-4,16], leading for example to well-known damages of high-power transformers and other grids. This problem is characterized by the value ΔB/Δt which could reach a few 1000 nT/min for giant CME, according to our estimations [11], which is comparable with the local ΔB-changes of auroral electrojets [17]. Magnetic field B_{CF} of Chapman-Ferraro current system (at semi-spherical MP) is a quasi-uniform [12] with the level $B_{CF}\approx\mu/R_m^3$ from which its independence from dipole µ followed, for both MHD-expression R_{mp} and R_m^* for MP-position. Data of GOI (Figure 3**a,b**) show an effect of two-fold compression of MP by LPP in BP up to the size of $R_m^*\approx 8$ cm for the given case (µ = $5*10^5$ G*cm^3) of LPP in vacuum (**c**), since a scale of LPP interaction with BP [4,11] is $R_*=(3N_{e0}<m/z>/4\pi n_*m_*)^{1/3}\approx 75$ cm and larger than R_0 = 46 cm, as corresponds to the value of specific criterion for BP-problem $\xi = R_*/R_0\sim 2$ also in space (at $E_0\geq10^{27}$ J). GOI-data give dependence of MP-size for BP+LPP cases rather close to LPP (in vacuum, Figure 4).

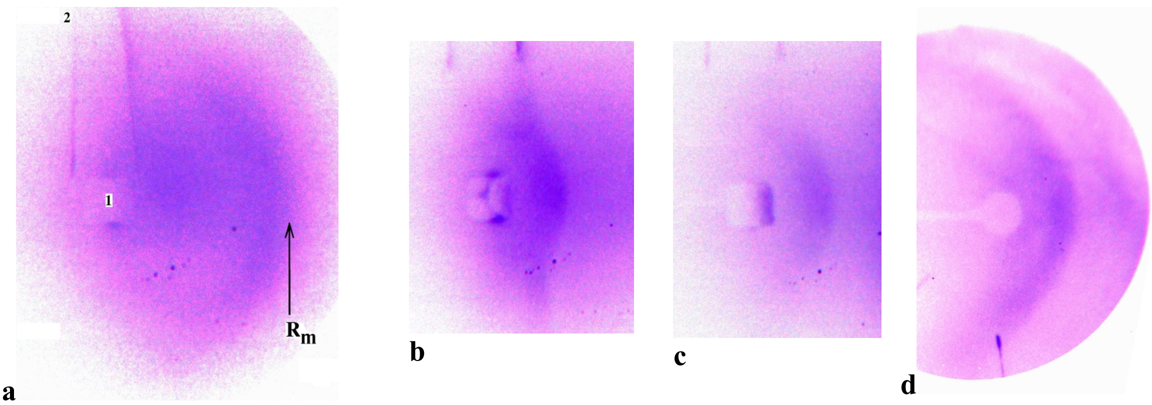

Figure 3. Meridian shape of MP formed by Background Plasma (BP):1–dipole (∅5,5 см); 2–probes

The same for joint action of both BP and LPP at t=2,2 µs.

Meridian (**c**) and equatorial (**d**) shapes of MP formed by Laser-Produced Plasma (LPP) in vacuum (t=2,2 µs and t=2,9 µs).

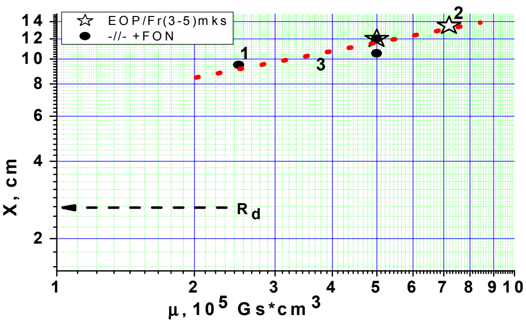

Figure 4. GOI data on MP-position depending upon dipole μ for regimes:**1**–Laser Plasma with Background one; **2**–Laser Plasma only; **3**– scaling $R_x \propto \mu^{1/3}$ from R_m^* (left point at t≈3 μs, others t≈4,8÷5 μs). R_d - dipole rad.

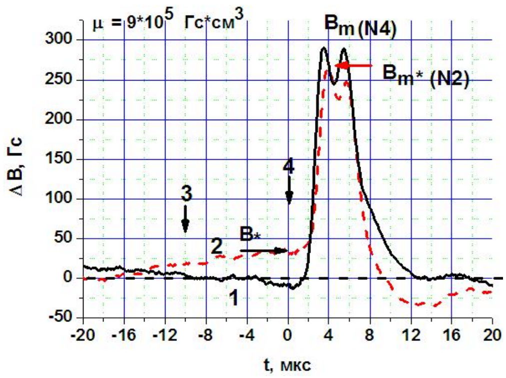

Figure 5. Compression of magnetic field near dipole by Laser Plasma: **1** – B_m in vacuum; **2**– B_{m*} with Background Plasma (its ΔB=B_* starts at point **3**); **4**–Laser starts.

Typical examples of magnetic field compression ΔB is shown at Figure 5 and for both values of ΔB (from BP and LPP) were are almost independent from the μ-value (as was expected). Indeed the both corresponding quantities ΔB=B_* and B_{m*} are slightly increase, when μ decrease from initial (at Figure 5), as $B_*/B_{m*} \approx$ 35/267; 40/283 and 47/310 (in G) for μ = 9; 5 and 2,5 (in 10^5 G*cm^3). Although BP did not affect onto MP, it seems that at presence of background, some more complicated plasma (and field) structures are formed near dipole surface (Figure 3b), like a FAC with negative ΔB at Figure 5 (t=12 μs). Therefore, in the case of “Superflare” [18] with $E_0 \sim 10^{29}$ J, not only a super-compression of magnetopause up to $R_m^* \approx 2R_E$ could occur, but also extreme FAC near polar regions could be generate.

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References

[1] Antonov V M, Boyarintsev E L, Zakharov Yu P, Melekhov A V, Posukh V G, Ponomarenko A G, Shaikhislamov I F 2013 in *Plasma Heliogeophysica*, 20 p. – In Press
[2] Ponomarenko A G, Zakharov Yu P, et al. 2006 *IAU Symposium “Solar Activity…”* **233**, 389
[3] Manchester W B, Ridley A J, Gombosi T I et al. 2006 *Adv. Space Res*. **38** 253 and 263
[4] Zakharov Yu, Nikitin S, Ponomarenko A, et al. 1997 *Annals New-York Academy Sc.* **822** 583 and Zakharov Yu, Nikitin S, Ponomarenko A. 1996 *Computational Technologies* **1**, 36 (In Russ.) in https://www.researchgate.net/profile/Yuri_Zakharov/publications/4?sorting=published
[5] Gevorkyan L, Orishich A, Ponomarenko A, Soloukhin R, et al. 1976 in *Physical Gasdynamics*, **6** Novosibirsk, Inst. Pure and Applied Mechanics AN USSR 192 (in Russ.)
[6] Zakharov Yu P 2003 *IEEE Trans. Plasma Sci.* **31** 1243
[7] Zakharov Yu P, Antonov V M, Boyarintsev E L, Vchivkov K V, Shaikhislamov I F, Melekhov A V, Posukh V G, Ponomarenko A G, et al. 2009 *Int. Conf. on Space Science and Commun.* 96
[8] Zakharov Yu P, Antonov V M, Shaikhislamov I F, et al. 2011 *Contrib. Plasma Phys.* **51** 18
[9] Shaikhislamov I F, Antonov V M, Zakharov Yu P, et al. 2013 *Adv. Space Res*. **52** 422
[10] Fujita K 2004 *J. Space Technol. Sci.* **20** 26
[11] Ponomarenko A G, Zakharov Yu P, Antonov V M, et al. 2007 *IEEE Trans. Plasma Sci.* **35** 813
[12] Zakharov Yu P, Antonov V M, Boyarintsev E L et al. 2008 *J. Phys.: Conf. Ser.* **112** 042011
[13] Zakharov Yu P, Ponomarenko A G, Horton W, et al. 2009 *Astrophys. Space Sc.* **322** 151
[14] Omidi N, Blanco-Cano X, Russell C T, Karimabadi H 2004 *Adv. Space Res.* **33** 1996
[15] Ponomarenko AG, Zakharov Yu P, et al. 2008 *Plasma Phys. Contr. Fus*. **50** 074015
[16] Kuznetsov V D, Makhutov N A 2012 *Herald Russian Academy Sciences* **82** 36
[17] Kappenman J G, in *Space Storm and Space weather Hazards*, NATO Sci. Ser., **38**, 335 (2001)
[18] Schaefer B E, et al. 2000 *Astrophys. J.* **529** 1026; Maehara H, et al. 2012 *Nature* **485** 478