New Type of Laser-Plasma Experiments to Simulate an Extreme and Global Impact of Giant Coronal Mass Ejections onto Earth’ Magnetosphere

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Abstract. The goals, technical approach and first results of a new-type Laser-Plasma experiment AMEX for the simulation of over-compression effect of the Earth’ magnetosphere by Giant Coronal Mass Ejections are described. Parameters of large-scale KI-1 facility of ILP with kJ-laser provide such values of dimensionless criteria which are in the range of very rare and enormous Solar flares that could cause a shift of magnetopause from the usual distance of 10\(R_E\) down to \((2-3)R_E\). These extreme “Artificial Magnetosphere” states with highly compressed dipole field could result in world-wide damage phenomena in various networks and its physics could be explored in laboratory only by using of compact dipoles with a large moment. In a series of experiments with a variable magnetic moment and plasma blobs of effective energy up to 500 J an important role of plasma instabilities at magnetopause was revealed. The data on the magnetopause shape and stand-off size show a good correspondence both to general magnetospheric models and to expected scaling of “Artificial Magnetosphere”.

1. The problems of formation and simulation of “Artificial Magnetosphere”
More than 3-fold compression of the Earth’ magnetosphere caused by giant Coronal Mass Ejections (CME), driven by recently discovered Mega Solar Flares with the total released energy \(\geq 10^{34}\) ergs, is potentially so hazardous in after-affects, that requires an advanced and detailed investigation, by means of new laboratory simulations as well [1]. A physical conditions of such rare and enormous phenomenon could be understood on the base of our concept [2,3] of a non-stationary “Artificial Magnetosphere” (AM) which forms when an exploding plasma flows aroud of magnetic dipole.

According to the MHD-model [1-3], the stand-off distance \(R_m^*\) of AM magnetopause is determined by a main energetic parameter of the problem \(\vec{\alpha} = 3E_0R_0^3/\mu^2\) (for effective plasma energy \(E_0\) and distance \(R_0\) between dipole center and energy release point). For the case \(\vec{\alpha} \gg 1\) it could be expressed approximately as \(R_m^* \approx 0.75R_0^{\vec{\alpha}/3}\). This scaling was confirmed for the fist time in the Laser-Plasma (LP) experiment of ILP [3] at KI-1 target-chamber \(\Omega 120\) cm and recently in our PIC-simulations [1,5] by 3D/Hybrid-code of KU [6]. Our first experiment was characterized by unmagnetized ions in a sense...
that their Larmor radius $R_L(\propto V_0)$ at magnetopause was larger than $R_m^*$, i.e. criterion $\varepsilon_m=R_L/R_m^*\sim3 (>1)$, like in the pioneer work of W.H. Bostick [7]. To correctly simulate AM-formation around the Earth in details we carried out AMEX experiment in the required MHD range of dimensionless criteria $\varepsilon_l >> 1$ and $\varepsilon_m < 1$. So far the problem was explored in this range only in 2D [8] and 3D [6] PIC- simulations, but only for stationary overflowing, while for the non-stationary and CME related phenomena, a 3D/MHD-code [9] appears recently. To analyze our laboratory results and apply them to extreme geophysical phenomena we used a PIC hybrid code of KU, which was verified in turn by AMEX data.

2. AMEX simulative experiment at KI-1 laser facility

All simulative experiments were done on the base of the same set up (see figure 1a), but with different parameters of explored regimes, main part of which (# 1-6) are listed in the table 1.

A CO₂-laser LUI-2M with 500 J, 100 ns output pulse was focused into a spot ~ 1 or 3 cm² at a plastic target made in a plane (# 1-3) or convex (# 4-6) forms, accordingly. Generated plasma consisted mainly of H⁺ and C⁺ iv ions with $<m/z> = 2.5$ a. e. m. expanding with front velocity $V_0$ (of maximum dynamic pressure). In the case of convex target and larger focusing spot the velocity was smaller, while the density profile had two maximums also. The effective energy $E_0$ of the first such
blob, defined as $E_0 = (dE_0/d\Omega) * 4\pi$ with maximal $dE_0/d\Omega$ taken into direction of dipole, is listed in table 1. At figures 1 c,d the second and freely expanding maximum (marked as LP_2) is seen in front of magnetopause already formed by the first maximum. The front and lateral sizes of magnetopause are marked as $R_X$ and $R_Y$. These photos of quasi-stationary MP, taken at times $t \approx 3.5-4.5\mu s$ after the laser pulse by Gated Optical Imager (GOI) with 100 ns exposition, reveal substantial spatial modulation of luminosity along to MP-boundary, probably produced [7] by its flute-like instability (see figure 1d).

Table 1. Main parameters and dimensionless criteria of simulative experiments in various regimes.

| Parameters | Regimes | $R_0$, cm | $E_0$, J | $V_0$, km/s | $\mu_0$ | $G^*\text{cm}^3$ | $\alpha = 3E_0R_0^3/\mu^2$ | $R_m^*$, cm | $R_X$, cm | $\epsilon_m = R_t/R_m^*$ |
|------------|---------|-----------|----------|-------------|--------|----------------|-----------------------------|----------------|-----------|---------------------|
| N (natural)| 1.5*10^{13} | $\geq 10^{27}$ | $\geq 2000$ | $8*10^{25}$ | $2*10^{22} \gg 1$ | $2*10^9$ | ? | 0.001<<1 |
| M (modeling)| 85 | 5600 | 250 | $1.1*10^7$ | $\sim 700$ | 21.3 | 21 | 0.24 (<1) |
| 1 | 75 | 500 | 220 | $1.1*10^6$ | 5000 | 13.5 | 18 | 0.9 |
| 2 | 75 | 500 | 220 | $2*10^6$ | 1600 | 16.5 | 19^a | 0.7 |
| 3 | 75 | 500 | 220 | $1.1*10^7$ | $\sim 50$ | 28.5 | 32^a | 0.4 |
| 4 and 5 | 65 and 61.5 | 200 | 180 | $2*10^6$ | 400-350 $\gg 1$ | 18-17.5 | 20.5 | 0.7-0.6 < 1 |
| 6 | 61.5 | 200 | 180 | $1.1*10^7$ | $\sim 10$ | 28^b | 29 | 0.35 (<1) |

^a Determined by GOI on maximal plasma luminosity near magnetopause
^b Determined more precisely (at $\alpha \leq 50$) by MHD-model [2]

3. Structure and shapes of laboratory magnetopause at various values of energetic criterion $\alpha$

In figure 2 a typical profile of the main (B_z) magnetic field' changes $\Delta B(x)$ along the central axis of interaction is shown. It corresponds to one of the most important regimes #5 and is measured at the moment $t = 3\mu s$ when magnetic field compression inside of MP is at its most. At times 3-4 $\mu s$ the magnetopause remains quasi-stationary and has the shape and size rather close to the picture 1d. The actual position of MP boundary was determined as a curve where $B_z=0$, for which data of a whole set of magnetic probes positioned in the X-Y plane was used. The main dimensions of MP curve were measured to be $R_X \approx 20.5$ cm and $R_Y \approx 50$ cm as was shown in Figure 1c.

To calculate analytically magnetic fields inside of magnetopause we use a well-known method [10] of “Image Dipole”. Its moment $\mu_i$ and position $a_i$ could be derived from the measured $R_X$ and $R_Y$. According to [11], the MP surface could be described by a sphere of radius $\rho$ with a center at distance $\Delta$ from dipole center (see figure 1c). All values are determined by expressions (1) via parameter $j = [(R_Y/R_X)^{j+1}]/[(R_Y/R_X)^{j-1}-1]$, which are given in this case for regimes #4-5, as the following:

$$j \approx 1.4, \quad \rho = a_i/(j^2-1) \approx 72 \text{ cm} \quad \text{and} \quad \Delta = \rho/j \approx 51 \text{ cm} \quad \text{for} \quad a_i = R_X(j+1) \approx 49 \text{ cm} \quad (1)$$

The moment of “Image Dipole” is expressed as $\mu_i = j^2 \mu(2f-1)$ for the geometric factor $f$, depending upon the shape of “super-conductive” MP-surface. Since this factor varies from $f = 1$ for simplest geometry of infinite plane MP (with corresponding $j = 1$ of our case #6 at $\alpha \sim 10$) up to $f = 1.5$ for the exactly spherical one (with $j \to \infty$ and additional uniform field $2\mu/R_X^3$ inside of MP with $\rho = R_X$), we choose intermediate partially convex case with $f = 1.2$. This yields $\mu_i = 7.7*10^6 \text{ G}\text{cm}^3$, and the field of this imaginary dipole $B_i = \mu_i/(a_i-X)$, shown in figure 2 by dashed line $B_i$, is in a rather good agreement with experimental data. Since this model reproduces well enough almost all magnetic measurements in equatorial X-Y plane, including region of small $X \leq 10$ cm (at $Y>0$), we could use it to study an important dependence of the maximum field compression $\Delta B^*$ near the dipole surface upon the energy $E_0$ of the exploding Laser Plasma, which simulates CME in AMEX experiment.
Figure 2. ΔB-disturbances near and inside of magnetopause: 1 – with additional uniform field 100 G (at Y=0); 2 – the same (for Y ≤ 13 cm); 3 – without additional field for Y≠0.

In the usual case of quasi-stationary changes in dynamic pressure \( P_d = n m V^2 \) of solar wind, the registered levels of a Sudden Commencement (SC) are described by the so called Chapman-Ferraro Scaling (CFS) as \( \Delta B^+_{\text{CFS}} \propto P_d^{1/2} \) [12], based on the same “Image Dipole” model and traditional scale \( R_m = (\mu^2/4\pi P_d)^{1/6} \). In our case of explosive-nature changes we should use its modified MHD relation \( R_m^* \approx 0.75 R_0^{1/6} \), which agrees with the experimentally measured \( R_X \) at small values of \( \epsilon_m \) parameter, according to set of data in a table 1. Calculation of \( \Delta B^+ \) by the same approach as in the CFS model gives a new scaling for a super SC as \( \Delta B^+ \approx 2 (E_0/R_0^3)^{1/2} \). This new scaling gives estimation up to 400 nT for the Earth (case #N with \( j \approx 2.6 \)) and \( \Delta B^+ \approx 100 \) G for the AMEX case #5 with smaller \( j \approx 1.4 \) in accordance with dependence \( \Delta B^+ \propto (j^{1/2}+j)^3 \). In laboratory this new scaling was verified by the data (figure 3) of magnetic probe fixed in a front of dipole at a distance \( X=13 \) cm, with taking into account of which, a corrected value \( \Delta B^+ \approx 200 \) G could achieve a registered maximum level at this point.

Thus, we can affirm that the novel approach for simulation of various magnetospheric phenomena that was developed in recent laser experiments [1,13], really opens new opportunities in this field.

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