Laboratory simulation of energetic flows of magnetospheric planetary plasma

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Abstract. Dynamic interaction of super-sonic counter-streaming plasmas moving in dipole magnetic dipole is studied in laboratory experiment. First, a quasi-stationary flow is produced by plasma gun which forms a magnetosphere around the magnetic dipole. Second, explosive plasma expanding from inner dipole region outward is launch by laser beams focused at the surface of the dipole cover. Laser plasma is energetic enough to disrupt magnetic field and to sweep through the background plasma for large distances. Probe measurements showed that far from the initially formed magnetosphere laser plasma carries within itself a magnetic field of the same direction but order of magnitude larger in value than the vacuum dipole field at considered distances. Because no compression of magnetic field at the front of laser plasma was observed, the realized interaction is different from previous experiments and theoretical models of laser plasma expansion into uniform magnetized background. It was deduced based on the obtained data that laser plasma while expanding through inner magnetosphere picks up a magnetized shell formed by background plasma and carries it for large distances beyond previously existing magnetosphere.

1. Introduction
Laboratory modelling of space plasma processes is an important method of study of basic physics. Despite of significant progress in spacecraft measurements and numerical simulations a laboratory experiment remains a source of unique data inaccessible by other means. One of the fields where namely laboratory experiments with lasers have pushed the advances in theory and numerical simulation is interaction of counter-streaming plasma flows in presence of magnetic field. In 1970-s and 80-s a number of works with laser-produced plasma expanding with super-Alfvenic velocity into magnetized background have been carried out with the aim to model active near-Earth releases AMPTE, CRRES, Argus, Starfish. The other field which was extensively studied by means of laboratory experiment is magnetosphere. At KI-1 simulation Facility such studies are based on two sources of plasma – induction Θ-pinches and Laser Plasma (LP) – which interact with compact magnetic dipoles. Combination of energetically and spatially different plasma flows allowed modelling of extreme compression of the Earth’s magnetosphere by super powerful CME or by artificial near-Earth releases [1]. Such complex systems as field-aligned currents connecting boundary layer with ionosphere have been studied in detail [2]. Namely laboratory experiments supplied necessary data to formulate and verify a Hall model of mini-magnetospheres [3] which explains its unusual features. In the present experiment we investigate essentially new combination of interacting flows and magnetic field. Θ-pinches plasma fills the vacuum chamber and creates around magnetic dipole a magnetosphere.
with estimated size of about 30 cm. The novel feature is that laser plasma is generated inside of this magnetosphere at two targets symmetrically placed at dipole cover (figure 1). LP is directed opposite to the O-pinch flow and has kinetic energy large enough to sweep previously existing plasma and dipole magnetic field. We study the interaction at distances 40÷90 cm from the dipole beyond the previously existing magnetosphere. The specific case of plasma expansion from the inner region of magnetic dipole outward into the background flow has at least two possible applications. It directly relates to the concept of magnetosail. The other field is Hot Jupiters – close orbiting exoplanets heated by ionizing stellar radiation to a point of super-sonic expansion of upper atmosphere. The interaction of expanding planetary flow with counter-streaming stellar plasma in a case when such a planet possesses weak magnetic field [4, 5] was one of motivations of the present experiment.

2. Experimental set up and results

Before the laser plasma is produced on the surface of the dipole, the flow of background plasma creates around it a magnetosphere with size of about 30 cm. Thus, LP, when created, expands at first in the dipole magnetic field of inner magnetosphere filled from about X=15 to X=30 cm by background plasma and after that across magnetopause into the background plasma proper where magnetic field is zero. Such scenario principally differs from the previous experiments on LP expansion in magnetized uniform background in that the magnetized background in the present case is a compact localized shell. The energy density of LP (total energy about 16 J in initial volume of about 8 cm$^3$) is comparable to that of dipole magnetic field already at the laser target and with further LP expansion quickly becomes dominant. It was found that the LP flowing through background plasma partially expels it due to Coulomb collisions. However, collisional interaction is rather weak and counter-streaming flows deeply penetrate into each other, so LP expansion isn’t significantly affected at distances up to 100 cm. The main dimension and dimensionless parameters are listed in the table 1 while figure 1 shows experimental set up.

![Figure 1. Experimental set-up superimposed on snapshot of laser-produced plasma.](image)

| Table 1. Parameters of experiment. |
|-----------------------------------|
| **Background plasma parameters**  |
| Velocity $V_*$, km/s              | 20-60 |
| Density $n_*$, cm$^{-3}$          | 2·10$^{12}$ |
| Mach number $V_*/C_s$             | ~1 |
| **Magnetospheric parameters**     |
| Magnetosphere size $L_m$, cm      | 30 |
| Relative dipole radius $R_D/L_m$  | 0.1 |
| Knudsen number $\lambda_*/L_m$    | ~2 |
| Reynolds number $4\pi\sigma L_m V_*/c^2$ | ~100 |
| Hall parameter $L_m \omega_{pi}/c$ | 2 |
| Degree of ion magnetization $L_m/R_i*$ | 3 |
| **Laser plasma parameters**       |
| LP energy to magnetic energy $Q_{LP}/Q_d$ | ~1 |
| Velocity relative to background $V_*/V_*$ | $\approx 3$ |
| Mean free path $\lambda_{pi}$, cm | $\approx 500$ |

1 Evaluated close to the dipole location at $X=0$.
2 Calculated as pressure balance distance between O-pinch plasma and dipole field pressures.
3 Ion gyroradius is calculated for the value of magnetic field of $B_m=50$ G.
4 $Q_{LP}$ is calculated as total energy of a single LP blob (16 J) divided by initial LP volume ($\sim 8$ cm$^3$). $Q_d$ is calculated as dipole field energy density at a distance of $X=3.5$ cm where the LP target is positioned.
5 Coulomb scattering length of LP test ion in the O-pinch plasma at a density of $4 \times 10^{12}$ cm$^{-3}$. 
The main finding of the experiment is that when background plasma pre-fills the vacuum chamber LP carries with itself across distances 40÷90 cm the magnetic field order of magnitude larger than in case without ambient plasma. This field is also much larger than the vacuum dipole field at these distances. Typical measurements are demonstrated in figure 2. Spatial profile at the left panel shows that magnetic field carried by laser plasma decreases with distance much more weakly than the cubic fall off of the laser plasma density. Obtained results impose a question of origin of such magnetic field carried by LP. They suggest a novel and unexpected feature that LP captures magnetospheric field rather than simply stretching it and that effectiveness of this capture is directly related to the density of background plasma which creates magnetosphere.

![Figure 2](image.png)

**Figure 2.** Right - typical dynamic signals of ion current and magnetic field measured by probes at a distance of 63 cm. Left - spatial profiles of ion current and magnetic field measured along the interaction axis. For the ion current amplitude the maximum of the second LP flow is taken. For the magnetic field the averaged value carried by the second and the third LP flows is calculated. Straight lines plotted over ion current data indicate square and cubic behavior.

In previous experiments with uniform background the compression and strong increase of magnetic field at the LP front and its total expulsion inside of LP proper has been observed [6]. Such behaviour is explained in the frame of displaced electrons model [7]. When the electron density of expanding plasma significantly exceeds that of background, which is true in our case at distances X<30 cm where magnetized shell exists, the electrons of background together with frozen-in magnetic field are displaced and strongly compressed at the front of LP. However, in present experiment no such compression is seen. Measured fields don’t exceed the expected values of >50 G in the initial magnetized shell. Moreover, observed magnetic field is present in the whole LP flow.

On the base of the obtained experimental results a following conclusion was made, demonstrated in figure 3. Plasma expanding outward from the inner region of magnetic dipole can interact with it by catching and dragging the magnetic field lines. The effectiveness of such process of transfer of magnetic field far from the dipole is directly related to the density of background plasma prefilling the magnetic field lines close to the dipole. Without pre-made plasma magnetized into dipole field lines the impulsive energetic plasma doesn’t carry any significant field after crossing the dipole region. There can be two reasons why the LP catches and carries within itself the magnetized shell formed by background plasma. First, the dipole field lines loaded with plasma can’t move faster than with the Alfven speed, and sufficiently fast impulsive flow can overcome the magnetized shell instead of displacing it. Second, the curvature of dipole field lines makes it possible for electrons of LP to mix with electrons of magnetized shell. Only by such mixing the LP might pick up the magnetic field instead of displacing it. The last feature is a main difference of the present work from previous studies of LP interaction with uniform magnetized background.
Figure 3. Schematic representation of the experimental results. Left picture – mini-magnetosphere including magnetized shell formed by $\Theta$-pinch plasma around magnetic dipole. Right – laser plasma expanding flow which picks up and carries the magnetized shell. Dashed lines indicate magnetic field lines.

Acknowledgments
This work was supported by SB RAS Research Program (project II.10.1.4 N 01201374303), Presidium RAS program on fundamentals of double technologies and by the Russian Foundation for Basic Research (grant nos. 14-29-06036, 16-52-14006).

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