Interaction of counter-streaming plasma flows in a dipole magnetic field

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Received 25 April 2016, revised 4 July 2016
Accepted for publication 7 July 2016
Published 8 September 2016

Abstract

The transient interaction of counter-streaming super-sonic plasma flows in a dipole magnetic dipole is studied in a laboratory experiment. First quasi-stationary flow is produced by θ-pincho and forms a magnetosphere around the magnetic dipole, while laser beams focused at the surface of the dipole cover launch a second explosive plasma expanding outward from the inner dipole region. The laser plasma is energetic enough to disrupt the 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 an order of magnitude larger than the vacuum dipole field at considered distances. Because no compression of the magnetic field at the front of the laser plasma was observed, the realised interaction is different from previous experiments and theoretical models of laser plasma expansion into a uniform magnetized background. It was deduced based on the obtained data that, while expanding through the inner magnetosphere, laser plasma picks up a magnetised shell formed by background plasma and carries it for large distances beyond the previously existing magnetosphere.

Keywords: counter-streaming plasmas, laser-produced plasma, magnetised background, magnetosphere

(Some figures may appear in colour only in the online journal)

1. Introduction

Laboratory modelling of space plasma processes is an important method of studying basic physics. In spite 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 have pushed the advances in theory and numerical simulations is the interaction of counter-streaming plasma flows in the presence of magnetic fields. In the 1970s and 80s a number of works with laser-produced plasma expanding with super-Alfvenic velocity into a magnetised background have been carried out (Paul et al. 1971, Cheung et al. 1973, Borovsky et al. 1984, Antonov et al. 1985) with the aim to model active near-Earth releases active magnetospheric particle tracer explorers, combined release and radiation effects satellite, Argus, Starfish. Based on obtained results, a new dynamic model of interaction—magnetic laminar mechanism (Golubev et al. 1978) or finite Larmor coupling (Winske and Gary 2007)—has been developed which supplemented the earlier kinematic model of displaced electrons (Longmire 1963, Wright 1971). Our recent experiments (Zakharov et al. 2013, Shaikhislamov et al. 2015) provided detailed data verifying both of the models.

The other field that was extensively studied by means of laboratory experiment is the magnetosphere (Podgorny and Sagdeev 1970). At the KI-1 Simulation Facility such studies were based on two sources of plasma—induction-pinch and laser plasma (LP)—which interact with compact magnetic dipoles (Ponomarenko et al. 2001, 2004). The combination of energetically and spatially different plasma flows allowed for the modelling of the extreme compression of the Earth’s magnetosphere by super powerful CME or by artificial near-Earth
releases (Zakharov et al 2008, 2016, Ponomarenko et al 2008). Such complex systems as field-aligned currents connecting the boundary layer with the ionosphere have been studied in detail (Shaikhislamov et al 2009, 2011). In the latest experiment a pulse of plasma with a frozen-in transverse magnetic field interacting with the magnetosphere has been modelled (Shaikhislamov et al 2014a). The flow with transverse frozen-in field has been generated by means of laser-produced plasma cross-field expansion into background plasma, which fills the vacuum chamber along the externally applied magnetic field prior to interaction. The related subject studied intensively at the KI-1 Facility is a mini-magnetosphere, which can be found above Lunar magnetic anomalies or possibly around magnetised asteroids. Laboratory experiments supplied necessary data to formulate and verify a Hall model (Shaikhislamov et al 2013, 2014b, 2015b), which explains the unusual features of mini-magnetosphere observed in earlier numerical simulations (Omidi et al 2002, Blanco-Cano et al 2003).

In the present experiment we are investigating an essentially new combination of interacting flows and magnetic fields. θ-pinches plasma fills the vacuum chamber and creates a magnetosphere with an estimated size of about 30 cm around the magnetic dipole. The novel feature is that the laser plasma is generated inside this magnetosphere at two targets symmetrically placed at the dipole cover. The LP is directed opposite to the θ-pincho flow and has a kinetic energy large enough to sweep the previously existing plasma and dipole magnetic field. We studied the interaction at distances 40 ÷ 90 cm from the dipole beyond the previously existing magnetosphere. It was found that the LP flowing through background plasma partially expels it due to Coulomb collisions, and carries along a magnetic field which is an order of magnitude larger than the vacuum dipole field value at these distances. Obtained data suggest a novel and unexpected feature that LP captures the magnetospheric field rather than simply stretching it and the effectiveness of this capture is directly related to the density of background plasma that creates the magnetosphere.

The specific case of plasma expansion from the inner region of the magnetic dipole outward into the background flow has at least two possible applications. It directly relates to the concept of magnetosail (Winglee et al 2000), which was extensively studied theoretically (Khasanov et al 2005), numerically (for example, Moritaka et al 2010) and also in laboratory experiments (Funaki et al 2007, Slough et al 2001, Antonov et al 2013). The other field is hot Jupiters—close orbiting exoplanets heated by ionizing stellar radiation to a point of super-sonic expansion of the upper atmosphere (for example, Shaikhislamov et al 2014a). The interaction of the expanding planetary flow with counter-streaming stellar plasma in a case whereby a planet possesses weak magnetic field (Khodachenko et al 2015) was one of motivations of the present experiment.

The paper consists of two sections on the experimental set-up and results, followed by the discussion and conclusions.

2. Experimental setup and results

The experiment has been carried out at the KI-1 Space Simulation Facility, which includes a chamber 500 cm in length and 120 cm in diameter operating at a base pressure of 10⁻⁶ Torr. Induction θ-pincho exit aperture of Ø20 cm ejects ionised hydrogen plasma which, for the conditions of the present experiment, expands and propagates with a velocity of 20 ÷ 60 km s⁻¹ along the chamber axis and is sustained for a duration of about 100 µs. A magnetic dipole was placed at the chamber axis at a distance of 310 cm from the θ-pincho exit aperture. The magnetic moment with a value of μ = 7.5 × 10⁵ G cm³ and a fall off time 250 µs was oriented perpendicularly to the chamber axis. The dipole has an epoxy cover in the form of a cylinder with a size of 5 cm on which a polyethylene target was fastened. Two CO₂ laser beams each of 70 ns duration and 150 J energy are focused symmetrically into spots with a size of about 2 cm. The vectors normal to the surface planes along which the plasma plumes expand were slightly divergent relative to each other. The experimental set-up is shown in a snapshot of the plasma generated by laser beams in the presence of a dipole magnetic field (figure 1) where all elements and the used GSM frame are indicated.

LP plasma consisted mostly of H⁺ and C⁺ ions in approximately equal parts and each plume expanded initially with a front velocity of 170 km s⁻¹ in a cone with half-angle of about 30°. The total number of electrons per solid unit angle of both plumes measured far from the target was about N_e,Ω ≈ 2.2 × 10¹⁸ sr⁻¹ and the kinetic energy of ions W₁ ≈ 32 J sr⁻¹. Due to a specific pulse and tail generation mode of the laser oscillator, there were, besides the first plasma bunch, secondary and tertiary flows generated 550 ns and 1100 ns later. The second flow was largest in amplitude and twice as slow in comparison to the first one. Diagnostics consisted of miniature Langmuir and three-component magnetic probes with spatial resolution better than 0.5 cm. There were also directional ion collectors operating similar to a Faraday cup. A more detailed description can be found in our previous papers (Ponomarenko et al 2004, Shaikhislamov et al 2014c). Most electric and magnetic measurements were made at distances between 40-90 cm from the target. There were also Langmuir probe and ion collector measurements at a distance of 90 cm from the θ-pincho aperture corresponding to a distance of X = 207 cm from the target.

Figure 2 shows typical probe measurements of θ-pincho plasma obtained close and far from the θ-pincho aperture. The flow has a sharp switch and decay fronts. Calculated velocities of these and other telling points in both dynamic signals are shown by crosses in the same plot. The velocity profile is aligned with the ion current measured at X = 67 cm so that the first and last crosses correspond to the switch and the decay fronts. One can deduce that at the time when the laser plasma is created (if the laser operates at a time zero), the first front of the θ-pincho flow moving with a velocity of 60 km s⁻¹ reaches the point X = − 300 cm, that is very far downstream of the dipole and laser target. Meanwhile the decay front moving with a velocity of about 25 km s⁻¹ is positioned at this time at X = 150 cm. Thus, the θ-pincho flow creates around the magnetic dipole quasi-stationary magnetosphere, and the laser-produced plasma which starts to expand at t = 0 in the opposite direction interacts with the plasma column of 150 cm in length. Because of the expansion, the density decreases with...
distance from the \( \theta \)-pinch plasma origin and corresponding measurements (figure 3) show that it is close to the expected cubic fall off. Note that the density in the region of interest (40–90 cm) is about \( n_3 \approx (3 \div 5) \cdot 10^{12} \text{cm}^{-3} \). Further on the \( \theta \)-pinch plasma is called, when convenient, the background plasma.

Laser-produced plasma flow is demonstrated in figure 4. The second maximum in the flow has a sharp front, is the largest by amplitude and produces the strongest interaction with the \( \theta \)-pinch plasma. Such interactions are demonstrated in figure 5. Probe signals show dynamically as the background plasma fills the chamber and then the passage of counter-streaming laser plasma. A comparison of signals between the directional ion collector and Langmuir probe reveals that the second LP flow effectively sweeps the background, significantly decreasing its density.

Despite the expulsion of the background the interaction is rather weak because laser plasma practically is not affected. First of all, it has not decelerated even after passing large distances through the background. This is shown in time-of-flight
diagrams (figure 6) plotting the fronts of the first and the second LP flows. Second, dynamic signals of LP measured at \( X = 67 \) cm in vacuum, with added dipole magnetic field as well as background plasma, show little difference (figure 7). The significant difference was seen only at \( X = 207 \) cm. The amplitude of the second LP flow was observed to decrease 3-fold, while the first LP flow was affected to a much lesser degree. Note that the attenuation of the second LP flow depends only on the background plasma regardless of dipole magnetic field, which proves that the interaction takes place due to the Coulomb collisions.

To summarise very briefly, the data presented so far show weak collisional interaction of counter-streaming plasma flows, which leads to partial sweeping of the background. Next we present magnetic field measurements. They mostly concern the largest component collinear to the dipole moment, which is the Z-component in the equatorial plane. Figure 8 shows its dynamics in three cases. The first one is when LP expands into the background plasma but the dipole field is switched off. At the foremost LP front a weak and short lived signal of about 2 G was measured. This could be a small irregular magnetic field carried by \( \theta \)-pinch plasma and swept by laser plasma. When the dipole is switched on but the background plasma is absent the LP carries a field with itself of the same sign and about the same value as an undisturbed dipole magnetic field \( B_d \) at the corresponding distance. The last signal in figure 8 was measured when both dipole fields and background plasma are present. One can see that the LP passage brings a magnetic field that is of the same direction but much larger in amplitude. The generation by counter-streaming plasma flows of a significant transverse magnetic field far from the dipole is a novel finding within the reported experiment.

It should be noted that, when sufficiently far from the dipole, the \( \theta \)-pinch plasma expels the dipole magnetic field if it is present. This was observed in our earlier experiments as well in the present one up to the closest distance from the dipole \( X = 44 \) cm where magnetic measurements were made. Thus, at distances of \( X = 40 \div 90 \) cm the LP expands in an unmagnetized background in which the initial magnetic field is virtually zero. Therefore, the observed fields are brought by LP from a region close to the dipole where the initial magnetic field prior to LP generation is not zero.

Figure 9 demonstrates in more detail the dynamics of the magnetic field in question, together with the ion current, at three different locations along the X-axis. Each measurement has been performed simultaneously at a given position during a single shot by the probe set that combines Langmuir and magnetic probes. At the location nearest to the dipole, one can see that the \( B_z \) component closely follows the laser...
Three consequential LP flows carry local \(B_z\) maxima. The first one is the largest, while the second and the third are of about the same amplitude. Signals at \(X = 44\) and 63 cm show that the first maximum of \(B_z\) gradually falls behind the front of the first LP flow, while at the farthest distance of \(X = 90\) cm it disappears altogether. At such a distance from the target only \(B_z\) associated with the second and third LP flows remain. Further on we will consider only the part of \(B_z\) signal related to the second and third LP flows, which is a much a more permanent and durable feature than the first maximum. The fact that the generated by LP magnetic field depends on the density of background demonstrates figure 10 where dynamic signals of \(B_z\) are shown for rarified and dense \(\theta\)-pinch plasmas. It is seen that in the rarified case the maximum field is carried by the LP front. In a denser background the magnetic field is significantly larger and is carried by the LP second flow, while the first LP flow does not carry a magnetic field at all.

By measuring dynamic signals at various locations, the dependence of amplitude on the distance can be plotted. Figure 11 shows such plots for the second maximum of the ion current and carried by its magnetic field. One can see an expected cubic decrease of the LP flow with distance. At \(X < 60\) cm the fall off is slower. This is probably explained by the two stream structure of LP consisting of two overlapping cones. The magnetic field shows a relatively weak dependence on the distance from the target. At the largest \(X\), it levels off at a value of about 12 G. Without \(\theta\)-pinch plasma and an in-vacuum dipole field the amplitude of the magnetic field carried by LP also varies a little with distance, and its level of about 2 G remains much smaller than in a case when background plasma is present.

Measurements along the \(Z\) axis revealed that the \(B_z\) component is broadly distributed above and below the equatorial plane. Besides that, there were anti-symmetric (reversible) \(B_x\) components. They could be observed only when both background plasma and dipole fields were present. Otherwise the values were below the resolution of magnetic measurements \(\leq 1\) G. The sign of a \(B_x\) component corresponded to the stretching of dipole field lines. The sign and value of \(B_y\) component corresponded to the positive electric current of the order of 1 A cm\(^{-2}\) flowing along the \(X\) axis. All three components of the magnetic field are shown in figure 12 for two positions along the \(Z\) axis. For time reference, the ion current is plotted as well.
The upper panel reveals that reversible $B_x$ and $B_y$ components, like $B_z$, have a strong maximum associated with the first LP flow. The second and third LP flows carry relatively smaller $B_x$ and $B_y$ fields of the order of 5 G. Measurements closer to the equatorial plane (lower panel) show that these components are practically zero at the time of passage of second and third LP flows.

3. Discussion and conclusions

To access the conditions of the experiment we list in table 1 some of the most important parameters of $\theta$-pinch plasma, the magnetosphere created by it around the magnetic dipole and of the laser plasma, created inside the magnetosphere and expanding into the background plasma. Before the laser plasma is produced on the surface of the dipole, the flow of background plasma creates a magnetosphere around it. While measurements close to the dipole were not conducted in this work, such data on laboratory magnetosphere are available from our previous studies (Ponomarenko et al 2004, 2008, Shaikhislamov et al 2009). In fact, in the present case, the background plasma density of the order of $2 \times 10^{12}$ cm$^{-3}$ is sufficiently rarified that it should create a mini-magnetosphere, as was shown in a series of our dedicated experiments (Shaikhislamov et al 2013, 2014b, 2015b). The so-called Hall parameter, which is the relation of pressure balance distance ($L_m = (\mu^2/2\pi n_m v^2)^{1/6} \approx 30$ cm) to ion inertia length ($c/\omega_{pi} \approx 15$ cm), is equal to two. For this value the structure of the mini-magnetosphere differs from a typical planetary magnetosphere by partial penetration of plasma across the magnetopause and inside of the dipole dominated region. Based on the experiment with the same value of Hall parameter (Shaikhislamov et al 2013) it can be deduced that in the present case the plasma should penetrate by as much as $L_m/2 \approx 15$ cm. Thus, laser plasma when created first expands in the dipole magnetic field of the inner magnetosphere filled from about $X = 15$ to $X = 30$ cm by background plasma, and after that across the magnetopause into the background plasma proper where the magnetic field is zero. The value of the magnetic field at the magnetopause estimated from the pressure balance condition is about $B_m = 50$ G. At the magnetopause the local Alfvén speed is equal to the $\theta$-pinch velocity, which is about 50 km s$^{-1}$. Due to compression, the magnetic field inside of magnetosphere behaves as $B = B_m/2 + \mu X^3$ and the Alfvén speed reaches 100 km s$^{-1}$ at a distance of about $X = 20$ cm. Considering now the laser plasma as it expands in magnetosphere, one can see that even the second laser plasma flow, which moves with a velocity of 100 km s$^{-1}$, becomes super-Alfvénic at $X > 20$ cm due to the loading of the dipole magnetic field with background.

Figure 7. Ion current measured at a distance of $X = 67$ (left) and $X = 207$ cm (right) in cases when only laser plasma is present (grey line), when the magnetic dipole is also switched on (dotted, marked $B_d$) and when $\theta$-pinch plasma is added as well (solid thick black, marked $B_d + \theta$). The right panel also shows the case when there is $\theta$-pinch plasma but no dipole field (solid thin black, marked $\theta$). The measurements at $X = 67$ (left) were performed by the Langmuir probe so the ion current generated by $\theta$-pinch plasma prior to LP arrival has been deducted from the signal $B_d + \theta$ for better comparison with other signals.

Figure 8. Dynamics of the main component of the magnetic field measured by probe when laser produced plasma interacts with $\theta$-pinch plasma without dipole magnetic field (thin solid line), with dipole field without $\theta$-pinch plasma (dotted), and when both $\theta$-pinch plasma and dipole field are present (thick solid). The probe is positioned at $X = 67$ cm.
The experimental results show that the expanding laser plasma sweeps and partially expels background (figure 5). This takes place due to Coulomb collisions. Due to the strong dependence of cross-section on velocity, the faster first LP flow interacts much weaker than the slower second and third flows (figure 7). The probability of Coulomb collisional scattering of the background proton by the LP flow is equal to:

\[ tZ \nu n t^2 \approx \pi ii i \int \nu \approx - . \]  

The density over time integral can be expressed through total flux which depends on distance as:

\[ Vn/t F X/2 \approx \pi i i \int \nu \approx - . \]  

Here we

Figure 9. Examples of probe measurements of the magnetic field (solid lines) and ion current (dashed) at three locations along the X-axis. Numerals mark the consequential phases of magnetic perturbation generated by the first, second and third flows of laser plasma.

Figure 10. Dynamic signals of the ion current (lower graph) and magnetic field (upper graph) measured at a distance of X = 67 cm in rarified (dotted lines) and dense (solid lines) background plasma (levels prior to LP arrival are indicated by dashed horizontal lines).

Figure 11. Spatial profiles of the ion current (crosses) and magnetic field (circles) 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 the ion current data indicate square and cubic behavior.

scattering of the background proton by the LP flow is equal to:

\[ \nu \pi d \approx 2.8 \cdot 10^{-2} Z_i ^2 \int V_i ^2 n dt. \]  

The density over time integral can be expressed through total flux which depends on distance as:

\[ \int Vn/dt \approx F_i /X^2 ; \]  

\[ \nu \pi d \approx 1.8 \cdot 10^{-3} V_i ^2 F_i /X^2. \]  

Here we
\[ V_0 \approx 5 \cdot 10^7 \text{ cm s}^{-1}, F_1 = 6.7 \cdot 10^{11}, \nu_{pl} \approx 1.4 \cdot 10^{2}/X^2, \text{ and for the second} - V_2 \approx 10^7 \text{ cm s}^{-1}, F_2 = 6.7 \cdot 10^{12}, \nu_{pl} \approx 1.2 \cdot 10^{3}/X^2. \]

It follows that, when already at \( X = 40 \text{ cm}, \) the probability to scatter the background proton by the first LP flow is below 10\%, while for the second it is a significant 27\%, even at a distance of 67 cm. These estimates agree well with figure 5.

Despite a decrease in the amplitude of the second LP maximum in the range between \( X = 100–300 \text{ cm} \) induced by background, the collisional interaction in general is rather weak and counter-streaming flows deeply penetrate into each other.

By comparison the dynamic signals in figure 7 show that the applied dipole field also does not significantly affect the laser plasma. According to the estimate in table 1, the energy of LP is comparable to that of a dipole magnetic field already at the laser target, and with LP expansion quickly becomes dominant. In a vacuum LP carries with itself the magnetic field collinear to the dipole magnetic field. When background plasma pre-fills the vacuum chamber, this magnetic field is an order of magnitude larger. It raises a question of origin of such magnetic fields carried by LP.

The described conditions principally differ from the previous experiments on LP expansion in a magnetised uniform background in that the magnetised background in the present case is a compact localized shell. Beyond this magnetised shell, the background plasma does not contain any magnetic field and the initially present dipole field is also totally expelled. In a uniform magnetised background, the super-Alfvenic LP expansion eventually decelerates and generates a non-linear magnetosonic wave (Shaikhislamov et al 2015b) or, if strong enough, possibly a shock wave (Zakharov et al 2013). In the present case, LP expansion remains super-sonic for very long distances and, without the global magnetic field, is not decelerated by background plasma, due to the magnetic laminar mechanism or finite Larmor coupling, though it is gradually scattered by Coulomb collisions. The novel feature is that LP picks up the magnetised compact shell and carries it along. The value of the carried magnetic field remains significant for distances much larger than the initial width of the shell.

The magnetic field is carried by electrons which move with ions to keep the plasma quasi-neutral. When LP density is larger than that of the background, the dynamics of the magnetic field should closely follow LP passage. This is precisely observed at distances of \( X < 70 \text{ cm} \). However, when the background density becomes comparable or larger than the LP density, the dynamics of the magnetic field uncouples from LP and is governed by the background. Because of this the first LP flow progressively loses magnetic field with distance until it is observed in time only when the second LP flow arrives at the point of measurement. It was also observed that the amplitude of the carried magnetic field increases with the density of background plasma (figure 10).

Let us consider the interaction in the frame of the displaced electrons model developed for super-Alfvenic spherical expansion of explosive plasma into a uniform magnetised background (Longmire 1963, Wright 1971). According to this model, when the electron density of expanding plasma significantly exceeds that of the background, which is true in our case at distances of \( X < 30 \text{ cm} \) where the magnetised shell exists, the electrons of the background, together with frozen-in magnetic fields, are displaced and strongly compressed at the front of LP. The compression and strong increase of the magnetic field at the LP front and its total expulsion inside of LP proper were measured in detail in our previous experiment with a uniform background (Shaikhislamov et al 2015b). However, in the present experiment no such compression is seen. Measured fields do not exceed the expected values of \( > 50 \text{ G} \) in the initial magnetised shell. Moreover, the observed magnetic field is present in the whole LP

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**Table 1. Parameters of experiment.**

| Background plasma parameters |  |
|-----------------------------|--|
| Velocity \( V_x, \text{ km s}^{-1} \) | 20–60 |
| Density \( \rho, \text{ cm}^{-3} \) | 2 \cdot 10^{12} |
| Mach number \( V_i/C_{is} \) | \< 1 |

| Magnetospheric parameters |  |
|----------------------------|---|
| Magnetosphere size \( L_m, \text{ cm} \) | 30 |
| Relative dipole radius \( R_0/L_m \) | 0.1 |
| Knudsen number \( \lambda/L_m \) | \< 2 |
| Reynolds number \( 4\pi\sigma L_m V_i/C_{is}^2 \) | \< 100 |
| Hall parameter \( L_{m\omega_i}C_{is} \) | 2 |
| Degree of ion magnetization \( \lambda_{ci}, \text{ cm} \) | \< 500 |

\( a \) Evaluated close to the dipole location at \( X = 0 \).

\( b \) Calculated as pressure balance distance between \( \theta \)-pinch plasma and dipole field pressures.

\( c \) Ion gyroradius is calculated for the value of the magnetic field of \( B_0 = 50 \text{ G} \).

\( d \) \( Q_{LP}/Q_0 \) is calculated as the total energy of a single LP blob \((16 J)\) divided by the initial LP volume \((\sim 3 \text{ cm}^3)\). \( Q_0 \) is calculated as the dipole field energy density at a distance of \( X = 3.5 \text{ cm} \) where the LP target is positioned.

\( e \) Coulomb scattering length of LP test ion in the \( \theta \)-pinch plasma at a density of \( 4 \cdot 10^{12} \text{ cm}^{-3} \).

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**Figure 12.** Dynamic signals of the magnetic field components and ion current (grey lines) measured at a distance of \( X = 67 \text{ cm} \) and two different locations relative to the equatorial plane. Solid lines—\( B_x, \) dotted—\( B_y, \) dashed—\( B_z \).
flow. It seems that in the process of the LP sweeping over the magnetised shell, LP electrons catch the magnetic field of the shell so it becomes frozen-in into the LP itself. And the effectiveness of this process increases with the density of background plasma initially present in the magnetised shell. It is seen even without background plasma, though the field caught and carried by LP in this case is much smaller. Most probably, without \( \theta \)-pinch, the role of background plasma plays the foremost and rarified part of LP that cannot disrupt dipole field lines and instead fills them, creating the magnetised shell, which later interacts with the main part of LP. The scenario of interaction inferred from the findings of the experiment is illustrated in the pictures of figure 13.

On the basis of the obtained experimental results, the following general conclusion can be made. Plasma expanding outward from the inner region of the magnetic dipole can interact with it by catching and dragging the magnetic field lines. The effectiveness of such a process of transfer of the 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 magnetised into the dipole field lines, the impulsive energetic plasma does not carry any significant field after crossing the dipole region. There can be two reasons why the LP catches and carries within itself the magnetised shell formed by background plasma. First, the dipole field lines loaded with plasma cannot move faster than with the Alfvén speed, and a sufficiently fast impulsive flow can overcome the magnetised shell instead of displacing it. Second, the curvature of dipole field lines make it possible for electrons of LP to mix with electrons of the magnetised shell. Only with such mixing might the LP pick up the magnetic field instead of displacing it. The last feature is a main difference between the present work and previous studies of LP interaction with a uniform magnetised background.

Acknowledgments

This work was supported by SB RAS Research Program (project II.10.1.4 N 01201374303) and Russian Fund for Basic Research grants 14-29-06036 and 16-52-14006.

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Figure 13. Schematic representation of the experimental results. Left picture—mini-magnetosphere including magnetised shell formed by \( \theta \)-pinch plasma around the magnetic dipole. Right—laser plasma expanding flow which picks up and carries the magnetised shell. Dashed lines indicate magnetic field lines.
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