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Laser-produced plasma for simulation of plasma jets propagation in geoplasma

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This work presents the results concerning dynamics of laser-produced plasma streams from a flat target placed in a transverse magnetic field of $B_0 < 0.9$ T which were obtained during joint experiments carried out at IPPLM. They include data about main stages of plasma-field interaction, creation of the diamagnetic cavity, plasma deceleration and heating, and transformation of kinetic energy into electromagnetic one.

1. Introduction

The interaction of plasma streams with a transverse magnetic field (in the presence or absence of the background plasma) plays the key role in understanding many processes in space plasmas. In spite of investigations on the interaction of plasma streams with a magnetic field performed in laboratories (*e.g.*, [1], [2]) and in cosmic space (*e.g.*, [3]–[5]), numerous effects still remain unexplained. This, in particular, relates to the case of long-range propagation of high-β streams at small values of an ion-gyroradius. The effects requiring more precise investigation include the initial diamagnetism of a plasma stream and its later polarization causing a cross-field ($\bar{E} \times \bar{B}$)-drift, as well as the development of instabilities in the front of the stream. An important and most unclear effect occurring in active experiments in the geoplasma is the influence of the background plasma on the interaction of the plasma stream with the magnetic field.

At the Institute of Plasma Physics and Laser Microfusion (IPPLM) we developed a "KE-1M" laser plasma facility with a magnetic field up to 1 T for the laboratory simulation of interaction phenomena in ionospheric and magnetospheric plasmas. The investigations, carried out with the participation of Russian team from the Institute of Laser Physics (IPL) RAS in Novosibirsk, are an extension of their earlier studies [2], [6], [7] carried out at "KI-1" facility with the field of 0.05–0.5 T, and they were performed [8] under conditions rendering the simulation of effects occurring in active space experiments more possible.

2. Experimental arrangements

As a driver, an Nd:glass laser system ($\lambda = 1.06$ μm, $E_L = 2$ J, $t_L = 2-5$ ns, $I_L = 5 \cdot 10^{10}$ Wcm^{-2}) was used. The laser beam was focused on a $(CH_2)_n$ target located inside Helmholtz coils generating a magnetic field of up to 2 T in parallel to the target surface.

Double Langmuir probes (LPO, LPR), with a flat reference electrode and a cylindrical collecting electrode [9], were placed along the same magnetic line and were oriented in parallel to it. Thus, a potential difference between them was sufficient to measure the laser-produced ion flow. An additional double Langmuir probe (LPF) was used to estimate the initial ionization of the background gas under the influence od XUV radiation from the laser-produced plasma without a magnetic field. The LPF probe had flat electrodes of equal size, spaced by 5 – 10 mm and oriented parallel to both the ion flow and the XUV radiation.

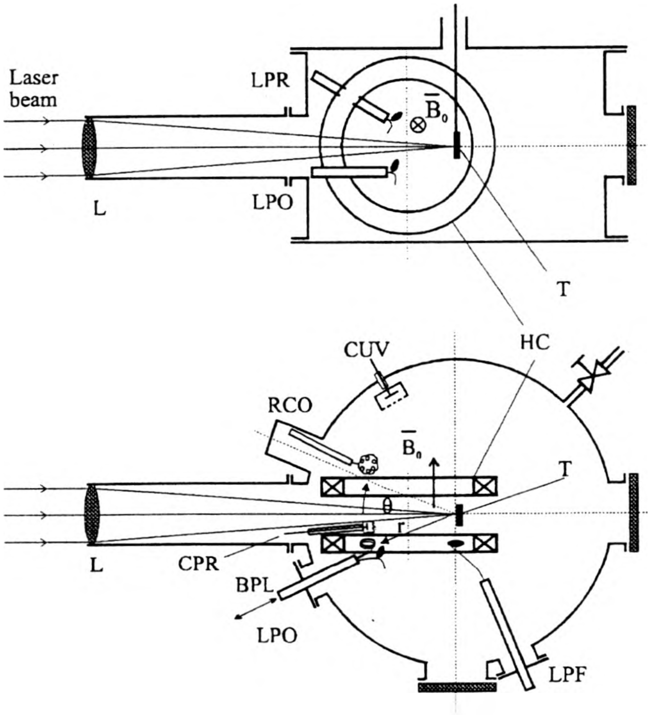

Fig. 1. Experimental arrangement: T – target, HC – Helmholtz coils, LPO and LPR – double Langmuir probes, LPF – Langmuir probe for background plasma, CPR – floating screened ion-collector, LPF – Langmuir probe for background plasma, RCO – shielded Rogovski coil, BPL and BPR – magnetic probes, CUV – combined ion and XUV collector.

A small-size (∅ 5 mm) floating ion collector (CPR) with a screen was used for the registration of an ion flow nearly parallel to the laser beam axis. It could operate properly only at a high magnetic field (0.7 – 1 T) and low voltage ($U = -20$ V).

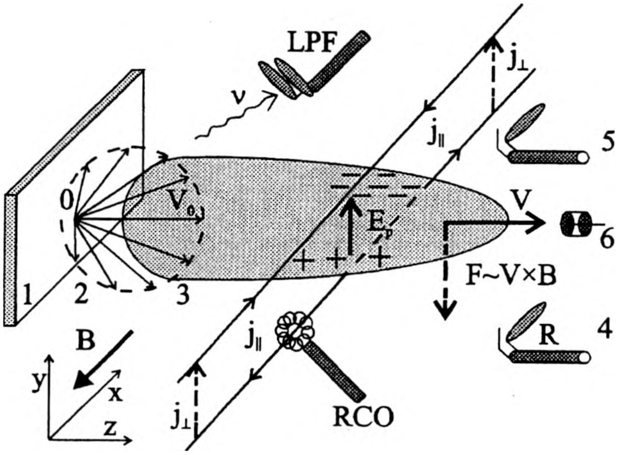

Fig. 2. Physical scheme of simulation experiment: 1 — target, 2 — initial plasma shape coinciding with the quasi-spherical form of its diamagnetic cavity, 3 — plasma jet, 4 and 5 — bouble Langmuir probes (LPO and LPR), 6 — floating screened ion-collector (CPR), B — external magnetic field, LPF — Langmuir probe for background plasma, RCO — shielded Rogovski coil for registration of field-aligned currents $j_{\parallel}$.

To study the interaction processes between the plasma stream and the magnetic field, we used reference electrodes of the double Langmuir probes (LPO, LPR) for measurements of a polarizing electric field, as well as small-size (∅ 5 mm) magnetic probes (BPL, BPR) with an electrostatic shielding [9].

A scheme of the experimental arrangement is shown in Fig. 1. A physical scheme of the experiment and the location of the diagnostics are shown in Fig. 2.

3. Results

In conditions of our experiment, we can obtain laser-produced plasma streams of a moderate velocity of the free expansion (without the magnetic field) equal to about $v_0 = 2.5 \cdot 10^7$ cms^{-1}. The initial plasma shape is roughly a sphere being in contact with the target surface [10], [11]. At magnetic field $B_0 = 0.9$ T, the maximum size of the diamagnetic cavity in vacuum as measured by means of the magnetic probe is $R_c \approx 1.5$ cm. This value is in good agreement with the theoretical one, $R_b = (3E_0/B_0^2)^{1/3} = 1.5$ cm, calculated from the model [12] of the deceleration of a spherical plasma cloud in a homogeneous magnetic field ($E_0 = 10$ J is the effective initial plasma energy, corresponding to the 4π solid angle of the plasma expansion [6], [13]).

We have observed an effective creation of the diamagnetic cavity, the plasma stream deceleration and formation from it of a plasma jet under conditions of the ion magnetization level $\varepsilon_b = R_h/R_b \leqslant 1$ ($\varepsilon_b = 0.7$ for a directed Larmor radius $R_h = v_0 mc/B_0 ez \approx 1$ cm at $B_0 = 0.9$ T). These effects were previously studied for the lower value of the magnetic field ($B_0 < 0.5$ T) at ILP RAS [6], [9] and they were also observed at NRL [14] in the field of 1 T range.

Outside the cavity, we registered a long-range drift propagation of the plasma stream in the form of a cross-field polarized jet (transverse to B_0 electric field E_p), deflected into the direction of an ion Larmor rotation (in the presence of a background plasma). These data have been obtained from the frame pictures [15] and with the use of the Langmuir probes (LPO, LPR) and collectors (Fig. 3**a**–**f**).

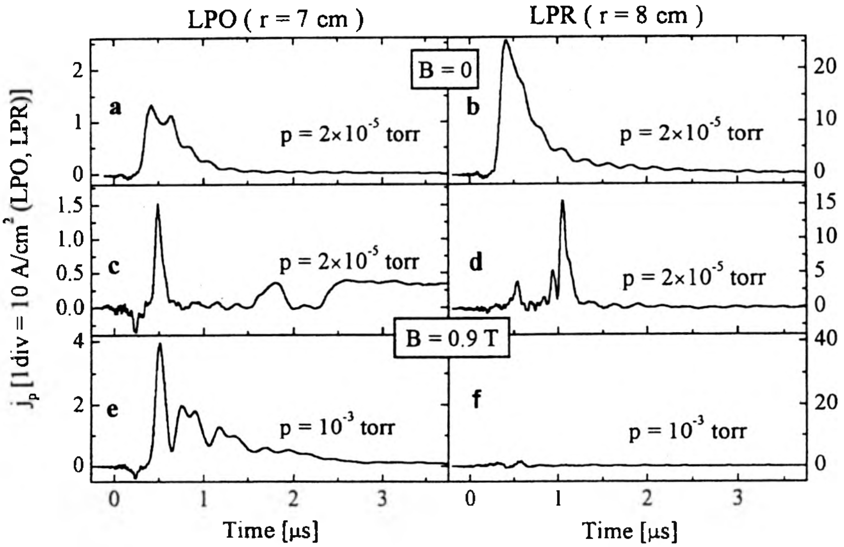

Fig. 3. Langmuir probe singals for various experimental conditions shown in the diagrams **a**–**f** (B – magnetic field, p – pressure, r – distance of the Langmuir probes LPO and LPR from the target).

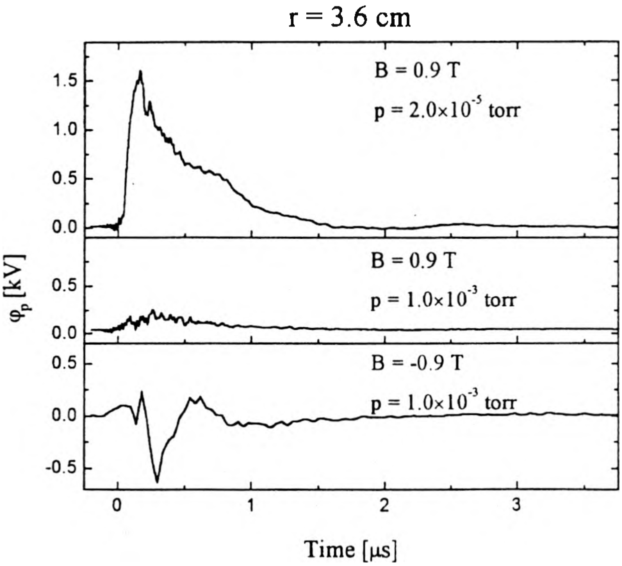

Fig. 4. Plasma potential measured using Langmuir probes.

Measurements of the floating potential of the reference electrode of the LPO (Fig. 4) probe give an average value of the E_p field equal to about 700 Vcm^{-1} which is fairly close to the theoretical values, $E_{\mathrm{th}} = vB_0/c = 850\ \mathrm{Vcm}^{-1}$, for the minimum velocity registered ($v = v_0/2$). Such a plasma penetration into the magnetic field beyond R_b is usually caused by the development of instabilities at the plasma boundary and related processes of an enhanced anomalous field diffusion [9] or by the formation of flutes [14].

In the presence of the background plasma of the density n_0, very interesting phenomena of its collisionless interaction with the plasma streams can occur [2], [16] under conditions of a low Alfven – Mach number ($M_{\mathrm{A}} \leqslant 1$) that is very typical of active experiments. We have found that for air and Ar background pressure of $\sim(0.5-1)10^{-3}$ torr, the straight-line motion of the plasma stream across the magnetic field does not take place and the plasma jet begins to be deflected into the direction of the ion Larmor rotation. However, because depolarization is incomplete, the jet trajectory does not correspond to the ion cyclotron radius ($R_h \approx 1$ cm). We can conclude that a decrease of the polarization potential φ_{p} observed in the background plasma is an important process which can lead to the jet deflection observed if the polarization field $E_{\mathrm{p}} < E_{\mathrm{th}}$. This jet deflection is observed in the decreasing and disappearing ion flux at the "top" LPR probe (Fig. 3f). On the other hand, an increase in the ion flux has been observed at the "bottom" LPO probe (Fig. 3e). We have also proved that these effects swap when the magnetic-field direction is changed to the opposite one (Fig. 4).

4. Discussion

These fairly new phenomena in laser-produced plasma experiments, related to the polarized plasma jet deflection, but not with its deceleration (as was observed in plasma streams studied at weaker fields [16] without plasma streams jetting), could be very similar to some speculative processes [17], [18] of the interaction between an artificial plasma jet and a geoplasma jet background. Here we discuss additional data of such "KE-1M" experiments which confirm the suggestion [8], [11] about applicability of the "space model" [17], [18] interaction of polarized plasma jet with plasma background. It helps to explain our results and therefore gives us an opportunity to use plasma streams experiments for simulation of some artificial plasma releases in space.

The main idea of the "space mode" is a short-circuited effect of a plasma background on the plasma jet transverse polarization (Fig. 3) via field-aligned current (FAC) $j_\parallel$, which could be shortened out by a cross-field current $j_\perp$ (Fig. 2) due to anomalously low plasma conductivity. We suppose that in our case this conductivity [9] corresponds to an electron collision frequency $\sim 0.3\ \omega_{ce}$, that leads according to [18] to the following curvature radius $R_d \sim R_h(nV_0 0/n_0 v_{e,0})^{1/2}$ of a partly polarized plasma jet (with half-angle $0 \approx 0.15$ of the expansion and average density $n \sim 2 \cdot 10^{13}\ \mathrm{cm}^{-3}$), where $v_{e,0}$ is electron thermal velocity of plasma background with usual temperature of ~ 1 eV. Such a relation could describe quite well the observed [11], [15] scale of $R_d \approx 1.5-2$ cm, if we take into account the process of the photoionization of a plasma background by the VUV-emission from laser target (with the total number of photons $\sim 10^{17}$). An ionized fraction of the plasma background with $n_0 = 10^{12}$ cm^{-3} at distance $r = 3.5$ cm was measured directly in the "Bohm" regime of LPF-probe (with electrodes parallel to $\vec{r}$), whose current $\leqslant 0.1$ A/cm^2 in time between the photopeak and peaks of plasma streams was proportional to the background pressure. This sufficiently high value of the plasma background density n_0 (decreasing with $1/r^2$ law) could indeed supply conditions of the FAC-generation and their short-circuiting within a rather extended region $L_x \sim L_z R_d \omega_{ce}/R_h v_{eff} \sim 10$ cm, that is needed [17] for the conduction of current through bakground plasma to depolarize a plasma jet (at scale R_d) during its propagation at distance $L_z \sim 3$ cm along v_0 (outside of cavity $R_c \approx 1.5$ cm). The observed deflection of partly polarized plasma jet into $\mathbf{v} \times \mathbf{B}$ direction should be caused [17] by a Hall current j_H (parallel to v_0 inside of plasma jet, see Fig. 2) with its typical amplitude up to $j_H \sim 8enR_h L_z^2 0^2 0_d/\tau_d \sim 30$ A for the deflection time $\tau_d \sim 100$ ns, which should be supplied by FAC with $j_\parallel \sim j_H/L_z^2 0 \sim 20$ Acm^{-2} which was really measured by Rogovski coil (see Fig. 2) at a number of positions ($y > 0$ or < 0; $z = 2.2-3.7$ cm and $x = 2-3$ cm) as well as for various background plasma conditions (Fig. 4).

5. Conclusions

The new phenomena of the strong influence of a plasma background ($n_0 \leqslant n$) on dynamics of small ion-gyroradius plasma jets (with cross-section $\Delta \geqslant R_h$) in transverse magnetic fiels, as revealed in our cooperative experiments [11], [15], are very different from the known effects [1] (with the threshold $n_0 \gg n$ for $\Delta/R_h \ll 1$ beams) and they could be described by the "space model" [8], [17], [18]. So in terms of the similarity criteria of the problem such as Alfven–Mach number M_A of a polarized plasma jet and a level of the ion magnetization in the background plasma $\tau_d \omega_{ci}$ we would apply oure results for the simulation of relevant space experiments, *e.g.*, in Fig. 4, an essential effect of the jet's depolarization, very similar to "Porcupine" [3] one, can be seen. These results are helpful for understanding a "suppression" of a plasma flute instability in the presence of the plasma background with $M_A = 1$, a very important problem for the ICF.

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