On the opportunity of Laser Plasma simulation of Plasma Jets formation in moderate magnetic fields ~ kGs

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Abstract. Today a number of various experiments with Laser-Produced Plasmas (LPP), done at very-high Magnetic Fields (up to \( B_0 \geq \text{MG} \)) are using to model the physics of Astrophysical and Space Jets, a various processes of their formation and possible long-range propagation at various angles \( \theta \) to magnetic fields. We discuss the opportunity and present the first results of new-type experiments on simulation of Jets with LPP at KI-1 facility of ILP, at moderate magnetic field ~ kGs, oriented quasi-transverse (\( \theta \approx 60^0 \)) of LPP-blob expansion (with velocity \( V_0 \)) relative to \( B_0 \). They were done on the base of all our preliminary studies, both at large-scale, high-vacuum chamber (\( \varnothing 120 \text{ cm} \) of KI-1) and others devices with LPP (oriented earlier at \( V_0 \) transverse to \( B_0 \), with \( \theta = 90^0 \)).

1. Introduction
Since 1991 a lot of investigations at KI-1 facility of ILP were done [1-7] on the expansion of LPP across magnetic field \( B_0 \), including a few cases with multi-kGs ones, of dipole type [1-3, 5] and quasi-uniform [4, 6, 7] of small Helmholtz Coils (\( \varnothing \leq 15 \text{ cm} \)). Therefore, a data about revealed Jet-like structures (in both cases) were very preliminary, and only recently we could study initial stage of Jet formation from LPP (with the flat target) in the field \( B_0 = 300 \text{ Gs} \) [8] at scale \( \sim 100 \text{ cm} \), comparable with the diameter \( \varnothing 120 \text{ cm} \) of vacuum chamber KI-1. Now, with the purpose to develop the methods of laboratory simulation in the LPP-experiments, into the center of chamber was installed a spherical plastic target \( \varnothing = 10 \text{ mm} \) with the system of its symmetrical irradiation by 4 beams (of tetrahedral scheme). As a result, we had started a new kind of experiments [10] to generate a spherically-symmetrical plasma cloud and to study its collisionless interaction with magnetic field and magnetized plasma background (for verification of new 3D-Codes). In our previous experiment MHD [7] with a small spherical target (\( \varnothing = 3 \text{ mm} \) and 2-beams irradiation), in the field 8 kGs we had observed formation of 2 Jets (along to beams) with velocity \( V_i \approx 50 \text{ km/s} \) \( \sim V_0/3 \) (at radius \( R > 2 \text{ cm} \)). For the initial total energy of this LPP, \( E_0 \approx 10 \text{ J} \), its deceleration radius [11] by field is \( R_{B} = (3E_0/B_0^2)^{1/3} \approx 1,7 \text{ cm} \) and directed (\( \approx V_0 \)) ion Larmor radius \( R_{L} \approx 0,5 \text{ cm} \), so, the criterion of ion magnetization had enough small value \( \epsilon_{b} = R_{L}/R_{B} \approx 0,3 < 1 \) for the effective interaction of LPP with \( B_0 \)–field at scale \( \sim R_{B} \), including its deceleration and cavity formation [7].
2. Experiments on generation and study of Jets in moderate magnetic fields 300-400 Gs

Therefore we had tried to realize in the given 4-beams scheme, attempt to form a Jet-like structure from a larger spherical target (C$_2$H$_4$), by using only 2 beams, from the left entrance laser window. At Figure 1 one can see the relevant part of this scheme with 2 copper mirrors (at the bottom and at left), reflected 2 beams (here) of CO$_2$-laser to the target above them. As a result, with magnetic field $B_0 = 400$ Gs, we could register by time-integrated photos (Figure 1a), a long red plasma stream from target downwards at presence of H$_2$-gas (with pressure $\approx$ 1.5 mTorr). With gas, but without field, only small blue sphere appears shifted from target (Figure 1c). The photo (Figure 2) of Gated Optical Imager (GOI) in the same field (in vacuum) have revealed (at time $t = 2.5 \mu$s with exposition $1.5 \mu$s, without gas) a Jet-like structure (of size up to $S \approx 25$ cm into the same down-left direction, with the velocity $V_0 \approx 100$ km/s, rather well corresponding to the initial expansion velocity of LPP-sphere, generated in the case of total 4 beams (when LPP energy $E_0 \approx 25$ J).

The red color of observed luminosity well corresponds to the Balmer Alfa (656.2 nm) of Hydrogen and we also seen such an effect before, during previous experiment Super-Jet [8] with the flat target (C$_2$H$_4$) and real kinetic energy of LPP 50 J (with effective energy 300 J, into 4$\pi$) in the field $B_0 = 300$ Gs. In the given case, with expected LPP kinetic energy $E \approx 12$ J and $B_0 = 400$ Gs, expected cavity radius could be $R_b = (3E/B_0^2)^{1/3} \approx 13$ cm and ion Larmor $R_L \approx 10$ cm, and so the $\epsilon_b \approx 1$ and we have presented at Figure 2, a GOI-data on Jet-like structure up to the radius $R \approx 25$ cm (see Figure 2.).
Figure 2. GOI-data on the Jet-like plasma expansion (from 2 laser beams) at the moment $t=2\text{ mks}$, with exposition $\tau = 1.5\ \mu s$, (negative) in vacuum $3*10^{-6}\ \text{Torr}$ at field $B_0=400\ \text{Gs}$. The dark spot in center is a slow plasma near target, while below – fast stream with a front velocity $V_0=R/t \approx 125\ \text{km/s}$ close to the initial velocity of LPP expansion without field. This velocity was measured by Langmuir probe (at its maximal $R = 25\ \text{cm}$ ), which support are seen lower.

3. Magnetic probes data on propagation “2-Beams” Jets at large distances with $B_0 = 400\ \text{Gs}$

Since it was impossible to study such Jets at distances $R > 25\ \text{cm}$ by GOI (to get such GOI-Photos in later times, we need to increase $P$ more than $5\cdots 7\ \text{mTorr}$) and also by Langmuir probes (in this direction), we did additional measurements by the pair of magnetic probes (see Figure 1a, at the left). Their main data on magnetic disturbances by Jet are presented at Figures 3, 4, 5.

Here (above) at the moment $t=2\ \text{mks}$ (by black arrow at bottom) is marked the moment, when the decline of $B_z$-derivations (RM-probe) was stopped, before its rising (data of 10 September 2021). Laser shot was done at the moment $t = 0$. 

Figure 3. Example of preliminary data of magnetic probes signals obtained at distances $R_1 = 26\ \text{cm}$ (IAP-probe) and $R_2 = 32\ \text{cm}$ (RM) by black, it is magnified by factor 5). They are oriented mutually by orthogonally, with effective area $S_1 = 16.5\ \text{cm}^2$ and $S_2 = 2\ \text{cm}^2$. 

IAP – oriented to measure $B_\varphi$, and 

RM - to measure $B_z$ variations.
Figure 4. Examples of the moments (by red arrows) when a spikes of $B_\phi$-field were registered by IAP-probe in front of Jets arriving to probe.

At the Figure 5, the main moments of Jets arriving to probe RM are presented, first of all, the a-time 2 mks (of RM at distance 25 cm), which is rather close to AIP-signal at distance 26 cm (at Figure 4b). Therefore we could combine the both data into general R-t diagram at Figure 6.

Figure 5. The data on the dynamics of magnetic disturbances Derivatives (D) at various distances of magnetic probe RM (25, 32 and 35 cm) at the moments $T_1 = 2$, $T_2 = 2.5$ and $T_3 \approx 2.8$ mks (when the decline of D stops). Initial decline of D explains by magnetic field $B_z$ exclusion near target and it stops, when the LPP reaches the probe. These moments are well correlated with the spikes in $B_\phi$-field (Figure 4), registered by IAP-probe, as a result, a joint R-t diagram of Jets front was found (Figure 6).

4. Discussion and Conclusions

Presented at Figure 6 (below), R-t diagram of Jet front, corresponds to its motion without deceleration accordingly insufficient level of ion-magnetization on $\varepsilon_b = R_L/R_b \approx 1$ [7]. Since in the given case ion-Larmor radius $R_L \approx 10$ cm and we register Jet propagation up to the length $L \approx 50-60$ cm (see Figure 1a,b), we can conclude that also in the case of low-level of ion-magnetization, the Jets could propagate in the Regime of Long-Range Propagation of Large-Scale Jets [12].
Figure 6. Joint R-t diagram of Jet front by the data: RM – probe, IAP – probe, GOI – Gated Optical Imager (photo at Figure 2). The Line corresponds to the velocity 120 km/s, rather close to the initial velocity of LPP expansion (V_0 ~ 100 km/s) in the full 4-beams scheme [10], in contrast to our previous data [7], with multi-kGs field and with high-level of ion-magnetization on ε_b ≈ 0.3<1, While in the given case we have ε_b ≈ 1, only.

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