Production of dense laser-driven plasma jets using a cylindrical channel

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Abstract: A simple method of production of supersonic plasma jets with parameters relevant to laboratory astrophysics applications is proposed and demonstrated. The method consists in using a cylindrical channel for guiding and collimating the plasma generated from a laser-irradiated thin foil target. In the experiment, a 120 J, 1.315 µm, 0.3 ns laser pulse irradiated a thin (10 or 20 µm) CH foil placed at the entrance of the cylindrical channel (made in the aluminum cylinder) of diameter \( d_{Ch} = 0.3 \) mm and length of 2 mm. It was found that when the focal spot diameter \( d_{fs} \) is well matched to the channel diameter \( d_{Ch} \approx (2/3) d_{fs} \), the channel can form a collimated, high-density (up to \( 10^{20} \) cm\(^{-3} \)) plasma jet of the Mach number \( \geq 10 \). The method seems to be flexible in the generation of jets of various hydrodynamic parameters and atomic numbers and does not require high-energy lasers for the jet production.

Generation of dense supersonic plasma jets is a subject of great interest in the laboratory study of astrophysical phenomena [1] and is also investigated in the ICF context [2]. Such plasma jets can be produced by laser irradiation of conical [3], planar [4] or triangular (V-shaped) [5] surface of a solid target. In these cases the jet is emitted in a backward direction (against the laser beam or in some angle to the beam), which can limit practical use of the jet for investigation of its interaction with some specific objects. Moreover, efficient production of plasma jets from planar targets seems to be limited to the high-Z or medium-Z plasmas. For the production of forward-emitted plasma jets a strong shock wave produced by a high-energy (\( \geq 1 \) kJ) laser in a massive target with a hole [2, 6] or in the foam filling a short conical channel [7] was used.

In this contribution, we propose and demonstrate the formation of a supersonic forward-emitted plasma jet using a cylindrical channel for guiding and collimating plasma produced from a laser-irradiated thin foil target. This method seems to be flexible in the production of jets of various hydrodynamic parameters and Z numbers and does not necessary need high-energy lasers.

The experiment was performed at the Prague Asterix Laser System (PALS) facility in Prague. A 1.315-µm, 0.3-ns laser pulse of energy about 120 J and intensity up to \( 4 \times 10^{15} \) W/cm\(^2 \)
The interferograms and the corresponding electron isodensitograms and spatial distributions of electron density for the plasma leaving the channel of the length $L_{Ch} = 2$ mm at various instants after the laser pulse ($t = 0$) are presented in Fig. 2. It can be seen that a collimated plasma jet of electron density increasing in time (up to $10^{20}$ cm$^{-3}$ at $t = 17$ ns) is formed at the channel output. Comparing the plasma flux leaving the channel with that produced without the channel we observed that the first one is much more collimated, denser, faster, and the total number of electrons in the flux is higher than that of freely expanding plasma (without the channel).

The parameters of the plasma jet formed in a channel depend on the irradiated foil’s thickness $l_f$. The time evolutions of the plasma jet velocity and the total number of electrons in the jet produced from the CH target of $l_f = 10$ or 20 µm are shown in Fig. 3. The jet produced from the thinner target is faster, while the number of electrons in the jet is only a little bit higher than that for the thicker target. The spatial distributions of electron density in the jets were similar for both cases.

Another factor determining efficacy of the jet formation is the ratio $d_l/d_{Ch}$. We observed that at fixed laser energy the most collimated and the fastest jet was produced at $d_l = 200$ µm ($d_l/d_{Ch} = 2/3$). The parameters and collimation of the jet both at $d_l = 100$ µm and at $d_l = 400$ µm were not so good, probably due to too large angle of the plasma expansion in the first case and due to too low laser intensity in the second case.

For application of laser-produced plasma jets in the laboratory study of astrophysical phenomena some dimensionless numbers characterizing these jets should be of the same order of magnitude as the ones for astrophysical jets. In particular, this relates to [1, 7]: the Mach number $M = v/r_\gamma$, the Peclét number $Pe = v r_\gamma/\kappa$, and the Reynolds number $Re = v r_\gamma/\nu$, where $v$, and $r_\gamma$ are the jet characteristic velocity and transverse radius, respectively, $c_\gamma = 9.79 \times 10^5 (\gamma Z T_e A)^{1/2}$ cm/s is the ion sound velocity [8] in the jet, $\gamma$ is the polytropic index, $\kappa = 2 \times 10^{21} T_e^{5/2}/A(Z+1) n_e$ cm$^2$/s is the thermal diffusivity [9], $\nu = 2 \times 10^{-5} T_e^{5/2} A^{-1/2} Z^{1/2} /\Lambda n_e$ cm$^2$/s is the kinematic viscosity [9], $T_e$, $Z$, $A$ and $n_e$ are the electron temperature, ion charge state, atomic mass number and electron density of plasma in the jet, respectively, and $\Lambda$ is the Coulomb logarithm. For astrophysical objects like the Herbig-Haro jets $M \sim 10$, $Pe >> 1$, $Re >> 1$ [1, 7]. To estimate the values of $T_e$ and $Z$, which we have to know to determine the above dimensionless numbers for the jets produced in our experiment, we utilized the results of measurements using the ion diagnostics as well as numerical simulations with the one-dimensional HYADES code. The electron temperature of plasma at the source (close to the CH target rear surface) was estimated from the formula [10]: $T_e = E_i / (4Z+1)$ where $E_i$ is the mean ion energy of a thermal group of ions emitted forward from the plasma (determined from the ion collector measurements) and $Z$ is the average ion charge state (estimated from the Thomson parabola measurements). For the CH target of the thickness $l_f = 10$ µm we obtained $T_e = 110 \pm 26$ eV.
This value of temperature corresponded fairly well to the one obtained from the numerical simulation which, at the end of laser-target interaction ($t \approx 0.5$ ns), resulted in $T_e \approx 90 – 100$ eV. After the time $t = 8$ ns, which is roughly equal to that needed to pass through the 2-mm channel by the front part of expanding plasma, the calculated plasma temperature dropped to 12 eV and the plasma front velocity reached about $2 \times 10^7$ cm/s. The consistency of these results with our measurements justifies the assumption that the temperature in the plasma jet observed at the 2-mm channel output is roughly equal to $T_{ej} \approx 10$ eV $= T_e/10$. Taking the above value of the plasma jet temperature and also: $v_j = (1.5 – 4) \times 10^7$ cm/s (Fig. 3), $r_j = 0.015$ cm, $n_e = 3 \times 10^{19}$ cm$^{-3}$, $Z = 3$, $A = 12$ we arrive at: $c_s \approx 1.8 \times 10^6$ cm/s, $M = 8 – 22$, $P_e = (1.2 – 3.3) \times 10^2$, and $R_e = (2.4 – 6.5) \times 10^4$.  

Fig. 2. The interferograms and the corresponding electron isodensitograms and space profiles of electron density distributions for the plasma leaving the channel of the length of 2 mm. $l_T = 20 \mu$m, $d_l = 200 \mu$m, $E_l = 127$ J.

Fig. 3. Evolution of the plasma outflow velocity (a) and the total number of electrons (b) in the plasma flux leaving the 2-mm channel for the CH targets of different thicknesses. $d_l = 200 \mu$m, $E_l = 120 \pm 10$ J.

For the CH target of $l_T = 20 \mu$m the electron temperature at the source (deduced from the measurements) was lower than that for the thinner target and was estimated to be $T_e = 70 \pm 20$ eV. The measured velocity of the plasma jet at the 2-mm channel output was also lower: $v_j = 1.3 \times 10^7$ cm/s (Fig. 3) and the values of dimensionless parameters of the jet were as follows: $M = 8$, $P_e = 32$, and $R_e = 6.3 \times 10^4$. We can see that for both $l_T = 10$ and $20 \mu$m the values of $M$, $P_e$ and $R_e$ correspond fairly well to the ones required for a proper simulation of astrophysical jets.
In conclusion, it has been shown that using a cylindrical channel for guiding and collimating plasma created at its entrance at the interaction of a laser pulse with a thin foil target can be an effective way of production of high-Mach-number, dense ($n_e \sim 10^{19} - 10^{20} \text{cm}^{-3}$), forward-emitted plasma jets of parameters relevant to laboratory astrophysics applications. The production of jets using the channel does not necessarily need high laser energy as efficacy of the jet formation is determined mainly by laser intensity $I_L$ and the $d_L/d_C$ ratio (for a fixed laser pulse duration) and the required values of these parameters can also be attained with low-energy (~J) lasers. It opens a prospect for using compact commercial lasers for the jet production and for some laboratory astrophysics experiments.

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