Parameters of supersonic astrophysically-relevant plasma jets collimating via poloidal magnetic field measured by x-ray spectroscopy method

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Abstract. Application of external magnetic field to a laser-generated plasma flows allows to investigate stable, large aspect ratio plasma jets which are relevant to a number of astrophysical cases. In the experiment with 0.6 ns, 40 J laser pulses focused to 700 µm focal spot at solid CF₂ target in presence of 20 T poloidal magnetic field the parameters of the plasma jet were studied by means of spatially resolved x-ray spectroscopy. Focusing spectrometer with spatial resolution was used to record the temporally-integrated x-ray emission spectra of the plasma with spatial resolution along the jet propagation. Using the relative intensities of spectral lines emitted by F He-like ions, the electron temperature $T_e$ and density $N_e$ profiles of the plasma are obtained. It is shown that $N_e$ decreases monotonically in the case without B-field, but demonstrates an extended density profile up to 10 mm when 20 T magnetic field is applied. $N_e$ values are consistent with that observed via interferometry diagnostics, thus providing the confidence in our x-ray spectroscopy analysis techniques.

1. Introduction

Last laboratory studies [1,2] have shown the new evidences of the jets formation in astrophysical systems, such as young stellar objects (YSO). In particular, relatively stationary conical shock is suggested to be the origin of long-time x-ray emission observed from such objects (e.g. Hebrig-Haro 154). YSOs are associated with the accretion phase of the stellar evolution, which can last for around the first $10^5$ years of a star life. The jets are seen propagating away from the star at speeds of the order of hundreds km/s, with lengths up to 0.1 parsec, and with aspect ratio (jet length/jet width) of 10 or more. The laboratory-produced jets are fully scalable to such YSOs as both are ideal magnetohydrodynamic (MHD) systems. The focus of this paper is to demonstrate the capability of x-ray spectroscopy method [3] to characterize laser-generated jets, and to measure electron temperature and density of the plasma jet collimated via external poloidal magnetic fields.
2. Experimental setup

The experiments have been performed at Laboratoire pour l’Utilisation des Lasers Intenses (LULI), Ecole Polytechnique. Nanosecond laser system ELFIE and the platform to study magnetized high-velocity shocks [4] were used for astrophysical phenomenon modelling. Plasma jet was created by laser beam with wavelength $\lambda = 1.057$ nm with pulse duration of $\sim 1$ ns and energy of 40 J focused on a thick, 2 mm diameter ($\text{CF}_2$) target in spot with diameter of $\sim 700$ $\mu$m. The laser was incident at $10^\circ$ on the front surface of this target. Intensity on the target at these conditions achieved $1.7 \times 10^{13}$ W/cm$^2$. Magnetic field was applied with amplitude of 20 T. The main motivation for such experiments was researching of plasma jet evolution inside the external magnetic field with force lines which are normal to the target surface. Scheme of experimental installation is shown on figure 1. Consequent spatial “frames” along the jet propagation was taken by varying the position of the target along the laser axis. Experimental conditions are assumed to be similar at these conditions.

Focusing spectrometer with spatial resolution (FSSR) was used for x-ray measurements. FSSR was equipped with spherically bent mica crystal with a lattice spacing $2d = 19.9376$ Åand curvature radius of $R = 150$ mm. The crystal was aligned to operate at $m = 1$ order of reflection to record the emission spectra of multicharged fluorine ions in 13–16 Åwavelength range (800–
950 eV corresponding energy range). Spectra were recorded on fluorescence detector Fujifilm Image Plate which was situated in a cassette holder shielded from the optical radiation. Aperture of the cassette was covered by two layers of filters made of polycarbonate (2 µm) evaporated by aluminum (7 nm).

Several theoretical models can be used to describe the plasma jets parameters using x-ray emission registered. A population kinetics model incorporates the results of atomic structure codes and scattering theories, plasma and statistical physics to describe atomic processes in atoms embedded in plasma. The goal is to determine ionization and level population distributions of a plasma for a given electron temperature, \( T_e \), and density, \( N_e \), and then to assist in the analysis and prediction of spectroscopic observables. For the case of dense plasma in the area of laser-target interaction the collisional-radiative code PrismSPECT to simulate the atomic and radiative properties might be applied. For a grid of user-specified plasma conditions, PrismSPECT computes spectral properties (emission and absorption) and ionization properties for LTE and non-LTE plasmas. Its capabilities include computing the properties of plasmas irradiated with external radiation fields, plasmas with non-Maxwellian electron distributions, and inner-shell (e.g., K-alpha and K-beta) satellite line emission spectra [5].

However in the case of strong recombining plasma at some distance from the target the applicability of PrismSPECT is limited. Instead, a new method analyzing relative intensities of the resonance transitions in He-like and H-like ions was developed allowing to measure both electron density and temperature of recombining plasma. The method is described in details in [3] and here is applied for diagnostics of plasma evolution along the jet axis. It was shown the method is sensitive when the electron density is in the range of \( 10^{16} - 10^{20} \) cm\(^{-3} \) while the temperature ranges from 10 to 100 eV for ions with nuclear charge \( Z_n \sim 10 \). Method is based on the quasi-steady model of expanding plasmas which also takes into account recombining plasma with “frozen” ion charge. In this paper the calculations were carried out for F VIII ion and allowed to determine parameters of plasma jets.

3. Results and discussion

Density and electron temperature were determined for free-propagating plasma jets and for that ones immersed in the magnetic field of 20 T. Various shots have been performed to study the plasma in different conditions. Taking into account PrismSPECT simulations the plasma temperature at surface can be as much as 300–320 eV (figure 2). The spectrum here contents of Fluorine Lyα line and its satellites in the range 800–830 eV. In simulations non-LTE regime was used at critical electron density of plasma for actual laser wavelength. The given spectra are normalized to Lya intensity. It is seen that at the target surface the temperature can be determined with the precision of \( \sim 10\% \) (of about 30 eV in the range considered).

The placement of target at different positions along the laser axis and within the magnet coil allows to observe the different areas of the plasma jet fitting it into diagnostic window and optical probe beam path. Considering quite long focal distance (~ 2 m) of ns laser beam and homogeneity of B-field it is assumed the experimental conditions for the plasma generation and expansion to be the same wherever the target was shifted in the range of 20 mm along the laser axis. The example of the joined electron density map of the plasma jet obtained with optical interferometry diagnostics combining 3 different spatial frames along the jet is shown in figure 3.

By the same way x-ray spectroscopy data were taken for 3 target positions and 3 corresponding spatial frames observable through the diagnostic window in the coil, and then combined to provide the measurements on electron temperature and density over 15 mm along the plasma jet expansion. Analyzing the relative intensities of Heβ, Heγ and Heδ lines of Fluorine (corresponds to 3p–1s,4p–1s,5p–1s transitions in He-like multicharged ions) and normalizing the data taken from different spatial frames the plots were obtained for \( T_e \) and \( N_e \) versus the distance from the laser irradiated surface (see figure 4).
Figure 2. PrismSPECT simulation (red, black dash, black narrow lines) and experimental spectrum measured by FSSR (solid black) for CF\textsubscript{2} target and containing most intense F Ly\textalpha{} (right) line and the group of satellites sensitive to the plasma parameters. Best fitting of PrismSPECT simulations corresponds to $T_e = 320$ eV at critical density $N_e = 10^{21}$ cm\textsuperscript{-3}. All spectrum lines are normalized to Ly\textalpha{} line intensity.

Figure 3. Electron density map taken via optical interferometry for the plasma jet propagating from CF\textsubscript{2} target in the presence of B-field. The map is combined of three frames acquired while the target positioned at three different places along the laser beam axis within the magnet coil (see the scheme in figure 1).

Plasma is assumed to be optically thin in experiments (optical thickness is $\ll 1$) due to the transverse size of a dense plasma region is of $\sim 0.4$–$0.9$ mm as it follows from optical interferometry data using a criteria of plasma density $N_e > 5 \times 10^{18}$ and $N_e > 10^{18}$ cm\textsuperscript{-3} respectively. As in the interferometry data, the electron density decreases monotonically in the case without B-field, but shows an extended density profile up to 12 mm in the case with an applied 20 T field. It provides quite valuable data and necessary confirmation on the effect of jet collimation by poloidal B-field. The electron temperature in figure 4 peaks at 50–80 eV and then decreases with the distance from the target. In the case without B-field, the temperature drops to below the diagnostic resolution at around 3 mm. On the other hand, with 20 T field the electron temperature remains virtually constant at $\sim 10$ eV level for many millimeters. This is interesting, because it suggests that the impact of poloidal magnetic field creates well collimated plasma jet not only of constant density but of constant temperatures at long scales.
Here the temperature near the surface is shown as 80 eV which is the highest temperature recorded on the FSSR. However, as the FSSR data is time-integrated one, the temperature is expected to be underestimated in the range near the target surface. Moreover, the plasma close to surface is not recombining, and the approach of PrismSPECT simulation suits better in this area giving the temperature above 300 eV at target surface and of about 150 eV at first few hundred microns nearby.

Another feature in the case of 20 T field impact is a small decrease in density around 2.5–3 mm as compared to the 0 T case. This location is similar to the location of the cavity as seen from interferometry data (figure 3). After the cavity, the conical shock is observed due to the impact of B-field, and corresponding increase in electron density and temperature is observed via x-ray spectroscopy diagnostics as well at 4 mm distance, providing remarkable consistency for optical and x-ray diagnostics data.

4. Conclusion

We have investigated laboratory astrophysical jets over various length scales. Using the relative intensities of x-ray spectral lines emitted by H- and He-like F ions, the electron temperature and density profiles of the plasma are obtained. It is shown that electron density decreases monotonically along the plasma jet axis in the case without B-field, but demonstrates an extended density profile when magnetic field is applied. Obtained data is consistent with that one observed via interferometry diagnostics, thus providing the confidence in present x-ray spectroscopy analysis techniques. While at the laser irradiated target surface the electron temperature peaks at 300–320 eV, at 3 mm distance it cools down to ~ 20 eV. Then, due to the impact of B field providing the collimation of the jet, Te and Ne are measured to keep at almost constant values along many mm’s along the jet. Another feature in the 20 T case is a decrease in temperature at 2.5–3 mm distance, which is consistent with the evidence that in this range the cavity of cooler and low-density plasma is created. Then due to the impact of magnetic field the conical shock is formed at the tip of the cavity, which leads to the plasma heating as well as to the jet collimation.

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