Plasma jet experiments in vacuum and in ambient medium using high energy lasers

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Abstract. We present promising experimental results for laboratory astrophysics. These experiments were performed in France at the LULI2000 facility to study jet propagation in vacuum and in Japan at ILE using Gekko XII HIPER Laser for jet evolution in an ambient medium. A foam filled cone target was used to generate high velocity plasma jet, and a gas jet nozzle was used to produce the ambient medium. Using visible and X-ray diagnostics, we measured the jet parameters such as: density, temperature and velocity. We were able to determine experimentally the jet dimensionless quantities to compare with astrophysical objects.

1. Introduction

High-energy density facilities allow the exploration of extreme state of matter and a replication of some of the plasma physics encountered in astrophysical objects [1]. Using carefully designed targets and an array of diagnostics, we are able to measure plasma conditions and their evolution to enable tests and possible validation of theoretical understanding and/or computer simulation codes. Many and detailed astronomical observations have been made of Herbig-Haro objects yet questions such as jet collimation remain unsolved. These questions motivate our experimental work. In the presented experiments, most of the dimensionless parameters required to scale from the laboratory to the astronomical jet were experimentally determined.
2. Jet propagation in vacuum and parameters measurement

The experiment was performed using LULI2000 laser facility [2]. We used the two kJ beams (2ω, 500 μm focal spot diameter, 1.5 ns pulse duration) giving a maximum laser intensity of \( I_L \approx 10^{14} \text{W.cm}^{-2} \). The target was composed of a three layer pusher and a cone filled with foam [3]. We used various foam densities to change initial jet conditions, and we used high-Z material doped foam to enhance contrast for the X ray diagnostic. The key point is to create the jet at the rear side of the target to avoid any interference between the laser beam [4] and the ambient medium on the jet side. Our main goal, regarding the diagnostics implementation, was to measure the jet characteristics and explore the best target design to produce a collimated plasma jet and match the scaling. The experimental set up is described figure 1.

![Figure 1](image)

**Figure 1.** Experimental setup for jet propagation in vacuum using LULI2000 laser. For the X ray diagnostic, one of the two beams was used as a backlighter.

2.1. Visible transverse diagnostics: jet shape and velocity measurements

Transverse to the jet propagation direction, we used shadowgraphy and interferometry using a probe beam at 532nm. The probe laser goes through the plasma and is then split, temporally delayed in the two arms of the VISAR and recombined to obtain an interferogram which is imaged into the streak camera. When the electron density approaches \( n_c/10 \), the probe beam begins to be completely absorbed and refracted so no light can be collected by the camera. Hence by measuring in the interferogram the slope of the absorbing zone, we can extract the jet velocity (see figure 2). We measured a jet velocity up to 150km.s\(^{-1}\). We also used two Gate Optical Imagers with a 120ps integration to record the 2D jet shape evolution in shadowgraphy.

2.2. Rear side diagnostic: jet temperature measurement

The rear side diagnostic was Self-emission Optical Pyrometry. To perform temperature measurement (\( T_{\text{jet}} \)), we adopted an absolute photon counting technique. The thermal emission was observed at 450 nm and the total energy emitted by the jet was linked to the number of CCD counts recorded assuming black body emission. We also measured the jet radial evolution. Depending on the foam density, the temperature ranged from 2eV to 4eV. The jet radial velocity is slow compared to its propagation velocity (\( V_{\text{Rjet}} \approx 30 – 50 \text{km.s}^{-1} \)). Due to this high initial jet...
propagation velocity, the plasma remains quite collimated later after the main drive beams which was confirmed by comparing the two GOI results for the same shot at two different times. The jet radial evolution is well described analytically using Euler equations with a polytropic pressure law.

2.3. Jet density measurement
In order to get the jet density, we performed a transverse 2D X-ray monochromatic shadowgraph of the jet at around 5 keV (He-alpha V line) using a spherical bent crystal [5]. We could extract the density from the transmitted x-ray intensity after propagation through the jet using the Beer’s law. Figure 4 represents the radiograph and the radial density profile of the jet along the propagation axis. An Abel inversion was performed to extract the density assuming cold brominated foam absorption. Hence, with the cone guiding effect, the foam compression reaches 10.

3. Jet propagation in ambient medium
The experiment was performed at ILE in Japan using Gekko XII HIPER Laser (4 beams, 3ω, 300μm focal spot diameter, 500ps pulse duration) for a laser intensity of $10^{15} \text{W.cm}^{-2}$. The main diagnostic was a visible transverse Mach-Zender interferometer using a YAG 2ω probe beam. As detectors, we used a streak camera to get the jet velocity and an ICCD camera (200ps time
resolution) to get the jet 2D electronic density map. We used the same target but without a pusher on the laser side to generate faster and hotter jet than in LULI experiment propagating radiative shock through the foam. The ambient medium was helium gas with an electronic density of $1 \times 10^{16}$ cm$^{-3}$. The analysis is still in progress, nevertheless the first conclusions are: high jet velocity (up to 285 km.s$^{-1}$) as expected and a gas effect of the low dense plasma ahead of the jet which slow down its propagation.

4. Dimensionless parameters

The jet dimensionless parameters to consider are [6]: the Mach number, the cooling parameter, the jet-to-ambient density ratio to describe the global dynamic properties of the jet and for the fluid parameters, the Reynolds number, Peclet number and the localization parameter. Typical values for astrophysical jets are $M \approx 10$, Peclet and Reynold numbers $\approx 10^5$, a density ratio of 0.01-10 and a localization parameter, $\delta <\!\!< 1$. For the jet propagation in vacuum only two dimensionless parameters, the density ratio and cooling parameter (optically thick to visible light), were not verified. For the jet experiment with an ambient medium the complete analysis is not yet finished, and the dimensionless quantities remain to be calculated.

4.1. 2D simulation

Using DUED simulation, which is a Lagrangian 2D multigroup radiative hydrodynamic code developed in Rome, the jet generation and propagation is well simulated for the LULI2000 experiment. The experimental and simulation results are in good agreement in density, velocity and shape as shown figure 3.

5. Conclusions

To conclude we obtained supersonic plasma jets in vacuum with good similarities with astrophysical jet, and we began to explore propagation in an ambient medium. We were able to measure all the necessary parameters to get the dimensionless parameters. Finally, using DUED, good results were obtained to simulate the shock propagation through the cone and its propagation in vacuum.

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