Creating Astrophysically Relevant Jets with Locally Heated Targets

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Abstract

The sources of astrophysical jets are not accessible to direct observations due to the small scales on which the jet formation mechanism operates. Simulations suggest that jets emenating from young stellar objects originate from conically converging flows, generated when the stellar wind obliquely encounters the inward facing reverse shock. The use of high intensity lasers to reproduce astrophysical phenomena in the laboratory is an extremely promising approach for verifying and investigating such astrophysical models. Jets produced in laboratory experiments have, until now, usually been created by directly creating a conical flow that converges to produce a jet. This mechanism omits the first part of the mechanism in which the stellar outflow is focused into the conical flow. In this contribution we propose a new experimental setup, with simple initial conditions, that is able to reproduce both stages of the mechanism, including the inward facing reverse shock. By selectively heating a small region inside a target, irradiated by a high-intensity laser pulse, a jet can be driven into the plasma behind the rear target surface. We present three dimensional simulations of the formation of the jet. We find jets with aspect ratios of over 15 and Mach numbers between 2.5 and 4.3. The influence of simulation parameters is investigated and the applicability of the jets to their astrophysical counterparts is discussed.

1 Introduction

Investigations in recent years have shown found that resistivity gradients in solid density targets can effectively control the flow of fast electrons within the target [1] by self generated magnetic fields. Fast electrons are generated by the ponderomotive force of a high intensity laser, interacting with the critical density surface near the front of the target. Structuring the target, using materials of different Z, allows to confine the fast electrons within the high-Z material [2, 3]. The fast electron current is neutralised by a return current of thermal background electrons. This return current deposits energy into the target via Ohmic heating. By adapting the geometry of the high-Z material and the parameters of the laser the region heated in this way can be precisely controlled. For some configurations the heated region can be reduced in size to the order of 10μm [4]. By using short laser pulses the timescale of the heating process can be made much shorter than the hydrodynamical timescales. This makes the rapid heating by resistively guided fast electrons an ideal driver for shocks in the solid density target which can be studied in their own right, or which can be used to drive jets into an ambient medium behind the target.

We propose a new mechanism for generating astrophysically relevant jets by selectively heating a small high-Z region within a solid density target. We start with simple initial conditions, consisting of a heated disk embedded in the target and small conical crater on the rear surface. We point out that, in the context of this work, we do not include the electron transport or the Ohmic heating by the return current in our simulations. Instead, we assume that the fast electrons can be controlled by resistive guiding to deposit energy in a localised region inside the target. Our simulations start with a prescribed temperature profile.

2 Simulations

We use a newly developed 3 dimensional Eulerian MHD code to simulate the expansion of a heated region inside a solid target into vacuum. The code is based on the central-upwind scheme of Kurganov [5], combined with the constrained transport technique [6]. The method has been extended to include different temperatures for ions and electrons as well an arbitrary number of ion species. Electron thermal conduction can be included but its effect has been found to be negligible for the current investigation.

In our setup the target consists of CH with an effective ion mass of $6.5m_p$ and an effective Z of 3.5. The mass density of the target is initially $\rho = 1\mathrm{g\,cm^{-3}}$. The thickness of the target material is chosen to be 50μm. A carbon disk, $m_i = 12m_p$ and $Z = 6$ with a density of $\rho = 2.7\mathrm{g\,cm^{-3}}$ and a temperature of 100eV is embedded in the target. The disk has a radius of 10μm, a thickness of 5μm and is located 15μm away from the rear surface. A small conical crater is dug into the rear surface of the target. The radius of this crater is the same to the radius of the disk and the opening angle ϑ of the cone is given by $\tan\vartheta = 2$.

The target is surrounded by low density CH foam with a density of $\rho = 0.01\mathrm{g\,cm^{-3}}$. The temperature of the bulk of the target is chosen to be 1eV and the temperature of the foam is 20eV. The simulation box has a size

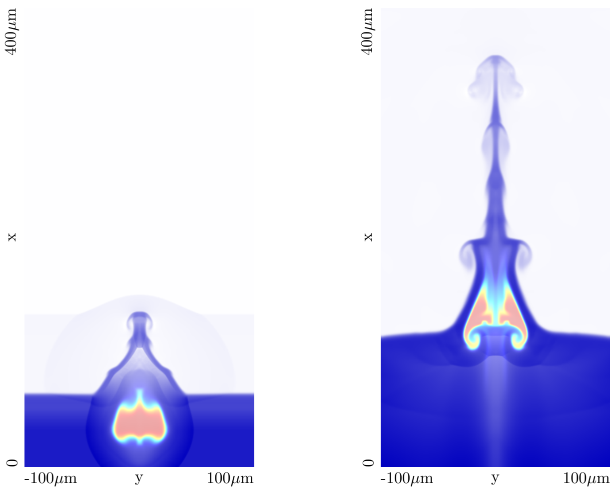

Figure 1: Logarithm of the mass density ρ at $t = 1.6$ns (left panel) and at $t = 8$ns (right panel) for the reference run. The colour from red to blue encodes the material, red indicates carbon, blue indicates CH. The intensity of the colour encodes $\log_{10} \rho$.

of $200 \times 200 \times 400\mu\text{m}^3$ and is resolved by $400 \times 400 \times 800$ grid points. Open, zero-gradient, boundaries have been imposed on all sides.

3 Results

Figure 1 shows the logarithm of the mass density together with the ratio of the two ion species. Initially the heated disk explodes and ejects high density target material into the low density region behind the target. An outer shock propagates into the foam, ahead of the ejecta. The left panel of figure 1 shows the simulation at time $t = 1.6$ns. At this time a jet with a length of approximately 15μm has formed on the axis moving into the shocked foam material. The right panel of figure 1 shows the jet at the end of the simulation, at $t = 8$ns. The jet extends over a length of 150μm while the radius of the stem of the jet of just 10μm. Only at the head, where the jet flows back on itself, the radius is increased to around 15μm.

The formation of the jet depends on the conical shell of high density material seen in the left panel of figure 1. Additional simulations with different geometries have shown that this structure is caused by the crater in the target's rear surface. In the initial stages of the simulation a shock travels from the heated disk through the dense target, compressing and accelerating target material. Due to the indentation at the rear surface the shock reaches the ambient foam material first on the axis. In the ambient material the outer shock travels much faster than in the dense target. This leads to the dense ejecta moving ahead on the axis while the material at the rim of the crater is ejected later and trails behind. In turn, this leads to the formation of the conical dense shell pointing away from the rear surface. The angle of the crater causes the flow to be directed along the axis instead of outward away from the axis. This collimated flow hits the conical dense shell at an oblique angle. As described above, the system of two oblique shocks created by the shell, the reverse shock and the secondary on-axis shock, focuses the outflow into a narrow jet.

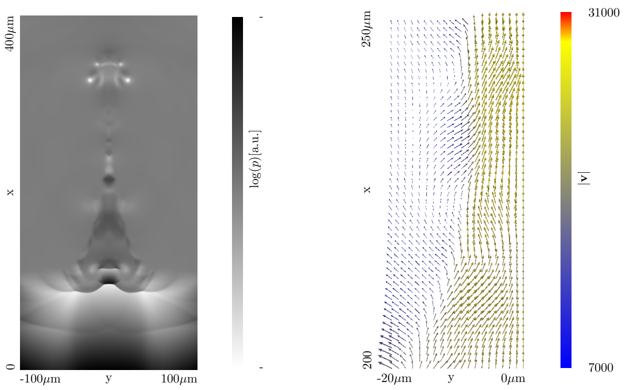

Figure 2: Logarithm of the pressure p at $t = 8$ns (left panel). Flow vectors in a small region inside the jet. The radial component of the vectors has been exaggerated by a factor of 10.

Once a jet-like outflow has formed it must remain stable in order to produce a substantial jet. The jet has a significantly higher density than the surrounding shocked ambient medium and, in order for the jet to survive some pressure balance between the jet and the ambient medium has to be maintained. The left panel of figure 2 shows the logarithm of the pressure at time $t = 8$ns. One can identify regions in the jet with pressures larger than the surrounding ambient medium and other regions where the pressure is substantially lower. Comparing this with the density in figure 1 at the same time, one can see that the high and low pressure regions inside the column of the jet correspond to the criss-cross pattern observed in the density. In contrast to the discontinuity in the density that separates the jet from the ambient medium, the pressure shows a smooth transition at the edges of the column. This indicates that the column is in approximate pressure balance with the ambient medium. The criss-cross patterns appear to result from the process that establishes this balance. The flow on axis accelerates leading to lower density and pressure. The decrease in the pressure leads to the flow being drawn in towards the axis where it then forms an oblique shock which repressurises the jet material and directs it forward. The right panel of figure 2 shows the magnitude and direction of the flow velocity in a small region of the jet. In order to emphasise the radial flow the v_y component of the flow vectors has been scaled up by a factor of 10 in the plot. The colour of the flow vectors indicates the magnitude of the velocity vector. Regions of large flow velocity correspond to regions of low pressure. The discontinuities in the flow, where the velocity suddenly decreases and aligns with the axis, can be clearly made out.

4 Discussion

The simulations have been performed using a geometry and scale lengths applicable to laser-plasma experiments. We have analysed the applicability of the simulationsto an astrophysical context based on the similarity criteria as proposed by Ryutov [7]. The analysis shows that the results can be compared to hydrodynamical flows in YSOs.

The mechanism responsible for jet formation in our simulations is reminiscent of the jet formation in YSOs. Canto [8] suggested that a system of two oblique shocks, which are able to focus a tenuous fast flow into a dense jet, is responsible for the formation of interstellar jets from YSOs. In case of a pressure gradient of the ambient medium around the star, the bubble produced by the wind will be deformed into an ovoidal shape with the long axis along the poles. The stellar wind hits the ovoidal reverse shock at an oblique angle, causing the flow to focus towards the poles. At the poles a conical shock redirects the flow towards the radial direction which results in the jet. This mechanism was later confirmed by simulations of YSOs by Frank & Mellema [9]. Our simulations show that it is possible to reproduce this mechanism in the laboratory from simple initial conditions.

The mechanism of jet formation in our configuration differs from earlier descriptions of laboratory astrophysics jets. In previous investigations on the formation of jets by conically converging flows, the conical flow was imposed directly either by ablating a conical dimple [10], backlighting a conical target [11] or by the implosion of a conical wire array [12]. This corresponds to the second step in the two step process originally proposed by Canto [13]. Here we have described a jet formed in a two step process. In the first step a tenuous fast flow from the explosion of the heated region encounters the reverse shock at an oblique angle. Only the normal component of the flow is stopped, while the tangential component causes the flow to focus towards the axis. This first step is responsible for producing the conical flow that converges on axis and is then redirected into the axial direction in the second step to form the jet. In this way the jets presented here are formed by the complete two step mechanism proposed by Canto. We therefore believe that our approach provides an interesting alternative to existing techniques of creating astrophysically relevant jets in the laboratory.

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