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Counter-propagating plasma jet collision and shock formation on a compact current driver

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ABSTRACT

In this paper we report on the ability of a compact current driver yielding 250 kA in 150 ns to produce counter-propagating plasma flows. The flows were produced by two vertically-opposed conical wire arrays separated by 1 cm, each comprised of 8 wires. With this array configuration, we were able to produce two supersonic plasma jets with velocities on the order of 100–200 km/s that propagate towards each other and collide. Aluminum wires were tested first; we observed a shock wave forming at the collision region that remained stationary for an extended period of time (~50 ns) using optical probing diagnostics and Extreme Ultraviolet imaging. After this period, a bow shock is formed that propagates at 20 km/s towards the cathode of the array, likely due to small differences in the density and/or speed of the jets. The inter-jet ion mean free path was estimated to be larger than the shock scale length for aluminum, indicating that the shock is not mediated by collisions, but possibly by a magnetic field, whose potential sources are also discussed. Radiative cooling and density contrast between the jets were found to be important in the shock wave dynamics. We studied the importance of these effects by colliding jets of two different materials, using aluminum in one and copper in the other. In this configuration, the bow shock was observed to collapse into a thin shell and then to fragment, forming clumpy features. Simultaneously, the tip of the bow shock is seen to narrow as the bow shock moves at a similar speed observed in the Al–Al case. We discuss the similarity criteria for scaling astrophysical objects to the laboratory, finding that the dimensionless numbers are promising.

1. Introduction

Collimated outflows, or jets, are produced by astrophysical objects such as planetary nebulae [1], active galactic nuclei [2], and young stellar objects [3] on various scales, possessing a diverse set of physical parameters and features. Irrespective of their differences, much remains to be learned about these outflows – specifically their formation and the effect of an ambient medium on their propagation. Several studies have been done using numerical simulations [4,5], and recently some work has been done with scaled experiments in the laboratory to improve our understanding of the outflow dynamics.

Depending on the governing physics, some similarity criteria can be established between astrophysical and laboratory plasmas. In order to apply the ideal hydrodynamic equations, the systems in question must have the following: a localization parameter $\delta << 1$, Reynolds number $R_e >> 1$, and Peclet number $P_e >> 1$. If these conditions are met, the two systems will evolve similarly when they have the same Euler number (E_u), provided similar initial conditions [6,7]. If the physics is governed by ideal magnetohydrodynamics (MHD), which requires that the magnetic Reynolds number be $R_{eM} >> 1$, we must also have the β parameter (ratio of thermal to magnetic pressure) be the same for the systems to be scalable. Observations indicate that radiative cooling significantly affects the behavior of astrophysical jets [8,9], this is quantified by the cooling parameter, χ, defined as the ratio of the radiative cooling time to the hydrodynamic timescale, which is less than 1 for radiatively cooled systems. Hence, if we want to include radiation in scaled experiments, an additional dimensionless number must be equal in both systems. Ryutov et al. [10] gives an expression for this dimensionless parameter when radiative cooling has a simple power-law type function with respect to pressure and density, although it is usually a complex form of the arguments. If the radiative losses in an astrophysical system can be approximated by a power-law function, it can easily be reproduced in the laboratory system.

Laboratory experiments have been performed in recent years using high-intensity lasers [11–13] and pulsed power facilities

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[14–16] to produce supersonic jets with scaling criteria to jets emanating from young stellar objects (YSO). Particularly in pulsed power, work has been done on the interaction of supersonic, radiative cooling jets with a cross wind [17]. The deflection of the jet observed in their work was consistent with simulations and developed models on astrophysical jet deflection. Some work has also been done on the interaction of plasma jets with a quasi-stationary background medium in order to replicate astrophysical jets propagating through the interstellar medium. Features resembling Herbig–Haro objects were identified [18,19].

In this paper, we show preliminary results on the interaction of counter-propagating plasma jets using a compact current driver. Shock formation is studied and the relevance to astrophysical YSO jets is discussed. The configuration can be easily modified to vary parameters such as radiative cooling by using high atomic number materials or jet density by varying the array diameter. This configuration is also suitable for collisionless shock studies, where the underlying physics is not yet well understood [20,21]. While jet-related work has been done on experiments using high-intensity laser and large pulsed power facilities, these experimental resources are beyond the scope of most university laboratories, emphasizing the critical importance of studying such phenomena in small-scale experiments for the development of the field.

The remainder of this paper is organized as follows: in Section 2, we have outlined the experimental setup of the colliding plasma jets and diagnostics. In Section 3 we present experimental data on the shock formation and evolution. In Section 4 we discuss the relevance of this work for astrophysical phenomena. In Section 5 we summarize our findings and address future work.

2. Experimental setup

This work was performed on GenASIS, a compact, low-inductance current driver capable of producing 250 kA in about 150 ns on a short circuit load at a nominal voltage of 75 kV. The details of the driver can be found in Ref. [22]. Fig. 1 shows a schematic of the load configuration used to produce two counter-propagating plasma jets. Due to the dimensions of the array, which has a larger inductance than the short circuit configuration, the driver current decreased to a peak value of 190–200 kA. The setup consisted of two opposing conical wire arrays driven by the same current pulse. The physics of conical wire arrays has been broadly studied [15,16]. Ohmic heating from the current passing through the wires quickly melts down and vaporizes their surface, forming a low-density coronal plasma around a high density core. At this point, the current flows mainly in the coronal plasma. The Lorentz force produced by interaction between the self-generated global magnetic field and the current density drives the coronal plasma towards the array axis, perpendicular to the axis of each of the wires. As the plasma stagnates on axis, it produces a standing conical shock that drives a plasma jet away from the cone's apex. The plasma jet is accelerated mainly by two mechanisms: the aforementioned standing shock that diverts the plasma flows, coming from the wires, in the axial direction and the plasma pressure gradient along the standing shock. The middle electrode seen in Fig. 1, which provides the arrays' aperture, is held by two plastic insulators against the top electrode in order to provide full current through the top array. These electrodes were attached to each other using only two posts in order to have a larger field of view of the collision region. We also used 5 mm diameter lead apertures on each of these electrodes in order to assure that the plasma jets are freely propagating above (below) 2 mm from the aperture and are not perturbed by streaming plasma coming off the wires (see Fig. 1). This allowed us to more accurately follow the plasma jets using interferometry and estimate their velocity. Note that the apertures are only blocking a small portion of the streaming plasma from the wire array (<10%) so the collimation of the jets is not significantly affected.

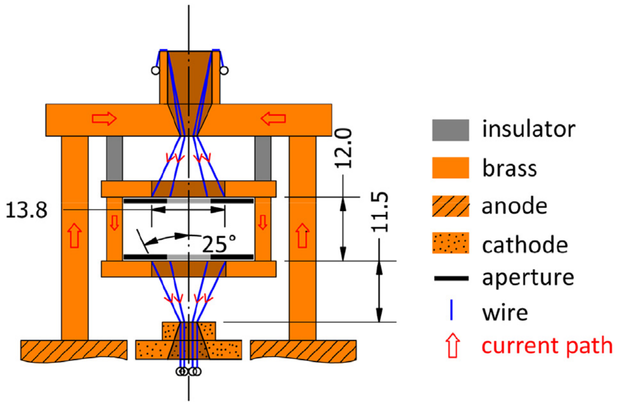

Fig. 1. Cross-section of the experimental setup. Two conical wire arrays were used, driven by the same current pulse, to produce counter-propagating plasma flows. The dimensions are in millimeters.

We employed a number of diagnostics to examine the evolution of the jets. The main diagnostic was 4-frame interferometry with a 5 ns laser pulse width at 532 nm and 15 ns inter-frame separation. The images were recorded with a charge-coupled device (CCD) camera, with a final resolution of the optical system of ~40 μm. The recorded interferograms were then unfolded using the analysis software IDEA [23] for two-dimensional areal electron density mapping. The four beams were distributed so that they converge at the array center with a separation of ~5°: each beam has an almost identical viewing axis, allowing us to directly compare the interferograms to one another. A four-frame Extreme Ultraviolet (XUV) gated camera with unfiltered 50 μm pinholes was also implemented. Each frame took a 5 ns exposure, the magnification of the system was ~1, and the spatial resolution was ~100 μm. The cut-off energy of the photocathode is ~5 eV, but diffraction effects become comparable to geometric effects at ~25 eV. At lower photon energy, light is diffracted away and hardly reaches the quadrant camera [24].

3. Experimental results

The motivation for this work was to create a platform for launching counter-propagating plasma jets using a compact current driver at UCSD to study astrophysical phenomena. The current driver gave high-quality data despite several limitations of the driver, such as the current amplitude and the driver impedance. The former limits the maximum density achieved in the precursor plasma and the jets, while the latter constrains the inductance and hence the size of the setup. We found that the dimensions shown in Fig. 1 were sufficient, as they gave enough density to be detected by interferometry and have adequate size to use multiple diagnostics simultaneously. As there is abundant work on aluminum wire arrays, we tested our setup using aluminum wires for comparison. Fig. 2 displays a time sequence of unfolded interferograms showing the evolution of the jet interaction. The grey areas in the pictures are products of broken fringes in the interferograms that were not possible to unfold. Each row of 4 frames in Fig. 2 is from the same shot.

The evolution is as follows: at 200–220 ns the plasma jets stagnate at a position above the center of the experimental setup, indicating that the bottom jet is faster than the top one. The average