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A plasma deflagration accelerator as a platform for laboratory astrophysics

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ABSTRACT

The replication of astrophysical flows in the laboratory is critical for isolating particular phenomena and dynamics that appear in complex, highly-coupled natural systems. In particular, plasma jets are observed in astrophysical contexts at a variety of scales, typically at high magnetic Reynolds number and driven by internal currents. In this paper, we present detailed measurements of the plasma parameters within deflagration-produced plasma jets, the scaling of these parameters against both machine operating conditions and the corresponding astrophysical phenomena. Using optical and spectroscopic diagnostics, including Schlieren cinematography, we demonstrate the production of current-driven plasma jets of ~100 km/s and magnetic Reynolds numbers of ~100, and discuss the dynamics of their acceleration into vacuum. The results of this study will contribute to the reproduction of various types of astrophysical jets in the laboratory and indicate the ability to further probe active research areas such as jet collimation, stability, and interaction.

1. Introduction

Astrophysical plasma jets are ubiquitous throughout the universe, occurring in environments such as planetary nebulae, active galactic nuclei, and young stellar objects. Many of the jets arising from these sources achieve high velocities, v ~100–300 km/s, while still maintaining remarkable collimation over vastly different timescales [1,2]. For example, planetary nebulae have been observed to produce periodic jets with characteristic timescales around 1000 years where as Herbig–Haro objects yield outflows lasting up to 10^5 years. In terms of spatial evolution, the majority of jets are fractions of parsecs in length and feature large length-to-width ratios indicating they remain narrow as the jets propagate over vast spatial scales [3]. Even with the ubiquitous nature and contemporary interest in plasma jets, there is still little known about the formation dynamics, role of instabilities, and the nature of interactions with their respective backgrounds.

Many of the remaining unknowns in astrophysical systems are driven not only by the complexity of the environments but also the vast disparity in scales involved. When also considering the enormous distances such objects are from Earth, it comes with little surprise that many astrophysical data sets are limited in their spatial, temporal, and even spectroscopic resolution. Laboratory experiments overcome much of these shortcomings by offering a repeatable, high resolution platform that can be used to complement astrophysical observations and numerical simulations. Although the benefits of superior repeatability and access are apparent for laboratory experiments, it is still a challenge to ensure that a *similarity* is maintained to relevant astrophysical systems. Without such similarity, there is no guarantee that predictions made regarding the behavior of laboratory experiments will hold when scaled larger systems. The most direct way of ensuring this similarity is by achieving the exact astrophysical conditions in the laboratory. For situations where this is not possible, similarity is still maintained when quantities of interest (such as pressure, density, space, time, etc.) can be mapped between the systems via multiplicative constants. With the advent of high energy devices (lasers, fast z-pinches), it has become possible over recent years to produce and study hypersonic jets in the laboratory setting [4,5]. Using such facilities as the OMEGA laser, recent work [6] has produced and studied the interaction of jets with ambient media leading to the formation of bow shocks. Other research [7,8] has utilized fast z-pinches in the form of a conical array of fine exploding wires to produce radiatively cooled hypersonic jets. Although scaled jets with impressive velocities and densities can be produced with such devices, there is significant research [9–11] that points to the jet's magnetic field, associated electric current, and lifetime as important metrics when trying to emulate the structure and dynamics of astrophysical flows.

In this work we present detailed experimental measurements of a plasma deflagration accelerator to gauge its ability to produce scaled astrophysical jets. The experiment and resulting flows

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detailed in this paper provide a unique combination of being completely driven by internal current and boast added stabilization mechanisms that result in jets lasting much longer that conventional pinch schemes. In Section 2 of this paper the physics and unique features of the plasma deflagration accelerator are discussed. Section 3 presents a comprehensive characterization of the device by discussing the experimental setup and resulting data. Finally, Section 4 combines the data detailed in Section 3 into relevant dimensionless groups and discusses how these numbers relate to astrophysical systems.

2. Plasma deflagration accelerator

The plasma source employed as a part of this work is a pulsed Lorentz force accelerator that is an extension of the classic Marshall plasma gun [12]. The device, as shown schematically in Fig. 1, features a coaxial rod configuration which has been used extensively in past studies for a variety of applications [13–16]. In terms of geometry, the entire accelerator region is 26 cm long, 5 cm in diameter and features a set of stainless steel rod anodes and a single central copper cathode. To ensure consistent and reliable performance, the accelerator is connected to a vacuum chamber that is maintained at 10^{-7} Torr between firing events.

The production of plasma jets first requires charged high voltage capacitors to be connected between the rod electrodes. A 56 μF capacitor bank was used throughout this study with charging voltages ranging from 3 to 9 kV. Given the accelerator is initially under high vacuum conditions, the anodes float at high voltage until a breakdown path occurs. To provide that, a fast rise-rate, variable mass-bit gas puff valve, detailed in [17], is used to inject neutral gas to the device upstream of the electrodes continuously during the firing process. Typically for the operating conditions considered in this paper, hydrogen gas is injected for ~1 ms where as the energy transfer and thus plasma dynamics occur over 20 μs. As the neutral gas accelerates in vacuum, it is ionized by the applied electric field resulting in a net radial current flow inward toward the cathode (as depicted by the blue arrows in Fig. 1). As this current is collected by the copper cathode and travels out of the system, an azimuthal B-field is produced. As a result of both the current flow and induced B-field, a strong $\boldsymbol{J} \times \boldsymbol{B}$ force accelerates the quasineutral plasma to high velocities.

As the plasma jet moves along the length of the accelerator, the $\boldsymbol{J} \times \boldsymbol{B}$ force remains the primary source of axial acceleration until the field topology changes near the end of the electrodes. At this point, the behavior of the device is strongly dependent on the operating mode of the accelerator. Previous work [18] has focused on understanding these modes and specifically investigating the transition of the device between the so-called delfagration and detonation or snowplow mode. For the geometry and operating parameters considered in this paper, the deflagration mode occurs for the first ~10 μs of the capacitor discharging process after which a transition occurs. For astrophysical applications, it is this delfagration mode that is of interest as it produces collimated, high-density jets.

As detailed in Fig. 1, the deflagration mode ensures the production of such jets by creating a radial compression in the form of a pinch. This pinch is produced because near the end of the accelerator volume, the current streamlines are still forced to terminate at the cathode which cause a radially directed $\boldsymbol{J} \times \boldsymbol{B}$ force. The remaining structure and dynamics of the jet are determined by the current convected downstream by the plasma in addition to the associated conversion of magnetic pressure to kinetic energy. One of the unique features of this device is the comparatively long lifetime of the jet. Research points to the shear flow [19] around the pinch as a stabilization mechanism against inherent instabilities that limit its lifetime.

3. Experimental characterization

Separate measurements of plasma density, velocity, and the resulting pinch structure were made to better understand the inherent properties of the plasma jet. These specific properties along with calculations of both the plasma temperature and magnetic field were determined to be critical parameters in deciding whether or not there may be relevant similarity to astrophysical flows.

3.1. Plasma density

Plasma density was measured at the exit plane of the deflagration accelerator, operating on hydrogen, where a maximum in optical emission and pinch dynamics have previously been observed [20]. To quantify the density, Stark broadening of the $n = 3$ to $n = 2$ hydrogen Balmer-alpha (Hα) electronic transition at 656.28 nm was measured using the configuration detailed in Fig. 2. Light was collected and focused on the entrance slit of a 0.75 m Spex 750 M spectrometer. Within this spectrometer, a 1200 groove/mm grating, blazed at $5^{\circ}10^{'}$, was used to disperse the light and tune the output window to be centered around 656.28 nm. The light leaving the system was recorded using a Princeton instruments intensified CCD camera that was triggered coincidentally with the breakdown of the gas and featured a gate window of 10 μs to capture the entire deflagration event. The wavelength calibration factor (0.125 Å/pixel) and height calibration factor (0.16 mm/pixel) of the system were determined by placing a mercury lamp at the location of the plasma jet. Finally, the instrument broadening of the system was determined and eventually deconvolved from the measured Stark broadening using a hydrogen lamp.

An Abel transform was employed to convert the raw chord integrated intensity profiles to radially resolved plasma density. This

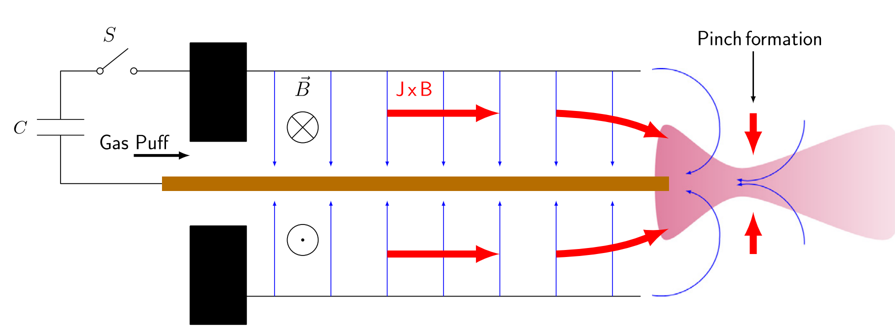

Fig. 1. Schematic detailing the underlying physics involved with the coaxial plasma deflagration accelerator operating in deflagration mode. Unique features of this device include its internally generated magnetic field and shear flow stabilization. In the diagram, blue arrows represent current conduction pathways (from anode to cathode via neutral gas ionization) which produce a resulting $\boldsymbol{B}$ where as the red arrows indicate the direction of the $\boldsymbol{J} \times \boldsymbol{B}$ force. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)