High Energy Density Physics 17 (2015) 52–62

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Experimental results from magnetized-jet experiments executed at the Jupiter Laser Facility

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ARTICLE INFO

Article history:
Available online 20 August 2014

Keywords:
Plasma jets
Magnetized plasma
Laboratory astrophysics

ABSTRACT

Recent experiments at the Jupiter Laser Facility investigated magnetization effects on collimated plasma jets. Laser-irradiated plastic-cone-targets produced collimated, millimeter-scale plasma flows as indicated by optical interferometry. Proton radiography of these jets showed no indication of strong, self-generated magnetic fields, suggesting a dominantly hydrodynamic collimating mechanism. Targets were placed in a custom-designed solenoid capable of generating field strengths up to 5 T. Proton radiographs of the well-characterized B-field, without a plasma jet, suggested an external source of trapped electrons that affects proton trajectories. The background magnetic field was aligned with the jet propagation direction, as is the case in many astrophysical systems. Optical interferometry showed that magnetization of the plasma results in disruption of the collimated flow and instead produces a hollow cavity. This result is a topic of ongoing investigation.

1. Introduction

Magnetized plasma jets are ubiquitous in the universe and found in many classes of astrophysical objects [1,2]. Often these jets are found as outflows from accretion systems at stellar [3] and galactic [4] scales. The typical magnetohydrodynamic (MHD) model in collimated astrophysical systems relies on shearing the poloidal field ($\mathbf{B}_{\text{pol}} = B_r\hat{\mathbf{r}} + B_z\hat{\mathbf{z}}$) that penetrates the accretion disc. In this geometry, the disc is toroidal (θ) and its axis is aligned in the z-direction. The sheared poloidal field generates a toroidal component (B_θ) which further collimates the flow [5] along the z axis. The collimation of the jet is related to the Lorentz force component ($F_\perp$) perpendicular to the poloidal field,

$$F_\perp = -\frac{B_\theta}{\mu_0 r}\nabla_\perp(rB_\theta) + j_\theta B_{\text{pol}}, \tag{1}$$

where j_θ is the toroidal component of the current, and r is the distance from the symmetry axis in SI MKS units. The first term in Eq. (1) describes self-collimation of the jet due to the varying toroidal field and the last term describes magnetic pinching effects. The latter term is studied in this work. These astrophysical systems may be well represented by the Euler MHD equations and scaled [6] to laboratory experiments.

In recent years, multiple platforms have been developed at various laser facilities to create astrophysically relevant plasma jets. Direct irradiation of planar foils has been shown to create plasma jets [7] that may be magnetized by a strong B-field [5]. Also, laser-irradiated hollow cones have been used to hydrodynamically create collimated plasma jets [8,9]. Results from magnetized-jet experiments executed at the Jupiter Laser Facility (JLF) at the Lawrence Livermore National Laboratory (LLNL) using hollow cone targets are reported herein.

An outline of this paper is as follows. Section 2 describes the targets used in these experiments and the diagnostics implemented to characterize the plasma jet. Field measurements from the pulse-powered solenoid, designed and built at the University of Michigan, are described in Section 3. Measurements taken of unmagnetized jets are shown in Section 4 and optical data taken of magnetized jets are discussed in Section 5. The results of these

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http://dx.doi.org/10.1016/j.hedp.2014.07.003
1574-1818/

experiments are summarized in Section 6 and this paper concludes in Section 7 where future projects derived from this work are presented.

2. Experimental setup

2.1. Targets

Irradiated, plastic cones generated collimated plasma jets [8] on the Titan laser. Targets were driven by a 10-ns square pulse, with typical rise and fall times of ~10% and ~20% of the pulse duration, respectively. Each pulse contained ~300 J of 2-ω light, of wavelength $\lambda = 0.527$ µm. Distributed phase plates shaped the beam to a super Gaussian profile with a ~600-µm diameter. The laser spot was centered on the apex of the cone, as illustrated in Fig. 1a, to drive a shock through the cone. When breakout occurs on the backside of the ~90-µm-thick target, material is accelerated normal to the back surface. These targets were fabricated with a 80° cone-half-angle, thereby directing the plasma to the central cone axis. As plasma accumulates on-axis, it is further heated and directed outwards, producing a mm-scale, collimated plasma-jet.

Targets were produced using 3D-printing facilities available at the University of Michigan due to the large number of targets required for these experiments. Multiple iterations were performed to optimize the printer settings for these targets. To eliminate part-to-part variation due to environmental effects, all targets were made at the same vertical location and were produced during the same run. Small volumes of 3D-printed plastic were analyzed and found to have a density of $\rho_{3D} \approx 1.2$ g/cm^3 and an atomic composition of $C_5H_8O_2Sb_{0.03}$, similar to that of standard acrylic. Cones were scanned using a Micro Computerized Tomography (MCT) facility at the University of Michigan and image stacks were processed using ImageJ [10,11]. Fig. 1b illustrates two orthogonal cross-sections derived from the MCT scans. Cones were found to be symmetric in the horizontal (x) direction and slightly asymmetric in the vertical (y) direction due to gravitational effects [12] during the vertical printing process. Small asymmetries (<10 µm) were not detrimental to the formation of the mm-scale jets these targets were designed to create.

2.2. Diagnostic configuration

Plasma jets were created in the gap of a solenoid as schematically shown in Fig. 2a. Plastic cones were placed in the gap against the edge of the coil housing such that the jet could propagate ~4-mm before crossing into the coil on the opposite side. The long-pulse laser was aligned along the solenoid axis as shown in Fig. 2a to create jets parallel to the B-field. An optical probe ($\lambda_p = 0.532$-µm) and short-pulse, proton radiography [13] imaged the plasma in orthogonal directions. The pointing of the Titan short-pulse was orthogonal to the long-pulse on the same horizontal plane. It irradiated a gold-coated silicon wafer [14] to generate protons by target-normal sheath acceleration (TNSA) that were recorded on a filtered radiochromic film (RCF) stack. The film stack was attached to an imaging proton spectrometer [15] that measured the proton spectrum [16] on every shot.

The optical probe beam had a ~12-ns pulse containing ~2 mJ of energy. It propagated under the solenoid to a beam splitter beneath the target to vertically probe the plasma jet. A mirror above the target redirected the beam to a splitter, sending half of the beam intensity to a shadowography/Schlieren arm, and half to recombine with the reference beam of the interferometry system, as shown schematically in Fig. 2b. The shadowography diagnostic could be switched to Schlieren by inserting a knife edge at the focal plane of that optical path.

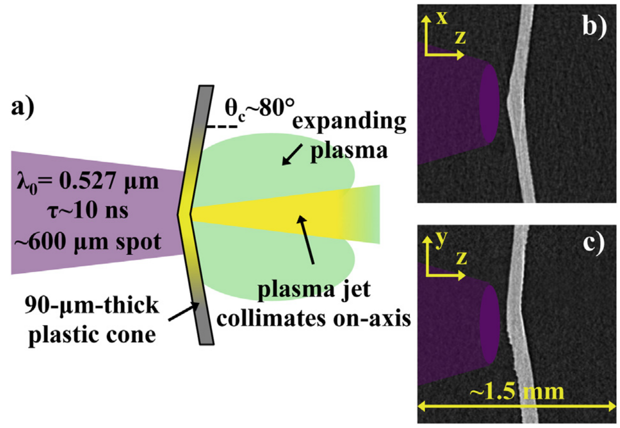

Fig. 1. a) Schematic of cone targets irradiated by a 10-ns laser drive. When shocks breakout on the backside, material accelerates to the central axis, generating a dense, collimated jet surrounded by background expanding plasma. Orthogonal cross-sections taken at the cone apex of an un-driven, 3D-printed target in the b) horizontal and c) vertical directions. A scaled laser-spot is shown for reference.

3. Solenoid implementation

3.1. Design parameters

A custom-built solenoid delivered axial magnetic field strengths of up to ~5 T to magnetize laser-generated plasma jets. Details of the manufacturing techniques employed to construct the compact solenoid is discussed by Klein et al. [17], but the design and field characterization is discussed herein. The following formulas were instrumental in determining the final geometry of the system. The vector components of the B-field, as a function of r and z, from a

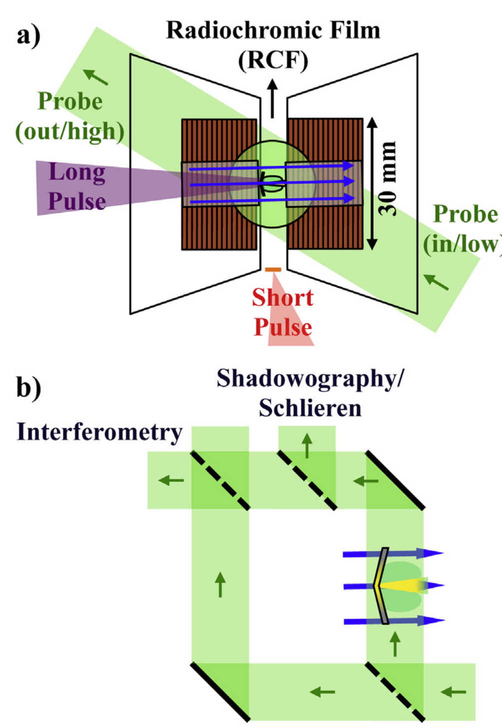

Fig. 2. a) Top–down schematic of the plasma jet in the solenoid gap with the laser configuration illustrated. b) Side-view schematic of the optical path for the probe beam.