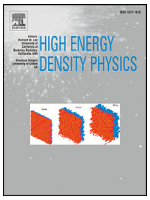
High Energy Density Physics 23 (2017) 48–59

Contents lists available at ScienceDirect

High Energy Density Physics

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



Detailed characterization of laser-produced astrophysically-relevant jets formed via a poloidal magnetic nozzle

D.P. Higginson*[a,b], G. Revet[a,c], B. Khiar[d,e], J. Béard[f], M. Blecher[g], M. Borghesi[h,i], K. Burdonov[c], S.N. Chen[a,c], E. Filippov[j,k], D. Khaghani[l], K. Naughton[h], H. Pépin[m], S. Pikuz[j,k], O. Portugall[f], C. Riconda[n], R. Riquier[a,o], S.N. Ryazantsev[j,p], I.Yu. Skobelev[j,k], A. Soloviev[c], M. Starodubtsev[c], T. Vinci[a], O. Willi[g], A. Ciardi[d,e], J. Fuchs*[a,c]

[a] LULI - CNRS, École Polytechnique, CEA: Université Paris-Saclay, UPMC Univ Paris 06: Sorbonne Universités - F-91128 Palaiseau cedex, France
[b] Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[c] Institute of Applied Physics, RAS, 46 Ulyanov Street, 603950 Nizhny Novgorod, Russia
[d] Sorbonne Universités, UPMC Univ. Paris 6, UMR 8112, LERMA, F-75005, Paris, France
[e] LERMA, Observatoire de Paris, PSL Research University, CNRS, UMR 8112, F-75014, Paris, France
[f] LNCMI, UPR 3228, CNRS-UGA-UPS-INSA, 31400 Toulouse, France
[g] Institut für Laser -und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany
[h] The Queen's University of Belfast, Belfast BT7 1NN, United Kingdom
[i] Institute of Physics of the ASCR, ELI-Beamlines project, Na Slovance 2, 18221 Prague, Czech Republic
[j] Joint Institute for High Temperatures, RAS, 125412, Moscow, Russia
[k] National Research Nuclear University 'MEPhI', 115409 Moscow, Russia
[l] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[m] INRS-ÉMT, 1650 bd. L. Boulet, J3X1S2 Varennes, Québec, Canada
[n] LULI, Sorbonne Universités–UPMC Univ. Paris 06, École Polytechnique, CNRS, CEA, 75005 Paris, France
[o] CEA, DAM, DIF, 91297 Arpajon, France
[p] M. V. Lomonosov Moscow State University, Moscow 119991, Russia

ARTICLE INFO

Article History:
Received 3 October 2016
Accepted 5 February 2017
Available online 24 February 2017

Keywords:
Magnetohydrodynamics
Astrophysical plasmas
Laser-plasma interactions
Jets
Outflows

ABSTRACT

The collimation of astrophysically-relevant plasma ejecta in the form of narrow jets via a poloidal magnetic field is studied experimentally by irradiating a target situated in a 20 T axial magnetic field with a 40 J, 0.6 ns, 0.7 mm diameter, high-power laser. The dynamics of the plasma shaping by the magnetic field are studied over 70 ns and up to 20 mm from the source by diagnosing the electron density, temperature and optical self-emission. These show that the initial expansion of the plasma is highly magnetized, which leads to the formation of a cavity structure when the kinetic plasma pressure compresses the magnetic field, resulting in an oblique shock [A. Ciardi et al., Phys. Rev. Lett. **110**, 025002 (2013)]. The resulting poloidal magnetic nozzle collimates the plasma into a narrow jet [B. Albertazzi et al., Science **346**, 325 (2014)]. At distances far from the target, the jet is only marginally magnetized and maintains a high aspect ratio due to its high Mach-number ($\mathbb{M} \sim 20$) and not due to external magnetic pressure. The formation of the jet is evaluated over a range of laser intensities (10^{12}–10^{13} W/cm^2), target materials and orientations of the magnetic field. Plasma cavity formation is observed in all cases and the viability of long-range jet formation is found to be dependent on the orientation of the magnetic field.

1. Introduction

1.1. Recent work and astrophysical implications

Recent laboratory studies [1–3] and pertinent astrophysical simulations [4–6] have shown the viability of poloidal (i.e. axial) magnetic fields to directly result in the collimation of wide-angle outflows and the formation of jets in astrophysical accreting systems [7,8], such as young stellar objects (YSO). In particular, this mechanism has been shown to generate large aspect ratio (length:diameter $>$ 1:10) jets and, through the formation of a long-standing and relatively stationary conical shock, is suggested to be at the origin of long-time x-ray emission observed from such objects (e.g. HH 154) [9–11].

The dynamics of the laboratory-produced jets was shown to be scalable to YSOs jets [1,2] as both systems are to a first approximation well described by magnetohydrodynamics (MHD) [12,13]. The

---

* Corresponding authors.
E-mail address: higginson2@llnl.gov (D.P. Higginson), julien.fuchs@polytechnique.edu (J. Fuchs).

http://dx.doi.org/10.1016/j.hedp.2017.02.003
1574-1818/Published by Elsevier B.V.

laboratory evidence for the poloidal collimation of jets thus offers an explanation of the observed long range collimation of young stellar jets [14]. We note that this mechanism is complementary to magneto-centrifugally launched disk winds [15] (i.e. self-collimation) which explain the launching of wide-angle outflows and their collimation into jets, as well as the removal of angular momentum from accretion disks; a mechanism that has been studied both via simulations [16] and experiments [17–19]. Shown below in Eq. (1) is the radial Lorentz force exerted on an ideal MHD plasma in cylindrical coordinates. The force associated with self-collimation in magneto-cetrifugal models is due to the toroidal magnetic field B_φ. On the other hand, the poloidal collimation mechanism that is explored in this paper is due to the presence of an initially axial magnetic field B_z.

$$F_r = \underbrace{-j_z B_\phi}_{\text{self-collimation}} + \underbrace{j_\phi B_z}_{\text{poloidal collimation}} \tag{1}$$

The process of poloidal magnetic collimation of a laser-ablated plasma is illustrated in Fig. 1. Without a strong poloidal B-field, the plasma is heated to high temperature and expands into vacuum in all directions, creating a quasi-hemispherical expansion (Fig. 1a). When a strong B-field is applied, as shown in Fig. 1b, the plasma is restricted from expanding radially by the field and expands only until reaching an equilibrium between the total plasma kinetic pressure and magnetic pressure. This causes a conical shock to form and the plasma is subsequently redirected onto the radial axis. As the plasma converges on axis a conical jet is formed and the plasma is collimated into a high Mach-number, high aspect-ratio jet.

The focus of this paper is to robustly characterize these laboratory-generated jets produced by laser-matter interaction and collimated via external axial magnetic fields that we have recently investigated [1,2], as well as to highlight their stability over long temporal duration and under a variety of plasma conditions. Of particular interest is the conclusion that the plasma is only marginally magnetized at distances far away from the target. This indicates that the high aspect ratio of the jet is due mainly to the collimation at the base and then to the high Mach-number Lagrangian ballistic expansion of the flow at large distances. In other words, at large distances from the target, the presence of the magnetic field is unimportant to the collimation of the flow. To make this point clear, we characterize this collimation mechanism as a poloidal magnetic nozzle (PMN) in order to highlight that the collimation mechanism is active near the base of the jet. We note here that the B-fields are called poloidal due to the toroidal symmetry of a jet ejected from an accreting system. In the experimental setup, cylindrical symmetry is apparent and the fields are referred to as axial. Since the system size is very large in the poloidal astrophysical case, these two descriptions are equivalent near the base of the jet.

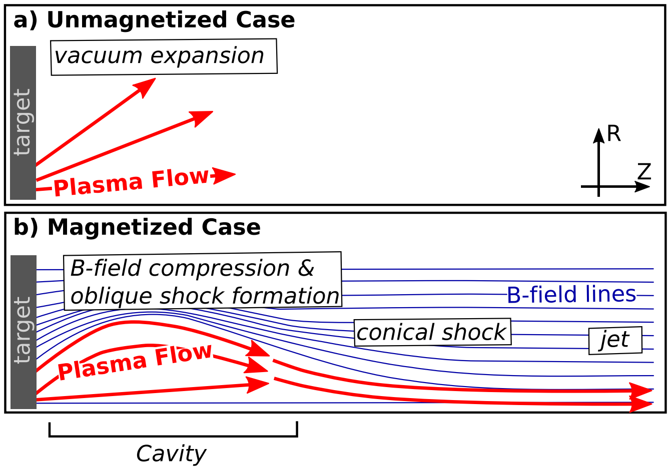


Fig. 1. Schematic of plasma expansion into vacuum following the laser-irradiation of the front (right) side of the target. (a) Without a strong B-field, the plasma expands in a wide-angle flow. (b) With a strong poloidal B-field, the plasma is confined laterally by the B-field, forms an oblique conical shock and is redirected onto the radial axis. The on-axis conical shock collimates the flow into a jet.

In Section 2, we explain the experimental configuration of the laser, the Helmholtz coil that drives an external magnetic field, and the suite of experimental diagnostics for observing the electron density (2D-space, time), optical self-emission (1D-space, time) and electron temperature (1D-space). In Section 3 we characterize the plasma based on measurements in different regions and we estimate related plasma parameters in order to give a context to the plasma confinement and jet formation. Note that the characterization of the dynamics of laser-produced plasma expansion into vacuum has been an active subject of research for over 50 years and is on-going. Thus, this (unmagnetized) expansion will not be the focus of the present paper, rather we will focus on how such a plasma is shaped into a narrow jet through its interaction with the poloidal B-field.

In Section 4, we describe the formation and evolution of the jet over 23 mm in space and over 70 ns in time when the B-field is applied. We detail the formation of a cavity near the target caused by the generation of an oblique shock along the plasma expansion front, which leads to a strong conical shock and the subsequent formation of a long-aspect-ratio jet. In Section 5, we examine the fidelity of the jets to a variety of experimental parameters: we vary the kinetic energy of the expansion by changing the laser energy incident on the target, we vary the atomic composition of the jet by varying the target material and we vary the magnetic field orientation by tilting the target by 45°. We observe that varying the laser energy and target material leads to quantitative differences in the jet formation, but shows similar overall behavior in that the plasma is confined radially and a jet is formed. When the magnetic field is tilted by 45°, the plasma is still confined radially, but the formation of a long-range, narrow jet is not observed.

1.2. Historical context

Investigating the possibility of influencing and guiding the hydrodynamics of high-temperature laser-produced plasmas using magnetic fields has been the subject of many investigations, including some very early studies [20,21]. Most experiments investigated plasma dynamics across B-field, revealing a fraction of the plasma to be confined while another part can move across the B-field via an $E \times B$ drift allowed by the development of polarization E-field in the plasma [21–24]. The growth of flute-like instabilities affecting the plasma dynamics at intermediate levels of magnetization was also demonstrated [25,26]. We should note however that all these studies were conducted in a regime where only the electrons in the plasma were magnetized, the ions being not or weakly magnetized.

Strong plasma magnetization of laser-produced plasmas has become possible only recently with the development of adequate systems, e.g. at the Laboratory for Laser Energetics [27–29] (Rochester, NY, USA) and at the Institute of Laser Engineering [30] (Osaka, Japan). However, the B-fields they develop have short spatial (mm) and temporal (10–100 ns) scales. The platform [31,32] developed in collaboration between the LNCMI and LULI laboratories (France) lifts these limitations by allowing magnetization of laser produced plasmas up to 40 T over much larger (> cm) and longer (> µs) scales. Such homogeneous and stationary field generation is a key factor in allowing the present observations as it ensures that a homogeneous magnetic field exists over several cm. This field is obtained through the use of large-scale pulsed coils, similarly as what had been done earlier at the Institute of Plasma Physics and Laser Microfusion [33] (Warsaw, Poland) and at the Lawrence Livermore National Laboratory [34] (Livermore, CA, USA), but here we use larger scales and higher-strength B-field so to induce stronger plasma magnetization.