Production of radiatively cooled hypersonic plasma jets and links to astrophysical jets

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Abstract
We present results of high energy density laboratory experiments on the production of supersonic radiatively cooled plasma jets with dimensionless parameters (Mach number $\sim 30$, cooling parameter $\sim 1$ and density contrast $\rho_j/\rho_a \sim 10$) similar to those in young stellar objects jets. The jets are produced using two modifications of wire array Z-pinch driven by 1 MA, 250 ns current pulse of MAGPIE facility at Imperial College, London. In the first set of experiments the produced jets are purely hydrodynamic and are used to study deflection of the jets by the plasma cross-wind, including the structure of internal oblique shocks in the jets. In the second configuration the jets are driven by the pressure of the toroidal magnetic field and this configuration is relevant to the astrophysical models of jet launching mechanisms. Modifications of the experimental configuration allowing the addition of the poloidal magnetic field and angular momentum to the jets are also discussed. We also present three-dimensional resistive magneto-hydrodynamic simulations of the experiments and discuss the scaling of the experiments to the astrophysical systems.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Highly collimated outflows (jets) are a common feature of many astrophysical objects, as diverse as active galactic nuclei (AGN) [1, 2], young stellar objects (YSO) [3] and planetary nebulae (PNs) [4]. In many situations these jets represent high Mach number flows with remarkable collimation characteristics. In the case of Herbig–Haro jets, observed to emanate
from newly formed stars, typical velocities are of the order of $\sim 200 \text{ km s}^{-1}$, Mach numbers are in excess of 10 and radiation losses play a fundamental role in cooling the jet and assisting its collimation [5]. Despite the remarkable progress in the studies of astrophysical jets there are still many unresolved issues, which could be broadly divided into those related to the propagation/interaction of the jets with interstellar medium and those related to the mechanism of jet launching. Although it is now commonly accepted that magnetic fields play a dominant role in creating these outflows [6–10], the launching mechanism and even the initial field configuration are not well constrained.

For the jets propagating far away from the source, the role of the magnetic fields is less clear and this is a topic of ongoing discussions. For the YSO jets, for example, it is most probable that magnetic fields are not dynamically significant there [11].

The goal of the laboratory plasma astrophysics [12–14] is to reproduce in the laboratory conditions and processes which are scalable to the astrophysical environment. Similarity criteria between the equations governing the astrophysical and the laboratory systems were discussed [15, 16] and applied to several experiments conducted on high power lasers (see review [17]). In particular for jets, the relevant dimensionless parameters are the density contrast (ratio of the jet density to ambient density), the Mach number and the cooling parameter (the latter describes the effects of radiation losses on the jet dynamics). In addition, the validity of a fluid description of the plasma and large values of the magnetic and viscous Reynolds numbers and Peclet number are also necessary.

Experiments and numerical modelling of astrophysically relevant supersonic jets, produced using high intensity lasers, have been performed by a number of authors [18–23]. Using conical wire arrays on pulsed power facilities ($Z$-pinch), laboratory jet experiments with dimensionless parameters similar to young stellar object jets were also produced [24, 25]. All of the laboratory jets were formed hydrodynamically, through converging conical flows, which were either shock or ablatively driven. These experiments have shown the importance of radiative cooling on the collimation of the jets and have also proved capable of addressing issues relevant to astrophysical outflows, such as the propagation of a jet through an ambient medium [19, 21, 22, 26] and a cross wind in which wind ram pressure can drive shocks into the jet beam and deflect its path [27–29].

To obtain information relevant to the launching mechanisms of the jets the experimental set-up should incorporate a dynamically significant magnetic field, which is thought to operate near the launch region of astrophysical jets. A magnetically driven jet experiment with high magnetic Reynolds number was proposed in [30]. Experiments with magnetically driven jets of low ($\ll 1$) plasma $\beta$ ($\beta = P_T / P_B$ ratio of thermal pressure to magnetic pressure) were also recently performed [31, 32].

In this paper we present results from two sets of experiments on the MAGPIE pulsed power facility addressing different aspects of physics relevant to the astrophysical jets. The first experiment, described in section 2, studies the propagation of the hypersonic ($M > 30$) radiatively cooled jet through a plasma cross-wind. In the astrophysical environment a number of the jets show C-shaped bending, and these observations are interpreted as jet deflection by the ram pressure of the crosswind [33, 34]. The second experiment (described in section 3) studies the formation of magnetically driven jets (‘magnetic tower jets’). The jet in this experimental configuration [35, 36] is driven by the pressure of the toroidal magnetic field in a configuration similar to astrophysical models, has plasma $\beta$ of the order of unity and is radiatively cooled. In section 4 we discuss the scaling between the laboratory and the astrophysical jets and show that the dimensionless parameters of the laboratory jets are in the astrophysically relevant regime. Conclusions and discussion of the future work are presented in section 5.
2. Experiments with radiatively cooled, hydrodynamic plasma jets

2.1. Experimental configuration

The schematic of the experimental configuration [36] is shown in figure 1(a). The conical array of fine metallic wires is driven by 1 MA, 240 ns current pulse on the MAGPIE pulsed power facility. Typically the array is formed by 16 tungsten wires with a diameter of 18 µm. The small radius of the array is 8 mm and the wires are inclined at an angle of ∼30° with respect to the array axis. The axial length of the array is 12 mm. The dynamics of the system was investigated using a laser probing system (λ = 532 nm, pulse duration 0.4 ns) with interferometer and several schlieren channels, time-resolved XUV and soft x-ray imaging. The interferometer provided two-dimensional (2D) data on the distribution of the electron density in the observed outflow system, while the schlieren diagnostic is sensitive to the gradients of the refractive index. Four-frame gated soft x-ray pinhole cameras (2 ns gate with 9 ns separation and 5 ns gate with 30 ns separation) were used to record 2D time-resolved images of the outflow structure emission. The spatial resolution for the laser probing was ∼0.1 mm and for the soft x-ray imaging ∼0.3 mm. Differentially filtered time-integrated x-ray images were used to estimate the characteristic temperature in the plasma of the central column of the observed jet.

2.2. Jet evolution in conical wire array Z-pinches

The current driven resistive heating of the wires converts them in a few nanoseconds into a heterogeneous structure consisting of a cold dense core surrounded by a hot (∼20 eV) low density (∼10¹⁷ cm⁻³) coronal plasma. The net \( J \times B \) pinching force generated by the global magnetic field accelerates the coronal plasma towards the array axis. The wire cores act as a reservoir of material, allowing the process of formation and sweeping of the coronal
plasma from the cores to continue for the entire duration of the current pulse. As a result, an approximately steady-state plasma flow converging from the wires to the axis forms, with a characteristic velocity of \(\sim 1.5 \times 10^7 \text{ cm s}^{-1}\) and a corresponding Mach number \(M \sim 5\) [37].

The short rise-time of the current in this system means that current flow is along the path with the smallest inductance (at the largest possible radius), remaining predominantly in the vicinity of the wire cores. Therefore the converging plasma streams are virtually current-free.

The collision of the coronal plasma streams on the axis form a standing conical shock. Here the kinetic energy of the streams associated with the component of the velocity perpendicular to the shock is thermalized, increasing the plasma internal energy. The axial component of velocity is continuous and the flow exits the collimating shock as a jet with typical velocities \(\sim 200 \text{ km s}^{-1}\) (figure 1(b)). The characteristic parameters of the formed jets depend predominantly on the rate of radiative cooling, which removes internal energy from the plasma, lowering its sound speed and increasing its Mach number and collimation. In the experiments, the rate of radiation losses can be changed by varying wire material (Al, Fe or W). Increasing the atomic number increases the rate of energy losses from the plasma stagnating on the axis and leads to the formation of better collimated jets [24].

The experimental jets described above are ejected from the conical array and propagate in vacuum. In contrast, astrophysical jets typically propagate through an ambient medium with density comparable (for YSO jets) to the jet density. The conical wire array configuration lends itself to the introduction of an ambient plasma in front of the jet and allows the study of how the interaction affects the propagation of the jet.

2.3. Interaction of the jet with a transverse plasma wind

In this section we describe a set of experiments in which the jet propagates through a transverse flow of plasma (the cross-wind). This cross-wind plasma is produced by radiative ablation of a thin plastic foil installed above the anode plate and parallel to the axis of the jet. The foil is exposed to the XUV and soft x-ray radiation originating from both the standing conical shock and the wires. The intensity of this radiation is sufficient to produce a plasma flow with a characteristic electron density of \(\sim 10^{18} \text{ cm}^{-3}\) and velocity of \((2–4) \times 10^6 \text{ cm s}^{-1}\) [28]. Because of the increasing radiation flux, the ablation rate of the foil increases with time, furthermore some degree of control over the parameters of the cross wind impacting the jet can be achieved by simply changing the position of the foil with respect to the jet axis.

In the first series of experiments the length of the foil, parallel to the jet axis, was 3–5 mm. Most of the experiments were performed with 1.5 \(\mu\)m thick polycarbonate (C\(_{16}\)H\(_{14}\)O\(_{3}\)) foils. The offset of the foil from the jet axis was varied between 1.8 and 4.6 mm. It was found that although the jet remains well collimated after passing next to the foil, it is deflected by \(\sim 4^\circ\). The deflection depends on the position of the foil and it is larger when the foil is placed closer to the jet axis. The impact of the wind on the jet leads to formation of internal structures in the jet [28]. The presence of internal structures appearing in the jet in the process of deflection is best seen in the laser schlieren images of the jet (see, e.g. figure 2(a)). The image shows the presence of strong density gradients in the direction perpendicular to the jet axis. These sharp density gradients are significant in that they could be interpreted as internal shocks in the jet, formed by the action of the cross-wind plasma flow.

To allow these shocks to be reflected from the jet boundary at a position that is still subject to the pressure from the wind (as is believed to be the case for astrophysical jet deflections) it is necessary to use a longer target. The time taken for a shock to cross the jet beam is \(\tau_c \sim 2r_j/c_s\), where \(r_j\) is the jet radius and \(c_s\) is the internal sound speed. For a shock to be allowed to cross the jet (and potentially be reflected) the transit of the shock should be less than the time that the
jet is influenced by the wind \( t_i \sim L/v_j \), where \( L \) is the length of the foil and \( v_j \) is the jet velocity. For the case discussed above, the length of the interaction is \( \sim 10r_j \) and \( t_i \ll t_c \) implying that a longer foil and therefore interaction time is necessary to model a steady-state deflection. In the ‘long foil’ experiments in order to achieve a more uniform irradiation the target was inclined with respect to the jet axis. In addition, analytical models of jet deflection [34] in astrophysics are applied to the stagnation point, where the jet is propagating perpendicular to the wind. With an angled foil, such point occurs at higher axial position, where observation is easier and the jet path before and after the stagnation point can be better traced. Figure 2(a) shows the deflection of a jet in this modified configuration. The jet is again propagating from the base of the image and the wind is flowing from right to left. The interaction of the jet is much more complex than was seen in any of the previous images, with numerous shocks present between the jet and foil, suggesting that shocks unseen in the previous experiments have had the time to develop. For clarity, in figure 2(b) many of these features have been highlighted and labelled. Computational and experimental results suggest that these features fall into three distinct groups. First, as with the shorter foil experiments, internal oblique shocks (labelled OS) are seen to develop inside the jet; however because of the longer interaction region multiple shocks have now formed. Second, because of a low density plasma halo surrounding the jet, shocks form at the base of the foil (HS). Finally, a working surface is observed to develop part way along the jet (labelled WS2). The development of shocks in the jet and the appearance of a working surface along the jet beam can be seen in figure 3. The four panels show a time series of 2D slices of density from a three-dimensional (3D) simulation. Although the interaction is for a uniform jet and wind with typical parameters relevant to the experiments, the character of the dynamics does not change when more realistic, time-varying parameters are used. The jet and wind are injected from the lower and the right boundary, respectively. In all frames the internal oblique shock is seen to persist in the jet beam and in this shock the jet plasma is compressed, heated and redirected. At the head of the jet a dense shell of plasma forms where the jet rams into the wind, forming a bow shock. This working surface is not visible in the experiments because the density of the jet/wind material may initially be too low, so that the interaction could be collisionless. We shall discuss the collisionality of the main interaction in a later section. Nevertheless, in experiments where initial target densities were significantly

Figure 2. Laser schlieren image of a jet propagating through an extended region of side-wind at 343 ns after the start of current. The jet trajectory and various shock-like features are labelled in the right-hand images; the details of these labels are discussed in the text.
higher, such working surface was clearly observed [24, 26, 27]. As the first working surface is advected downstream by the wind, a secondary working surface appears and as time proceeds a more complex internal structure develops in the jet and wind. Clearly jet–wind collision dynamics is an inherently 3D interaction, and simple analytical models can only provide an approximate estimate of the system parameters. In figure 4, a fit to the jet trajectory for the region of the jet (z = 3.1–10.7 mm) near the stagnation point is shown. This type of parabolic trajectory is discussed in astrophysical models of jet deflection [34], which give a relation between the radius of curvature and physical jet and wind variable. In the experimental fit, we see that a quadratic curve matches the data for the full extent of the jet, except near the base of the jet where no wind is present. Near the stagnation point the radius of curvature of the jet is calculated to be λ ≈ 33 mm. Using a jet velocity of \( v_j \approx 120 \text{ km s}^{-1} \), a jet mass flux \( m \approx 0.086 \text{ kg s}^{-1} \) and a wind density of \( \rho_w \approx 0.017 \text{ kg m}^{-3} \), all determined at the same point, would predict a sound speed of \( c_s \approx 60 \text{ km s}^{-1} \). This would suggest a temperature far in excess of that estimated from filtered x-ray and XUV images, and it is well in excess of the upper limit of \( c_s < 15 \text{ km s}^{-1} \). The reason for this discrepancy requires further study.
2.4. Plasma jets with angular momentum

It is commonly accepted that astrophysical jets emanating from accretion discs should have angular momentum. Thus the ability to produce rotating jets in the laboratory experiments is very important but has not been demonstrated yet.

By imposing a twist on the conical wire array (figure 5(a)), the jet formation can be modified by the introduction of a non-zero angular momentum in jet. In this case the azimuthal component of the current ($J_\theta$) generates an axial magnetic field, which combined with the radial component of the current leads to the appearance of an azimuthal component of the Lorentz force ($F_\theta = J_r \times B_z$). The action of this force is to introduce an azimuthal velocity ($V_\theta$) component in the converging plasma flow.

Figures 5(b) and (c) shows end-on XUV images of two conical wire arrays. Figure 5(b) is for a standard untwisted array, while figure 5(c) shows the effect of rotating clockwise the upper electrode by $\pi/8$ with respect to the lower electrode. It should be noted that in the end-on image of the twisted array the streams for all positions along the wire are integrated, however they are not above each other, hence there is a false impression that the streams are less collimated than in the untwisted case. The end-on image of the twisted array (figure 5(c)) shows that the conical shock is hollow. Such emission may be due to the presence of an axial magnetic field, which hinders the compression by the convergent plasma. Alternatively, the $V_\theta$ component of the precursor streams will cause the flows to ‘miss’ the axis and impart angular momentum on the conical shock. Control experiments using twisted cylindrical array show that the angular momentum is the main, if not the only reason for hollow shock formation. It is important to note that the angular momentum of the flow is transferred to the ejected jet. Shadowgraph images of a rotating jet (figure 6) clearly show a poorly collimated, divergent jet. The jet also displays significantly more internal structure than in the untwisted jet cases. Furthermore, electron density measurements of the propagating jet indicate a relatively hollow profile, which is consistent with an increased expansion due to rotation. In this particular instance, angular momentum is seen to have a significant detrimental effect on jet collimation.

3. Magnetically dominated (‘magnetic tower’) jets

In the jets described so far, the magnetic field does not contribute to the jet collimation. The launched jets are largely magnetic field free and the plasma beta is much larger than one.
In YSO jets, for example, such conditions are thought to be relevant at large distances from the jet formation region [11]. In this section we describe modifications of the experimental set-up which allow the production of magnetically driven and collimated plasma jets. Because of the fundamental role now played by the magnetic field, these experiments are more relevant to the mechanism of launching of astrophysical jets.

3.1. Overview of the formation of ‘magnetic tower’ laboratory jets

Magnetically driven jets were produced using radial wire arrays, which consist of a pair of concentric electrodes connected radially by thin metallic wires. In the present experiments, the radial array was made with 16 tungsten wires (13 µm diameter), the central electrode of the array had a diameter 4 mm and the outer electrode 70 mm. The wires were positioned in the radial plane or inclined at an angle of ∼10’ to the axis to form an inverse cone.

The plasma formation and the flow dynamics during the initial stage of the experiment are the same as those observed in conical wire arrays. The main difference in the present set-up is that the system reaches a stage when the wire cores become completely depleted of material, triggering the formation of a ‘magnetic bubble’ and a magnetically dominated jet. The development of the jet in this system is shown schematically in figure 7. During the first stage (figure 7(a)) ablated plasma is accelerated axially by the Lorentz $J \times B$ force and fills the region above the radial array, forming an ambient medium into which the magnetic tower will eventually expand. As with the conical arrays, the magnetic field and thus the currents remain confined in the proximity of the wires, leading to a relatively high-$\beta$ background plasma. Characteristic parameters for this plasma are electron densities of $\sim 10^{17} – 10^{18}$ cm$^{-3}$, temperatures of $\sim 20$ eV and an ionization level of $Z \sim 10–15$. Injection of plasma into the upper regions will continue until the wires are fully ablated and stop acting as mass sources. Previous experiments with different configurations of wire array $Z$-pinches [37] have shown that the ablation rate of the wires increases with the magnitude of the global magnetic field, which in a radial wire array changes as $1/r$. Thus the ablation rate is highest close to the axis and at some moment in time a section of the wires near the central electrode will be fully ablated. The disappearance of parts of the wire cores means that the swept up plasma cannot be replenished, and the current path shown schematically in figure 7(a) is no longer available.
Figure 7. Schematic of a radial wire array experiment. Currents flow radially through fine metallic wires and along the central electrode, producing a toroidal magnetic field which lies below the wires. (a) The $J \times B$ force acting on the plasma ablated from the wires produces a plasma background above the array, and because of resistive diffusion, the current path remains close to the wires. (b) Full ablation of the wires near the central electrode leads to formation of a magnetic cavity, which evolves (c) into a magnetic tower jet driven upwards by the pressure of the toroidal magnetic field.

Wire breakage thus leads to development of a magnetic cavity in the background plasma, which is pushed by the rising toroidal field loops (figure 7(b)). This is the beginning of the second stage of the experiment: the formation of a magnetically driven jet. The current is now forced to flow along the surface of the cavity and through the central region, where a dense jet-like plasma column develops (figure 7(c)). The pressure of the toroidal magnetic field, associated with the current flowing in the plasma column, leads to radial and axial expansion of the magnetic tower and to the axial acceleration of the jet column. It is possible to modify the experimental configuration (e.g. by varying the inclination of the wires to the axis or by variation of the inner electrode diameter) to control the density distribution of the plasma into which the magnetic tower jet propagates. This would allow the study of the effects of the ambient pressure on the jet formation.

3.2. Magnetically driven jets

A time sequence of soft x-ray self-emission images, taken during the same experiment, is shown for a laboratory magnetic tower jet in figures 8(a) and (b). The images were obtained using two x-ray cameras, filtered to transmit emission in the 150–280 eV range, observing the same jet from two different azimuthal directions, separated by 135°. The brightest emission originates from the plasma on the axis which is pinched and accelerated by the magnetic field.
Figure 8. Time sequence of soft x-ray images obtained during the same experiment showing expansion of the magnetic cavity and development of instabilities in the central jet column. The four images in part (b) were taken with smaller inter-frame time separations and from different viewing angle.

Emission from the expanding walls of the magnetic cavity indicates the position of the return current path. The size of the magnetic cavity increases in time both radially and axially, with a velocity $\sim 200 \text{ km s}^{-1}$ in the axial direction and a factor of $\sim 4$ slower ($\sim 50 \text{ km s}^{-1}$) in the radial. This differential expansion leads to the elongation of the cavity in the $z$-direction. The two factors contributing to the faster growth in the axial direction are a decrease in the magnetic pressure force acting on the wall of the cavity and a steep decrease of the density of the ambient plasma in the axial direction. It is also important to note that the diameter of the magnetic tower is essentially fixed at the base, where the outer wall of the cavity (return current path) connects to the wires. Due to mass accretion, the walls of the cavity are expected to have high density gradients and the shadow images indeed show sharp boundaries with characteristic thickness of the wall of $\sim 0.5 \text{ mm}$ (figures 9(a)–(c)). At early time ($\sim 230 \text{ ns}$) it is evident that the wall of the magnetic cavity is formed by discrete number of current paths, corresponding to the number of wires in the radial array. Despite the relatively small number of the wires in this experiment (16), the overall symmetry of the magnetic tower is very high, indicating equal division of the return current between the poloidal current loops. With time the magnetic tower elongates in the axial direction and the discreteness of the current paths becomes less pronounced. At late times (figure 9(c)) the outer wall of the magnetic cavity opens up at the top. This could be related to the steep decrease of the ambient plasma density with axial position $z$. The corresponding decrease in the decelerating (snowplough) force produces a rapid acceleration of the tip of the magnetic cavity and stretching of the plasma in the wall could also lead to the disruption of the path for the return current. In addition the current path supporting the toroidal magnetic field in the cavity could also be disrupted by the development of instabilities in the central jet. The development of a kink instability ($m = 1$) in the jet is observed in the simulations. Figure 10 shows an iso-density surface from a 3D resistive
Figure 9. Laser shadowgraphs of the magnetic jet evolution. (a) At 233 ns the magnetic cavity is well developed. A collimated jet is clearly visible on axis inside the cavity. (b) The magnetic cavity elongates axially and expands radially. Because of instabilities sections of the jet on axis are no longer visible and the jet assumes a clumpy structure. (c) The upper edge of the magnetic cavity breaks up and disappears. On axis is still visible a well collimated clumpy jet. (d) Schematic of the last stage of the magnetic jet evolution, showing how currents re-connect at the foot-point of the magnetic tower and a jet is ejected with entrained magnetic fields.

magneto-hydrodynamic (MHD) simulation of a radial array. In the picture, a section of the front wires and magnetic cavity was removed to allow the visualization of the jet. Magnetic field lines are also shown. An \( m = 1 \) kink instability is seen to develop at the base of the jet. In the simulations the instability is responsible for the detachment of the upper part of the jet.

The evolution of the magnetic tower jet requires the presence of a current which supports the toroidal magnetic field inside the cavity. The increase of the magnetic flux due to expansion of the cavity or, at later time, disruption of the current path through the central plasma column (or the wall of the magnetic cavity) should lead to an increase of the voltage applied to the gaps in the wires through which the inflation of the magnetic tower started. As a result it becomes energetically favourable for the current at some stage to reconnect through these gaps and to flow radially from the central electrode to the remaining length of the wires. This process is facilitated in the experiment by the filling of the gaps by plasma expanding from the electrode and from the wires which occurs with a characteristic time of \( \sim 50 \) ns, comparable with the inflation time of the tower. As the magnetic tower/plasma jet becomes detached from the source, it will continue its motion in the axial direction with the velocity acquired during the stage of magnetic tower inflation. The detached jet could still have magnetic
Figure 10. Results of 3D MHD simulations of a radial wire array. The plot shows an iso-density contour surface and the magnetic field topology inside the cavity.

flux associated with the toroidal magnetic field and the decay of this magnetic flux will be determined by the value of the magnetic Reynolds number (see figure 9(d)). For the plasma temperature in the central jet column of $\sim 120$ eV and $Z \sim 20$, as estimated above, the magnetic Reynolds number $Re_M$ is $\sim 10$. It is important to note that reconnection of current from the wires to the electrode restores the initial magnetic configuration, with the toroidal magnetic field concentrated in the region below the plane of the wires. The pressure of this toroidal magnetic field acting on the plasma filling the gap between the central electrode and the remaining length of the wires could drive the second episode of magnetic tower jet formation. A smaller amount of material is likely to participate in this process, suggesting a higher expansion velocity of the second magnetic cavity. The possibility of formation of the subsequent jet will be studied in the follow-up experiments.

4. Scaling of the experiments to astrophysical jets

Laboratory astrophysics experiments seek to replicate in laboratory an adequate representation of the dynamics of an astrophysical system by attaining a valid set of dimensionless parameters which are in the appropriate range of the astrophysical environment. The scaling conditions required in the hydrodynamic and MHD regimes can be found in [15, 16]. In the present experiments the plasma is highly collisional so that the ratio of the mean free path to the size of the system is small, $mfp/jet$ radius $\sim 10^{-5}$, and the plasma can be described by the fluid equations. The effects of kinematic viscosity and thermal conduction are exemplified by the Reynolds ($Re$) and Peclet ($Pe$) numbers, respectively. In general the Reynolds number is large, $Re \sim 10^4$, and the viscous effects can be neglected. The Peclet number is $Pe \sim 5–20$, indicating that although heat conduction may play some role in smoothing out some of the flow features, advection of thermal energy is the dominant transport mechanism. The cooling parameter ($\chi$) is defined as

$$\chi = \frac{\epsilon_T}{P_R \tau_H},$$

where $P_R$ is the power radiated per unit volume, $\epsilon_T$ is the thermal energy density and $\tau_H$ is a characteristic hydrodynamic time of jet evolution. In radiatively efficient regimes $\chi < 1$ and cooling through radiation is important in the dynamics and energy balance of the system.
Using the radiated power calculated from the cooling tables given in [38], we estimate a cooling parameter in the range $\chi \sim 10^{-4}$–$10^{-3}$ for the magnetic jets and $\chi \sim 0.1$–1 for the hydrodynamic jets. The experimental jets are radiatively cooled. The internal Mach numbers also vary considerably, $M \sim 3$–5 in the magnetically driven case while $M > 30$ for the hydrodynamic jets.

In the jet–wind interaction, we also need to consider the collisionality between the jet and wind plasmas. For typical jet and wind physical conditions we find that the mean free path of the wind ions interacting with the jet ions is significantly smaller than the jet radius and the interaction can be described hydrodynamically [28].

For the magnetic jets, we also take into consideration the plasma $\beta$ and the magnetic Reynolds $Re_M$ numbers. The advected magnetic field in the background plasma, away from the foot of the magnetic cavity, is small and the plasma $\beta$ increases with height until thermal pressure dominates over the magnetic pressure, $\beta \sim 5$. The magnetic tower is thus confined by the thermal pressure of the ambient medium, and the collimation will depend on its pressure distribution. The magnetic Reynolds number also increases with height, resulting in $Re_M \sim 5$ and a characteristic diffusion time $\tau \sim 40$–50 ns, which is comparable to the magnetic tower evolution time. Inside the envelope, in the magnetic cavity, the magnetic field dominates ($\beta \sim 0.01$) and the plasma is attached to the field lines ($Re_M \gg 10$). In the jet instead, there is balance between the thermal and magnetic pressures and the plasma $\beta \sim 1$; here again the advection of the field is dominant and $Re_M \sim 10$. As the magnetic cavity breaks up, the jet detaches and magnetic fields are entrained in the jet as it propagates upwards. The characteristic magnetic field diffusion time in the detached jet is $\tau > 100$ ns, which should allow the experimental detection of any currents present there.

5. Conclusion

In this paper we have presented results from high energy density plasma experiment designed to investigate the physics of supersonic radiatively cooled plasma jets which have dimensionless parameters similar to those in astrophysical jets.

The first experiment investigated deflection of jets by a plasma cross-wind. Deflection of astrophysical jets occurs in the context of both YSO and AGN jets. In both cases astrophysical models (analytic and simulation based) have demonstrated that the most likely explanation for the deflection is the ram pressure of a cross-wind. In this experiment the jet was hydrodynamic, without a dynamically significant magnetic field. We found that the jet deflection is qualitatively described by simple analytical models developed for astrophysical jets. In addition, experiments show development of a complex series of features: internal oblique shocks in the jets and the formation of secondary working surfaces. Computer simulations of the experiment using laboratory plasma 2D and 3D MHD codes and the 3D astrophysical MHD [39] code are capable of recovering main features of the observed jet dynamics but also show considerable differences. Thus, the real situation may be more complex than can be recovered in either the higher resolution 2D simulations or lower resolution 3D simulations. This point should receive more attention in future studies.

We have also performed laboratory jet launching experiments that demonstrate how laboratory plasma experiments can provide insight into the physics of magnetically mediated astrophysical jet models. The experiments probe the launch region of the jet and reveal a magnetically dominated cavity, produced by toroidal magnetic field pressure and a thermally dominated axial plasma core inside the magnetic cavity. This core is collimated by magnetic hoop stress and although later in the evolution MHD instabilities develop, a clumpy radiatively cooled jet is still persistent. This indicates that instabilities can be non-destructive. At later
stages the jet becomes detached and moves away from the source. In the resulting clumpy jet there may be some entrained magnetic fields; however, given the high radiation losses and the resulting high Mach number of the flow, we expect the jet divergence to be small irrespective of whether magnetic confinement is still at play. Future experiments will probe the long term evolution of the clumpy jet and will try to determine the presence of any entrained magnetic field. Furthermore, in real accretion discs, the source of the toroidal magnetic field may result from the conversion of poloidal magnetic field due to differential rotation. In the present experiment no global poloidal fields are present and the toroidal field is the result of the current imposed on the radial wire array. The presence of a poloidal field could increase, for example, the stability of the jet. This possibility will be investigated in forthcoming experiments, where a poloidal field will be introduced in the system by rotating the wires around the central electrode, as in a solenoid. The addition of a poloidal magnetic field in this configuration could also lead to the introduction of angular momentum into the jet, similar to the addition of angular momentum to the hydrodynamic plasma jets which was demonstrated in the present experiments.

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