

# Laboratory Astrophysics Experiments with Magnetically Driven Plasma Jets

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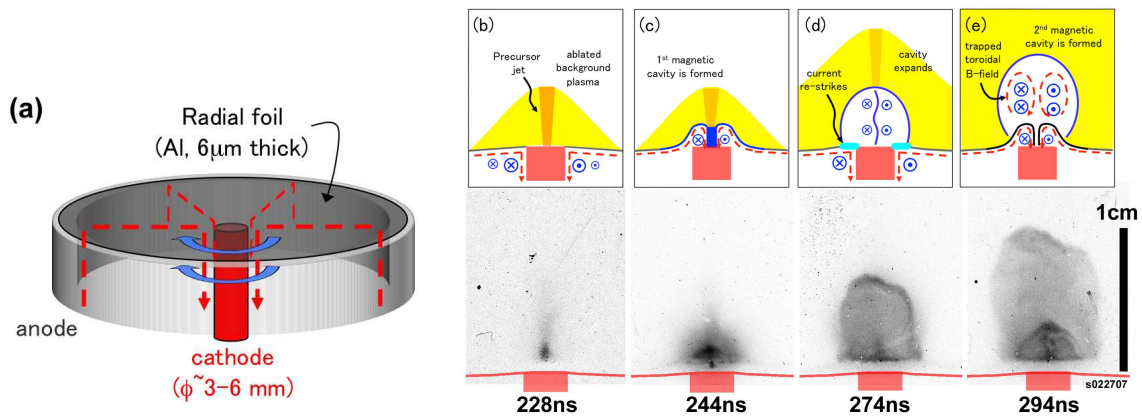
**Abstract.** We present experimental results on the formation of supersonic, radiatively cooled jets driven by the toroidal magnetic field generated by the 1.5 MA, 250 ns current from the MAGPIE generator. The morphology of the jet produced in the experiments is relevant to astrophysical jet scenarios in which the jet on the axis of a magnetic cavity expanding into an ambient medium is collimated by a toroidal magnetic field. The jets in our experiments have similar Mach number, plasma beta and cooling parameter to those in protostellar jets and additionally the Reynolds, magnetic Reynolds and Peclet numbers are much larger than unity, allowing the experiments to be scaled to astrophysical flows. The experimental configuration generates episodic magnetic cavities, suggesting that periodic formation of jets in astrophysical situations could be responsible for some of the variability observed in astrophysical jets. The dynamics of the formation of laboratory jets are presented, together with new results including preliminary measurements of magnetic, kinetic and Poynting energy of the outflows. In addition first estimates of jet temperature and trapped toroidal magnetic field are presented and discussed.

## 1. Introduction

Collimated outflows (jets) are observed in different types of astrophysical objects, spanning a very broad range of spatial scales [1]. Some examples include bipolar outflows from galaxies, with typical lengths of thousands of light-years, to jets from young stellar objects, with characteristic lengths of hundreds of astronomical units. Astrophysical jets are typically studied with high-resolution observations and computer simulations. Nevertheless there are still many open questions regarding their dynamics (e.g. the jet-launching mechanism close to the ejection source), and the mechanisms which generate and sustain the high degree of collimation in the outflows far from the launching point.

Laboratory astrophysics, the study of astrophysical phenomena by the means of carefully designed scaled experiments, has seen major advances in the past years due to the development of High-Energy Density Physics (HEDP) facilities [2]. One of the applications of this new research area is the study of astrophysical jets from young stars. Astrophysical jets can be appropriately scaled to laboratory conditions if their dimensionless parameters are sufficiently





**Figure 1.** (a) Schematic view of the radial foil setup. (b)-(d) Dynamics of the formation of episodic magnetic cavities from a radial foil, shown schematically (top panel) and from XUV self-emission from the plasma (bottom panel). In both figures the red arrows represent the current path and the blue arrows the toroidal magnetic field.

similar to those in the laboratory system (e.g. Mach, Reynolds, magnetic Reynolds and Peclet numbers [3, 4]).

Astrophysical jet experiments typically use high-power lasers and high-current generators, with both approaches allowing for the generation of supersonic, radiatively cooled plasma jets with similar dimensionless parameters to those from young stars (e.g. [5, 6]). High-current pulsed-power generators, however, allow for the formation of plasma jets in which magnetic fields are dynamically significant in the formation and subsequent collimation of the jet [7, 8]. These experiments are relevant to the study of astrophysical jet launching scenarios, as models propose magnetic fields to be the mechanism behind the formation of jets from young stars. Such models rely on the twisting of an initial poloidal magnetic field due to differential rotation between a star surrounded by an accretion disk. After many rotations, the topology of the magnetic field evolves into that of a predominant toroidal (azimuthal) field. A magnetic cavity is formed which is confined by the ambient medium, confining ejected material as a jet on its axis [9, 10]. Our experiments are characterized by the presence of a predominant toroidal magnetic field which is responsible for the formation of a magnetically driven jet. This configuration makes our experiments relevant to astrophysical jet models that rely on such a topology for driving collimated outflows.

## 2. Experimental setup

The experiments were conducted in the MAGPIE generator [11], which produces a current pulse of 1.5 MA in 250 ns. The current is introduced into a radial foil [12, 13] (Fig. 1a), an aluminium disc with thicknesses between 6-15  $\mu\text{m}$ . The foil is placed between two concentric electrodes as the load of MAGPIE, with the central electrode having a selection of diameters between  $\sim 3$ -6 mm. The current path along the electrodes and the foil generates a initial toroidal magnetic field, which can reach magnitudes of  $B_\phi \sim 100$  T at the radius of the cathode.

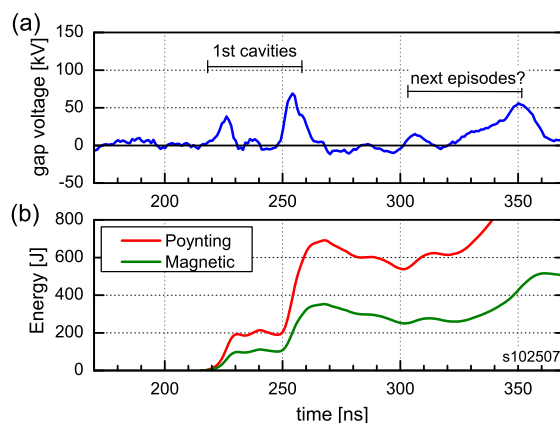
The overall dynamics of the radial foil are shown both schematically and from time-resolved XUV emission images, obtained from the same experiment, in Figs. 1b-d. As the current increases, the foil is Ohmically heated and converted into plasma, a process which lasts for the first  $\sim 100$  ns. The plasma is ablated from the foil following the direction of the  $\mathbf{J} \times \mathbf{B}$  force, which points in a direction normal to the surface of the foil. This forms a low-density

background plasma above the foil (Fig. 1b). The Lorentz force is strongest towards the radius of the cathode, and thus a fastest rate of ablation in this region leads to the formation of a radial gap due to the complete ablation of foil material. Plasma is then driven upward by the magnetic pressure, beginning to form a magnetic cavity, with the toroidal magnetic field now moving to a new position above the initial surface of the foil (Fig. 1c). The cavity expands into the ambient plasma due to the magnetic pressure inside it, and the toroidal magnetic field inside the cavity confines a plasma jet on the axis (Fig. 1d).

The formation of the first magnetic cavity is similar to that observed in radial wire array experiments [7, 8, 14]. From a radial foil, however, it is possible to produce subsequent magnetic cavities during the same experiment. This process occurs as the current re-strikes at the base of the first magnetic cavity. This is possible due to the larger mass available in a foil compared to a radial wire array. The generation of multiple cavities is shown schematically in Figs. 1d-e. This process is repeated throughout the duration of the current pulse, typically producing 3-4 magnetically driven jets per experiment.

### 3. Magnetic and Poynting energy in a magnetic cavity

The formation of a new current inside the magnetic cavities leads to the generation of an additional inductance in the system. This additional inductance was measured using an inductive probe. This diagnostic consisted on an inductance connected to the central electrode, close to the point where the magnetic cavities are formed. The voltage across the radial gap at the base of the cavities was measured ( $V$ ), which is proportional to the current inside the cavity ( $I$ ) and the additional, time-dependant inductance due to the new current path ( $L_{bubb}$ ). Fig. 2a shows the measured voltage as a series of episodic spikes, which are correlated with the formation of the subsequent magnetic cavities in the experiment. From these results it is possible to estimate the magnetic energy ( $E_M = L_{bubb} I^2 / 2$ ) and the Poynting energy, i.e. the total energy delivered to the cavity by the Poynting flux through the radial gap ( $E_P = \int V I dt$ ). Fig. 2b shows these estimates, resulting in  $E_M \sim 100$ -300 J and  $E_P \sim 200$ -600 J.

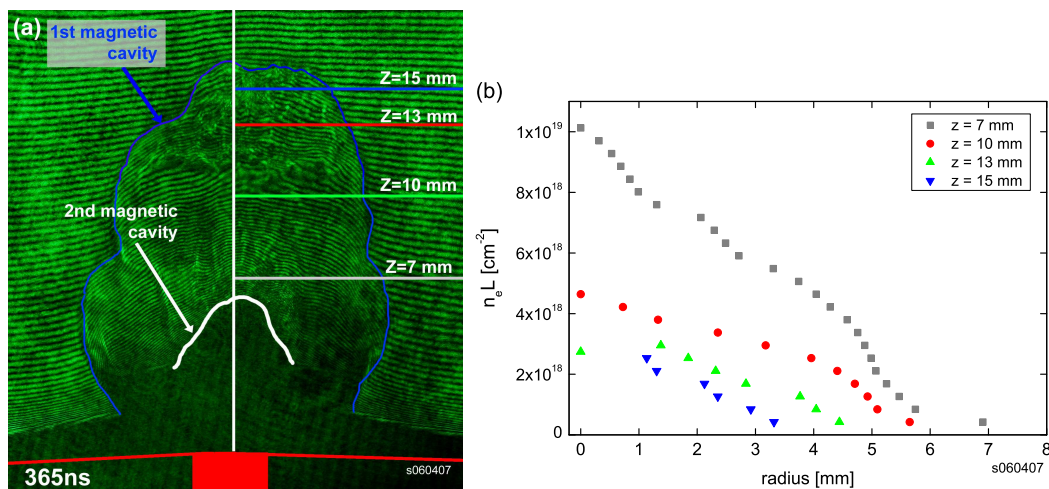


**Figure 2.** (a) Measured voltage across the radial gap of the episodic magnetic cavities. (b) Measured Poynting and magnetic energy.

### 4. Kinetic energy estimate

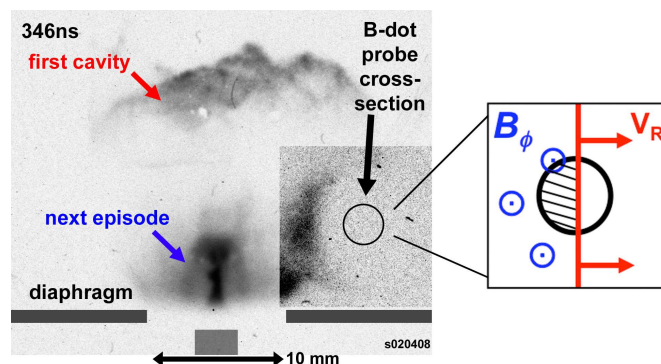
By using optical laser interferometry ( $\lambda=532$  nm, 0.2 ns exposure) it is possible to obtain 2-D maps of electron density integrated along the probing path ( $\int n_e dL \approx n_e L$ ). An example image is shown in Fig. 3. Radial line outs at different heights were obtained from this image, and

electron densities were integrated in order to estimate the total number of electrons inside the outflow. The tip velocity of the cavity was measured from time-resolved XUV emission imaging, resulting in  $V_Z \sim 130$  km/s. By assuming a level of ionization in the plasma of  $Z=5$ , obtained from the measured electron temperatures in Sec. 5, the mass inside the cavity  $m$  was estimated. The kinetic energy of the outflow was then calculated as  $E_K = mV_Z^2/2 \sim 100$  J. This estimate is of the right magnitude when compared to the energy delivered to the cavity as Poynting flux, shown in the previous section. Future experiments will allow to measure the distribution of velocities along the jet and thus obtain a more accurate measurement of the kinetic energy inside the cavities.



**Figure 3.** (a) Optical laser interferometry image at 365 ns, showing the formation of two subsequent magnetic cavities. The horizontal lines show the positions for the measured contours of electron density integrated along the probing beam, shown in (b).

## 5. Trapped toroidal magnetic flux



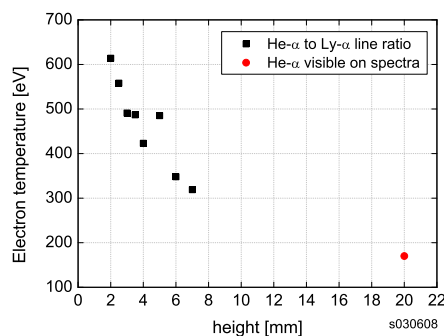
**Figure 4.** Measurement of toroidal magnetic field inside the expanding magnetic cavities.

The dynamics of the episodic magnetic cavities in radial foils indicate that a toroidal magnetic field is responsible for their formation, as in previous experiments with radial wire arrays ???. The generation of subsequent jet episodes in radial foils could imply that some toroidal magnetic flux

will remain in the first cavity at the time when the secondary outflow is formed. The presence of toroidal magnetic field inside the expanding magnetic cavities was measured with a magnetic probe, shown in Fig. 4. The probe was positioned above the foil at a radius of  $\sim 13$  mm from the axis, and a height of  $\sim 10$  mm from its surface. A metal diaphragm was placed above the foil in order to shield the probe electrostatically. The probe was positioned in order to measure a toroidal magnetic field. The response of the probe is proportional to the change in the magnetic flux as the cavity reaches the cross-section area of the probe. This changing flux is proportional to the radial expansion velocity of the side-wall of the magnetic cavity  $V_R$ . The interaction from the first magnetic cavity with the probe is shown in Fig. 4. The measured radial expansion velocity of the cavity of  $V_R \sim 90$  km/s indicates that the signal from the probe corresponds to a magnetic field of  $B_\phi \sim 0.3$  T. This estimate can be compared with the expected magnetic field assuming that the initial toroidal magnetic flux in the first cavity is conserved as the cavity expands and the central jet is pinched. The resultant magnetic field is of the right magnitude, though an accurate estimate of the expected field is not possible due to the uncertainty of the current path through the plasma at the time when the cavity reaches the magnetic probe.

## 6. Temperature of the central jet

The temperature of the central jet was estimated using time-integrated X-ray spectroscopy (photon energies of  $h\nu > 1$  keV). The spectrum was measured using a spherically-bent mica crystal, which provided spatial resolution along the height of the jet. The electron temperature of the jet was estimated by considering the ratio of the combined intensity of Helium-like aluminium lines. The dependence of these line ratios on temperature has been modelled by [15], assuming similar plasma conditions as those encountered in the jet. Fig. 5 shows the measured temperatures as a function of height along the jet. Electron temperatures of the order of  $T_e \sim 170$ -600 eV were measured, and thus the magnetic Reynolds number was estimated. Assuming a value for the ionization of  $Z=5$  (obtained from ionization balance for a temperature of  $T_e = 100$  eV), a characteristic spatial scale of the jet of  $L \sim 1$  mm, and a typical flow velocity of  $V \sim 100$  km/s, we calculate a value of  $Re_M \sim 1000$ .



**Figure 5.** Electron temperature of the jet as a function of height, obtained from time-integrated X-ray spectroscopy.

## 7. Summary

We have presented new experimental data from radial foil experiments which complement previous results [12] and enhance our understanding on the dynamics of episodic magnetically driven jets. Preliminary measurements of the kinetic energy ( $E_K \sim 100$  J) and magnetic energy ( $E_M \sim 300$  J) inside the magnetic cavities are in good agreement with the total electromagnetic

energy injected as Poynting flux ( $E_P \sim 600$  J), measured with an inductive probe connected at the base of the cavity. The electron temperature of the jet/outflow, determined by time-integrated spectroscopy, resulted in  $T_e \sim 170$ – $600$  eV, providing a first estimate of this parameter. These high temperatures are consistent with measurements of toroidal magnetic field inside the cavity, indicating that magnetic flux is conserved as the cavity expands and that the plasma has a magnetic Reynolds number larger than unity. Our results indicate values of the order of  $Re_M \sim 1000$ , consistent with previous results from computer simulations [13] thus validating the scaling of these experiments to astrophysical jets.

## 8. Acknowledgments

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