Observation of energetic protons trapped in laboratory magnetic-tower jets

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Abstract. Preliminary results of the self-emission of charged particles from magnetically driven plasma jets has been investigated. The jets were launched and driven by a toroidal magnetic field generated by introducing a \(~\text{1.4 MA, 250 ns electrical current pulse from the MAGPIE generator into a radial wire array. This configuration has shown to reproduce some aspects of the astrophysical magnetic-tower jet launching model, in which a jet is collimated by a toroidal magnetic field inside a magnetic cavity. The emission of ions and protons from the plasma was recorded onto Columbia Resin 39 plates using time-integrated pinhole cameras. In addition a fly-eye camera, an array of 25–496 cylindrical apertures allowed estimating the location of the ion emitting source. The results show the ion emission comes from both the jet and its surrounding magnetic cavity, with the emission extending to a height of at least \(~\text{9 cm from the initial position of the wires. The emission of ions is consistent with the}}

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dynamics of the jet obtained from time-resolved imaging diagnostics, i.e. optical laser probing and self-emission of the plasma in the extreme ultra-violet. These preliminary results suggest the ions are trapped inside the cavity due to the strong toroidal magnetic field which drives the jet. In addition these studies provide first estimates of the energy and fluence of protons for future laser-driven proton probing diagnostics aimed at measuring the magnetic field in these experiments.

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1. Introduction

Highly collimated jets are ubiquitous in the Universe and are observed in objects as diverse as supernovae, active galactic nuclei (AGN), planetary nebulae and young stellar objects and it is believed that magnetic fields play a key role in their launching and collimation (Livio 2002). Among the different models of magnetically driven jets we are interested in magnetic-tower jets (Lynden-Bell 2003, Uzdensky and MacFadyen 2006, Huarte-Espinosa et al 2012), which have been recently approached experimentally through the use of dense, magnetized plasmas (Lebedev et al 2005). In this model a jet on the axis of a cavity is confined by a predominantly toroidal magnetic field, which in turns is confined by the external pressure of an ambient medium. The cavity expands due to the magnetic pressure inside it and the confined central jet propagates in the axial direction developing nonlinear stages of magneto-hydrodynamic (MHD) instabilities. Experiments show that these instabilities not necessarily disrupt the formation of the jet, and for large enough radiative cooling it evolves into a well collimated but clumpy outflow. Many AGN outflows are characterized by strong synchrotron radiation (Gallo et al 2005), which indirectly demonstrates the presence of energetic trapped electrons. In non-relativistic, stellar jets (Hartigan et al 2011) the jet-launching region cannot be resolved through observations, however trapped energetic particles could be also present inside the magnetic cavity in the launching region. In this paper we present first experimental evidence of the presence of a long-lasting population of energetic charged particles, i.e. ions and energetic protons, which exist inside a laboratory driven, magnetic-tower jet. The observation of such particles could provide an indirect estimate of the magnetic field strength inside the cavity. In addition these studies are useful for designing diagnostics to measure magnetic fields based on laser-driven protons (Petrasso et al 2009) which are planned to be fielded in future experiments.
2. Experimental setup

2.1. Magnetic tower-jet formation using radial wire arrays

Magnetic-tower jets are produced experimentally by introducing a $\sim 1.4$ MA, 250 ns electrical current pulse from the MAGPIE pulsed-power generator (Mitchell et al 1996) into a radial wire array, an arrangement of thin metallic wires (typically 8, 16 or 32 tungsten wires each with a diameter of 7.5–18 $\mu$m) placed radially and equally spaced on a plane between two concentric electrodes. A schematic diagram of a radial wire array is shown in figure 1(a). The current flows axially along the central electrode (diameter of 6.35 mm), radially along the wires and then returns to ground along four rods. The current resistively heats the wires and converts them into plasma and a strong toroidal magnetic field is generated below the plane of the wires. The toroidal magnetic field reaches $\sim 100$ T at the electrode radius and decreases inversely proportional to the radial distance from the axis.

The formation of magnetic-tower jets in radial wire arrays has been studied in detail both experimentally (Lebedev et al 2005, Suzuki-Vidal et al 2010b) and numerically (e.g. Ciardi et al 2007) and are depicted schematically in figures 1(b)–(d). The initial phase of the evolution is governed by the ablation from the surface of the wires converted into plasma. The current flows preferentially at the wire edges owing to the lower resistivity while the dense wire cores act as a mass reservoir for a large duration of the evolution. The direction of the ablation is normal to the plane of the wires due to the interaction of a radial current with the toroidal magnetic field, leading to the formation of a low-density, ambient plasma above the wire array. The regions of the wires in proximity to the cathode experience a faster ablation rate due to a stronger magnetic field, resulting in full-ablation of plasma which is pushed by the magnetic field. This leads to the formation of a magnetic cavity (figure 1(b)), with the current now flowing along the edge of the cavity and returning on axis. The toroidal magnetic field inside the cavity leads to axial and radial expansion of the cavity and, most importantly, to the formation of a highly collimated, magnetically driven plasma jet on axis. As the current rises the magnetic cavity expands predominantly in the axial direction. A combination of increasing magnetic field and radiative losses cause the central plasma jet to collapse or pinch into a narrow jet. At this stage the jet is affected by current-driven, MHD instabilities (figure 1(c)) which make the jet to develop clumpy features. The disruption of the axial current path due to these instabilities makes it more favourable for the current to follow its initial path at the base of the cavity.
which can be formed at some stage due to expansion of plasma from the central electrode and wires. This triggers the jet to detach from the base and propagate away together with the surrounding magnetic cavity. The magnetic field of the expanding cavity could provide conditions for confinement of energetic particles inside it (figure 1(d)). It should be noted that quasi-episodic magnetic-tower ejections can also be obtained experimentally by replacing the wires by a radial foil (Ciardi et al 2009, Suzuki-Vidal et al 2010a).

2.2. Diagnostics

2.2.1. Ion detector. The detection of ions emitted from the magnetically driven plasma jets was achieved by using 50 × 50 mm square Columbia Resin 39 (CR-39) plates as detectors. Ions deposit energy in the bulk material as they traverse through it, breaking the bonds within the polymer material causing localized damage. The damage can be visualized by etching the plate in a solution of 6.25 molar of sodium hydroxide (NaOH) at 85 °C. The etching occurs at a preferential rate in regions where there is ion damage compared to bulk material. This results in the formation of pits at each interaction site which can be observed under a microscope and counted for quantitative analysis. Since each ion forms one pit, the detector offers nearly 100% quantum efficiency. The size of the pits depends on the etching duration, however due to the challenges of counting individual pits the data was etched to saturation to visualize large-scale features. CR-39 plates are commonly used as a solid-state nuclear track detector (Fleischer et al 1965) and have a low threshold for saturation of ∼10^6 particles cm$^{-2}$ (Gaillard et al 2007). Recent work has shown that ions with energies as low as ∼85 keV can be detected (Doyle 2012). One of the main advantages in using CR-39 is that is exclusively sensitive to ions as the interaction with electrons and photons does not cause any localized damage, in contrast with other detectors such as radiochromic film (RCF).

2.2.2. Ion diagnostics. In order to image the self-emission of ions from the plasma, the present experiments used two types of diagnostics based on time-integrated pinhole imaging. The first diagnostic consisted of using a single pinhole to image onto a CR-39 plate. The diameter of the pinhole was varied between 100 µm and 1 mm in order to control the ion flux onto the CR-39. The camera was positioned inside the vacuum chamber at a distance of ∼22 cm from the jet. This diagnostic offers a simple and cost-effective method of imaging the emission of ions from the plasma.

The second diagnostic was a fly-eye camera, which consisted of a two-dimensional array of cylindrical apertures, with the CR-39 plate placed at one end. The geometry of the apertures, e.g. their diameter, length and position in respect to the emitting object, sets a range of angles through which ions can reach the detector resulting in shadows from which information on the location and size of the source can be inferred. This diagnostic is based on the principle of coded aperture imaging whereby information about the source can be inferred from the pattern which a known aperture mask leaves on the image. Like pinhole cameras, it is a useful and simple way of imaging radiation which is difficult to focus and is widely used in astronomy (e.g. Caroli et al 1987). The apertures were machined onto a solid piece of aluminium or alternatively, three-dimensional (3D) printed using an ultraviolet-light cured epoxy resin. Both materials were thick enough to block the emission of ions besides those passing through the apertures. The resolution of the camera depends on the number, length and the diameter of the apertures.
Two designs were tested during the present experiments. A first, low-resolution version consisted of 25 apertures (5 × 5 array), each with a diameter of 6 mm equally spaced onto a 50 × 50 mm cross-section area. A second, high-resolution camera consisted of 496 apertures (24 × 24 array) each one with a diameter of 1.2 mm. For both versions the length of the apertures was \( \sim 50 \text{ mm} \). In addition a 6.5 \( \mu \text{m} \) thick aluminium foil was placed in front of the CR-39 as a filter to limit the range of ion energies reaching the detector. The stopping power for this filter was calculated using a SRIM Monte-Carlo simulation (Ziegler and Biersack 1985) resulting in a threshold proton energy of \( \sim 600 \text{ keV} \).

In addition a magnetic spectrometer was fielded to measure the energy spectrum of protons emitted from the plasma with energies between 0.1–5 MeV. A pair of crossed-entrance slits collimates an ion beam which is then deflected by a constant magnetic field generated by a pair of permanent magnets (\( B \sim 0.85 \text{ T} \)). The deflection of the ions is proportional to the Lorentz force \( \propto v \times B \), where \( v \) is the incoming velocity of the ions and thus proportional to their energy. A large detection area is achieved by placing four CR-39 plates in an L-shape configuration. Using solely a magnetic field does not allow to distinguish between different ion species, however this diagnostic is a simple method to obtain a preliminary energy spectrum of the ion emission. The fly-eye camera and the spectrometer are shown schematically in respect to the experimental jet in figure 2.

2.2.3. Other diagnostics. Time-resolved imaging diagnostics were also fielded to study the evolution of the magnetic cavity and the jet on axis. The self-emission of radiation from the plasma in the extreme ultra-violet (XUV, photon energy > 40 eV) was recorded by the means of pinhole cameras (diameter of 100 \( \mu \text{m} \)) backed by a micro-channel plate (MCP) detector. The MCP is divided into four quadrants capable of giving four independent frames in a single shot, separated by 30 ns with \( \sim 2 \text{ ns} \) exposure time (Bland et al 2004). In addition optical laser probing using a commercial Nd:YAG laser (200 mJ, \( \lambda = 532 \text{ nm} \), \( \sim 0.3 \text{ ns} \)) was used to image the plasma by the means of shadowgraphy and dark-field Schlieren. Both diagnostics are sensitive to gradients of the electron density in the plasma, i.e. they are particularly useful to image shocked plasma regions such as the edges of the magnetic cavity.
3. Results and discussion

3.1. Jet evolution

The formation and evolution of a magnetic-tower jet can be seen from XUV emission images shown in figure 3. The first image of the sequence (at 180 ns after the start of the current) shows the initial formation of the magnetic cavity inside the low-density halo plasma ablated from the wires. At 210 ns the jet is visible on the axis of the cavity. The cavity expands radially and axially due to the magnetic pressure inside it, with radial and axial velocities of $V_R \sim 65 \text{ km s}^{-1}$ and $V_Z \sim 265 \text{ km s}^{-1}$, respectively, estimated from the first two frames. As peak current is reached at $\sim 250 \text{ ns}$ the jet is affected by current-driven instabilities which disrupt the current path on the axis of the cavity leading to detachment of the jet from the base. This process is clearly seen on the image at 240 ns, with the jet evidencing the formation of a kink-type instability. The detachment, however, does not greatly affect the collimation of the jet as it continues to propagate axially. Instead the plasma retains some of the magnetic field, leading to the formation of a series of collimated clumps which continue to propagate supersonically. The late-time evolution of the clumps is shown in figure 4(d) at 370 ns using a larger field of view of the XUV camera.

3.2. Ion pinhole imaging

Time-integrated pinhole images of ion emission for different pinhole diameters (1 mm, 300 $\mu$m and 100 $\mu$m, respectively) are shown in figures 4(a)–(c). The images were obtained from different shots, however the magnification was kept constant ($M = 0.5$) in order to make meaningful comparisons. In all cases the etching time was chosen to produce saturated images in order to distinguish large-scale ion features, particularly to determine the overall size of the ion emitting region. It should be noted that the etching duration was approximately constant for all the data shown. The smaller pinhole diameter reduces the ion fluence reaching the detector and effectively highlights regions of higher flux. The results using 1 mm and 300 $\mu$m pinhole diameters show images very resemblant of the shape of the magnetic cavity (e.g. see figure 3 at 210 and 240 ns). For the smallest pinhole diameter of 100 $\mu$m (figure 4(c)) the aspect ratio of the ion emission becomes more ‘jet-like’, implying the central axis emits more ions compared...
Figure 4. (a)–(c) Time-integrated ion pinhole images for different pinhole diameters (1 mm, 300 µm and 100 µm, respectively). The increase in aspect ratio of the jets indicates that the central axis emits more ions. (d) Large field of view XUV emission at 370 ns showing the late-time development of the clumpy jet provides a comparison of the spatial extent of the emission with a time-resolved diagnostic.

to the surrounding magnetic cavity. This is consistent with the regions of strongest toroidal magnetic field, which pinches the jet into a narrow column. The increased emission of ions from the axis of the magnetic cavity can be studied quantitatively by analysing a non-saturated pinhole image, and results of radial lineouts at different heights from the base of the cavity are shown in figure 5. The data were obtained by counting the number of pits as a function of position using a cell-counting routine on ImageJ (Rasband 1997–2012). The profiles show an increase of ion emission from the axis which is consistent with the saturated pinhole images. In addition the profiles show a systematic increase of peak ion emission with height, becoming maximum at $z = 31$ mm. The peak emission is a factor $\sim 7$–13 times higher than the average
Figure 5. Individual ion counts as a function of radius across an unsaturated pinhole image. The profiles were obtained at different heights respect to the base of the magnetic cavity.

Background ion count at large radii. This increase might be related to the formation of highly emitting clumps from the jet, which is consistent with results obtained with the fly-eye camera, which are presented next.

3.3. Fly-eye camera and magnetic spectrometer

Results from fly-eye cameras with 25 and 496 apertures (with 6 and 1.2 mm diameter apertures, respectively) are shown in figure 6. In comparison with the pinhole cameras, the fly-eye cameras had a 6.5 µm thick aluminium filter to look at emission of more energetic particles. The results are characterized by a distinct shadow pattern imprinted on the CR-39, e.g. as observed in the low-resolution version of the fly-eye in figure 6(a). The results show that the top-central apertures are fully illuminated, however the rest of the apertures show only partial illumination with a well-defined azimuthal asymmetry in respect to the central apertures. By using the known position, diameter and length of the apertures it is possible to discern the location of the ion-source assuming the emission is azimuthally symmetric. Each aperture is able to give one point of information which corresponds to the furthest a source can be to give the required pattern. This allows a locus of points to be plotted which encompass the extended source. The analysis of the low-resolution version of the fly-eye camera using 25 apertures is shown in the right hand side of figure 6(a). The source is located at a height of ∼30 mm from the plane of the wires, with a width of ∼6 mm (limited by the diameter of the apertures) and an axial extension of ∼12 mm. A similar analysis performed using the high-resolution fly-eye (figure 6(b)) resulted in a source with a width of ∼3.5 mm and an axial extension of ∼9 mm. The inferred position of the ions is consistent with the location of the unstable, detached jet that develops on the axis of the cavity, which is shown from a time-resolved, dark-field Schlierman results presented in the right hand side of figure 6(b). The pinching and subsequent development of a kink-type MHD instability in the jet has been reported in previous experiments with radial wire arrays in Lebedev et al (2005), Suzuki-Vidal et al (2010b) and in radial foil Z-pinchex, in which the wires are replaced by a continuous metallic foil.
Figure 6. Results of ion emission from fly-eye cameras: (a) low-resolution version with 25 apertures, each one with 6 mm diameter, (b) high-resolution version with 496 apertures, each one with 1.2 mm diameter. A comparison with a time-resolved dark-field Schlieren image at 240 ns shows the source of ion emission is consistent with the position of the unstable jet once it detaches from the base of the magnetic cavity.

(Suzuki-Vidal et al 2007, 2009, 2011, Ciardi et al 2009, Gourdain et al 2009, 2012, 2013). The development of a kink instability in the latter leads to the formation of strong, tangled magnetic fields as studied from numerical simulations of radial foils Z-pinch using the code GORGON (Ciardi et al 2009).

The aluminium filter used on the fly-eye cameras means the emission is due to either tungsten ions, with energies in excess of 50 MeV, or protons with energies of ∼600 keV. The emission of protons from the jet is consistent with the measured energy spectrum of ions using a magnetic spectrometer, which is shown in figure 7. The spectrometer slits were located at ∼31 mm above the cathode which is the region where the higher energy ions were seen to originate from. The CR-39 counts were converted into absolute fluence values using cross-calibrated RCF film which measures the dose accurately. The spectrum in figure 7 reveals a low energy peak at ∼100 keV and a tail which stretches out to ∼4 MeV. There is no significant spike

New Journal of Physics 15 (2013) 125008 (http://www.njp.org/)
in the spectrum to account for the higher energy protons seen from the fly-eye data, suggesting they are indeed just the tail of the spectrum. Although the spectrometer cannot differentiate between ion species, etching durations and pit sizes confirmed that the bulk of the signal was indeed due to protons. Although there might be a contribution from high-energy tungsten ions to the spectra, we believe the majority is due to protons from impurities (e.g. CH) which are always present in the tungsten wires.

4. Discussion and future work

Charged particles confined inside the magnetic cavity with predominantly toroidal magnetic field evolve together with the cavity expansion. After reaching the boundary of the cavity due to drifts, collisions or increase of Larmor radius due to decrease of the magnetic field, protons can propagate towards the ion diagnostics and form an image of the cavity/jet. The observation of ions and protons emitted in experimental magnetic-tower jets provides us with an indirect method to understand the dynamics of the magnetic field that drives and collimates the jet inside the magnetic cavity. The emission region from time-integrated pinhole images is consistent with the late-time evolution of the magnetic cavity, and there is evidence of increased emission from the axis. The results show that the emission extends axially at least \(\sim 6.5\) cm from the initial position of the wires, limited by the field of view of the camera. The peak of the proton spectra of \(\sim 100\) keV is consistent with measurements of the voltage across the base of the magnetic cavity using an inductive probe (Suzuki-Vidal et al 2011, Burdiak et al 2013). Observation of the large emission region is consistent with the conditions needed to trap low-energy protons. For instance 100 keV protons would need a toroidal magnetic field of 4.5 T to be confined to a radius of the order of the cavity radius (\(\sim 1\) cm). This required value is consistent with measurement of magnetic field strength from radial foils \(B_\phi \sim 1.5–5\) T (Gourdain et al 2010, Suzuki-Vidal et al 2010a).

The data from the fly-eye cameras suggest that protons with energies \(> 600\) keV come from a region on axis located at \(\sim 20–30\) mm from the base of the cavity with a typical width.
of \( \sim 3-6 \text{ mm} \). This region coincides with the minimum width of the jet as it is pinched by the toroidal magnetic field which is maximum at peak current (i.e. at \( \sim 250 \text{ ns} \)). The emission of protons from the axis, where the magnetic field is strongest, together with a tail in the proton spectrum of \( \sim \text{MeV} \) suggests an acceleration mechanism which is not clear at present. A possibility might be from the evolution of the initially toroidal magnetic field into a more complex topology, i.e. turbulent magnetic fields, and this has been investigated with numerical simulation using the 3D MHD code GORGON (Ciardi et al 2009). Future experiments will look into fielding time-resolved particle diagnostics in order to further understand the dynamics of proton and ion emission from experimental magnetic-tower jets.

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New Journal of Physics 15 (2013) 125008 (http://www.njp.org/)