Plasma outflows from wire-based z-pinch experiments driven at currents of hundreds of kiloamperes.

Felipe Veloso¹, Gonzalo Muñoz-Cordovez, Luis Donoso-Tapia, Vicente Valenzuela-Villaseca, Mario Favre and Edmund Wyndham
Instituto de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile

E-mail: fveloso@fis.puc.cl

Abstract. Preliminary results on the latest experiments regarding plasma outflows from different wire-based z-pinch configurations performed in the Llampudken generator (~350kA in ~350ns) are presented. These outflows are produced from three different experiments: cylindrical, conical and nested conical arrays. Our experiments show that it is indeed possible to produce plasma outflows from moderate size pulsed power drivers with currents of some hundreds of kiloamperes. Each one of the configurations studied here can produce a dense plasma outflow characterized by its own set of dimensionless parameters; such as Reynolds number, magnetic Reynolds number, amongst others. A dense magnetized, magneto-hydrodynamically unstable plasma outflow is produced using a modified cylindrical wire array, whereas strongly collimated jets are produced from the conical configurations. Moreover, it is possible to mimic the episodic emission of plasma outflow in a collimated jet by producing temporally separated implosions from the nested conical configuration. Finally, the characteristic and dynamics of each outflow are presented and discussed.

1. Introduction
Wire-based z-pinch configurations are highly dynamic plasma configurations and an efficient technique to heat small amount of masses into extremely high temperatures. In this kind of configuration, the current flowing through thin metallic wires produces their ablation forming coronal plasma over their solid cores which act as mass reservoirs during the ablation stage [1]. In addition, this current also produces a global magnetic field as the summation of the local fields of each one of the wires. As the coronal plasma of each wire is driven by the \( J \times B_{\text{global}} \) Lorentz force, the connection path of the wires between cathode and anode determinates the global plasma dynamics of the configuration. Among these wire-based z-pinch plasmas, several experiments can be included such as single-wires[2], crossed-wires[3], cylindrical[4], nested cylindrical [5], conical[6] or radial[7] wire arrangements. These wire-based plasmas are used as load of pulsed power generators, where fast rising electrical currents above 100’s kA in 100’s ns drive the experiments.

Nowadays, it is known that the wire-based z-pinch configurations are efficient and powerful x-ray radiation sources. They are also used in a variety of research areas such as inertial confinement fusion,

¹ To whom any correspondence should be addressed.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
laboratory astrophysics, radiation science and high energy density studies among others. An extensive review on the physics of z-pinch plasmas can be found in ref [8]. Depending on the geometry of the configuration, the global $J \times B$ force can produce plasma accumulation on the region where the magnetic field is zero, and it can be later expelled out of the configuration as a plasma outflow. These outflows provide useful information to study not only the basic plasma physics principles of wire-based z-pinch plasmas, but also a laboratory approach scenario for studying plasma outflows from different sources where magnetohydrodynamical (MHD) similarities can be found through comparing their dimensionless parameters. This paper presents some of the latest results on wire-based z-pinch plasmas driven at the Llampudken generator, where plasma outflows are produced. The preliminary results discussed on this paper shows that a moderate size current driver at hundreds of kiloamperes is capable of producing interesting plasma outflows for basic physics and applications studies.

2. Experimental setup

The experiments were performed using the Llampudken pulsed power generator [9] located at the Instituto de Física of the P. Universidad Católica de Chile. This generator consists of two Marx capacitor banks, each of 0.25 $\mu$F, 240kV and 7.4kJ. Each Marx drives a series of transmission lines connected by line switches towards a couple section composed of an exponential line to the load section. In addition, an auxiliary exponential transmission line is coupled in parallel to the load in order to optimize the energy coupling from the transmission lines to a time-varying impedance load, as it is the case of z-pinch plasmas. A schematic diagram of the generator and the transmission lines currently in use can be seen on Figure 1. Further details on the design and construction aspects of the Llampudken generator can be found elsewhere [9]. At present operation, the generator delivers a peak current of ~350kA in ~350ns. A characteristic current trace is shown in Figure 2a. The wire arrays are mounted as load for the generator and their length and diameter can be adjusted on each experiment. The wire arrays are composed typically of either aluminium or tungsten wires having diameter of ~10s of $\mu$m diameter. The connection path of the wires between cathode and anode can be easily changed according to the experiment and it determinates the global magnetic field of the configuration and consequently, the dynamics of the wire-based z-pinch experiment under consideration.

![Figure 1. Schematic diagram of the transmission lines in the Llampudken pulsed power generator. $TL$ represents transmission lines, $SW$ are high voltage switches, whereas $Z_p$ represents the plasma load.](image-url)

The plasma dynamics were diagnosed using time-resolved imaging diagnostics in the side-on direction (i.e., perpendicular to the axis between electrodes). Extreme ultraviolet (XUV) self-emission imaging is performed using unfiltered pinhole imaging onto two 2-frame micro-channel plate cameras (MCP)
with ~5ns temporal resolution. In addition, time-resolved laser shadowgraphy is performed using a frequency doubled Nd:YAG laser (532nm, 12ps) recorded using open shutter CMOS cameras with interference filters at the laser wavelength to avoid the recording of the plasma self-emission. In the conical wire array experiments described in section 3.2, time-integrated pinhole imaging is obtained in both end-on (i.e., collinear to the axis of the configuration) and side-on directions. The pinhole camera images are recorded on HP5 photographic paper, then scanned and contrast enhanced by an image processing program.

Figure 2. (color online) (a) Experimental current trace of the Llampudken generator (b-d) Schematic diagrams of the experiments (b) End-on view of 2x 10µm + 2x 25µm, (c) Side-on view of conical wire array, (d) Sliced side-on view of nested conical wire array.

In addition to the experimental equipment, some of the experiments are complemented with numerical simulations using the 3-dimensional resistive magnetohydrodynamical code GORGON [10]. This code has been developed at Imperial College of London, and it has proved to be a robust and accurate tool for modelling z-pinch plasmas. This code solves the set of equations that governs plasma dynamics such as the resistive-MHD, thermodynamics, ionization, radiation emission amongst others altogether in a single fluid approximation on a Cartesian grid. These numerical simulations are performed in a 128GB ram, 64-cores cluster located at the Instituto de Física, which is used exclusively on plasma experiments simulations. The input parameters of the code are the initial geometry of the experiment, current profile and the properties of the wire material (such as ionization levels, mass density, etc). In order to match experimental results with the numerical simulations, the initial temperature of the wires can be adjusted. For the experiments described here, a cell by cell random temperature perturbation along each wire length of the form \( T = 0.3(1 + \chi) \text{eV} \) (where \( \chi \) is a random number between 0 and 1) is introduced. This randomly distributed temperature causes different rates of initial expansion along the wires, producing structures and results similar to those experimentally observed in different wire array configurations [11].

3. Results and discussion

3.1. Plasma outflows from cylindrical wire arrays under temporally variable B-field topology

Cylindrical wire array z-pinches are composed of several wires of a given material and diameter arranged in an axisymmetrical cylindrical configuration with the wires equally spaced among each other similar to a bird cage. Due to the azimuthal symmetry imposed on these arrays, the ablation flows from each wire radially converge toward the array axis, where plasma accumulates, forming a precursor plasma column. Even after most of the wires have been fully ablated and during the implosion phase as well, the null magnetic field region (and consequently, the precursor) remains at the array axis. However, the symmetry of the global magnetic field on this configuration can be modified by replacing a pair of consecutive wires with wires of a larger diameter. This modification leads to two separate effects; firstly, current is unevenly distributed between the wires and secondly the thicker wires take longer to fully ablate. Both of these effects impact the dynamics of the precursor plasma due to the production of non-axially symmetric temporal variations of the magnetic field.
topology. Since plasma accumulation on the precursor remains at the null magnetic field region, the variation on the global field topology also displaces the region where the magnetic field is zero, displacing the precursor accordingly. In order to produce a plasma outflow from the wire array precursor, the mass per unit length of the load must be kept similar (or below) those required for producing full ablation of the wires during the current rise of the generator. For the Llampudken generator and according to the 0D model for wire array implosions [8], it is equivalent to \( \sim 3 \mu g/m \) in an 8mm diameter cylindrical array. For this reason, the experiments described here use four Al wires, \( 2 \times 10 \mu m + 2 \times 25 \mu m \), in a cylindrical configuration of 23 mm in length and 8mm diameter. An schematic diagram of the array observed in end-on direction is shown in Figure 2b. These wire diameters meet both conditions: they produce temporal variation of the magnetic field topology and provide an appropriate mass per unit length for the production of plasma outflows.

Figure 3. (color online) Experimental results of \( 2 \times 10 \mu m + 2 \times 25 \mu m \). (top) Laser shadowgraphy and XUV imaging and (bottom) End-on view from numerical simulations together with isocontour of magnetic field. Dashed vertical yellow lines delimit the original array diameter. Green arrows indicate the direction of the plasma outflow.
solid core or a fixed position in space, it gains momentum directed towards the gap produced in the inter-wires space increasing its mass from the ablation of the remaining thicker wires. These effects cause the precursor plasma to move outside the region delimited by the positions of the wires in the array as shown in the XUV images of Figure 3. From these results, a characteristic velocity of the precursor column as a plasma outflow from the wire array can be estimated. The precursor is observed to move from the axis to the array boundary during the time interval of ~190ns to 366ns, from which the average plasma velocity can be estimated as $\sim 3 \times 10^4$ m/s. However, it is worthwhile mentioning that this characteristic velocity is not necessarily uniform along the precursor due to the development of instabilities (such as $m=1$ MHD mode observed in the shadowgraphy images) along the plasma column. Moreover, the numerical simulations of Figure 3 show how the global field topology is being temporally modified, with the consequent movement of the plasma accumulated originally on-axis toward the outer region of the array.

In order to provide characteristical parameters of these plasma outflows, some dimensionless parameters can be evaluated after some estimations on the plasma. Considering the velocity estimation of the plasma outflow and assuming a plasma temperature of 30eV, an average ionization state of 8, a characteristic length scale of $L \sim 1$mm (i.e., of the order of precursor diameter), and considering transverse Spitzer resistivity, the Reynolds number has a high value ($Re > 10^5$) and the magnetic Reynolds number is $Re_m \sim 1.5$. This indicates that the movement of the plasma is more likely to produce turbulence and that both magnetic diffusion and advection are similarly important on the global magnetic field dynamics with characteristic timescales ($L/v$) on the order of $\sim 30$ns. Further details on the ablation dynamics in cylindrical wire arrays using temporal variations of the magnetic field topology can be found elsewhere [12]. Future experiments will include further detail on the dynamics of the plasma outflow from these arrays, together with their interaction with obstacles as a research tool for shock studies in high density plasmas.

3.2. Plasma outflows from conical wire array experiments

In conical wire arrays, the dynamics of the precursor plasma is intentionally modified by changing the angle of the wires with respect to the $z$-axis of the configuration, in contrast to the cylindrical wire array $z$-pinches previously discussed where the wires are placed parallel to it. Therefore, the diameter of the array at the cathode differs from its diameter at the anode, making a truncated cone-shaped array. Since plasma ablation from the wires is given by the global Lorentz force, the ablated plasma is driven perpendicular to them regardless of the array geometry. In the conical wire arrays, the plasma ablated from the wires reaches the array axis bottom first and then top, creating a zipper effect in the precursor. Hence, the precursor gains upwards momentum generating a collimated highly supersonic jet that is expelled at the top of the array. It has been studied that the collimated plasma outflows from these conical arrays could provide relevant information to the observations of astrophysical environments regarding the jet emission from young stellar objects, since both outflows can be compared using an appropriate set of dimensionless parameters [13-16]. In addition, numerical simulations have suggested that some of the properties of the plasma outflows from conical wire arrays, such as collimation and propagation velocities, depend on the current driver parameters [17]. However, most of the experiments have been conducted in megaampere devices having a large current rate; namely MAGPIE (1.4MA, $\sim 5$kA/ns) and COBRA (1MA, 10kA/ns). Therefore, there is a lack of experimental results in lower current rate devices, which is the case of Llampudken (350kA, 1kA/ns). The experiments described here use sixteen equally spaced tungsten wires of 25$\mu$m diameter each using 20mm cathode-anode separation. The array diameter at the cathode is 8mm, whereas the anode diameter is interchangeable between 16mm and 32mm. The anode has a central aperture to allow the propagation of the plasma out of the interelectrode region. An schematic diagram of the configuration is shown in Figure 2c.
Figure 4a shows shadowgraphy imaging of the comparison between preshot array and precursor formation just before the jet is expelled out over the top of the upper electrode. It can be measured that the precursor plasma diameter of half height of the interelectrode space (lower part of the image) is 1.6 times wider than the top of it, showing the zipper-like formation of the precursor [6]. Later in time, this plasma is expelled as a jet which can be observed in the XUV images shown in Figure 4b. In order to measure a characteristic propagation velocity of the jet, the upper part of the jet for images of a single shot is considered providing a value of $\sim 4 \times 10^4$ m/s [18]. It is worthwhile mentioning that this measurement provides an estimation of the velocity rather than an accurate value, since MCP cameras might have different gains for recording the self-emission of the plasma. In order to avoid this difficulty, it would be more adequate to follow a particular structure within the jet. However, there is no a clear structure which can be followed in the present results. Besides this, a highly collimated jet with aspect ratio (length/width) $\sim 15$ is clearly observed. The complete evolution of the plasma dynamics can be observed in the time-integrated images shown in Figure 4c-4d, showing that the initially collimated jet expands radially at later times than those observed in the time-resolved XUV images. From these results, and considering the jet as a 10eV, $10^{17-18}$ cm$^{-3}$ plasma $Z_{\text{eff}} = 5$ and a magnetic field $\sim 0.7$ T, the dimensionless parameters shown in Table 1 can be calculated. These dimensionless parameters agree with measurements of jet emerging from young stellar objects [15,16]. Future experiments will include improved diagnostics to measure the jet density, ionization level and temperature in order to avoid some of the estimations previously shown. Additionally, the interaction
of the jet with a background atmosphere will be studied with the aims of comparing the possible shock structures to be formed with astrophysically relevant objects (such as Herbig-Haro observations [19]).

Table 1. Dimensionless parameters for plasma outflows.

| Parameter                        | Llampudken conical array | Typical young stellar object [15,16] |
|----------------------------------|--------------------------|--------------------------------------|
| Aspect ratio (length/width)      | ~ 15                     | 10-100                               |
| Mach number ($v_{jet}/c_s$)      | ~5                       | > 1                                  |
| Collisionality ($\lambda_{mfp}/L$) | $10^4$                   | $<<1$ ($\gtrsim 10^5$)              |
| Resistivity ($Re$)                | $>> 1$ ($10^7$)          | $>> 1$ ($\gtrsim 10^{15}$)          |
| Heat conduction ($Pe$)            | $>> 1$ ($10^3 - 10^4$)   | $>> 1$ ($\gtrsim 10^7$)             |
| Plasma beta ($\beta$)            | ~8                       | > 1                                  |

3.3. Mimicking episodic plasma outflows using nested conical wire arrays.

Many astrophysical observations from the Hubble Space Telescope, and ALMA telescope, amongst many others have observed that the propagation of jet structures from young stellar objects present discontinuities on the plasma emissions propagating towards the interstellar medium. These structures are plasma jets emitted from a protostar (known as a Herbig-Haro object in astrophysics), where discontinuities are observed as variation on the luminosity along the jet which are often interpreted as perturbations to a relatively steady flow [16,19]. The origin of these discontinuities remains as an open issue in astronomy which can be addressed using laboratory experiments. A possible explanation has been provided by radial wire and foil array z-pinches as the formation of periodic episodic ejections of magnetic bubbles from the source naturally evolving into a heterogeneous jet propagating inside a channel made of self-collimated magnetic cavities [20]. In order to provide an alternative source of episodic emissions in the laboratory, a nested configuration of conical wire arrays is investigated using numerical simulations. These nested arrays have a common anode diameter, but differing on their cathode diameters. The difference on the base angle of these conical arrays produces two plasma outflows which are combined in the array axis and propagating as a single object. The simulations use eight 25µm diameter tungsten wires for each array, with base angles of 45° and 60° for 14mm height cones, and the Llampudken current parameters. A schematic diagram of the nested conical array is shown in Figure 2d.

Figure 5 shows an sliced 3D plot of the electron density, where close-ups of the jet at different times are included. As expected from a conical wire array, a plasma jet is emerging from the bottom of the configuration axially towards the open anode as a collimated plasma outflow. In addition, it can be observed that there is a reduction on the electron density which is propagating as part of the jet with a velocity ~4x10^4 m/s. This reduction in electron density is a discontinuity in the jet which can be seen as a gap similar to those described in the astronomical observations of the Herbig-Haro objects. This gap is formed over the anode between two regions of high density plasma at about 400ns, as shown in Figure 5. The gap between these high density regions is explained from the different times on convergence of the plasma streams coming from the different arrays towards the center of the configuration. When performing independent simulations of each array that compose the nested configuration separately, there is no observation of the gap in the plasma jet regardless the amount of current driving the wire array (either full or half of the Llampudken current); i.e., the gap is only observed in the nested configuration, which coincides with the experimental results discussed in section 3.2. It is worthwhile mentioning that the reduction in density of the nested configuration is sufficient to be experimentally observed on interferometry images of the jet on the future planned
experiments to be performed. Besides this, the dimensionless parameters of the jet from the nested configuration are similar to those from a single conical array presented in Table 1. These observations suggest that the observed episodic emissions can also be produced by successive pulses of plasma outflows due to concentric sources imploding at different times. In the near future, experiments on the Llampudken generator will be carried out in order to complement these numerical simulations for providing a full description of the episodic emission phenomena from nested conical arrays.

![Figure 5](color online) Numerical simulations of nested conical wire arrays driven at Llampudken. Yellow arrows in close-ups indicate the gap in electron density.

4. Final remarks and conclusions
The preliminary results described in this paper obtained from the Llampudken generator demonstrate that the production of dense transient plasma outflows is indeed possible in moderate size pulsed power generators driving currents of some hundreds of kiloamperes. These plasma outflows are not only useful for understanding the basic physics of wire-based z-pinch plasmas, but also they provide an optimal scenario where the plasma source of the outflow and the outflow itself can be studied together in detail. In cylindrical array using different wire diameters, the outflow is originally the dense precursor plasma which is driven out of the array due to temporal variations on the magnetic field topology. In contrast to the outflows produced in conical array experiments, the precursor outflow from cylindrical arrays carries an important fraction of the total current and therefore, there is a growing of an $m=1$ MHD instability while it moves through a diluted plasma background. This opens the possibility of studying different regimes of current-carrying plasmas, where the emission of high energy particles from the turbulent plasma motion or the growing of different kind of instabilities can be developing simultaneously. On the other hand, the plasma outflows from conical wire arrays are mainly hydrodynamic flows in nature once they come out of the array. It has been shown that these outflows produced in Llampudken provide an scenario for comparing them to astrophysically produced jets with the appropriate set of dimensionless parameters. It has also been shown that the episodic emission of outflows can be ascribed to temporally separate convergent sources of the same nature.

The experimental capability of easily performing modifications to the load parameters enables the modification of the plasma source in almost any sense for studying its impact on the plasma outflow, which is also beneficial for application studies. Further investigations on the three kinds of experimental configurations described here will be carried out in order to improve the simultaneous characterization of the source and outflow, which will be reported elsewhere.

The authors acknowledge Prof. J Chittenden for his collaboration and for providing us the GORGON code for the numerical simulations of the experiments. This work has been supported by Fondecyt
Iniciacion 11121621. G Muñoz-Cordovez and L Donoso-Tapia acknowledge financial support of CONICYT scholarship for graduate studies.

References
[1] S V Lebedev, F N Beg, S N Bland, J P Chittenden, A E Dangor, M G Haines, S A Pikuz and T A Shelkovenko 2000 Phys Rev Lett 85 98
[2] F N Beg, A E Dangor, P Lee, M Tatarakis, S L Niffkeer and M G Haines 1997 Plasma Phys Control Fusion 39 1
[3] I H Mitchell, J A Gomez, F A Suzuki, R Aliaga-Rossel, H Chuaqui, M Favre and E Wyndham 2005 Plasma Sources Sci Technol 14 501
[4] F Veloso, F Suzuki-Vidal, F Molina, I H Mitchell, H Chuaqui, M Favre and E Wyndham 2012 IEEE Trans Plasma Sci 40 3319
[5] C Deeney, M R Douglas, R B Spielman, T J Nash, D L Peterson, P L’Eplattenier, G A Chandler, J F Seamen and K W Struve 1998 Phys Rev Lett 81 4883
[6] D J Ampleford, et al 2007 Phys Plasmas 14 102704
[7] S V Lebedev, A Ciardi, D J Ampleford, S N Bland, S C Bott, J P Chittenden, G N Hall, J Rapley, C A Jennings, A Frank, E G Blackman, T Lery 2005 Mon Not R Astron Soc 361 97
[8] M G Haines 2011 Plasma Phys Control Fusion 53 093001
[9] H Chuaqui, E Wyndham, C Friedli and M Favre 1997 Laser Part Beams 15 241
[10] J P Chittenden, S V Lebedev, C A Jennings, S N Bland and A Ciardi 2004 Plasma Phys Control Fusion 46 B457
[11] J P Chittenden and C A Jennings 2008 Phys Rev Lett 101 055005
[12] F Veloso, G Muñoz-Cordovez, L Donoso-Tapia, V Valenzuela-Villaseca, F Suzuki-Vidal, G Swadling, J Chittenden, M Favre and E Wyndham, Ablation dynamics in wire array z-pinches under modifications on global magnetic field topology submitted to Phys Plasmas
[13] D D Ryutov, R P Drake and B A Remington 2000 Astrophys J Suppl Series 127 465
[14] D D Ryutov, B A Remington, H F Robey and R P Drake 2001 Phys Plasmas 8 1804
[15] D D Ryutov, R P Drake, J Kane, E Liang, B A Remington and W M Wood-Vasey 1999 Astrophys J 518 821
[16] B Remington, R P Drake, D D Ryutov 2006 Rev Mod Phys 78 755
[17] J P Chittenden, private communication
[18] G Muñoz, V Valenzuela, F Veloso, M Favre and E Wyndham 2014 AIP Conf Proc 1639 92
[19] P Hartigan, A Frank, J M Foster, B H Wilde, M Douglas, P A Rosen, R F Coker, B E Blue and J F Hansen 2011 Astrophys J 736 29
[20] F Suzuki-Vidal et al 2011 Astrophys Space Sci 336 41