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

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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-pinches 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 $\mathbf{J}\text{x}\mathbf{B}_{global}$ Lorentz force, the connection path of the wires between cathode and anode determinates the global plasma dynamics of the configuration. Amongst 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-pinches are efficient and powerful x-ray radiation sources. They are also used in a variety of research areas such as inertial confinement fusion,

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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 $\mathbf{J}\text{x}\mathbf{B}_{global}$ 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 0.25μF, 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 μm 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.

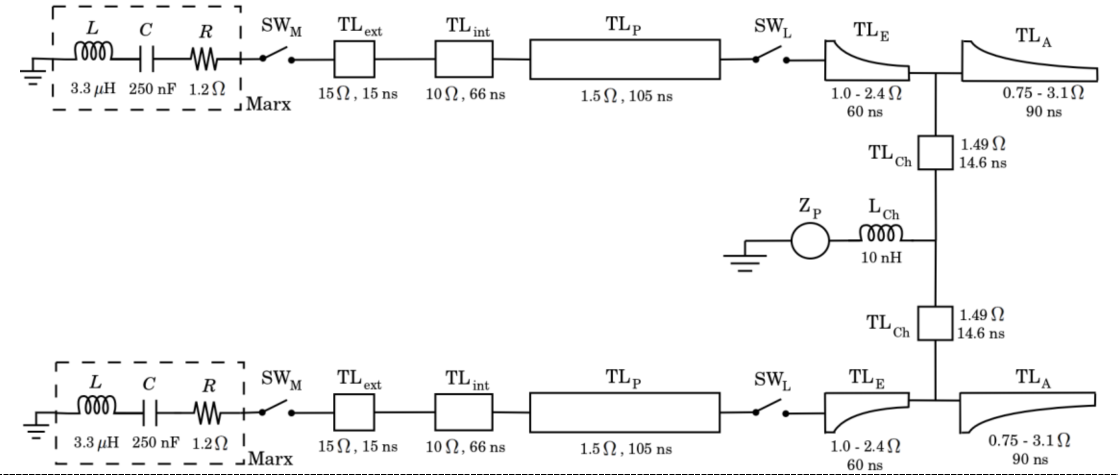

Figure 1. Schematic diagram of the transmission lines in the Llampudken pulsed power generator. *TL* represents transmission lines, *SW* are high voltage switches, whereas Z_p represents the plasma load.

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.

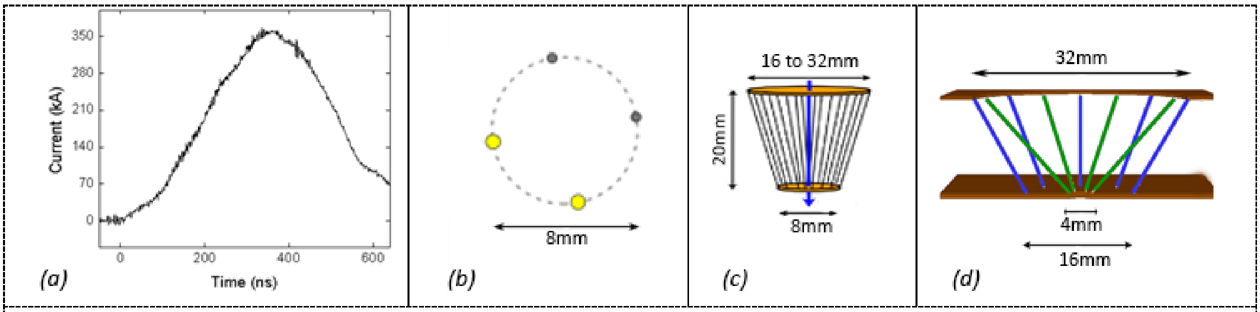

Figure 2. (color online) (a) Experimental current trace of the Llampudken generator (b-d) Schematic diagrams of the experiments (b) End-on view of 2x 10μm + 2x 25μm, (c) Side-on view of conical wire array, (d) Sliced side-on view of nested conical wire array.

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 $T=0.3^{(1+\chi)}eV$ (where χ 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 ~3μg/m in an 8mm diameter cylindrical array. For this reason, the experiments described here use four Al wires, 2x 10μm + 2x 25μm, 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.

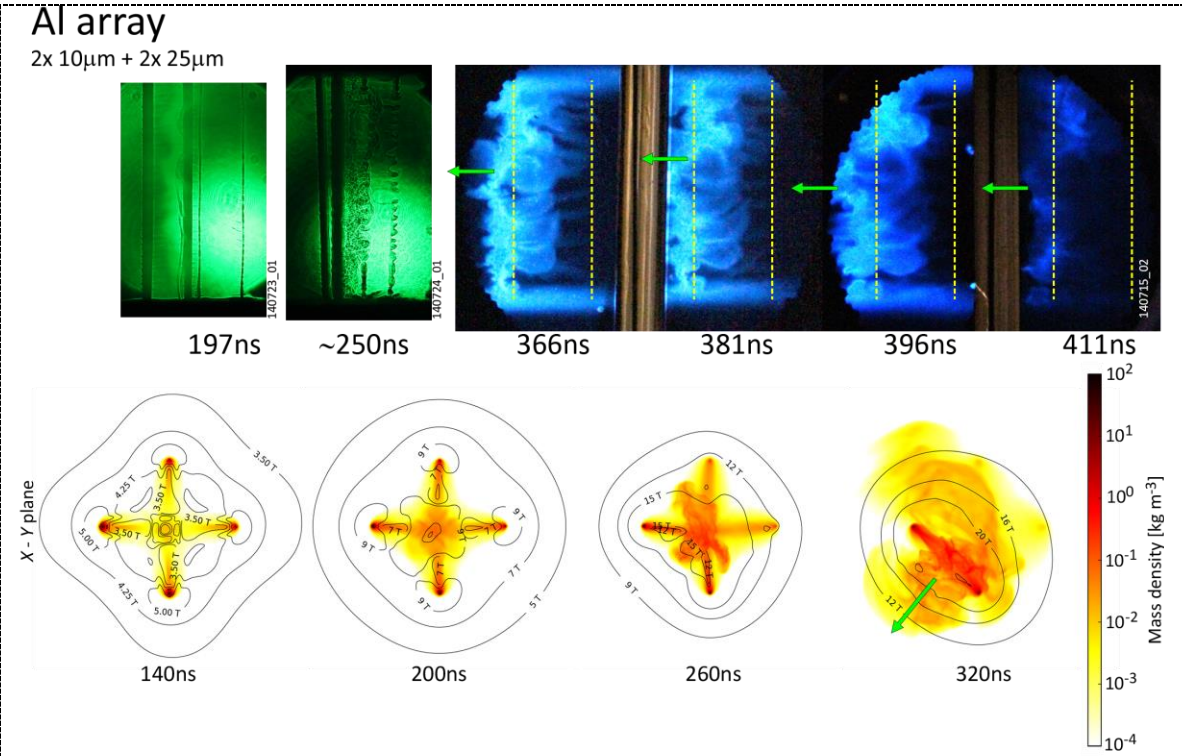

Figure 3. (color online) Experimental results of 2x 10mm + 2x 25mm. (top) Laser shadowgraphy and XUV imaging and (bottom) End-on view from numerical simulations together with isocontour of magnetic field. Dashed vertical yellow lines delimit the original array diameter. Green arrows indicate the direction of the plasma outflow

Figure 3 shows both laser probing and XUV self-emission of the plasma at different times of the discharge. It can be observed from early times in the discharge (~200ns) that the plasma ablated from the wires accumulates near the symmetry axis, but slightly shifted towards the side of the thicker wires (almost hidden by a thick wire). This indicates that the global magnetic field topology has been affected from a symmetric configuration, and the null magnetic field region is already located off-axis. This is ascribed to an uneven current distribution amongst thin and thick wires since early times of the discharge. However, it is possible to observe the precursor movement towards the outer region of the array after the appearance of breakages along the dense cores of the wires (at ~250ns). These discontinuities on the wires increase their equivalent impedance, producing the redistribution of the current towards the precursor and the remaining thicker wires. Since the precursor does not have a 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 characterical 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~1mm (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 turbulences 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 ~30ns. 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, ~5kA/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 25μm 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.

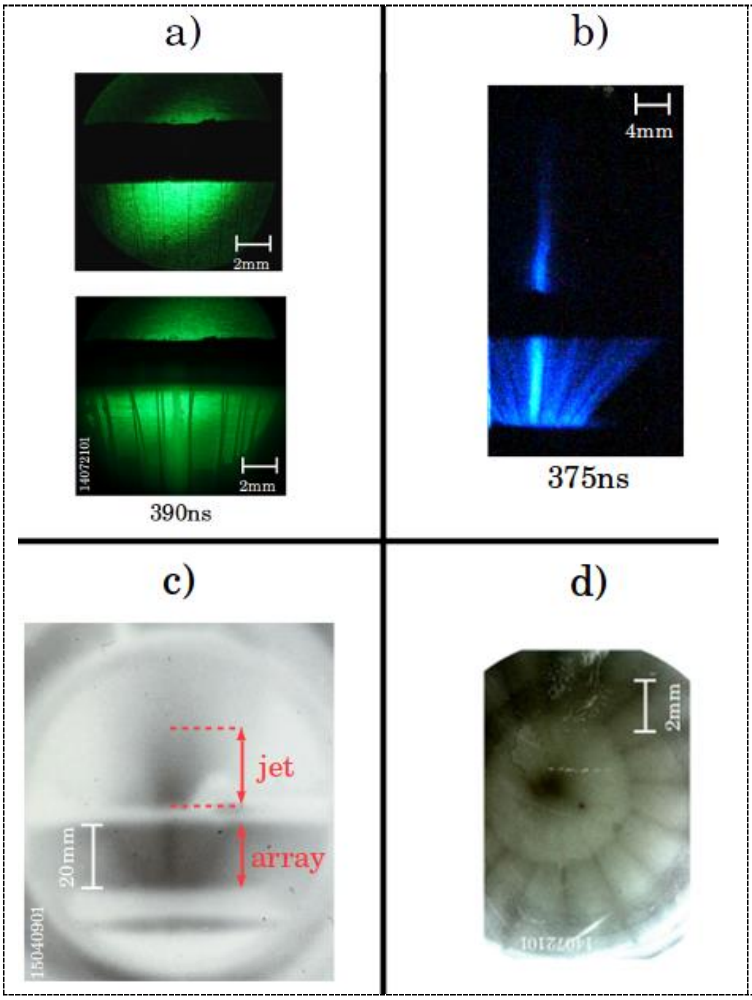

Figure 4. (color online) Experimental results from conical wire arrays. (a-b) Time-resolved side-on images (a) shadowgraphy of 16x 25μm W wires with 16mm anode diameter. (b) XUV image of 16x 25μm W wires with 32mm anode diameter. (c-d) Time-integrated visible images (c) Side-on of 16x 25μm W wires with 32mm anode diameter and (d) End-on of 16x 25μm W wires with 16mm anode diameter.

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 ~4 x 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 (lenght/width) ~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_{eff} = 5 and a magnetic field ~0.7T, 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.

	Aspect ratio (length/width)	Mach number (v_{jet}/c_s)	Collisionality (λ_{mfp}/ L)	Viscosity (Re)	Resistivity (Re_m)	Heat conduction (Pe)	Plasma beta (β)
Llampudken conical array	~ 15	~5	10^{-4}	>> 1 (10^7)	~20-30	>> 1 (10^3 - 10^4)	~8
Typical young stellar object [15,16]	10-100	> 1	<< 1	>>1 ($\gtrsim 10^8$)	>>1 ($\gtrsim 10^{15}$)	>>1 ($\gtrsim 10^7$)	> 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.

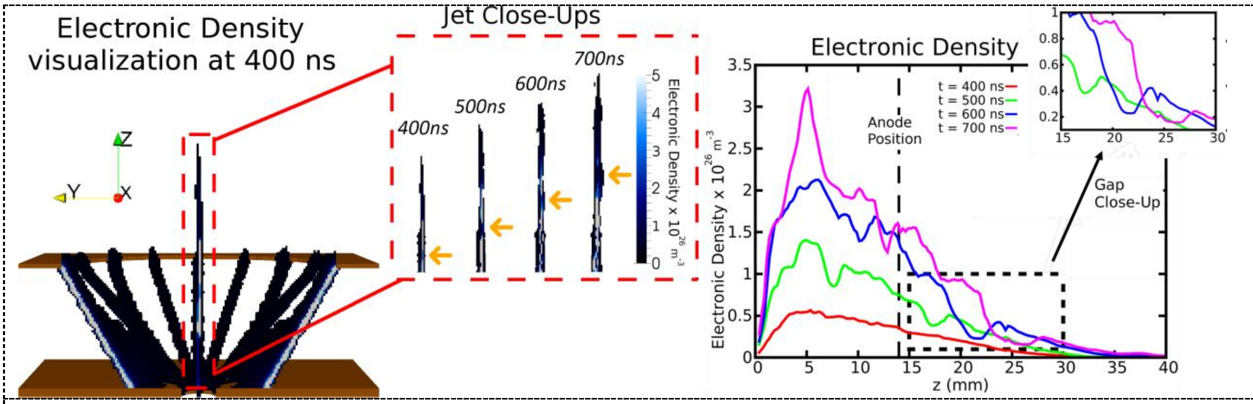

Figure 5. (color online) Numerical simulations of nested conical wire arrays driven at Llampudken. Yellow arrows in close-ups indicate the gap in electron density.

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.

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