Slow energy deposition in an exploding wire and plasma evolution for longer times than the electrical discharge time

G. Rodríguez Prieto\(^a\) and L. Bilbao\(^b\)

\(^a\)INEI, University of Castilla-la Mancha, Ciudad Real, Spain
\(^b\)Instituto de Física del Plasma, UBA-CONICET, Buenos Aires, Argentina

E-mail: gonzalo.rprieto@uclm.es

ABSTRACT: Plasmas are created by means of explosive systems in laboratories to explore plasma densities and temperatures not attainable in a controlled manner with other systems. Usually, when such systems are modelled, a key characteristic is the delivery of all the explosion energy in a time much shorter than the after explosion dynamic time. Therefore, systems where the whole energy delivery has a characteristic time of the order of the dynamical motion of resultant elements had received less attention in the scientific literature. In order to study this kind of systems, using an exploding wire experiment, first measurements of the late dynamics of its final plasma products had been made with iron, platinum and tungsten wires of a fixed length of \(\approx 7\) cm. Wires were surrounded by air and maximum current was on the order of kiloamperes, with a period of 5 \(\mu\)s. One framing camera with arbitrary waiting time between the 16 frames and a minimum of 5 nanoseconds acquisition time for imaging the wire expansion directly has been used to observe the shock wave radial expansion dynamics. Using the images acquired at later times from the frame camera, plasma evolution at a time much larger than time of the energy deposition at the wire are here presented for the first time.

KEYWORDS: Plasma diagnostics - high speed photography; Plasma diagnostics - interferometry, spectroscopy and imaging; Pulsed power

\(^1\)Corresponding author.
1 Introduction

The flow of electrical current through a metallic wire transforms the state of metal from solid to plasma when the amplitude of the electrical current is of the order of kilo-ampere, and the discharge time is not longer than microseconds. It begins with Joule heating of the wire, that leads to its transformation into liquid metal, that with further electrical energy deposition evaporates so it finishes in a plasma state [1, 2].

Commonly known as exploding wire system, one of the first documented uses was to deposit gold into a glass to observe wavelength changes on the transmitted light in experiments performed by Faraday in 1856 [3]. At present, they have a promising future as an alternative method to generate metallic powders of industrial interest [4, 5]. On the other hand, it is also used in pure scientific endeavours, as the cylindrical shock waves studies of Bennett in 1958 [6] or more recent applications, like the first experimental results on copper gas resistivity limits [7].

Exploding wire phenomena are highly dynamical, with many different fundamental scales, both in time and space. Usually, time scales involved in these phenomena go from the phase changes duration in the metallic wire material to the microseconds of the electrical discharge duration and are important in the later formation of plasma instabilities, as recently shown by E. Kaselouris et al. [18]. Radial dimension of the explosion products varies from few hundreds micrometers of the solid wire to few centimetres of plasma cylinders, producing different space scales with several orders of magnitude among them.

In this work, results on the plasma morphologies at a time larger than the electrical current duration (for microsecond electrical discharges) are presented for the first time, which present a clear difference to the results of initial moments of the discharge [19]. Experiments show that the plasma morphological evolution is halted after 14 µs of the electrical discharge, with a no clear evolution in time of instabilities, until the last times measured, close to 30 µs after the beginning of the electrical discharge.
2 Experimental setup

Experiments were performed with the ALEX, *ALambre EXplosivo*, exploding wire in Spanish, an exploding wire system situated at INEI, *Instituto de Investigaciones Energéticas y Aplicaciones Industriales*, a research institution of the University of Castilla-la Mancha in Ciudad Real, Spain. It has two capacitors in parallel, with 1.1 \( \mu \)F capacity each that are connected to the wire holders through a spark gap switch, triggered by a high voltage trigger source. Details on the set-up can be found elsewhere [8], and are shown on figure 1.

![Figure 1. ALEX experimental set-up scheme.](image)

Wires of tungsten, iron and platinum were used in these experiments. Their diameters were 50 and 125 \( \mu \)m, except for tungsten, where 100 \( \mu \)m diameters were employed. The length of the wire was 69.80 \( \pm \)0.03 mm for all the metals and diameters. Nominal charge on the capacitors was arranged at 10, 15 and 20 kV and combined with the three metals in their different diameters. Reproducibility of the results is assured by a observed variation of less than 3% when experimental parameters are maintained constant.

In order to observe the obtained plasma, electrical and optical probes were used. As voltage dividers were placed in direct contact with the wire holders, see figure 1, no further calculation was
necessary to obtain the wire or plasma voltage but the subtraction of the calibrated voltage between the two probes. In a more detailed description, the voltage signals recorded in the oscilloscopes were, first, scaled by a factor previously measured and individual to the voltage dividers, as they have different resistive ratios, see figure 1. Later, subtraction of the scaled values proportionate the voltage between the wire or its products, used in this work to calculate the energy deposited as a function of time, figure 4.

This is a not common method in exploding wire systems, as it is usually necessary to operate with the obtained signal to remove the inductive effect of the circuit that lies between the probe and the wire. Such operation add uncertainties and potentially shape changes to the obtained voltage. Indeed, in the experiments for probing the wire core performed by Sarkisov et al. [9] or the studies on strata formed in aluminium wire by Roussikih et al. [10] such errors, although not important for their research, may be present due to the reported position of the voltage probes. So, the measurement voltage method previously outlined allow for a maximum error on the voltage signals of less than 2%.

Calibrated Rogowski coil voltage was also recorded with the other electrical signals in oscilloscopes placed at a room-size Faraday cage, and the electrical current was obtained by numerical integration of the Rogowski signal. Maximum values of the order of 100 kA can be obtained with the setup here used, and figure 2 shows a typical current evolution with the dark pause presence, when a large part of the wire is becoming metallic vapour.

![Figure 2](image-url)

Figure 2. ALEX typical current(black line) and $di/dt$ (blue line) evolution with the dark pause visible. Wire metal was Platinum, its diameter 50 $\mu$m, and the capacitors bank was charged at 10 kV.

Frame camera, up to 16 frames, has been used to image the visible region plasma light emission at a time much longer than current discharge time with a fixed 2 $\mu$s timing between frames. It is
formed by a composition of 8 different intensified CCD cameras that point at the same position using a reflective pyramid with eight facets that direct the light through mirrors to the intensified CCD cameras. It is placed at a fixed position ≈ 3 meters away from the wire holders, in order to avoid the electromagnetic noise produced by the atmospheric wire explosion. All its control units and recording computers are placed inside the already mentioned Faraday cage, also to be protected from the electromagnetic noise generated at the explosion, and communicates with the camera through a high velocity net cable, allowing for the individual setting of the timing between frames and the gain in every intensified CCD. Imaging system attached to the camera is composed of commercial objectives and expanders rings, producing images with a spatial resolution better than 0.1 mm.

3 Results

Exploding wires systems with slow current rise like the one used in these experiments, exhibit development stages that can be separated according to the light production, as figure 3 shows.

![Figure 3](image_url)

**Figure 3.** Normalized typical optical emission captured by photodiode. Marks and signals correspond to different wire stages. Details are given in the text. Notice that light emission is not totally zero at the recording end. Wire metal was tungsten, and capacitors were charged at 20 kV in this case.

After an deposition of energy that may lead or not to a metallic gas expansion stage, known as “dark pause” [11] because of the almost null electrical current, plasma is generated by Joule heating and starts to produce light, which increases its luminosity in a few nanoseconds until it reaches the maximum. After this moment, plasma cools down and light emission slowly reduces until at rather larger times reaches zero again.
Figure 4. Normalized typical optical emission (black line) and voltage (blue line) during an experiment. Tungsten wire with a diameter of 100 µm with the capacitors charged at 15 kV is presented. Any other case is similar.

During the first two stages, electrical current flows through the plasma, but voltage decreases to zero after ≈ 13 µs from the closure of the spark-gap, determining the end of the plasma energy deposition. Figure 4 shows a typical case for a 100 µm diameter tungsten wire with the capacitors charged at 15 kV. Other cases are similar at the end of energy deposition, when voltage values approach zero. In fact, when voltage through the wire drops to zero, the total energy given to the exploding wire, calculated numerically by integration of the voltage times the electrical current flowing through the wire, also reaches a plateau, as figure 5 indicates for same metal with the capacitors charged at 20 kV and a diameter of 50 µm.

Frame photography of the phenomenon during energy deposition period shows the corresponding behaviour of plasma expansion and light decrease as the current and voltage drops. As figure 6 indicates, typically initial maximum in light emission is correlated with stages in wire evolution without large radial expansion, and large and dense stages. Such plasma expands because of its internal energy, and so it becomes less dense and hot, therefore decreasing its light emission at the later times depicted in the figure. Following the evolution of the plasma, in figure 7 the initial instabilities depicted in the last frames of the previous figure have grown and are noticeable larger, making the plasma borders much more irregular at all the times observed. Understanding the merging mechanism for the instabilities is currently a very active physics field, still under investigation.
Figure 5. Time evolution of the energy deposition at the exploding wire and formed plasma for a tungsten wire with 50 µm diameter and capacitors charged at 20 kV. Notice the absence of change in the energy after ≈ 13 µs from the beginning of the electrical discharge and the oscillation after wire metal has been transformed into plasma and so the circuit became a RLC series.

after many years of research [12]. Currently is considered that the shorter wavelength merge into larger wavelengths with time.

At later times of the evolution, when the voltage and current reaches zero, there is no plasma energy deposition. At a first thought, its subsequent evolution is expected to be characterized by growing up hydrodynamic instabilities of various types, that would lead to a turbulent mixing of the plasma with the surrounding air, so the observed borders of the plasma would evolve in time quite dramatically.

Our experiments show a very different situation. For a long time lapse, on the order of two discharge cycles or longer, plasma changes in the visible wavelength range are negligible. There are no large changes on the plasma borders along the 6 µs between the upper and lower photos of figure 7. Other metals at all the charging voltages exhibit a similar behaviour, as figures 8 to 13 show. In all these figures, time scale origin is chosen at the beginning of the electrical discharge.

Notice that although there is a plasma evolution in time, observed borders on the photographs remain at similar positions for all the recorded time. Actually, plasma instabilities can be ruled out as a factor on the evolution of these plasma due to the lack of border evolution in time: if plasma hydrodynamic instabilities would play a prominent role on the noticed dynamics here presented, the plasma borders would noticeable move during the recorded time.

Indeed, iron experiments depicted in figures 8 and 9 show a remarkable similarity at 14 µs in the whole voltage range, which is maintained on the last recorded image, at 30 µs after the electrical
Figure 6. (Colour online) Time evolution of the plasma created for a platinum wire, diameter of 50 µm, with capacitors charged at 15 kV during energy deposition. Photos taken at 1.4 (a), 3.4 (b), and 5.4 (c) µs after the electrical discharge beginning. Horizontal scale is 7 cm. This and all the other images are shown in false colour to highlight the plasma borders.

Unsurprisingly, wire diameter has a clear influence in the observed plasma morphologies: smaller diameters means that the plasma presents more irregular borders. When the iron wire has

 discharge beginning. Notice how in the chosen examples at 15 and 20 kV of iron wire with 50 µm diameter, the initial indentations on the plasma maintain their position across all times although the total light emitted by it has greatly diminished, as confirmed not only by lower intensity at 30 µs images respect the initials, but also by the light captured by the photodiode, not shown here, which follows the same trend.

Unsurprisingly, wire diameter has a clear influence in the observed plasma morphologies: smaller diameters means that the plasma presents more irregular borders. When the iron wire has
Figure 7. (Colour online) Late time evolution of the created plasma for a platinum wire under the conditions described in figure 6. Photos taken at 27.4 (a) and 33.4 (b) µs after the beginning of the discharge. Vertical scale corresponds to 1 cm and time origin is the same as previous panel.

Figure 8. (Colour online) Time evolution of iron plasma at different charging voltages (rows) and times (columns) when the wire diameter is 50 µm.

a diameter of 125 µm, there are less “ripples” present on the plasma than with the smaller diameter of 50 µm, indicating the mentioned influence of the wire diameter on the plasma border.

Wire diameter influence in the final morphology of the plasma is also present for the platinum wires, figures 10 and 11. Similarly to the iron wires, smaller explored diameters lead to an increase in the number of irregularities in the border of the photographs, that grow larger with the voltage. Again, note that although there is a clear movement of the plasma borders with time, the morphology and shape of the plasma remains almost constant through all the recorded time.
Figure 9. (Colour online) Time evolution of iron plasma at different charging voltages (rows) and times (columns) with a diameter of 125 µm.

Figure 10. (Colour Online) Time evolution of platinum plasma at different charging voltages (rows) and times (columns) with a diameter of 50 µm.

Figure 11. (Colour Online) Time evolution of platinum plasma at different charging voltages (rows) and times (columns) with a diameter of 125 µm.
Tungsten wires experiments are challenging in their results (see figures 12 and 13). With the 50 μm diameter wires, the presence of a non illuminated phase surrounding the main light-emitted plasma is obvious in the initial frames, figure 12. Also, it is clear from the images that plasma region increases its size as the charging voltage in the capacitors bank is larger.

![Figure 12](image12.png)

**Figure 12.** (Colour online) Time evolution of tungsten plasma at different charging voltages (rows) and times (columns) with a diameter of 50 μm.

It is a well known fact that under vacuum conditions, the structure of the exploding wire is divided in an external coronal plasma and an inner dense core [13, 14]. But the presence of a fluid or insulator around the wire halts or greatly diminish the coronal plasma, enhancing the radial expansion and temperature [15, 16]. So, such coronal plasma cannot be formed under the experimental conditions here reported. Furthermore, coronal plasma is a high light-emitting plasma, due to its density and temperature conditions.

![Figure 13](image13.png)

**Figure 13.** (Colour Online) Time evolution of tungsten plasma at different charging voltages (rows) and times (columns) with a diameter of 100 μm.

Panels at 14 μs in figure 12 show the opposite behaviour, with the stronger emission coming from the inner part of the plasma produced by the wire; therefore, further experiments and investigations are necessary to clearly asset the nature of the external, less illuminated part of the tungsten plasma wires. Independently of that, time evolution of these wires is remarkably similar to the previous cases in that the morphology of the produced plasma does not change strongly with time. Radial expansion and border shape stay still in the last two recorded frames and present small differences in relation to the 14 μs frames.
Aside from the already commented similarity in the photographs on different times for each metal, last recorded frames are unexpectedly similar for all the metals and voltages regarding the spatial length frequency count. Spatial separation of the features, peaks and valleys, in the last frames of the multiframe sequence for every experimental condition was obtained. After manually

![Image of multiframe sequence](image_url)

**Figure 14.** (Colour online) Sequence of multiframe image of the explosion of a platinum wire of 50 µm with capacitors charged at 15 kV with the peaks and valleys signalled in the last frame. Space scale is the same in all frames, and approx. 7 cm the line in \( \approx 0.5 \mu s \) frame.

signalling the peaks and valleys positions in a manner similar to figure 14, a computation of the distance between two consecutive peaks or valleys was performed by a program written in Octave. From these lengths, a frequency count on the number of times that lengths interval appear in a given frame were obtained, and figure 15 shows the final result. Computed length distribution do not show any grouping by voltage, metal, or any other relevant parameter of the exploding wire system.

Note that inner structures appearing in some photographs, most prominently observed in iron, as figures 8 and 9 clearly show, have not a clear interpretation. Possible ghost imaging on the CCD employed in the multi-frame system cannot be ruled out as the reason of its appearance, and clearly the circular line present in some frames at 22 µs is an artefact of the optical system. But such problems pertain to the inner structure of the photographed plasma, not the external border, which is clearly imaged without having any camera artefact, as the ones described above.

## 4 Conclusions

This work provides the first optical measurements for the morphology of exploding wire products at a larger time than the electrical discharge time in exploding wire systems with microseconds electrical discharge times. To the knowledge of the authors, only a brief mention of the morphology and shape of the plasma at a time longer than the electrical discharge time is addressed by Yaakobi [17], who states: “The diameter then increases only little beyond the main expansion of the earlier short stage, when the wire is transformed from a metal to an ionized gas.”

The presented results demonstrate that the final observed stages of the exploding wires have common morphological features for different initial charging voltages, diameters and metals and agree with the fact that instabilities evolve into a global magnetohydrodynamics mode for steady-state systems [12]. Notice that a direct comparison of the images presented in this work and similar ones obtained in previous years, [1] is not possible. Their results were obtained at times that are
close, less than a microsecond, or directly before the dark pause and therefore in a physical situation totally different to the one depicted here, when all the electrical energy had been deposited much before the time when images had been taken.

Acknowledgments

This work has been financed by the projects “MATERIA CON ALTA DENSIDAD DE ENERGIA EN FUSION POR CONFINAMIENTO INERCIAL”, reference number ENE2016-75703-R from the Ministerio de Ciencia, Innovación y Universidades of Spain and “HIDRODINAMICA DE LA MATERIA CON ALTA DENSIDAD DE ENERGIA”, reference number SBPLY/17/180501/000264 from the Junta de Comunidades de Castilla-la Mancha. Authors thanks prof. Roberto Piriz for the comments and suggestions on this work and the reviewers for their detailed comments.

References

[1] F.D. Bennett, R. Hefferlin and R.A. Strehlow, High-temperature exploding wires, in Progress in high temperature physics and Chemistry. Volume II, Pergamon Press, London (1969).

[2] S.V. Lebedev and A.I. Savvatimskiĭ, Metals during rapid heating by dense currents, Soviet Phys. Usp. 27 (1984) 749.

[3] M. Faraday, On the relations of gold and other metals to light, Proc. Roy. Soc. Lond. 8 (1856) 356.
[4] T.K. Sindhu, R. Sarathi and S.R. Chakravarthy, *Understanding nanoparticle formation by a wire explosion process through experimental and modelling studies*, Nanotechnology 19 (2007) 025703.

[5] R. Sarathi, T. Sindhu, S. Chakravarthy, A. Sharma and K. Nagesh, *Generation and characterization of nano-tungsten particles formed by wire explosion process*, J. Alloy. Comp. 475 (2009) 658.

[6] F.D. Bennett, *Cylindrical shock waves from exploding wires*, Phys. Fluids 1 (1958) 347.

[7] L. Bilbao and G.R. Prieto, *Neutral copper gas resistivity measurements by means of an exploding wire in air*, Appl. Sci. 7 (2017) 829.

[8] G.R. Prieto, L. Bilbao and M.M. Milanese, *Dynamics of a shock wave with time dependent energy release generated by an exploding wire in air*, Phys. Plasmas 25 (2018) 112113.

[9] G.S. Sarkisov, P.V. Sasorov, K.W. Struve and D.H. McDaniel, *State of the metal core in nanosecond exploding wires and related phenomena*, J. Appl. Phys. 96 (2004) 1674.

[10] A.G. Rousskikh, V.I. Oreshkin, S.A. Chaikovsky, N.A. Labetskaya, A.V. Shishlov, I.I. Beilis et al., *Study of the strata formation during the explosion of a wire in vacuum*, Phys. Plasmas 15 (2008) 102706.

[11] C.P. Nash and W.G. McMillan, *On the mechanism of exploding wires*, Phys. Fluids 4 (1961) 911.

[12] F.F. Cap, *Handbook on plasma instabilities*, Vol. 1, Academic Press (1976).

[13] S.I. Tkachenko, A.R. Mingaleev, S.A. Pikuz, V.M. Romanova, T.A. Khattatov, T.A. Shelkovenko et al., *Study of the core-corona structure formed during the explosion of an aluminum wire in vacuum*, Plasma Phys. Rept. 38 (2012) 1.

[14] D.H. Kalantar and D.A. Hammer, *Observation of a stable dense core within an unstable coronal plasma in wire-initiated denseZ-pinch experiments*, Phys. Rev. Lett. 71 (1993) 3806.

[15] G.S. Sarkisov, S.E. Rosenthal and K.W. Struve, *Transformation of a tungsten wire to the plasma state by nanosecond electrical explosion in vacuum*, Phys. Rev. E 77 (2008) 056406.

[16] A. Grinenko, S. Efimov, A. Fedotov, Y.E. Krasik and I. Schnitzer, *Addressing the problem of plasma shell formation around an exploding wire in water*, Phys. Plasmas 13 (2006) 052703.

[17] B. Ya’Akobi, *The power and energy balance of an electrically exploded wire*, J. Quant. Spectrosc. Radiat. Transfer 9 (1969) 1603.

[18] E. Kaselouris, V. Dimitriou, I. Fitilis, A. Skoulakis, G. Koundourakis, E.L. Clark et al., *The influence of the solid to plasma phase transition on the generation of plasma instabilities*, Nat. Commun. 8 (2017).

[19] S.I. Tkachenko, D.V. Barishpoltsev, G.V. Ivanenkov, V.M. Romanova, A.E. Ter-Oganesyan, A.R. Mingaleev et al., *Analysis of the discharge channel structure upon nanosecond electrical explosion of wires*, Phys. Plasmas 14 (2007) 123502.