Metallic gas resistivity measurements and testing of plasma radial expansion models with an exploding wire.

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Introduction

An exploding wire consists of an electrically conductive wire that is subjected to an electrical current that provokes the wire explosion and conversion into plasma. Destruction of an electric wire by means of a large and fast electrical current, on the order of 10^3 Amperes and with a duration shorter than 10^{-6} s, is well known from the XIX century [1, 2]. In recent times the interest on the exploding wire phenomenon comes from its possible technological uses, like the generation of powders with nanometric dimensions [3], and from the use of megajoules of power in exploding wires systems to generate matter under extreme pressure and temperature conditions [4].

Explosion of a metallic wire by an electrical current is a very dynamic phenomenon, as it transforms the state of the wire from solid metal to plasma and all the intermediate states. When the current starts to be delivered to the wire, it absorbs electrical energy by means of the joule heating, transforming the wire into liquid, gas and finally plasma. With such a rich and profound changes of state, exploding wires are excellent test benches for equations of state of metals under conditions difficult to reach with other experiments. Indeed, there is a large number of scientific works that use an exploding wire setup to either test equations of state of metals or directly to obtain experimental values of constitutive magnitudes of the metals, such as [5, 6, 7].

The dark pause, a halting of the current passing through the wire due to the increased resistivity of the wire metal meanwhile the wire material evolves from metallic gas to plasma, has not been equally addressed. In this work we present the use of the dark pause to obtain limits on the resistivity of the metallic gas through measurements of the voltage and current in addition with optical measurements of the radial expansion of the gas. In order to do so the exploding wire system is placed in atmospheric air and lets free to expand, to avoid any possible reflections that the shock wave could have otherwise. Measurement here presented are still preliminary, and they are the first measurements to be published in the open literature of metallic gas resistivity, to the knowledge of the authors. Also, and taking advantage of the systems used to measure the radial expansion, is presented a study of the dynamical behaviour of the radial expansion of the shock wave and its coincidence with self-similar solutions.

Experimental Setup

Experiments were made with the ALEX system, an exploding wire based on a RLC circuit, see fig. 1. When the capacitors are charged to the desired voltage, the Spark Gap trigger connects the capacitors with the rest of the circuit, including the wire, starting the wire explosion process. Results presented in the work were obtained with Copper wires of lengths of 3.3 and 5.1 cm, and 50 and 100 μm diameters. The longer wires were employed in the exploration of the resistivity of the metallic gas, meanwhile the shorter ones, 3.3 cm, were used in the study of the shock wave expansion. The capacitors bank of 2.2 μF was charged from 5 to 25 kV in 5 kV steps allowing for initial energies values in the range from 27 to 687 Joules. Total circuit impedance has been measured as 150 nH using short circuit signals.

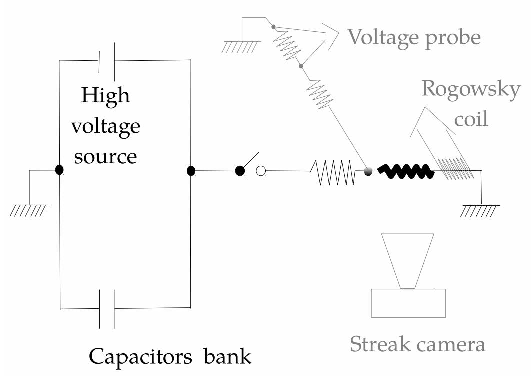

Figure 1: *ALEX electrical and experimental scheme.*

In order to characterize the wire, its current and voltage are measured by a Rogowsky coil and a voltage probe based on a resistive divider, respectively. Both sensors had been designed, constructed and calibrated in the laboratory. These signals are recorded by an osciloscope and latter stored in a computer to further analysis, to obtain the voltage and current that circulates through the wire regardless of its state. To do that, the resistive voltage should be used, eliminating from the measured voltage all the part that corresponds to the circuit, like its general inductance. A typical example of the voltage and current obtained with a dark pause are shown in fig. 2

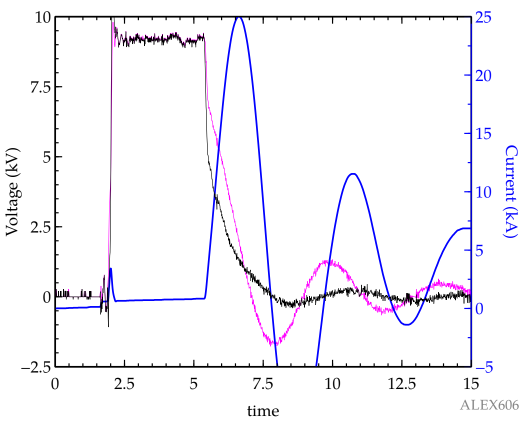

Figure 2: *Electrical measurements on a 50 μm diameter and 5.1 cm copper wire charged at 10 kV. (– Resistive voltage, – Measured voltage) Notice the dark pause in the current signal.*

Dynamics of the plasma and metallic gas ra-

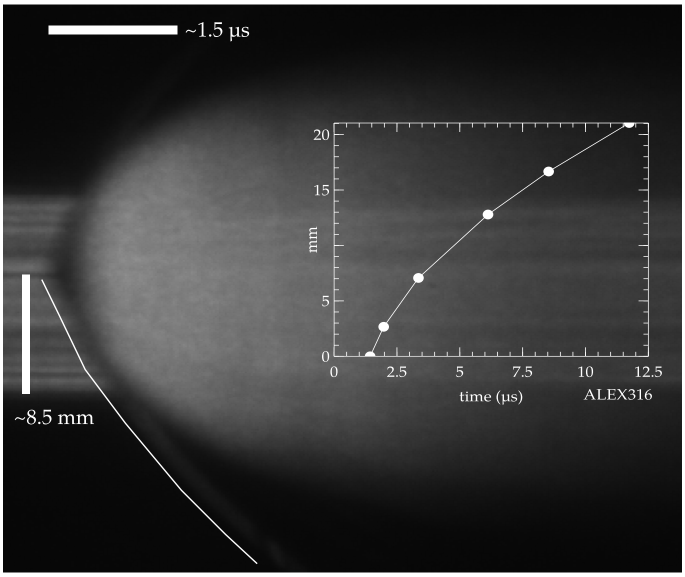

Figure 3: *Streak image of a Copper wire, diameter of 100 µm and charging voltage of 20 kV, with the obtained shock wave over imposed. Notice the different scales o fthe graph and the image. White line is a guide to the eye for the shock wave position. The presence of a short dark pause is clear at the beginning of the expansion.*

dius, in addition to the preceding shock wave are recorded in the streak camera images, thanks to the illumination by a laser light source of the wire, aligned with the camera objective. From these digitized images the radius of the shock wave and the plasma radial expansion are obtained for each experiment. The radial expansion of a shock wave here presented is made with the aggregation of data from different experiments with the same experimental conditions. Figure 3 shows an example of a streak image with the shock wave radial position measured from it.

Results

Using together the voltage and current data with radial expansion measurements of the metallic gas, it is possible to experimentally obtain upper and lower limits for the metallic gas resistivity, shown in fig. 4 in a preliminary form. Although detailed explanations for the calculations of the limits will be published in an ongoing publication, it is worth to mention briefly here the models and assumptions used.

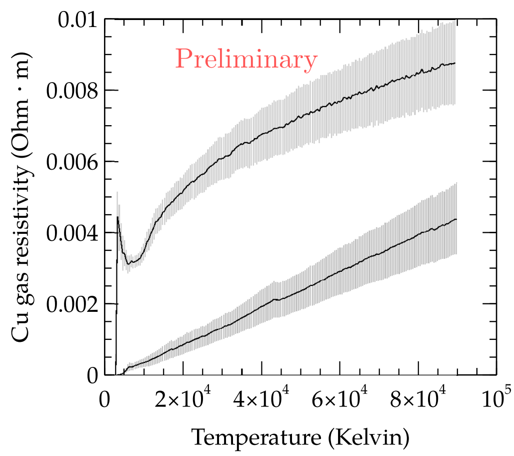

Figure 4: *Copper gas resistivity limits. Preliminary data*

Lower limits are calculated considering that dur-

Voltage	Fitting function	χ^2/ν	R^2	Voltage	Fitting function	χ^2/ν	R^2	Voltage	Fitting function	χ^2/ν	R^2	Voltage	Fitting function	χ^2/ν	R^2	Voltage	Fitting function	χ^2/ν	R^2
5 kV	Self-similar	0.12	0.92	10 kV	Self-similar	0.96	0.97	15 kV	Self-similar	0.90	0.98	20 kV	Self-similar	0.75	0.98	25 kV	Self-similar	0.34	0.99
	Linear	0.84	0.95		Linear	3.30	0.88		Linear	3.30	0.93		Linear	1.30	0.97		Linear	1.30	0.97
	n-exponential	0.85	0.99		n-exponential	0.99	0.96		n-exponential	0.85	0.98		n-exponential	0.41	0.99		n-exponential	0.81	1.00

Table 1: Table with the fitting parameters for the shock wave radial expansion.

ing the dark pause, the wire conversion in gas is not homogeneous, leaving a central core of liquid metal. This structure of the wire explosion must be considered in order to obtain meaningful data [8]. Upper limits for the resistivity can be calculated after some calculations based on the thermodynamics of the conversion from liquid to plasma states of the wire.

The dynamics of a cylindrical strong shock wave had been previously studied [9]. Analytical expressions for cylindrical self-similar expansions there presented indicate that the radius is proportional to the square root of the time($r \propto \sqrt{t}$). Figure 5 shows the radial expansion of a Copper wire with two voltages, and table the χ^2/ν and R^2 values for some models. Of the three models tested, the statistical significance of the "self-similar" and the "n-exponential" is similar for all the situations depicted and only the "linear" expression can be ruled out.

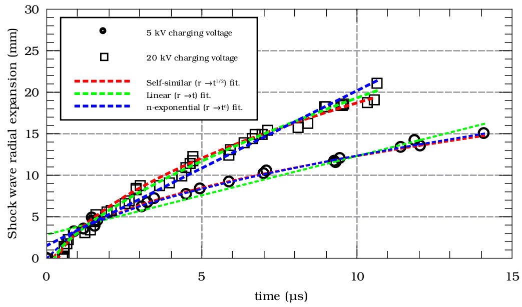

Figure 5: Shock wave radial expansion for a Copper wire with a diameter of 100 μm at two voltages

To summarize this work, two main results are presented. First, a new method to measure the resistivity of a gas by means of an exploding wire has been shown. Also, the dynamics of the shock wave produced in an exploding wire has been explored.

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