

High Velocity Flyer Plate Developments on Two High Pulsed Power Generators Based on a Strip Line Design (GEPI and CEPAGE)

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Abstract— The GEPI machine (*Générateur Electrique de Pressions Intenses*) was the first low inductance high pulsed power (HPP) generator based on the strip line design. It was developed initially for the study of quasi-isentropic dynamic behaviour of inert materials. A maximum current of 3.5 MA can be delivered with a 500 ns rise time. These electrical characteristics allow also the use of GEPI for the projection of plane projectiles (i.e. flyer plates), with velocity over 10 km/s being yet demonstrated.

The new low inductance pulsed power generator CEPAGE (*Conduite d'Eléments Projetés Adaptable par Générateur Electrique*) has been developed to combine transportability, compactness and low cost maintenance. This compactness relies on the use of high energy, low inductive capacitors and switches, holding currently 80 kV and allowing to store more energy, up to 100 kJ. Its size has been optimized to house it in an existing pyrotechnic facility, for performing shock wave experiments on High Explosive (HE) materials with high velocity metal flyer plates of controlled planarity.

We describe the experimental and numerical works, done on these two generators, for high velocity flyer plate projection and characterization.

Index Terms—Electromagnetic launching, flyer plate, high velocity impact, magnetohydrodynamic simulation.

I. INTRODUCTION

High pulsed power generators have shown over the last decade great versatility to cover the scope of isentropic compression experiments. This technology has been recently applied for shock wave experiments and required more research and development to explore all the scope of capabilities. It has to solve key issues, such as planarity and phase changes of flyer plates as a function of the impact velocity.

This paper presents the principles and performances of two low inductance high pulsed power (HPP) generators based on a strip line design GEPI [1]-[6] and CEPAGE [7], with

Manuscript received February 11, 2010. This work was supported by different DGA (French Ministry of Defense) contracts.

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emphasis on specific developments on high velocity flyer plate projection. This technology is very attractive, as neither water, nor oil, nor vacuum are used for high voltage insulation and because Multigap Multi-Channel Switches (MMCS) are operated with dry air, reducing the cost and time for maintenance. These generators have been developed with CEG by the French company ITHPP (International Technologies for High Pulsed Power), in collaboration with HCEI (High Current Electronic Institute) Tomsk, Russia. Preliminary testing and last developments on the GEPI machine, concerning planarity measurements and recovery of flyer plates, are presented. For CEPAGE, we show the feasibility to control and monitor the velocity, actual thickness, and planarity of aluminium flyer plates for different configurations.

II. DESCRIPTION OF THE HPP GENERATORS

A. GEPI generator and strip line configuration

The first version of GEPI went on line in 2001. It's a low inductance generator, initially designed to perform quasi-isentropic experiments on inert materials. A picture is presented Fig. 1. Its overall dimensions are 6 m x 6 m x 2.3 m.

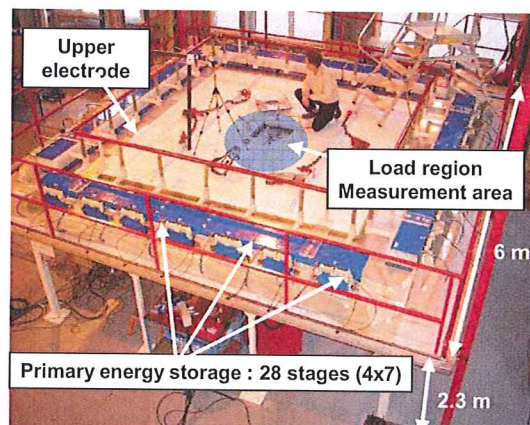


Fig. 1. General overview of GEPI generator

The primary storage is made of 28 stages connected in parallel, and triggered simultaneously. The total energy stored is around 70 kJ for an 85 kV charging voltage. The total capacitance is 19 μ F. Each stage holds 4 caps and a low inductance multi-gaps multi-channels (MMCS) switch. These

switches are working at atmospheric pressure, with simple dry air blowing.

The trigger system is divided into two subsystems located under the platform, which trigger 14 stages each. A strip line connects the 28 stages to the load. Dielectric insulation is made with Mylar and Kapton films, allowing minimal inductance. In 2002, an electric improvement was performed by adding peaking capacitors. A simplified electric schema of this new configuration is given Fig. 2, which increases the peak current, and improve the current shape in order to push away shock formation when pressure waves propagate into the materials. With these peaking capacitors, the current reaches from 2.8 to 3.5 MA in 500 ns depending on the load geometry.

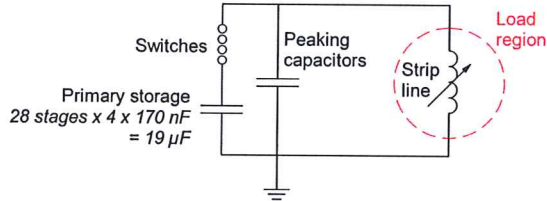


Fig. 2. Schematic electric diagram of GEPI in its final configuration.

A scheme of the load region is shown in Fig. 3. The current coming from the stages flows to the centre of the generator and is concentrated in the load strip line, concentrating the magnetic field in this area.

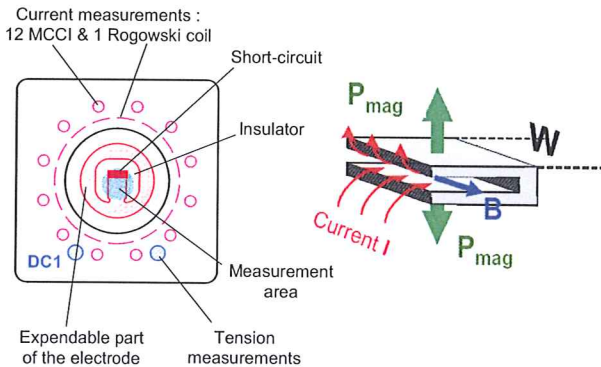


Fig. 3. a) Illustration of the load region, b) with the principle of strip line configuration.

The theoretical magnetic pressure in the strip line is given by

$$P_{mag} = k_p \frac{B_{th}^2}{2\mu_0} = k_p \frac{\mu_0}{2} \left(\frac{I}{W} \right)^2 \quad (1)$$

where k_p is the edge effect coefficient, B_{th} the magnetic field in a theoretical strip line, μ_0 the free space magnetic permeability, I the current and W the width of the strip line. Coefficient k_p is mainly a function of the effective gap out of the width. This effective gap is the real gap plus a mean skin depth of the magnetic field [3]. During the current pulse, as the electrodes move and the magnetic field diffuses inside, the effective gap at the peak pressure can be much larger than the initial gap. Therefore, for high pressure shots, the maximum pressure can be reduced to more than 30% compared to the ideal one. Typical current and tension wave forms are exemplified Fig. 4.

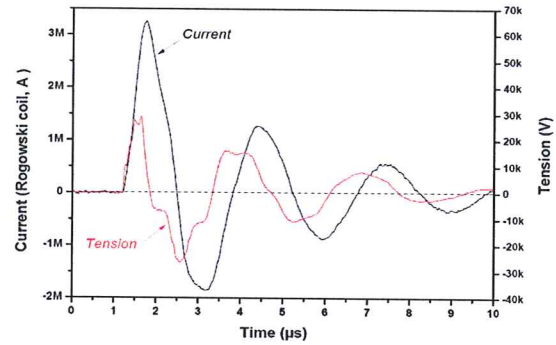


Fig. 4. Tension and current wave forms for a CuAl strip line, $W = 30$ mm. All 28 stages used and charged at 80 kV. Current measured with Rogowski coil. Tension measured at DC1 point (see Fig. 3a).

The high pressures (1 GPa to 100 GPa on GEPI) obtained with the strip line configuration can be used to propel non-shocked flyer plates at very high velocities [4] [8-10].

B. CEPAGE generator

CEPAGE is illustrated Fig. 5. It is also a low inductance pulsed power generator based on a strip line design with coaxial MMCS. The qualification tests ended in April 2009. Based on a transportable platform to perform experiments in an existing pyrotechnic test facility, it's a very compact generator with overall dimensions of 3.5 m x 2.5 m x 2.5 m, including utility subsystems (120 kV trigger system, power supply, remote control unit, etc.).

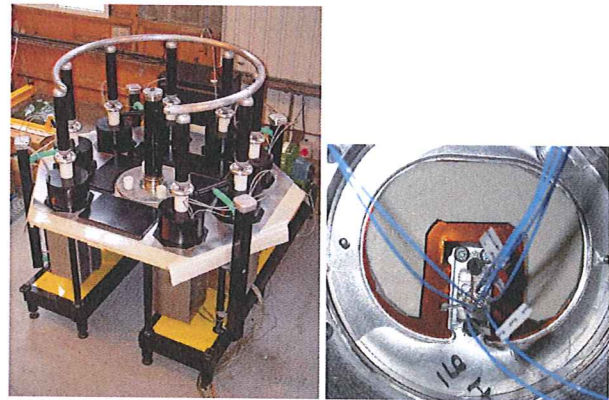


Fig. 5. a) General view of CEPAGE generator and b) view of an instrumented strip line for flyer plate experiments.

The circular design of GEPI load has been applied for CEPAGE. The load is located in the center of the generator surrounded by 8 low inductance MMCS connected to 8 Trench capacitors (4 μ F, 10 nH, 90 kV). The current flows, via the upper platform transmission line, from the capacitors to the loading region. Compared to the previous compact generator developed in 2005-2006, called VELOCE [11-12], CEPAGE is a direct drive scheme without peaking capacitors and sharpening switches. The MMCS have been improved to hold 90 kV on a single test bed, allowing CEPAGE to operate at 80 kV. Depending on the strip line width and on the capacitor voltage, the current reaches between 3.0 to 3.7 MA with a rise time of 550 ns. The maximum stored energy is about 100 kJ.

III. STRIP LINE GEOMETRY

The strip line geometry has evolved over the years, as illustrated in Fig. 6.



Fig. 6. Evolution of the strip line geometry. Major improvements have been achieved with type III regarding pressure homogeneity.

Type III, firstly tested in 2008 on GEPI, has greatly improved the pressure homogeneity in the central part of the electrodes, a critical parameter for the quality of flyer plate experiments. Thus type III is used at present on both generators. The electrodes are made of aluminum or copper. They are insulated with a stack of 50 μm Mylar and/or 25.4 μm Kapton films, to obtain an inter-electrode gap from 0.4 to 0.5 mm. The lower electrode is generally a symmetric of the upper one and thus shares exactly the same magnetic pressure loading, allowing reference measurements to be made. The last type III design has the following specific features:

- the electrodes are machined directly from thick plates to limit electric connecting parts and give good mechanical stiffness,
- a step (1 mm x 1 mm) is machined on the inner sides to limit current flowing on the edges,
- the gap between the 2 electrodes is controlled by a shorting peg perpendicular to the current flow, which act as a short-circuit at the end of the strip line,
- notches located at the entrance of the strip line have optimized radius to force current homogenization.

Experiments correlated with magneto hydrodynamic simulations [13-14] have demonstrated the critical influence of parameters such as peg's height or inner surface planarity of the electrodes. Tolerances of the order of $\pm 20 \mu\text{m}$ are aimed on these critical dimensions in order to secure pressure homogeneities better than $\pm 2\%$ in the central useful part.

IV. HIGH VELOCITY FLYER PLATES EXPERIMENTS

A. GEPI experiments

The highest velocities so far obtained on GEPI, have been reached on aluminium samples during exploratory experiments, as illustrated Fig. 7.

The strip line width was 6 mm and the initial sample thicknesses were 0.40 mm and 0.90 mm. Velocity measurements were done with VISAR interferometers [15]. The stabilized velocity on the thick sample was 7.65 km/s. The thin sample reaches 10.24 km/s before extinction of the VISAR signal. As the pressures applied to the two samples were the same, the stabilized velocity of the thin electrode has been calculated to be around 17 km/s.

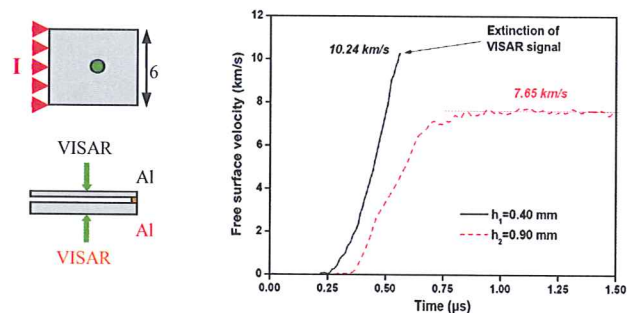


Fig. 7. High velocity Al flyer plates obtained with type I strip lines of 6 mm width (W). Initial sample thicknesses were 0.40 mm and 0.90 mm.

Planarity and recovery experiments with type III strip lines, have recently been done on “low” velocity flyer plates, using IDF-PDV velocity interferometers [16-17] to perform 4 points measurements. Fig. 8 illustrates the good planarity of the flyer during its flight, up to its stabilized velocity. Recovery was obtained by “braking” flyer into low density foam, and stopping it into water. Its metallographic characteristics are thus “frozen” and analyses of phase transitions (solid-liquid-vapor) will aid to tune magneto hydrodynamics numerical models.

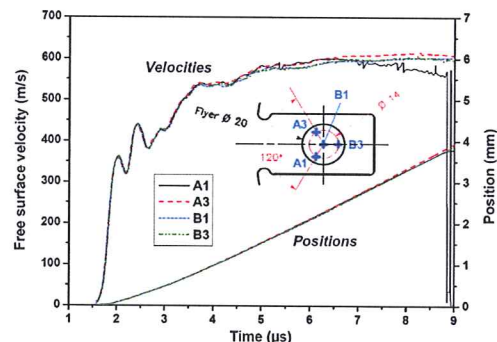


Fig. 8. Four points velocity and displacement measurements on a type III CuAl stripe line $W = 30 \text{ mm}$

Hypervelocities tests ($v > 7 \text{ km/s}$) are in preparation, using upgraded IDF-PDV velocimeters and very high frame camera (Imacon 200) to visualize flyer during its first millimeter's course.

B. CEPAGE experiments

The velocity of Al flyers is measured directly using VISAR interferometers. The final flyer thickness is determined by recording the velocity and duration of a shock produced by the impact on an Al target backed by a LiF window. The planarity is measured using optic fibers located behind the Al target and recorded with a streak camera (Fig. 10).

The shock experiments depend on the following parameters: charging voltage, width (W), length (L), initial thickness of the flyer, radius of the notch, flight distance and Al target thickness. The optimization of electro technical and geometrical parameters has significantly improved the control of the velocity, final thickness and planarity of the flyers.

For the 20 mm diameter configuration (Fig. 9 and 10), the

impact velocity of 3000 m/s has been achieved with a tilt near 1 mrad on 16 mm diameter, and a sustained shock duration of 86 ns. For the 10 mm diameter configuration (Fig. 11 and 12), the impact velocity of 6400 m/s has been obtained with a tilt near 3 mrad on the longitudinal axis and a sustained shock duration of 12 ns.

Different numerical simulation tools are used to explain and predict experimental results. MHD calculations are essential to follow the actual phases transition of the drive due to the high current flow: solid – liquid, liquid – boiling and boiling – vapor plasma. MHD calculations with the 3 MA GEPI generator was used for the ICE configurations and gave good results on copper [14]. For the 20 mm diameter configuration, the comparison between CEPAGE experiments and 1D MHD calculations is presented Fig. 10 on aluminum using Sesame tables. The EOS and electric resistivity are taken from Sesame tables n°3717 and n°23715 [18]. We get good agreement between experiment and numerical simulation.

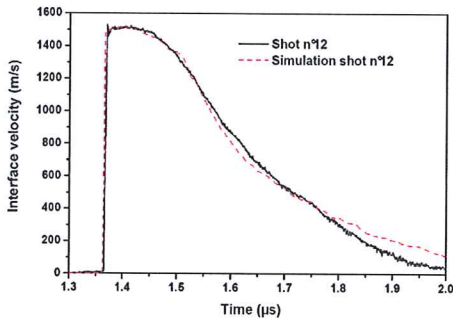


Fig. 9. Target velocity with type III Al strip line, Voltage 78 kV, W = 24 mm, L = 42 mm, Notches radius 2.5 mm, initial flyer and target thicknesses 1.008 mm and 0.485 mm, flight gap 1.755 mm. 1D MHD calculation using measured current and Sesame tables.

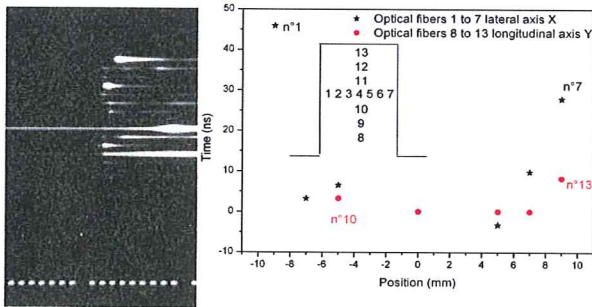


Fig. 10. Planarity measurement with type III Al strip line, Voltage 75 kV, W = 30 mm, L = 50 mm, Notches radius 3 mm, initial flyer and target thicknesses 0.553 mm and 0.49 mm, flight gap 2.95 mm.

a) The arrival of the shock behind the Al target ionize the air, generating light collected by an array of optic fibers and recorded by a streak camera. b) Planarity at impact is recorded on the longitudinal and transversal axis.

For the 10 mm diameter, the current density is about 4 times higher. The 1D MHD simulations are ongoing to check the key issues related with this configuration : mesh size effect, current flow between electrode and flyer during “punching”, magnetic field influence on target before impact, effect of EOS and electric resistivity modelisation, numerical scheme for the differential calculation during phase changes, etc.

A classical 1D hydrocode (Godlag [19]) is used to estimate

the ideal dense Al flyer, in order to get the same target velocity and shock duration of the experiment. For shot n°9 (Fig.12), simulation gives an ideal solid Al flyer thickness of 140 μm for a 6400m/s impact velocity, based on VISAR A measurement.

Preliminary designs of the experiments were performed using a MHD code called MP1D. This 1D MHD code developed by ITHPP, using analytical laws for multiphase EOS [20] and resistivity calculations [21]. It is coupled to the well known circuit solver SABER used to integrate the whole RLC circuit. The calculated drive velocities show good agreement with the experimental results (Fig. 11), using a validated geometric dependence of k_p coefficient (see formula (1)). This k_p formulation was built upon 1D code simulations without SABER code, but using numerous experimental measurements of current and velocity profiles.

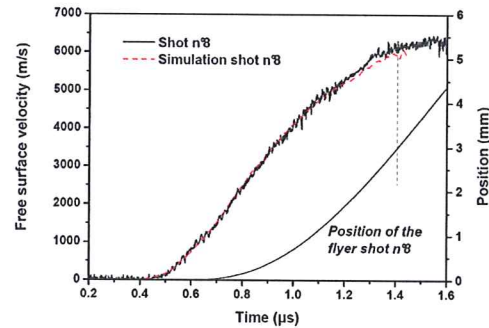


Fig. 11. Flyer velocity with type III Al strip line, Voltage 75 kV, W = 15 mm, L = 27 mm, Notches radius 1.2 mm, initial flyer and thickness 0.74 mm. MP1D MHD numerical prediction using SABER circuit solver, without assumption on current wave shape.

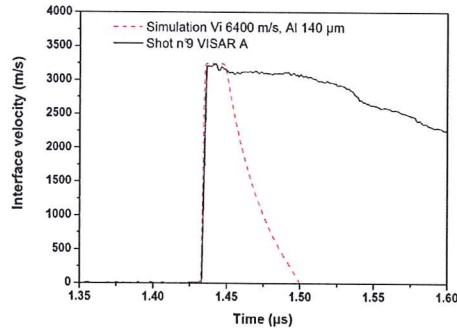


Fig. 12. Target velocity with type III Al strip line, Voltage 75 kV, W = 15 mm, L = 27 mm, Notches radius 1.7 mm, initial flyer and target thicknesses 0.72 mm and 0.3 mm, flight gap 3.13 mm. Godlag 1D hydrocode simulation for an ideal 140 μm thickness solid flyer.

V. CONCLUSION

GEPI and CEPAGE have shown their capabilities as operational facilities for shock wave experiments with high impact velocities. Pulsed power generators based on a strip line design are very attractive and versatile technologies to cover the scope of isentropic compression and shock wave experiments. Research is in progress to characterize the planarity and phase changes of the flyer as a function of impact velocities.

MHD numerical simulation efforts are pursued to take into

account the more challenging high current density configurations. Especially to take into account with increased accuracy the effects of liquid-vapor phase transitions and ruptures, even in liquid phase.

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He then joined the company International Technologies for High Pulsed Power (ITHPP), acting consecutively as computational scientist, mechanical officer and project manager. His technical experience includes the development of numerical tools, such as a 1D MagnetoHydroDynamic code, and the design of HPP devices. A significant part of his work has been dedicated to high current generators for experiments on isentropic compression and high strain rates in metals.



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