

# Ramp compression of a metallic liner driven by a shaped 5 MA current on the SPHINX machine

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**Abstract.** SPHINX is a 6MA, 1- $\mu$ s Linear Transformer Driver operated by the CEA Gramat (France) and primarily used for imploding Z-pinch loads for radiation effects studies. A method for performing magnetic ramp compression experiments was developed using a compact Dynamic Load Current Multiplier inserted between the convolute and the load, to shape the initial current pulse. We present the overall experimental configuration chosen for these experiments and initial results obtained over a set of experiments on an aluminum cylindrical liner. Current profiles measured at various critical locations across the system, are in good agreement with simulated current profiles. The liner inner free surface velocity measurements agree with the hydrocode results obtained using the measured load current as the input. The potential of the technique in terms of applications and achievable ramp pressure levels lies in the prospects for improving the DLCM efficiency.

## 1. Introduction

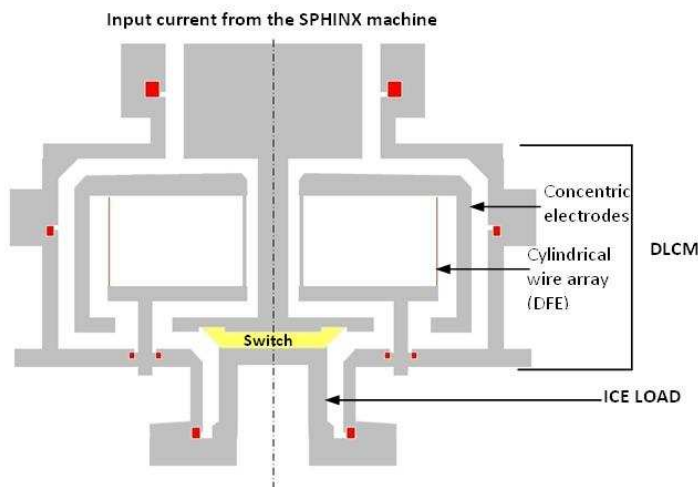
Over the last decade, numbers of magnetically driven Isentropic Compression experiments (ICE) have been conducted, mostly on the Z accelerator at Sandia National Laboratories [1-4], on the GEPI generator at the Centre d'Etudes de Gramat- France (now CEA Gramat) [5, 6], and on the compact VELOCE power generator, also operated at Sandia [7]. Prior to obtaining the desired current pulse shape for a specific material, the natural pulse produced by the generator needs to be tailored. On the Z accelerator, this operation is realized through complex staggered discharge of multiple switches [8] guided by extensive Magneto-Hydro-Dynamic (MHD) and Particle in Cell (PIC) simulations.

In this paper, we present an approach that requires no change to the generator discharge scheme, and utilizes a very compact pulse-shaping Dynamic Load Current Multiplier (DLCM) inserted in vacuum between the convolute and the ICE load for achieving magnetic ICE on the SPHINX 6MA microsecond Linear Transformer Driver [9]. We report the results of an initial set of experiments on a cylindrical aluminum liner.

## 2. Dynamic Load Current Multiplier

The conceptual diagram of the DLCM [10] is represented in figure 1.





**Figure 1.** Conceptual diagram of the Dynamic Load Current Multiplier. The main components of this system are: 1) a network of concentric electrodes which serves as a self-transformer and current multiplier, 2) a Dynamic Flux Extruder (DFE) made of a cylindrical wire array whose implosion creates a variable impedance enabling current pulse shaping, and 3) a closing switch located upstream of the load which steepens the current rise front.

The DLCM can be operated either with a switch whose triggered closure at a desired time enables current transfer to the load, or without switch, in which case the current transfer is achieved based on inductive division. Different types of loads can potentially be connected to this DLCM, including Z-pinch loads and solids for magnetic ramp compression experiments. Both planar and cylindrical ICE load geometries can be studied this way.

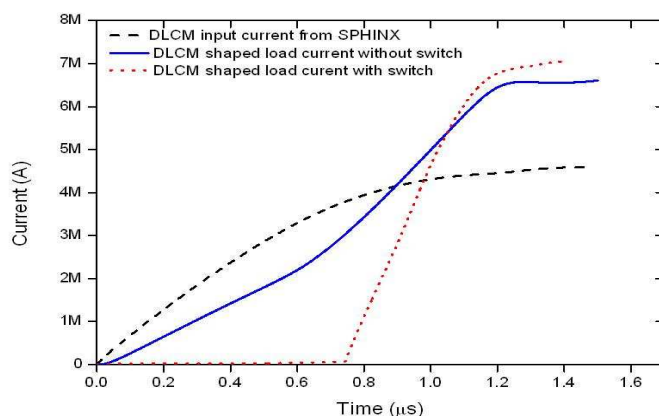
While efforts are underway to develop a DLCM system equipped with a closing switch, the present study was carried out in the microsecond regime, using a cylindrical liner directly connected to the DLCM exit, without closing switch.

### 3. Numerical simulations

#### 3.1. GORGON simulations

The DLCM overall operation was simulated using the MHD 3-D code GORGON [11] in order to predict the load current profile. An equivalent circuit model was coupled to this code to reproduce the current delivered by the SPHINX generator. The GORGON code, which simulates the implosion of the wire array of the Dynamic Flux Extruder (DFE), also calculates the spatiotemporal distribution of both electric and magnetic fields across the system.

Simulations of the DLCM input current pulse delivered by the generator and the shaped current delivered to the load were carried out for a DLCM operated with and without closing switch.



**Figure 2.** Current profiles simulated with the MHD code GORGON. These outputs correspond to a wire array made of 200 aluminum wires (12.7  $\mu\text{m}$  diameter and 43 mm height) and a 5 mm diameter, 16 mm height aluminum cylindrical load.

Figure 2 shows an example of simulated shaped currents in a cylindrical load. When the DLCM is operated with a switch, no current flows through the load until the switch is closed. Upon switch closure, the load current rises within a shorter time and with higher amplitude compared to the initial current delivered by the generator.

If the DLCM is used in direct drive mode without switch, the load current rise front displays an initial slow increase followed by a steeper rise. This inflection in the load current profile occurring at about  $0.6\mu\text{s}$  indicates the onset of wire array compression. At this point, the current transfer to the load becomes more efficient as the DFE to load inductance ratio increases sharply. With the experimental parameters considered here, assuming no current loss, the shaped peak current should be approximately 6.5 MA when the machine is fired at a charging voltage of 50 kV. Parametric simulations show that this current profile can be further modified, depending on the desired ramp profile, by adjusting various parameters in the DFE, such as inductance (length of the wires) and mass (number of wires). For instance it appears from simulations presented elsewhere [12], that a ~50 percent reduction in the wire length (the total mass is kept constant by a commensurate increase in the wire diameter), delays the onset of compression by ~120 ns. On the other hand, these simulations suggest that for a given value of inductance, the current rise time, during the wire array implosion, may be tuned by varying the mass of the DFE.

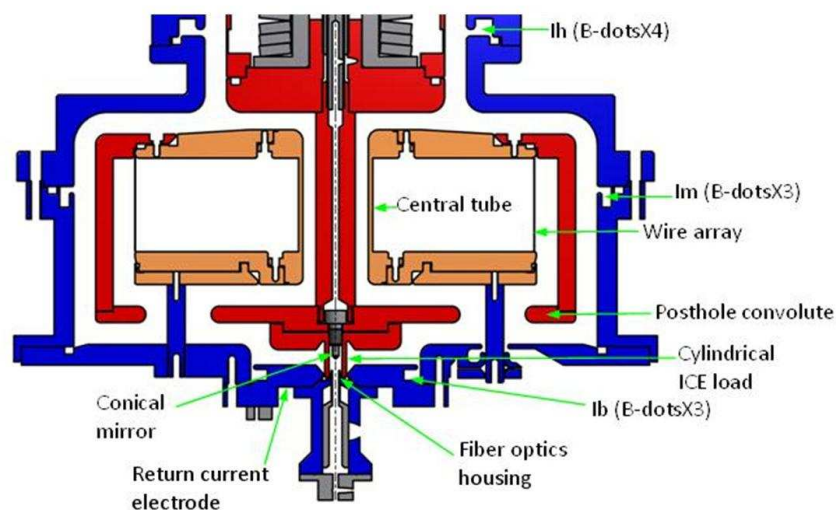
### 3.2. UNIDIM simulations

Using the load current profile from the GORGON simulations as the input, the magnetic loading of the aluminum liner is simulated using the UNIDIM [13] 1D Lagrangian hydrodynamic code developed at the CEA Gramat. This code, based on a finite-difference method solves Maxwell's equations and simulates both the magnetic diffusion and stress wave propagation.

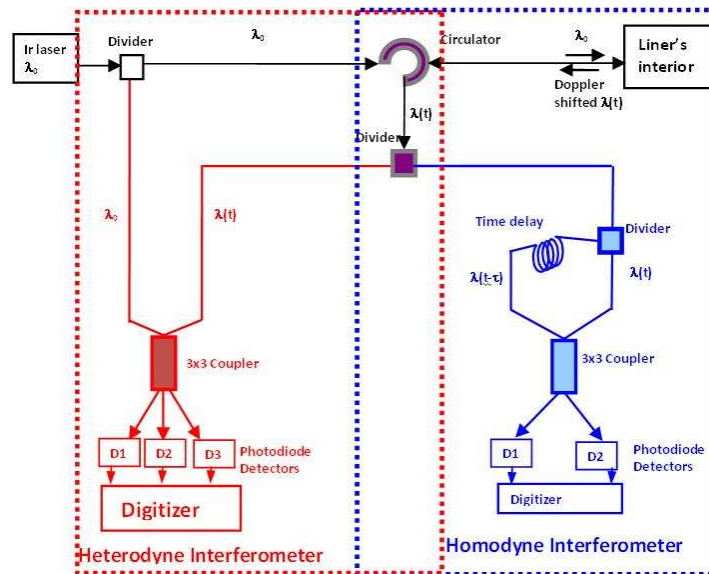
The output of the UNIDIM hydrodynamic code is valuable for designing the load experimental configuration. The UNIDIM code also serves for a detailed quantitative hydrodynamic analysis of the experimental data. Using the measured load current as the input, the inner free surface velocity profile is calculated and compared to the experimental velocity profile.

## 4. Experimental configuration

The overall experimental configuration is shown in figure 3. The upper part is made of the DLCM electrodes and the wire array of the DFE. The lower part, from the post-hole disc onwards, is comprised of the ICE load unit, the return current electrodes and the housing for the fiber optics head for velocimetry.



**Figure 3.** Sectioned view of the experimental setup.



**Figure 4.** Schematic of the interferometer setup.

In the present study, the load outer and inner radii were 5 mm and 3 mm, respectively and the corresponding 2 mm thickness was constant along a 16 mm length. Current measurements were fielded at multiple critical locations along the current circulation path, using both B-dot and Rogowski current probes. Upstream of the SPHINX main convolute, Rogowski coils are used to measure the current delivered by the generator to the DLCM ( $I_g$ ). Just upstream of the DLCM, four B-dot measurements  $I_{h1}$  to  $I_{h4}$  are carried out within the upper primary return current electrode. Within the DLCM, three B-dot measurements, noted  $I_{m1}$  to  $I_{m3}$  are carried out half-way down the outer loop of the transformer. The load current is measured with 3 B-dots probes ( $I_{b1}$  to  $I_{b3}$ ) located downstream of the liner within its return current conductor.

In order to measure the inner surface velocity over a broad timeline, a laser interferometer using both the homodyne (similar to Velocity Interferometer System for Any Reflector, VISAR [14]) and the heterodyne (Photon Doppler Velocimeter, PDV [15]) techniques was fielded based on the diagram shown in figure 4.

The interferometers use a single continuous wave 1550 nm laser directed via a fiber-based optical circulator (OZ-optics, Inc) onto the inner surface of the liner by a conical reflector.

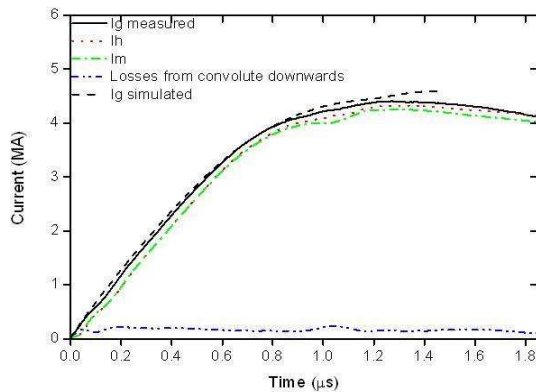
A 8 mm diameter focusing optical head with a 50 mm focal length and 0.14 numerical aperture was used in the first experiment. It was later replaced by a collimated fiber of same diameter resulting in a 600  $\mu\text{m}$  diameter illuminated spot on the conical reflector. The latter was machined on the tip of a 3mm diameter stainless steel rod designed as an extension of the screw which binds the top of the load unit to the DLCM posthole disc. The probed region on the liner inner wall is 0.3 mm height.

## 5. Results and discussion

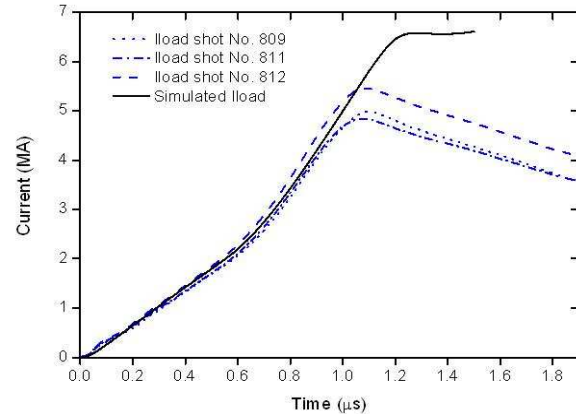
A set of data were obtained over three shots (No. 809, 811 and 812) driven with the generator fired at 50 kV charging voltage.

### 5.1. Electrical diagnostics

Figure 5 shows the current profiles measured upstream ( $I_g$ ), and in the upper and middle parts of the DLCM ( $I_h$  and  $I_m$  are obtained by averaging the  $I_{hi}$  and  $I_{mi}$  values) in shot No. 812 (similar profiles are obtained in the other 2 shots).



**Figure 5.** Current profiles measured upstream ( $I_g$ ), and in the upper ( $I_h$ ) and middle ( $I_m$ ) parts of the DLCM for shot No. 812.



**Figure 6.** Measured load current shaped by the DLCM in all three experiments. The simulated load current provides an estimate of current losses.

The input current from the generator simulated with the equivalent circuit model in the code GORGON is also shown. A reasonable agreement is found between the simulated and measured current upstream of the DLCM.

The simulated and measured load currents in all three shots are shown in figure 6. The significantly higher load peak current obtained by simulation (6.56 MA) suggests the existence of current losses within the DLCM, upstream of the ICE load.

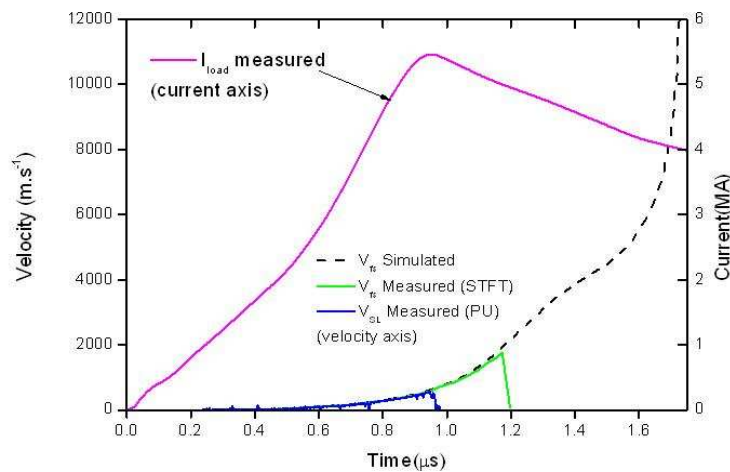
### 5.2. PDV diagnostic

The homodyne interferometer did not yield any exploitable signal throughout the experiments, while the heterodyne measurements were successful in two shots out of three. The heterodyne data obtained in shots No. 811 and 812 was processed using both the Short Time Fourier Transform (STFT) and the Phase Unwrapping (PU) techniques [16]. Figure 7 shows the experimental velocity profile extracted from the PDV signal up to 1.17  $\mu$ s for shot No. 812. The result for shot No. 811 is similar. Beyond this time the signal was significantly deteriorated, most likely because the surface velocity reached the limit of the detection system bandwidths. Further improvements in the surface treatments of the mirror and the liner have since been undertaken to enhance the intensity of the light return in order to achieve simultaneous homodyne interferometric monitoring of the surface velocity in future experiments.

### 5.3. Hydrodynamic analysis

Using the experimental load currents as the input, hydrodynamic simulations are carried out using the code UNIDIM. As can be seen in figure 7 for shot No. 812, experimental and calculated free surface velocities are in good agreement over the signal acquisition timescale. The same agreement is found for shot No. 811. The inner surface velocity is simulated up to its arrival time on the cylinder axis (1.75  $\mu$ s). Due to the deterioration of the light detection from the inner surface, the experimental velocity profile could not be extracted beyond 1.17  $\mu$ s.





**Figure 7.** Surface velocities from PDV and from simulation using the measured load current as the input to the hydrocode UNIDIM for shot No 812. According to these simulations, the inner surface peak velocity was  $14500 \text{ m.s}^{-1}$  at the end of the implosion ( $1.75 \mu\text{s}$ ), when its trajectory reached the cylinder axis. The inflection in the simulated velocity profiles around  $1.3 \mu\text{s}$ , seems to correspond to the load current reaching a maximum  $\sim 300 \text{ ns}$  earlier, which is about the transit time across the  $2 \text{ mm}$  thick liner.

## 6. Conclusion

A magnetic loading technique was developed for quasi-isentropic compression experiments on the SPHINX microsecond Linear Transformer Driver. This technique is based on current pulse shaping using a compact DLCM. In the present work, the latter was used in a microsecond regime, with a cylindrical load directly connected to its exit, without closing switch.

The fielded electrical diagnostics were valuable for tracking the current circulation across the DLCM unit and accurately measuring the ICE load current. The latter was extremely useful for the post-shot hydrodynamic analysis. The free surface velocity measurements agreed well with free surface velocities calculated using the experimental load current as the input to the hydrocode. Further improvements are underway to monitor the inner surface velocity over a longer timescale using homodyne velocimetry. Efforts are underway at the CEA Gramat to further develop magnetic loading techniques and related diagnostics capabilities.

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