UPDATE ON PHELIX PULSED-POWER HYDRODYNAMICS EXPERIMENTS AND MODELING

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Abstract

The PHELIX pulsed-power driver is a 300 kJ, portable, transformer-coupled, capacitor bank capable of delivering 3-5 MA, 10 μs pulse into a low inductance load. Here we describe further testing and hydrodynamics experiments. First, a 4 nH static inductive load has been constructed. This allows for repetitive high-voltage, high-current testing of the system. Results are used in the calibration of simple circuit models and numerical simulations across a range of bank charges ($\pm 20 < V_0 < \pm 40$ kV). Furthermore, a dynamic liner-on-target load experiment has been conducted to explore the shock-launched transport of particulates (diam. ~ 1 μm) from a surface. The trajectories of the particulates are diagnosed with radiography. Results are compared to 2D hydro-code simulations. Finally, initial studies are underway to assess the feasibility of using the PHELIX driver as an electromagnetic launcher for planer shock-physics experiments.

I. INTRODUCTION

Pulsed-power, magnetically driven shock physics experiments offer certain advantages when compared to high explosive drive. First, the energy in a capacitor bank can be varied with voltage such that precise, variable drive strength can be achieved. Second, diagnostic X-ray imaging is simpler since magnetic fields are invisible to X-rays in contrast to high explosives that add additional areal density. Finally, since the energy can be initially stored at some distance from the experiment and electric current can be delivered via a transmission lines, collateral damage and confinement are simpler.

Typically, capacitor-bank, pulsed-power facilities that deliver MAmp currents are large fixed installations within a large laboratory. In contrast a small-scale system with comparable performance is more adaptable to a variety of experiments and requires less capital investment. The Precision High Energy-density Liner Implosion Experiment (PHELIX) is just such a system[i,ii]. It is a portable and can be operated at a fixed diagnostic facility (e.g. proton radiography) or in a small, dedicated laboratory. It can produce multi-MAmp current pulses into low inductance loads. Cylindrical liners or planer flyer plates can achieve km/s velocities and kbar pressures. A schematic of PHELIX is shown in Figure 1. Each of the two capacitor banks stores ~150 kJ of energy. A set of 40 coaxial cables (not shown) delivers a total peak current of I ~ 1MAmp to the toroidal transformer where their inner conductor forms the primary winding. The whole system resides on a transportable palette that is enclosed within an EMI shielding box.

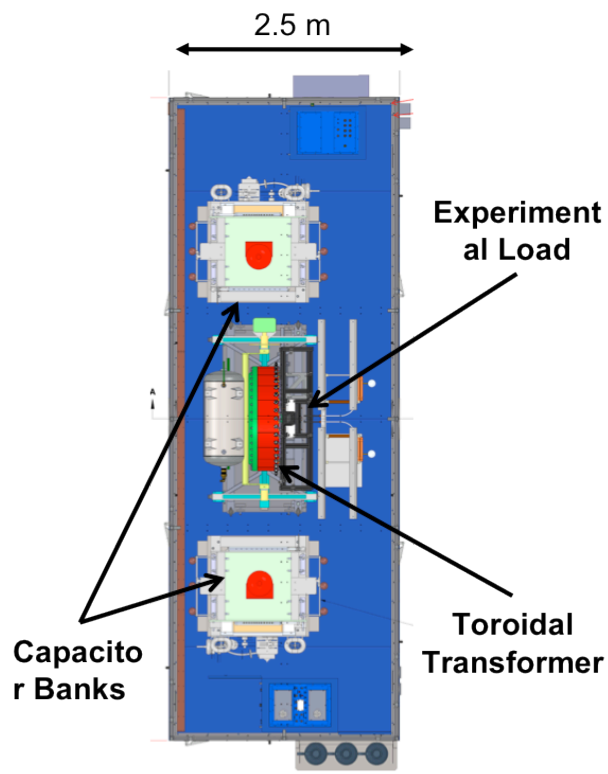

Figure 1. Schematic of the PHELIX portable pulsed-power system.

II. TOROIDAL TRANSFORMER

The key technology to achieving high-current pulses with a small footprint is a toroidal current step-up transformer. The toroidal geometry confines magnetic flux self-consistently and keeps losses to a minimum. In this design, 40 coaxial cables form a multi-filar, four-turn primary winding. The torus is divided into twenty, 18° segments for ease of fabrication. Two cables per segment are wound four times onto a 3D-printed, internal, helical support. The single turn secondary winding and radial

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transmission line is formed from an aluminum, monolithic base-plate, the aluminum shells of the twenty segments, and a smaller aluminum top-plate. The whole structure keeps the magnetic field confined within the transformer. A static or dynamic load is installed in the center of the transformer for experiments. A schematic of the system is shown in Figure 2.

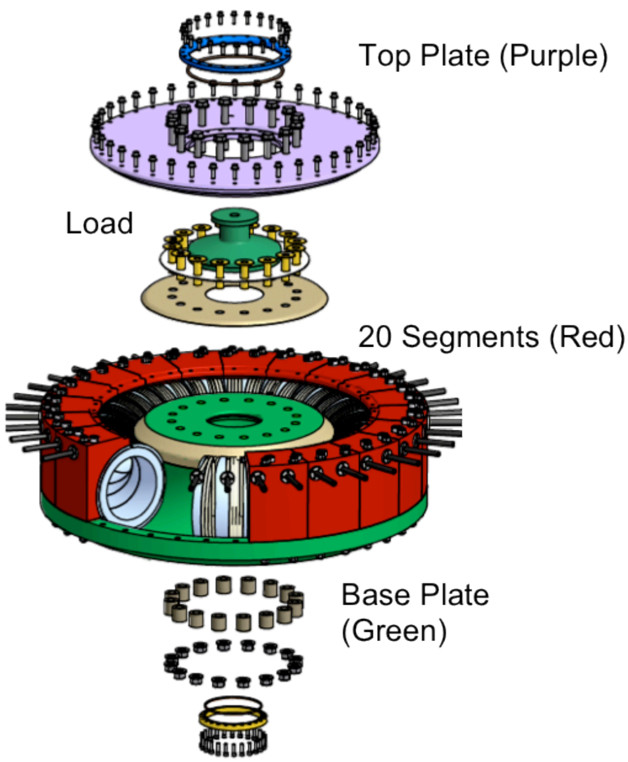

Figure 2. Schematic of the PHELIX transformer.

III. PHELIX PERFORMANCE

The PHELIX system performance is evaluated by installing a static inductive load. This provides a 4 nH inductance that can be incorporated into an analytical circuit model and compared to experiment. In this analysis the standard two-loop circuit model is reduced to a single-loop by replacing the transformer coupling with a single effective inductance of 160 nH. For diagnostics, two optical Faraday rotation fibers are incorporated into the top plate of the transformer accurately measure the load current to within one-percent. As an example, the 68 μF capacitor bank is charged to 80 kV. A 25 mΩ damping resistor is also present to protect the capacitors from extreme voltage reversals. Figure 3 compares the data with an analytic solution to a series LRC circuit, and to a numerical solution of the tranformer circuit equations. Due to the negligible resistance (<0.5 mΩ) in secondary winding the two-loop transformer model and the single-loop model compare well to the data.

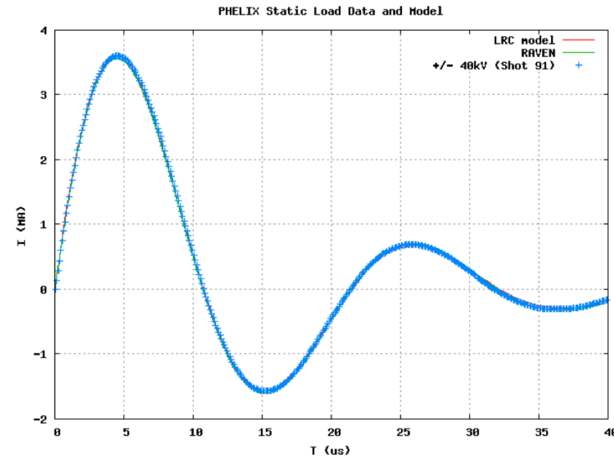

Figure 3. Circuit model and measured PHELIX static load current.

Figure 4. Static and dynamic flash X-radiographs of PHELIX liner system. The central measuring unit (CMU) holds fiber optic probes for velocimetry.

IV. PHELIX LINER SYSTEM

The static inductive load is replaced by a dynamic one-shot liner system. Flash X-radiography of a thin-walled, cylindrical liner system shown in **Figure 4**. On the top, the T = 0.0 μs, static image shows the liner (0.8 mm thick) at its initial radius of R = 2.7 cm. The central measuring unit (CMU) holds twelve fiber optic probes for a photon-Doppler-velocimetry (PDV) diagnostic. The probes are arrayed along both the axis (3-stations) as well as azimuth of the inner surface of the liner.

On the bottom, the liner at T =14.5 μs, the liner is traveling ~0.8 km/s. It reaches a peak velocity of over 1 km/s before it hits the CMU. Load current is, once-again, measured by the optical Faraday rotation diagnostic. It showed a peak of 4.1 MAmps in a ~ 10 μs pulse.

V. SHOCK IMPACTOR IN CYLINDRICAL GEOMETRY

The PHELIX liner system can be used as an impactor for shock-physics experiments in cylindrical geometry. In Figure 5, a simulation of the liner-on-target system is shown. The T = 0.0 μs is show at the top. The liner maintains electrical contact through axial copper glide planes (GP) shown in red. In order to diagnose the experiment with axial proton radiography, the central portion of the Cu GP has been replaced with an Al insert shown in green. This allows the proton beam to enter the load, interact with the target, and pass through to the magnetic lens and imaging system. The bottom portion of the computational domain is colored by pressure.

In the bottom frame of Figure 5, at T = 25.0 μs, the liner has collided with the target and propelled it into the field of view of axial radiography. The inserted plot shows the velocity profile of both the liner (green trace) and target (red trace) inner surface. While there is a significant amount of bowing of the target at the GP interface, ~1.5 cm of the target remains planer. Also, while a significant 2D shock structure is launched by the impact of the liner on the target into the GP assemblies, the reverberations dissipate without causing damage to the GP.

It should be pointed out that a similar liner-on-target configuration with a fluid intermediary (such as water) between the liner and target could produce a shockless drive in the target. In this configuration the target is loaded to strains ~100% with strain rate ~10^5 s^{-1} and peak pressures of 5 kbar.

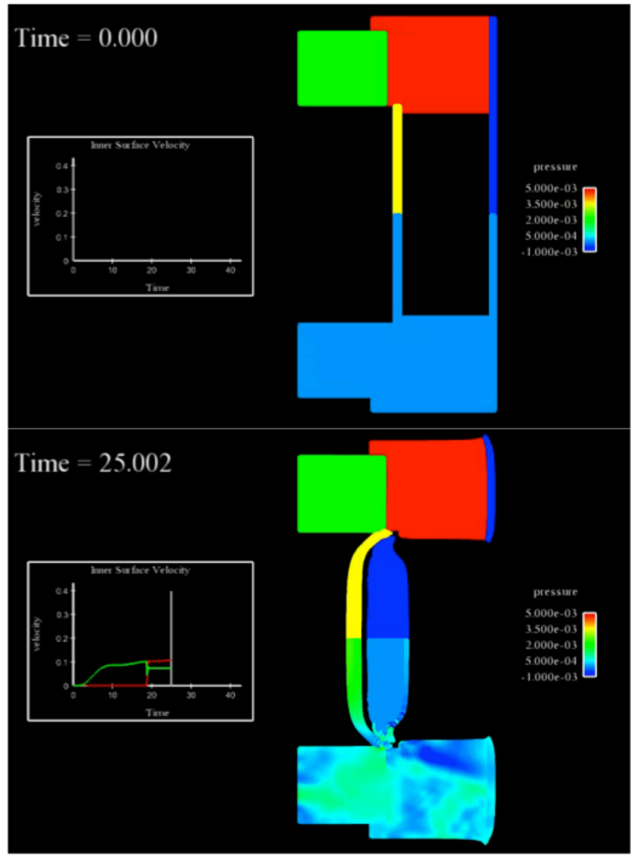

Figure 5. 2D Lagrangian calculation of a dynamic PHELIX liner-on-target experiment.

VI. PHELIX ELECTROMAGNETIC FLYER PLATE

Figure 6(a) shows a conceptual electromagnetic flyer plate system driven by the PHELIX capacitor bank and transformer. The system would be installed at the center of the transformer in the same method as the liner system. The flyer plate configuration consists of static inner and outer cylindrical conductors (stator) with a circular cap. The cap completes the circuit between the inner and outer cylindrical conductors and is driven axially by the magnetic forces produced by the current pulse.

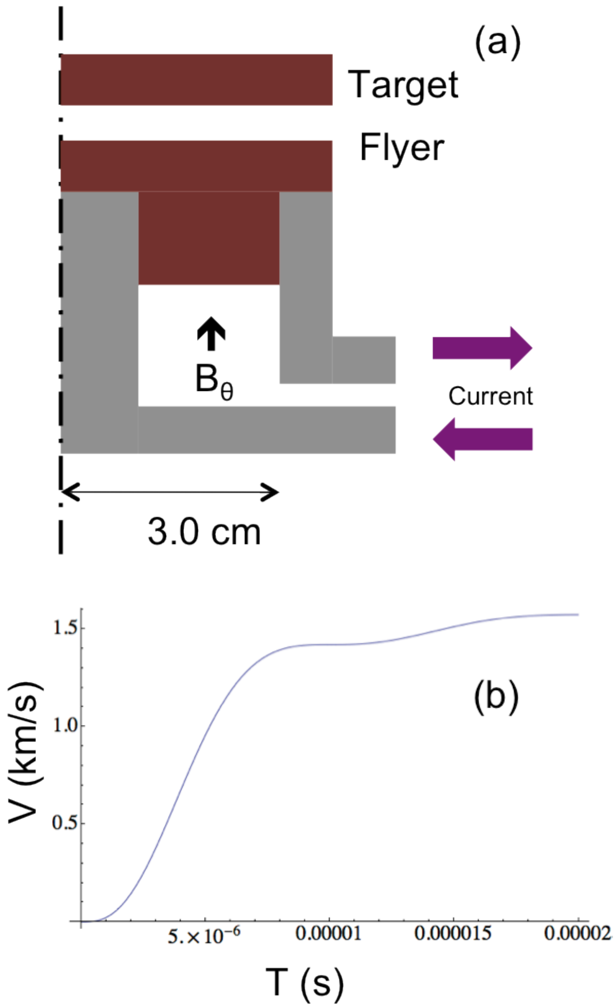

Figure 6. Conceptual planer electromagnetic flyer plate configuration.

A simple computational model with a set of coupled ordinary differential equations (ODE's) is sufficient to analyze the performance of a flyer plate system. The velocity profile is plotted in **Error! Reference source not found.** (b). It shows that the flyer can be accelerated to > 1 km/s. It should be noted that the flyer reaches full velocity in less that 4 cm of motion. This means that a flyer plate experiment with target, diagnostics, and containment could be fielded within the footprint of the PHELIX system.

VII. SUMMARY

PHELIX is a small-scale pulsed-power driver under development. It has been shown to produce multi-MAmp pulses of 10 μs duration. The system's performance has been calibrated by comparison to analytic as well numerical circuit models. A precision, dynamic liner system has been demonstrated. There the liner achieves velocities > 1 km/s. This system is useful as a shock and shock-less impactor. Finally, a conceptual PHELIX electromagnetic flyer plate configuration has been investigated. The flyer's performance is shown to be similar to the cylindrical liner reaching speeds of > 1 km/s. The flyer experimental system could be fielded in relatively small volume within the portable PHELIX platform.

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[i] P. J. Turchi, *IEEE Trans. Plasma Sci.*, **34**, 1919-1927, 2006.
[ii] P. J. Turchi et al., *IEEE Trans. Plasma Sci.*, **39**, 2006-2013, 2011.