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Title: PHELIX

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PHELIX

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Abstract

The Precision, High-Energy density, Liner Implosion eXperiment (PHELIX) pulsed power driver is currently under development at Los Alamos National Laboratory. When operational PHELIX will provide 0.5-1.0 MJ of capacitively stored energy into cm size liners that will reach implosion velocities of 1-4 km/s with approximately 10-20 microsecond implosion time. Peak load currents will be in the 5-10 megamp range. To do this the machine will employ a reusable, multi-turn primary, single-turn secondary transformer to couple the 100-120 kV Marx capacitor system to the load. The transformer has been designed toward a coupling coefficient of 0.9.

PHELIX is designed to be portable with only an 8 x 25 ft^2 footprint. This will allow the machine to be taken to the experiment designer's diagnostic of choice. The first such diagnostic will be the LANL proton-radiography facility. There the multi-frame, high-resolution, imaging capability will be used to study hydrodynamic and material phenomena

I. Introduction

MaRIE (Matter and Radiation in Extremes) is Los Alamos National Laboratory's next-generation, conceptual signature facility. MaRIE will build on LANL's core capability in materials science. Here the term extreme doesn't have to mean the very hottest or most dense conditions. Extreme can also mean the bifurcation points in a parameter, which lead to dramatically different dynamics of a system. For example, the phenomena of spall damage of a material occurs when two reflected shock waves combine to put a ductile material into extreme tension and cause the material to tear apart. Over a very small range of shock strengths there can be a range behavior. For low shock pressure, no observable damage occurs. Just below the spall damage threshold, incipient spall takes place where only void formation is observed. Finally, above the damage threshold, full spall occurs where the material is completely ripped in two. In Fig. 1 the dynamic spall of a cylindrical metal coupon is observed.

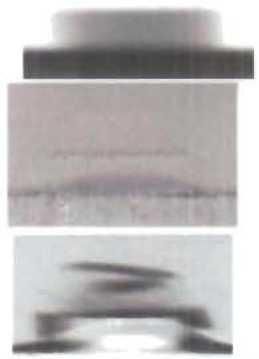

Figure 1. Sequence of proton radiographs of dynamic spall with time running from top to bottom.

MaRIE aims to bridge the "micron-gap" in material science diagnostics. At the submicron spatial scale there is scattering diagnostics which image crystal structure. This is the domain of defect consequences and microstructure interactions that drive material strength and damage evolution. On the super-micron scale there is imaging diagnostics either with x-rays or protons. The major goal of MaRIE is merge these regimes and transition from mere observation and validation to prediction and control of material properties. This truly represents an experimental and theoretical frontier in science.

The PHELIX project is aligned with the long-term goals of MaRIE. It will furnish a dial-able, and reproducible drive for continuum size material samples. Also, magnetically driven cylindrical liners have shown to have high azimuthal precision (< 50 μm for cm size liners). The fundamental cylindrical geometry of liners has property of being a converging while still admitting diagnostic access in the axial direction.

PHELIX is to be fielded within the existing LANL proton radiography facility. Proton radiography offers the potential of 70 μm spatial resolution with 10-20 images over a few microsecond time interval. This higher spatial diagnostic resolution means that the experiment can be scaled down in size [1]. This means that less energy is needed from the driver, which means a less costly capital investment. The higher frame rate means that fewer shots need to be conducted in an experimental series, which translates into more economical science. Fig 2. shows a conceptual picture of how a liner on target experiment would utilize proton radiography.

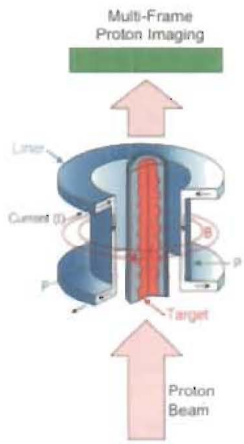

Figure 2 Schematic of a pulsed power driven liner on target experiment utilizing proton radiography as an axial diagnostic.

II. PHELIX the Machine

The PHELIX machine is designed to be portable and modular [2]. The general specifications are as follows:

- 4 Module – Single stage marx
- 120 kV air operation
- ATLAS rail gap switches
- $U_c \sim 0.5$ -1.0 MJ
- $I_{pk} \sim 5$ -10 MA
- B ~ 0.1 1.0 MG
- $T_{rise} \sim 2$ -5 μs
- 8 ft x 25 ft footprint
- $R_{liner} \sim 3$ cm
- $V_{liner} \sim 1$-4 km/s
- Toroidal transfomer coupling

Fig. 3 shows the PHELIX machine with the major features, including the vertically oriented transformer and experimental cassette.

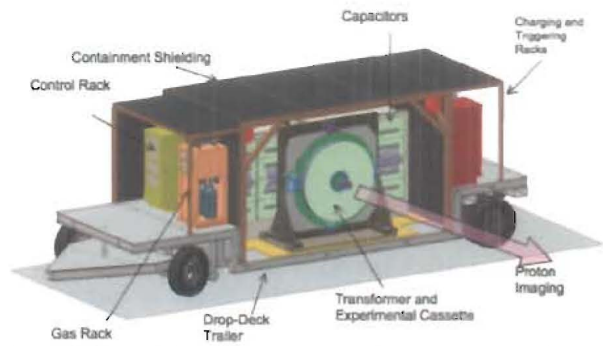

Figure 3. The PHELIX portable pulsed power machine.

The major feature of the PHELIX machine is the current step-up transformer. This allows for modest size energy storage in the capacitor bank while still providing multi MAmps of current to the liner. Fig. 4 shows an exploded view of the components of the transformer.

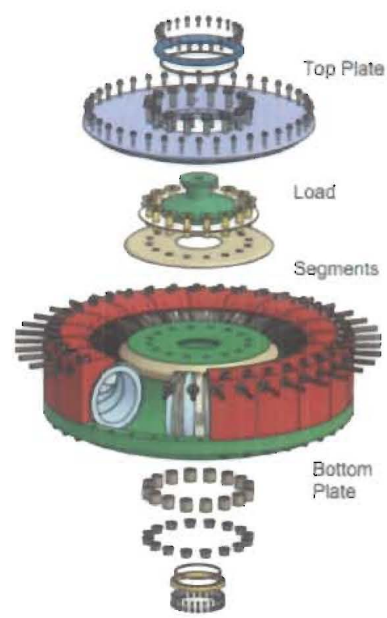

Figure 4. Exploded view of the PHELIX transformer.

The primary windings of the transformer are formed by 40, RG217 coaxial cables that deliver current from the capacitor bank. Pairs of cables are inserted into 20 segment pieces. These segments facilitate assembly of the transformer. The outer braid conductor of the cables is stripped back and connects to the segment. The inner conductor and insulator are internally wound 4 times around a plastic core. The cores have helical channels to support the cables. They are constructed via a 3D printing technology. Finally, the inner cable conductor is terminated on the segment via an exit hole.

The aforementioned segments and a single bottom plate form the single-turn secondary winding of the transformer. The bottom plate and single top plate form a short, narrow, low inductance (< 1 nH) transmission line to the cassette load. The top and bottom plates are held together by a series of post-hole bolts, which are insulated with top-hats and stand-offs.

The minor radius of the torus (R_{minor} ~ 12 cm) is chosen so as to achieve a primary to secondary winding coupling efficiency of 90% (k = 0.9). The major radius of the torus (R_{major} ~ 36 cm) is chosen based on R_{minor} and a close-packed spacing of the primary windings on the inside of the torus.

III. Modeling

A lumped element circuit model has been constructed for use with the RAVEN 1D MHD code [3]. RAVEN solves the circuit equations along with the MHD for an experimental liner and target. Shown in Fig. 5 is a diagram of the circuit. Here C = 68 μF and 50 kV < V_0 < 100 kV are the capacitance and initial voltage on the bank. R_p = 20 mΩ and R_s = 0.1 mΩ are the accumulated internal resistances of the primary and secondary sides of the transformer. It should be noted that R_p consistes primarily of a damping resistance to prevent voltage reversal of the capacitors. R = 10^9 Ω is an isolation resistor for modeling purposes. L_0 = 1 nH and L_1 = 34 nH are the net uncoupled inductances. These include cables inductances, capacitor and switch space inductance, and transmission line inductance. L_p = 395 nH and L_s = 24 nH are the coupled inductances of the toroidal transformer. The mutual inductance which couples the circuit loops is given by $L_m = k\,(L_p\,L_s)^{1/2}$. In RAVEN, the MHD load is implemented as a time-varying inductance and resistance for the circuit. The circuit provides a time-varying current (here I_s) which specifies a magnetic field boundary condition for the MHD.

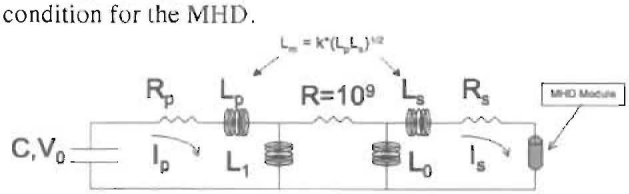

Figure 5. Lumped element circuit model of PHELIX.

Solution of the circuit equations and the MHD can proceed by specifying a simple liner and return conductor geometry. A liner cassette is shown in Fig. 6. The nominal dimensions are 2 cm axial length, 2.5 cm initial radius, 0.1 cm liner thickness, 0.1 cm gap between the liner and return conductor, and 0.5 cm thick return conductor.

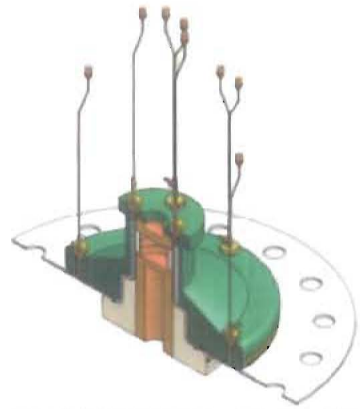

Figure 6. Simple PHELIX liner cassette with several leads for b-dot probe diagnostics.

Fig. 7 shows the RAVEN solution of the system. In Fig. 7(a), the current profiles for the primary and secondary windings of the transformer are shown. These correspond to I_p and I_s in Fig. 5. I_s is 180° out of phase with I_p and is approximately a factor of 4 greater in magnitude as is expected from a current step-up transformer. Rise time is slightly longer than 2 μs.

In Fig. 7(b) the voltage on the capacitor is shown. A value of 90 kV is the initial charge. Due to the 20 mΩ damping resistor, the voltage reversal is limited to < 30% to prevent damage to the bank.

In Fig. 7(c) the trajectories for the surface of the liner and return conductor are shown. RAVEN is a Lagrangian code, so that this amounts to tracking a given element over the duration of the calculation. The liner is driven radially inward and the return conductor radially outward under the jxB force of current running through their surfaces. Owing to its greater thickness, the inertia of return conductor moves more slowly than the liner.

In Fig. 7(d) the corresponding surface velocities of the liner and return conductor are shown. The liner accelerates to ~ 1 km/s in ~ 3 μs, while the return conductor reaches a speed of ~ 0.2 km/s. Though not shown here, over the course of the implosion, the Joule heating only melts the outer 10% of the liner. The integrity of the liner is especially important if it is to be used as a driver to shock a central target for damage type experiments.

IV. Summary

The Precision High-Energy density Liner Implosion eXperiment, PHELIX, is being designed and constructed at for use in conjunction with the LANL proton radiography diagnostics. It is aligned with the goals of the next-generation LANL signature facility, MaRIE. When operational, PHELIX will be capable of delivering 5-10 MA of peak current to a centimeter size liner load. Peak liner velocities will be in the range of 1-2 km/s. This driving capability can be used to place continuum size targets in the extreme conditions necessary to explore material science issues of dynamic spall.

PHELIX will be portable so that it can be taken to the diagnostic of choice. The high spatial resolution and high frame rate of the LANL proton radiography facility will reduce the number of shots in any particular experimental campaign, thus making PHELIX an economical platform for material science.

V. References

[1] P. J. Turchi, "Scaling of Pulsed Power-Driven Hydrodynamics Experiments with Capacitors and Flux-Compressors," IEEE Trans. on Plasma Science, 34, 5, 1919 (2006).

[2] P. J. Turchi, W.L. Atchison, J. R. Griego, W. A. Reass, R. E. Reinovsky, C. L. Rousculp, "PHELIX: Design of Transformer-Driven Liner Implosion System," in *Proc. of 12th Intern. Conf. on Megagauss Magnetic Field Generation and Related Topics*, Novosibirsk, 13 – 18 July 2008. G.A. Shvetsov, ed.

[3] T. A. Oliphant and K. H. Witte, RAVEN, LA-10826, 1987.

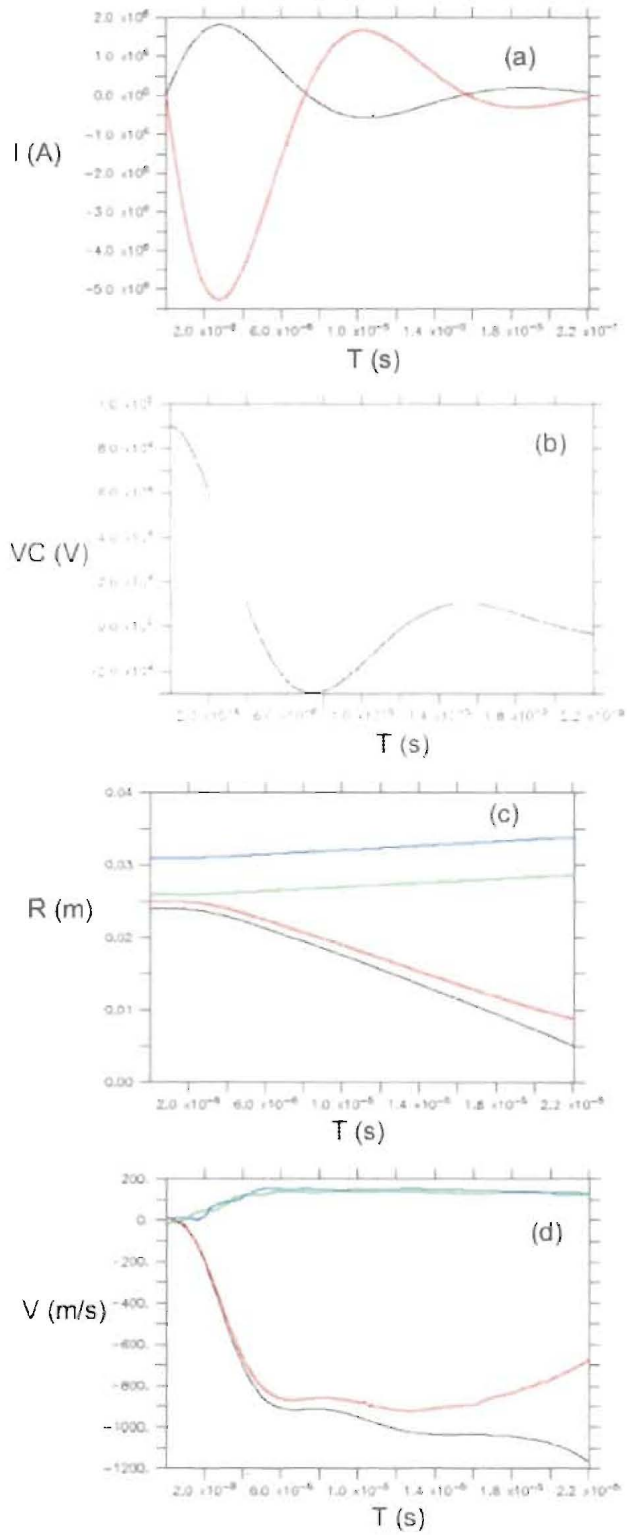

Figure 7. Solution for coupled PHELIX circuit and MHD of a simple liner: (a) Transformer primary (black) and secondary (red) currents, (b) capacitor voltage, (c) liner (red/black) and return conductor (blue/green) surface trajectories, (d) liner (red/black) and return conductor (blue/green) surface velocities.