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PHELIX: Design of Transformer-Driven Liner Implosion System

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ABSTRACT

Experiments involving electromagnetically-imploded, solid-density liners can be achieved at reduced cost and energy if we start with a scale-size based on diagnostic resolution, rather than on the largest capacitor bank or generator we could bring to bear. For minimum resolution of 100 microns or less, many useful experiments could be performed with initial liner diameters that are factors of two to three smaller than used on high-energy systems, such as Atlas, thereby reducing energy requirements to sub-megajoule levels. Reduction in scale-size, however, also decreases the inductance change associated with liner motion relative to other inductances in the circuit. To improve coupling efficiency to liner kinetic energy, we invoke a current step-up transformer. Scaling relations have been developed for reducing the size and energy of such systems and compared with detailed numerical simulations. We discuss these calculations and describe the engineering embodiment of the resulting design for a system called PHELIX (Precision High Energy-density Liner Implosion eXperiment).

I. INTRODUCTION

Experimental studies of material behavior and dynamics at high energy-densities can utilize electromagnetic forces to achieve speeds above several km/s. Operation in the geometry of an implosion can concentrate the energy-density associated with such speeds to even higher values. Numerous experiments in high energy-density physics have been performed on a variety of pulsed power systems, including multi-megajoule capacitor banks, such as Shiva Star [1,2] and Atlas [3]. Typically, the energy of these installations was determined by factors that are both technical and strategic. For example, the size of Shiva Star is based, in part, on the original goal of generating copious amounts of soft X-radiation [4,5]. Plans for the Atlas facility initially comprised a broad program of scientific endeavors [6] and therefore sought the largest stored energy that the construction budget could support.

At stored energies of 5-25 MJ, and speeds for solid-density liner implosions in the range of 5 km/s, implosion dimensions of a few cm can be accommodated. These dimensions are quite consistent with diagnostic techniques, such as flash X-radiography with pulses of a few tens of nanoseconds. Unfortunately, the cost of maintaining a multi-megajoule facility and performing experiments at these levels can exceed available operating budgets. As fewer experiments are accomplished, interest diminishes and budgets decrease further, leading, for example, to the present status of Atlas as a system in "cold-standby".

Suppose, however, diagnostic capabilities could improve to allow finer resolution and useful experiments with liner implosions of smaller dimensions. It would then be possible to design experiments that could operate with pulsed power drivers of much lower energy (< 1 MJ). Not only would the construction cost for such a driver decrease significantly, but operating expenses would be reduced for those portions of the experiment that are destroyed each shot and for the associated damage to nearby apparatus. Proton radiography [7] offers the opportunity to obtain the desired reduction is size for dynamic experiments, perhaps achieving factors of three or so in resolution (100 vs 300 microns) compared to X-radiography. The present paper accepts this possibility and addresses the design of a scaled-down pulsed power driver for experiments at reduced total energy. The intent is an experimental arrangement that would preserve energy-densities, while making use of the precision of electromagnetically-driven implosions diagnosed with proton radiography (pRad). This arrangement is called PHELIX, for Precision High Energy-density Liner Implosion eXperiment.

II. SCALING OF PULSED POWER-DRIVEN IMPLOSIONS

For dynamic systems governed by the Euler equations, such as many liner implosion experiments, there is no size-scale, only relations among the various dimensions (e.g., ratio of initial radius to thickness of the liner) and the ratio of material speeds to the appropriate sound speeds, i.e., Mach numbers. More complex arrangements that involve dissipation, diffusion and other processes require additional considerations and may be characterized by other dimensionless numbers, such as the viscous or magnetic Reynolds numbers for the flow (Rey and Rm, respectively). While specification of all the dimensionless numbers for a system will result in only the full system itself, smaller versions might still provide useful experimental arrangements, if care is exercised to maintain dimensionless parameters in the same operating regimes. For example, if Rey >>1 in the full system, it may be possible to have Rey >>1 in the scaled-down system, albeit at a lower actual value.

Circuit parameters for the pulsed power system driving the liner implosion may also be scaled with the size of the experiment. Such scaling has been considered [8] for several kinds of driving circuit, including the usual LRC-circuit, a transformer-coupled capacitor-based circuit and a flux-compression generator. Figure 1 displays an example of a simple LRC-driven implosion, while Fig. 2 has similar plots for the transformer-driven situation. In both cases, there are five dimensionless parameters that govern the behavior of the normalized circuit and liner implosion:

LRC-Circuit:

Dynamic parameter

$$\Gamma = [W_c /m]/[(L_o/C)^{1/2}/L_{do}]^2 \qquad (1a)$$

Inductance parameter

$$\Lambda = L_o/L_{do}r_o \qquad (1b)$$

Liner and circuit resistance parameters

$$\theta = R_o /(L_o/C)^{1/2} \qquad (1c)$$

$$\theta_c = R_c /(L_o/C)^{1/2} \qquad (1d)$$

Liner heating parameter

$$K = 2\beta\eta_o W_c /[A^2(L_o/C)^{1/2}] \qquad (1e)$$

where the characteristic energy for the LRC-circuit is $W_c = CV_o^2/2$. The liner mass is m, the initial inductance (outside of the initial position of the liner) is L_o, and the inductance gradient for radial motion is L_{do}. The resistance of the liner increases from an initial value of R_o, based on a resistivity $\eta_o(1 + \beta w_d)$ that rises linearly with energy deposition per unit volume w_d, based on a constant coefficient β; in the present example the current density is uniform over the cross-sectional area A. Other resistance in the circuit is expressed by R_c.

Transformer-driven Circuit:

Dynamic parameter

$$\Gamma = [W_c/m]/[L_S / L_{do}(L_E C)^{1/2}]^2 \tag{2a}$$

Inductance parameter

$$\Lambda = L_S/L_{do}r_o \tag{2b}$$

Liner and circuit resistance parameters

$$\theta = (L_E C)^{1/2}/(L_S/R_o) \tag{2c}$$

$$\theta_c = (L_E C)^{1/2}/(L_S/R_c) \tag{2d}$$

Liner heating parameter

$$K = 2W_c(\beta\eta_o/A^2)(L_E C)^{1/2}/L_S \tag{2e}$$

where the characteristic energy for the transformer-driven circuit is $W_c = \kappa C V_o^2/2$. The additional parameter κ depends on the coupling coefficient k and the relative uncoupled inductances on the primary and secondary sides of the transformer:

$$\kappa = k^2 / [(1 + \lambda_1)(1 + \lambda_o) - k^2](1 + \lambda_o) \tag{3a}$$

with

$$k = M/(L_P L_S)^{1/2} \tag{3b}$$

where M is the mutual inductance and L_P and L_S are the inductances of the primary and secondary turns. For uncoupled inductances on the primary and secondary sides, L_1 and L_o, respectively, and an inductance increase due to liner motion L(t), the normalized uncoupled inductances are

$$\lambda_1 = L_1/L_P, \quad \lambda_o = L_o/L_S, \quad \lambda(t) = L(t)/L_S \tag{3c}$$

and the equivalent inductance is:

$$L_E = L_P \, [\, k/(1 + \lambda_o) \,]^2 \, /\kappa \quad (3d)$$

In order to confirm the scalings indicated in the above analyses, we used the Raven 1-D MHD code to simulate operation of a liner implosion on Shiva Star and of a liner of half the initial radius and length with normalized circuit parameters for the LRC case. Raven has been used to design numerous liner implosion experiments by LANL and includes nonlinear magnetic diffusion into the liner material. In terms of the normalized analyses indicated in Fig.1, the Raven results for the full-scale (Shiva Star) and half-scale conditions were essentially identical for both circuit and liner dynamical behavior.

III. DESIGN OF A TRANSFORMER-DRIVEN IMPLOSION SYSTEM

In reducing the size of the pulsed power driver, we quickly encounter design problems due to the so-called "parasitic" inductances of components, such as switches and capacitor headers. These inductances usually become negligible in high energy systems for which many units are operated in parallel. As the system energy is reduced, however, the number of parallel units tends to decrease, so parasitic inductances can dominate over the reduced inductance change associated with motion of a smaller liner. One approach to ameliorate this problem uses a current step-up transformer (i.e., multi-turn primary and single-turn secondary) that effectively increases the liner inductive impedance seen by the driving source.

Suppose we assume (to obtain estimates for a design budget), the number of primary turns N = 12, and parameter values (Eqns. 3) of $k = 0.9$, $\lambda_o = 0.1$, $\lambda_1 = 0.1$, so κ

= 1.841. With Λ = 2.5 and h = 2 cm, L_s = 10 nH, which allows us 1 nH on the secondary side. For N =12, L_p = 1.44 μH, so we have an opportunity for 144 nH of uncoupled inductance on the primary side. The effective inductance is L_E = 0.5236 μH.

At fixed values of Γ and K, and (scaled-down) liner radius and length of r_o = 2.75 cm and h = 2 cm, we proceed to unfold the other values for the circuitry by dividing Eqns.(2a) and (2b):

$$\Gamma/K = (L_E C)^{1/2} L_{do}{}^2 A/(2\beta\rho\eta_o L_s h) \quad (4)$$

$$= (L_E C)^{1/2} L_{do}(2\pi r_o \delta_o)/2\beta\rho\eta_o h\Lambda r_o$$

where the initial liner thickness δ_o is given [8] by:

$$\delta_o = (\eta_o/\mu)\ [\ 2\beta\rho\,\Gamma\ /\ K\theta\ ]^{1/2} \quad (5)$$

= 1.27 mm for an aluminum liner.

We then have:

$$\Gamma/K = L_E C/2\beta\rho\theta\Lambda^2 r_o{}^2 \quad (6)$$

Thus, the capacitance is:

$$C = 2\beta\rho(\theta\ \Gamma/K)\Lambda^2 r_o{}^2/L_E \quad (7)$$

$$= 2\beta\rho(\theta\ \Gamma/K)\Lambda^2 r_o{}^2\kappa/N^2 L_S[\ k/(1+\lambda_o)\ ]^2$$

With r_o = 2.75 cm, we find C = 13.5 μF. We may now compute the characteristic time $(L_E C)^{1/2}$ = 2.66 μs, and, with a liner mass of 13 g, the characteristic energy:

$$W_c = \Gamma m[L_S\ /L_{do}(L_E C)^{1/2}]^2 \quad (8)$$

= 1.1 MJ

The initial energy in the capacitor bank is W_c/κ = 597 kJ. This is significantly less than the energy required by direct-drive from an LRC-circuit, but the charging voltage is much higher, V_o = 297 vs 56 kV. While the total energy does not depend on the number of turns, the value of charging voltage can adjust as a trade-off between capacitance and inductance:

$$V_o = [L_S^{3/2} / L_{do} t_c] m^{1/2} [\, k/(1 + \lambda_o) \,] \, N \, / \, [\beta \rho \theta / K)]^{1/2} \Lambda r_o \kappa \quad (9)$$

Thus, we could reduce the necessary charging voltage to below Atlas values by decreasing the number of turns from twelve to eight; so V_o = 198 kV. The effective inductance decreases to 0.233 μH and the capacitance increases to C = 30.4 μF. This is comparable to a single maintenance unit of Atlas (~34 μF). With some additional adjustments, there appears to be a reasonable solution for the transformer-drive using the (equivalent) of a maintenance unit of Atlas charged to about 208 kV and discharging into an eight-turn primary; the stored energy is 658 kJ. If we decrease the number of turns to four, we can operate at 104 kV, which would avoid the need for oil. Figure 3 displays the results of Raven calculations (with the transformer-drive circuit option) for liner trajectories with three values of primary turns, indicating the expected common dynamic behavior with proper scaling.

IV. DESIGN OF PROTOTYPE PHELIX SYSTEM

We have proceeded to convert the idealized estimates for a transformer-driven liner implosion system into a real prototype design. This involves a set of design choices which have included the use of high-voltage cables to create the multi-turn primary, thereby eliminating concerns for oil-handling systems. Figure 4 indicates the basic approach for converting insulated cables to primary turns. A plurality of such cables provides a multi-filar, four-turn primary, as shown in Fig. 5. The secondary side of the transformer connects to the central liner implosion load by means of disc-shaped parallel-plate transmission lines. The entire assembly of the transformer and implosion load can be adjusted in angle by fine-pitch screws, driven by stepper motors, in order to align the implosion axis with the pRad beam. The capacitors, switches, power supplies, triggers and transformer system are mounted on a wheeled cart for insertion at the pRad facility, as depicted in Fig.6. The system is about three meters high and eight meter long.

V. CONCLUDING REMARKS

The PHELIX system should permit extension of high energy-density physics experiments to laboratory situations in which the pulsed power driver is not the dominant feature in terms of size and cost. While PHELIX may be employed with conventional X-radiography techniques to obtain a few images per shot, its use with pRad offers the opportunity for multi-frame (~16) imagery that could trace the evolution of material dynamics within a single experiment, thereby offering close comparisons with state-of-the-art numerical simulations.

REFERENCES

[1] R.J. Kanzleiter, et al, "Using Pulsed Power for Hydrodynamic Code Validation", *IEEE Trans. on Plasma Science*, 30, 5, 1755 (2002).

[2] P.J. Turchi, et al, "Design, Fabrication and Operation of a High-Energy Liner Implosion Experiment at 16 Megamperes", *ibid.*, 1777.

[3] R.E. Reinovsky, et al, "Pulsed Power Hydrodynamics: An Application of Pulsed Power and High Magnetic. Fields to the Exploration of Material Properties and Problems in Experimental Hydrodynamics," *IEEE Trans. on Plasma Science*, 36, 1, 112 (2008).

[4] P.J. Turchi and W.L. Baker, "Generation of High Energy Plasmas by Electromagnetic Implosion," *J. Appl. Phys.* 44, 4936 (1973).

[5] W.L. Baker, et al, "Current Delivery and Radiation Yield in Plasma Flow Switch Driven Implosions," Fusion Technology, Vol. 27 (March 1995).

[6] R.J. Trainor, et al, "Overview of the Atlas Project," *Proc. of 11th IEEE International Pulsed Power Conference*, 29 June-2 July 1997, Baltimore, MD. IEEE Cat. No. 97CH36127. P.37 (1997).

[7] K. Kwiatkowski, et al, "Development of multiframe detectors for ultrafast radiography with 800 MeV protons," *IEEE Trans. on Nucl. Sci.*, 49 (II), 1, 293 (2002).

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

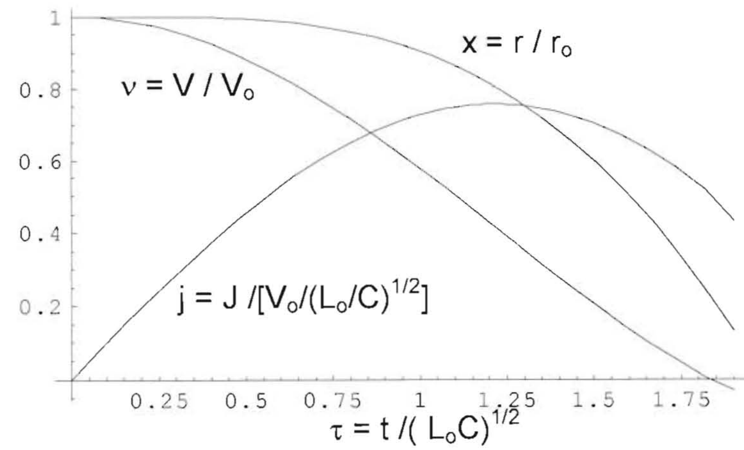

Figure 1

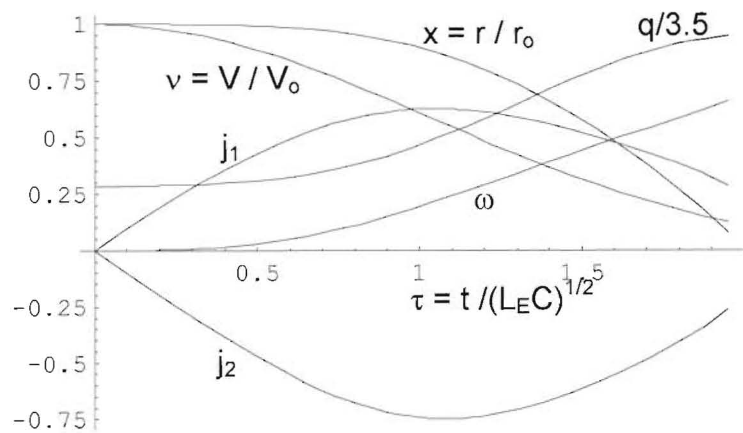

Figure 2

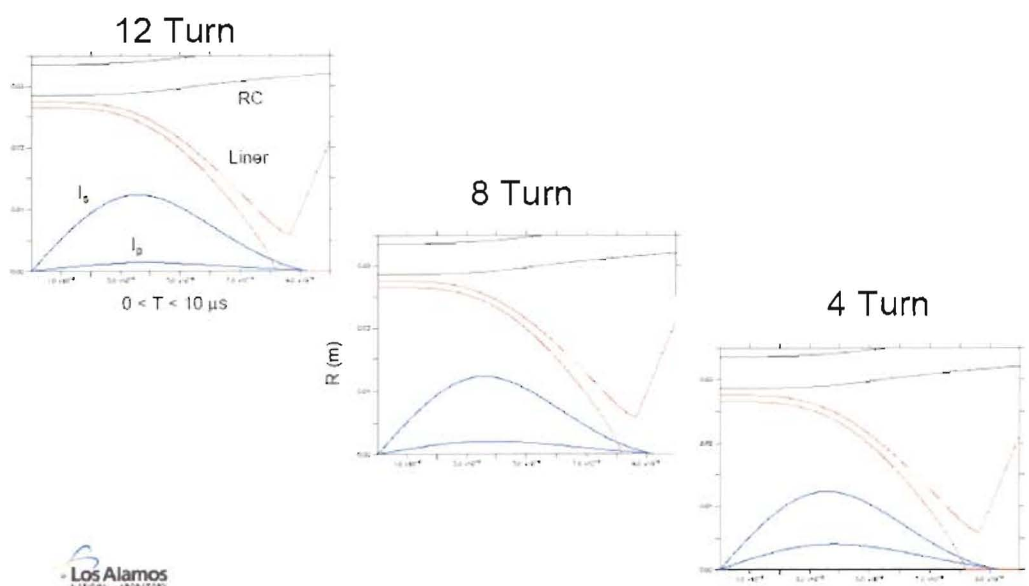

Figure 3

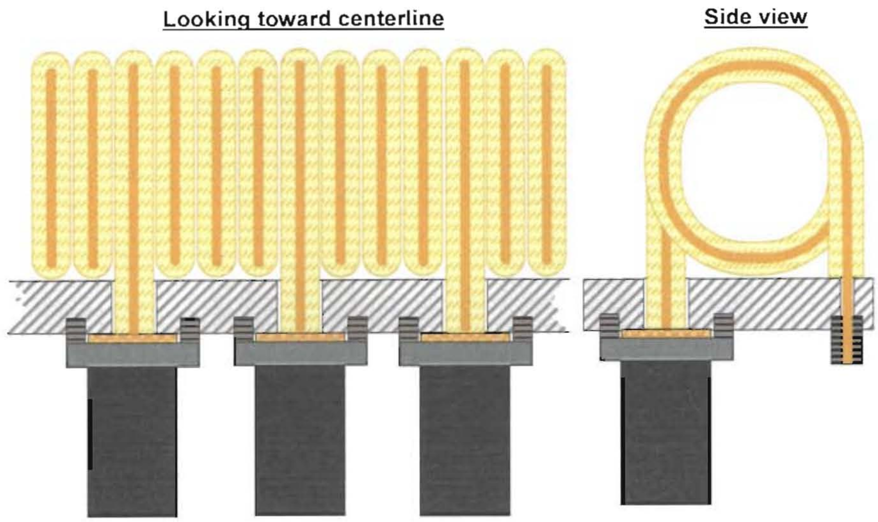

Figure 4

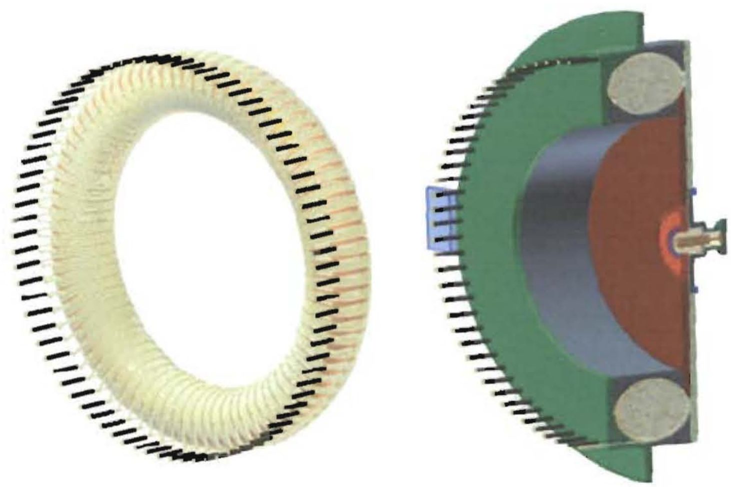

Figure 5

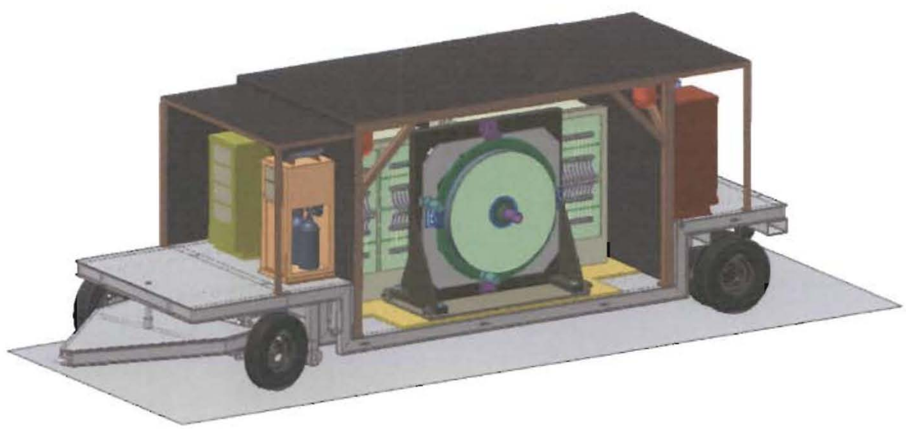

Figure 6

CAPTIONS

Figure 1: Current, voltage and liner radius normalized by their respective characteristic values vs time normalized by $(L_0C)^{1/2}$ for LRC-circuit driving a liner implosion. From Ref. [8], with dimensionless parameter values: $\Gamma = 0.75$, $K = 2$, $\theta = 0.001$, $\theta_c = 0.2$, $\Lambda = 2$.

Figure 2: Voltage, liner radius, primary and secondary currents, liner speed and resistance increase normalized by their respective characteristic values vs time normalized by $(L_EC)^{1/2}$ for transformer-driven liner implosion. From Ref. [8], with dimensionless parameter values the same as in Fig.1 and transformer circuit parameters $k = 0.9$, $\lambda_o = \lambda_1 = 0.1$.

Figure 3: Comparison of liner trajectories from Raven with primary turns of N = 12, 8 and 4, and parameters adjusted by scaling relations to achieve the same liner speed.

Figure 4: Sketch of windings for multi-filar, 4-turn primary made from high-voltage coaxial cables.

Figure 5: Full multi-filar, 4-turn primary and single-turn secondary. Secondary connects to liner implosion load by disc-shaped parallel-plate transmission line.

Figure 6: View of PHELIX system with transformer and liner implosion load on mount that permits fine adjustment of position and angle of implosion axis. Wheeled-cart carries capacitors, switches, triggers and power supplies inside EMI-shielding box, and allows insertion of PHELIX at proton radiography facility.