Title: High Energy Density Physics Experiments with Compact Pulsed Power Drivers and Advanced Diagnostics

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Pulsed Power Hydrodynamics (PPH) is an application of low-impedance, pulsed power technology used to study implosion hydrodynamics, instabilities, turbulence, material properties at high energy densities in a highly precise, controllable environment at the extremes of pressure, density and material velocity.

While the relatively large-scale Atlas facility was designed and built at Los Alamos, specifically to explore such applications, other platforms including the AF Shiva Star system, the Z-Machine at Sandia, explosive pulsed power systems and a number of newer, smaller scale pulsed power systems, providing the advantages of electromagnetic drive can offer new and interesting platforms for PPH experiments. For example, PPH experiments that employ advanced diagnostics such as sensitive, penetrating, multi-frame proton-radiographic imaging can be considered if smaller scale drivers consistent with the available footprint at an accelerator beamline can be developed. Options for such extensions the scope of PPH experiments are also being explored.

The Precision, High-Energy density, Liner Implosion eXperiment (PHELIX) pulsed power driver is currently under development at Los Alamos National Laboratory. When operational, later in 2010, PHELIX will initially provide 0.5 MJ of capacitively stored energy to low impedance experimental assemblies, with simple extension to the 1 MJ energy level. Peak load currents will be initially ~5 Megamp with 3-5 microsecond current rise-time. PHELIX employs compact 120 KV air insulated Marx modules patterned after the oil insulated Atlas Marx coupled to the experiment through a reusable, four-turn primary, single-turn secondary toroidal transformer. The transformer has been designed for a coupling coefficient of 0.9. PHELIX is portable, with its rectangular footprint limited to less than 3x6 meters, allowing the driver to be taken to the experimenter's diagnostic of choice. PHELIX is specifically configured to be compatible with an 800 MeV proton beam-line at the LANL LANSCE facility where the multi-frame, high-resolution, imaging capability of proton radiography will be used to study implosion hydrodynamic and material phenomena.

The high-precision, cylindrically imploding liner is the tool most frequently used to convert electromagnetic energy into the hydrodynamic (particle kinetic) energy needed to drive strong shocks, quasi-isentropic compression, or large volume adiabatic compressions. In planned implosion experiments, the PHELIX 5 MA currents will drive centimeter scale liners (approximately 25% the size of Atlas liners) to implosion velocities of 1-4 km/s with approximately 10-20 microsecond implosion time.

While conceived as a hydrodynamic liner implosion driver, the exceedingly low, 5-8 mΩ, impedance of PHELIX lends itself to a variety of other applications such as (shock-free)
isentropic compression of materials to explore off-hugoniot properties of materials, and even linear (rail gun like) mass acceleration for traditional gas-gun driven shock physic experiments.

In this paper we will describe the status of PHELIX development, but focus on a variety of High Energy Density applications – especially those that capitalize on the use of proton radiographic diagnostics.


Contemporary Research in High Energy Density topics requires modern experimental techniques across a broad spectrum parameters and conditions including condensed matter, warm dense matter and warm and hot plasmas.

- High Explosives, accelerators and especially ultra fast and high energy lasers are important platforms.
- For MB level, STATIC experiments DAC are very practical
- or >MB level DYNAMIC especially in planar experiments: HE, gas guns and powder guns
- Specialized needs of HED experiments sometimes require bringing the driver to the diagnostic.
  - Synchrotron light sources for x-ray diffraction measurements.
  - Particle accelerators for x-ray, or particle (proton) imaging
  - Or where hazardous materials require special cautions
- Pulsed Power is attractive way to power dynamic experiments in condensed matter and warm-dense matter in addition to its traditional role in particle, radiation and plasma physics
  - An emerging application of pulsed power is those physics problems that require compact configurations that allow application of sophisticated diagnostics.
In Los Alamos, a long term focus on Materials and Radiation Interactions in Extremes (conditions), MaRIE, is the centerpiece for advanced experimental capability in condensed matter, warm-dense matter, and plasma research.

- MaRIE is a family of related facilities and capabilities for national security science missions and the research challenges of the future.
- The "micron gap" is a scientific frontier that limits our ability to "predict and control" materials.
  - Crossover from continuum to atomic scale models
  - Interface between scattering & imaging
  - Nexus of discovery science & predictive validation
- Explicit focus on dynamic (~ns/ps), stochastic processes requiring simultaneous measurements.

With its 800 MEV proton accelerator LANSCE has been a centerpiece for Los Alamos nuclear physics research for decades. Proton Radiography for studying dynamic events adds another dimension to the LANSCE mission.

- Proton Radiography
  - National security research
  - Dynamic Materials science,
  - Hydrodynamics
- WNR
  - National security research
  - Nuclear Physics
  - Neutron Irradiation
- Lujan Center
  - National security research
  - Materials, bio-science, and nuclear physics
  - National user facility
- Isotope Production Facility
  - Medical radioisotopes
Utilizing LANSCE, MaRIE will be a unique set of co-located tools to realize advances in materials performance in extremes.

Multi-Probe Diagnostic Hall, provides unique scattering and imaging capabilities to bridge the micron gap in extreme environments
- High-energy (50-115 keV) X-FEL photon source (for multigranular sample penetration) with high intensity and high repetition rate (quantitative imaging of dynamic processes)
- Proton microscopy at 0.8 GeV to provide multiple time resolved measurements
- Robust suite of dynamic loading and material heating techniques

Fission and Fusion Materials Facility
Unique in-situ diagnostics and irradiation environments beyond best planned facilities

Make, Measure, Model Materials (M-4)
Comprehensive, integrated resource for materials synthesis and control, with national security science infrastructure

MaRIE will provide unprecedented international user resources

Small, confined, HE driven Richtmyer-Meshkov Instability experiment, using p-Rad 3X imaging, explores spike and bubble formation and breakup.

Small ("h"), PBX 9501 HE system drives a 2 mm thick Sn target to 340 kbar (melted) and 2.4 mm/msec

Free surface of target is ruled with multi-mode sinusoidal perturbations
- $l = 0.6\text{mm}, \, A_0 = 0.025\text{mm}, \, k_a = 0.25$
- $l = 2.5\text{mm}, \, A_0 = 0.10\text{mm}, \, k_a = 0.25$
- $l = 0.6\text{mm}, \, A_0 = 0.10\text{mm}, \, k_a = 1.00$

Three backgrounds:
- Vacuum, Xe at 4 atm, Ne at 4 atm.
- Relative to "flat" free surface
  - Spikes at $k_a = 0.25$ grow at 3 mm/msec
  - Spikes at $k_a = 1.00$ grow at 4 mm/msec
- Short wavelengths grow fastest, but saturate sooner
P-Rad imaging provides unprecedented spatial resolution and temporal history of Richtmyer-Meshkov Instability.

P-Rad imaging provides unprecedented spatial resolution and temporal history of Richtmyer-Meshkov Instability in backgrounds.
The sensitivity of p-Rad to density variations makes it a good tool for following the evolution of complex shock structures in HE systems.

A compact 40 mm powder gun operating at 1-2 km/sec enables exploration of the Solid-Solid Phase Transition in Iron.
Magnetic drive, (using cylindrical implosions) offers important advantages for conducting detailed physics experiments.

- Magnetic fields are transparent to x-rays and visible light.
  - Diagnosability
- Magnetic fields are fundamentally cylindrical (complementing planar techniques)
  - Phenomenology with convergence, plus radial and axial diagnostic access
  - Intrinsically high azimuthal symmetry, aiding interpretation of images
- Magnetic field drive is "dial-able", controllable, and reproducible
  - 5X operating range produces 25X pressures
  - Demonstrated better than 1% control/reproducibility (limit of measurement)
  - Power Conditioning (switching) allows precise application, and removal, of drive
- Magnetic fields drive large targets (complementing lasers)
  - Affording access to true continuum properties
- Magnetic drive produces HE-like pressure without shocks
  - Affording access to off-Hugoniot states
  - May be usable in situations where HE is prohibited
- Electro-magnetic drive delivers energy at "c" without mass (complementing HE)
  - Higher material velocities (2X)
  - Minimal collateral damage, making containment much easier

PHELIX is a compact, transportable, pulsed-power driver, whose size is compatible with LANL Proton Radiography architecture.

- Proton Radiography, as a diagnostic, complements magnetically driven experiments because enhanced resolution permits smaller experiments and lower energies.
  - pRad resolves 70 micron features in cm-scale implosions with multi-frame (~20) imaging
  - Smaller (1 cm) experiments imply lower energies implying cheaper drivers and less collateral damage
  - Economy of both size and cost implies higher data rate - 5-10 shots / year maps a 2-D parameter space in 1-2 years
- PHELIX will provide a demonstration of the feasibility of magnetically imploded liner experiments using axial proton radiographic imaging.
The Precision High Energy Liner Implosion Experiment (PHELIX) driver is portable, modular, and conservative in its design.

**General Specifications**
- \( U_c = 0.5 - 1.0 \text{ MJ} \)
- \( I_p = 5 - 10 \text{ kA} \)
- \( B = 0.1 - 1.0 \text{ MG} \)
- \( T_{\text{dis}} \approx 3 - 5 \mu\text{s} \)
- 8 ft x 25 ft footprint
- \( V_{\text{line}} \approx 1 - 4 \text{ kV/m} \)
- 4:1 Current multiplying toroidal transformer \( (k = 0.9) \)
- System uses proven capacitors and rail-gap switches
  - Capacitor lifetime ~500 shots with 55% reversal
  - Resistive damping to limit fault currents
- Demonstrated 120 kV operation in air in LANL (elev 2000 m)
  - Many thousands (50k) of shots
- RG-217 cable system interconnects
  - Proven performance at 130 kV
- Bank damping resistance (20 mΩ) using Reticulated Vitreous Carbon (RVC) Foam
  - RVC tested at 850 kA, 17 kA/cm²
  - 120 kV, 130 J/µs

Central technologies for PHELIX are a compact modular MARX and a current multiplying transformer.

**PHELIX Transformer**
- \( k = 0.9 \)
- 20 Modular sections facilitate assembly
- \( R_{\text{major}} = 30 \text{ cm} \)
- \( R_{\text{minor}} = 12 \text{ cm} \)
- Winding Ratio - 4:1
- Primary - 40 x RG-217 cables
- Secondary - Solid Al 6061-T6
PHELIX dynamic load calculation with 1D RAVEN RMHD code illustrate km/sec velocities for an 8 gram liner, with 5 MA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Length (cm)</td>
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<tr>
<td>$R_0$ (cm)</td>
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<tr>
<td>Liner thick (cm)</td>
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<tr>
<td>Gap thick (cm)</td>
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<tr>
<td>RC thick (cm)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

90% Liner remains solid

The Damaged Surface Hydrodynamics experiment is a first application of PHELIX. DSH tracks the propagation of pre-formed "damage" materials in a cylindrical implosion to test "fluid-like" (instability) models of particle propagation in a gas.

1. Liner impact
2. Release of "damaged" material at shock breakout
3. Drift of converging kinetic liner
4. Imploded liner overtakes target, providing second acceleration to target/damage material interface
5. Recollection of "damaged" material by re-accelerating target layer
6. Stagnation, bounce, mixing

Critical Diagnostics:
- ~20 Axial p-Rad images
- ~4 Transverse images
For very large energies, LANL teamed with VNIIEF to conduct the High Energy Liner (HEL-1) experiment, producing world record liner implosion kinetic energy with a 100-MA current drive.

• With more than 50% of the 1-kg liner mass unmelted, 2D effects were manifested (computationally) primarily in “glide plane run-ahead.” Experimental measurements were consistent.

• Liner velocity at CMU was 6.7 km/sec - 8.4 km/sec

• Liner kinetic energy at CMU (4:1 radial convergence) was between 22 MJ and 35 MJ

Liner implosion techniques, compressing initially solid, or initially gaseous target can convert many megajoules of liner kinetic energy into internal energy, producing WDM.

• Techniques to deliver 20-30 MJ of kinetic energy (at 5-6 MJ/cm) with impact velocities approaching 10 km/sec have been demonstrated. Higher impact velocities also reported.

• In hydrodynamic design calculations, an aluminum impactor at 10 km/sec (2 MJ/cm) compresses a (matched) Al target to 8 gr/cc (~3X normal density) and energy densities approaching 140 kJ/gr (>1MJ/cc) maintaining the conditions for several 100 ns.

• Compressing the Al sample between a Tungsten liner and the tungsten core at 10 km/sec (14 MJ/cm) could reach densities of 10 gr/cc (>4X normal) and 150 kJ/gr (1.5MJ/cc) at velocities of 10 km/sec.

• Temperature in the compressed target of 1- few eV are estimated – depending on EOS model.
Summary

- Contemporary Research in High Energy Density topics requires modern experimental techniques across a broad spectrum parameters and conditions including condensed matter, warm dense matter and warm and hot plasmas.
- High Explosives, gas/powder guns, lasers are attractive platforms. Pulse power techniques complement the more traditional platforms and offer some unique advantages.
- Increasingly advanced diagnostics, such as multi-image proton radiography are the key to performing new and interesting experiments, and experimental platforms that are consistent with the needs of the advanced diagnostics must gain corresponding increase in attention.