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<th>Title:</th>
<th>PHELIX for Flux Compression Studies</th>
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<tbody>
<tr>
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</table>
A long-standing problem in magnetic flux compression by liner implosion has been the delineation of the magnetic field distribution near the surface of the liner. Typically, surface irregularities and imprecision of implosion can prevent use of simple probes. High-density vapor/plasma can obscure the view and also preclude the use of spectroscopic techniques for field measurement because of absorption and line-broadening. Recently, we have been developing a system known as PHELIX (Precision High Energy-density Liner Implosion eXperiment) for use with proton radiography. This approach requires that we have a portable pulsed power and liner implosion apparatus that can be operated in conjunction with an 800 MeV proton beam at LANSCE (Los Alamos Neutron Science Center). Such proton beams have been previously used to radiograph dynamic events at speeds of a few km/s and dimensions of a few cms. The high resolution (< 100 micron) provided by proton radiography combined with similar precision of liner implosions driven electromagnetically can permit close comparisons of multi-frame experimental data and numerical simulations within a single dynamic event. For example, the development of surface perturbations can be followed for sixteen frames during the same implosion, instead of comparing similar perturbations at different times in separate tests. To achieve a portable implosion system for use at high energy-density in a LANSCE laboratory area requires sub-megajoule energies applied to implosions only a few cms in radial and axial dimension. The associated inductance changes are therefore relatively modest, so a current step-up transformer arrangement is employed to avoid excessive loss to parasitic inductances that are relatively large for low-energy banks comprising only several capacitors and switches. We describe the design, construction and operation of the PHELIX system and discuss applications to liner implosion and magnetic flux compression experiments. For the latter, the ability of strong magnetic fields to deflect the proton beam offers a novel technique for measurement of field distributions near perturbed surfaces.
PHELIX for Flux Compression Studies

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The PHELIX (Precision High Energy-density Liner Implosion eXperiment) approach seeks to achieve the benefits of high energy-density experiments with scaled down systems.

- Electromagnetically-driven liner implosions are capable of very high precision and reproducibility
- Scaling down such implosions to lower total energy and size offers lower cost, both capital and operating
- Smaller systems can operate in conjunction with large, expensive diagnostics, such as proton radiography (pRad)
- pRad can provide high resolution and multiple frames during a single dynamic event (e.g., growth of perturbations)

The combination of PHELIX with pRad offers the opportunity for close comparison of experiments and simulations.
Reduced size results in lower inductance change by the implosion relative to parasitic inductances and favors a current step-up transformer circuit.

Lower system energies with "standard" capacitors and switches mean there are fewer elements to reduce the effects of parasitic inductances and resistances.
The PHELIIX current step-up transformer system comprises a four-turn primary wound from multiple starts of cable center-conductors inside a single-turn secondary.

Current from two 2-stage Marx banks power the primary via forty cables, each with a four-turn coil.

The central liner "cassette" receives the current from the secondary via disk transmission plates.
PHELIX is designed to fit as a self-contained system on a trailer that allows insertion in the 800 MeV proton beam at the Los Alamos Neutron Science Center (LANSCE).

Presently, PHELIX is located at separate site where X-radiography can diagnose liner implosions. Access to the proton beam is always limited in order to support many other users.
Scaling of electromagnetically-driven liner implosions benefits from a non-dimensional formulation that provides dimensionless parameters for important processes.

Current and voltage vs time from RAVEN 1-D MHD code

Normalized circuit and dynamic behavior from dimensionless 0-D code

\( (\Gamma = 0.1267, K = 0.616, \theta = 0.00064, P = 0.002, R_m F = 0 \text{ and } H_F = 0) \)

The normalized solutions allow rapid understanding of PHELIX behavior. The RAVEN code provides detailed and accurate results.
The dimensionless analysis has been extended to imploding liner flux compression, including nonlinear resistive heating.

Flux compression w/o loss

\[ \eta = 0 \]

Flux compression w/ loss

\[ \eta = \eta_0 (1 + \beta Q_F) \]

Resistive diffusion allows flux loss through the inside surface of the liner. The associated heat deposition in the liner material increases the resistivity promoting more diffusion.
The dimensionless analysis indicates that megagauss field levels can be attained with PHELIX at inside radial dimensions of a few mm. Proton radiography may allow multi-frame diagnosis of the field and liner material.

Gyroradius of 800 MeV proton in megagauss magnetic field

$$r_g = \frac{\gamma \beta m_p c}{eB}$$

$$= 4.88 \text{ cm}$$

Azimuthal speed due to entering high field region

$$v_\theta = \frac{(e/\gamma m_p)r_p B_z}{2}$$

Resulting angular deflection by axial field in rz-plane

$$\Delta \theta = \frac{v_r}{\beta c} = \frac{r_p h}{2r_g^2}$$

$$= 21 \text{ mrad}$$

Proton radiography may offer a new and unique capability for studying imploding liner flux compression.