LA-UR- 10-04459

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*Intended for:* Proceedings of the
13th International Conference on
Megagauss Magnetic Field Generation and Related Topics
Shanghai, China
6 – 10 July 2010

Los Alamos
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Form 836 (7/06)

# PHELIX for Flux Compression Studies

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PHELIX (Precision High Energy-density Liner Implosion eXperiment) is a concept for studying electromagnetic implosions using proton radiography. This approach requires a portable pulsed power and liner implosion apparatus that can be operated in conjunction with an 800 MeV proton beam at the Los Alamos Neutron Science Center. 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. To achieve a portable implosion system for use at high energy-density in a proton 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 application to liner-driven, magnetic flux compression experiments. For the latter, the ability of strong magnetic fields to deflect the proton beam may offer a novel technique for measurement of field distributions near perturbed surfaces.

## I. INTRODUCTION

Use of high energy capacitor banks to drive imploding liners is a well-established practice and has found many applications for materials studies [1], high magnetic field generation [2] and controlled fusion schemes [3]. Typically, performance benefits from assembling the largest amount of energy-storage capability, perhaps at the highest practical charging-voltage, so that losses to parasitic inductances and resistances are minimized. The latter loss includes resistive diffusion into the imploding liner during attempts at magnetic flux compression, which is mitigated by higher speed and larger radial dimensions (i.e., more energy) for the liner. The countervailing problem is the expense of construction, siting, operation and maintenance of a large capacitor-bank facility. This problem led to the notion of a more miniature implosion system, PHELIX (Precision High Energy-density Liner Implosion eXperiment)[4] that could operate with sophisticated, precision diagnostic systems, such as proton radiography [5]. The implosion system would then not be the largest and most expensive part of the experimental program (compared, for example, to an 800 MeV proton accelerator) and

might therefore survive the vicissitudes of funding. The present paper discusses the continued development of PHELIX and its potential application to studies of magnetic flux compression.

## II. PHELIX

The principal difficulty in miniaturizing an electromagnetically-driven implosion system is the reduction in the inductance change of the implosion relative to other circuit inductances. In particular, operation with standard capacitor and switching elements at reduced system energy means that the usual amortization of component inductances over a large number of elements is not available. Scaling analyses [6] indicated that adequate design margin for circuit inductances could be achieved even with simple current step-up transformer techniques. More detailed analyses [7] confirmed these basic zero-dimensional calculations and we have proceeded to construct the first PHELIX apparatus.

Figure 1 provides a view of the basic current step-up transformer, surrounding the implosion load cassette (shown with the leads for an array of magnetic probes). An exploded-view is given in Fig. 2. The primary turns are formed by the insulated center conductors of forty (RG-217) cables, each wound as four turns around a plastic bobbin to provide a 4:1 current step-up. The cables are fed, via damping resistors, from the output of railgap switches at two energy-storage sections, each comprising four capacitors in a two-stage Marx arrangement. The total of eight capacitors, at 34 μf each, provides a stored energy of 490kJ (at 60kV). At 35kA per cable, the perfect secondary current would be 5.6 MA. Figure 3 has an example of the expected secondary current.

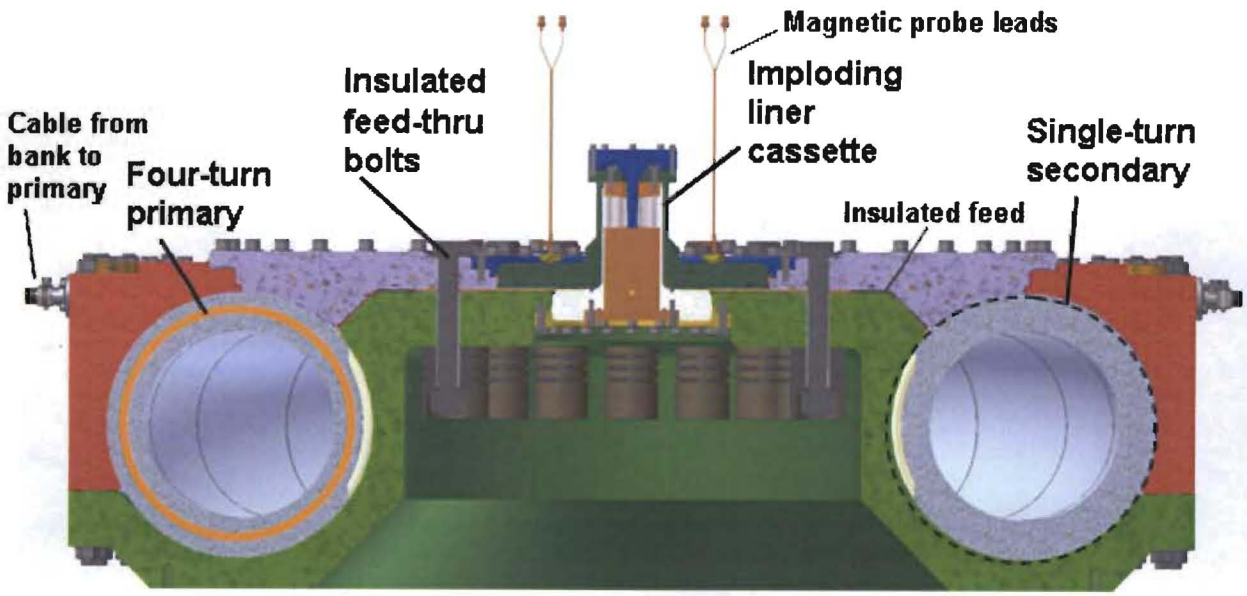



Figure 1: Sectional view of the PHELIX transformer, indicating the cross-section of primary turns made up of the insulated center conductor of cables from the capacitor modules. The single-turn secondary feeds the central liner cassette by insulated disk-shaped transmission plates, held together by insulated feed-thru bolts. The major radius of the secondary is 1 meter and its minor radius is 12 cm.

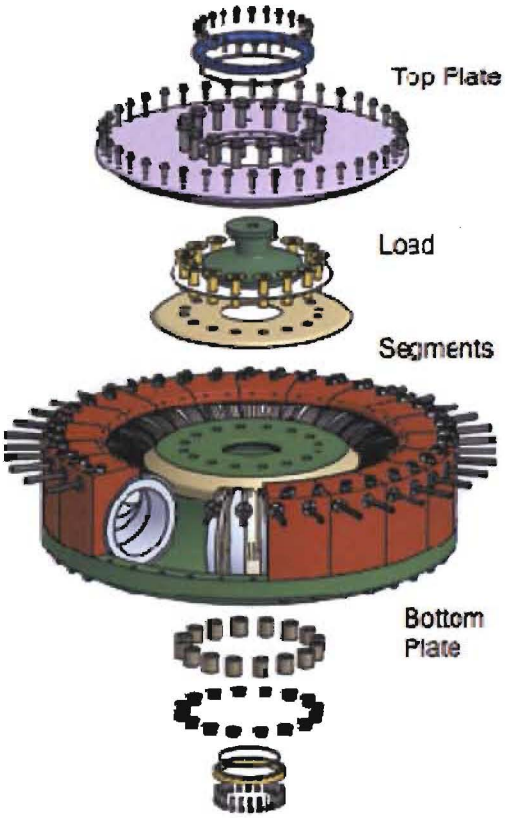
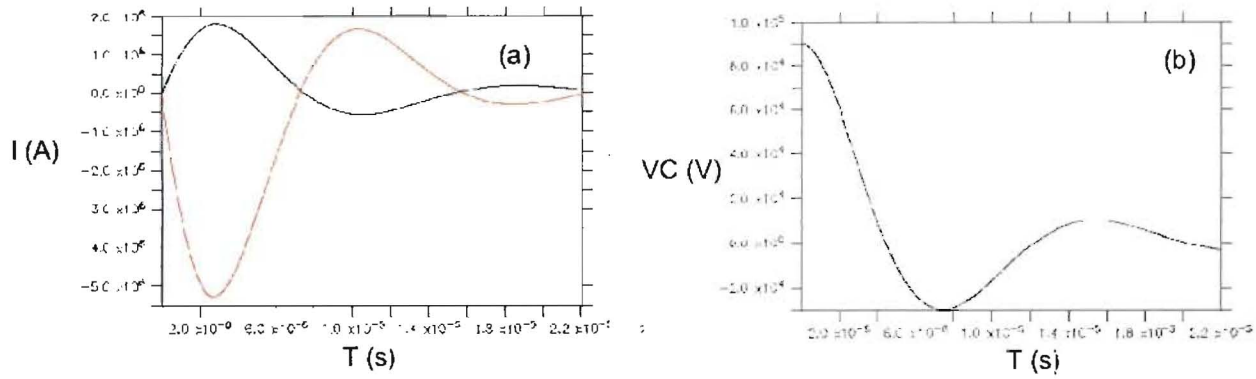



Figure 2: Exploded view of the PHELIX transformer indicating the 40 four-turn primary coils made of cables from the two energy-storage sections. The connecting bolts are each insulated by polyethylene "top-hats". Machined polyethylene is also used for the top-hat insulator of the liner cassette. Along the transmission plates, two or three layers, each 0.46mm thick, of stretchable, polyurethane elastomer sheet (Rhino-hide®) connect the cassette insulator to the insulation in the primary-turn region.

Figure 3: Photograph of PHELIX transformer indicating forty cables with four turns each (seen as copper conductors through insulation).




(a) Currents vs time for primary and secondary circuits (b) Capacitor voltage vs time

Figure 4: Example of circuit behavior for PHELIX with an implosion load, calculated with the RAVEN code. The initial voltage for the "erected" two-stage Marx is 90kV, so the stored energy is 275 kJ. The aluminum liner has initial dimensions: radius 2.5 cm, length 2.0 cm and thickness 1 mm. In these simulations, the liner attained a speed in excess of 1 km/s in a few microseconds.

The PHELIX system is designed for insertion in the 800 MeV proton beamline at the Line C experiment area of the Los Alamos Neutron Science Center (LANSCE). Access to this area occurs in limited increments (less than two weeks), so all of PHELIX will be set on a trailer as indicated in Fig. 4. Presently, PHELIX is assembled in a separate area in preparation for initial tests, using X-radiography, photon Doppler velocimetry (PDV), magnetic probes and electrical circuit diagnostics to assess the liner implosion.

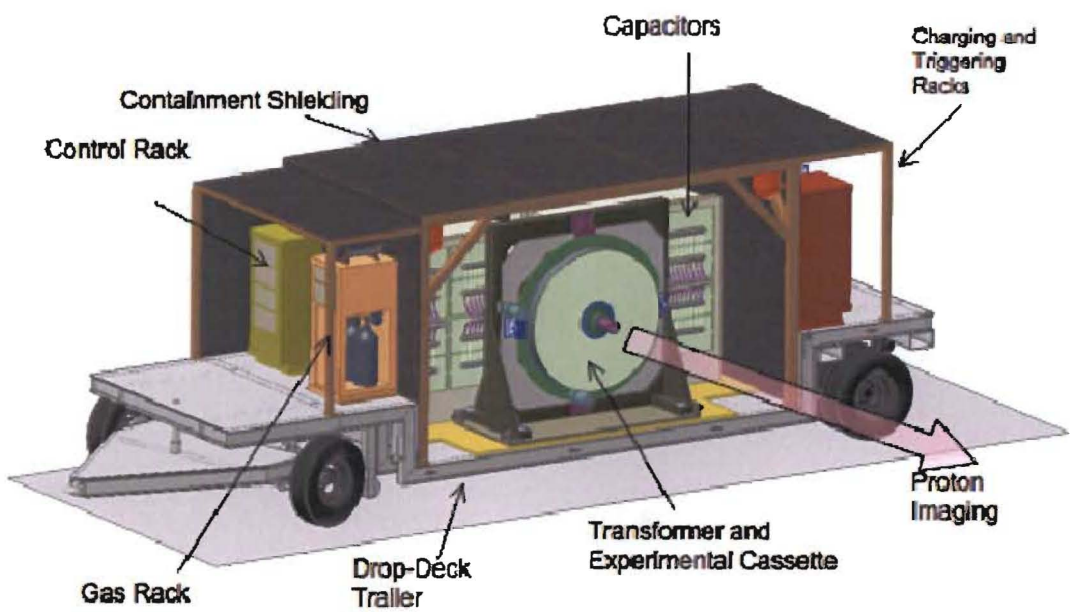



Figure 5: Sketch of PHELIX system mounted on trailer for rapid installation and removal from the proton beam experiment area at LANSCE. The 800 MeV proton beam enters from the upper left and continues, after slight deflections in the target, to the multi-frame imaging system toward lower right.

## III. PHELIX AND MAGNETIC FLUX COMPRESSION

To estimate the performance of PHELIX in the context of imploding liner compression of magnetic flux, we return to the earlier non-dimensionalized scaling formulation [6]. In this formulation, we find that the electrical and dynamic behavior of pulsed power-driven liner implosion systems can be defined by a set of dimensionless parameters, providing normalized solutions for currents, voltages, implosion radii and speeds. For the transformer-driven circuit of Fig. 6, we have dimensionless ratios of circuit components, such as the usual coupling coefficient, $k = M/(L_P L_S)^{1/2}$, and normalized uncoupled inductances

$$\lambda_1 = L_1/L_P, \quad \lambda_o = L_o/L_S, \quad \lambda(t) = L(t)/L_S \tag{1}$$

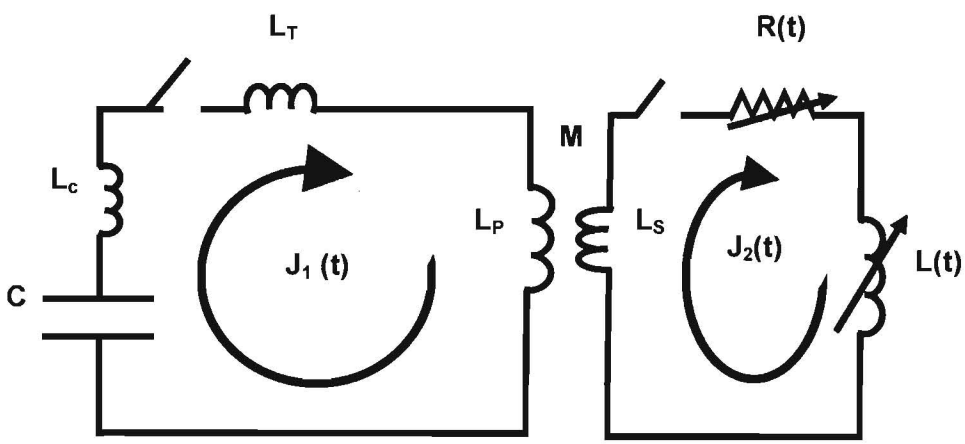



Figure 6: Circuit for transformer-driven liner implosion system (from Ref. [6]).

These parameters combine as

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

to provide an equivalent inductance

$$L_E = L_P [ k/(1 + \lambda_o) ]^2 / \kappa \tag{3}$$

by which we can write a characteristic time $(L_E C)^{1/2}$, a characteristic impedance $(L_E/C)^{1/2}$ on the primary side, a characteristic impedance on the secondary side $L_S/(L_E C)^{1/2}$ and a characteristic energy $W_c = \kappa C V_o^2/2$. These are used to define normalized primary and secondary currents

$$j_1 = J_1 /[V_o/(L_E/C)^{1/2}]$$
$$j_2 = J_2 /[\kappa^{1/2} V_o/(L_S/C)^{1/2}] \tag{4a,b}$$

and lead to dimensionless parameters for system behavior:

*Dynamic parameter*

$$\Gamma = [W_c/m]/[L_S / L_{do}(L_E C)^{1/2}]^2 \tag{5a}$$

*Inductance parameter*

$$\Lambda = L_S/L_{do} r_o \tag{5b}$$

*Liner and circuit resistance parameters*

$$\theta = (L_E C)^{1/2}/(L_S/R_o) \tag{5c}$$

$$\theta_c = (L_E C)^{1/2}/(L_S/R_c) \tag{5d}$$

*Liner heating parameter*

$$K = 2W_c(\beta\eta_o/A^2)(L_E C)^{1/2}/L_S \tag{5e}$$

where m is the liner mass, $r_o$ its initial (outer) radius and A its cross-sectional area for axial current flow. The inductance "gradient" associated with the increase of inductance due to liner implosion is:

$$L_{do} = (\mu/2\pi)h/r_o \tag{6}$$

for a liner of constant length h. The resistance parameters are defined in terms of resistances on the secondary side that include a fixed value $R_c$ for the circuit and a resistance for the liner (outer surface) that increases from an initial value $R_o$ due to resistive heating. Such heating is characterized in developing the liner heating parameter K by an increase of resistivity as:

$$\eta = \eta_o(1 + \beta Q) \tag{7}$$

where $\eta_o$ is the initial electrical resistivity, $\beta$ is the resistivity parameter [8], and Q is the heat deposition per unit volume.

With the dimensionless parameters, we may derive [6] the associated dimensional properties of the system. For example, the initial thickness $\delta_o$ of the liner is given by:

$$\delta_o = (\eta_o/\mu)\,[2\beta\rho\Gamma/K\theta]^{1/2} \tag{8}$$

where $\rho$ is the mass density used in calculating the liner mass $m = 2\pi r_o h \delta_o \rho$. With $\Gamma = 0.1267$, $K = 0.616$, $\theta = 0.00064$, and aluminum ($\rho = 2.7 \times 10^3$ kg/m$^3$, $\beta = 2.11 \times 10^{-9}$ m$^3$/J, $\eta_o = 2.7 \times 10^{-8}$ $\Omega$-m), the initial liner thickness would be 1.3mm.

Without further recapitulation of Ref [6], we can use the liner momentum equation to illustrate the process of non-dimensionalizing the differential equations of the zero-dimensional model:

$$mdu/dt = L_d J_2(t)^2/2 \tag{9}$$

$$\text{with } L_d = L_{do} r_o/r$$

We normalize the secondary current as Eqn (4b), the time by the characteristic time $(L_E C)^{1/2}$, liner (outer) radius by the initial outer radius, and the speed by a characteristic speed $u_c$ that is determined by inspection of the resulting dimensionless differential equation. This, with

$$J_2 = j_2\,[\kappa^{1/2} V_o/(L_S/C)^{1/2}]\ ,\quad t = \tau\,(L_E C)^{1/2}\ ,\quad r = r\,r_o\ ,\quad u = \omega\,u_c \tag{10}$$

we obtain

$$d\omega/d\tau = \Gamma j_2^2/r \tag{11}$$

where the characteristic speed is defined as

$$u_c = (L_S/L_{do})/(L_E C)^{1/2} \tag{12}$$

To the momentum equation of the earlier model, we now add the force of the magnetic pressure on the inside surface of the liner during flux compression:

$$mdu/dt = L_d J_2(t)^2/2 - 2\pi r_i h\,(B^2 - B_o^2)/2\mu \tag{13}$$

where $r_i$ is the radius of the inside surface, determined within the simplifying assumption of incompressible liner motion, $r^2 - r_i^2 = r_o^2\,[1 - (1 - \delta_o/r_o)^2]$. The magnetic field B within the inside surface of the liner is based on the surrounded magnetic flux:

$$\phi = B\pi r_i^2 \tag{14}$$

which has an initial value $\phi_o = B_o\,\pi r_o^2(1 - \delta_o/r_o)^2$, where $B_o$ is the initial axial field provided for flux compression. The magnetic field is naturally normalized by the initial field $B = B_o b(\tau)$. With flux compression, the non-dimensional momentum equation becomes:

$$d\omega/d\tau = \Gamma\,\{\,j_2^2/r - P\Lambda\,[\,b^2(\tau) - 1\,]r_i(\tau)\,\} \tag{15}$$

where $r_i$ has been replaced by $r_i(\tau) = r_i/r_o(1 - \delta_o/r_o)$ and we have introduced a new dimensionless parameter:

$$P = \pi r_o^2 h(B_o^2/2\mu)/W_c \tag{16}$$

to characterize the relative importance of flux compression in the dynamic behavior of the system.

Flux compression, of course, depends on our ability to retain flux within the inside surface of the liner. Flux is lost at this boundary by resistive diffusion at a rate:

$$d\phi/dt = - 2\pi r_i \eta_F j_F \tag{17}$$

where $\eta_F$ and $j_F$ are the resistivity and current density at the inside surface, respectively. The proper solution for flux requires solution of the time-dependent partial differential equation, with variable transport coefficients. For our purposes, merely to attempt a correction for resistive loss, we approximate the current density near the surface by:

$$j_F = (B - B_o)/\mu x_F \tag{18}$$

where $x_F$ is an effective skin-depth $(\eta_F t_F/\mu)^{1/2}$ based on the instantaneous, local resistivity and a variable characteristic time $t_F$:

$$t_F = 1/[(1/t) + (2u_i/r_i)] \tag{19}$$

with the speed of the inside surface given by $u_i = ur/r_i$, continuing the incompressible assumption. Note that this somewhat arbitrary construction is reasonable in the two limits of small liner motion at early times and a reduced skin-depth as the liner attains high speed at small radius. It is, of course, quite inaccurate after peak compression, when the current density at the inside surface would reverse and some flux actually diffuses out of the surface.

During resistive diffusion, the liner material near the inside surface is heated, so we should include the associated increase of resistivity. This is accomplished in a manner similar to that for heating the liner driven by the secondary current. The resistivity near the inside surface increases by a factor dimensionless $q_F = (1 + \beta Q_F)$ given by:

$$\begin{aligned} dq_F/dt &= \beta \eta_F j_F^2 \\ &= \beta B_o^2 (b - 1)^2/\mu t_F \end{aligned} \tag{20}$$

In non-dimensional form, we have:

$$dq_F/d\tau = H_F(b - 1)^2/\tau_F \tag{21}$$

where we obtain an additional dimensionless parameter $H_F = \beta B_o^2/\mu$ to account for the resistive heating of the inside of the liner during flux compression. With the associated enhancement of resistivity, the magnetic flux surrounded by the inside surface of the liner decreases at a rate given by converting Eqn. (17) to non-dimensional form in terms of the ratio f of flux to initial flux:

$$df/d\tau = -2r_i\, q_F^{1/2}(b-1)^2/R_{mF}\,\tau_F \tag{22}$$

where $R_{mF} = r_o(1 - \delta_o/r_o)/[\eta_o(L_E C)^{1/2}/\mu]^{1/2}$ is an effective magnetic Reynolds number for the flux compression event. Note that the normalized magnetic field is then just:

$$b(\tau) = f(\tau)/r_i(\tau)^2 \tag{23}$$

Also note that there is yet another dimensionless parameter $d_o = \delta_o/r_o$ that captures the effect of liner thickness in accelerating the inside surface above the average speed of the liner. Eqn. (8) provided the initial thickness of the liner in terms of liner material properties and dimensionless parameters. In a similar way, we obtain the initial value of axial magnetic field:

$$B_o = 2\,[(\eta_o/r_o)(\rho/2\beta)^{1/2}(K\Gamma/\theta^3)^{1/2}P]^{1/2} \tag{24}$$

For example, with the same material values and dimensionless parameters used previously ($\Gamma$ = 0.1267, K = 0.616, $\theta$ = 0.00064), $r_o$ = 2.5 cm and P = 0.002, the initial magnetic field is $B_o$ = 10.9T. A reasonably modest compression ratio should therefore allow access to megagauss magnetic field levels, even in the face of significant resistive diffusion.

Figure 7 displays the basic circuit behavior for the preceding parameter choices, but with resistive diffusion in the liner surface neglected. Figure 8 provides the results of this idealized imploding liner flux compression event. With $R_{mF}$ = 54.6 and $H_F$ = 0.2, characterizing resistive diffusion and enhanced resistivity, we obtain the corresponding results in Figs. 9 and 10. As expected, there is flux loss for the latter case, resulting in lower values of magnetic field and heating of the inside surface of the liner. For the calculated value of $B_o$, we would attain megagauss magnetic field levels at radii of the inside surface of about 5-6mm, and with enhanced resistivity by factor of several. This last result suggests the loss of accuracy even beyond the greatly simplified model used here, namely a constant value of $\beta$ appropriate for liner heating while in the solid-phase must yield to more sophisticated treatment of material properties and transport. The primary purpose of the present calculations has been to explore the possibility of using scaled-down liner implosions for flux compression studies. Even allowing for enhanced resistive diffusion, it appears that megagauss field levels would be accessible with PHELIX.

## IV. PHELIX, Proton Radiography and Flux Compression

One immediate consequence of scaling to smaller liner dimensions is the reduced radial in which to examine megagauss fields and liner behavior. Simple probe techniques can certainly record the production of a megagauss field shortly before destruction by the liner (including by possible debris and asperities that may precede the inside radii calculated here). With the multi-frame capability of proton radiography, we may be able to observe the evolution of the field and liner surface material. A brief estimate of the

possibility of useful interaction of the proton beam is a first step toward more detailed analyses. The 800 MeV proton beam at LANSCE represents a relativistic $\gamma = 1.85$, with an associated relativistic $\beta = 0.84$. The gyro-radius of a proton with such values in a megagauss magnetic field is:

$$r_g = \gamma\beta m_p c/eB \tag{25}$$

$$= 4.88 \text{ cm}$$

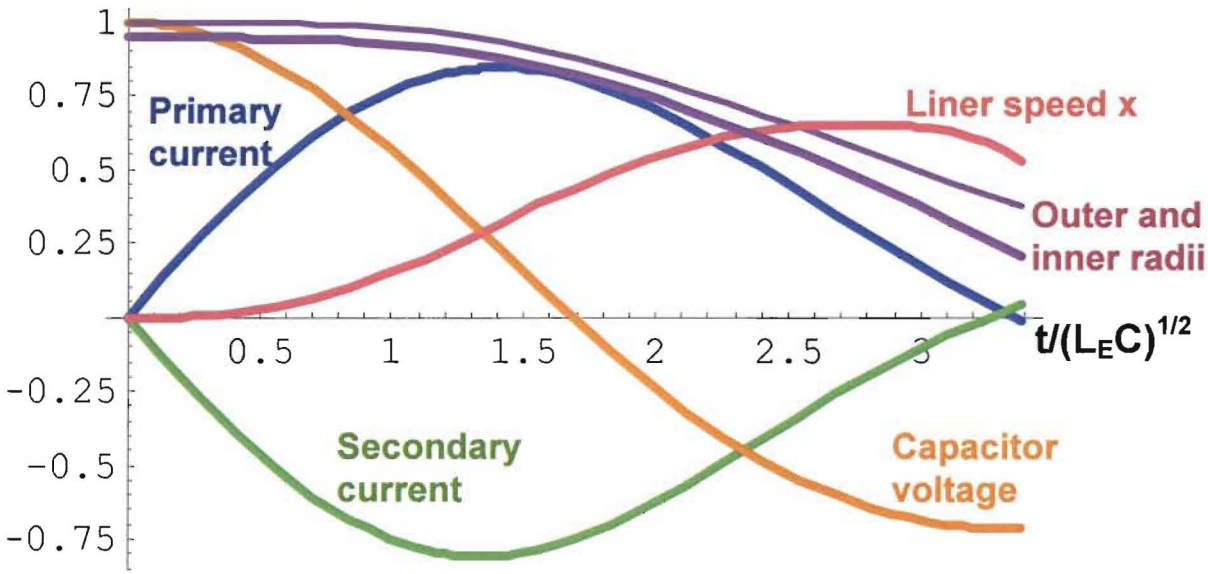



Figure 7: Normalized solutions for basic circuit behavior for flux compression without resistive losses. ($\Gamma = 0.1267$, $K = 0.616$, $\theta = 0.00064$, $P = 0.002$, $R_{mF} = 0$ and $H_F = 0$)

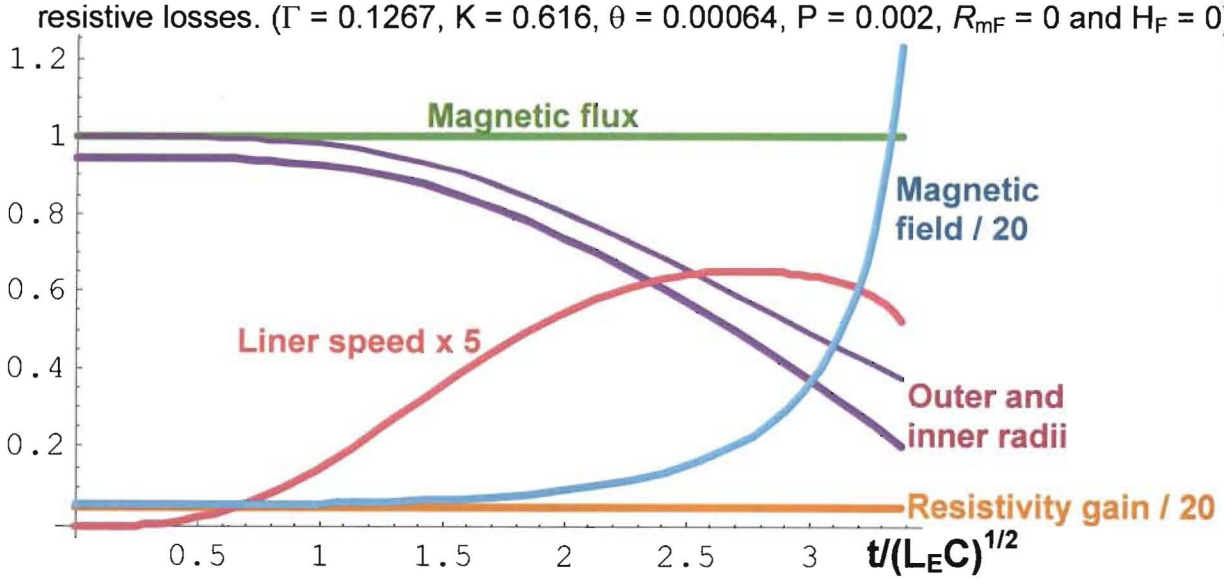



Figure 8: Magnetic flux compression without resistive losses.

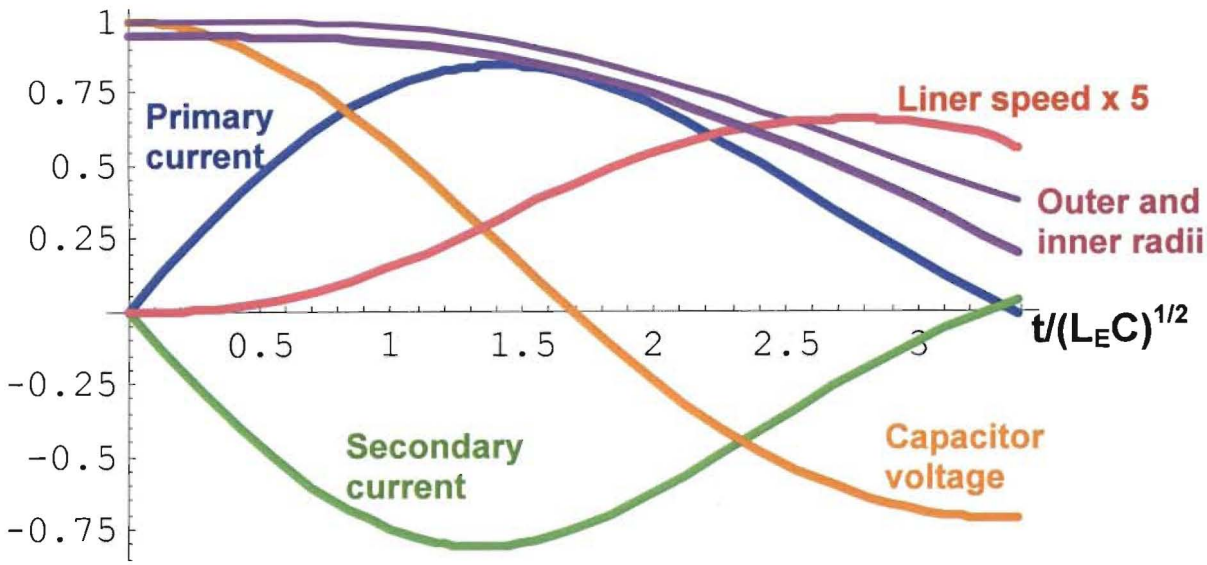



Figure 9: Normalized solutions for basic circuit behavior for flux compression without resistive losses. ($\Gamma$ = 0.1267, K = 0.616, $\theta$ = 0.00064, P = 0.002, $R_{mF}$ = 54.6 and $H_F$ = 0.2)

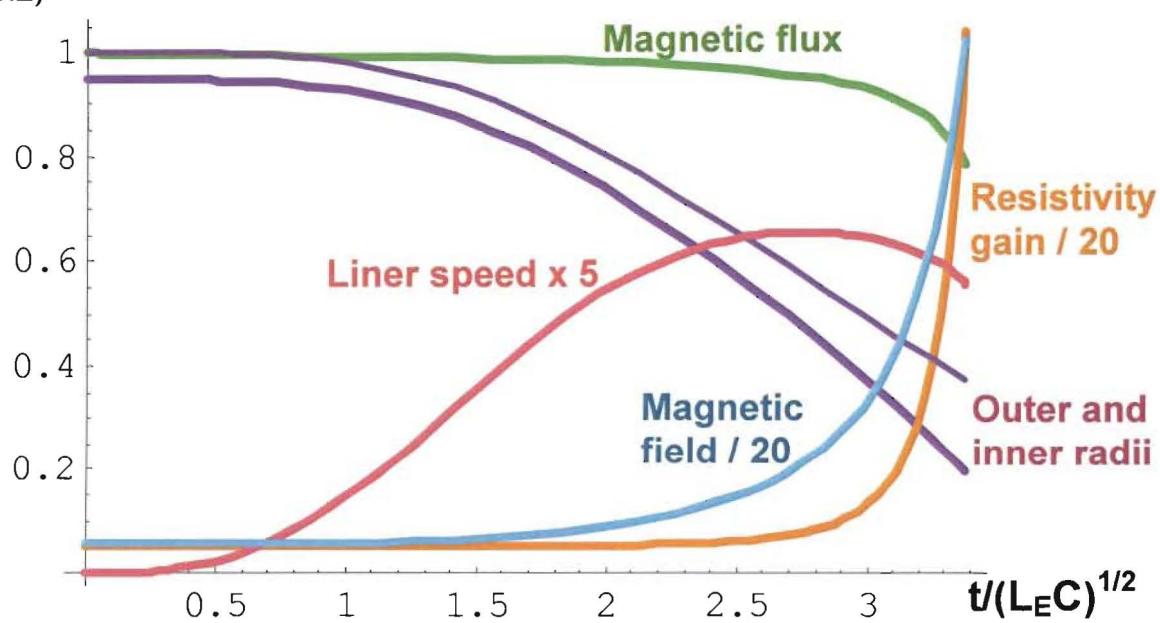



Figure 10: Magnetic flux compression with resistive losses.

A proton directed initially parallel to the axis of the implosion, but with a radius $r_p$, will experience an azimuthal deflection due to crossing the radial magnetic field that occurs at the end of the liner in connecting flux-lines from the megagauss field $B_z$ to the initial field. The resulting azimuthal speed is approximately:

$$v_\theta = (e/\gamma m_p) r_p B_z/2 \tag{26}$$

This azimuthal motion will interact with the subsequent axial field to provide a radial deflection in speed, given approximately by:

$$v_r = (e/\gamma m_p)^2 B_z^2 r_p h/2\beta c$$
$$= r_p h\, \beta c\, /2r_g^2 \tag{27}$$

where we have a small deflection, so the axial speed of the proton remains about equal to $\beta c$. The angular deflection of the proton in the rz-plane is then simply:

$$\Delta\theta = v_r/\, \beta c = r_p h\, /2r_g^2 \tag{28}$$

For $r_p$ = 5mm and h = 2cm, the deflection would be about 21 mrad, which is comparable to values associated with the proton radiography (pRad) system at LANSCE. While more elaborate calculations of proton dynamics through the magnetic field and liner material are needed, it appears possible that pRad could provide quantitative diagnosis of a PHELIX flux compression event, including behavior near the inner surface of the liner. This would represent a new and unique capability for studies of imploding liner flux compression.

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