Title: Evaluation of Conductor Stresses in a Pulsed High-Current Toroidal Transformer

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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 5-10 MAmps of peak current with pulse rise-time of ~5-10 ms. Crucial to the performance of PHELIX is a multi-turn primary, single-turn secondary, current step-up toroidal transformer, $R_{\text{major}} \sim 30 \text{ cm}$, $R_{\text{minor}} \sim 10 \text{ cm}$. The transformer lifetime should exceed 100 shots. Therefore it is essential that the design be robust enough to incur the magnetic stresses produced by high currents. In order to evaluate our design, two methods have been utilized. First, a theoretical evaluation has been performed. By identifying the magnetic forces as $J^2/2 \cdot \nabla L$, where $J$ is the electric current and $L$ in the inductance of the system, estimates of stress can be obtained for a simple steady-state system. These results are then compared to a computational MHD model of the same system. Results will be discussed.
PHELIX Toroidal Transformer Integral for High Performance Hydrodynamics at Reduced Spatial Scales

- Precision High-Energy Liner Implosion eXperiment – Couple portable pulsed-power hydrodynamics to Los Alamos proton radiography.
- Smaller Scale Experiment Requires Less Stored Energy
- Proton Radiography Provides 10-15 images per experiment, reducing the shots in an experimental series, further improving the economics
- Step-Up Transformer Increases Load Current and reduces parasitic, transmission-line inductances.
- Large-Aspect, Reusable, Toroidal transformer reduces flux loss, thus increasing coupling efficiency.

However, Small Spatial Scales Increase Magnetic Pressures, Current Densities and Conductor Stress

Toroidal Step-Up Transformer Design Parameters

- Geometry - Toroidal with primary coils inside of the secondary coil
- Winding Ratio - 4:1
- Primary Winding - RG-217 stripped of outer conductor, 40 total
- Secondary Winding - Aluminum (6061-T6) with integral transmission line to the load
- 20 Segments for ease of assembly
- \( R_{\text{minor}} \approx 12.0 \, \text{cm} \) (determined by estimate of coupling coefficient \( k = 0.9 \))
- \( R_{\text{Major}} \approx 36.6 \, \text{cm} \) (determined by min. spacing of primary winding and Minor Radius)
- \( L_p = 395.5 \, \text{nH} \)
- \( L_a = 89.0 \, \text{nH} \)
Transformer Segment Prototype Has Been Fabricated

- 20 segment primary ($\delta \theta = 18^\circ$)
- 2 cables per segment
- Utilized 3D printing technology
- Center section is the 'real' part
  - Cables sit in helical channels
  - Easily wound

Approximate Stresses on Conductors by Inductance Gradient Method for a Cylindrical Solenoid

- Unwrap torus into a cylinder
  - $2\pi R_{\text{major}} \Rightarrow L$
  - $R_{\text{minor}} \Rightarrow R$
- Evaluate using inductance formulae for concentric solenoids
- Neglect fringing fields
- Static Approximation

\[ F_1 = \frac{I_1^2 \nabla L_1 + 2 I_1 I_2 \nabla M_{12}}{2} \]

\[ L_1 = \frac{\mu_0 \pi N_1^2 R_1^2}{L} \]

\[ M_{12} = \frac{\mu_0 N_1 N_2 \pi R_2^2}{L} \]

\[ \nabla = \hat{r} \frac{\partial}{\partial r} + \hat{\theta} \frac{\partial}{\partial \theta} \]

Force on Coil-1
Self Inductance
Mutual Inductance
Gradient Definition
Analytic Inductance Gradient Method

Primary Coil

\[ F_{1,\text{c}} = -\mu_0 N_1^2 I_1^2 \frac{R_1}{L} \left( \frac{R_1}{R_2} \right)^2 \left( 1 - \frac{1}{2} \right) \]  
Compression

Secondary Coil

\[ F_{2,\text{c}} = \mu_0 N_1^2 I_1^2 \frac{R_1}{2L} \left( \frac{R_1}{R_2} \right)^4 \]  
Tension

\[ F_{2,\text{t}} = \mu_0 N_1^2 I_1^2 \frac{R_1}{4L} \left( \frac{R_1}{R_2} \right)^4 \]  
Tension

Parameters

- \( R_1 = 11.4 \text{ cm} \)
- \( R_2 = 12.0 \text{ cm} \)
- \( L = 2\pi \times 36 \text{ cm} = 226 \text{ cm} \)
- \( I_1 = 1 \text{ MA} \)
- \( N_1 = 4 \)

Stresses on Secondary Coil

- \( S_{2,r} = 44 \text{ bar} \)
- \( S_{2,z} = 136 \text{ bar} \)

RAVEN Calculation of Single Turn Secondary Coil as the Outer Conductor of Cylindrical \( \theta \)-pinch

- 1D MHD Code with Circuit
- Unwrap torus into a cylinder
  - \( L = 2\pi R_{\text{major}} = 226 \text{ cm} \)
  - \( R = R_{\text{minor}} = 12 \text{ cm} \)
- Apply Expected \( I(t) \)
  - \( T_{\text{rise}} \sim 2 \mu\text{s} \)
  - \( I_{\text{peak}} \sim 5 \text{ MA} \)
- Keep \( J \sim 10^{10} \text{ A/m}^2 \)

\( r \text{ (MA)} \)

\( T \text{ (\mu s)} \)

\( \rho \text{ (g/cc)} \)

\( P < 100 \text{ bar} \)

\( Y_0 \)

\( T = 2 \mu\text{s} \)

\( J_\theta \times 10^{-10} \text{(A/m}^2) \)
High Fidelity 3D Modeling of Transformer is Underway

- ANSYS™ Multi-Physics
- 18° Wedge (1/20 Torus)
  - 3.5 M Nodes
  - Brick and Tet Elements
- Parallel Flux BC at Cable Inputs
- Periodic BC at the lateral faces
- I(t)/40 applied to 2 coils

Initial Results Indicate the Skin Effect is Captured within the 3-Element Surface Layers

- ~1 hr Runs
- E&M Results will be fed into a structural/thermal model
- Open loop approximation
- Field highly concentrated
- Computed forces consistent with analytic theory
- B field (T)
  - 0.1456 - 0.0456
  - 1.943
  - 9.293
  - 12.3
  - 15.371
  - 185.679
  - 216.624
  - 247.57
  - 278.516
- The skin effect is captured in the 3-element layer at the surface
- Insulation is not plotted
Summary and Conclusions

- Reusable, Toroidal, Current Step-up Transformer is being Designed and Constructed as an integral part of the Portable PHELIX Pulsed-Power Machine at LANL.

- Stresses on transformer components and transmission line have been analyzed theoretically and computationally in a cylindrical approximation.

- Full 3D finite element analysis is underway.

Extras
\( R_{\text{minor}} \) Determined by Cable Dimensions and Coupling Coefficient.
\( R_{\text{major}} \) Determined by \( R_{\text{minor}} \) and Close Packing Along Inner Wall

- Assuming Uniform Field, the coupling coefficient \( (k = 0.9) \) is just the ratio of the areas of the primary and secondary.

\[
\frac{R_p}{R_s} = \sqrt{k}
\]

\[
R_p = R_s - \frac{\delta x}{2}
\]

\[
R_s = \frac{\delta x}{2} \left(1 - \sqrt{k}\right)
\]

\( R_s = 12.0 \, \text{cm} \)

- \( N = 40 \) Cables
- Zero spacing between cables on inner wall

\[
R_{\text{Major}} = R - \frac{\delta x}{2} + R_{\text{Minor}}
\]

\( R_{\text{Major}} = 36.6 \, \text{cm} \)

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Simple Analysis Gives Minimum Disposable Experimental Cassette Radius

\[
B_g = \frac{\mu_0 I}{2\pi R}
\]

\[
P_{\text{Mag}} = \frac{B^2}{2\mu_0}
\]
Theoretical Analysis in Cylindrical, Steady-State Approximation Prompted Detailed Analysis/Simulation

- Multi-Turn, Primary Coils want to shrink in diameter
- Single-Turn Secondary Coil wants to expand
- Torque – Toroidal coils want to align
- Transmission Line – Minimum radius for no plastic deformation