MagNIF Conceptual Design and Coil Testing

Meeting on Magnetic Fields in Laser Plasmas

Laboratory for Laser Energetics, University of Rochester

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Outline

- MagNIF Lab Pulser
  - Requirements, main components, system diagram and basic electrical schematic

- Pulser Components
  - Energy storage, switch, transmission line and load

- Experimental Results
  - Numerical simulations, PSPICE, magnetic probes, high-speed imaging, two-color pyrometer and debris catcher

- Proposed Design
  - Conceptual CAD, Controls

- Pulse Power Future Plan
Gas pipe disassembly imaged with 10 MHz video camera
Pulser Specific Requirements

- **Electrical**
  - Max voltage 40 kV, short circuit current of 50 kA, pulse widths ~ $\mu$s
  - Max inductance ~ 750 nH

- **Vacuum Integrity**
  - Must pass NIF vacuum cleanliness standards

- **Volume**
  - Constrained to an airbox that must fit within TANDM payload adapter (or slightly modified)

- **Input power**
  - +28 VDC

- **Radiation resistance**
  - Needs to withstand NIF harsh radiation environment
MagNIF Lab Pulser

Offline lab pulser allows significant development and understanding of the dynamics of exploding solenoids.

Original design by M. Rhodes, F. Allen and S. Hawkins

Figure 1 – MagNIF lab pulser.

Diagnostics not shown:
- B-dot probes
- 10 MHz video camera
- Two-color pyrometer
- Debris and shrapnel catcher
Lab Pulser System Diagram

Figure 2 – System diagram of MagNIF lab pulser.
MagNIF lab pulser simplified electrical schematic

Figure 3 – Side view of MagNIF lab pulser with basic electrical schematic.

MagNIF lab pulser reduces to four main components: energy storage, switch, transmission line and load.
Energy Storage and Switch: MagNIF lab pulser uses a high voltage capacitor paired with a commercial spark gap for reliable and economical switching

- **4 μF self-healing metallized polypropylene oil filled capacitor**
  - max voltage 40 kV
  - peak current 70 kA
  - max stored energy 3.2 kJ, stored charge 0.16 Coulomb
  - ESR < 15 mΩ, ESL 52 nH

- **Trigatron spark gap**
  - working voltage 20-50 kV ($N_2$)
  - peak pulsed current 100 kA
  - inductance < 35 nH
  - breakdown delay and jitter of < 0.5 μs and < 0.2 μs respectively ($V_g = 0.8V_{sb}$)
  - Max charge transfer 0.5 Coulomb
Pulser delay and jitter is dominated by spark-gap breakdown

- Total delay $t_d$ is measured from time to current peak and jitter $t_j$ is estimated from spread in that measurement.

![Breakdown curves for SG-121 spark-gap.](image1)

![Pulser Jitter vs Spark Gap Pressure (Dry Air).](image2)

Note: operating at 6 psig (67% $V_{sb}$) $t_j \sim 120$ ns, however will drastically reduce chance of pre-fire.
Electrical triggering provides cost effective and reliable switching

- **Electrical trigger system block diagram**

  ![Diagram](image.png)

- **Concerns**
  - Neutron and X-ray radiation resistance of electronics

- **Possible alternative**
  - Laser triggered spark-gap
Radiation Damage Component Testing

- Largest concern is integrated electronics and discrete components at voltage such as capacitors, FETs and IGBTs.
  - Capacitors will most likely degrade over time.
  - IGBTs and FETs are susceptible to catastrophic failure from prompt dose.

- Plan 1: Test current hardware selection under normal operation in a similar radiation environment.
  - Turn off radiation susceptible components before the shot?
  - Relocate components within the airbox?

- Plan 2: Relocate high voltage power supply to rack. Laser triggered spark gap.
Transmission line: Kapton strip-line provides very low inductance, high voltage standoff and vacuum compatibility.

- Tested prototypes to 32 kA and 12 kV (drop over strip-line and load)
- Working on new prototype for 50 kA and 40 kV
- Passed NIF cleanliness testing

![Figure 4 – CAD model and prototype strip-line potted in a vacuum flange.](image)

![Figure 5 – Kapton strip-line layup.](image)
Load: During testing, simple solenoids are wound on ABS and PEEK mandrels and terminated with ring lugs.

- **Gas Pipe Coil**
  - 14 turn
  - 1 mm pitch
  - 9 mm diameter
  - 26 AWG Kapton coated silver-plated solid-core copper wire
  - 52 mΩ (300 K) – 448 mΩ (1350 K)$^1$
  - ~ 800-900 nH

- **Warm Hohlraum Coil (less defined)**
  - 5.5-6.5 turn
  - 0.7 mm pitch
  - 6 mm diameter
  - 24 AWG Kapton coated silver-plated solid-core copper wire
  - 14 mΩ (300 K) – 90 mΩ (1350 K)$^1$
  - ~ 200 nH

$^1$Matula Ra, Journal of Physical and Chemical Reference Data 1979
PSPICE Model and action dependent coil resistivity accurately predicts pulser performance

Figure 7 – PSPICE model of the MagNIF lab pulser.

Figure 8 – Comparison of PSPICE model with experimental gas pipe 28 kV data.

PSPICE simulation and plot courtesy of Glen James
Typical magnetic pick-up probe measurements for gas pipe and Hohlraum style coils

Figure 11 – Typical magnetic measurements of gas pipe and Hohlraum style coils.

\[ B(t, z) = \frac{I(t)\mu_0 N}{2l} \left( \frac{z + \frac{l}{2}}{\sqrt{r^2 + \left( z + \frac{l}{2} \right)^2}} - \frac{z - \frac{l}{2}}{\sqrt{r^2 + \left( z - \frac{l}{2} \right)^2}} \right) \]
Numerical Studies\textsuperscript{1} of 5.5 Turn Hohlraum Coil

Figure 12 – On axis magnetic field strength of 5.5 turn Hohlraum coil with varying currents.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure12.png}
\caption{On axis magnetic field strength of 5.5 turn Hohlraum coil with varying currents.}
\end{figure}

Figure 13 – Spatial profile of magnetic field for 5.5 turn Hohlraum coil at 40 kA.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure13.png}
\caption{Spatial profile of magnetic field for 5.5 turn Hohlraum coil at 40 kA.}
\end{figure}

\textsuperscript{1}Simulation plots courtesy of Charles Brown
Electrostatic Simulations\(^1\) of Pulser Hardware Allow for Optimization

Figure 12 – Electrostatic field simulation of pulser hardware. Simulation voltage is 1 V, with a maximum electric field strength of 43.3 V/m, which corresponds to 1.7 MV/m when scaled to 40 kV. The dielectric strength of air at 1 atmosphere is 3 MV/m.

\(^1\)Simulation plots courtesy of Charles Brown
Multi-channel magnetic probes have been developed using PCB inductor chips with spatial resolution of ~ 2 mm.

\[ V_{\text{induced}} = N \frac{d\Phi}{dt}, \quad V_2 = \frac{1}{RC} \int V_1(t)dt \]

\[ \therefore V_{\text{measured}} = \frac{NA\cos(\theta)}{RC} B \]
To help quantify coil melting, debris is captured in Aerogel pucks and analyzed under a microscope.

- Python script adjusts contrast, converts RGB information into scalar intensity maps, finds “blobs” and measures their relative size.

Figure 17 – Microscope image of debris captured in Aerogel puck.

Figure 18 – Python script is used for further processing and tracking blobs.
2D temperature maps are estimated using two-color pyrometry at 10 MHz

- Two-color pyrometer is used to measure the temperature of the coils to ensure adequate melting just after the peak of the current pulse
Conceptual Design

- Trigger Head
- Trigger Transformer
- Dump Resistor
- HV Charging Supply
- Spark-Gap Switch
- Trigger Pin (or collimating optics)
- Vacuum Relay (or Ross Relay)
- HV Capacitor
- Damping Resistors
- Shunt Resistor
- Kapton Strip Line
- Return Current
- Vacuum Interface
Three high-voltage vacuum connections are required to connect the pulser to the target.

- Rigid Strip-line (potted)
- Rigid Strip-line
- Flex Circuit
- Twisted Pair Wire
- Multi-lam pin and crimp or ring lugs to target coil wires
Strip-line to wire connection: ring lugs are a simple connection that have proven reliable in lab testing.
Experimental Summary

- Achieved 30 Tesla in gas pipe coil targets
- Achieved 35 Tesla in Hohlraum coil targets
  - Limited by pulser voltage and inductance in lab
- Developed a full suite of diagnostics for continuing coil development
- Integrated pulser into DIM compatible volume
Pulse Power Plan Forward

- **Current Design Status**
  - Conceptual design that fits inside of an airbox in TANDM with tested components that should be compatible with the NIF facility

- **Current Experimental Status**
  - 50 kA, 40 kV strip-lines in development
  - Need to test strip-line performance in vacuum
  - When new high-speed camera arrives, can finish pyrometer diagnostic and resume coil testing
  - Testing connection methods for rigid and flexible strip-lines to pulser and coil loads.

- **Risks**
  - Strip-line vacuum integrity
  - Radiation resistance for electronics
  - Connections from pulser to coil load
  - High voltage standoff in pulser airbox
Backup Slides
- Warm B-field requirements review on 12/18/17
- Warm B-field FMEA review on TBD
- Warm B-field pulsed power CDR on 2/14/18
  - Focused session on electrical design concept
  - Reviewed by SMEs from LLNL, LLE, SNL, Univ. of Michigan
Radiation Resistance of Kapton Film

Table 12. Effect of Gamma Radiation Exposure on Kapton® Polyimide Film (Cobalt 60 Source, Oak Ridge)

<table>
<thead>
<tr>
<th>Property</th>
<th>Control 1 mil Film</th>
<th>$10^4$ Gy 1 h</th>
<th>$10^5$ Gy 10 h</th>
<th>$10^6$ Gy 4 d</th>
<th>$10^7$ Gy 42 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, MPa ($\times 10^5$)</td>
<td>207 (30)</td>
<td>207 (30)</td>
<td>214 (31)</td>
<td>214 (31)</td>
<td>152 (22)</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>80</td>
<td>78</td>
<td>78</td>
<td>79</td>
<td>42</td>
</tr>
<tr>
<td>Tensile Modulus, MPa ($\times 10^5$)</td>
<td>3172 (460)</td>
<td>3275 (475)</td>
<td>3378 (490)</td>
<td>3275 (475)</td>
<td>2903 (421)</td>
</tr>
<tr>
<td>Volume Resistivity $\Omega$·cm $\times 10^{13}$ at 2°C (392°F)</td>
<td>4.8</td>
<td>6.6</td>
<td>5.2</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Dielectric Constant 1 kHz at 2°C (73°F)</td>
<td>3.46</td>
<td>3.54</td>
<td>3.63</td>
<td>3.71</td>
<td>3.50</td>
</tr>
<tr>
<td>Dissipation Factor 1 kHz at 23°C (73°F)</td>
<td>0.0020</td>
<td>0.0023</td>
<td>0.0024</td>
<td>0.0037</td>
<td>0.0029</td>
</tr>
<tr>
<td>Dielectric Strength V/μm (kV/mm)</td>
<td>256</td>
<td>223</td>
<td>218</td>
<td>221</td>
<td>254</td>
</tr>
</tbody>
</table>

Table 13. Effect of Electron Exposure on Kapton® Polyimide Film Mixed Neutron and Gamma

<table>
<thead>
<tr>
<th>Flux at 175°C (347°F)</th>
<th>5 x $10^7$ Gy</th>
<th>10$^8$ Gy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Film Darkened</td>
<td>Film Darkened and Tough</td>
</tr>
</tbody>
</table>

Table 14. Effect of Ultraviolet Exposure on Kapton® Polyimide Film

<table>
<thead>
<tr>
<th>1000 h Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, % of Initial Value Retained</td>
</tr>
<tr>
<td>Elongation, % of Initial Value Retained</td>
</tr>
</tbody>
</table>

*Vacuum environment, 2 x $10^{-6}$ mmHg at 50°C (122°F). UV intensity equal to space sunlight to 2500A.

Summary box has a full-width bleed. Delete if not needed.
Inductance Calculations

- Gas pipe solenoid (single layer coil approximation)\(^1\)
  
  \[ L = \frac{0.004 \pi^2 a^2 N^2 K}{b} = 1.05 \mu H \]

  Where, \(a\) = mean radius, \(b\) = length, \(N\) = number of turns, \(K\) = tabulated end-effect correction factor

- Hohlraum Solenoid

  \[ L = \frac{0.004 \pi^2 a^2 N^2 K}{b} = 0.191 \mu H \]

\(^1\)Grover F., Inductance Calculations 1973
Transmission Line Impedances

<table>
<thead>
<tr>
<th>Transmission Line Capacitance and Inductance per Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constants</td>
</tr>
<tr>
<td>$\mu_0$</td>
</tr>
<tr>
<td>$\mu_r$</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
</tr>
<tr>
<td>$\pi$</td>
</tr>
<tr>
<td>Coaxial Line</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>$Z_0$</td>
</tr>
<tr>
<td>2 Parallel Open Wire Line</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>$Z_0$</td>
</tr>
<tr>
<td>Parallel Plate Line</td>
</tr>
<tr>
<td>w</td>
</tr>
<tr>
<td>s</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>$Z_0$</td>
</tr>
<tr>
<td>Single Wire Above Conducting Plate</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>h</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>$Z_0$</td>
</tr>
</tbody>
</table>

1Smith F., Pulse Electronics

Summary box has a full-width bleed.
Delete if not needed.