The Design of Magnetically Insulated Transmission Lines*

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We design magnetically insulated transmission lines using a circuit code and the Z flow MITL model

• Our goal is to provide a MITL profile that optimizes the coupling of electrical energy to a reactive load.
  – Multi-disk vacuum transmission lines and a post hole convolute are modeled.
  – We use a z-pinch load.

• We use Screamer, an open-source circuit code, originally developed by Sandia National Laboratories to model the MITL performance.
  – Screamer contains physics-based models for magnetically insulated transmission lines (MITLs).

• We also use the $Z_{\text{flow}}$ model developed by Mendel and Ottinger to examine the “quality” of the magnetic insulation.
  – Compare the vacuum impedance $Z_{\text{vac}}$ to the flow impedance $Z_{\text{flow}}$.
  – Compare the cathode current to the vacuum electron flow current.
  – Calculate the sheath thickness of the vacuum electrons.
We will model a short, 2-Ω impedance MITL as Part of a Two-Disk Design Operating at 15 TW

• Time prohibits us from showing the iterative steps in the design.
• A constant vacuum impedance provides a constant E/cB over the entire transmission line (if terminated in a constant impedance).
  – This is not true if the MITL is terminated into a reactive load.
• The desire for a low, total vacuum inductance drives us to low impedance MITLs as \( L_{\text{MITL}} \sim Z_{\text{vac}} \tau \), where \( \tau \) is the length of the MITL in seconds.
• Limitations on the minimum MITL impedance (inductance) include:
  – Magnitude of the electron losses during the set up of magnetic insulation.
  – Characteristics of the steady-state MITL including vacuum electron flow and sheath thickness.
• Clearly the final choice for MITL impedance is driven the desire for low inductance (driving \( Z_{\text{vac}} \) down) and minimum electron flow and sheath thickness (driving \( Z_{\text{vac}} \) up).
• With this as the background we describe the modeling and performance of a MITL with \( Z_{\text{vac}} = 2 \) Ω driven by a 0.125-Ω, 15-TW pulsed-power system.
This idealized configuration is modeled in Screamer.

We start with a non-emissive vacuum feed (vacuum flare) and transition to the 2-Ω MITL as quickly as possible.

- The minimum gap in the MITL is 1 cm.
- The MITL is divided into 10, individual MITL segments for physics clarity.
Screamer inputs a voltage pulse (from constant-impedance water lines) to drive the MITL

![Graph showing voltage over time]

- **V_stack_B**
- **V_stack_A**

**Zmitl = 2 Ω**
Each Disk Feed has Its Own Current

- $Z_{m, I} = 2 \text{ } \Omega$

- $I_{\text{stack}_B}$
- $I_{\text{load}}$
- $I_{\text{stack}_A}$
We Can Examine the Current in the 10, B-Level MITL Segments
We Now Examine the Electron Loss Current in the 10, B-Level MITL segments

![Graph showing current vs. time for different segments of MITL with Zmitl = 2 Ω.](image)
We Now Examine the Electron Loss Current Density in the 10, B-Level MITL segments
Here Are the Quantitative $Z_{\text{flow}}$ MITL Characteristics at Peak Voltage

<table>
<thead>
<tr>
<th>MITL Seg.</th>
<th>Radial Location (cm)</th>
<th>AK Gap (cm)</th>
<th>$V_a$ (MV)</th>
<th>$E_c$ (kV/cm)</th>
<th>$I_a$ (MA)</th>
<th>$Z_{\text{flow}}$ (Ω)</th>
<th>$I_c$ (MA)</th>
<th>$I_{\text{vac}}$ (kA)</th>
<th>$h_{sh}$ (mm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>144.95</td>
<td>4.835</td>
<td>1.28</td>
<td>265</td>
<td>2.77</td>
<td>1.978</td>
<td>2.693</td>
<td>77</td>
<td>0.52</td>
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<td>2</td>
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<td>4.431</td>
<td>1.22</td>
<td>275</td>
<td>2.77</td>
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<td>2.701</td>
<td>69</td>
<td>0.45</td>
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<td>3</td>
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<tr>
<td>5</td>
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<td>3.220</td>
<td>1.07</td>
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<td>2.723</td>
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<td>7</td>
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<td>8</td>
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<td>0.906</td>
<td>451</td>
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<td>2.732</td>
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<td>9</td>
<td>48.15</td>
<td>1.606</td>
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<td>10</td>
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<td>1.202</td>
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<td>1.986</td>
<td>2.740</td>
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<td>0.08</td>
</tr>
</tbody>
</table>

- **What are the key points here?**
  - The electric field increases with decreasing radius - the inner MITL emits first.
  - $Z_{\text{flow}} \sim Z_{\text{vac}}$ - good insulation
  - The vacuum electron current $I_{\text{vac}}$ is a small fraction of the cathode current $I_c$.
  - The sheath thickness $h_{sh}$ is a small fraction of the gap
- At all locations in the MITL the $Z_{\text{flow}}$ characteristics are consistent with super insulated vacuum flow.
The Simulation of the 2-Ω Disk MITL on B-Level Shows a Well-Behaved Low-Loss MITL

- The electron losses are concentrated on the inner MITL elements.
  - The electron loss current density is the key parameter for anode losses per cm$^2$
    - and the potential for raising a problematic anode plasma (400 °C).
  - Optimization of the MITL design to decrease the impedance (gap) of the outer MITL segments are possible.
- The equilibrium $Z_{\text{flow}}$ analysis shows that the MITLs always operate with well-insulated electron flow.
  - Specifically, the high value of $Z_{\text{flow}}$ and the low vacuum electron current $I_{\text{vac}}$
    show the high quality of the magnetic insulation.
  - Lowering the MITL impedance (smaller gaps) would eventually degrade the $Z_{\text{flow}}$
    performance of the MITL.
- Finally, the final MITL design should be validated with a highly resolved, 2-D (or 3-D) E&M PIC code.
Summary and Conclusions

• We have shown that it is possible to iteratively design MITLs for a 15-TW driver using the SCREAMER circuit code.
  – This SCREAMER calculation takes ~ 1 minute on a standard PC.
• The performance of the 2-Ω disk transmission line shown is excellent.
  – Electron losses are manageable and are lower than found on Z.
• The Z_{flow} MITL model can provide detailed information on the performance of MITLs throughout the pulse.
• 2-D or 3-D E&M PIC codes need only be used to validate the final design.
• The MITL design shown should not be considered optimized. Significant improvements are possible that lead to improved energy coupling to the load.
• SCREAMER (source code, run decks, installation instructions, and the manual) is available for download from http://www.iac.isu.edu/screamer.html and the detailed run deck used here is freely available upon request.