# The Design of Magnetically Insulated Transmission Lines*

R. B. Spielman & D. B. Reisman
Idaho Accelerator Center
Idaho State University
Pocatello, ID

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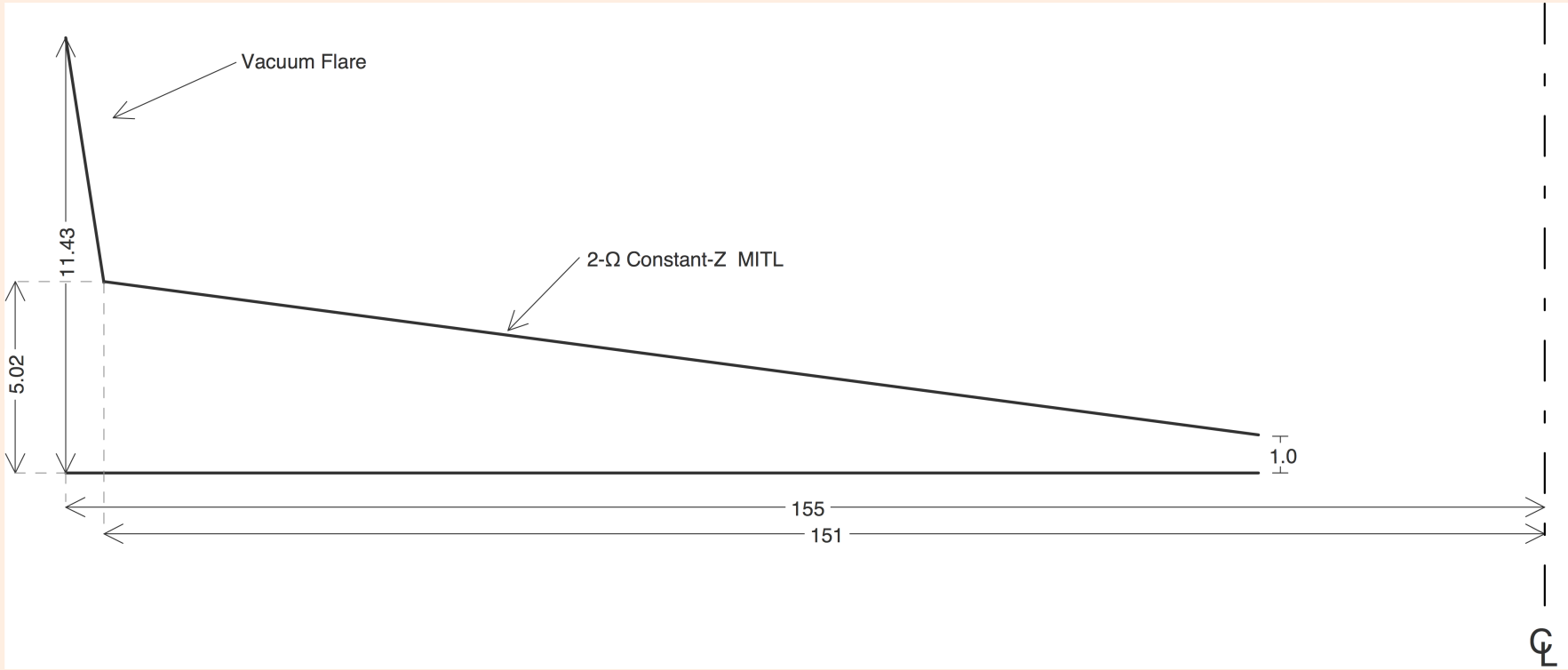
# We design magnetically insulated transmission lines using a circuit code and the Z flow MITL model

- 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 $Z_{flow}$ model developed by Mendel and Ottinger to examine the "quality" of the magnetic insulation.
  - Compare the vacuum impedance $Z_{vac}$ to the flow impedance $Z_{flow}$.
  - 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

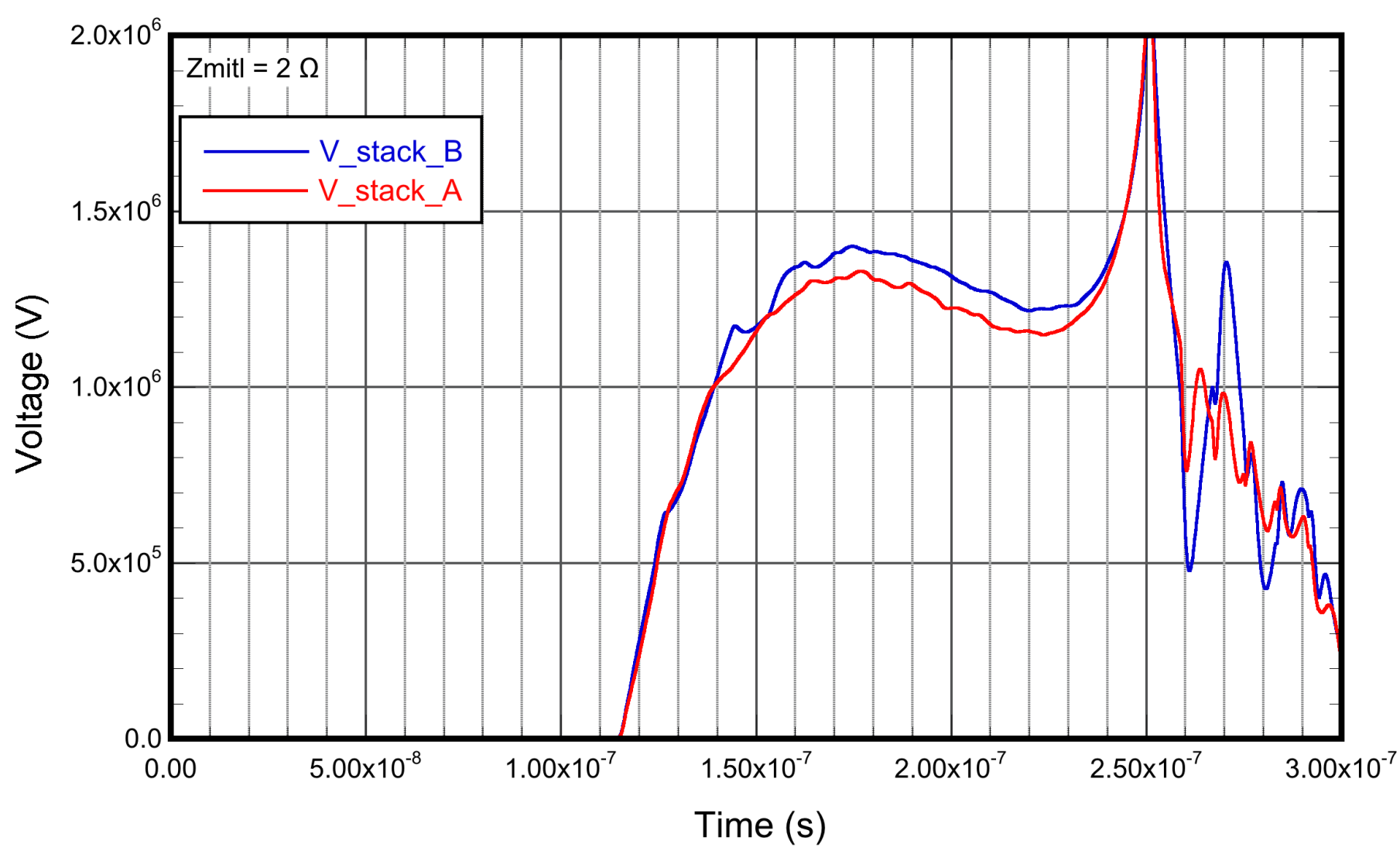
- Time prohibits us from showing the iterative steps in the design.
- A constant vacuum impedance provides a constant E/cB over the entire transmission line (if terminated in a constant impedance).
  - This is not true if the MITL is terminated into a reactive load.
- The desire for a low, total vacuum inductance drives us to low impedance MITLs as $L_{MITL} \sim Z_{vac}\,\tau$, 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 $Z_{vac}$ down) and minimum electron flow and sheath thickness (driving $Z_{vac}$ up).
- With this as the background we describe the modeling and performance of a MITL with $Z_{vac}$ = 2 Ω driven by a 0.125-Ω, 15-TW pulsed-power system.

# Anode and Cathode Geometries for a Single Disk MITL

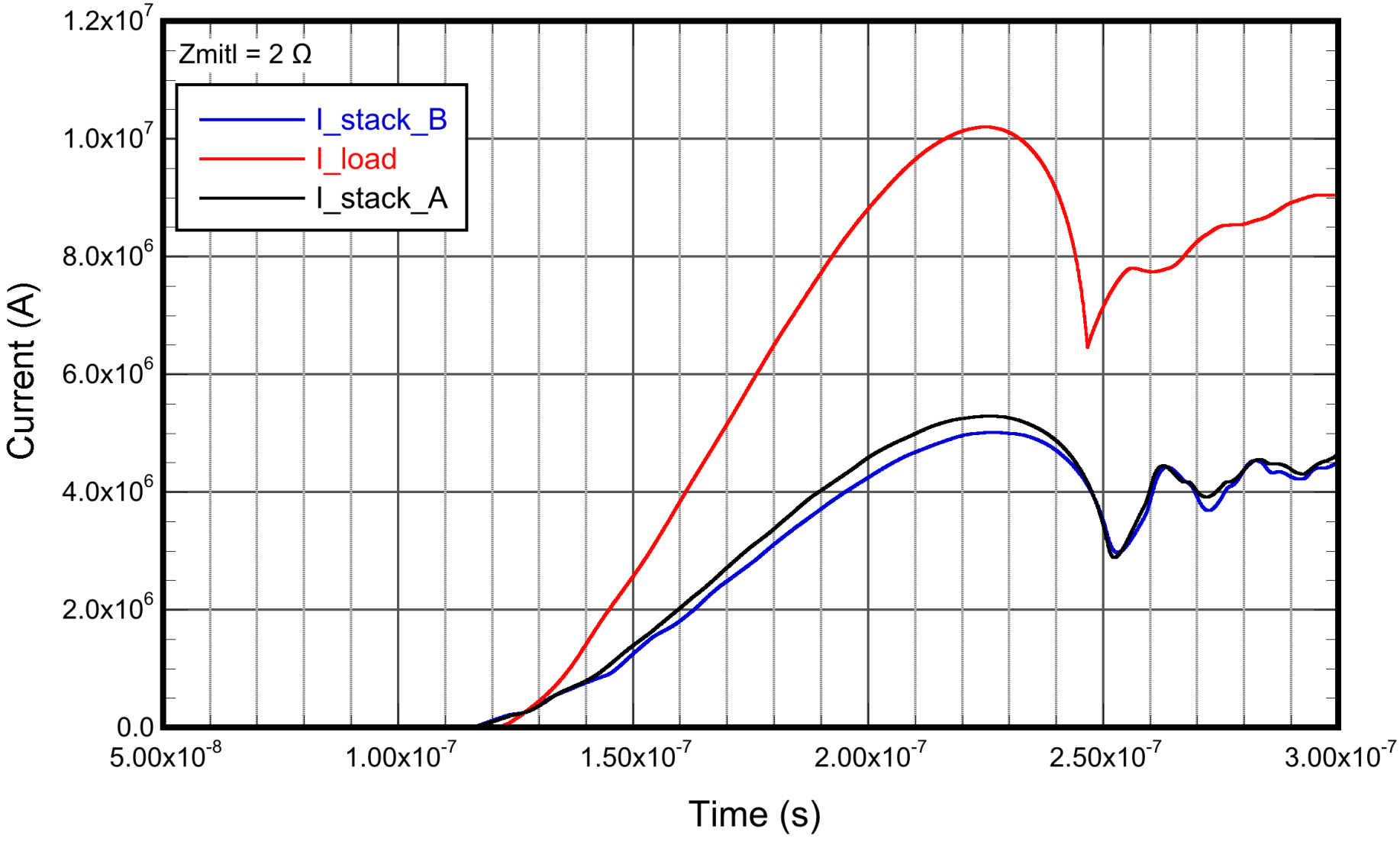



- This idealized configuration is modeled in Screamer.
- We start with a non-emissive vacuum feed (vacuum flare) and transition to the 2-Ω MITL as quickly as possible.
  - The minimum gap in the MITL is 1 cm.
  - The MITL is divided into 10, individual MITL segments for physics clarity.

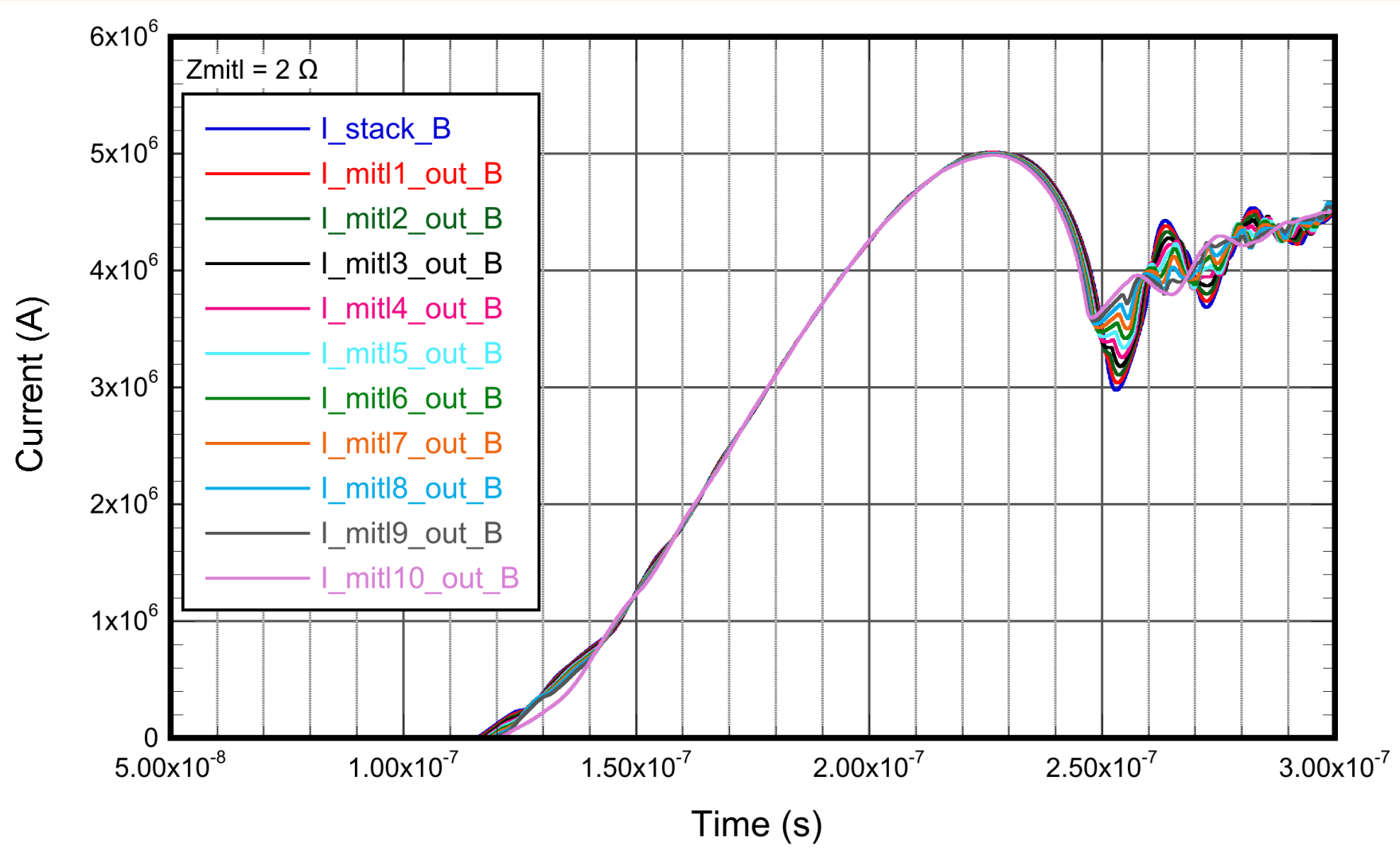
# Screamer inputs a voltage pulse (from constant-impedance water lines) to drive the MITL



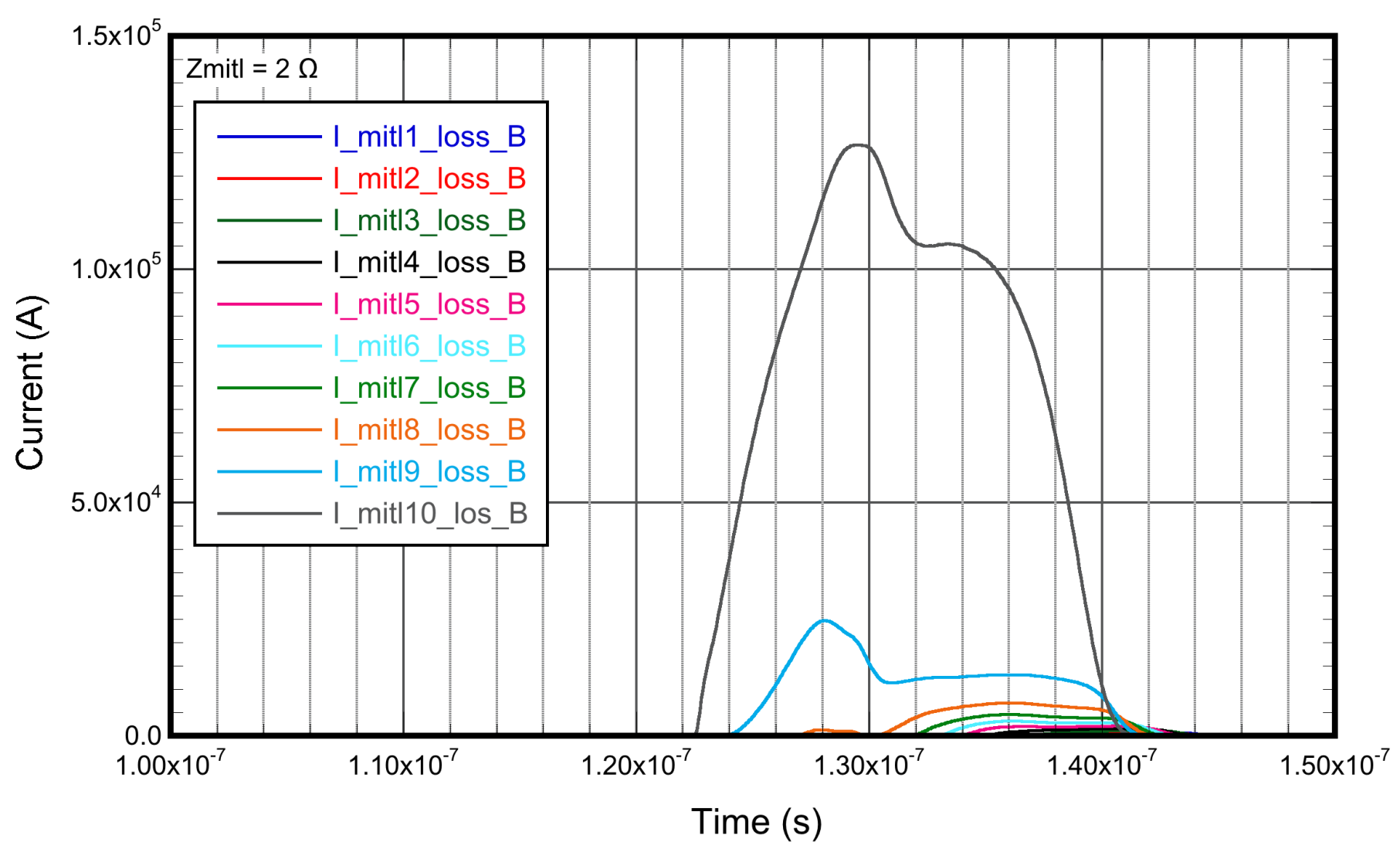
# Each Disk Feed has Its Own Current



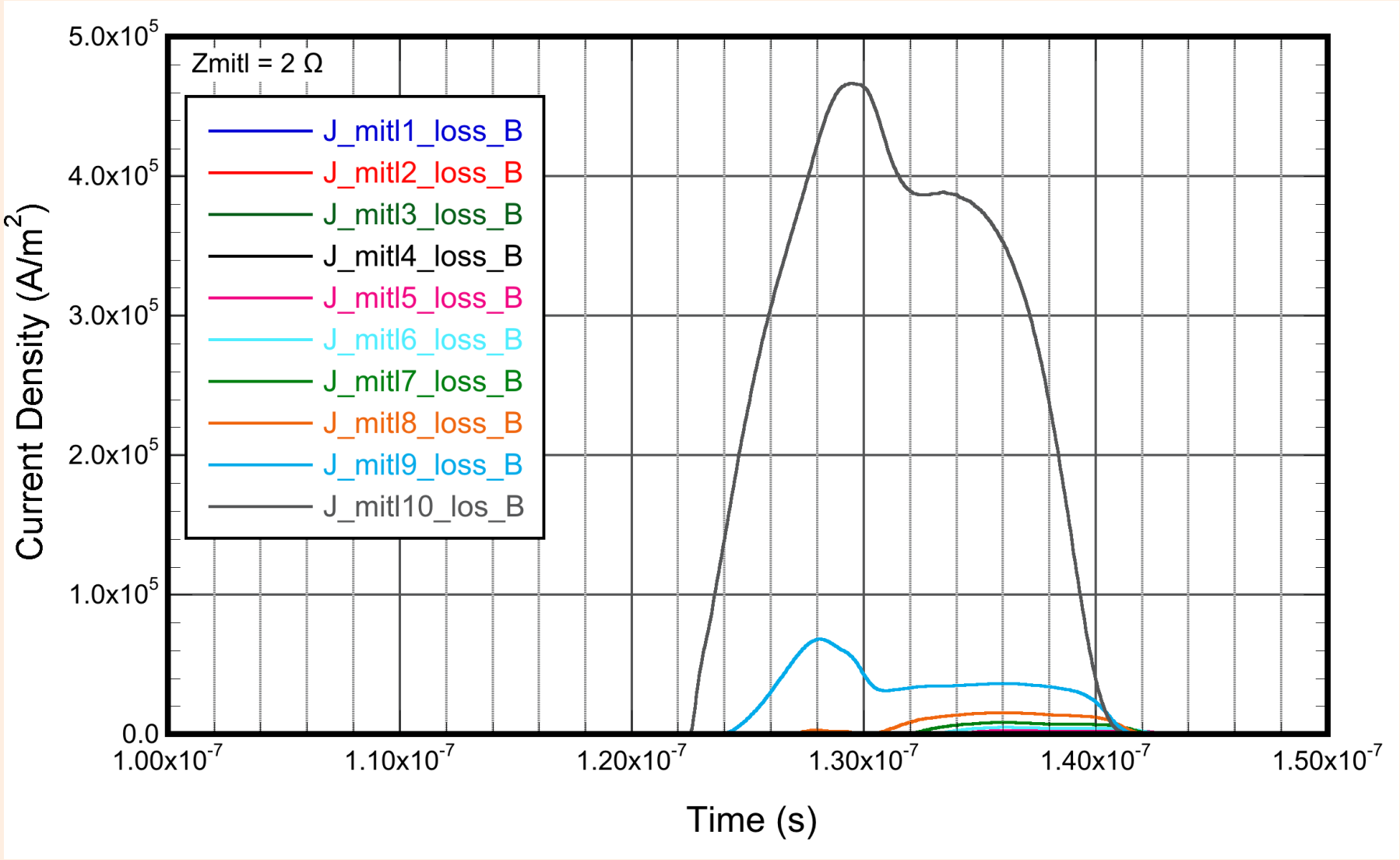
# We Can Examine the Current in the 10, B-Level MITL Segments



# We Now Examine the Electron Loss Current in the 10, B-Level MITL segments



# We Now Examine the Electron Loss Current Density in the 10, B-Level MITL segments



# Here Are the Quantitative $Z_{flow}$ MITL Characteristics at Peak Voltage

| MITL Seg. | Radial Location (cm) | AK Gap (cm) | $V_a$ (MV) | $E_c$ (kV/cm) | $I_a$ (MA) | $Z_{flow}$ (Ω) | $I_c$ (MA) | $I_{vac}$ (kA) | $h_{sh}$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 144.95 | 4.835 | 1.28 | 265 | 2.77 | 1.978 | 2.693 | 77 | 0.52 |
| 2 | 132.85 | 4.431 | 1.22 | 275 | 2.77 | 1.980 | 2.701 | 69 | 0.45 |
| 3 | 120.75 | 4.028 | 1.17 | 290 | 2.77 | 1.980 | 2.706 | 64 | 0.40 |
| 4 | 108.65 | 3.624 | 1.12 | 309 | 2.77 | 1.981 | 2.712 | 58 | 0.34 |
| 5 | 96.55 | 3.220 | 1.07 | 332 | 2.77 | 1.982 | 2.717 | 53 | 0.29 |
| 6 | 84.45 | 2.817 | 1.01 | 359 | 2.77 | 1.983 | 2.723 | 47 | 0.24 |
| 7 | 72.35 | 2.413 | 0.966 | 382 | 2.77 | 1.984 | 2.727 | 43 | 0.19 |
| 8 | 60.25 | 2.010 | 0.906 | 451 | 2.77 | 1.985 | 2.732 | 38 | 0.15 |
| 9 | 48.15 | 1.606 | 0.855 | 532 | 2.77 | 1.986 | 2.736 | 34 | 0.11 |
| 10 | 36.05 | 1.202 | 0.803 | 668 | 2.77 | 1.986 | 2.740 | 30 | 0.08 |

- What are the key points here?
  - The electric field increases with decreasing radius - the inner MITL emits first.
  - $Z_{flow} \sim Z_{vac}$ - good insulation
  - The vacuum electron current $I_{vac}$ 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 $Z_{flow}$ 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 $Z_{flow}$ analysis shows that the MITLs always operate with well-insulated electron flow.
  - Specifically, the high value of $Z_{flow}$ and the low vacuum electron current $I_{vac}$ show the high quality of the magnetic insulation.
  - Lowering the MITL impedance (smaller gaps) would eventually degrade the $Z_{flow}$ 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.