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4P63 - INFLUENCE OF VARIABLE IMPEDANCE TERMINATIONS AND INPUT VOLTAGES ON THE OPERATING CONDITIONS OF AN UNDER-MATCHED MAGNETICALLY-INSULATED TRANSMISSION LINE*

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SUMMARY

Termination of a magnetically-insulated transmission line (MITL) with an impedance that is less than the matched MITL operating impedance launches a re-trapping wave back up the MITL toward the source. A previous investigation[1] obtained the relationship for the MITL operating conditions (voltage and current) after the passage of the re-trapping wave that depended on the input voltage, the termination impedance, and the MITL operating conditions based on parapotential flow at minimum current. The relationship was in agreement with detailed particle-in-cell (PIC) simulations and experiments of the re-trapping wave process for large area diodes. The scaling law and simulations however were applied to a constant input (forward going) voltage and termination impedance. This work extends those PIC simulations and wave analyses to MITL operating conditions for termination impedances and input voltages that are functions of time. We examine the case in which the input voltage is constant and the impedance changes in a staircase manner. These results are extended to termination impedances that are continuously varying functions of time. The complementary case of fixed termination impedances and a variable input or forward going voltage will also be presented. The MITL operating conditions (V, I_{anode} and I_{anode}, $I_{cathode}$, Z diagrams) after the passage of the re-trapping will be examined as a function of the time history of the termination impedance and input voltage. Particle-in-Cell simulations are used extensively in the analyses and compared with linear and non-linear wave analyses. The objective of the work is to determine if the operating conditions of an under-matched magnetically insulated transmission line can be represented by a simple state function or do the final operating conditions depend on the previous time history of the termination impedance and input voltage.

1. Vernon L. Bailey, et al., “Re-trapping of Vacuum Electron Current in Magnetically Insulated Transmission Lines,” 15th International Conference on High-Power Particle Beams, July 18-23, 2004, pp. 247-250.

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Objectives

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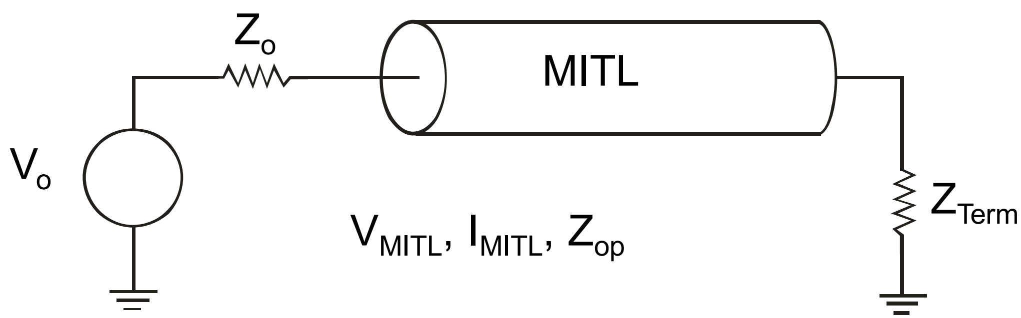
- Investigate the propagation of waves in an under-matched MITL.
- Waves include insulation waves that propagate from the source to the load and re-trapping waves that propagate from the load to the source due to reflection.
- Determine if hysteresis must be considered and if superposition can be used.
- Determine the constitutive relationship for the wave propagation.
  - +ΔV propagating from source to load
  - -ΔV propagating from source to load
    } Right Traveling Wave (in this discussion RTW)
  - +ΔV propagating from load to source
  - -ΔV propagating from load to source
    } Light Traveling Wave (in this discussion LTW)
- Determine the transmission and reflection coefficients for the waves.
- Consider the possibility of treating the MITL as a series of transmission lines.

Particle-in-Cell Simulations Used Extensively

- Code L-3 LSP
- Input



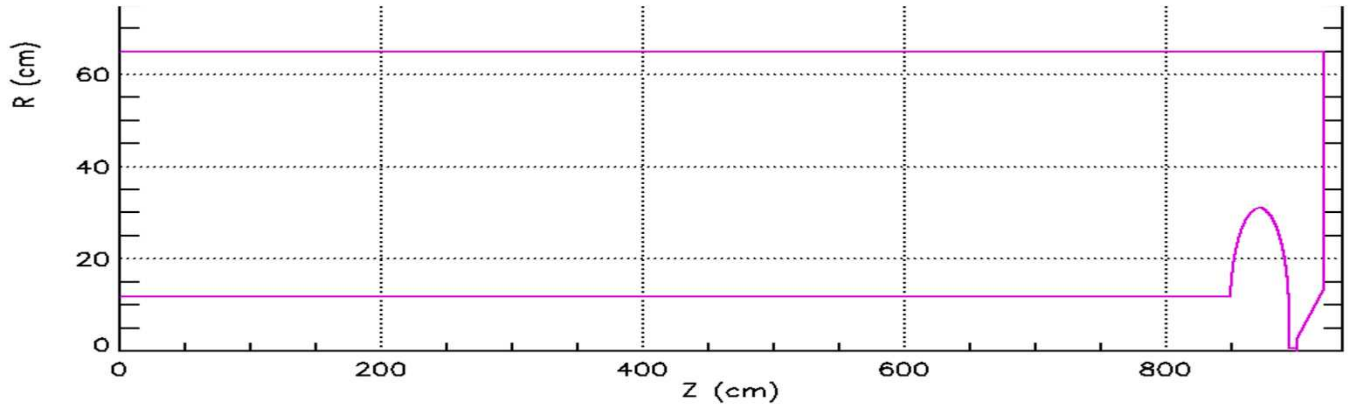
V_o	Source voltage or forward-going wave (RTW)
Z_o	Source impedance
V_{mitl}, I_{mitl}, Z_{op}	MITL operating conditions
Z_{term}	Termination impedance of MITL

- Geometry
  - Dustbin of RITS-6 with high-Z MITL matched to output of accelerator

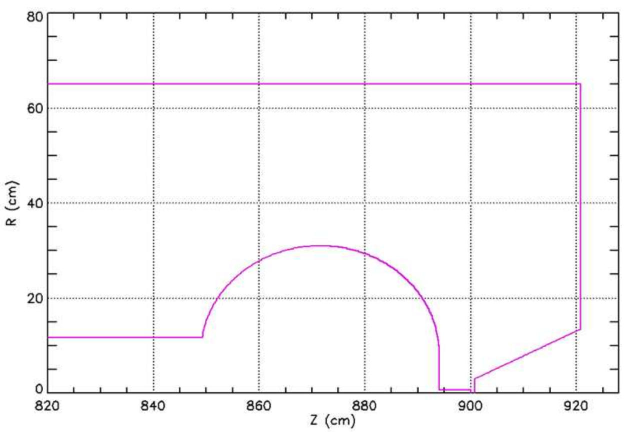
$$Z_{wave} = 102.8\ \Omega,\ Z_{op} \text{ at } 10.5\text{ MV} = 85.5\ \Omega$$

Non-Emitting Knob Plus Programmable Impedance Diode Used To Adjust MITL Termination Impedance

- MITL length used in simulations (~900 cm) much longer than RITS-6 dustbin (~150 cm) in order to separate wave transit effects



- Knob dimensions are those of RITS-6 experiments



  – Diode impedance programmed by adjusting the conductivity of a cylinder along the centerline that connects the cathode and anode

  – Dimension of cylinder chosen to crudely represent the self-magnetic pinch experiments being done on RITS-6

Effect of Boundary Conditions on MITL Parameters Behind Insulation Wave for Matched Case

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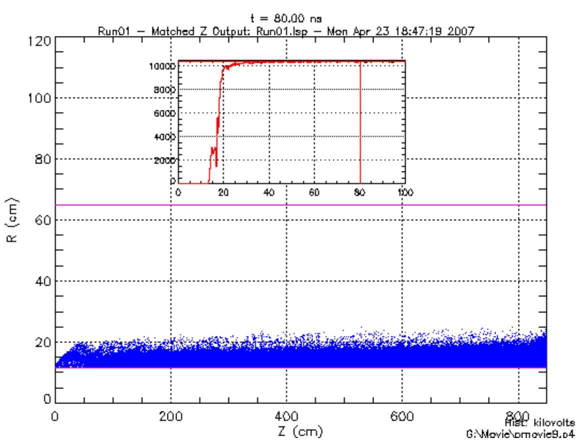
- Input
  - 10.5 MV matched to 85.5 ohm parapotential flow operating impedance
  - 5 ns rise and then flat
- Output
  - Outlet boundary at wave impedance (Z = 102.8 ohms)
- Three different numerical launch methods

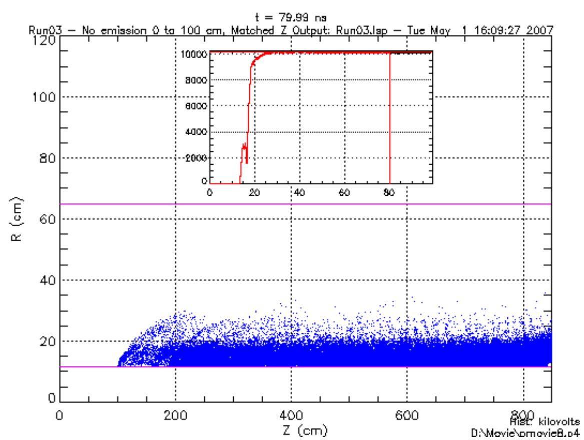
A



V_o launched axially at z = 0

Emission z > 0, 150 kV/cm

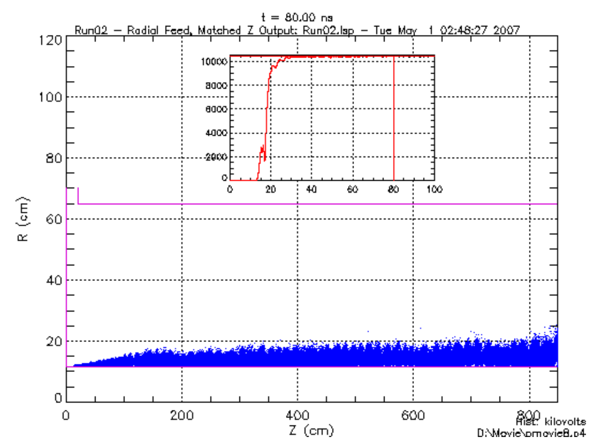
B



V_o launched axially at z = 0

Emission z > 100, 150 kV/cm

C



V_o launched radially inward at r = 65 cm

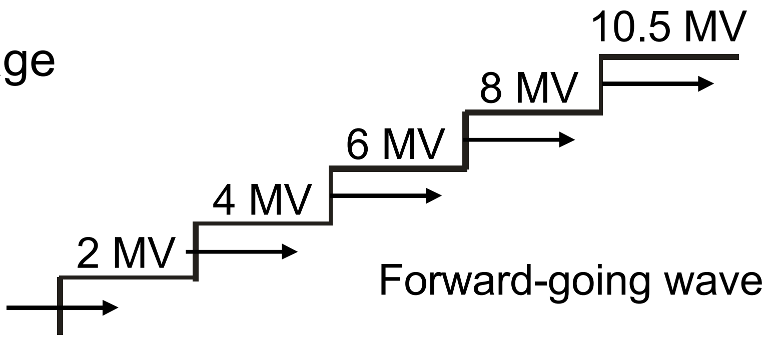
Emission z > 0, 150 kV/cm

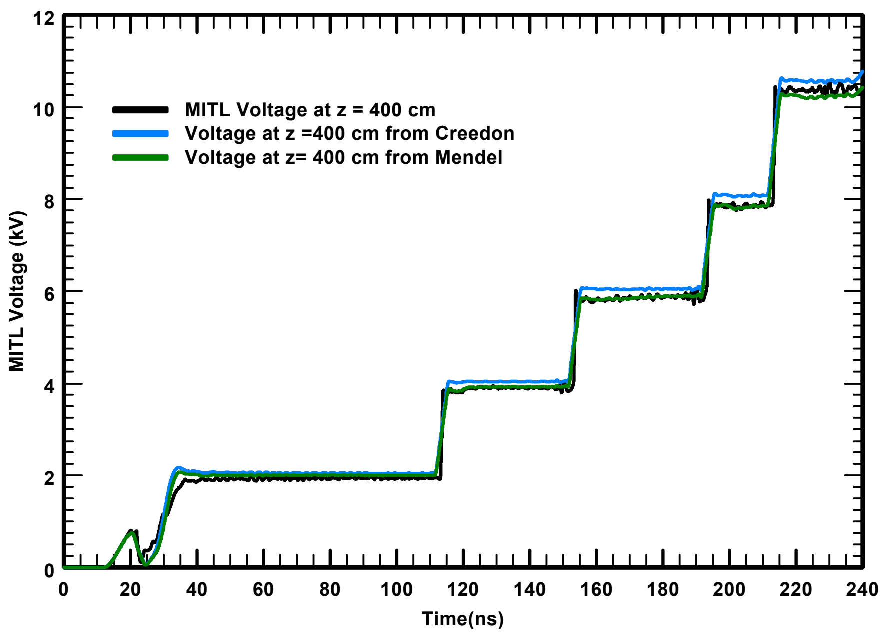
Comparison of Conditions Behind Insulation Wave for Three Launch Conditions

	Parapotential Flow Theory	A	B	C
V_{mitl}	10.5 MV	10.37 MV	10.12 MV	10.48 MV
I_{anode}	122.8 kA	125.2 kA	125.4 kA	125.7 kA
Z_{op}	85.5 Ω	82.8 Ω	80.7 Ω	83.4 Ω
$I_{cathode}$	49.0 kA	46 kA	42 kA	50 kA

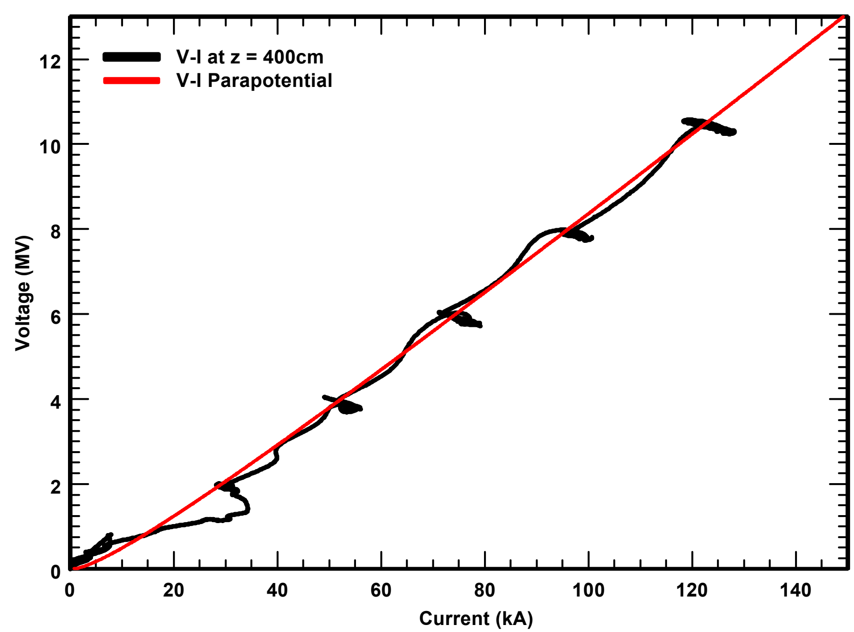
Launch Staircase (Increasing) Magnetic Insulation Wave Into Infinite Length MITL

- Forward-going wave with increasing voltage
- Parapotential flow theory used to launch voltages of 2, 4, 6, 8 and 10.5 MV
- There is only one lose front





MITL Voltage at z = 400 cm



V-I History at z = 400 cm

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Launch Staircase (Descending) Magnetic Insulation Wave Into Infinite Length MITL

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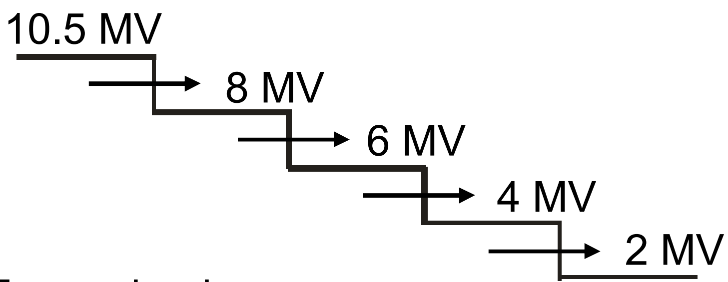
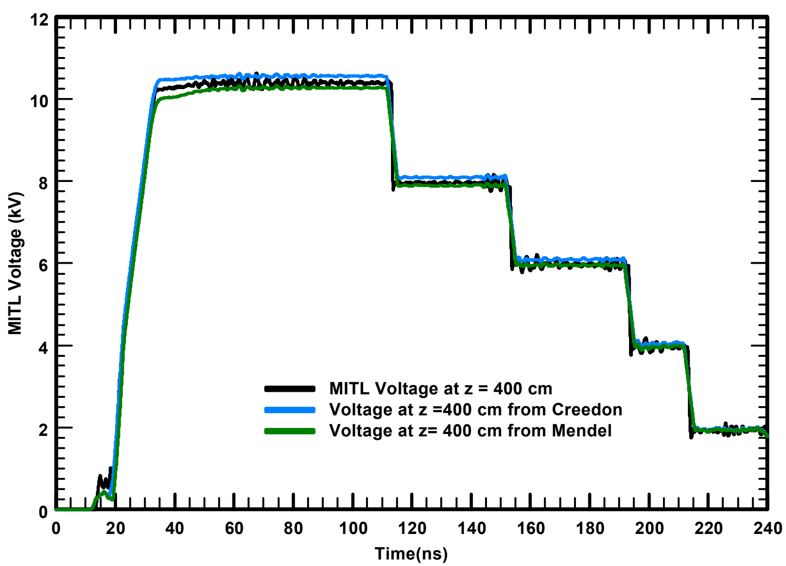
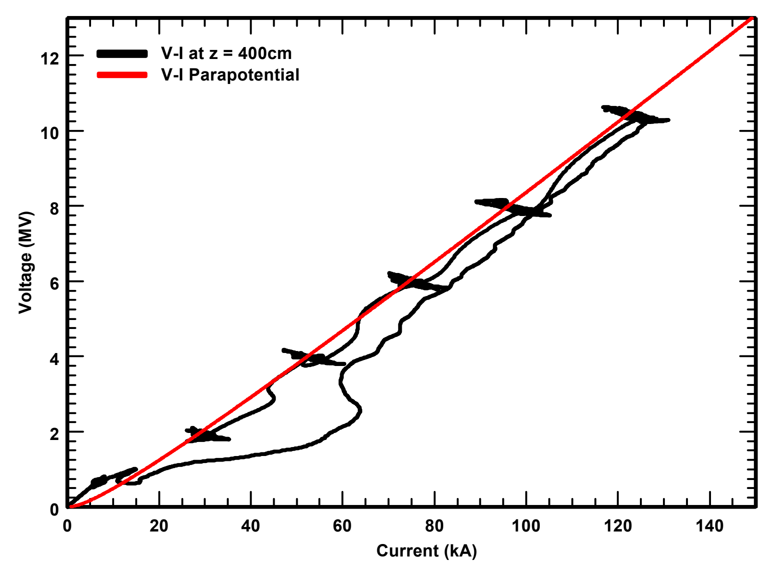
- Forward-going wave with declining voltage
- Parapotential flow theory used to launch voltages of 10.5, 8, 6, 4 and 2 MV



Forward-going wave



MITL Voltage at z = 400 cm



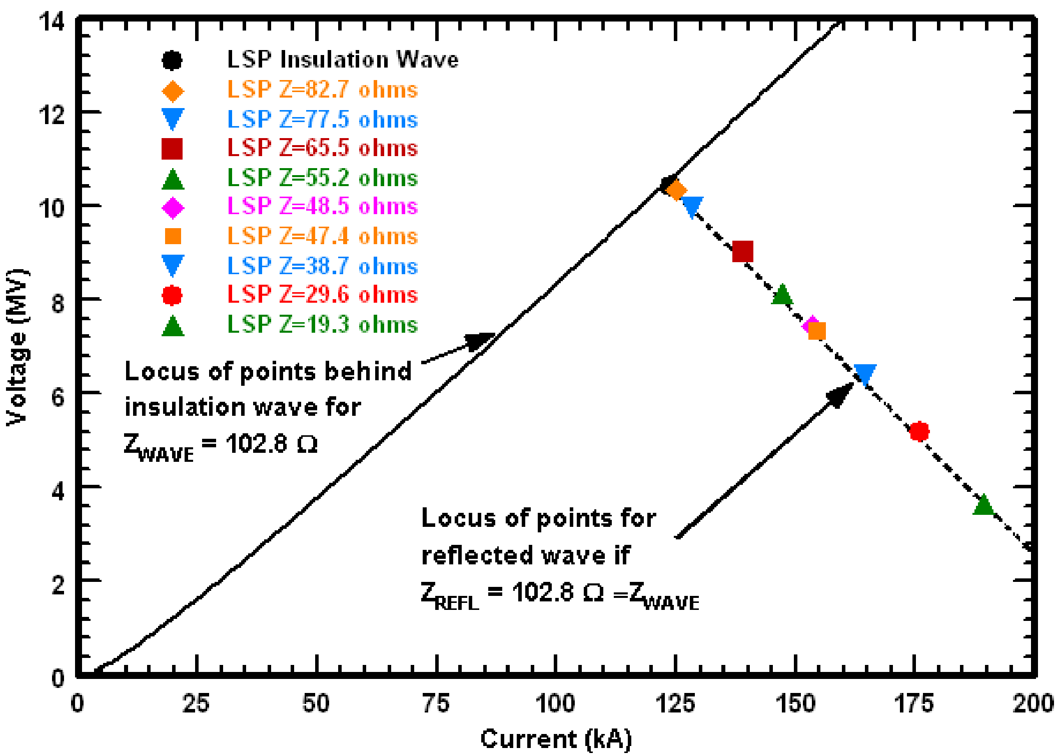
V-I History at z = 400 cm

V-I Diagram for Single Magnetic Insulation and Re-Trapping Wave on 10.5 MV RITS-6

- Input was a matched forward-going wave with V_o = 10.5 MV
- Termination impedance adjusted to obtain Z shown
- Simulation are for two different geometries with same wave impedance

Z > 48 ohms r_{inner} = 3.43 cm r_{outer} = 19.05 cm

Z < 48 ohms r_{inner} = 11.71 cm r_{outer} = 65.0 cm



$$V_{MITL} = \frac{V_{Imin}\left(1 + \frac{Z_{Wave}}{Z_{Imin}}\right)}{1 + \frac{Z_{Wave}}{Z_{Termination}}}$$

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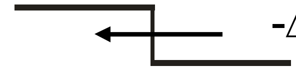
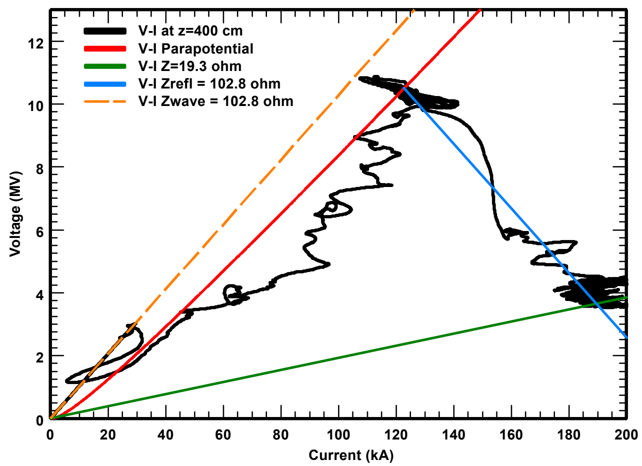
V-I Time History for Single Magnetic Insulation and Re-Trapping Wave on 10.5 MV RITS-6

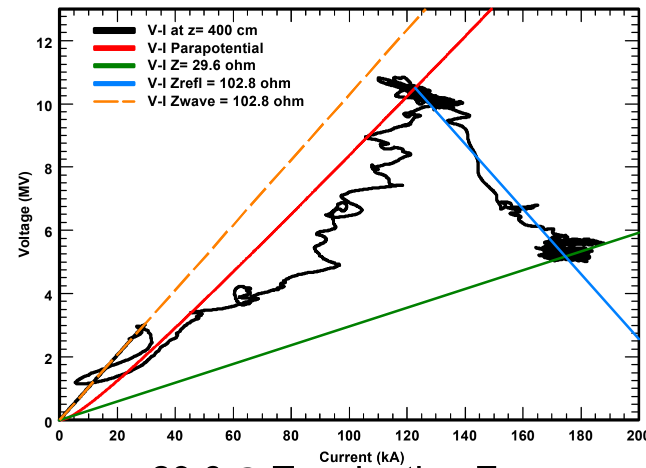
Insulation Wave



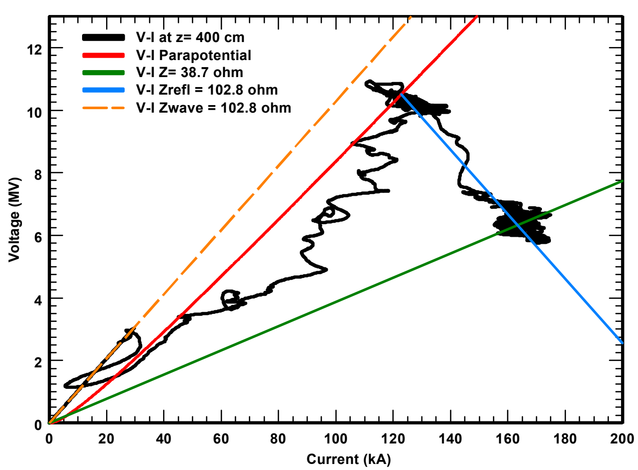
Re-trapping Wave



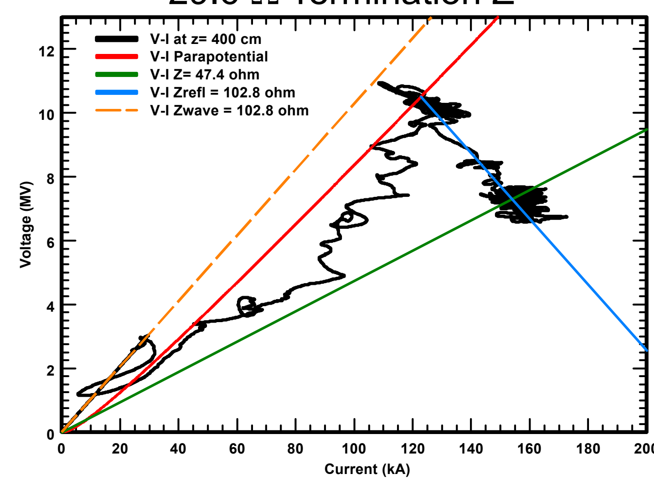
19.3 Ω Termination Z



29.6 Ω Termination Z



38.7 Ω Termination Z



47.4 Ω Termination Z

V-I Time History for Single Magnetic Insulation and Multiple Re-Trapping Waves on 10.5 MV RITS-6

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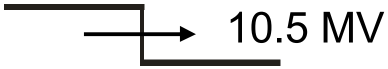
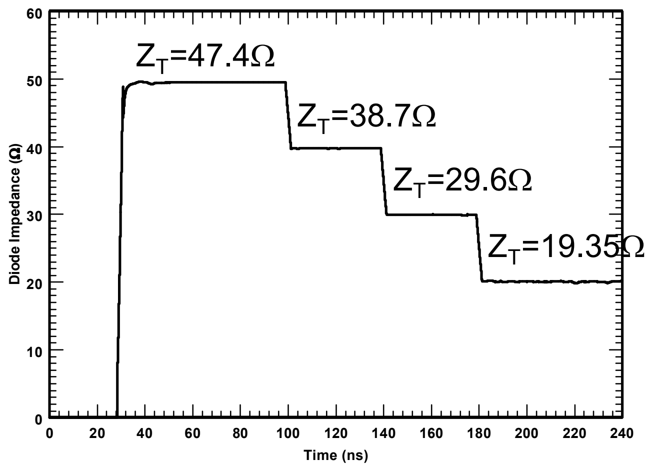
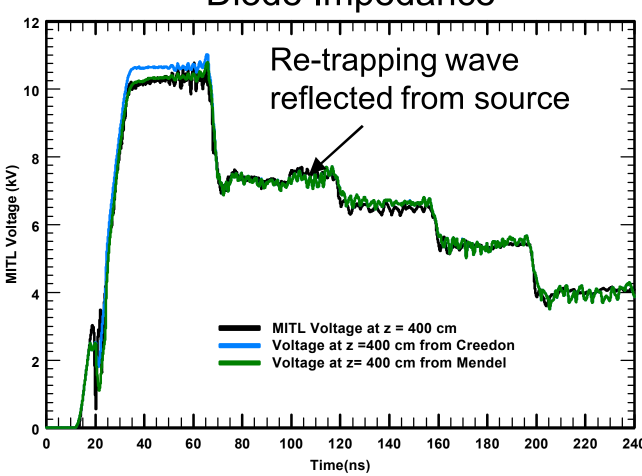


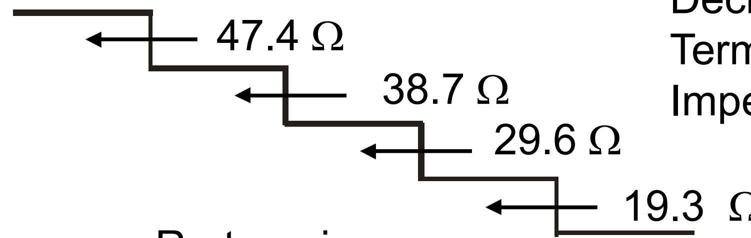
Insulation Wave



Diode Impedance

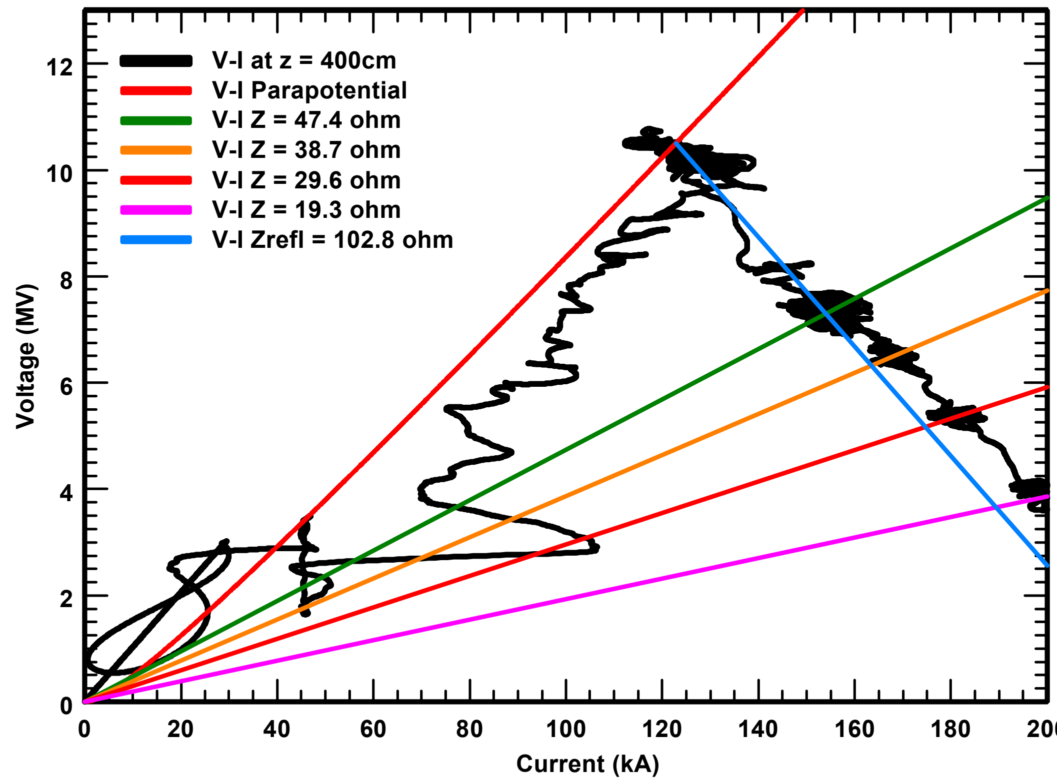


MITL Voltage at z = 400 cm



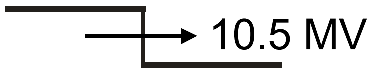
Decreasing Termination Impedance

Re-trapping waves

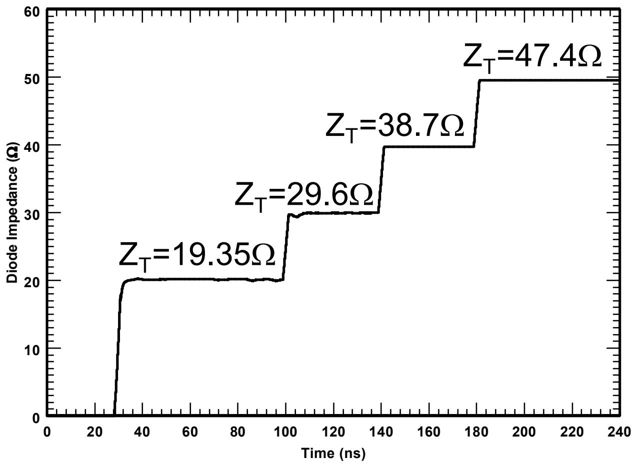


V-I Time History

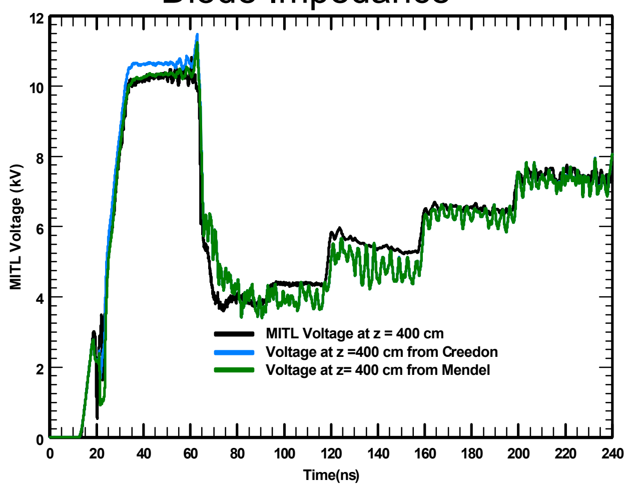
V-I Time History for Single Magnetic Insulation and Multiple Re-Trapping Waves on 10.5 MV RITS-6



Insulation Wave

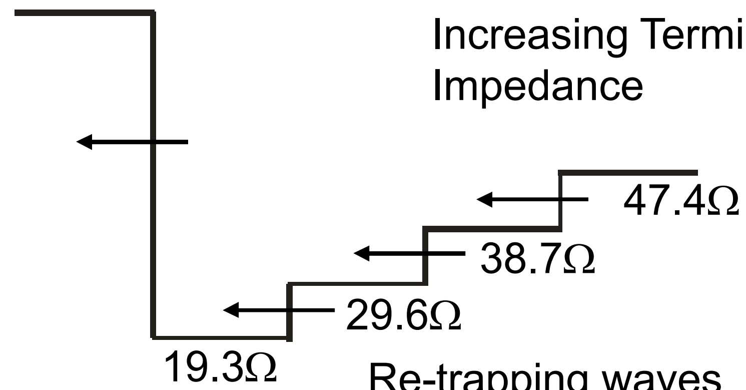


Diode Impedance

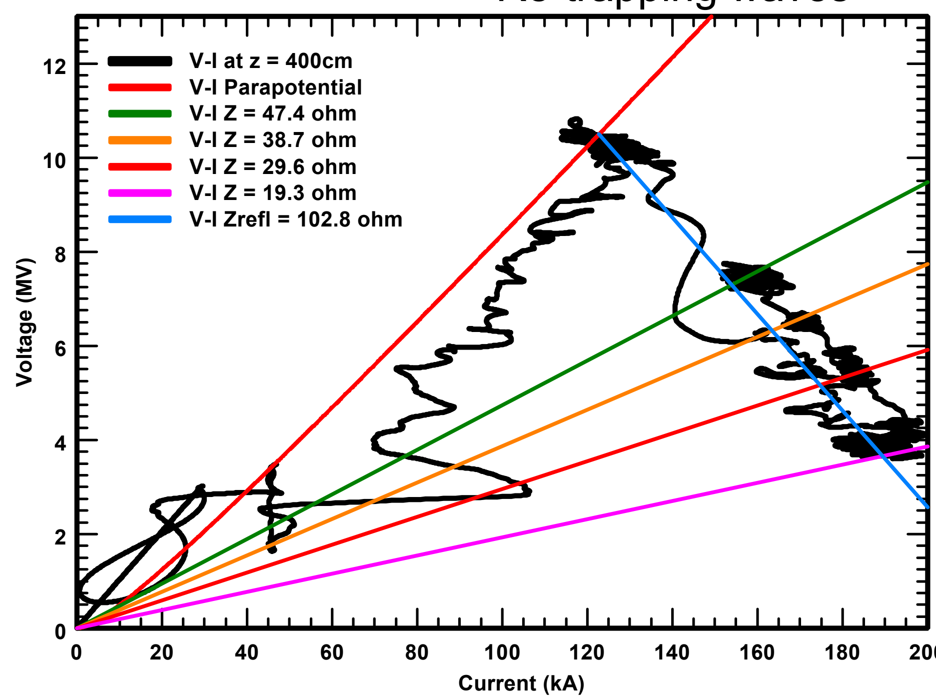


MITL Voltage at z = 400 cm

Increasing Termination Impedance



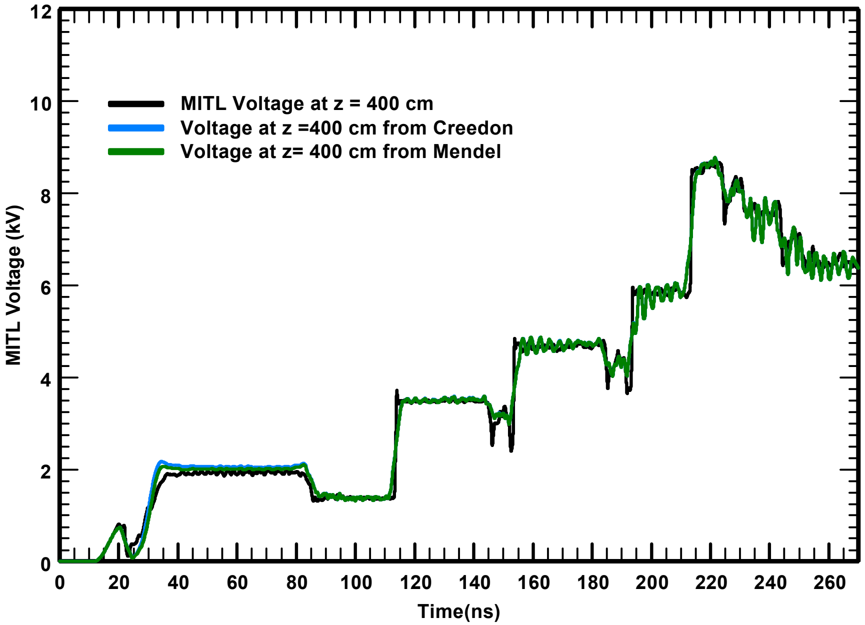
Re-trapping waves



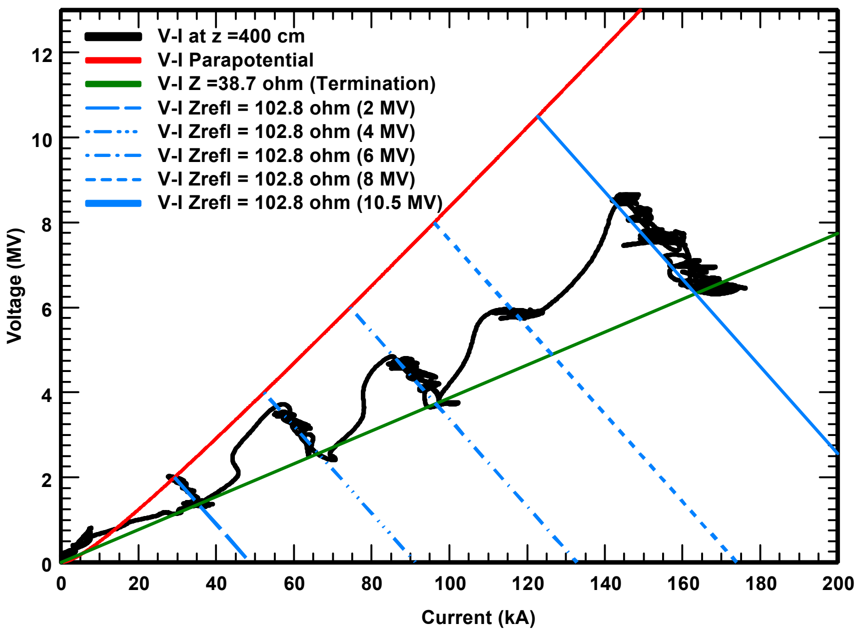
V-I Time History

Multiple Wave Interaction

- Input rising staircase (2, 4, 6, 8, and 10.5 MV matched forward-going wave)
  - Right traveling waves from source
- Terminated impedance ~Z = 38.7 ohm (40 ohm load)
  - Left traveling waves from reflection of right traveling with termination
- Right traveling waves that are the reflection of left traveling waves and the source impedance



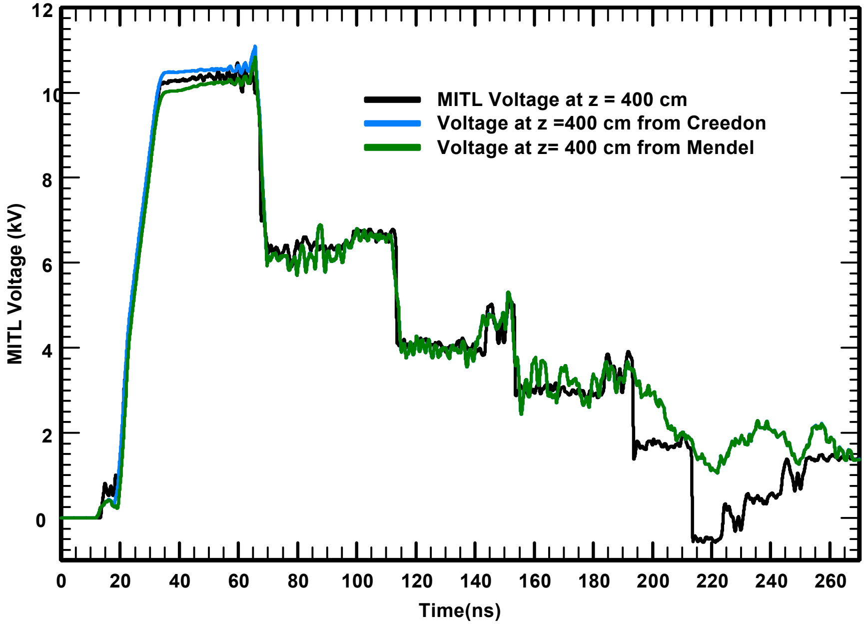
MITL Voltage at z = 400 cm



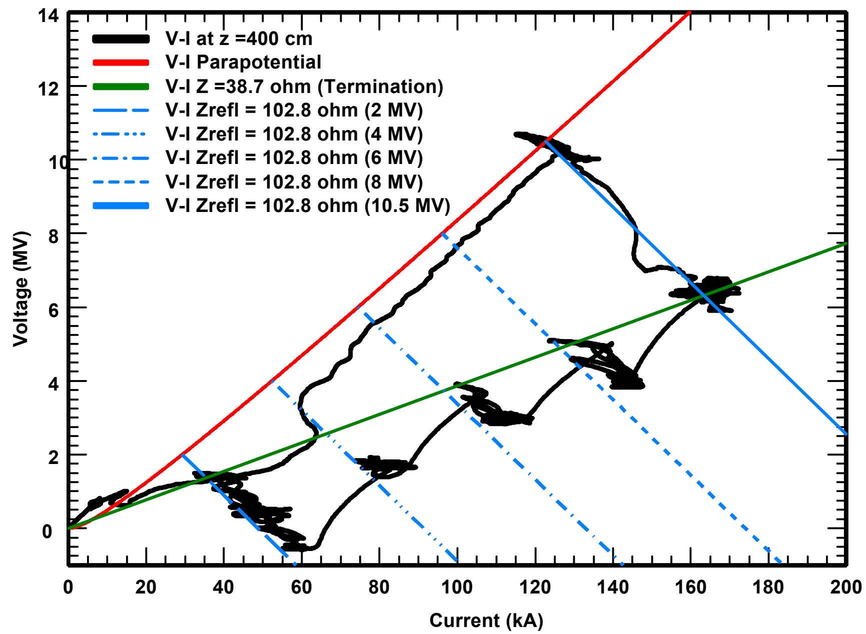
V-I History at z = 400 cm

Multiple Wave Interaction (cont.)

- Input declining staircase (10.5, 8, 6, 4 and 2 MV matched forward-going wave)
- Movie shows that as expected MITL flow (E x B drift) reverses direction when the voltage reverses sign



MITL Voltage at z = 400 cm



V-I History at z = 400 cm

Multiple Wave Interaction (cont.)

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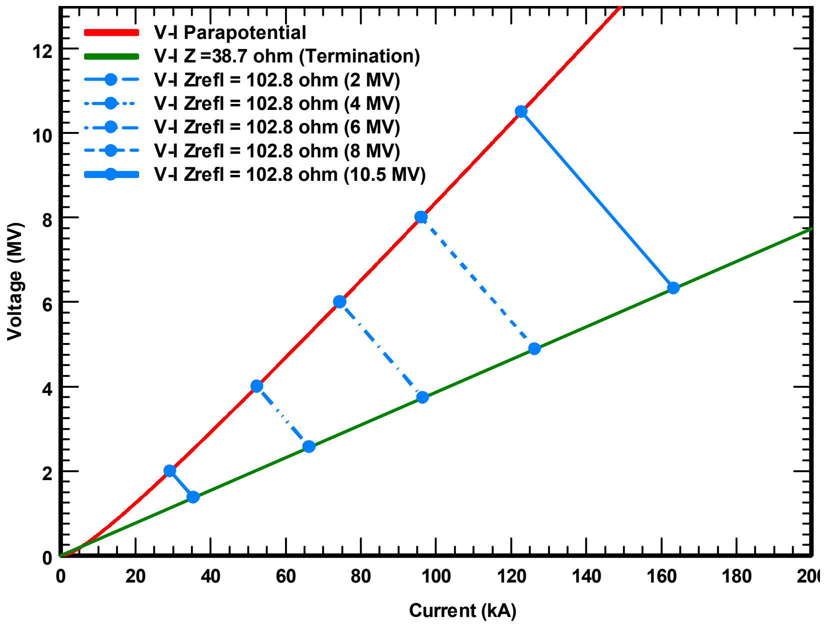
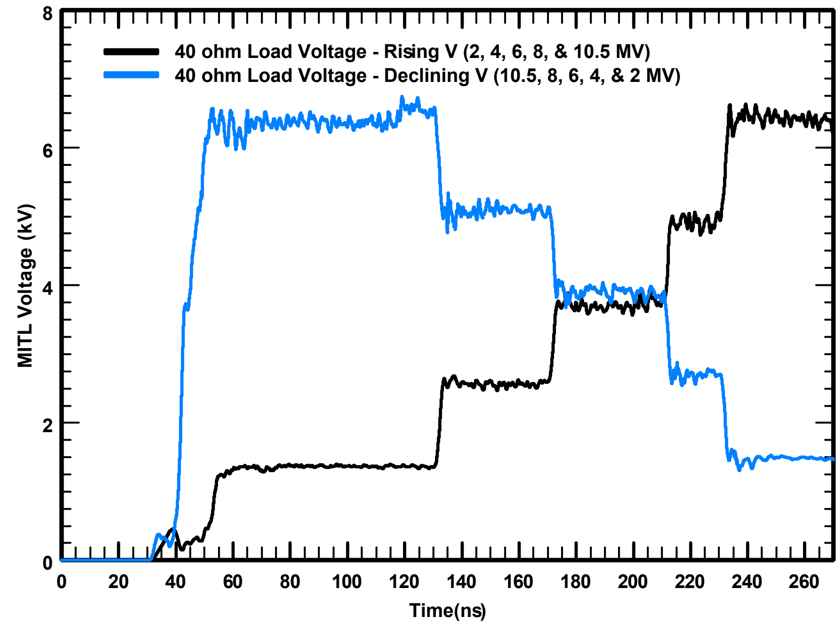
- The V-I history within the MITL is very different for the rising and declining staircase input voltage
- The load voltages however are similar (mirror image)
  - A given input voltage produces the same diode voltage independent of the order in which the voltage is injected
- Results are for a fixed termination impedance



V-I Diagram



Diode Voltage

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Summary

- Insulation waves have a cumulative effect
  - Several small steps are equivalent to one large step
  - There is only one insulation wave for an increasing staircase voltage input
- For a constant insulation wave amplitude the dI/dt of the operating point due to passage of re-trapping waves is characteristic of the vacuum wave impedance
- There is no evidence of hysteresis
- Superposition of the waves (source launched and reflected from load) most likely applies with certain rules
- Can the MITL be treated as a classic transmission line
  - dI/dt of insulation wave not equal to dI/dt of wave passing through an under-matched section
  - Velocity of wave propagation is different for insulation waves and re-trapping waves
  - Velocity of re-trapping wave depends on the $\Delta V/\Delta I$ jump across the wave (flux change)
  - Probably can develop a useful TL methodology that includes constitutive relationships

Summary (cont.)

- Other treatments may be better
  - PDE plus constitutive relationships are used extensively for wave propagation in solids (elastic/plastic, visco-elastic, and porous)
  - Characteristics plus constitutive relationships have been used for decades in hydrodynamic wave propagation