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

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Abstract

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 [2]. The relationship was in agreement with detailed particle-in-cell (PIC) simulations and experiments investigating the re-trapping wave process for large area diodes. The scaling law and simulations however were only applied to a constant input (forward going) voltage and termination impedance.

This paper extends those PIC simulations and wave analyses to MITL operating conditions for termination impedances and input voltages that are functions of time. The objective is to determine the constitutive relationships for the propagation of insulation waves that propagate from the voltage source to the load and re-trapping waves that propagate from the under-matched load to the source. Wave propagation questions of hysteresis, superposition, transmission, and reflection coefficients are addressed. Particle-in-Cell simulations based on the RITS-6 [3] dustbin geometry are used extensively in the analyses and compared with linear and non-linear wave propagation. The possibility of treating the MITL as a series of transmission lines is addressed.

I. INTRODUCTION

Magnetically-insulated transmission lines (MITL) are used as part of a high power inductive voltage adders to transport power to the load. The insulation wave that propagates from the adder sources to the load is not reflected from the load when the load impedance is equal to or greater than the matched operating impedance based on parapotential flow at minimum current. When the load impedance is less than the matched impedance, re-trapping waves are launched back up the MITL and wave-wave interaction occurs. Previous investigations, both analytical and numerical, have concentrated on an insulation wave comprised of a single voltage jump and a single re-trapping wave [1]. This paper examines the MITL operating conditions when the input voltages and load impedances are functions of time and the resulting waves move back and forth in the MITL during the output pulse.

II. PIC SIMULATION PARAMETERS

The MITL geometry used for the simulations was that of Sandia National Laboratories RITS-6 accelerator with the high impedance MITL. The nominal matched high impedance RITS-6 output is 10.5 MV, 123 kA, and 65 ns. Only the large radius dustbin output section of the accelerator was simulated. The outer radius, r_{outer} = 65.0 cm, is that of the experimental dustbin and the inner radius, r_{inner} = 11.7 cm, was chosen to give a matched output impedance, 85.5-ohm, equal to RITS-6 with the high impedance MITL. The length of the MITL in the simulations was set at 900 cm to separate the wave-wave interaction for clarity. The simulations were done with the LSP PIC code [4].

The diode structure used in the simulations (Fig. 1) includes the non-emitting knob used in the RITS-6 self-magnetic pinch experiments.

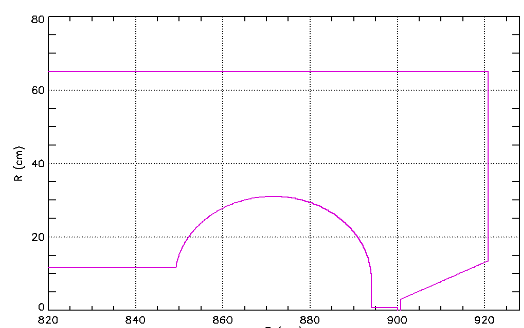

Figure 1. Diode geometry.

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The diode (termination) impedance was programmed by adjusting the conductivity of a cylinder along the centerline that connects the cathode and anode.

III. MAGNETIC INSULATION WAVES

To determine if the operating conditions in the MITL behind an insulation wave are a function of the time history of the input voltage, an increasing staircase magnetic insulation wave was launched into the MITL from the source at z = 0. Parapotential flow theory was used to choose the correct input voltages to launch voltages of 2, 4, 6, 8, and 10.5 MV down the infinite length MITL. The time history of the voltage in the MITL at 400 cm from the source is shown in Fig. 2 and the voltage-current operating conditions at the same position are given in Fig. 3.

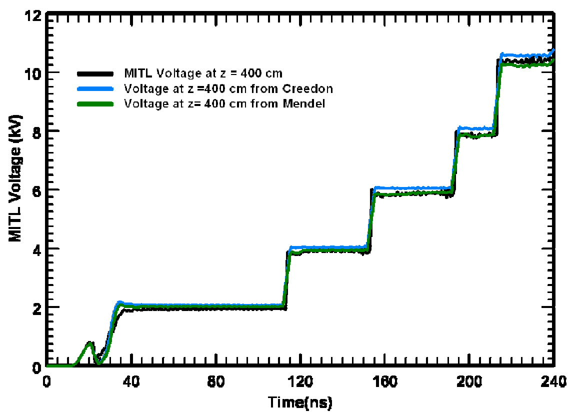

Figure 2. MITL voltage time history at z = 400 cm for increasing insulation wave voltage with no reflection.

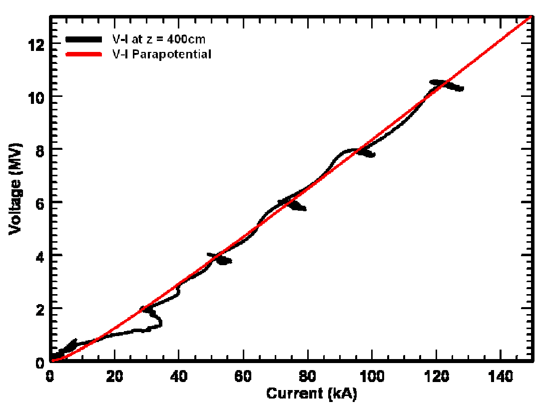

Figure 3. MITL V-I operating history at z = 400 cm for increasing insulation wave voltage with no reflection.

In Fig 2 the voltage calculated from the anode and cathode currents using the parapotential flow theory of Creedon [1] and the pressure balance theory of Mendel [4] are also shown. The full operating time history of the insulation wave is shown in Fig. 3 and compared to the parapotential flow theory. Only the first 2 MV wave is a true insulation wave in that the electron flow from the inner conductor to the outer conductor is stopped during the passage of that portion of the wave. The electron loss does not reoccur during the subsequent voltage increases. The reverse time history in which a large voltage jump is followed by smaller and smaller voltages was also considered. A staircase voltage time history with declining voltages of 10.5, 8, 6, 4, and 2 MV was launched into the MITL. The time history of the voltage in the MITL at 400 cm from the source is shown in Fig. 4 and the voltage-current operating conditions at the same position are given in Fig. 5.

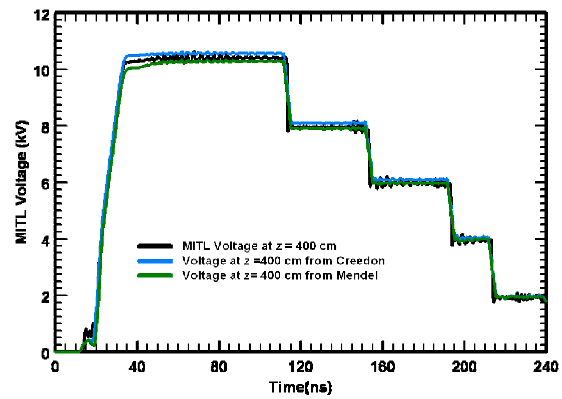

Figure 4. MITL voltage time history at z = 400 cm for decreasing insulation wave voltage with no reflection.

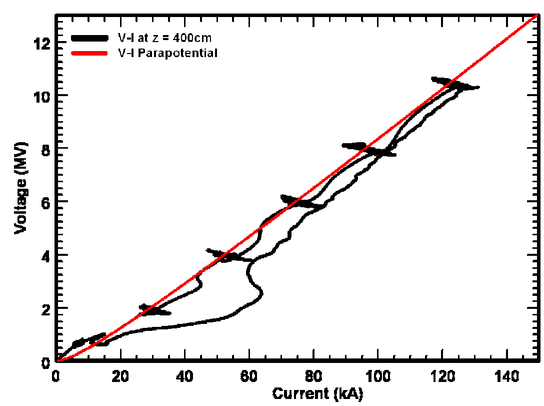

Figure 5. MITL V-I operating history at z = 400 cm for decreasing insulation wave voltage with no reflection.

Once again the first 10.5 MV wave provides the insulation and the electron loss does not reoccur during the following voltage decrease. The vacuum electron sheath near the cathode does become thicker for lower voltages.

IV. SINGLE RE-TRAPPING WAVE

The operating condition for a single re-trapping wave was obtained previously [1] for the high impedance RITS-3 (5.25 MV, 123 kA, and 65 ns) accelerator. Applying the same type of simulations to RITS-6 gives the operating parameters shown in Fig. 6. The results are summarized by the expression (Equation 1) that relates the input voltage, the termination impedance, and the MITL operating conditions.

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

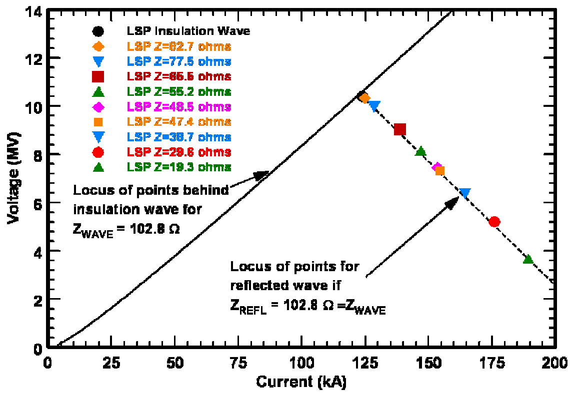

Figure 6. MITL operating parameters for a single re-trapping wave of different strengths.

V. MULTIPLE RE-TRAPPING WAVE

The MITL operating conditions for a single magnetic insulation wave and multiple reflected re-trapping waves were investigated by changing the MITL termination impedance in a staircase manner. Both decreasing and increasing staircases were simulated. A 10.5 MV insulation wave was launched from the source and a termination impedance staircase of 47.4, 38.7, 29.6, and 19.3-ohms was programmed for the termination impedance. The time history of the MITL voltage at z = 400 cm is contained in Fig. 7 and the V-I operating conditions at the same axial position are shown in Fig. 8. To first order the multiple re-trapping waves produce the same effect as a single re-trapping shown in Fig. 6. The slight deviation from the Z_{REFL} = 102.8 line is due in most part to the reflection of the preceding re-trapping waves from the source.

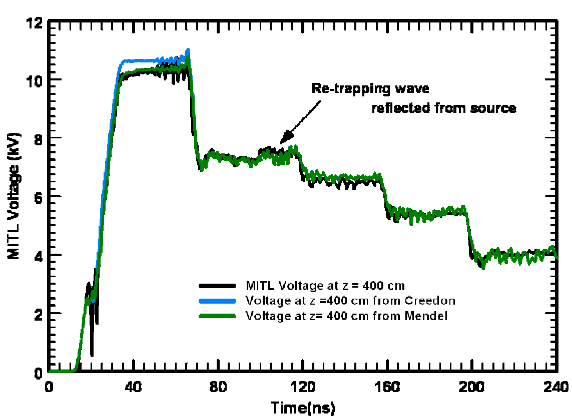

Figure 7. MITL voltage time history at z = 400 cm for a decreasing load impedance.

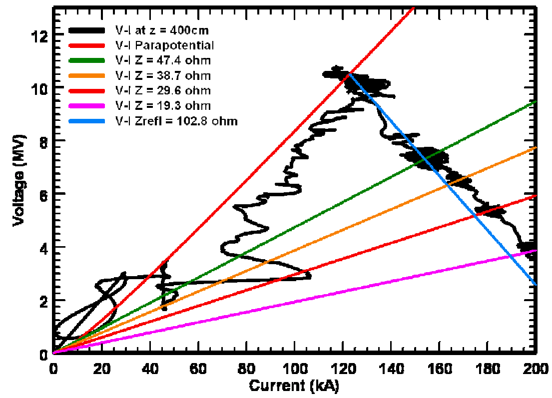

Figure 8. MITL V-I operating history at z = 400 cm for a decreasing load impedance.

The V-I plots for a constant impedance corresponding to the load impedances used to launch the re-trapping waves are overlaid on the MITL V-I operating history.

The MITL voltage time history and V-I operating conditions at z = 400 cm for termination impedances of 19.3, 29.6, 38.7, and 47.4 ohms are given in Fig. 9 and Fig 10 respectively. The large mismatch for the initial

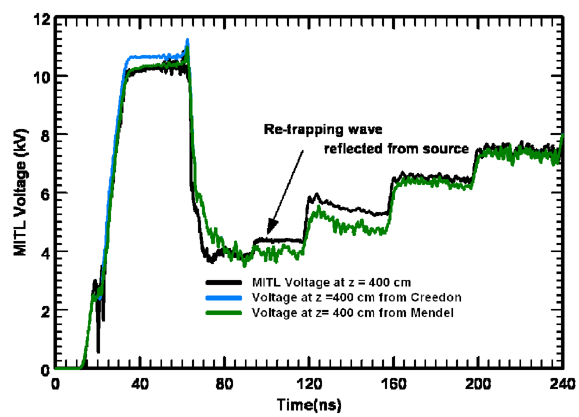

Figure 9. MITL voltage time history at z = 400 cm for an increasing load impedance.

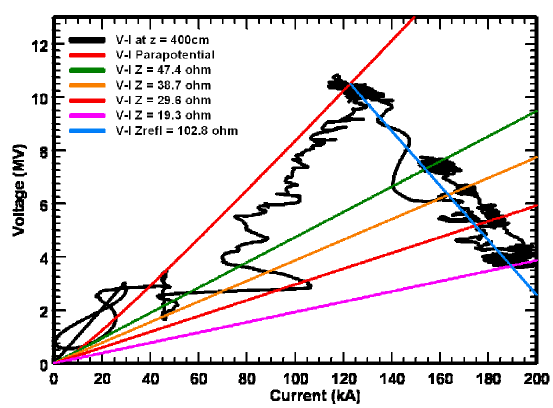

Figure 10. MITL V-I operating history at z = 400 cm for an increasing load impedance.

19.3 ohm impedance launches a strong re-trapping back toward the source. The subsequent increases in termination impedance cause more current to flow in the vacuum electron sheath and less in the cathode surface. To first order the operating conditions of the MITL lie along Z_{REFL}= 102.8 ohm operating condition.

VI. MULTIPLE WAVE INTERACTION

The interaction of insulation waves from the source and re-trapping waves from the termination was investigated by launching a rising input staircase (2, 4, 6, 8, and 10.5 MV) voltage and the inverse decreasing staircase (10.5, 8, 6, 4, and 2 MV) voltage into the MITL while maintaining a fixed 38.7-ohm termination impedance. The MITL operating parameters at z = 400 cm are shown in Fig. 11 for the increasing voltage time history and Fig. 12 for the decreasing voltage time history. Even though the MITL V-I operating conditions are very different the corresponding time histories of the termination voltage (Fig. 13) are approximately mirror images of each other, suggesting that there is no hysteresis in the behavior of the MITL operating conditions.

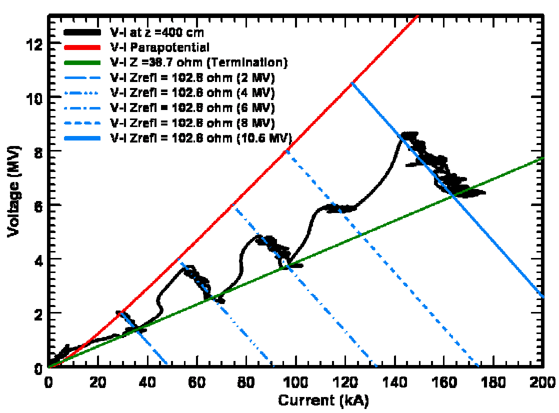

Figure 11. MITL V-I operating history for a fixed impedance load and an increasing input voltage.

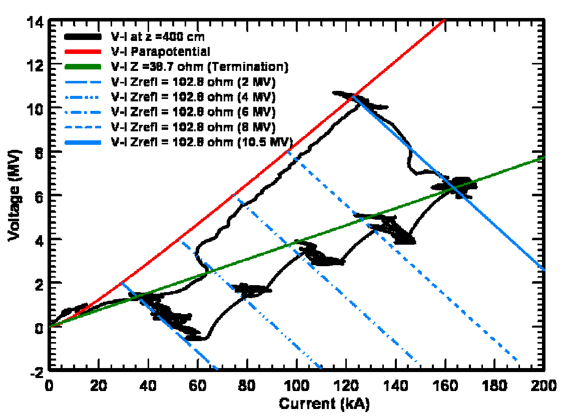

Figure 12. MITL V-I operating history for a fixed impedance load and a decreasing input voltage.

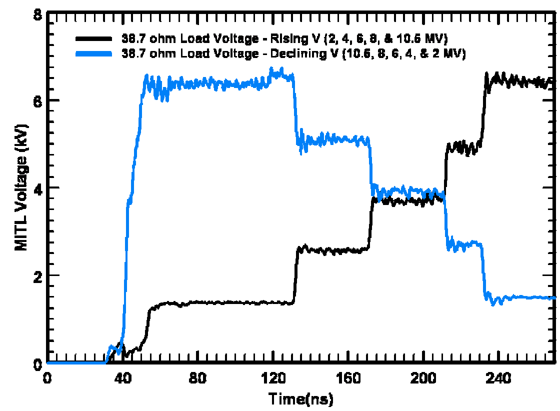

Figure 13. Load voltage for a increasing staircase voltage input and a mirror image decreasing voltage input.

VII. CONCLUSIONS

Insulation waves moving from the source to the load have a cumulative effect in the MITL operating conditions in that several small steps in voltage (increasing or decreasing) are equivalent to one large step in voltage. For a constant insulation wave amplitude the dI/dt of the MITL operating point due to passage of re-trapping waves is characteristic of the vacuum wave impedance. Superposition of the waves within the MITL (source launched and those reflected from the load) most likely applies with certain rules. A transmission line approximation that includes the constitutive relations mentioned above can probably model the wave propagation within the MITL.

VIII. REFERENCES

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