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VACUUM TRANSMISSION LINES FOR PULSE SHARPENING AND DIAGNOSTICS APPLICATIONS*

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Abstract

We investigated the propagation of MV electrical pulses along coaxial transmission lines (TL) in vacuum with network simulations and experiments. One goal was to establish how well a 3 m-long TL would sharpen the output pulse of a relativistic electron beam accelerator. Sharpening occurs as the cathode of the TL emits electrons and the current flow forces the TL into magnetic cut-off. The other goal was to determine how well field emission must be suppressed in a TL to avoid distortion of a propagating pulse. Simulations predict a four-fold risetime improvement (8 ns to 2 ns) through magnetic insulation in a TL with an electrical length (10 ns) comparable to the risetime of the input pulse. In the laboratory we have shown a five-fold improvement (15 to 3 ns) with a velvet covered 3-m line and a 7.5 fold improvement (2 ns) when a vacuum flashover switch was incorporated between the first third and the last two thirds of the TL. Simple arguments and TL simulations suggest that even a small fraction (1 or 2 %) of Child-Langmuir (CL) space charge limited emission will distort a propagating voltage pulse. This result, is of particular importance when the TL is part of a voltage diagnostic system.

Introduction

This paper describes investigations of non-stationary pulse propagation [1] in vacuum transmission lines (TL) with field emission. In the non-stationary regime, the risetime of the pulse injected at the input of the TL is shorter than the electrical length of the TL. If the fields at the cathode are large enough, current drawn by field emission in the TL can be sufficient to magnetically insulate the cathode. In this operating regime, TLs are commonly known as MITLs (magnetically insulated transmission lines).

The non-stationary behavior of long (5-10 m), high impedance (Z_0 > 30 Ω) MITLs are well understood experimentally [2,3,4] and comparisons of particle simulations and experimental measurements have appeared in the literature [5].

The bulk of the experience with lower impedance MITLs has been obtained with short MITLs (vacuum feeds, < 1 m-long) that drive imploding plasma loads [6,7,8]. The risetime of the driving pulses for these feeds is, in general, longer than the electrical length of the MITL. Consequently, one would expect non-stationary behavior at the very beginning of the pulse only. Experimental results with these feeds do show some sharpening of the leading edge of the pulse.

Data is also available with 1 and 2 m-long MITLs. An experiment with a 1-m long, 4.7 Ω cold impedance coax [9,10] at megavolt levels showed a small degree of pulse sharpening. Experiments with a 2-m, 4.7 Ω coax at 0.9 MV [10] showed a larger degree of pulse sharpening. The emphasis of these experiments, however, was to demonstrate efficient current transport so that the pulse sharpening properties of the MITLs were not exploited nor optimized. A 2 m-long, 56 Ω MITL in a flash radiography accelerator operating at 7 MV [11] also sharpened a 50 ns risetime pulse slightly. In this experiment, the emphasis was on prepulse suppression and efficient current transport rather than pulse sharpening.

A recent development in MITL technology is the use of velvet as a cathode material [12] to reduce the threshold of field emission (from 250 kV/cm [2] to 50 kV/cm). A 10-fold pulse sharpening (20 ns to 2 ns) with a 2.5 m-long 38 Ω MITL operating at 1 MV with a velvet cathode has been reported in the literature [13]. The most important observation of Ref. 13 is the absence of pulse sharpening with bare or carbon coated cathodes since the fields are not sufficiently high to turn-on the cathode uniformly. This confirms that uniform field emission, as described in Ref. 12, plays a fundamental role in the proper operation of a MITL. The lack of uniform field emission, in spite of carbon coated metal cathodes, may explain the marginal performance of the MITL feeds described in Refs. 6 through 10. It also explains why, the circuit simulations described in Ref. 6 required only 10 % of the Child-Langmuir (CL) space charge limited current to yield agreement with experiment.

Transmission Line Simulation Techniques

The circuit simulations we describe below follow the approach of Ref. 14. The model for the TL is a cascade of sections composed of a series inductance L, a shunt capacitance C and a shunt conductance G. A typical TL section appears in Fig. 6 of Ref. 1. The inductance and capacitance of a coaxial sections is:

$$L = \frac{\mu_0 \ell \, \ln(r_o/r_i)}{2\pi}, \qquad (1)$$

$$C = \frac{2\pi\epsilon_0 \ell}{\ln(r_o/r_i)} \qquad (2)$$

where ℓ is the length of the section, r_o is the outer radius and r_i is the inner radius.

The conductance G is the product of the CL conductance G and the magnetic cut-off function F. The conductance allows electron flow across

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the conducting cylinders that form the electrodes of the capacitor in the section. To derive the conductance associated with CL space charge limited flow across coaxial cylinders we divide the space charge limited current I_{CL} [15] by the voltage V to obtain:

$$G = \left(\frac{2e}{m}\right)^{1/2} \frac{8\pi}{9} \frac{\varepsilon_o V^{1/2} \ell}{r_c \beta^2} \qquad (3)$$

where r_c is the cathode radius and r is the anode radius. Reference 15 tabulates β^2 (p. 178) as a function of r/r_c for geometries where the inner conductor can be either the cathode or the anode.

The cutoff function F that appears in Fig. 1 is a function of the ratio I/I_c and models the process of magnetic insulation. This function is

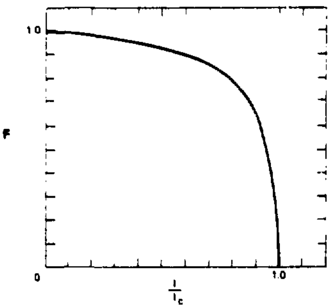

Figure 1. Cutoff function F as a function of I/I_c.

unity for zero current (undisturbed electron trajectories) and zero for a current greater than or equal to the critical current (electrons can no longer reach the anode and magnetic insulation has been fully attained). The critical current I_c [1] depends on the voltage and the geometry:

$$I_c = 2\pi \frac{m_o c^2}{e} \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} \frac{(\gamma^2-1)^{1/2}}{\ln\left(\frac{r_o}{r_i}\right)} , \qquad (4)$$

$$\gamma = 1 + eV/m_o c^2 \qquad (5)$$

In the equation above, γ is the relativistic factor, V is the voltage appearing across C, and $m_o c^2$ is the rest energy of the electron.

A non-dimensional analysis [16] is very useful to establish two distance scales. One is a distance over which field emission can draw currents comparable to the displacement currents and the other is a distance over which the cutoff current is reached. The first dimension establishes a bound on the longest TL that could be used to transmit pulses without distortion and the second establishes the shortest length the propagating front can attain.

To guarantee that the field emission currents are much smaller than the vacuum currents:

$$\alpha \frac{8\pi\sqrt{2}}{9} \left(\frac{e}{m}\right)^{1/2} \frac{\ell}{r_c \beta^2} V^{1/2}$$

$$<< \left(\ln \frac{r_o}{r_i} \frac{1}{2\pi} \left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2}\right)^{-1} \qquad (6)$$

The constant $\alpha<1$ represents the degree to which CL field emission can be suppressed. Simplifying this expression we obtain:

$$\frac{4\sqrt{2}}{9} \alpha \ln\left(\frac{r_o}{r_i}\right) \frac{\ell}{r_c \beta^2} (\gamma-1)^{1/2} << 1 \qquad (7)$$

To obtain the distance ℓ_F required to draw the cut-off current we compare the CL current to the critical current:

$$\alpha \frac{8\pi\sqrt{2}}{9} \left(\frac{e}{m}\right)^{1/2} \frac{\ell_F \beta^2}{r_c} V^{3/2} \qquad (8)$$

$$= 2\pi \frac{m_o c^2}{e} \frac{1}{\left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2}} \frac{(\gamma^2 - 1)^{1/2}}{\ln\left(\frac{r_o}{r_i}\right)}$$

Simplifying this expression we obtain:

$$\frac{\ell_F}{r_c} = \frac{9\sqrt{2}}{8} \frac{\beta^2}{\alpha \ln\left(\frac{r_o}{r_i}\right)} \frac{(\gamma + 1)^{1/2}}{\gamma - 1} \qquad (9)$$

Transmission Line Calculations

For pulse sharpening, the results of a 40 segment calculation of a 3 m-long MITL with r = 9.52 cm, r = 8.25 cm, appear in Fig. 2. The results show that a MITL is very effective at sharpening the risetime of a propagating pulse even when the electrical length of the MITL is comparable to the risetime of the pulse. Waveform F in the figure is the 10 ns risetime input pulse, waveform A is the voltage on the first element and waveforms B, C, D, and E are the voltage 1/4, 1/2, 3/4 and 1/1 of the way along the MITL. The risetimes of these voltages are 8, 5.4, 3.9, 3.0 and 2.1 ns respectively. A calculation for a 2 m-long MITL with a 5 ns linear ramp input shows a 4, 2.3, 1.8, 1.5, and 1.2 ns risetimes at the same locations.

We calculate the minimum length of transmission line necessary to accommodate the risetime of the pulse using Eq. 9. For the above radii (positive outer conductor), β^2 = 0.02186. Therefore, at 1 MV, ℓ_F/r_c = 0.246 for α = 1. In practice the distance will be somewhat longer because the cutoff condition gradually suppresses field emission. This distance may also determine the minimum segment length for stable simulations (circuit as well as particle in cell).

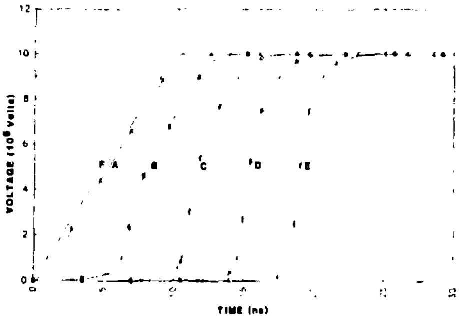

Figure 2. Voltage at successive positions in a 3 m-long MITL.

For fast, high voltage pulse transmission, limitations of coaxial structures are well known. For conventional applications, these limitations arise from: skin effect series resistance of the conductors that attenuates the high frequency components of the pulse [17], propagation of non-TEM modes that introduces dispersion [18], and a finite dielectric strength of the insulation limits the magnitude of the propagating pulse. Insulator conductances are so small that they do not play any role in ordinary practice.

We are interested in using a vacuum TL to transmit a 1 MV pulse to a diagnostic probe [19] with a minimum of distortion. Since we can show that for a 1 or 2 ns risetime pulse, the skin effect in TLs of a few cm diameter is negligible and higher order modes are not excited, the only source of pulse distortion is the conductance associated with space charge flow from one electrode to the other. The general theory of lossy TLs treats the effect of shunt conductance on pulse propagation. However, analytical solutions, even for the simple cases, are quite complicated [20].

We can estimate the effects of shunt conductance using Eq. 7 developed above. Let us consider a 4.5 m-long vacuum TL with $r_o = r_c = 3.645$ cm and $r_i = r = 1.429$ cm. For V = 1 MV, the CL current becomes equal to the displacement current when the multiplier α for the CL current is 0.017. Consequently, if we want to propagate a pulse without distortion and attenuation, electron emission should be kept well below this level.

Similarly we can ask the question: what value of α will cause the transmission line to behave as a MITL? Equation 9 yields $\alpha = 0.026$.

To check these simple estimates, we calculated the effect of shunt conductance for the 4.5 m-long TL using the same network model as for the MITL calculations. Fig. 3 displays the voltage at the input and the voltage at 4.5 m for varying levels of field emission ($0.001 < \alpha \leq 1$). α in the range between 0.001 and 0.01

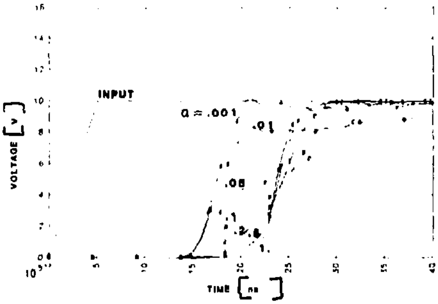

Figure 3. Voltage at 4.5 m in a transmission line with increasing levels of field emission.

attenuates the pulse but does not introduce severe distortion. For α above 0.05, the pulse is so severely distorted that all information about the leading edge has been lost.

The currents displayed in Fig. 4 are of even more interest. For α = .001 and .01 the current in the TL corresponds to the vacuum value. For α = .05 and above, however, the current reaches I_c indicating that emission is sufficient to allow cut-off of the electron flow in the TL.

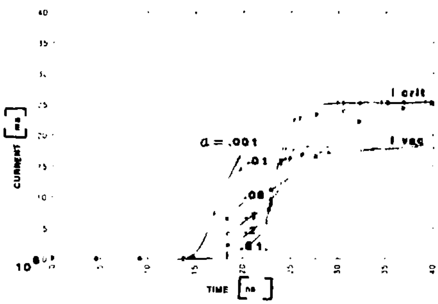

Figure 4. Current at 4.5 m in a transmission line with increasing levels of field emission.

Conclusions

We have demonstrated that is is possible to decrease the risetime of a propagating pulse using a transmission line with field emission and magnetic cut-off even when the length of the transmission line is shorter than the risetime of the input pulse. We have also demonstrated that even small levels of field emission will force a transmission line into magnetic cutoff. We have presented simple relationships that provide estimates of the effects of field emission on transmission line operation. Finally, laboratory experiments [21] show that a five fold risetime improvement without a vacuum switch and a 7.5 fold improvement with a switch are indeed possible.

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