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PRECISION ELECTRON FLOW MEASUREMENTS IN A DISK TRANSMISSION LINE

Jeremy P. Martin[1], Mark E. Savage[2], Timothy D. Pointon[2], Mark A. Gilmore[1]

[1]*University of New Mexico*
MSC01 1100 1
Albuquerque, NM 87131 USA

[2]*Sandia National Laboratories*[§]
PO Box 5800
Albuquerque, NM 87185 USA

Abstract

While a great deal of theory has been developed to successfully characterize the electrodynamics within a magnetically insulated transmission line (MITL), there have been some discrepancies with particle-in-cell (PIC) simulations of strongly insulated systems. As finer meshing is required, increased computing times can lead to inadequate resolution in the calculation of several important parameters describing the electron flow. Precise measurements of electron flow in low-impedance driven loads are essential in providing a benchmark for these widely used simulation techniques. Detailed measurements conducted on a low-impedance disk transmission line provide a useful comparison between the theoretical models and the simulation results. In addition a direct measurement of electron current at the load of a heavily insulated system is developed. This would circumvent the difficulty of typical diagnostic methods in resolving these electron flows which must be minimized for optimal efficiency.

I. INTRODUCTION

The efficient transport of significant electrical power densities originating from large pulsed-power drivers is a critical requirement in operating high power particle accelerator and intense radiation sources. Magnetic insulation in the vacuum section of these systems is critical given that the electric field generated between the conductors of the transmission line can easily approach field strengths on the order of 20-100 MV/m. At these large field strengths it has been experimentally observed that a plasma deposit is formed along the negatively charged conductor within a few nanoseconds, subsequently defining a space-charge-limited electron emitter [1]. Although the cathode in a vacuum line will freely emit electrons under such electric stress, the self-magnetic field of the transmission line current inhibits the electrons from reaching the anode. Insulated electrons are confined to the cathode by the relativistic Lorentz force and experience an average $\vec{E} \times \vec{B}$ drift in the direction of power flow. This average electron drift defines the electron flow current, which along with losses in the line, make up the measured difference between the anode and cathode currents.

This report describes the detailed measurements of insulated electron flow that were conducted on a low-impedance disk transmission line. While these measurements have never been conducted on this geometry before, the characterization of electron flow in low-impedance driven loads is useful in the design of z-pinch driven high energy density physics experiments.

Many of these systems possess strongly insulated electron flows at times of peak current, which result in complications for the particle-in-cell calculations used to model them. When the electron flow is restricted to a very thin sheath relative to the total vacuum gap, a large number of simulation cells are required to effectively describe the dynamics of the charged particles. This can cause small rounding and truncation errors in the energy calculations which can significantly affect the overall electron behavior. The hardware and data acquisition for this experiment were carefully designed for the most accurate measurements possible. An accurate description of the electron flow in this system will provide a better gauge for the validity of the computer simulated results.

II. DESIGN

In an ideal system, the electron flow at the load is minimized while maintaining a low inductance as to not suffer a decrease in system efficiency. While this trade-off is difficult to realize in a transmission line of constant

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gap spacing, a tapered line or conical disk configuration allows for an inductive profile to be built directly into the geometry of the electrodes while developing a radial reduction in electron flow along the cathode toward the load. The measurements of this study were conducted on the disk transmission line hardware shown in Fig. 1. Typically, the electron flow in the MITL section of a pulsed power system is measured as the difference between the anode and cathode currents. The electrodes in Fig. 1 were equipped with twelve sets of anode and cathode current monitors. These monitors were grouped into three branches, 120° apart. Each branch consisted of four monitor pairs, which were uniformly distributed in the radial direction.

For strongly insulated systems, the ability of typical diagnostic equipment to resolve the difference in the electrode currents becomes problematic. As a result, an electron collector cavity was placed at the center of the transmission line disk, introducing a sudden increase in vacuum impedance at the load. In a region of increasing line impedance, a reduction in the electric field strength leads to a decrease in the mean drift velocity of the electrons. The resulting build up of excess charge introduces an axial electric field component which pushes against the electrons flowing into the region. This electric force reduces the electron's canonical momentum until they are no longer insulated [2]. This allows the electrons to be trapped in the collector can region. A direct measurement of the electron current at the load can be obtained through a current viewing resistor (CVR) placed through the cathode near the entrance of the can to effectively "count" the electrons passing by.

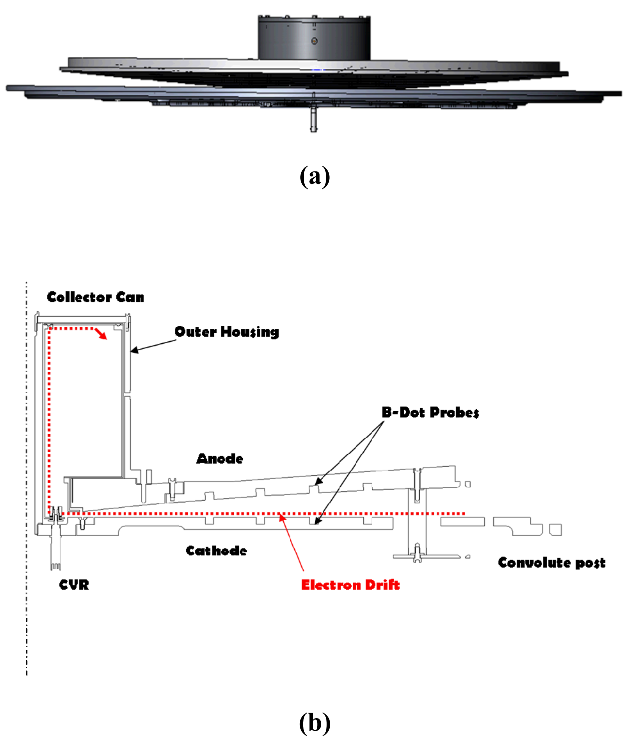

Figure 1. (a) Transmission line disk hardware assembly. (b) Azimuthal cross-section of MITL hardware.

A. Anode Profile

The efficiency of high current pulsed power sources are largely influenced by the vacuum inductance of the line. This inductance depends upon the characteristics of the electron flow and its localized energies. It is therefore advantageous to examine the rate of the electron flow with regard to the line inductance. The fractional change in electron current is defined as,

$$\beta = \frac{1}{I_e}\frac{\partial I_e}{\partial r} = 2\frac{\dot{L}^2 - \ddot{L}L}{L\dot{L}} \qquad (1)$$

where L is the radial dependent inductance of the line and $I_e \approx \frac{V^2}{2I_a Z^2}$ for strongly insulated electron flow (Appendix A).

For constant electron flow, $\beta = 0$, the radial gap profile is given by [3]

$$g_{const}(r) = \frac{g_o r}{r_o}\exp\frac{60 g_o (r - r_o)}{L_o r_o c} \qquad (2)$$

where g_o is the minimum gap spacing located at radius r_o, c is the speed of light in vacuum, and L_o is the inductance of the load which is determined by the dimensions of the electron can. Because the electron current flow is constrained against the cathode, the simulation data from this surface is of critical importance. To avoid stair-stepping in the PIC code MITL simulation, a flat cathode disk was incorporated into the gap spacing profile. Therefore, the curvature of the anode fully characterizes the radial dependence of the gap used to set the MITL vacuum impedance for a particular electron flow rate. Fig. 2 gives the calculated curvature of a constant flow anode with a 0.56 m radius. The minimum gap of the profile is located at a radius of 0.05 m coincident with the edge of the electron collector throat.

For, $\beta > 0$, the gap spacing profile describes a reducing electron flow into the load region. The curvature of these profiles tends to become slightly convex. The vacuum impedance of both the constant and reducing flow profiles are given in Fig. 3. A higher reduction in electron flow leads to a slight increase in vacuum impedance. Impedance profiles of constant flow geometries tend to be constant while reducing electron flow results in a slight radial reduction in line impedance. To provide a better comparison with the constant electron flow, initial simulations were conducted with a $\beta = 1.3$ to allow for a more appreciable flow reduction.

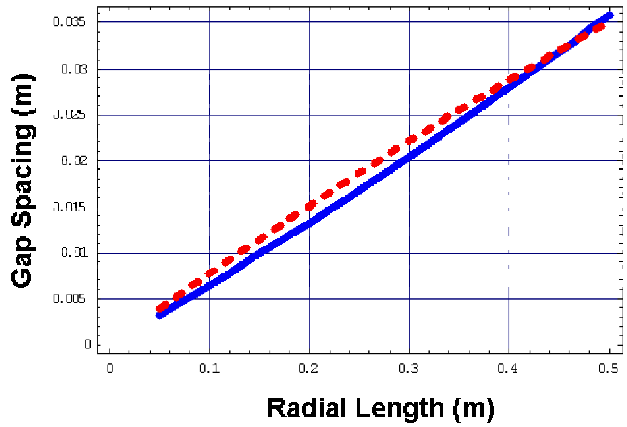

Figure 2. MITL gap spacing vs. radius. Solid line indicates constant flow. Dashed line indicates reducing flow.

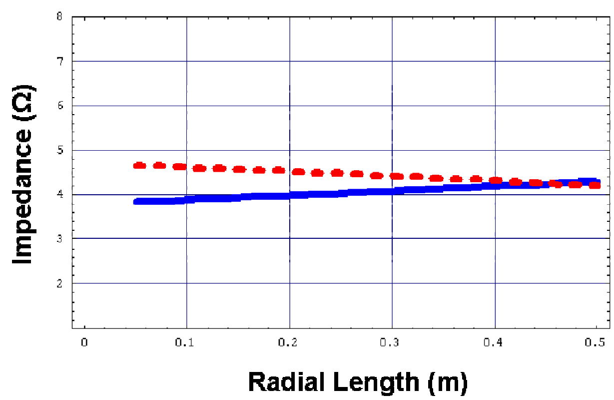

Figure 3. Line impedance vs. radius. Impedance profiles of constant flow geometries tend to be constant (solid line) while reducing electron flow results in a radial reduction in line impedance (dashed line).

B. Electron Collector

The lumped inductance of the load, L_o, is a key component in determining the curvature of the anode's gap spacing profile. This value was set to 51.2 nH to provide the necessary inductance relative to the diagnostic shielding conduit used in the pulsed-power driver. The dimensions of the collector can are set by the distributed load inductance section shown in Fig. 4. The dimensions of the electron can sections are given in Table 1.

The electron collector allows for a direct measurement to be made of the electron flow at the load. It encloses 97% of the magnetic flux in the load region. When electrons flow into the collector, this separate electrode appears like the anode surface. Because of the reduced electric field in the enlarged region of the load, the mean electron drift velocity decreases causing a build-up of space charge until enough electric field is created to allow the electrons to transit the magnetic flux and reach the anode. A CVR was placed at the base of this load to record the local current density at that location.

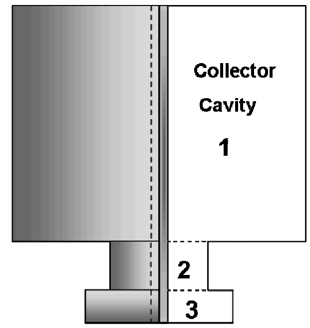

Figure 4. Cross-section of load inductance. Center post is shown and defines the inner radius, r_{in} (m) = 0.0079m, of the coaxial geometry. In order to calculate the total inductance the load has been divided into three sections: 1 – Collector, 2 – Throat, 3- Base.

Table 1. Electron Collector Dimensions.

Section	r_{out} (m)	*Length*(m)	*Inductance(nH/m)*
Collector	0.0953	0.0699	497.0
Throat	0.0508	0.0318	371.3
Base	0.0381	0.0175	313.7

C. Operation results

The radial disk MITL hardware was installed into Sandia National Laboratories' Tesla machine[1] and driven by its plasma switch triggering section known as T2. Tesla's triggering section is capable of supplying an 800 kV forward wave to a 2 Ω line. This is capable of providing the MITL with 500 kA within a 50 ns pulse width FWHM.

Preliminary experiments were conducted on the constant flow geometry. Initial CVR measurements were inconclusive due to inadequate spacing which resulted in a short between the electron collector can and the outer housing. The current monitors, however, worked exceptionally well and provided a clear illustration of the insulated flow (Fig. 5). Fig. 6 shows the comparison between the average electron flow of the outer most current monitors and those much closer to the load. The relative amplitudes illustrate the radial constant flow characteristic of the anode geometry used. Fig. 7 shows the comparison between the PIC simulation results and the measured electron flow. While there is good agreement in the time of insulation at peak current and the local voltage at the location of each of the current monitors, the simulation predicts an electron current with twice the amplitude than that which was measured.

Analytic theory predicts an electron current that is slightly less than the measured value (Fig.7). This discrepancy is most likely a result of the MITL not operating at high enough voltage. Pressure balance theory is only valid at very high voltages were the electric-kinetic pressure is much less than the magnetic pressure. This experiment was conducted at a voltage of

[1] Pulsed-power driver for the Triggered Plasma Opening Switch (TPOS) located in Tech Area IV.

approximately 550 kV and constitutes a “grey area” where the electron emission is just starting to initiate.

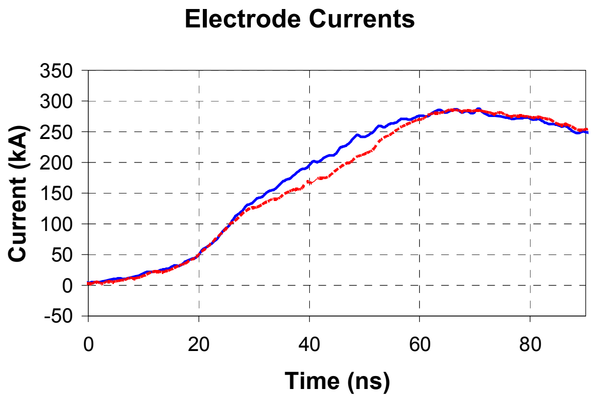

Figure 5. Anode (solid) and cathode (dashed) currents from the three sets of monitors furthest from the load and averaged azimuthally. The insulated electron flow is the gap between these waveforms.

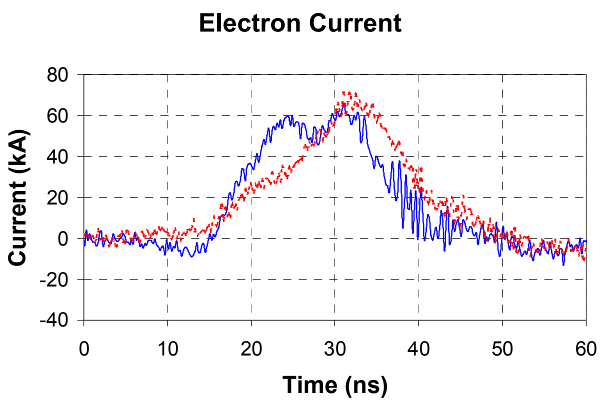

Figure 6. Azimuthally averaged electron current flow at distances of 53.69 nH (solid) and 55.24 nH (dashed) from the load.

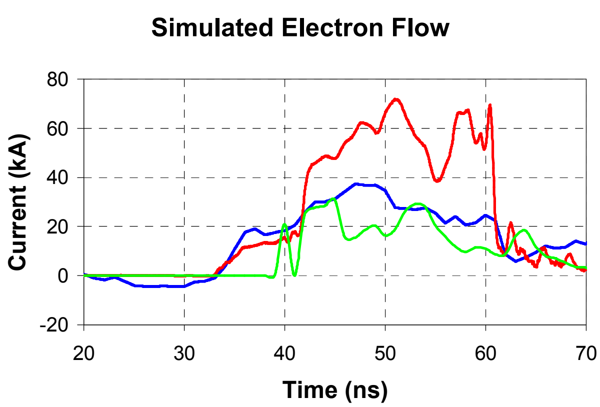

Figure 7. Simulated electron flow (red) vs. electron flow measured within the disk transmission line (blue). The electron flow calculated from analytical theory is shown in green.

III. SUMMARY

We have described a standard for paper submission to the 2007 IEEE International Pulsed Power and Plasma Science Conference. It is imperative that the authors carefully follow these guidelines.

IV. REFERENCES

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APPENDIX A

A. Electron Flow

The local electron flow current at a radius, r, is approximated with planar sections of transmission line. Using pressure balance arguments [4], the line voltage across the line in the presence of space charge is found to be,

$$V = Z\sqrt{I_a^2 - I_c^2} - \frac{m_e c^2}{2e}\left(\left(\frac{I_a}{I_c}\right)^2 - 1\right) \qquad (3)$$

where Z is the planar vacuum line characteristic impedance and I_a and I_c are the anode and cathode currents respectively. For strongly insulated lines where the $I_a >> I_e$, the above expression can be simplified using the definition of electron flow as the difference in anode and cathode current to obtain the following:

$$V = Z\sqrt{I_a^2 - (I_a - I_e)^2} - \frac{m_e c^2}{2e}\left(\frac{I_a^2}{(I_a - I_e)^2} - 1\right),$$

$$V \approx Z\sqrt{2I_a I_e}\,,$$

$$I_e \approx \frac{V^2}{2I_a Z^2}\,.$$