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MODELING THE RITS-6 TRANSMISSION LINE*

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Abstract

Sandia National Laboratories' Radiographic Integrated Test Stand (RITS-6) is a six-cell inductive voltage adder accelerator designed to produce currents of 186 kA at 7.8 MV in 70 ns in its low-impedance configuration. The six inductive-adder cells are connected in series to a coaxial magnetically insulated transmission line. Each cell has a single point feed to an azimuthal transmission line which distributes the pulse around the cell bore. To understand the extent to which power is distributed symmetrically around the coaxial transmission line and its effect on electron power flow downstream, particle-in-cell simulations were used to model the entire RITS-6 transmission line in 3D from pulse forming circuit to the diode load. Simulation results show electron flow current to be asymmetric by 16% at the exit to the sixth cell, but 3% or less at diagnostic positions near the load. Magnetic insulation in the trans-mission line does not appear to be impacted by the asymmetry, though flow impedance is not uniform axially.

I. RITS-6 DESIGN AND SIMULATION GEOMETRY

The Radiographic Integrated Test Stand (RITS) [1] at Sandia National Laboratories is a pulsed-power driven accelerator designed to develop electron-beam diode sources for x–ray radiography. RITS-6 [2] is the latest configuration of the accelerator, designed to deliver 186 kA at 7.8 MV in 70 ns. Six separate 70-ns pulses, generated in 7.8-Ω water-switched pulse forming lines (PFLs), are added in series through inductive voltage adder (IVA) [3] cells. The pulses are timed to arrive nearly simultaneously to form the single drive pulse for the accelerator.

Each IVA cell is connected to the common coaxial vacuum transmission line by an azimuthal transmission line designed distribute the pulse symmetrically around the center conductor. The azimuthal line was shown to reduce, but not eliminate, azimuthal asymmetry in the delivered pulse for the three-cell version of RITS [4,5]. Details of the IVA design and the azimuthal transmission line are presented in Ref. [1].

A schematic of the RITS-6 accelerator with six IVA cells and a large-area-diode load is shown in Fig. 1. Diagnostic positions labeled "E", "F", and "G" are fitted with B-dot point-probes to measure anode and cathode currents.

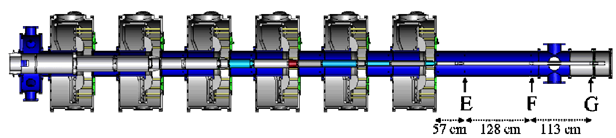

Figure 1. Schematic of the RITS-6 IVA accelerator.

The transmission line is configured for negative polarity with field stresses along the cathode in excess of the thresholds for electron emission (typically ~240 kV/cm [6]), such that the system operates as a magnetically insulated transmission line (MITL). Insulated flow is critical in preventing the loss of current across the coaxial gap which would degrade accelerator performance. Uniform, laminar flow is also a foundation for voltage calculations in the MITL which use equations from Mendel [7] and Creedon [8].

To understand the extent and impact of the azimuthal asymmetry in pulse delivery on power flow, and therefore

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measured currents, particle-in-cell (PIC) simulations were conducted in 3D using the fully relativistic, electromagnetic PIC code LSP [9]. Agreement between measured results on RITS-6 and simulations has been demonstrated previously [4,5,10], providing confidence in this method of investigating potential design problems. Simulations were conducted over the full RITS-6 geometry including the six azimuthal transmission lines and large-area-diode load. Spatial resolution along the transmission line cathode was 1.1 mm in x and y. This was chosen to sufficiently resolve the free electron current which was generated in the simulation via space charge limited emission. The simulation geometry is illustrated in Fig. 2 with cutaways in the y-z and x-z planes. Outputs from the PFLs to the IVA point feeds, labeled "input" in Fig. 2, are modeled as circuits.

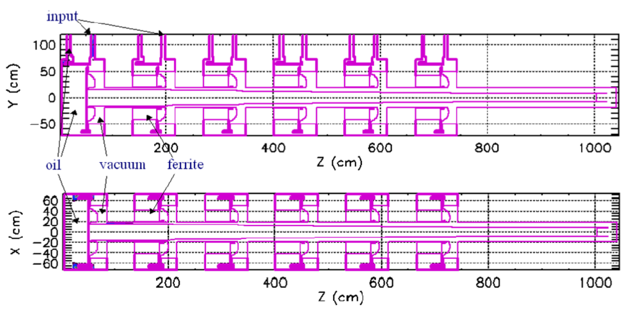

Figure 2. Geometry used in 3D LSP simulations of the RITS-6 accelerator.

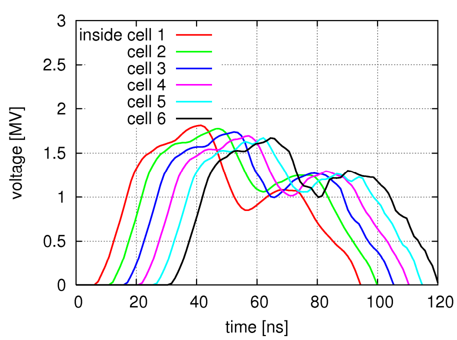

Figure 3. Voltage pulse from simulation recorded just below "input" locations in Fig. 2.

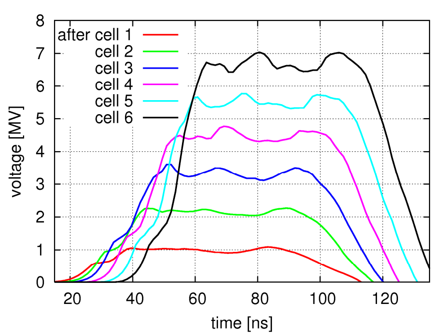

Figure 4. Voltage pulse from simulation recorded along the MITL in Fig. 2, just downstream from each IVA cell.

The pulse injected at each of the IVA inputs had a 12-ns rise to a 55-ns plateau followed by a 13-ns fall. This pulse, as measured just inside the input to each cell, is shown in Fig. 3. The MITL voltage just downstream from each IVA cell is shown in Fig. 4.

II. SIMULATION RESULTS

Electron flow from simulation at 90 ns into the pulse is shown in Fig. 5. The x-z plane is displayed for a thin slice in y, showing insulated flow consistent with Ref. 5. As expected, flow current is asymmetric at the azimuthal transmission lines, but becomes more symmetric downstream. The asymmetry is quantified in Fig. 6 which shows magnetic field probes at different azimuthal positions along the z axis. The flow is asymmetric just downstream from the last IVA cell (z = 7.51 m in Fig. 2) with a 16% variation in B_x between 0 and 180 degrees. It becomes more symmetric at position "E" in Fig. 1 (z = 8.03 m in Fig. 2) with an 11% variation in B_x. Mendel calculations made at this location typically use averaged current, which appears reasonable. Flow current is almost fully symmetric by position "F" with a max variation of 3% in B_x.

A more surprising result from this simulation is the variation in cathode boundary current with axial position. The flow is greater downstream as more electrons are drawn from the cathode. This is somewhat visible in the particle distributions of Fig. 5, but is clearly shown in currents plotted in Fig. 7.

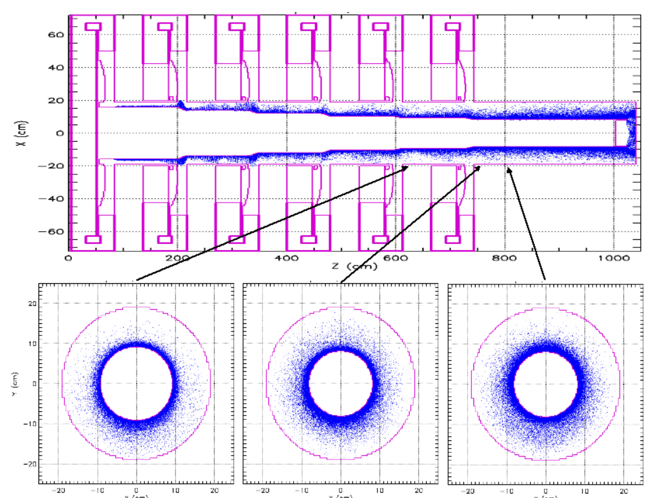

Figure 5. Electron macroparticle locations from the LSP simulation of RITS-6 in 3D. (top) Particles in the x-z plane for $0<y<1$. (bottom) Particles in the x-y plane at three locations in z marked by arrows.

It is not clear if axial changes in flow current affect calculations assuming laminar flow. Transmission line voltages are typically calculated using equations from Mendel's pressure balance theory [7]:

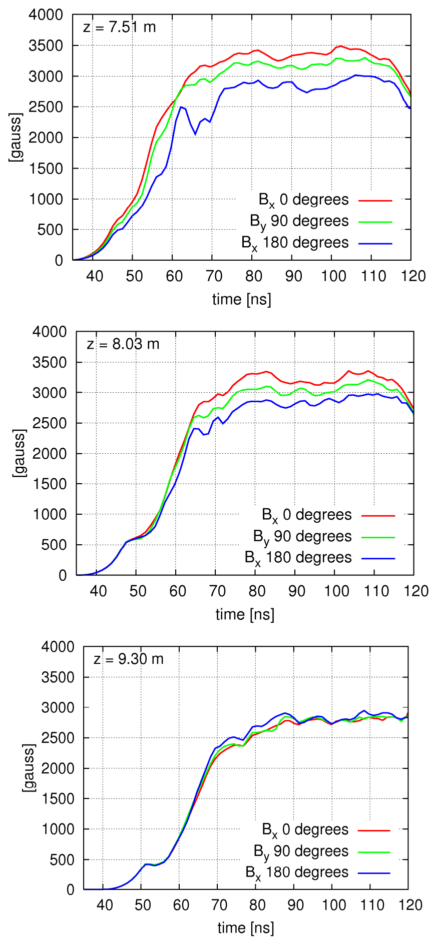

Figure 6. Magnetic field probes at 0, 90, and 180 degrees at z = 7.51, 8.03, and 9.30 m in Fig. 2.

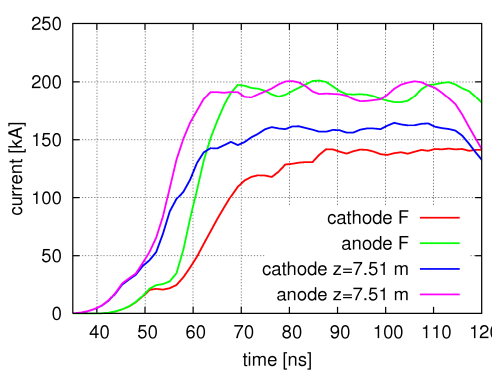

Figure 7. Anode and cathode boundary currents at z = 7.51 and 8.03 m (position "F") in Fig. 2.

$$V = Z_0 (I_a^2 - I_c^2)^{1/2} - 0.511 \left(\frac{I_a}{I_c} - 1 \right) \left[\left[2 \left(\frac{I_a}{I_c} + 1 \right) \right]^{1/2} - 1 \right],$$

or the Creedon model [7]:

$$V = Z_0 (I_a^2 - I_c^2)^{1/2} + 0.511 \left[\frac{I_a}{I_c} - \left(\frac{I_a^2}{I_c^2} - 1 \right)^{1/2} \ln \left[\frac{I_a}{I_c} + \left(\frac{I_a^2}{I_c^2} - 1 \right)^{1/2} \right] - 1 \right],$$

where Z_0 is the vacuum impedance, and I_a and I_c are the anode and cathode boundary currents, respectively, in MA. Voltages typically agree between these models and 2D simulations which have sufficient spatial resolution. While the flow current appears well resolved in the simulation presented here, the voltages calculated from Eqs. 1 and 2 using simulated currents disagree by more than 10%, as shown in Fig. 8. It is unclear whether operation for this diode is outside the range of validity for equilibrium theory or if the discrepancy will be resolved with higher spatial resolution or with an updated magnetically insulated flow theory [11].

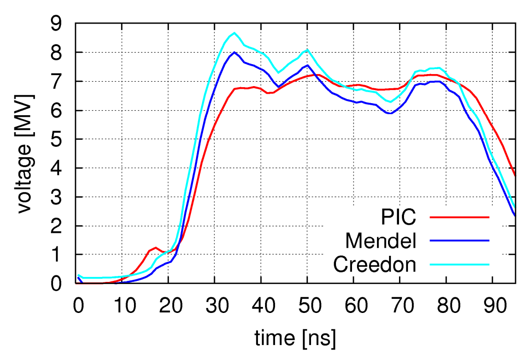

Figure 8. Voltages calculated from simulation currents using Eq. 1 (Mendel) and Eq. 2 (Creedon) compared to the simulation voltage (PIC) at the same location.

III. CONCLUSION

Simulations of the RITS-6 accelerator from the azimuthal transmission lines to the diode load have been performed in LSP with 3D, high-resolution geometry. Results show electron flow current to be asymmetric by 16% at the exit to the sixth cell, and becoming highly symmetric by diagnostic position "F" (<3% asymmetry). This is in qualitative agreement with experimental results which show greater asymmetry at diagnostic position "E" than at "F". The asymmetry does not appear to impact magnetic insulation, though flow impedance is not uniform axially.

The discrepancy between the voltages calculated with pressure-balance models and that from simulation may be resolved using more recent versions of magnetically insulated flow theory [11], which have relaxed assumptions on electron distribution but have been rescaled to match detailed PIC simulation results.

IV. REFERENCES

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