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Magnetically Insulated Electron Flow in the 2.5-MeV URSA Minor LTD

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Abstract

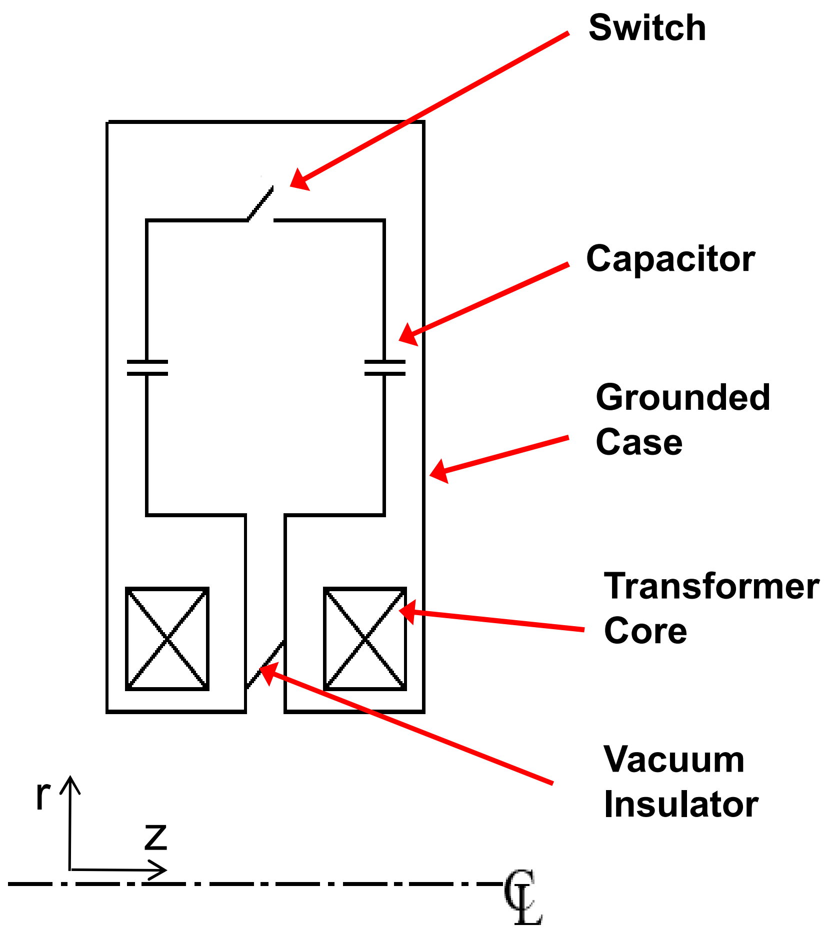
The Linear Transformer Driver (LTD) is a compact type of inductive voltage adder (IVA) with the primary energy storage inside the IVA cells. The 2.5-MV URSA Minor LTD is designed to drive a magnetically insulated transmission line (MITL) and electron beam diode load. Because of its compact architecture, control of the electron power flow in the MITL (e.g. early time loss currents) is paramount to efficient operation. Results from experimental testing and 2-D particle-in-cell (PIC) simulations of magnetic insulation and electron loss in the MITL using Quicksilver will be presented. The simulations compute the local energy deposition of electrons hitting the anode structures, including the dielectric insulator for each cavity. On URSA Minor, currents are measured in the cathode and anode conductors at four axial locations along the MITL. Measured currents and inferred voltages will be compared to the simulations.

Outline

- Introduction to LTD operation
- Description of URSA Minor, a 21-cavity LTD
- Data from initial experiments with URSA Minor
- PIC simulations of the URSA Minor MITL
- Comparison of PIC simulations and experimental data
- Future plans

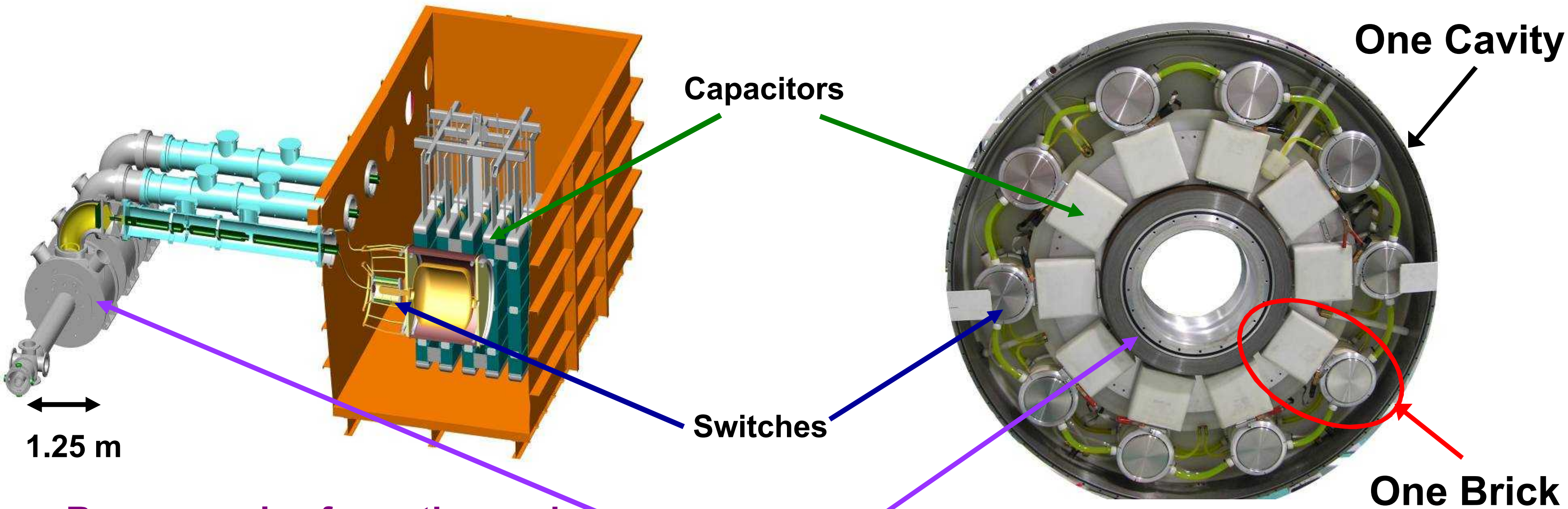
The basic building blocks of a linear transformer driver (LTD)

- The basic building block of a LTD circuit, the "Brick," is a single stage Marx generator with two capacitors and one switch.
- A "Cavity," is a single LTD stage with several parallel brick elements.
- LTD cavities are typically encased in a grounded metal case with inductive isolation.
- Cavities are stacked in series to form a voltage adder.



The LTD is much more compact than conventional IVAs

Inductive Voltage Adder (IVA) **Linear Transformer Driver (LTD)**



Remove pulse formation and compression hardware

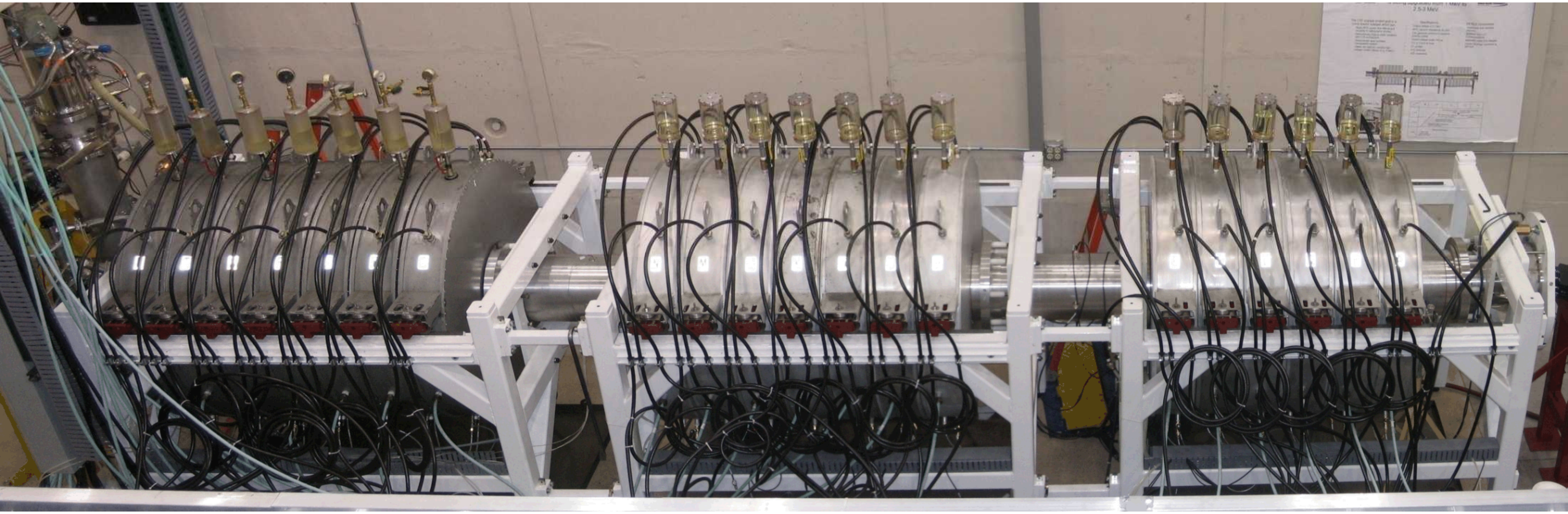
Inductive isolation

10 m

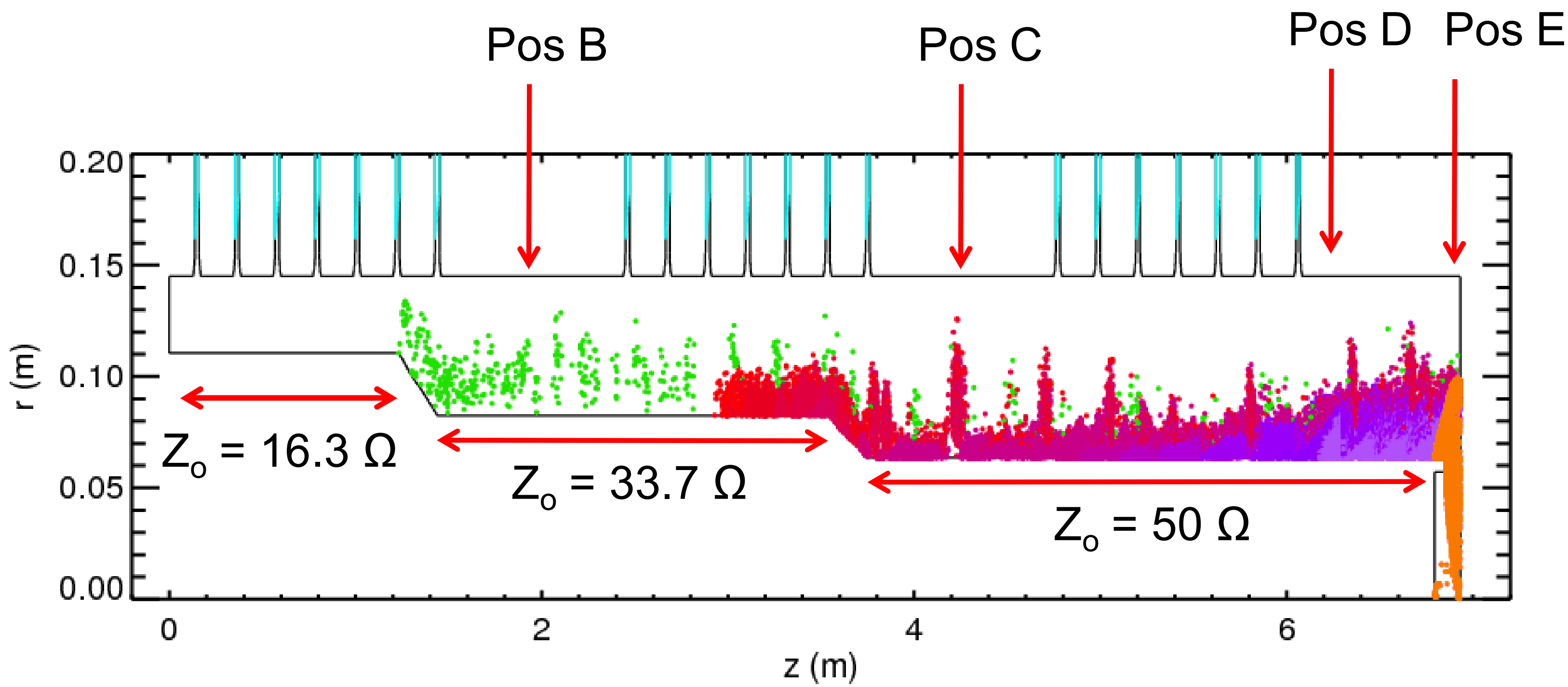
1.25 m

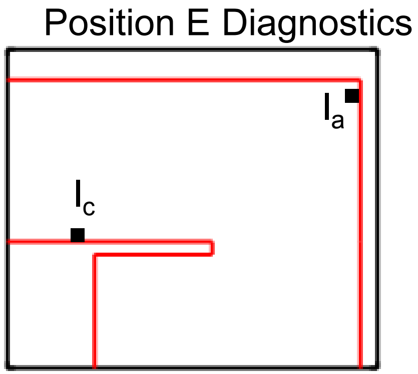
URSA Minor is a 2.5 MeV LTD for flash radiography research

- Upgraded from 7 to 21 cavities during 2010
- Cavities are assembled in groups of 7
- 7.5 m long and 1.5 m wide
- Total of 210 switches and 420 capacitors



MITL geometry and location of current measurements





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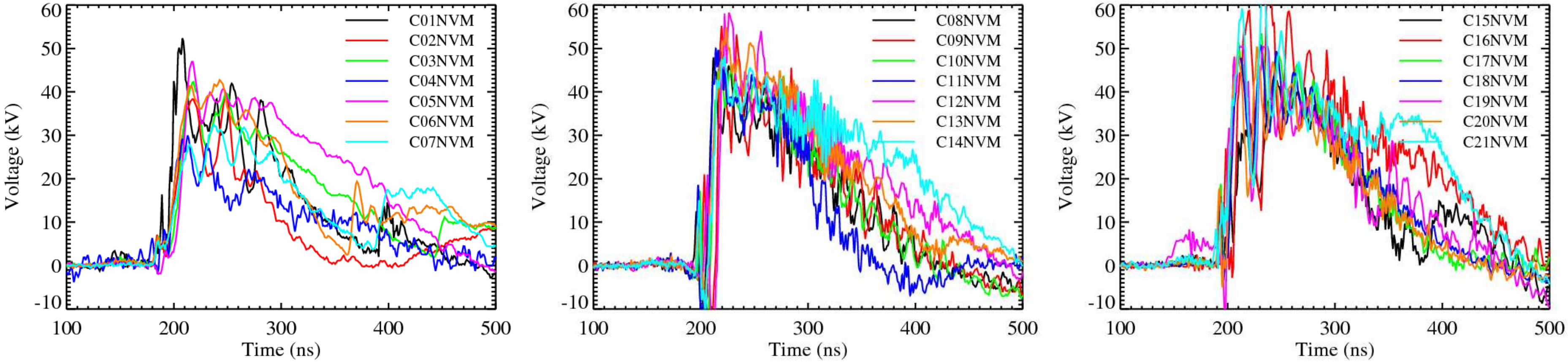
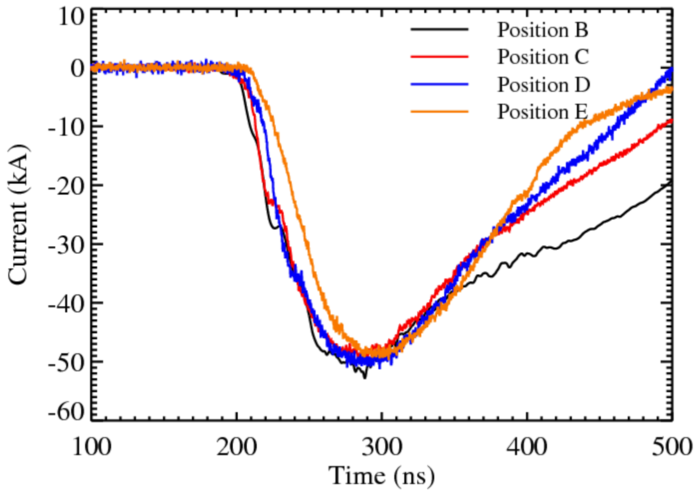
Cavity timing is good, but pulse shape varies between cavities

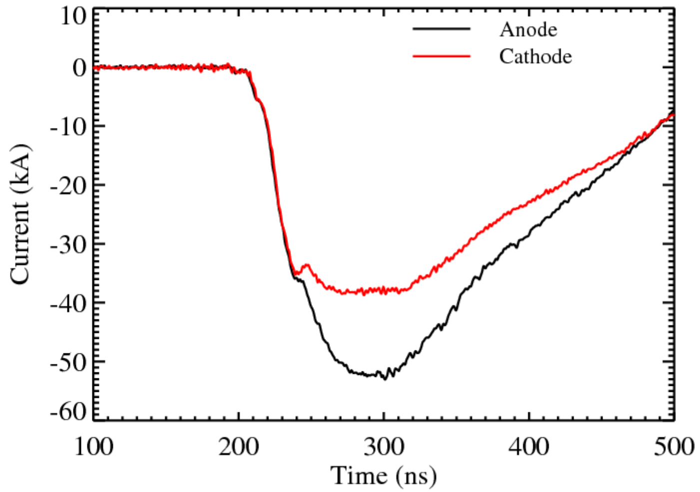
- Plots show cavity half voltages from a single shot with 21 cavities
- Prepulse and oscillations vary between cavities
- Some variation caused by differences in core materials in different cavities
- In some cavities, switches do not all fire at the same time, degrading pulse shape.



Measurement of electron flow and loss currents

- Anode current is measured at four axial locations in the MITL
- Peak current at these four locations indicate there is very little loss current at peak power
- After cavity 21 (position D) we measure ~14 kA of insulated electron flow at peak current.





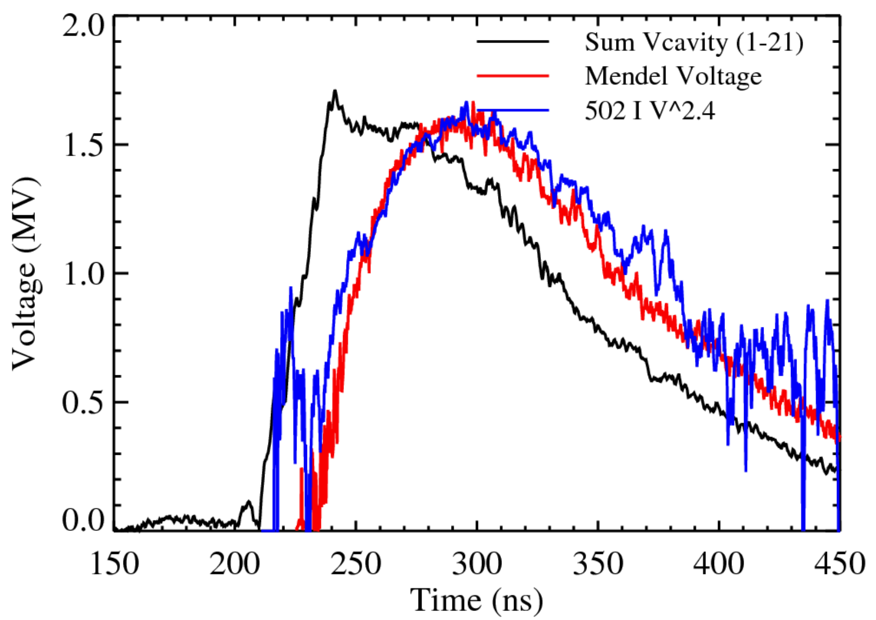
Comparison of voltage calculations methods for the experimental data

- **Plot shows a comparison of the MITL voltage calculated based on the sum of the cavity voltages to the Mendel voltage calculation and a voltage calculation based on the radiographers equation.**
- **The radiographers equation was derived using MCNPX calculations of the actual diode geometry.**

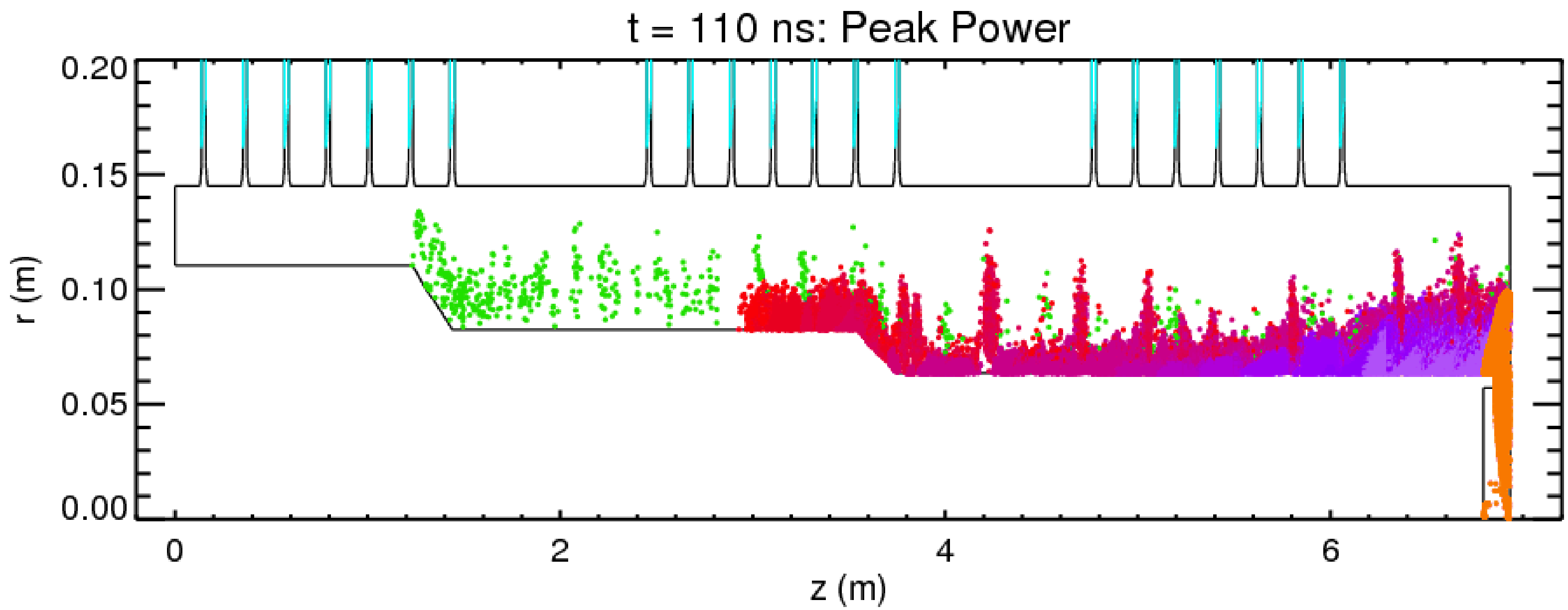
$$d = 502 I V^{2.4}$$

- **The Mendel voltage calculated from MITL currents at position D using the equation:**

$$V = Z\left(I_a^2 - I_c^2\right)^{\frac{1}{2}} - \frac{mc^2}{e}\left(\frac{I_a}{I_c} - 1\right)\left(\left[2\left(\frac{I_a}{I_c} + 1\right)\right]^{\frac{1}{2}} - 1\right)$$



We have set up a 2-D r-z model with the PIC code Quicksilver



- **1.0 mm resolution across the A-K gap of the 21 feeds**
- **500 K cells; 4-1/2 hour run time on 16 processors of Redsky**
  - **Can easily increase # of particles and/or cells if needed**
- **200 kV/cm emission threshold → emission from one corner cell at cavity #6, but bulk emission starts downstream of cavity #10**

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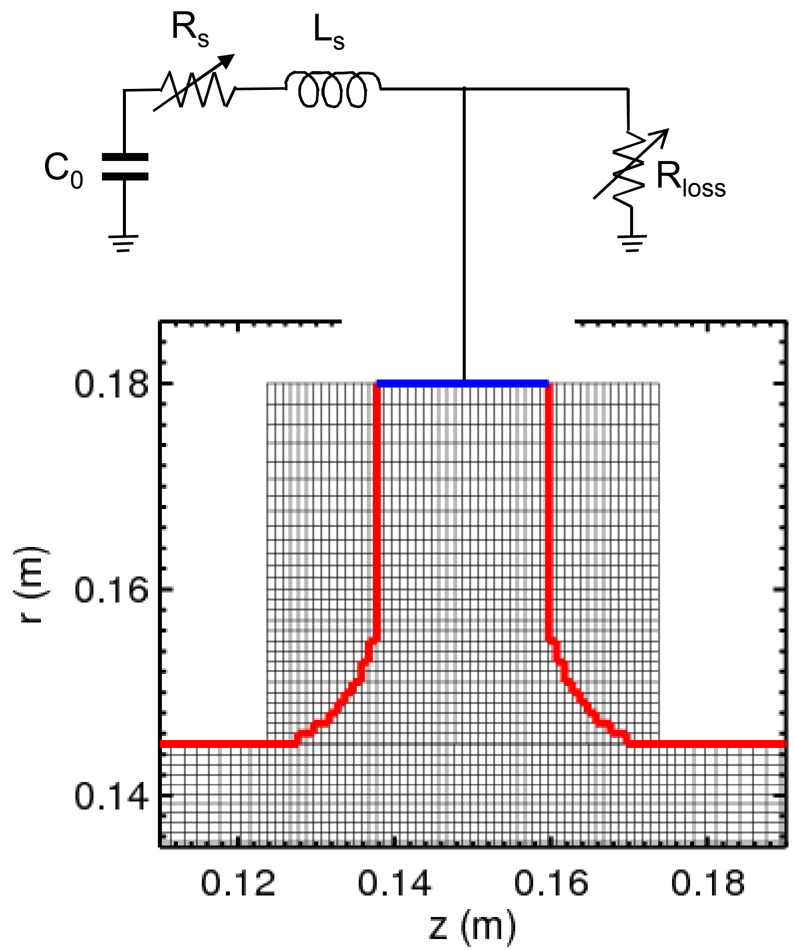
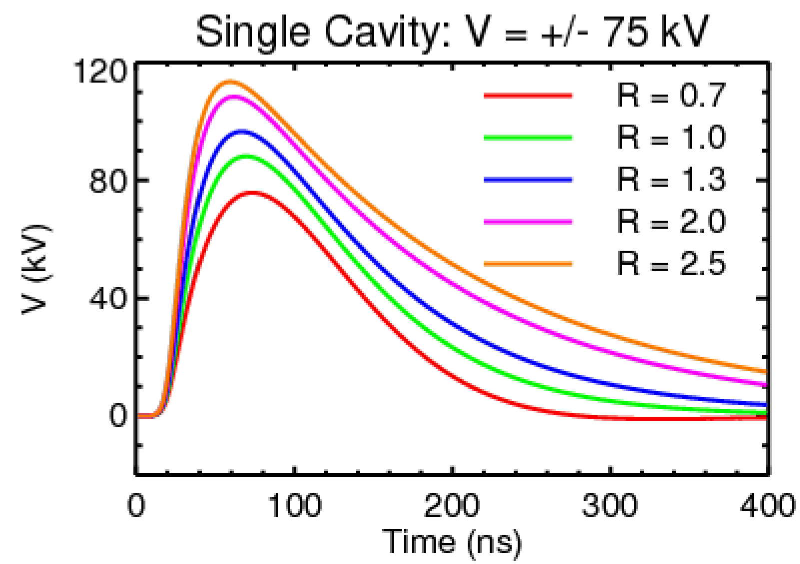
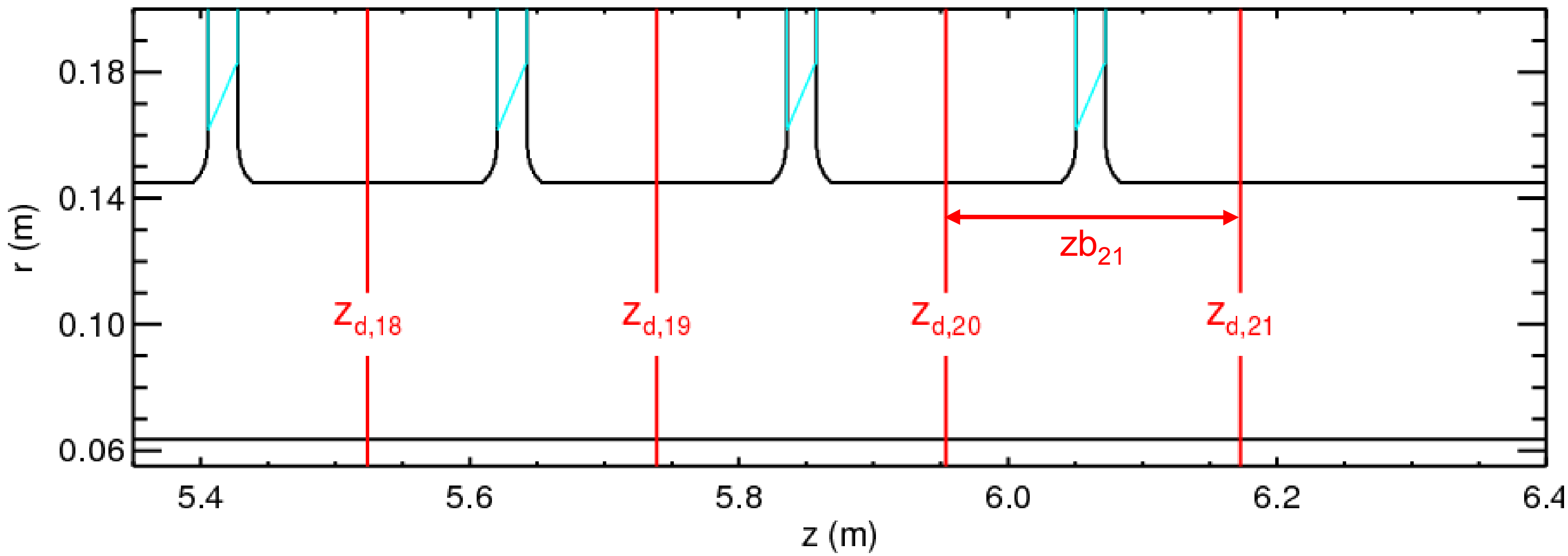
Each feed is driven with an RLC circuit including a resistive loss for the cores





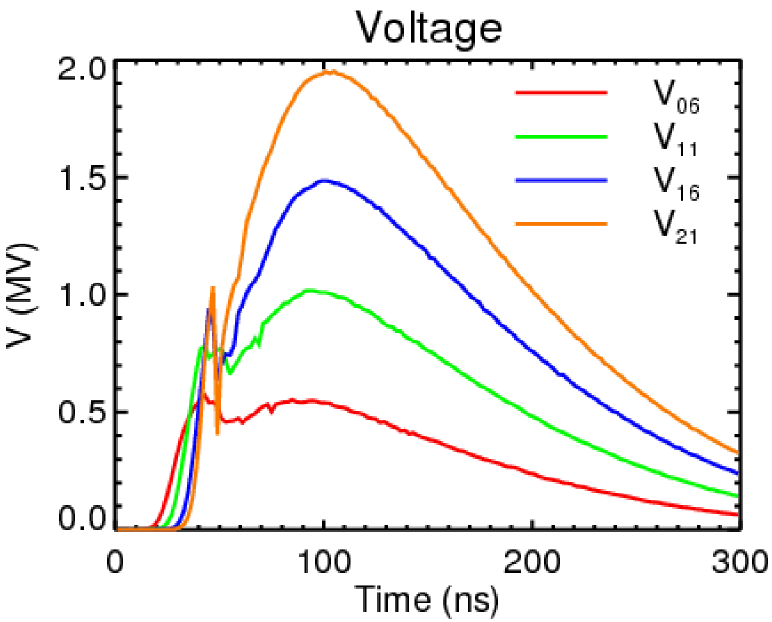
- **C_0 = 100 nF, L_s = 25 nH, R_{loss} = exponential decay from 4 Ω – 1.0 Ω**
- **R_s: $10^5 \rightarrow 0.2\ \Omega$ with 2 ns exponential decay**
- **Single cavity into resistive load R agrees to ~5% with more detailed circuit model**

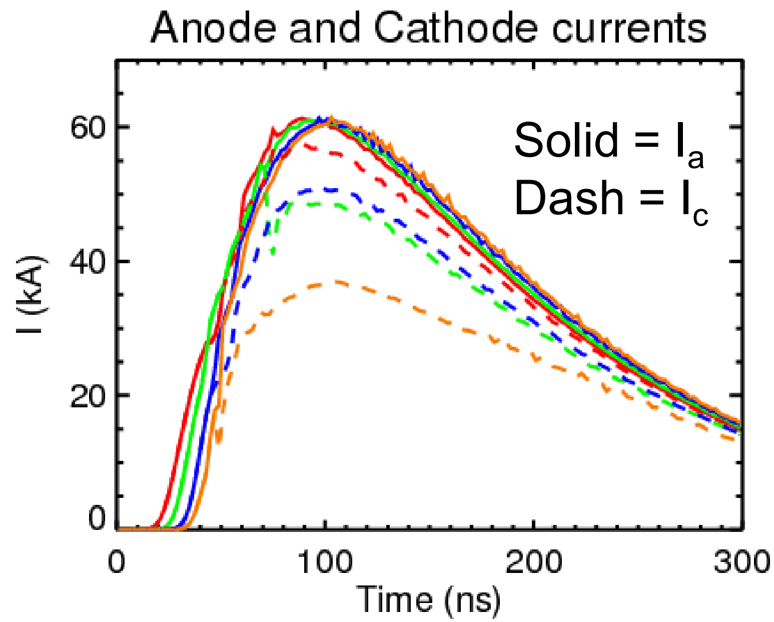
We have detailed diagnostics for power flow in the MITL



- **Define locations $z_{d,i}$ 10 cm downstream of *i*'th cavity**
- **Monitor voltage; and anode, cathode and flow currents at $z_{d,i}$**
  - **V_i, $I_{a,i}$, $I_{c,i}$ and $I_{e,i}$**
- **Electron loss to anode and insulators in "z-bins" zb_i: $z_{d,i-1} \leq z \leq z_{d,i}$**
  - **$I_{loss,i}$ and $E_{loss,i}$**

There is significant electron flow in the MITL





- **Particle plot shows electron flow turn on across from cavity #6**
  - **Turbulent flow launched at impedance transitions**
- **At $z = z_{d,21}$, flow current at peak power is ~38% of total**

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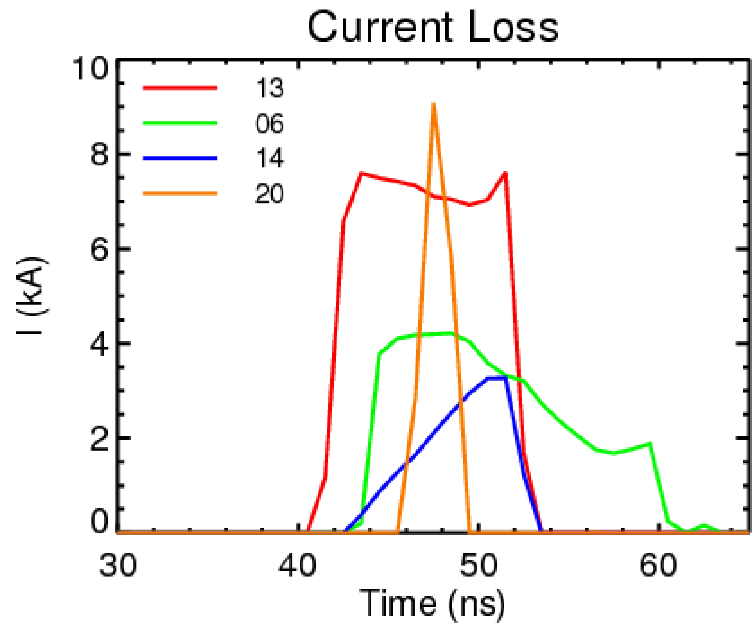
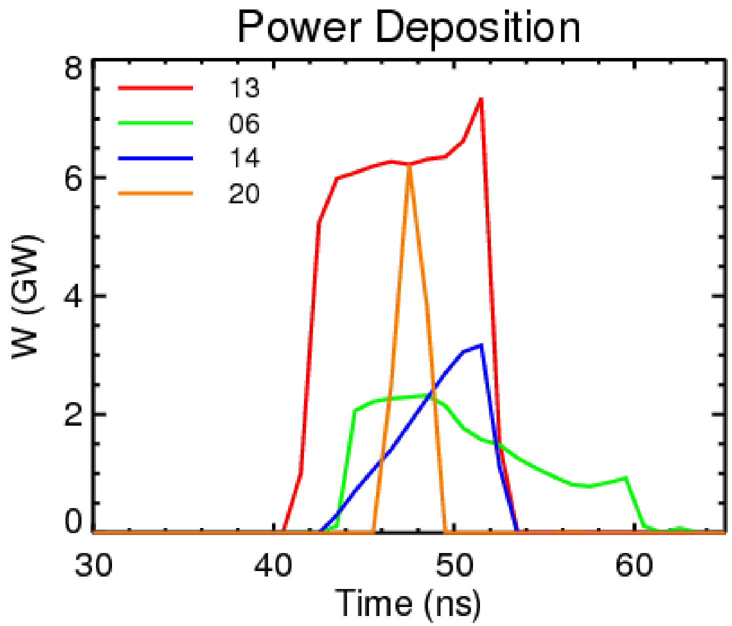
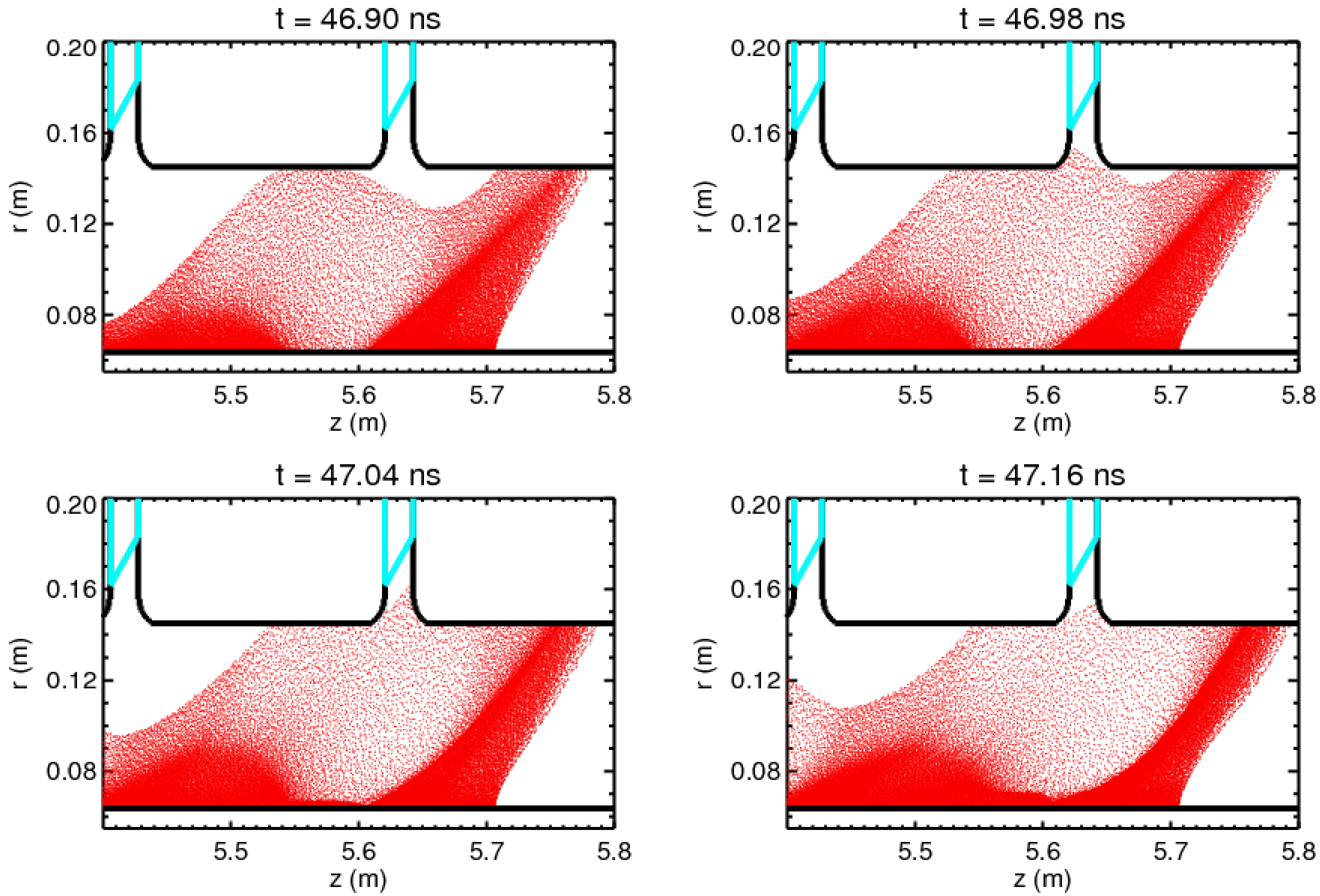
There is relatively little electron loss to the anode near the cavities





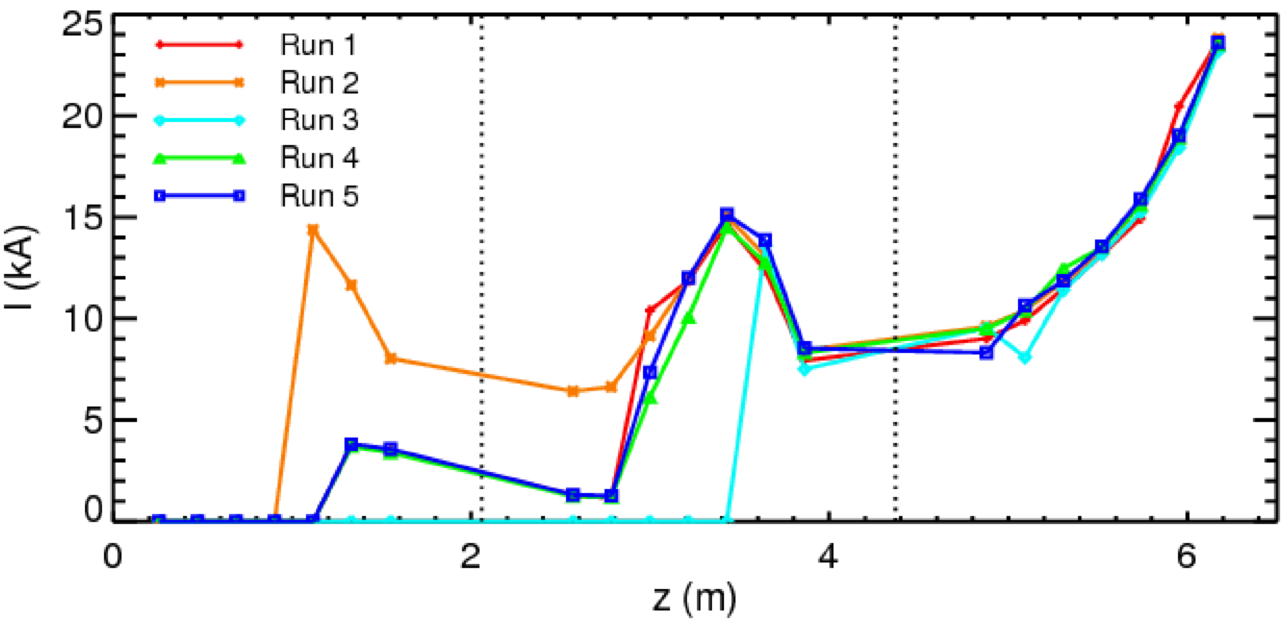
- **Figures show loss current and power to the entire outer structure – anode and feed conductors, and insulators – for each *z-bin***
  - **Shown are the top 4 in order of total deposited energy**
- **The MITL insulates very rapidly (< 20 ns even for these locations)**

High-resolution animations show electrons avoiding the insulators



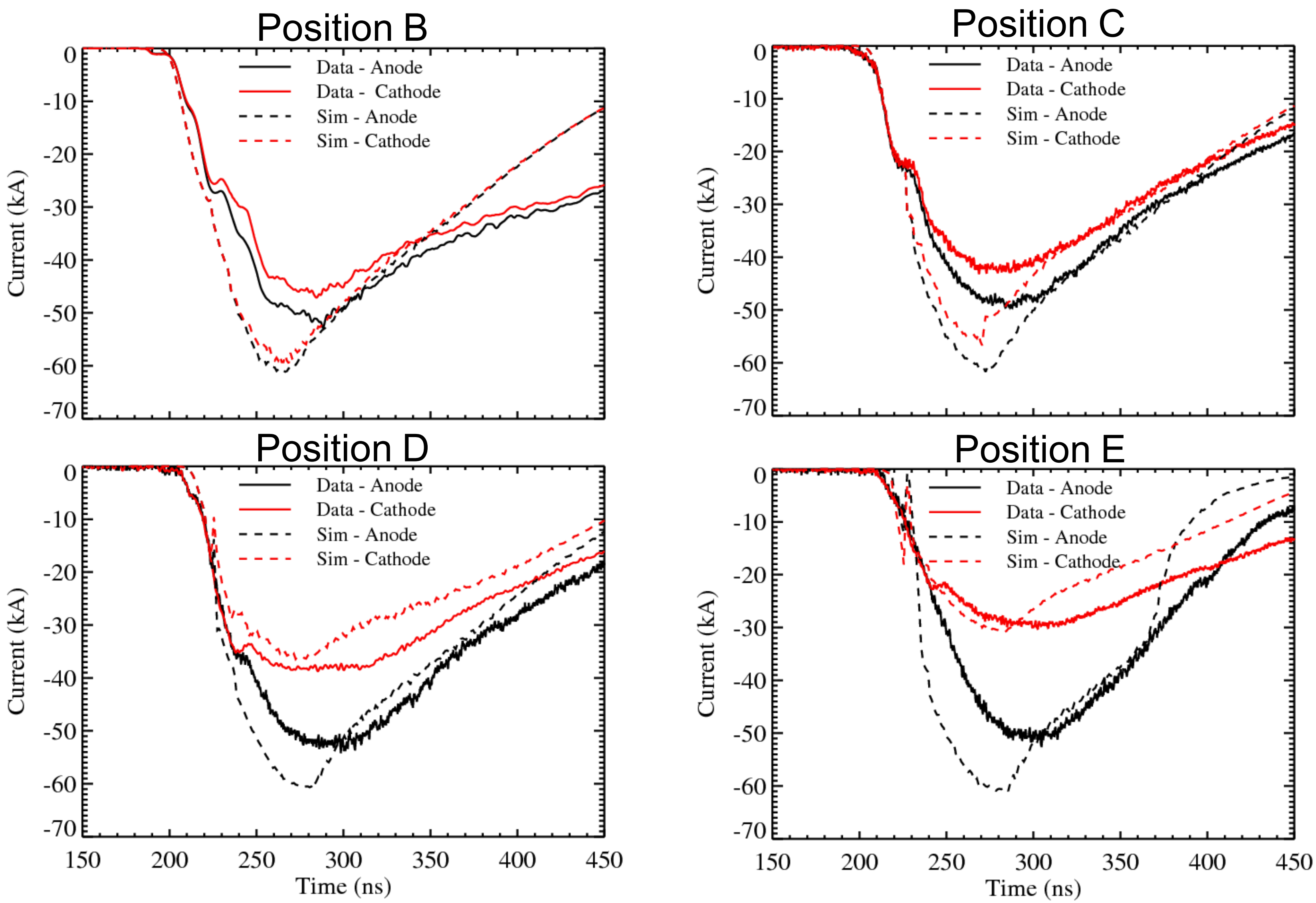
- **Electron loss front moving past cavity 19: maximum penetration into feed at t = 47.04 ns, then receding by 47.16 ns**

The electron flow current downstream of the cavities is insensitive to variations upstream



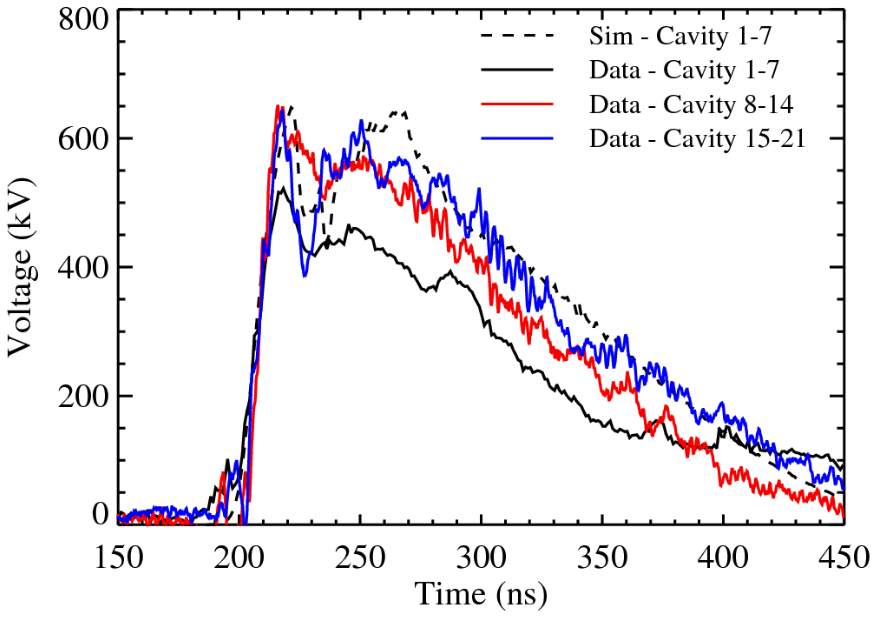
- **Figure shows spatial profile of *time-averaged* flow current from t = 90 to t = 120 ns, bracketing peak power at t ~ 110 ns**
- **Run 1: emission threshold E_{thr} = 200 kV/cm, ideal trigger timing**
  - **Runs 2 and 3 vary E_{thr}: 2 = 150, 3 = 250 kV/cm**
  - **Runs 4 and 5 add random trigger timing offsets at E_{thr} = 200 kV/cm**

MITL anode and cathode currents from experiment and PIC simulations



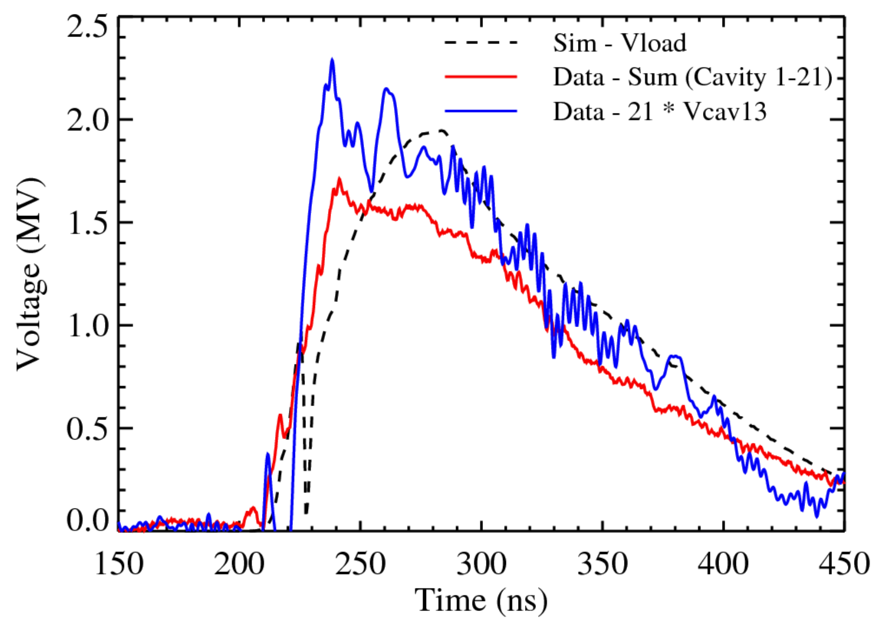
Comparison of voltage from each group of seven cavities

- **The experimental voltage from group 1 (cavities 1-7) is significantly lower than the voltage from the second and third groups.**
- **The simulation agrees well with the experimental measurements of groups 2 and 3.**
- **The lower voltage in group 1 is mostly due to switch triggering problems**
- **Waveforms are aligned based on risetime.**



Correcting switch triggering problems should raise experimental voltage to match simulation

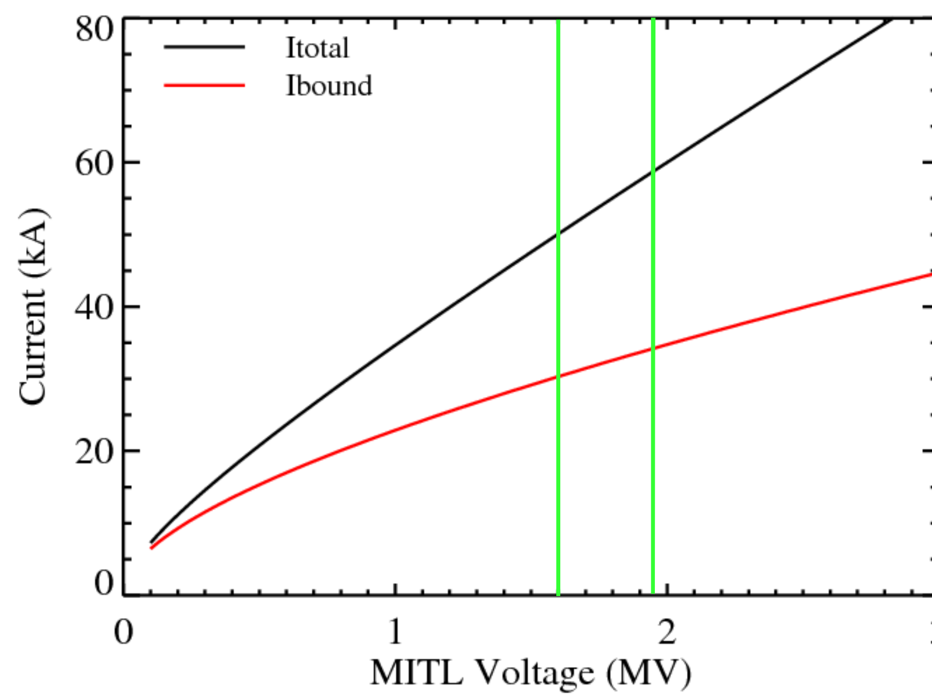
- Plots of individual cavity voltages on page 8 show a wide range of output voltages for the 21 cavities, partly caused by problems in switch triggering.
- One of the highest cavity voltages on this shot was cavity 13
- We can calculate what the experimental voltage would be if all switches fired when triggered and the output of each cavity was the same as cavity 13, shown here in Blue.
- This plot shows that when triggering and repeatability problems are corrected the output voltage will agree well with the simulated load voltage.



Comparison of simulation and data MITL currents with predictions from Creedon

- **PIC Simulation (Vpeak=1.94 MV)**
  - **Ia**
    - **Sim: 60.6 kA**
    - **Creedon: 58.5 kA**
  - **Ic**
    - **Sim: 36.1 kA**
    - **Creedon: 34.1 kA**
- **Data (Vpeak=1.6 MV)**
  - **Ia**
    - **Data: 52.0 kA**
    - **Creedon: 50.1 kA**
  - **Ic**
    - **Data: 38.3 kA**
    - **Creedon: 30.3 kA**
- **Total current in data and simulation agree very will with Creedon predictions. However, the experimental bound current is 25% higher than predicted by Creedon.**

- **Calculations of MITL anode and cathode current based relativistic Brillouin flow solutions of Creedon for a 50-ohm vacuum impedance line.**



* Sim and Data currents are peak current at position D

Future LTD research and development

- Continue full system testing to improve jitter and evaluate power flow
- Implement cavity changes to improve reliability and performance
- Test URSA Minor with self-magnetic pinch (SMP) diode to study effects of coupling LTD to radiographic diode
- Use PIC simulations to further investigate discrepancy between measured and simulated MITL bound current