SAND2011-4914C

LINEAR TRANSFORMER DRIVER (LTD) RESEARCH FOR RADIOGRAPHIC APPLICATIONS

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Abstract

URSA Minor is a 21-cavity Linear Transformer Driver (LTD) that has been built to evaluate LTD technology as a driver for flash radiography diode research. The LTD has been assembled and tested with initial testing being conducted at ±75 kV charge. In this configuration the generator has produced 1.7 MV on a 30-ohm MITL when driving an electron beam diode. Diagnostics during initial testing include cavity voltage, MITL currents, x-ray dose using TLDs, and x-ray dose rate using PIN diodes.

I. INTRODUCTION

URSA Minor is a Linear Transformer Driver (LTD) accelerator with 21 series LTD cavities in a voltage adder configuration. The LTD [1], [2] is a variant of the more well known Inductive Voltage Adder (IVA) accelerator architecture [3]. The primary energy storage in a LTD is configured inside the accelerating cavities in a low inductance geometry. The LTD architecture is more compact than typical IVA systems because they lack large oil tanks and pulse compression stages that are common to IVA systems. The output pulse shape from an LTD typically has longer rise and fall times than can be achieved in an IVA because the accelerating cavities are driven by capacitive discharge circuits rather than pulse forming lines.

The 21-cavity URSA Minor LTD is an expansion of the seven cavity LTD reported in previous publications [1], [4], [5]. The seven cavity LTD was designed by Sandia National Laboratories (Sandia) and the High Current Electronics Institute (HCEI) in Tomsk, Russia. The accelerator was transferred to Sandia in 2004 and tested from 2005-2010 with an electron beam diode load. The seven cavity LTD was capable of producing 800 kV pulses into a matched electron beam load.

The seven cavity system was designed to evaluate the LTD technology as a possible pulsed power driver for flash radiography. The system provided data on triggering multiple series cavities, interaction between cavities, component reliability, and coupling of LTD cavities to a dynamic impedance load. However, with peak voltage less than 1-MV, the system was not capable of investigating coupling of LTD cavities to a magnetically insulated transmission line (MITL) [6] or the effect of electron loss current in a MITL on the performance of the vacuum insulators.

The upgraded system (URSA Minor) is capable of operation up to 2.5 MV into a 30-50-Ω electron beam diode load in negative polarity. The new accelerator includes many small design changes compared to the original seven cavities. It is designed to drive a MITL for investigation of LTD coupling to a transmission line with electron power flow.

This paper discusses the commissioning and initial testing of the URSA Minor system at Sandia. Initial testing has been conducted at reduced charge voltage (±75-kV charge compared to the designed ±100-kV maximum) with a large area electron beam diode (LAD). Measurements of the anode and cathode current in the MITL are used to calculate the MITL and diode voltage. MCNPX [7] calculations are used to analyze the x-ray radiation production.

II. ACCELERATOR COMMISSIONING

URSA Minor consists of seven original cavities built at HCEI and 14 new cavities assembled at Sandia. All 21 cavities have an inner diameter of 29 cm and are 21-

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* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
‡ This work was performed under the auspices of an agreement between CEA/DAM and NNSA/DP on cooperation on fundamental sciences
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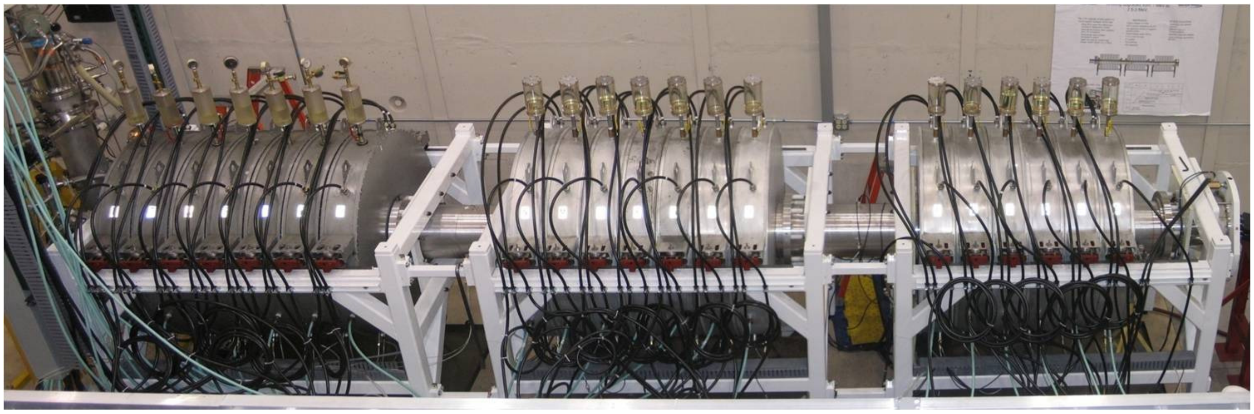

Figure 1. Photograph of the 21-cavity URSA Minor LTD system with one cavity removed. The electron beam load (not shown) is to the left of the accelerator in this photo.

cm long. The original seven cavities are 125-cm outer diameter whereas the 14 new cavities are 128-cm outer diameter. All 21 cavities have 10 switches each and 20 capacitors. The switches are L-3 model 40264-200 and the capacitors are 20-nF each manufactured by General Atomics Electronic Systems.

After assembling and testing each cavity, the full system was assembled as shown in Figure 1. The cavities are configured in three separate but connected stands with seven cavities in each stand. Cavities in each group of seven are aligned and compressed to form a vacuum seal. During initial testing, cavity 1, the furthest from the diode, was removed and replaced with a vacuum spool with a port for a vacuum gauge. After verifying that there was no significant pressure differential from one end of the accelerator to the other, the vacuum spool was removed and all 21 cavities were installed.

During the assembly process, each cavity was tested individually driving a 1-Ω resistive load. Testing included charging and firing between 10-30 shots with about half of the shots fired at ±90-kV charge. The cavity voltage was monitored using two resistive voltage dividers that measure the voltage from each output electrode to ground. The total cavity voltage is the sum of the two half cavity voltage measurements. Figure 2 shows a plot of 10 consecutive shots with one cavity at 90-kV charge. The timing jitter is defined as one standard deviation of the delay from the rising edge of the trigger pulse to the rising edge of the cavity voltage pulse. In Figure 2, the jitter is 0.75 ns. Individual cavity jitters are all in the range 0.5-2.0 ns when individually driving a resistive load.

Circuit simulations have been used to improve understanding of single cavity and multi-cavity accelerators [5], [8], [9]. Figure 2 shows a comparison of 10 consecutive tests with a single cavity to a simulation of a single cavity tested with a resistive load. In the simulation, the magnetic cores saturate at 185 ns to improve agreement with experimental voltage measurements.

The central cathode stalk of the MITL has three

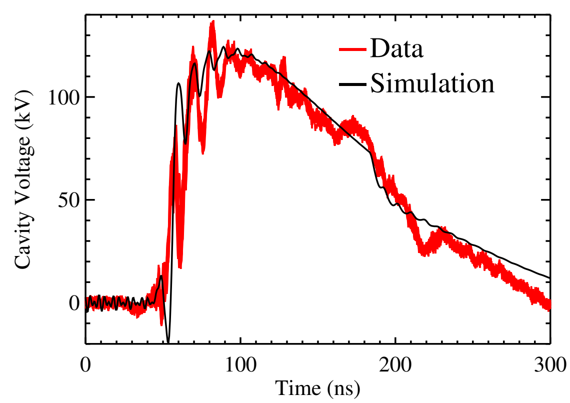

Figure 2. Cavity output voltage from 10 consecutive shots with a single cavity firing into a resistive load. The jitter from this set of shots, measured as one standard deviation of the timing of the rising edge of the pulse, is 0.75 ns.

impedance steps to approximately match the impedance of the LTD driver along the length of the accelerator. To exactly match the driver impedance, the MITL would need impedance transitions at each LTD cavity as is typically done in IVA accelerators such as RITS-6 [10]. However, circuit simulations and experience with the seven cavity system which had a constant impedance transmission line indicated that a simplified transmission line with only three different impedances would be adequate. The geometric vacuum impedance of the three constant impedance sections are 17, 24, and 50 Ω with impedance transitions positioned after cavity 6 and 13.

During initial testing, voltage was measured only on one side of the cavity. The cavity output voltage is approximately twice the voltage measured with one probe. Figures 3-5 show the half cavity voltages from a shot with 19 series cavities. The voltage plots are grouped by physical grouping of the cavities in the three stands. As shown in Figures 3-5, the rising edge of the cavity

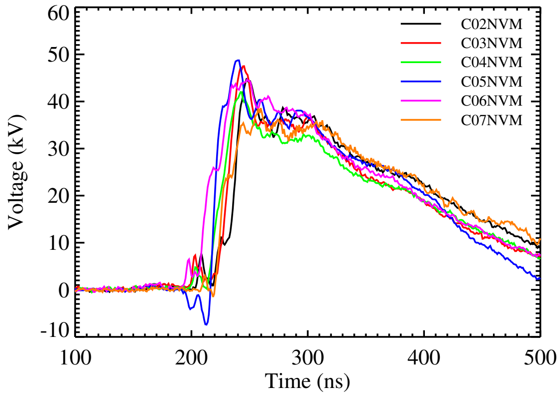

Figure 3. Plot of one half of the cavity output voltage from cavities 2-7 on a shot with 19 series cavities. Cavity 1 is replaced with a blank spacer on this shot.

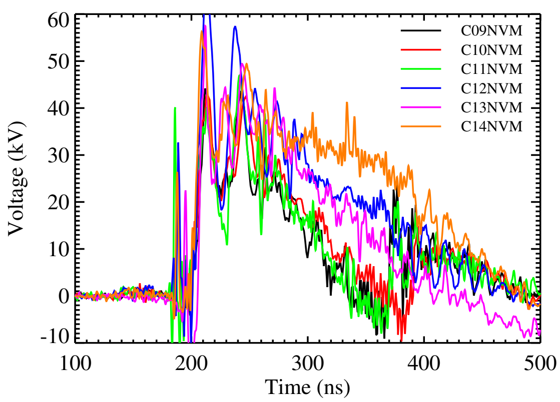

Figure 4. Plot of one half of the cavity output voltage from cavities 9-14 on a shot with 19 series cavities. Cavity 8 is replaced with a blank spacer on this shot.

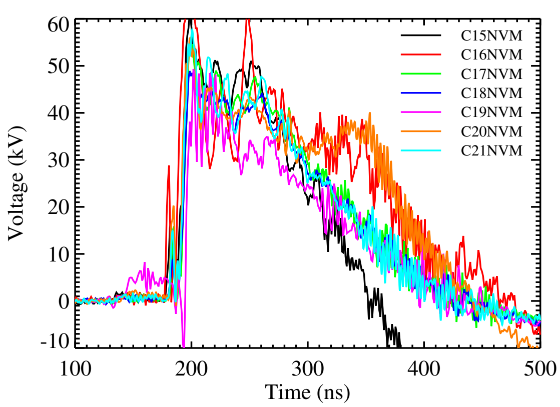

Figure 5. Plot of one half of the cavity output voltage from cavities 15-21 on a shot with 19 series cavities.

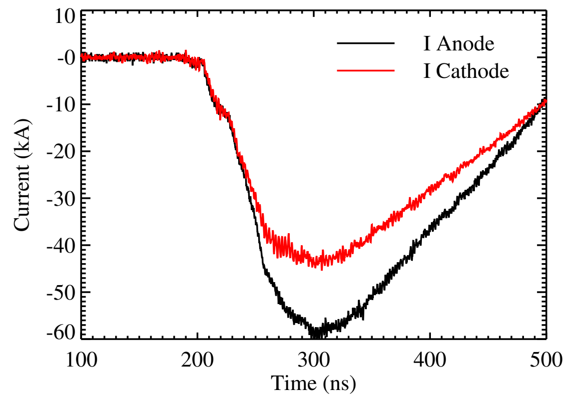

Figure 6. Anode and cathode currents measured in the MITL after the last cavity.

voltages are tightly grouped, especially in the second and third groups of cavities. However, there are differences in prepulse, oscillations, and pulse width of the various cavities. Variations in cavity oscillations were observed in the seven cavity system and are partly related to timing differences between adjacent cavities. Some of the variation in the measured prepulse voltage and signal noise between cavities is attributed to differences in the voltage monitors used in the preliminary testing. Some variation in pulse shape between cavities is attributed to variations in the cavity configurations, including variations in magnetic isolation core material. The differences in core material result in differences in cavity losses and thus differences in peak voltage and pulse width. Future experiments will include comparisons of the differences in core performance.

III. MITL POWER FLOW RESULTS

The anode and cathode currents in the MITL are measured after cavity 7, after cavity 14, after cavity 21, and at the diode. Electrons are emitted from the surface of the central cathode stalk when the voltage in the vacuum line is high enough for the field stress on the cathode conductor to exceed the electron emission threshold, $\sim$ 250 kV/cm for an aluminum conductor coated with graphite paint. In a coaxial negative polarity MITL, the anode current represents the total current in the MITL. The difference between the anode current and cathode current at a single location represents the insulated electron current flowing in the vacuum. Figure 6 shows the measured anode and cathode currents after cavity 21. At peak current, the anode current is 58 kA, the cathode current is 42 kA, and about 30% of the total current is insulated electron current in the vacuum.

The voltage in the MITL is calculated using the Mendel voltage calculation method [11],

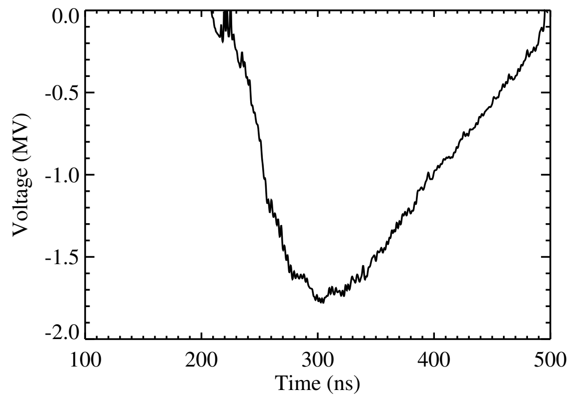

Figure 7. The MITL voltage is calculated from the currents in Figure 6 using the Mendel voltage equation (2).

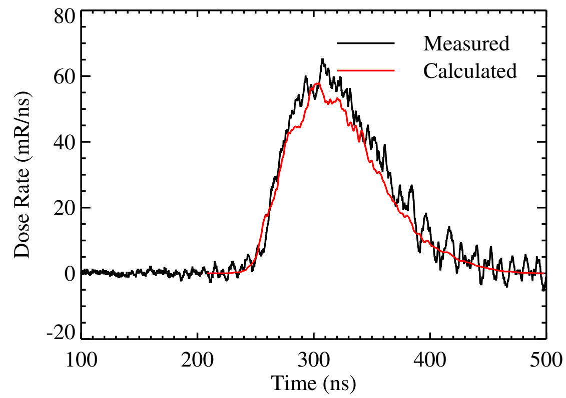

Figure 8. X-ray dose rate is measured using a PIN diode and calculated using equation (2).

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

The peak MITL voltage here is about 1.7 MV. Assuming that the voltage will scale linearly with increasing number of cavities and with charge voltage, then the system will produce a peak of 2.5 MV with 21 cavities charged to ± 100 kV each. This estimate agrees with the peak voltage predicted in circuit simulations.

Particle-in-cell (PIC) simulations using the QUICKSILVER code [12] are being used to study electron current loss and magnetic insulation [13]. The PIC simulations model all 21 cavities and measure loss current striking anode surfaces at each cavity. The simulations indicate that with cavity timing jitter of 5 ns, no electrons strike the cavity vacuum insulators.

IV. LARGE AREA DIODE RADIATION PRODUCTION

Testing of the URSA Minor LTD has been conducted with a large area electron beam diode (LAD). The cathode outer diameter is 12.70 cm, the same as the diameter of the MITL cathode stalk at the diode end of the accelerator. The inner diameter of the cathode is 12.07 cm and the edges of the cathode are sharp to increase field stress on the edges of the cathode. The anode is composed of a 1.27-cm thick carbon target mounted on a 1.9-cm thick aluminum plate. X-ray dose rate measurements are typically made on axis at a distance of 1 m from the face of the carbon target using PIN diodes. The PIN diodes are calibrated using TLDs that are also placed 1-m from the anode.

MCNPX calculations of radiation production and transport were used to determine a relationship between diode voltage, beam current, and x-ray dose rate 1 m from the x-ray converter. The calculations use the materials and thicknesses used in the negative polarity LAD experiments. For the range of electron energies expected in the experiment, the MCNPX-predicted dose rate is well-approximated as

$$\frac{dD}{dt} = 502 I V^{2.4}. \quad (2)$$

Figure 8 shows a comparison of the measured x-ray dose rate and the dose rate calculated from equation (2) using the MITL voltage in Figure 7 and the anode current in Figure 6. In this configuration the anode current is used to calculate the dose rate because electrons emitted from the cathode at the diode and electrons in the insulated flow current all strike the carbon target.

V. CONCLUSION

The 21-cavity URSA Minor LTD has been assembled and initial testing has been conducted at reduced charge voltage. The output voltage is consistent with the predicted 2.5 MV endpoint energy when operating at full charge voltage. MCNPX calculations have been used to determine a scaling equation relating x-ray dose rate to the diode voltage and current for the diode geometry fielded in these experiments. The measured x-ray dose rate matches the calculated dose rate and confirms the inferred voltage along the MITL based on the measured currents. Upcoming experiments with 21-cavities at full charge voltage will be used to evaluate the performance of the LTD when coupled to a MITL and radiographic electron beam diode.

VI. REFERENCES

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