MULTI-SHOT PERFORMANCE OF A 1-MV, 15-kA ROD-PINCH-LIKE DIODE FOR RADIOGRAPHY*

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Abstract

A rod-pinch diode, modified to operate in a non-pinching mode, is tested for multi-shot operation at 1 MV and 15 kA. Three different geometry diodes are used. A 3.2-mm or 4.7-mm diameter tungsten-rod anode, tapered on the end, is used to minimize anode damage and to maintain a small source size. The diode parameters are chosen to avoid beam pinching. The diode operates successfully for at least 5 to 9 shots depending on the geometry. The first shot operates at higher impedance due to late-time anode ion turn-on. Multi-shot operation is limited by anode rod damage. The dose on-axis at 1 meter from the source is 0.7 to 0.9 rad(Si) and varies by ±20% from shot to shot. The source diameter is 2 to 4 mm and decreases from the first to the last shot even though the dose is not degraded.

I. INTRODUCTION

The rod-pinch electron beam diode provides an intense, pulsed, small diameter bremsstrahlung source for radiography. The diode consists of an annular cathode and a small diameter anode rod that extends through the hole in the cathode. Well-behaved electrical operation has been demonstrated on the TriMeV pulser [1] at Bechtel-Nevada for peak voltages of 0.8 to 1.2 MV and currents of 20 to 40 kA in a 15-ns pulse [2]. For radiography applications, sub-mm source sizes in the forward direction have been achieved by using a 0.5-mm diameter tapered tungsten anode rod. Forward-directed doses are 0.4 to 0.7 rad(Si) at 1 meter from the source.

In radiography experiments, it is also desired to operate this source for multiple shots without breaking vacuum and replacing diode components. Multi-shot operation is useful for checking alignment and for testing detector responses. Normally, the anode rod is destroyed due to electron-energy deposition when the beam pinches onto the end of the rod. In this experiment, a simple diode modification is made to avoid beam pinching and to operate at the same diode parameters as for the 0.5-mm-diameter anode. Operation of this diode in a multi-shot, non-pinching mode is described in this paper.

II. EXPERIMENTAL ARRANGEMENT

The diode is operated at reduced voltage (1 MV) on the 3-MV TriMeV pulser to match the radiation source to the requirements for radiography experiments. The design of the diode is based on experiments where beam pinching was observed and interpreted in terms of a transition from space-charge-limited to magnetically-limited current [2,3]. The diode geometry is shown in Fig. 1. A several-mm-diameter tungsten rod is used to distribute the deposited electron beam energy over a larger area than for a sub-mm-diameter rod. One end of this rod is connected to the positive center conductor of the pulser and the other end is tapered over 15 mm. Two different diameter rods are used in the experiment: a 4.7-mm-diam rod tapered to 3 mm or a 3.2-mm-diam rod tapered to 2 mm. The tungsten rods are tapered to reduce the self-absorption of radiation emitted in the forward direction. A short-length cathode is used to limit the electron current so that critical current and beam pinching are not achieved. The cathode consists of two 0.5-mm-thick stainless-steel disks separated by a 2-mm-thick spacer. The anode rod extends 6 mm beyond the cathode so that the rod taper extends into the anode-cathode (A-K) gap. For the 14- or 16-mm diam cathode used in this experiment, the A-K gap is greater than 4.6 mm, minimizing gap-closure effects due to expanding anode and cathode plasmas.

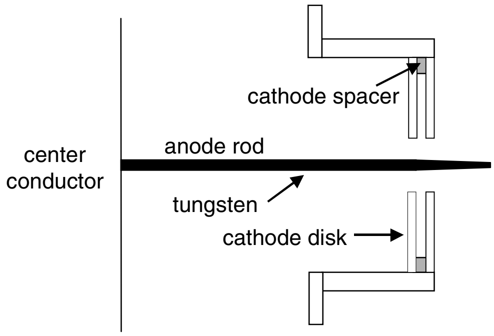

Figure 1. Schematic of the TriMeV rod-pinch-like diode.

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14. ABSTRACT
A rod-pinch diode, modified to operate in a nonpinching mode, is tested for multi-shot operation at 1 MV and 15 kA. Three different geometry diodes are used. A 3.2-mm or 4.7-mm diameter tungsten-rod anode, tapered on the end, is used to minimize anode damage and to maintain a small source size. The diode parameters are chosen to avoid beam pinching. The diode operates successfully for at least 5 to 9 shots depending on the geometry. The first shot operates at higher impedance due to late-time anode ion turn-on. Multi-shot operation is limited by anode rod damage. The dose on-axis at 1 meter from the source is 0.7 to 0.9 rad(Si) and varies by ±20% from shot to shot. The source diameter is 2 to 4 mm and decreases from the first to the last shot even though the dose is not degraded.

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To examine the damage to the rod after each shot, the rod was viewed through a 9.5-mm-thick plastic end plate. The dose from the rod in the forward direction was measured with thermoluminescent dosimeters (TLDs) and PIN diodes. A tungsten rolled-edge with x-ray film was used to measure the source diameter.

The voltage and current on the diode were inferred from measurements at the input to the TriMeV 60-Ω transmission line that drives the diode. Corrections for transit-time effects, inductive-voltage losses, and signal reflections at early time were required to extract the diode load voltage and current. These corrections are particularly significant for the fast-rise-time and short-duration power pulse on TriMeV.

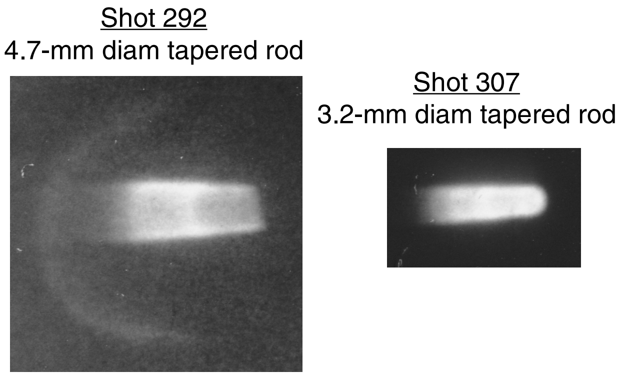

Figure 3. Pinhole camera images of tapered tungsten rods for two shots. The rods are tapered from left to right.

III. QUALITATIVE RESULTS

Three different multi-shot series were carried out, and the damaged rods for each series are shown in Fig. 2. The 3.2-mm-diam rod used in one series was severely damaged after 5 shots. This rod is compared with a virgin 3.2-mm-diam rod in Fig. 2. Two series used 4.7-mm-diam rods but with different cathode radii (R_c). For $R_c = 8$ mm (shots 292–300), the rod was damaged but is still intact after 9 shots. For $R_c = 7$ mm (shots 301–306), the rod suffered significantly more damage after only 6 shots, and a portion of the rod is missing. For all three series, radiation from the diode was not significantly reduced with rod damage. The cathode disks were not damaged. They were cleaned and reused when the rod was replaced.

A pinhole camera was used to image radiation from the length of rod extending beyond the cathode. The camera was located at 40° to the rod axis, and images were recorded on Polaroid films enhanced with intensifying screens. Typical images, shown in Fig. 3, were recorded through a 0.25-mm-diam pinhole with a magnification of about 0.9. Emission is observed along the rod length in both images, however emission is more intense toward the tip of the rod for the 3.2-mm-diam rod, consistent with the damage shown in Fig. 2. For the 4.7-mm-diam rod, most of the emission occurs along the rod length rather than from the tip, so that rod is less damaged.

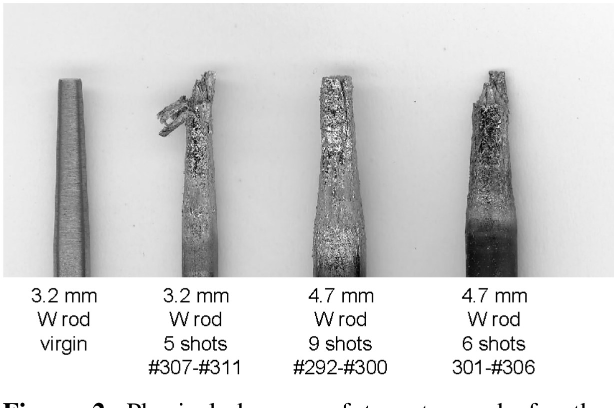

Figure 2. Physical damage of tungsten rods for three different multi-shot series on TriMeV.

IV. ELECTRICAL PERFORMANCE

The voltage, current, and impedance for the last shots in the two series with 4.7-mm-diam rods are presented in Fig. 4. Figure 4a is for R_c = 8 mm and Fig. 4b is for R_c = 7 mm. In both cases, the voltage increases rapidly to 1.2 MV and then decreases as the current increases. The impedance gradually decreases during the pulse consistent with gap closure. The impedance is systematically lower for R_c = 7 mm than for R_c = 8 mm due to the smaller A-K gap. The diode experiences late-time low-voltage pulses

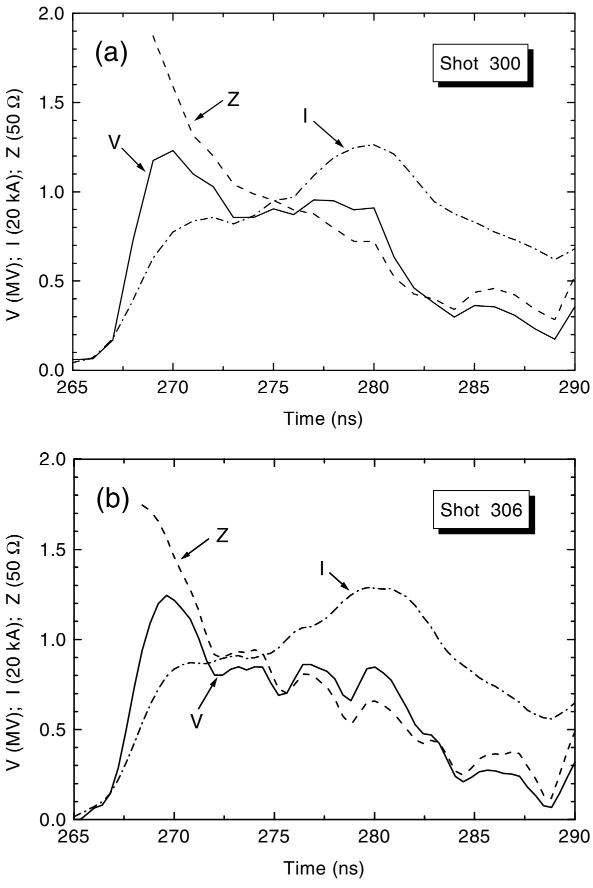

Figure 4. Voltage (V), current (I) and impedance (Z) waveforms (a) for R_c = 8 mm and (b) for R_c = 7 mm.

that are not shown in Fig. 4 (see Fig. 7). These pulses result from impedance mismatch of the diode to the 60-Ω driver.

The impedance is used to characterize the electrical performance for a series of shots. Impedances for the two series with 4.7-mm-diam rods are presented in Fig. 5. Near 275 ns, the impedance is 50 Ω for R_c = 8 mm and 40 Ω for R_c = 7 mm. The first shot in each series has higher impedance, but the remaining shots are reproducible.

The electrical measurements are compared with a diode model that includes space-charge-limited (Langmuir-Blodgett) and magnetically-limited (critical current) emission from the cathode, as well as ion production from anode-plasma formation, as described in Ref. 4. Anode and cathode motions during the pulse are included in this model. Results of this analysis are shown in Fig. 6 for shot 300. Initially, the Langmuir-Blodgett current (I_{LB}) follows the measured current (I_{load}) while the critical current (I_{crit}) exceeds the measurement. The beam current (I_B) is given by [3]: $1/I_B^3 = 1/I_{LB}^3 + 1/I_{crit}^3$. Later in the pulse, I_{LB} approaches I_{crit} and I_B agrees with the measured current. Anode ions are turned on at 271 ns but it takes 10 ns to realize their full effect on I_{LB} and I_{crit} in this analysis [4]. When this analysis is applied to the first shot in a series (e.g., shot 292), the model current (I_B) exceeds the measured current, but delaying the ion turn-on to later in the pulse reduces this difference. Consequently, higher

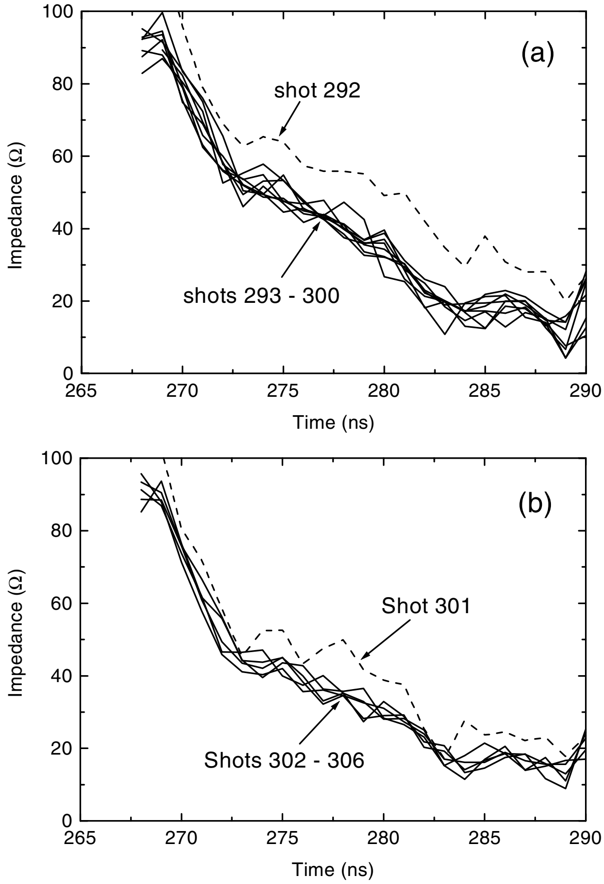

Figure 5. Impedance waveforms for multiple shots with (a) R_c = 8 mm and (b) R_c = 7 mm.

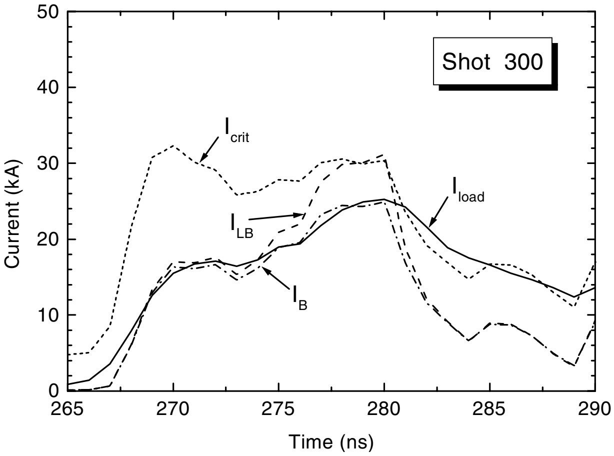

Figure 6. Measured and calculated currents for shot 300.

impedance on the first shot in each series is consistent with late-time anode ion turn-on. For later shots, early ion turn-on, as in Fig. 6, is required to fit the measured current. Finally, this analysis indicates that the diode operates in the space-charge-limited phase early in the pulse and approaches critical current late in the pulse. Consequently, beam pinching is not expected, consistent with the experimental observations.

V. DOSE AND SOURCE SIZE RESULTS

The radiation pulse in the forward direction was measured with Si PIN detectors located 37.5 cm from the tip of the rod. Results for a multi-shot series with a 4.7-mm-diam rod are shown in Fig. 7. Radiation is emitted for 80 ns with the most intense emission in the first 20 ns. The shape of the radiation pulse is reproducible, but some variation in amplitude occurs from shot-to-shot. Pulses later in time are associated with lower voltage on the diode due to impedance mismatch with the driver, and this radiation can be filtered out if necessary. The PIN diode signals are integrated to determine the dose. The dose is about equally divided between the first pulse and

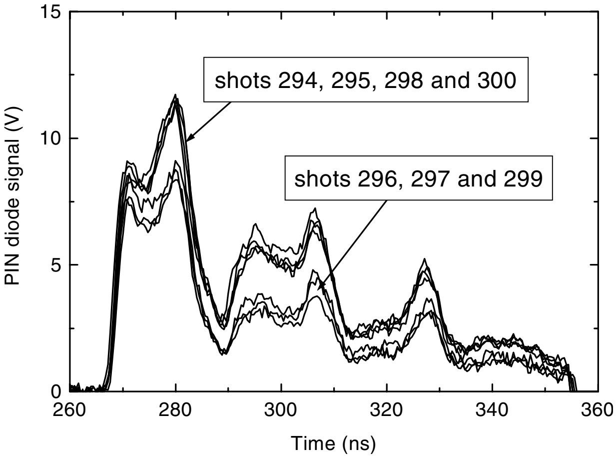

Figure 7. Signals from the PIN diode for R_c = 8 mm.

the later pulses. The PIN diode signals are integrated over 80 ns to compare PIN diode doses with doses from TLD measurements.

The dose in the forward direction was measured with CaF_2 TLDs located on the end plate 7.7 cm from the tip of the rod. The TLDs were mounted in aluminum containers to provide equilibration and were individually calibrated with a ^{60}Co source. Inverse-square scaling is used to determine the TLD dose at 37.5 cm. Two TLDs were fielded on each series and the TLDs accumulated dose for multiple shots. The average dose is compared with the PIN diode dose. Two calibrated PIN diodes were fielded on each shot and their average dose provides a measure of the dose from shot-to-shot. The dose is smaller for the first shots and then varies by ±20% from shot-to-shot. The average dose from the TLDs is in agreement with the average PIN diode dose. If the dose is scaled to 1 meter, the average dose is 0.7 rad(Si) for the 3.2-mm-diam rod, 0.85 rad(Si) for the 4.7-mm-diam rod with R_c = 8 mm, and 0.9 rad(Si) for the 4.7-mm-diam rod with R_c = 7 mm.

The diameter of the radiating source as viewed end-on is determined by measuring the image of a tungsten rolled-edge with x-ray film. For this measurement, a 1-meter-radius rolled-edge was located 40 cm from the rod tip and a film cassette was located 160 cm from the rod tip, corresponding to a source magnification of 4. The film image gives the edge spread function (ESF), which represents the transition from a maximally exposed region on film where photons pass near the rolled-edge to a minimally exposed region where photons are absorbed by the rolled-edge. The line spread function (LSF) is the derivative of the ESF, and the FWHM of the LSF provides a measure of the source diameter. Measured LSFs at the beginning and at the end of two multi-shot series are shown in Fig. 8. The double-peaked structure of these LSFs is indicative of emission primarily from the tapered section of the rod rather than the blunt end. For the 4.7-mm-diam rod, the FWHM decreases from 4.0 mm on the second shot to 3.3 mm on the 9th shot. For the 3.2-mm-diam rod, the FWHM decreases from 2.7 mm on the first shot to 2.1 mm on the 5th shot.

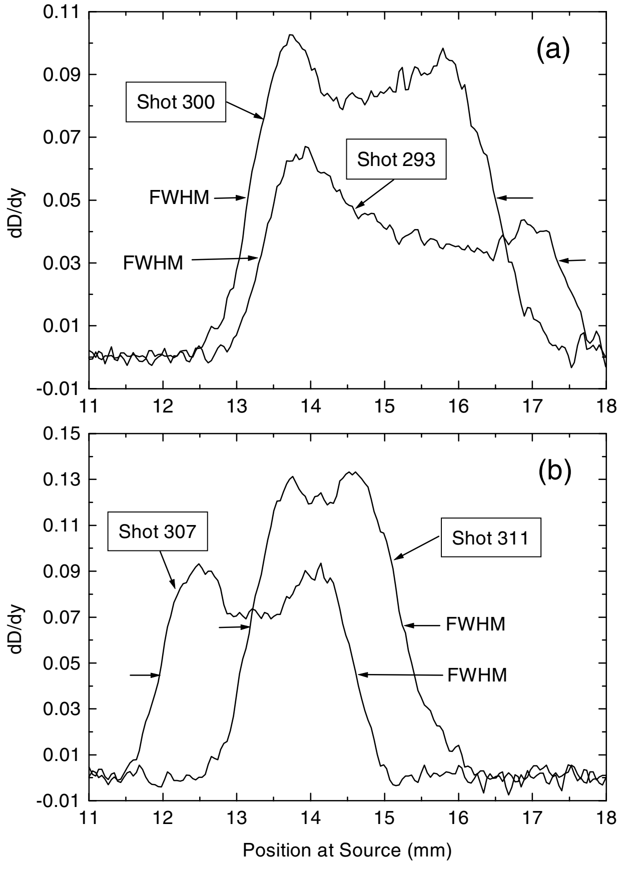

Figure 8. Measured line spread functions (a) for a 4.7-mm-diam rod and (b) for a 3.2-mm-diam anode rod.

VI. SUMMARY

The rod-pinch diode operates in a non-pinching (space-charge-limited) mode at the 1-MV, 15-kA level for most of the pulse. A 3.2-mm or 4.7-mm-diam tapered tungsten anode rod survives for multiple shots without breaking vacuum. The 3.2-mm-diam rod is severely damaged after 5 shots while the 4.7-mm-diam rod is damaged but intact after 9 shots. Despite damage to the end of the rod, radiation continues to be produced without degradation from successive shots. The dose on-axis at 1 meter from the source is 0.7 to 0.9 rad(Si) depending on the diode geometry. From shot-to-shot, the dose varies by ±20%. Radiation is emitted primarily from the tapered region of the rod rather than the blunt end, resulting in a double-peaked on-axis source emission profile. Source diameters are 3 to 4 mm for the 4.7-mm-diam tapered rod and 2 to 3 mm for the 3.2-mm-diam tapered rod. The source diameter is smaller on the last shot than on the first shot in a multi-shot series.

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