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REX, A 5-MV PULSED-POWER SOURCE FOR DRIVING HIGH-BRIGHTNESS ELECTRON BEAM DIODES

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Abstract

The Relativistic Electron-beam Experiment, or REX accelerator, is a pulsed-power source capable of driving a 100-ohm load at 5 MV, 50 kA, 45 ns (FWHM) with less than a 10-ns rise and 15-ns fall time. This paper describes the pulsed-power modifications, modeling, and extensive measurements on REX to allow it to drive high impedance (100s of ohms) diode loads with a shaped voltage pulse. A major component of REX is the 1.83-m-diam x 25.4-cm-thick Lucite insulator with embedded grading rings that separates the output oil transmission line from the vacuum vessel that containing the re-entrant anode and cathode assemblies. A radially tailored, liquid-based resistor provides a stiff voltage source that is insensitive to small variations of the diode current and, in addition, optimizes the electric field stress across the vacuum side of the insulator. The high-current operation of REX employs both multichannel peaking and point-plane diverter switches. This mode reduces the prepulse to less than 2 kV and the postpulse to less than 5% of the energy delivered to the load. Pulse shaping for the present diode load is done through two L-C transmission line filters and a tapered, glycol- based line adjacent to the water PFL and output switch. This has allowed REX to drive a diode producing a 4-MV, 4.5-kA, 55-ns flat-top electron beam with a normalized Lapostolle emittance of 0.96 mm-rad corresponding to a beam brightness in excess of 4.4×10^{8} A/m^2-rad^2 [1,2].

Introduction

The original purpose of REX was to test a low-inductance 5-MV design that could be scaled to voltages of 8- to 10-MV, producing a flat-top pulse having very fast rise and fall times with low pre- and post-pulse. The resulting pulsed-power source was to be used as a testbed to drive various diode geometries to produce xrays for flash radiography. This design was a cooperative effort between Los Alamos and Pulse Sciences, Inc. of San Leandro, CA, which was responsible for the design and fabrication of the transmission lines, insulator, and the diode vacuum vessel. Although REX exceeded the pulsed-power design goals at initial installation, a high-current diode was never installed. REX soon underwent extensive modifications by Los Alamos personnel to serve as a source to study the physics of generating, transporting, and focusing low emittance, 5-10 kA, 4-5 MeV, 60-ns flat-top electron beams. The result of these studies [1,2] was the selection of REX as the type of injector for the Dual-Axis Radiographic Hydrotest Facility (DARHT), 16-MeV induction accelerators. This effort has also resulted in a second generation pulsed-power driver, built for Los Alamos by Pulse Sciences, Inc., that is more compact, reliable, repeatable, and has a higher repetition rate as described in Ref.[3].

Fig. 2. REX experiment looking from the front end, showing the Marx generator in rear, transmission lines, dome-shaped vacuum vessel, and beam transport hardware.

REX [Fig. 1] presently consists of a 5.75-MV, 3.05-nf Marx generator that pulse charges various length (19.5-, 27-, and 34.5- ns) water PFL's with an epoxy-cast (102-cm-diam x 27.9-cm-thick) self-breaking sulfur hexafluoride gas output switch, with a uniform field gap

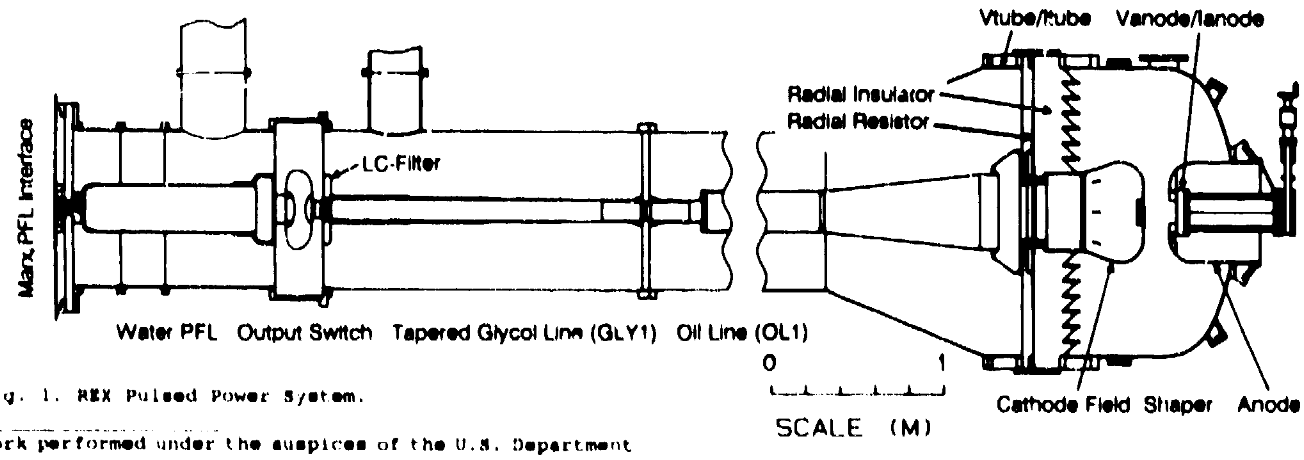

Fig. 1. REX Pulsed Power System.

Work performed under the auspices of the U.S. Department of Energy

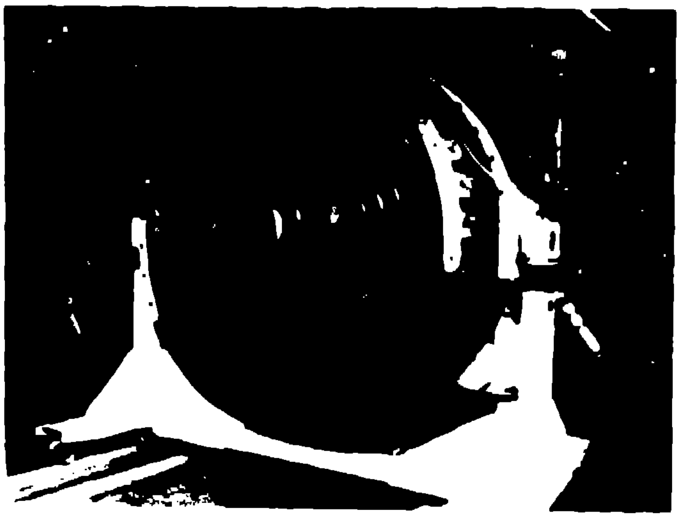

Fig. 3. REX Lucite insulator with grading rings.

of 6.35 cm. The PFL drives a 38-ns glycol- and a 35-ns oil-based transmission line in series ending with the cathode field shaping section of the vacuum vessel. The machine length is 12.15 m from the Marx/PFL interface to the beam output at the gate valve. The outer diameter of all lines is 91.44 cm, with PFL-, glycol-, and oil-line inner diameters of 27.94-, 12.7-, and 24.13-cm and impedances of 8.03-, 19.2-, and 53.3-Ω, respectively. The voltage step-up ratios for the line interfaces are 1.44, 1.47, and 1.47 for an effective parallel load of the radial resistor and the electron beam of 150 Ω. The REX facility is shown in Fig. 2. Details of the insulator design, low-current (long-pulse, 85-ns FWHM) operation, and high-current (short-pulse, 45-ns FWHM) operation follow in their respective sections.

Insulator Design

A major component and fabrication challenge of the REX design was the large 1.83-m-diam x 25.4-cm-thick Lucite insulator with the six embedded, hard-anodized, aluminum gradient rings [Fig. 3]. The assembly was made for Los Alamos by Reynolds Polymer Technologies, Inc. of Santa Ana, CA. and required numerous machining and annealing cycles of the plastic before the rings were shrunk to fit and slipped into place. To minimise the outer diameter and reduce the inductance of the insulator, the electric field on the vacuum side of the insulator was forced to be linear by a radial section that is predominantly resistive or capacitive, and by field shaping electrodes near the center conductor. Figure 4 is an equipotential field plot of the vacuum diode region obtained using the electromagnetic solver FLUX2D [4] for the case of a radial resistor of value 175 Ω. The equipotential lines are forced towards the outer conductor and then wrap around the cathode field-forming electrode to produce the desired profile for electron beam generation.

Figure 5 illustrates the variation of the radial electric field component vs radius for the cases of no field grading (log profile), field shapers plus the floating metal grading rings, and the final addition of the radial resistor. The required profile of the liquid-based radial resistor is formed by a thin wedge whose base is 7 mm at the inner radius of 35.6 cm tapering to 2 mm at a radius of 57.2 cm, and remaining at this width to the outer radius of 83.8 cm. The radial field averaged over the central portion of the surface of each plastic interface cut at 45° is 111 kV/cm ±5%. Although the field is nearly uniform over the entire insulator assembly, ideally eliminating any preferential flashover of an individual section, Fig. 6

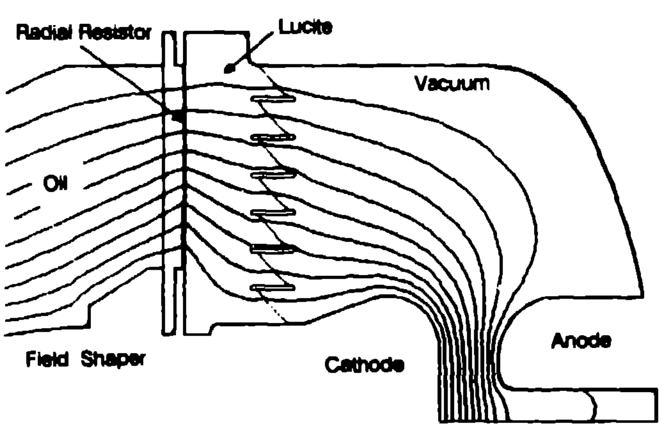

Fig. 4. Equipotential plot of vacuum vessel region.

indicates that the field is not uniform within each of the 7 regions. In fact, the field linearly increases by about a factor of 2 from the cathode to the anode of each ring as recommended by Spence of Pulse Sciences, Inc. [5]. The field points radially inward at 45° to the surface of the insulator near the intersections of the plastic and the rings, and at 30° over the central region of each insulator section.

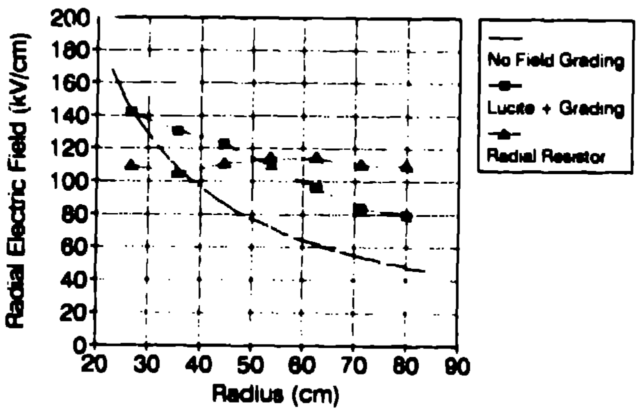

Fig. 5. Radial insulator electric field variation.

An uncertainty in the design of the REX insulator was the validity of typical voltage breakdown scaling laws associated with the large plastic surface area of 2.62 m^2. For negative pulses, J.C. Martin's historic

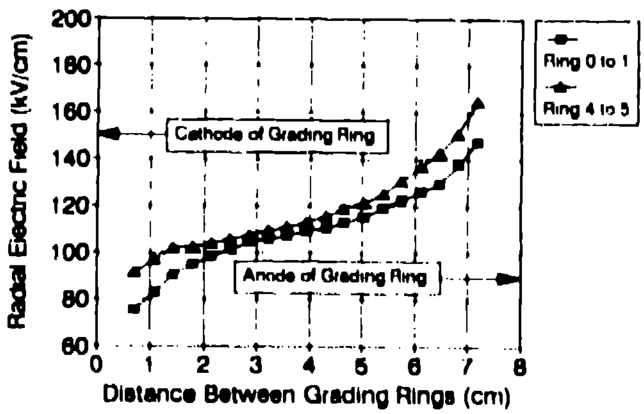

Fig. 6. Radial electric field across the surface of the most and least stressed insulator sections.

relationship [5] predicts a breakdown field of 111 kV/cm at 5 MV (t-eff ≈35 ns) for the short-pulse (45-ns FWHM) mode of REX. The average field between the rings on the vacuum side of the insulator is 90.5 kV/cm; hence, the unit is predicted to be stressed at a breakdown fraction (BDF) of 0.82. Spence's and Shipman's more recent relationships [5] predict the breakdown field along the surface of the plastic to be 89- and 78-kV/cm with BDF's of 0.66 and 0.76 for an average calculated surface field of 59 kV/cm. Although these BDFs are not conservative, REX operated without any noted field emission problems during initial short-pulse (45-ns FWHM) testing at 5.0 MV (100s of shots) and at 5.5 MV (10s of shots). For these early tests, the Lucite insulator was lightly coated with a mixture of 50% silicone oil and ethanol to help suppress field emission. The peak field on the cathode field forming electrode is 330 kV/cm for diode operation at 5 MV and occurs on the curved surface. Although red glyptal insulating varnish has been successful in preventing field emission over this highly stressed region, recent success with a very durable process of hard anodization and Teflon impregnation (Nituff) by Nimet Industries, Inc. of South Bend, IN has been experienced.

Low-Current (Long-Pulse) Operation

The present mode of operation drives a planar velvet diode producing a 4-MV, 4.5-kA, 55-ns flat-top (85-ns FWHM) electron beam. Voltages and currents, as indicated in Fig. 1, associated both with the pulse power and the electron beam are measured using E-dot and B-dot type monitors terminated with passive, 1-μs time-constant, 50-Ω integrators. The signals are transmitted to a screen room area along 18.8- or 37.6-m Andrews 12.7-mm-diam Superflex foam cable. Tektronix R7103 (1-GHz) oscilloscopes are used to record the data in digital format with their DCS01 Digitizing Camera System. The diode current (Ianode) transmitted through the anode aperture is sensed by four symmetrically located B-dots contained within the anode Beam Position Monitor (BPM). The A-K gap voltage (Vanode) is measured as the sum of four equally spaced E-dots mounted flush on the flat portion of the anode face. All signals are digitally corrected for the combination of cable loss and integrator droop. The diagnostics were calibrated using a 50-Ω coaxial test system and various pulsers; they were additionally calibrated in place using a biconic section driving the input of OL1.

Typical diode voltage and current waveforms are shown in Fig. 7; the time delay (≈ 7 ns) before the velvet diode begins field emission corresponds to a field of 95 kV/cm. The beam energy spread of ±1.5% is mostly due to the changing voltage at the beginning of the 55-ns flat-top portion. For a radial resistor value of 175 Ω, a change in beam impedance of 925 Ω ±10% is reduced to a diode voltage change of ±0.5% while providing an effective 150-Ω load to the pulsed-power drive. Figure 8 shows the tube voltage (Vtube) and current (Itube) drive waveforms of Fig. 1 for the beam conditions of Fig. 7. The tube current is peaked to charge the 125 pf associated with the vacuum diode region producing Vanode [Fig. 7], which has longer flat-top and shorter rise/fall times than Vtube [Fig. 8].

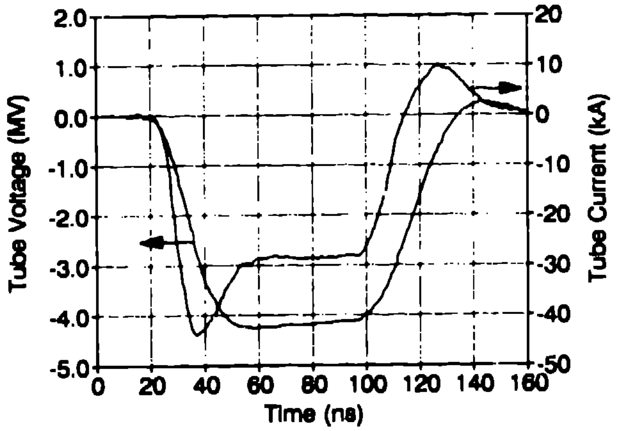

Fig. 8. REX pulsed-power drive for vacuum diode.

Figure 9 shows a progression of calculated waveforms (using Micro-CAP II, [6]) that lead to the measured pulse that drives OL1. The goal of the pulsed-power shaping was to tailor Vtube to have a [1-cos(t)] type rise/fall of about 20 ns to prevent unwanted transverse oscillations of the beam [2]. The PFL is charged through a 10 μh inductor to filter and isolate high frequencies generated during Marx erection. A peaking section [Fig. 1] as part of the PFL output is used to shape the field for the switch gap and to create a longer and flatter pulse. The Marx-to-PFL transfer time is 550 ns, and the gap is set to self-break before the peak at about 500 ns. The ≈185-nh self-inductance of the switch assembly, along with an ≈150 pf plate capacitor (40.5- cm-diam x 4.5-cm-thick) at the beginning of GLY1, forms the first LC-type filter for the pulse. This provides the peaking of the OL1 drive pulse to charge the vacuum vessel capacitance. GLY1 is tapered linearly in impedance, with four sections of 17.1-, 17.8-, 18.5-, and 19.2-Ω providing a droop of 0.085%/ns to compensate for the rising portion of the PFL. The input of OL1 has a high-impedance (≈135 nh) section as part of the second LC filter, with C ≈ 0 pf to further shape the initial portion of the pulse.

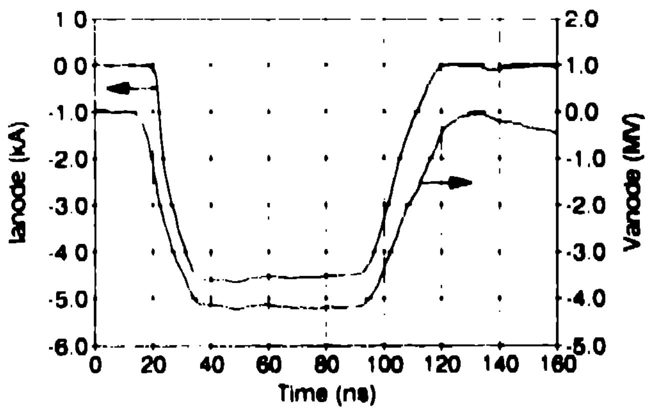

Fig. 7. REX A-K voltage and diode current for a 6-cm gap and a 6.35 cm diam velvet cathode.

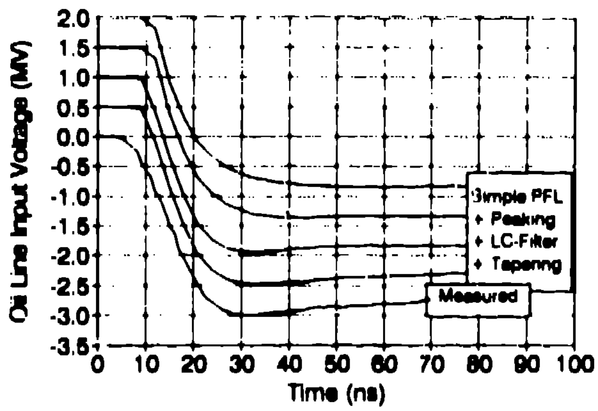

Fig. 9. Calculated waveforms showing the progressive shaping of the PFL output to drive OL1 as measured.

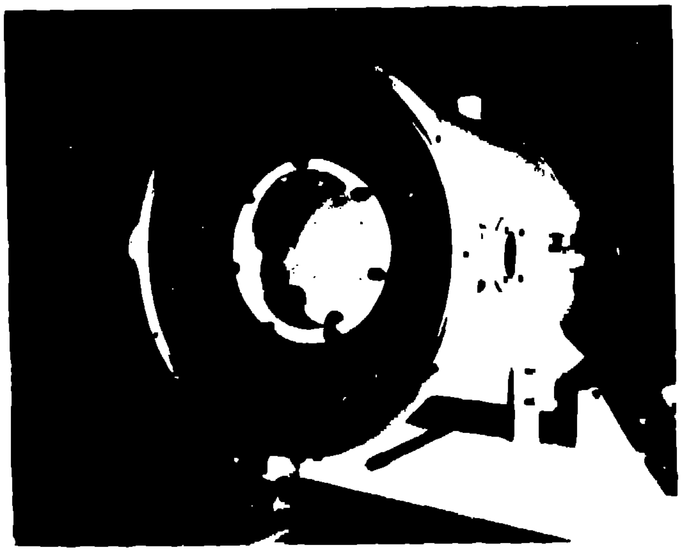

Fig. 10. Output end of OL1 showing the 7-pin, multichannel prepulse switch and peaking section.

Fig. 12. Input end of OL2 showing output side of the 7-pin multichannel prepulse switch.

High-Current (Short-Pulse) Operation

High-current diodes for flash radiography require low prepulse to prevent early field emission across the typical few-cm A-K gap, and low postpulse to limit the xray pulse length. This mode of operation for REX generated a 5-MV, 50-kA, 45-ns (FWHM) pulse and utilized pre- and post-pulse switches. In Fig. 1, the properties of the lines were: PFL (water, 19.5 ns, 10.2 Ω), OL1 (oil, 25 ns, 23.5 Ω), and OL2 (oil, 20 ns, 53.3 Ω) with voltage step-up ratios of 1.46, 1.40, and 1.30 driving a load of 100 Ω, respectively. OL1 had a point-plane diverter switch located 7 ns from the PFL/OL1 interface that was nominally set at 5-8 cm and terminated in a liquid 20-Ω dome resistor to reduce the postpulse to less than 5% of the energy delivered to the load. The input section of the 7-pin, multichannel prepulse switch was located at the end of OL1 [Fig. 10]; the outer conductor ground was stepped inward to an impedance of 10.5 Ω to peak the pulse to OL2.

The input to OL2 [Fig. 12] contained a ground plate through which the output side of the prepulse pins entered. This feature effectively eliminated the capacitive coupling between the two lines and reduced the prepulse to less than 2 kV at the load. These gaps were generally set at 5-10 mm, causing a holdoff of about 5 ns and resulting in less than a 5-ns rise-time pulse delivered down OL2 toward the vacuum vessel load. Figure 11 shows the output of the prepulse switch necessary to produce the tube voltage trace of Fig. 13. The fall time of the tube voltage is only slightly longer than the rise time and is controlled by the diverter.

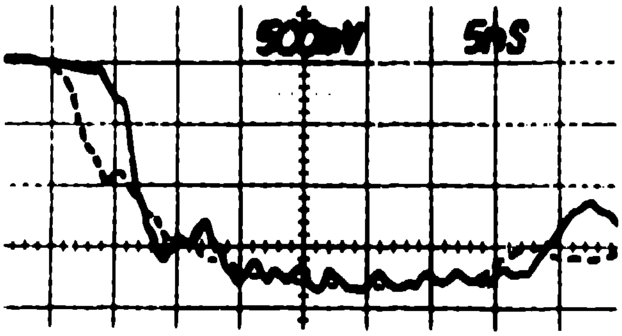

Fig. 11. Prepulse switch output, gaps set at 7.5 mm and closed (dotted trace). (0.82 MV/div, 5 ns/div)

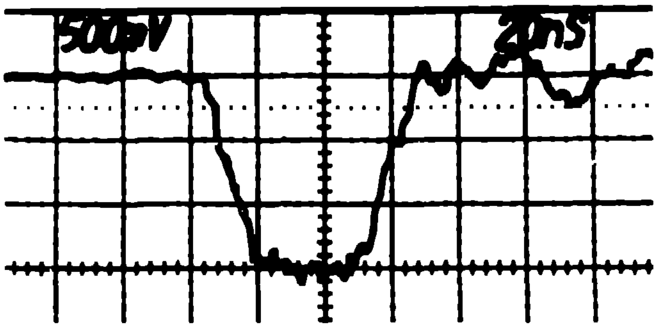

Fig. 13. REX Tube Voltage at 4 MV driving the 125-Ω radial resistor as the load. (1.33 MV/div, 20 ns/div)

Conclusions

REX has been operated in excess of 5000 shots and continues to be a valuable research machine for the investigation of the close correlation between the quality and properties of high-brightness electron beams and their associated pulsed-power driving source. Although the recent emphasis has been on addressing issues associated with using REX as a 4-MV, 4.5-kA, high-voltage injector, it can be operated at higher voltages (>5.0 MV) and currents (>15 kA) with the inclusion of the prepulse and diverter technologies as a stand-alone flash x-ray machine.

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