PBFA Z: A 55 TW/4.5 MJ ELECTRICAL GENERATOR*

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Abstract

PBFA Z is a new 55 TW/4.5 MJ short pulse electrical driver located at Sandia National Laboratories. We use PBFA Z to magnetically-implode plasma shells. These configurations are historically known as z pinches. The pulsed power design of PBFA Z[1] is based on conventional single-pulse Marx generator, water-line pulse-forming technology used on the earlier Saturn[2] and PBFA II[3] accelerators. PBFA Z stores 11.4 MJ in its 36 Marx generators, couples 4.5 MJ in a 55-TW/105-ns pulse to the output water transmission lines, and delivers up to 3.0 MJ and 40 TW of electrical energy to the z-pinch load. Depending on the initial load inductance and the implosion time, we attain peak currents of 16-20 MA with a rise time of 105 ns. Current is fed to the z-pinch load through self magnetically-insulated transmission lines (MITLs). Peak electric fields in the MITLs exceed 2 MV/cm. The current from the four independent conical disk MITLs is combined together in a double post-hole vacuum convolute with an efficiency greater than 95%. The measured system performance of the water transmission lines, the vacuum insulator stack, the MITLs, and the double post-hole vacuum convolute differed from preshot predictions by ~ 5%. Using a 2-cm radius and a 2-cm length tungsten wire array with 240, 7.5-μm diameter wires (4.1-mg mass) as the z-pinch load, we achieved x-ray powers of 200 TW and x-ray energies of 1.85 MJ as measured by x-ray diodes and resistive bolometry.

1 INTRODUCTION

The PBFA-II accelerator[3] at Sandia National Laboratories was originally used by the light-ion-beam ICF Program. We have made major modifications to the accelerator in order to optimize coupling to magnetically-imploded loads, typically z pinches. The facility, in operation since September 1996, has been renamed PBFA Z. Much of its electrical design and design philosophy was descibed in detail in Ref. 1.

This paper describes the electrical performance of PBFA Z and summarizes the overall pulsed power design and modeling that lead to the successful operation of the largest z-pinch driver in the world. To date PBFA Z has conducted more than 65 shots. We have demonstrated the generation of greater than 50 TW of electrical power in the constant impedance water tranmission lines in a 2.5-MV, 100-ns FWHM voltage pulse. The measured forward-going electrical energy is nearly 5 MJ.

The electrical energy is transmitted through a water-vacuum insulator interface and conducted via self magntically-insulated vacuum transmission lines (MITLs) to the z-pinch load. PBFA Z delivered a peak current of 18 MA to a low inductance z-pinch load. The load, a tungsten wire array, generated a peak x-ray power of 200 TW and an x-ray yield of 1.85 MJ.

The overall electrical design of PBFA Z pushed the limits of pulsed power engineering. The physics of MITLs and vacuum convolutes is still not well understood. Issues such as radiation-driven vacuum gap closure and limits on current density near the load need to be studied in detail in the future. PBFA Z is studying some of these fundamental pulsed power concerns while addressing the z-pinch physics necessary for the next generation of drivers.

2 PULSED POWER DESIGN

As described in detail in Ref. 1, PBFA Z's pulsed power design is based on Marx generator/water pulse-forming technology. PBFA Z contains 36 nearly identical modules. In each module a Marx generator, with 60, 1.3-μF capacitors charged to a voltage of 90 kV, delivers its energy to a water-dielectric coaxial capacitor in 1 μs. The capacitor reaches a peak voltage of 5 MV. A low-jitter laser-triggered gas switch is used to couple the energy into a second, lower inductance coaxial water capacitor in 200 ns. Self-breaking water switches are used to transfer the energy into a 0.12-Ω constant impedance water transmission line. The electrical pulse at this point has a voltage of 2.5 MV and a pulse width of 105-ns FWHM. The total power generated in the accelerator at this point is 50 TW. The electrical energy is delivered to an insulator where is passes into the vacuum portion of the accelerator. The electrical energy is then fed through four vacuum MITLs, through a vacuum convolute, to the z-pinch load. A schematic of PBFA Z is shown in Figure 1.

2.1 Water transmission Lines

The water transmission lines used on PBFA Z are a bi-plate, constant-impedance, constant-anode/cathode-gap design. This was done to optimize the energy efficiency of the transmission lines and to maximize the coupling of the energy in the transmission lines to an inductive load. The impedance of each of the 36 lines was 4.32 Ω. Each water line has a voltage and current monitor. (See Section 3.) We can accurately measure the voltage and current and, hence, the power and energy in each water transmission line. These measurements allow us to verify the operation of the water lines. These measurements are complicated

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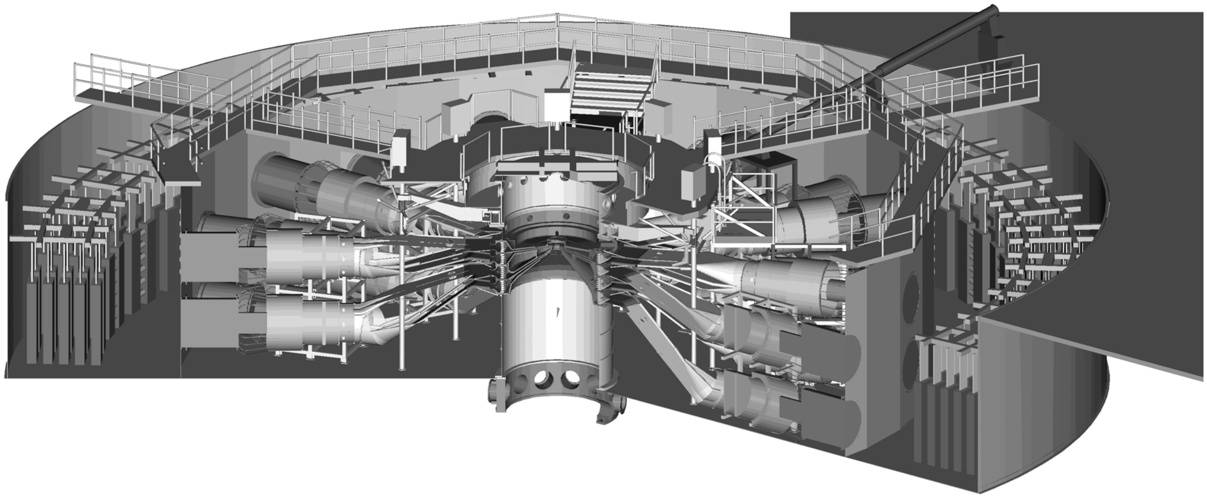

Figure 1 A schematic of PBFA Z showing the Marx generators, the water pulse forming section, the insulator stack, and the diagnostic line-of-sight.

by the spatially- and temporally-varying behavior of the electrical pulse and its reflection from the load. The transmission line gap is fixed at 14 cm. The peak voltage in the water lines varies with the proximity to the load due to the superposition of the reflected pulse on the main pulse. The water transmission lines were modeled with electrostatic codes to examine the issues of enhanced and fringing electric fields.

2.2 Insulator Stack

The insulator stack (See Figure 2.) is the boundry between the water dielectric and the vacuum that is necessary to drive the z-pinch load. The insulators, nearly 4 m in diameter, are made from Rexolite™, a high-density cross-linked polystyrene. Experience has shown that Rexolite™ has superior mechanical and electrical properties when compared with PMMA or polycarbonate. The electric field was carefully "graded" across each insulator to equalize the stress on each insulator component. The insulator stack was designed with a 2-D electrostatic code and then the final design validated with a 2-D electromagnetic code. We expect that future, more advanced designs, will use electromagnetic design codes exclusively. The voltages and currents were measured at each of the insulator stacks. (See Section 3.) These data gave a very accurate measure of the power and energy through the insulator stack boundary.

2.3 MITLs

One of the great achievements of PBFA Z is the design of the magnetically-insulated vacuum transmission lines (MITLs). The MITLs consist of four separate, conical disk feeds coupled together at the vacuum convolute. (See Section 2.4.) These MITLS operate successfully at a peak electric field of 2MV/cm with vacuum gaps as small as 1 cm. Issues such as vacuum electron flow and plasma formation were addressed with 2-D electromagnetic particle-in-cell (PIC) computer codes [1]. These MITLs must operate at fields 10X greater than the explosive emission threshold on the cathode and must hold off the full accelerator voltage for 100-150 ns. We place current monitors at two radial locations and 3-6 azimuthal postions in each of the four MITLs to better study losses.

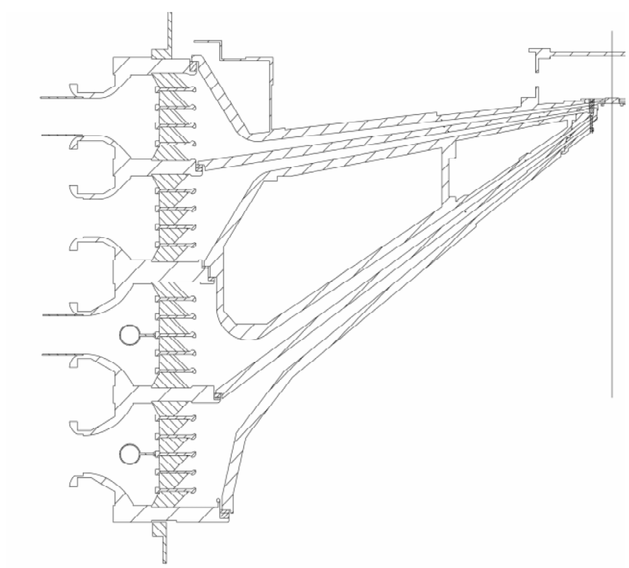

Figure 2 A schematic of the PBFA-Z insulator stack and MITLs is shown. Note, only half of a cylindrically-symmetric section is displayed. The diameter of the insulator stack is nearly 4 m.

2.4 Vacuum Convolute

The most critical part of the vacuum power flow is the double post hole convolute that couples the four, conical disk MITLs together. This is done in order to combine the current from each level and deliver the summed currents to a single z-pinch load. A vacuum convolute is necessarily a three dimensional object and will necessarily have a number of magnetic field nulls. It is the electron losses through these nulls that drive the convolute design. We based the PBFA Z design on the successful Saturn design. In addition, the convolute was partially modeled using QUICKSILVER [1], a 3-D E&M PIC code. A drawing of the convolute is given in Figure 3.

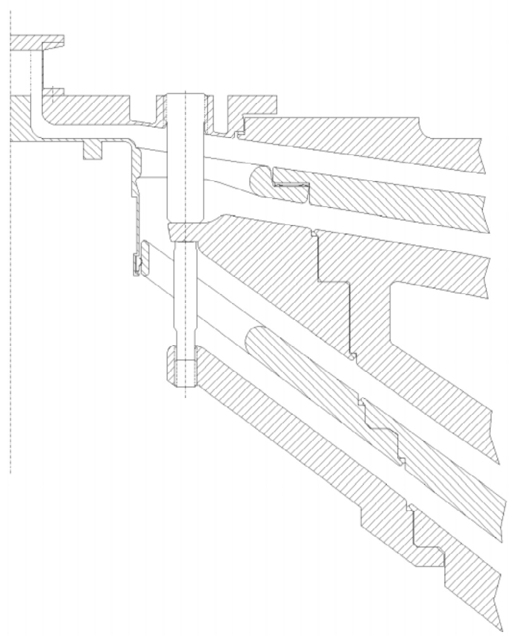

Figure 3 A line drawing of the posthole convolute for PBFA Z. The drawing shows the anode and cathode connections presently in use.

3 ELECTRICAL DIAGNOSTICS

One of the most important parts of any successful accelertor is the attention paid to electrical diagnostics. This is particularly true of single shot, pulsed accelerators. We field a full complement of diagnostics on every shot. With thirty six modules, this translates into hundreds of waveforms per shot.

3.1 Diagnostic Description

The operation of the Marx generators is monitored with 36, current viewing resistors (CVRs) located at the ground connection. The voltages on the water-dielectric intermediate store (IS) capacitors are measured with capacitively-couple voltage monitors, commonly referred to as dV/dt or V-dot monitors. Again, there are 36 of these V-dot monitors. The operation of the laser triggered gas switches is checked with these IS V-dot monitors. The electrical output of the IS capacitors charges the second intermediate store capacitor (the Line 1 or L1 capacitor). Again there are V-dot voltage monitors at this location. AS many as 36 monitors are used to measure the voltage and switching of the L1 capacitors. The output of the L1 capacitors is monitors with 36, V-dot voltage monitors and 36, magnetic loop current probes (B-dot monitors). These final 72 monitors give us a complete measure of the timing, voltage, current, power, and energy in each of the 36 accelerator modules. The voltage and the current at the insulator stack is again measured with 6, V-dot probes and 3, B-dot probes on each of the four levels. Current in the MITLs is measured with up to six B-dot probes at two separate radial positions in each of the four MITLs. The total load current is monitored with up to four B-dot probes located about 5 cm from the z-pinch load.

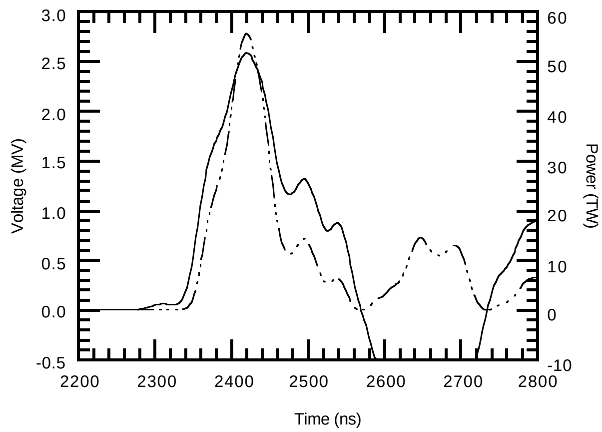

Figure 4 The average voltage (solid line) and total power waveforms in the water transmission lines measured on Shot 51.

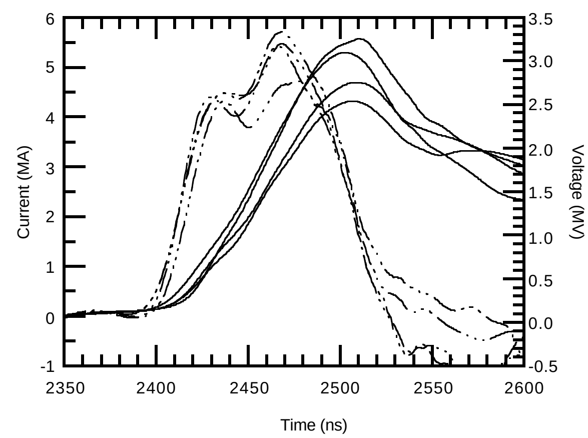

Figure 5 The currents (solid lines) and voltages for each level of the insulator stack measured on Shot 51.

3.2 Calibration

Calibration of all of the diagnostics is critical. Some of the calibrations are done in-situ with pulsers and reference monitors placed near the diagnostics under calibration while other calibrations were done externally. In all cases the pulsers are designed to provide electrical test pulses with nearly the same rise time as the actual accelerator pulse. The reference monitors are carefully calibrated against NIST-traceable standards. All calibration waveforms are stored and are available for examination or further checking at any time in the future. Typical electrical diagnostic calibrations were accurate to ~ 2-4%. We believe that the total error, including data acquisition and systematic errors, for most of the electrical diagnostics is better than 5%.

4 ELECTRICAL PERFORMANCE

This section of the paper describes the actual performance of PBFA Z element by element in the accelerator.

4.1 Water Transmission Lines

Measurements of voltage and current in the constant impedance water transmission lines comprise the backbone of the electrical performance of the accelerator. These data give the module spread, voltage, power, and energy for the entire accelerator. Figure 4 shows the voltage waveform from a single module of PBFA Z. The peak voltage is 2.5 MV with a 105-ns FWHM pulse. The power shown is the 36 times the power of a single line. These data give a total forward-going energy for the accelerator of ~ 4.5 MJ.

The peak stress measured in the water lines was 180 kV/cm. The water lines on PBFA Z can successfully operate at this stress level. Data show that breakdowns in the water transmission lines is dominated by edge effects, joints, and gaps. We see no evidence of electrical breakdown or losses in the uniform field portion of the water transmission lines.

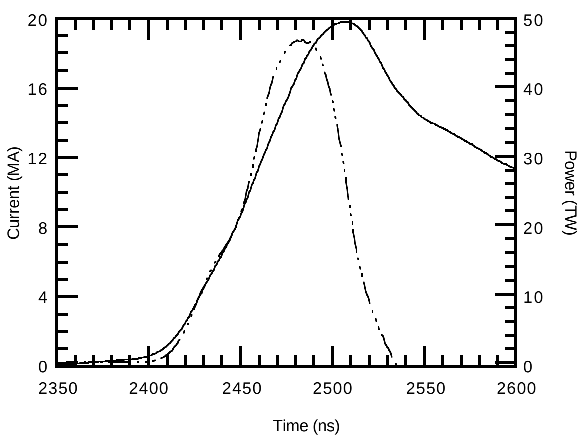

Figure 6 The total current (solid line) and power at the insulator stack measured on Shot 51.

4.2 Insulator Stack

Data show that the insulator stack is exposed to peak voltages exceeding 3 MV. Our data show that at peak electric fields of ~ 100 kV/cm the insulator stacks never flash. This voltage hold off value is at the extreme limit of classical insulator breakdown described in Refs. 1&4. In fact, even upon voltage reversal (after peak current) when the voltage reaches as low as -1 MV the insulator holds off the voltage for as long as 200 ns. Figure 5 shows the voltage and current waveforms measured on each of the four insulator stacks for PBFA-Z Shot 51. Figure 6 shows the total current through the insulator stack together with the electrical power (I*V) passing through the insulator stack. The peak electrical power measured on Shot 51 was 46.8 TW. The measured electrical energy at the insulator stack for Shot 51 was 2.9 MJ.

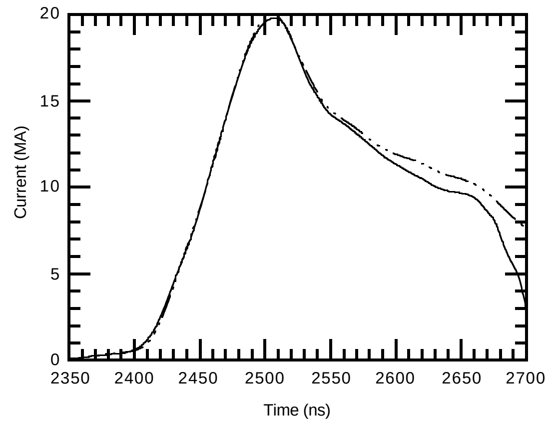

Figure 7 The total stack current (solid line) is plotted with the total MITL current for Shot 51. The stack flashes at ~ 2675 ns.

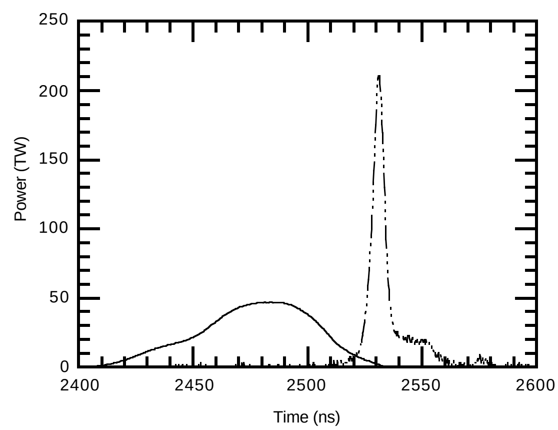

Figure 8 The total stack power (solid line) is plotted together with the x-ray power for Shot 51.

4.3 MITLs

Data from MITL current monitors for Shot 51 show that there is 100% current transfer from the insulator stack to a location just radially inside the MITL current monitors (a location just over 1 m from the load). The total current in the MITLs is compared with the total insulator stack current in Fig. 7. Note that the current has exactly the same shape as the insulator stack current at all times except when the insulator stack flashes late in time. At that time all of the magnetic flux is trapped in the MITLs and will only slowly LR decay away. MITL current data from other shots with MITL current monitors just outside

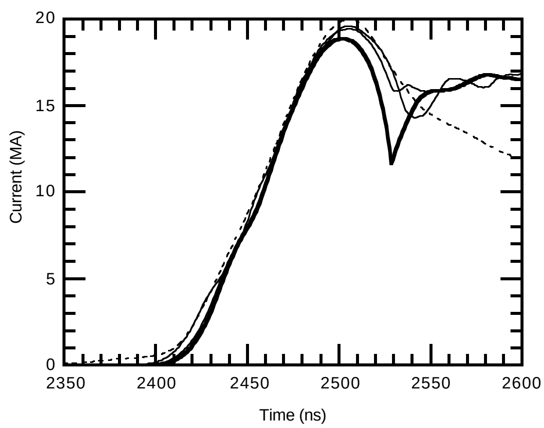

Figure 9 The total stack and MITL currents (dashed lines) for Shot 51 plotted together with the Screamer calculated values (solid lines). The Screamer load current is the bold line.

the vacuum convolute (30 cm from the load) show no MITL current losses to that radial location.

4.4 Comparison of Data with Modeling

The final piece of data required to compare with circuit calculations is from the z-pinch load. We measure the implosion time and have accurate knowledge of the initial load mass and radial position. The load data, the measured inductances, together with water transmission line, stack, and MITL current and voltage data allows a detailed model of the entire pulsed power system. We use the Sandia Screamer code[5] with only one adjustable parameter, the effective loss impedance at the vacuum convolute, to model PBFA-Z power flow.

Figure 8 shows the power and relative timing of the x radiation to the total insulator stack power. The timing accuracy of the two signals is measured to be ~ 2 ns. Note that the z pinch provided a 4X power gain over the electrical power delivered to the insulator stack. Using this time information and knowing that the load dynamics places a severe constrain on the actual current driving the load we calculate all relevant voltages and currents in the system. Figure 9 plots the stack and MITL currents against Screamer calculated values. In addition, the Screamer prediction for the actual load current (not measured) is included. The agreements are excellent. Using the same modeling methodology with a large number of shots has given us confidence in this technique for extracting the actual load current for a wide range of load parameters.

5 CONCLUSIONS

PBFA Z, representing the culmination of marx-driven water-pulse-line technology, is the world's most powerful electrical accelerator. We are successfully operating at the 50-TW design point. We routinely couple MJ's of electrical energy into imploding z-pinch loads thereby generating x-ray powers of 200 TW and x-ray energies of 1.85 MJ.

PBFA Z will be available for the next decade for a variety of scientific uses. Experimenters can access unique regions of plasma density and temperature parameter space for basic science and defense applications.

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