SAND97-1711C
SAND--97-1711C

CONF-9706113-4

PULSED POWER PERFORMANCE OF PBFA Z*

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JUL 14 1997
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Abstract

PBFA Z is a new 60-TW/5-MJ electrical driver located at Sandia National Laboratories. We use PBFA Z to drive z pinches. The pulsed power design of PBFA Z¹ is based on conventional single-pulse Marx generator, water-line pulse-forming technology used on the earlier Saturn² and PBFA II³ accelerators. PBFA Z stores 11.4 MJ in its 36 Marx generators, couples 5 MJ in a 60-TW/105-ns pulse to the output water transmission lines, and delivers 3.0 MJ and 50 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%. We achieved x-ray powers of 200 TW and x-ray energies of 1.9 MJ from tungsten wire-array z-pinch loads.

Introduction

This paper describes the electrical performance of PBFA Z and summarizes the pulsed power design¹ that lead to the successful operation of the largest z-pinch driver in the world. Since September 1996, PBFA Z has conducted more than 86 shots. PBFA Z has generated more than 60 TW of electrical power and 5 MJ of electrical energy in the constant-impedance water transmission lines in a 2.5-MV, 105-ns FWHM voltage pulse. The electrical energy is transmitted through a water-insulator-vacuum interface and conducted via self magnetically-insulated vacuum transmission lines (MITLs) to the z-pinch load. PBFA Z delivered peak currents of 18 MA to low inductance z-pinch loads. These loads, tungsten wire arrays, generated peak x-ray powers of 200 TW and x-ray yields of 1.9 MJ.

Pulsed Power Design

As described in detail in Ref. 1, PBFA Z's pulsed power design is based on Marx generator and water pulse-forming technology. PBFA Z contains 36 nearly identical modules. In each module a Marx generator, with 60, 1.3- μ F capacitors charged to a voltage of 90 kV, delivers its energy to a water-dielectric coaxial capacitor in 1 μ s. 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 60 TW. The electrical energy is delivered to an insulator where it 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.

The water transmission lines 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

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transmission lines to an inductive load. The impedance of each of the 36 lines was $4.32\ \Omega$. The transmission line gap is fixed at 14 cm. Each water line has a voltage and current monitor. We 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 by the spatially- and temporally-varying behavior of the electrical pulse and its reflection from the load. 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.

The insulator stack (See Figure 2.) is the boundary 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™ (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 giving a very accurate measure of the power and energy through the insulator stack boundary.

One of the great achievements of PBFA Z was the successful design of the MITLs. They consist of four separate, conical-disk feeds coupled together at the vacuum convolute. The upper two MITLs are $2\text{-}\Omega$ impedance and the lower two MITLs are $2.75\text{-}\Omega$ impedance. The MITLs operate successfully at a peak electric field of 2 MV/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 electric 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 positions in each of the four MITL anodes to better study losses.

A critical point in 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 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. The baseline convolute on PBFA Z is a 12-post/hole design with 1.0- to 1.5-cm diameter posts and post-to-cathode gaps of 1-2 cm. In addition, the convolute was partially modeled using QUICKSILVER¹, a 3-D E&M PIC code. A drawing of the convolute is given in Figure 3.

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.

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.

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

Electrical Diagnostics

We field a full complement of electrical diagnostics on every shot. With thirty-six modules, this translates into hundreds of waveforms being recorded per shot. 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 36, capacitively-coupled voltage monitors, commonly referred to as dV/dt or 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 V-dots can be used to measure the voltage and switching time of the L1 capacitors. The output of the L1 capacitors is monitored with 36, V-dots 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 voltages and the currents at the insulator stack are 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.

Accurate calibration of all of the diagnostics is critical. Some of the V-dot calibrations are done in-situ with pulsers and reference monitors placed near the diagnostics under calibration while most 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 digitally and are available for examination or further checking at any time in the future. Typical electrical diagnostic calibrations were accurate to $\sim 2\text{-}4\%$. We believe that the total error, including data acquisition and systematic errors, for most of the electrical diagnostics is better than 5%.

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

Electrical Performance

Measurements of voltage and current in the constant impedance water transmission lines give the module spread, voltage, power, and energy for the entire accelerator. Figure 4 shows a typical 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. The best data give a total forward-going energy for the accelerator of ~ 5 MJ.

The peak electric field 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 electrical breakdown in the water transmission lines is dominated by edge

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

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

Figure 7 The total stack current (solid line) is plotted with the MITL current for Shot 51.

effects, joints, and gaps. We see no evidence of electrical breakdown or losses in the uniform field portion of the water transmission lines.

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 ($I \cdot V$) passing through the insulator stack. The peak electrical power measured on Shot 51 was 50 TW. The measured electrical energy at the insulator stack for Shot 51 was 3.1 MJ.

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 L/R decay away. MITL current data from other shots with MITL current monitors just outside the vacuum convolute (30 cm from the load) show no MITL current losses to that radial location.

Data and calculations show electrical losses in the vacuum convolute. Depending on the load inductance, this loss can vary from 5% to 10% of the current delivered to the insulator stack. This loss has the effect of partially decoupling the load from the driver and lowering the peak current driving the z-pinch load.

Conclusions

PBFA Z is the world's most powerful electrical accelerator. We are successfully operating at the 60-TW/ 5-MJ electrical design point. We can deliver up to 20 MA to a variety of z-pinch loads. 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 1.9 MJ.

Acknowledgements

The author would like to thank the invaluable assistance of a large number of contributors, throughout government and industry, without whose pulse power expertise this work would have been impossible.

*This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

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