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PULSERAD 445W, A COMPACT HIGH-POWER BEAM GENERATOR

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Abstract

A 0.7 TW, 50 kJ, 5 ohm water dielectric beam generator, Pulserad 445W is described. A convertible output line allows efficient operation for 1-8 ohm load impedance. Reliable operation was achieved in accordance with equivalent circuit predictions, and magnetic insulation of the vacuum transmission line was in accordance with the parapotential model.

The Pulserad 445W High Power Relativistic Electron Beam Accelerator was designed and constructed by Phsyics International for the Institute of Plasma Physics at Nagoya University, Japan. The primary application for this accelerator is the injection of electron beams into toroidal magnetic confinement devices to produce a confining field and to heat the plasma.[1] In order to allow experimentation over a wide variety of beam characteristics, the Pulserad 445W was designed to operate over a range of impedance values.

Generator Description

The design point for the machine was to produce 50 kJ at a power of 0.7 TW and an impedance of 5 ohms. By use of a convertible output line, efficient operation of the machine can also be maintained over a range of 8 ohms-1 ohm. Output specifications are presented in Table 1.

TABLE 1

OUTPUT PARAMETERS OF PULSERAD 445W

	1 Ω	5 Ω	8 Ω
Cathode Voltage	0.7 MV	1.8 MV	1.8 MV
Diode Current	700 kA	360 kA	225 kA
Current Risetime (10-90)	36 ns	27 ns	27 ns
Beam Energy	30 kJ	50 kJ	30 kJ

At 5 ohms the energy efficiency of the generator is high, >50% from Marx generator to beam. In addition, the design is compact [3.2 m(H) x 3 m(W) x 7 m(L)] and has convenient access to all components for easy maintenance. The overall layout of the machine is shown in Figure 1, the physical configuration in Figure 2.

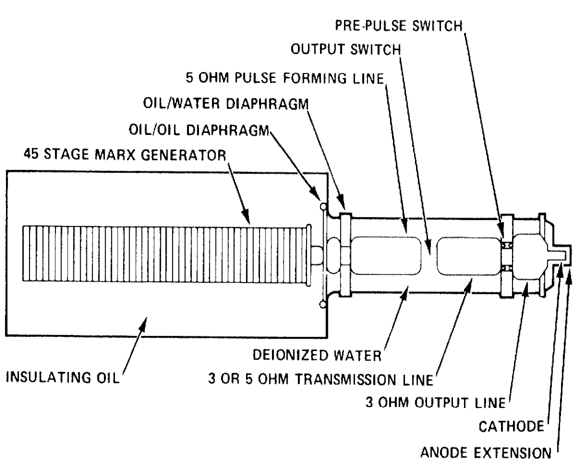

Figure 1 Pulserad 445W configuration.

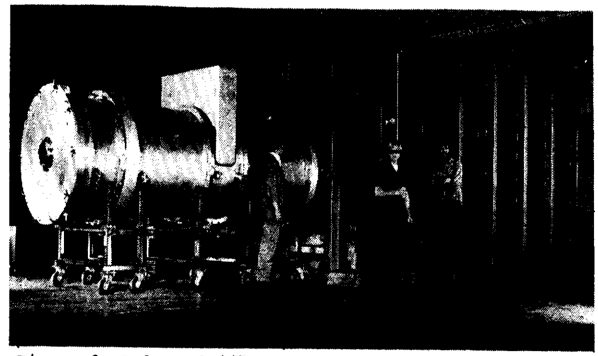

Figure 2 Pulserad 445W Marx generator and water line. Water switch pressure relief chamber projects above line at output end of PFL.

The Marx generator is constructed from 100 kV modular stages. The capacitors are low-inductance cylindrical units with 0.033 μF at 50 kV. Each stage has 48 of these capacitors mounted in a compact series/parallel array. Total Marx stage capacity is 414 nF. Each stage is balance-charged so that the spark gap trigger electrodes remain at ground potential during the dc charging phase. Spark gaps are Physics International Model T670, which are pressurized SF_6 gaps with a symmetrical configuration and a thin trigger electrode positioned precisely in the plane of symmetry. Triggering of the stages is accomplished by resistive coupling from stage to stage. The generator is triggered by a 140 kV Physics International Model TG-70 trigger amplifier. The 45 stages are supported on an insulating frame that is suspended in a steel tank filled with insulating oil (Figure 3). Stages are independently removable, allowing swift removal for maintenance. The overall Marx configuration is low in inductance, 5 μH, and has an erected capacitance of 9.2 nF.

Figure 3 Modular Marx generator suspended in tank with compact stages connected by charging and triggering resistors.

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The pulse forming line (PFL) is a water-insulated, 58 cm ID, 122 cm OD coaxial transmission line. The line impedance is 5 ohms, and the length is 130 cm resulting in a one-way electrical transit time of approximately 38.6 ns and a capacity of 7.7 nF. The PFL is charged by the Marx generator in a time of 400 ns to a peak voltage of about 4.2 MV with the Marx fully charged. Using the time-dependent breakdown characteristics of water[2], the breakdown field on the positive outer is calculated to be 210 kV/cm compared to the peak field there of 110 kV/cm. These values result in a safety factor of 1.9 for the line.

At the output end of the PFL is a water switch which self-breaks at a pulse line voltage determined by the gap spacing, which is adjusted by an externally operated hydraulic system. The switch is designed to have a small shunting capacitance as well as low inductance. The low capacitance minimizes prepulse signals applied to the diode before the main output pulse. The switch inductance is less than 0.1 μH.

The 77 ns pulse produced by the PFL is conducted to the diode by a length of transmission line. Two options of transmission lines are provided in this system such that the diode can be operated in the 1-8 ohm range. The 5 ohm line option uses the same dimensions as the PFL. A 3 ohm, 79 cm inner diameter coax option is provided to enable the system to operate at a low diode impedance regime of 1-4 ohms. The 77 ns length was chosen to delay pulse reflections from the prepulse switch and diode until the end of the main pulse. A prepulse switch consisting of five symmetrically positioned gas dielectric spark gap switches separates the transmission line from the output line. These switches isolate the diode from prepulse voltages which survive the capacitance division between the output switch and the transmission line. They also sharpen the output pulse risetime. A short section of a 3 ohm water line transmits the pulse from the prepulse switch through the radial insulator into the vacuum diode.

The radial plastic insulator separates the vacuum from the water dielectric filling the output line. The electrical pulse passes through the insulator and encounters a biconic vacuum line with wave impedance of 19 ohms, a coaxial cathode shank with wave impedance of 29 ohms, and finally a diode with adjustable impedance (Figure 4). This geometry was chosen in order to reduce

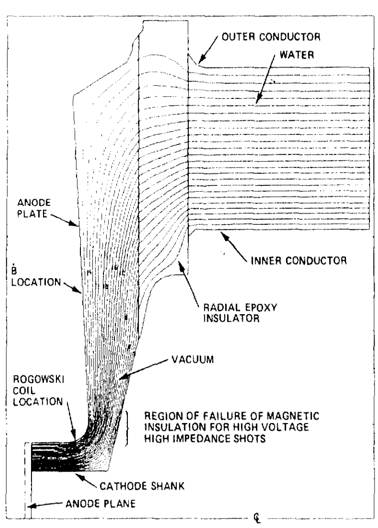

Figure 4 Tube region equipotential plot.

the inductance to approximately 55 nH while maintaining the magnetic insulation capability of the vacuum feed.

A linear Poisson solver was used to calculate the equipotential distribution for this geometry. Optimization of the electric field distribution on the vacuum surface of the insulator depends critically upon the electric field at the triple point where vacuum plastic and metal meet.[2] The design produces fields of approximately 25 kV/cm parallel to the insulator surface at both triple points. In practice this distribution was found to be extremely safe; operation at tube voltages as high as 2.6 MV was possible, and no cases of surface flashover on the insulator were found. The diode consisted of a 5-inch-diameter stainless steel cathode on a stainless steel shank. The cathode surface was dished to prevent diode shorting on the axis. Figure 5 shows output traces for a 5 ohm diode load. The generator was found to perform reliably and reproducibly in all the modes of Table 1.

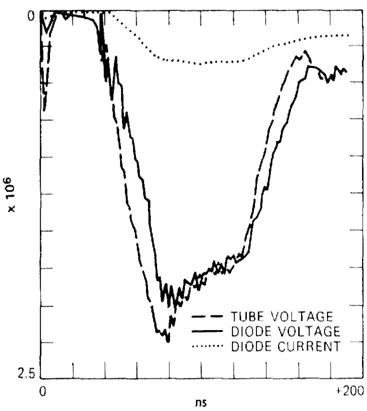

Figure 5 Data from Shot 360.

Generator Modeling

The equivalent circuit used for the design of the Pulserad 445W is a simple cost-effective model useful for predicting the major features of the pulse such as pulsewidths, pulse amplitude, and the timing of reflections. End effects of line segments are accounted for by increasing the line length at the dominant impedance and by including a lumped capacitance to model the discontinuity impedance for a traveling wave at those line ends not in close proximity to each other.

The switch model used consists of a switched inductance in series with a time-varying resistance, both shunted by a single fixed capacitance. This simple model is adequate for design purposes but fails to account precisely for the redistribution or dissipation of the energy stored in the switch capacitance which occurs during switch closure.

In the 445W, this stored energy peaks up output voltage and current artificially (Figure 6a). To eliminate this effect, one can open-circuit the switch capacitance at closure and remove all this energy from the circuit. This reduces outputs slightly below experimental values and severely enhances reflections by increasing the series impedance of the switches (Figure 6b). Conversely, leaving in the switch capacitance integrates and smooths reflections excessively (Figure 6a).

During switch closure, some of the charge initially in the switch capacitance is undoubtedly stored in the capacitance of the switch channels to the outer wall. It is likely that some of the energy required to close the switch is also derived from the initial switch capacitance. Neither of these time-dependent mechanisms is included in the model used here. Regardless of the manner in which the charge is redistributed, the region inside the switch channels does not contribute significantly to switch capacitance after closure. Therefore, for better modeling, switch capacitance should be decreased (but not eliminated) at switch closure.

The computer predictions (Figures 6a and 6b) are compared to the data of Shot 292 since the diode impedance characteristics of Shot 292 are very similar to the theoretical relativistic Langmuir-Child model. Shot 292 has an unusually slow risetime caused by nonoptimum choice of output switch timing. The predicted diode voltage risetime of 30 ns agrees well with the 27 ns risetime measured on shots with optimal switch timing (Figure 6).

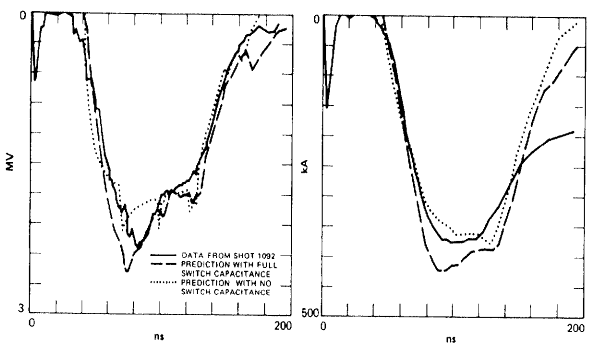

Figure 6 Predicted and actual tube voltage and diode current for Shot 292.

Magnetic Insulation

Vacuum transmission line magnetic insulation occurs when the magnetic field produced by the line current is sufficient to prevent field-emitted electrons from crossing the gap. Insulation properties of the tube were measured by: (1) a $\dot{B}$ current monitor recessed into the anode plane at 30 cm radius along the biconic 19 ohm section; and (2) a Rogowski coil located just past the beginning of the coaxial section. The weakest point in the biconic line is near the transition to the coax where the peak electric field at the cathode is 400 kV/cm for 2 MV tube voltage.

Magnetic insulation is complete for load impedance below 6 ohms; i.e., the current at both current monitors was identical to that measured in the Faraday cup. Insulation partially fails in the biconic region at higher load impedances. Our observations are:

1. Insulation is complete at any load impedance if $E \lesssim 350$ kV/cm in the tube. This is the critical field for onset of emission from the oiled cathode surface. For example, Figure 7 shows an 8 ohm shot. At 1.7 MV the peak field on the biconic is 350 kV/cm, insulation begins to fail, and a current difference of 16% develops.
2. When $Z_f/Z_o > 0.35$, insulation fails. Here $Z_f = V/I$ is the impedance of the current flowing in the bicone, Z_o is the line wave impedance, 19 ohms. Another way of stating this criterion is that the saturated parapotential current[3] must be exceeded. If $I > I_p$, no loss is observed for fields as high as 450 kV/cm. Van Devender[4] states a criterion $Z_f/Z_o > (\gamma-1/\gamma+1)^{\frac{1}{2}} \simeq 0.75$ for our voltages (1.5-2 MV). This criterion is for the wave regime, $\tau_B/\tau_L < 1$, τ_B = beam pulse length, τ_L = vacuum line double transit time. Our data are for steady-state conditions, $\tau_B/\tau_L >> 1$. Insulation may be significantly better in the wave regime compared to steady-state.
3. The geometric gradient of the bicone-coax transition does not appear to disturb the flow. Van Devender states that $\delta d/\delta x < 0.25$ is required for low loss flow when d is the gap spacing and x is taken along the direction of power flow. The rationale for this condition is that perturbations to the electron flow cause unstable oscillations resulting in current loss. In the bicone-coax transition, $\delta d/\delta x \sim 0.35$, and yet when $Z_f/Z_o <$ 0.35 no loss is observed. Perhaps if a lower gradient design were used, higher impedance load flows would be insulated.

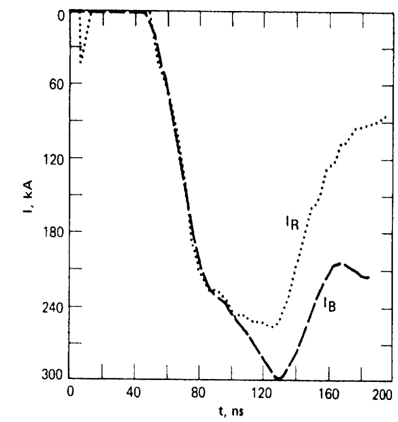

Figure 7 Current in biconic I_B and current in coax I_R.

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