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THE DESIGN OF A 2 TW PULSED POWER RESEARCH FACILITY*

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Summary

Physics International (PI) has designed a modular pulse generator for research in high-power switching, pulse compression, power flow, magnetic insulation, and dielectric breakdown. The generator is one wedge-shaped 1/20th "slice" of PI's conceptual design for a 40-50 TW, radial, tri-disk accelerator designed to drive imploded plasma or particle beam loads. The nominal design goal of the "slice" (or module) is to produce a 100 ns, 2 TW, 2 MV, 1 MA pulse into a resistive load, or a 150 to 200 ns pulse at lower power. The module consists of an 0.8 MJ Marx generator and four water-dielectric triplates with adjustable impedances. The first is a gas-switched transfer capacitor. Next are two water-switched pulse-compression stages, and last, an output line converging to a racetrack insulator. This article describes the design and planned experiments.

Introduction

In the 1980's, very large, high-power pulsed accelerators will be required to support research in nuclear weapons effects simulation and inertial confinement fusion (ICF). For simulation, the ultimate goal of this research is to build facilities capable of exposing full-scale military systems to threat-level radiation. ICF research has the additional goal of demonstrating commercial power production. Accelerator technologies for simulation and ICF are very similar, especially: (1) the imploded (Z-pinch) plasma radiator approach to the simulation of soft x-rays from exoatmospheric nuclear bursts, currently under investigation by PI[1], other DoD contractors, and several National Laboratories[2,3]; and (2) the light ion approach to ICF being investigated by Sandia National Laboratories, Albuquerque (SNLA)[4] and the Naval Research Laboratory[5,6]. Both of these approaches may ultimately require drivers capable of producing pulses in excess of 100 TW and 10 MJ. Specific driver requirements, of course, depend upon which approach is taken. The facility we describe here is part of the Z-pinch radiator approach to simulation.

Drivers for Z-pinch radiators must generate electromagnetic pulses that optimize radiation yield. Research at load voltages in the range of 1-2 MV with 5-10 TW, 50-100 ns pulses indicates that sufficient yields may be obtained by driving imploded plasmas with 100 TW, 2 MV, 50 MA, 100 ns, 10 MJ pulses. But intermediate-level load experiments are needed to determine how radiation yield scales with driving pulse parameters. To develop the technology for both an intermediate-level accelerator and a larger successor, the Defense Nuclear Agency has funded relevant pulsed power research at PI. EAGLE, the 2 TW research facility described here, is part of that phased development program.

PI's conceptual design for one intermediate-level accelerator, called ROULETTE, is shown in Figure 1. Its nominal 40-50 TW, 2 MV, 20-25 MA, 100 ns output pulse would be produced by a set of modular, triplate, water dielectric, pulse forming lines arranged to create a 30-m-diameter disk and driven by a ring of oil-immersed Marx generators. Power from the waterlines would be injected into magnetically insulated vacuum transmission lines through a set of modular plastic insulators at a distance of 2.5-3.0 m from the centrally located plasma load.

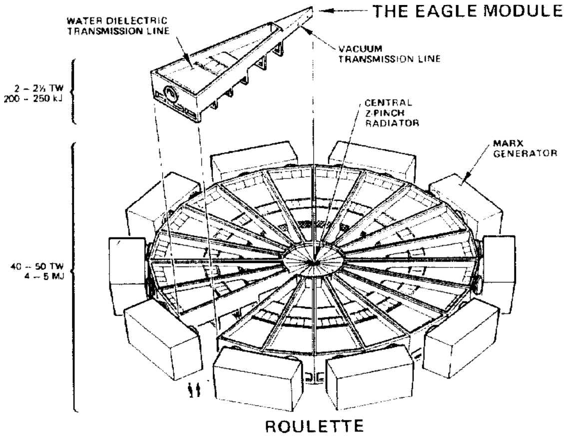

Figure 1 The ROULETTE accelerator system.

A wedge-shaped module of ROULETTE is also shown in Figure 1. This is EAGLE, presently under construction at PI. Representing a 1/20th "slice" of the full circle, it will be used to gather design data for ROULETTE. Experiments are planned in the areas of low-jitter, high power, triggered gas switching, untriggered water switching, pulse line circuit optimization, vacuum insulator flashover, breakdown-limited power flow in water and magnetically insulated vacuum lines, and vacuum convolute techniques.

System Description

A schematic of the EAGLE system is shown in Figure 2. Energy is stored in the 0.8 MJ Marx generator, then sequentially transferred through switches to three line-type, water dielectric pulse-compression stages: the transfer capacitor (TC); charging pulse line (CPL); and pulse forming line (PFL). Power amplification occurs with each successive transfer. The pulse from the PFL is injected into a converging output line (OL). A resistive load has been designed to terminate the OL during initial experiments. For a second set of experiments to study vacuum power flow, the resistive load will be replaced with a modular plastic insulator structure. Power will flow through this interface into a converging, vacuum transmission line terminated with a plasma load. The load will be located at the hypothetical center of the full ROULETTE system. In the following paragraphs, we discuss the design of various elements in the power flow chain of Figure 2.

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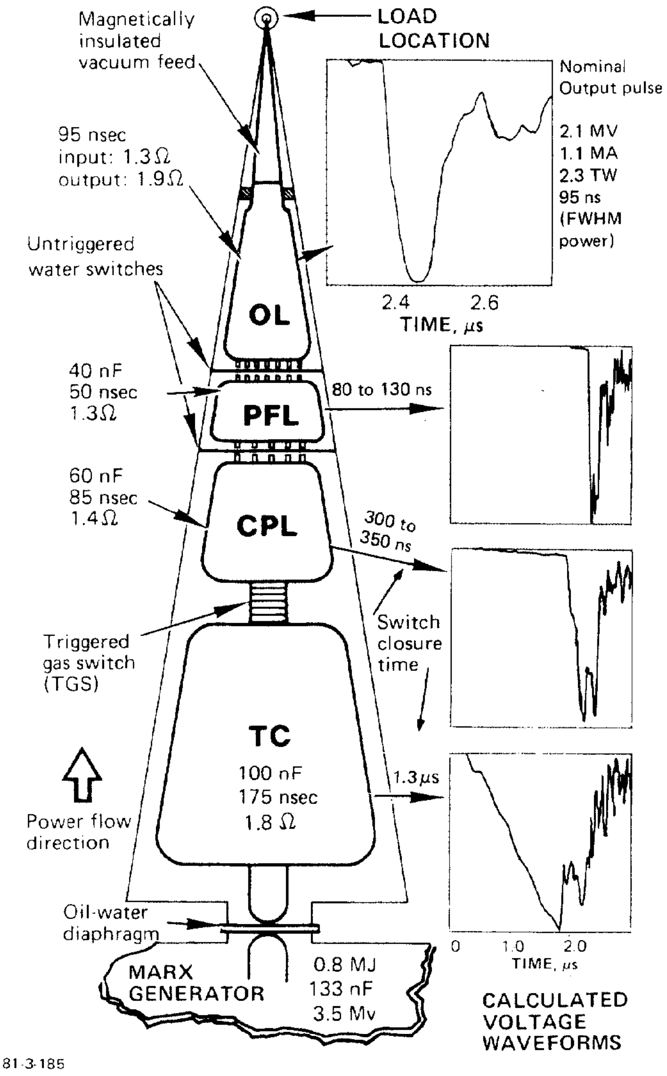

Figure 2 EAGLE schematic (plan view).

Marx Generator

EAGLE has two Marx generators (Figure 3) in a single 100 m^3 oil tank. Incorporating 100 3.2 μF, 75 kV capacitors, and 50 triggered SF_6 spark gaps, the Marxes can store 0.94 MJ at full charge. Erected capacitance is 133 nF, and full open-circuit voltage is 3.8 MV. Cross-coupling between Marxes is minimized by placing their grounded ends near opposite tank walls. Discharge current from each Marx flows through separate series resistors to a common feed. The feed pierces a single, 1.4-m-diameter urethane, oil/water interface, then connects to the 100 nF TC. Because the Marx capacitors and spark gaps are configured for low inductance, the TC can be fully charged in 1.6 μs.

EAGLE's low-inductance Marx circuit arrangement is similar to that of PBFA-1 at SNLA[7], but EAGLE stores more energy per unit volume because of an advanced capacitor design. The capacitors, Aerovox Model SX160E11, are made with eight series, extended-foil sections of paper/polypropylene/dioctylphthalate (DOP). Since each section can operate at 4573 volts/mil, each capacitor can store 9 kJ in a standard, LASL "Scyllac"[8] can. The energy density of a single Marx generator is 54 kJ/m^3. If the volume of insulating oil is included, the entire system stores 9.4 kJ/m^3.

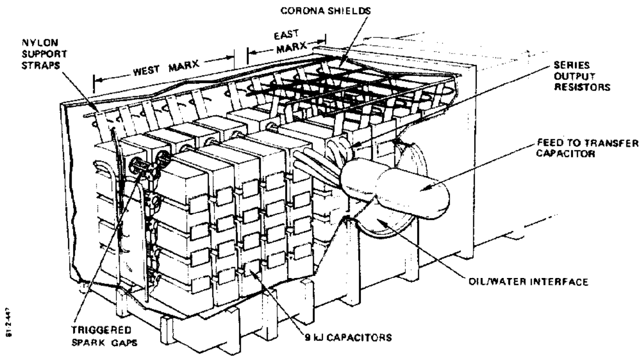

Figure 3 EAGLE Marx generators.

To construct EAGLE spark gaps, a novel technique is employed. End plates and electrodes are made of a single, nonporous brass casting, which eliminates troublesome high-current sparking. PI developed the basic spark gap (Model Number T-508) for the AURORA accelerator[9] over ten years ago, but the new version is more reliable. In EAGLE, each switch will withstand 150 kV dc, conduct 160 kA, and transfer 0.4 C.

Construction and testing of the EAGLE Marx generators is complete. Performance is excellent. Erection is possible at as low as 25-30% of single-gap self-fire (better than 3:1 triggering range), and shot-to-shot rms jitter for a single Marx is less than 10 ns (rms) at a constant ± 45 kV charge voltage over a spark gap pressure range of 1.3-2.7 atm abs. For both Marx generators in parallel, the measured inductance is 4.28 μH, including ground connections and the output feed. Inductance of a single 18 kJ, 150 kV stage averages 300 nH.

Waterlines

The waterlines of EAGLE include the TC, CPL, PFL and OL shown in Figure 2. These lines act in concert with the three high-power switches to form the EAGLE output pulse. The nominal pulse into a 2 Ω resistive load, produced by the PFL when the Marx-driven TC and the CPL are used as transient energy stores, is calculated to be 2.3 TW, 2.1 MV, 1.1 MA, and 95 ns FWHM (power). A longer (~ 170 ns), lower-power pulse can be produced by using the 85 ns (one-way transit) CPL as a pulse forming line. In either pulse mode, EAGLE output characteristics can be varied by using adjustments designed into the machine.

The ability to make such adjustments provides experimental flexibility. Line impedances, switch parameters, and charging voltage are adjustable over the ranges shown in Table 1. These ranges will allow us to use EAGLE to gather design data for ROULETTE at full system operating levels of voltage, current per unit line width, and pulse duration.

Table 1 EAGLE system variables.

Parameter	Adjustment Range
Marx Voltage	to ± 75 kV
TGS Pressure	0-100 psig
TC Impedance	1.37-1.55 Ω
CPL Impedance	Input: 1.06-1.62 Ω Output: 1.27-1.71 Ω
Number of CPL Switch Sites	1, 2, 3, or 5
CPL Ground Plane Hole Diameter	7.6 cm or 12.7 cm
PFL Impedance	Input: 0.95-1.73 Ω Output: 1.00-1.71 Ω
Number of PFL Switch Sites	0-30
PFL Ground Plane Slot Spacing	7.6 cm to 22.8 cm
OL Impedance	Input end: 1.07-1.74 Ω
Output Impedance	1.79-2.25 Ω

High Power Switches

For the three high-power switches in EAGLE, we selected one triggered gas switch (TGS) and two self-closing water switches to provide low loss, acceptable acoustic loading of structures, fast output pulse risetime, and low jitter.

The EAGLE TGS is a multi-stage, UV-illuminated SF_6 switch. A six-stage prototype of this switch has been built and tested[10]. In tests on the OWL generator at PI[11] and on the SUPERMITE facility at SNLA[12], we have measured jitter (1σ) values of 1.7 ns at > 525 kA, > 0.2 C, and 2.6 MV (~ 75% of self-break) with 1.2 μs switchout times. The EAGLE version of this switch will have eight stages and will be tested at 3.0 MV to provide additional ROULETTE design data. The switch will be triggered by a 200 kV pulse generator located inside the CPL inner line. The trigger system will be controlled by an optical link introduced directly across the CPL high-field region.

switches have discrete, multiple electrodes, which extend through prepulse-suppressing ground planes[13]. The CPL switch has five electrodes that extend through 7.6-cm-diameter holes. By removing inserts, the holes can be enlarged to 12.7 cm for operation at higher voltage. CPL switch design parameters are 2.8-3.3 MV, 0.8-1.2 MA, with switchout times of 300-350 ns.

Designed for 3.0 MV, 1.4 MA, the PFL switch has a switchout time in the range of 80-130 ns. We designed the PFL ground plane with a variable-spacing slot (like a straight-bladed guillotine) rather than with discrete holes in order to vary the number of switch sites over a wide range (see Table 1).

The electrode tips of both the PFL and CPL switches are field-enhanced, so breakdown streamer channels originate from the negative side. We determined electrode spacings, d, by using a negative streamer velocity relationship suggested by J. C. Martin[14] in 1977,

$$\bar{u}\, t^{1/2} = 10\ V \qquad (1)$$

where $\bar{u} = d/t$ in cm/μs, t is the time in μs the voltage is above 0.63 V, and V is the breakdown voltage in MV. This approximate relationship provides excellent agreement with shielded switch data collected on the DNA-PITHON generator.

Construcion

The EAGLE waterlines, shown in Figure 4, are housed in a wedge-shaped, 66,000 liter, stainless steel tank, which confines them to an 18° sector, in keeping with the ROULETTE design of Figure 1. The 2.4-m-high tank is nearly 5 m wide at the rear of the TC, and converges over a distance of 12.6 m to a width of just over 1 m at the water-vacuum interface location. This interface will be a single-piece "racetrack"-shaped insulator structure made by bonding cast urethane directly to metal gradient rings. The racetrack insulator will be attached to a 3-m-long, converging, magnetically insulated, vacuum transmission line (MITL). We will use the insulator-MITL hardware* for vacuum power flow experiments in support of the ROULETTE design.

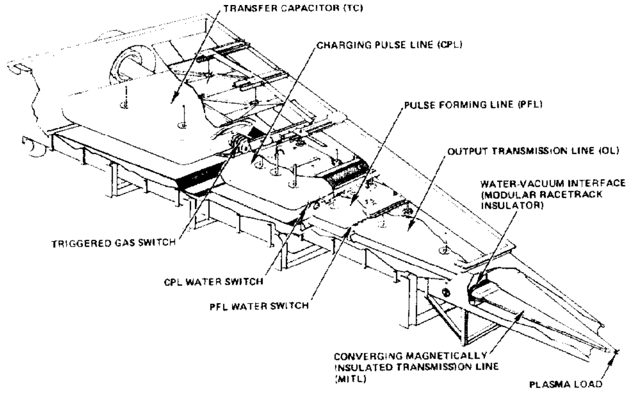

Figure 4 EAGLE waterline and front-end construction.

Construction of the EAGLE waterlines themselves is simple and rugged. The transmission lines are bounded triplates with adjustable spacings to allow for impedance variations. Main electrode surfaces are flat plates of 0.5-cm-thick stainless steel. The plates are pop-riveted to space frames to permit replacement if high-power experiments deform them badly. Access to components is easy. Most maintenance can be performed without draining the water. These mechanical design features should make ROULETTE data collection more efficient for us.

Circuit Discussion and Conclusion

The basic electrical design of EAGLE was shown in Figure 2. Viewed as lumped elements, each successive energy transfer stage is capacitively undermatched to provide a voltage ring-up. The voltage ring-up is used to compensate for switch losses and shunt conductance. This scheme allows each of the three high-power switches to operate at roughly the same voltage, in the range 2.5-3.0 MV. The converging geometry of EAGLE also helps to keep impedances similar without using excessive line lengths. The TC and OL have essentially the same impedance, and differ by only 15% in voltage. Losses and jitter are reduced because the switches are operated at reduced voltages.

Another technique for reducing switch voltage and electric stresses on the PFL will be investigated on EAGLE. This switching scheme, first suggested by

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*The development of this insulator structure will be the subject of a separate, future publication.

Ian Smith[15] in 1978, exploits transmission line reflections in the PFL. In principle, it can allow extraction of peak power in excess of the theoretical $V^2/4Z$ limit from an ideal transmission line. The technique works when a line like the CPL charges a PFL such that a well defined charging wave is doubly reflected, first from the open PFL switch, then from the CPL switch inductance. This double reflection can enhance output power without increasing PFL switch voltage under certain conditions. Those conditions are: (1) $\tau_1 < \ell/c$, where τ_1 is the CPL switch risetime, ℓ_1 is the PFL length, and c is the speed of light in water; (2) $\tau_2 << \ell/c$, where τ_2 is the PFL switch risetime; (3) the PFL switch closes at a time $\sim 3\ell/c$ after the CPL switch; and (4) the PFL end structure presents a close-to-ideal open circuit to charging waves. Experiments to test this concept are planned.

EAGLE is also designed to test the limits of power flow in water. Every line can be stressed to beyond breakdown, as defined by[16]

$$\bar{E} = 0.23\ t^{-1/3}\ A^{-0.058} \qquad (2)$$

where $\bar{E}$ is the breakdown field in MV/cm, t is the time in µs that pulses exceed 0.63 of their maxima, and A is electrode area in cm^2. We will be able to selectively overstress lines by using the adjustments of Table 1.

EAGLE is being assembled at this writing. Our first shot is scheduled for late May, 1981. Once operational, EAGLE will be solely dedicated to pulsed power research. Our primary objective is to collect a firm data base for the design of ROULETTE. But EAGLE's versatility will permit its use in more general experiments for many years to come.

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A companion paper to this one entitled "A Low Jitter Triggered Gas Switch to Synchronize Modular Accelerators" appears later in this section of the Proceedings.

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