# PULSED POWER DESIGN FOR A COMPACT X-RAY SIMULATOR*

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*Abstract*

The pulser system described here is being built to provide a transportable x-ray simulator for hardness testing of assemblies at their point of manufacture rather than at remote, dedicated simulator facilities. Operating voltage ranges are from 150 to 300 kV and 400 to 600 kV providing 1 mcal/cm$^2$ at the low end and greater than $10^9$ rad(Si)/s at the high end over areas up to 1000 cm$^2$. To be transportable the pulser and its subsystems are to be packaged in a standard 8 x 8 x 20 ft shipping container which has been modified to house a self-contained simulator system when assembled. The pulser is a Marx driven 1.6 MV, 3 Ω water pulseline using a self-closing multichannel water switch and gas dielectric prepulse suppression switch for waveform generation. Output impedance into a reflection or transmission e-beam diode is 1.5 Ω. A testbed was built to verify pulser and diode design prior to producing a prototype. This paper describes the Marx, pulseline, and switch designs and test results.

## I. DISCUSSION

This compact pulser is designed to produce the electrical pulses required for conversion by a bremsstrahlung x-ray diode to meet the radiation specifications listed in Table 1.

Table 1. X-ray requirements (condensed list of rad specs)

| Endpoint Voltages | X-ray Output | Area Uniformity | Pulse Shape |
|---|---|---|---|
| 150-300 kV | 1 mcal/cm$^2$ | 1000 cm$^2$ ± 20% | 20-50 ns FWHM |
| 400-600 kV | >$10^9$ rad (Si)/s | 500 cm$^2$ ± 20% | 15 ns 10-90% |

The required spectral range and shot rate (20 shots/day) caused consideration of two diode types; a reflection anode convertor for low voltages (100 to 300 kV) and a transmission anode for high (400 to 600 kV) voltages.

Models relating radiation output to diode input electrical parameter values were used to determine the pulsed power specifications [1]. From these modeling results, shown in Table 2, it initially appeared that matching these diodes would require multiple pulser output impedances to produce the specified performance.

However, further modeling showed that a fixed impedance pulser system could be used mismatched over some of the range with beneficial (higher dose and dose rate) results. The pulser impedance profile which evolved was a 3 Ω, 50 ns (2δ) pulseline operated at a maximum of 1.6 MV and switched into a 1.5 Ω output line connecting to a diode. The pulseline output switch would have to be less than 25 nH to meet rise time requirements, and due to the high shunt capacitance of a water dielectric switch, a prepulse suppression switch would be required in the output transmission line to isolate the diode from spurious voltage during pulseline charging by the Marx.

The components produced for verification testing were assembled into a test bed which is shown in Fig. 1. Having successfully accomplished this testing, most of the hardware shown is being repackaged to produce the prototype transportable simulator shown in Fig. 2. Considerations in the design of these pulser components are discussed next.

## II. PULSEFORMING LINE DESIGN

A pulseforming line circuit network was created that would produce the desired diode electrical pulse inputs. Network parameter values were based on engineering estimates of achievable performance based on adaptation of existing water dielectric pulseline and switch technology. The pulser equivalent circuit, shown in Fig. 3, coupled to our diode models showed code performance sufficient to justify design and construction.

### *A. Pulseline Structure*

Typically, pulseline design seeks the smallest diameter consistent with breakdown-free operation. Breakdown field depends upon voltage, diameter, impedance, stressed electrode area and effective stress time, and is predictable.

Table 2. Diode electrical input requirements for Compact Simulator.

| Endpoint Voltage (kV) | Converter Type | X-ray FWHM (ns) | Approx. Peak Electron Current (kA) | Approx. Load Impedance (Ω) | E-beam Energy Required (kJ) |
|---|---|---|---|---|---|
| 300 | Reflection | 20 | 830 | 0.4 | 2.4 |
| 600 | Transmission | 20 | 44 | 13.6 | 0.5 |

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14. ABSTRACT
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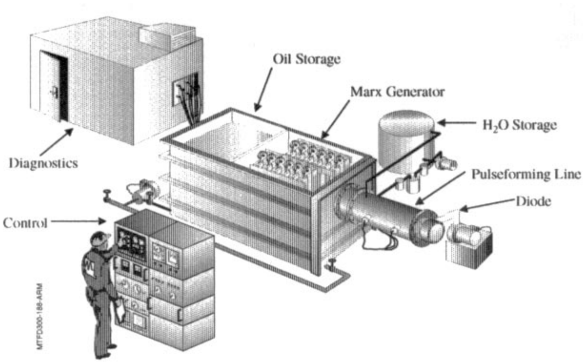


Figure 1. CXS components test bed.


Figure 2. CXS components packaged to form prototype system.

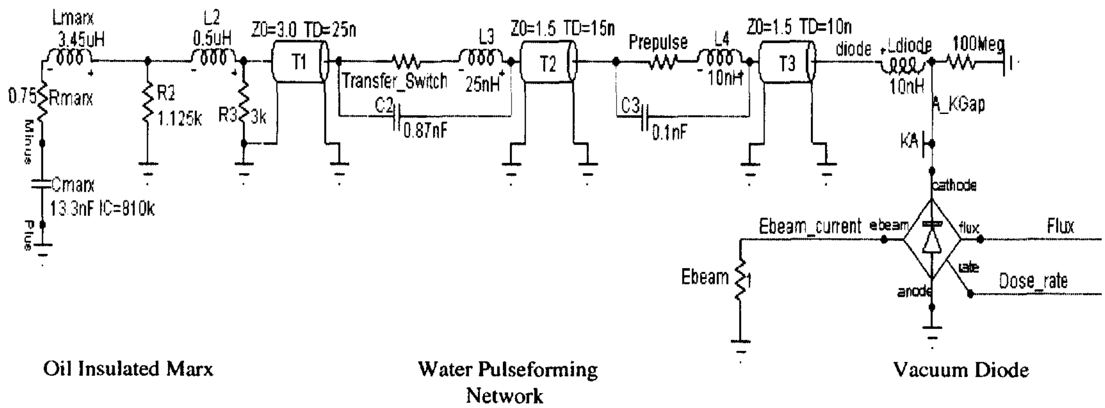


Figure 3. CXS model producing diode electrical input requirements.

In this case a large diameter is desirable to maximize the space available for multi-channel switch sites to reduce output switch inductance. Since the pulseline impedance is set by the ratio of interelectrode spacing to diameter, at fixed impedance larger diameters can reduce switch inductance while also reducing breakdown probability. The maximum diameter is limited by manufacturing cost and convenience in a compact design. A minimum (high breakdown probability) diameter is given by:

$$D_{crit} = \frac{120}{\sqrt{\varepsilon_r}} \frac{V}{Z} \frac{t_{eff}^{1/3} A^{0.058}}{0.23} \text{ cm}.$$

$$= \frac{120}{\sqrt{80}} \frac{1.6\,\text{MV}}{3\,\Omega} \frac{(0.21\,\mu\text{s})^{1/3} (17\text{x}10^3\,\text{cm}^2)^{0.058}}{0.23}$$

$$= 32.5 \text{ cm}$$

where the water breakdown constants are from [2].

A pulseline diameter of 66 cm was selected providing a safety factor of ~50% of breakdown with a switch inductance less than 25 nH. 70% of predicted breakdown is considered conservative.

Pulseline structure is built from 10 GA stainless steel sheet, rolled and welded with adequately sized mounting flanges. The polyurethane barriers at the Marx end serve to separate oil from water and insulate the inner conductor while mounting it in cantilever. A retractable adjuster is provided for setting the output switch gap. The output transmission line portion of the pulseline is 1.5 Ω and is also mounted in cantilever, but from the prepulse switch insulator which divides the output line into 15 ns and 10 ns sections. The diode is mounted to this section. The large pulseline diameter also mates well with a low inductance diode structure. The shorter effective time and lower voltage in the output section results in a lower breakdown probability there. A cross-section of the complete pulseline is shown in Fig. 4. Pulseline overall length is 2.3 m. The assembled line and diode are shown in Fig. 5.

## *B. Output Switch*

A self closing multi-channel multi-site water dielectric switch of the type used in larger terawatt level pulsers was chosen for robustness and simplicity, avoiding the development of a 1.5 MV plastic envelope gas switch having a required inductance of less than 25 nH.

The design issues for the pulseline output switch are choosing a gap length for the voltage, the number of parallel switch sites for the inductance, and electrode

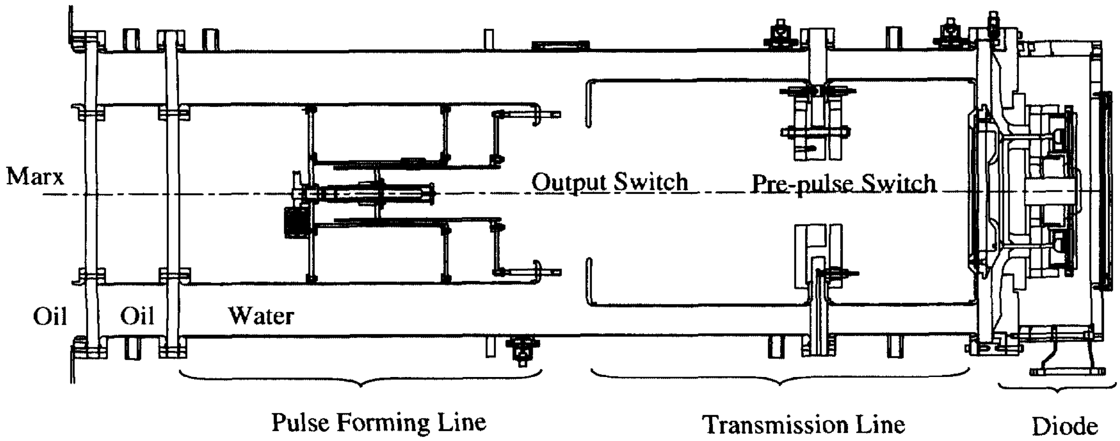


Figure 4. CXS pulse forming line cross-section.

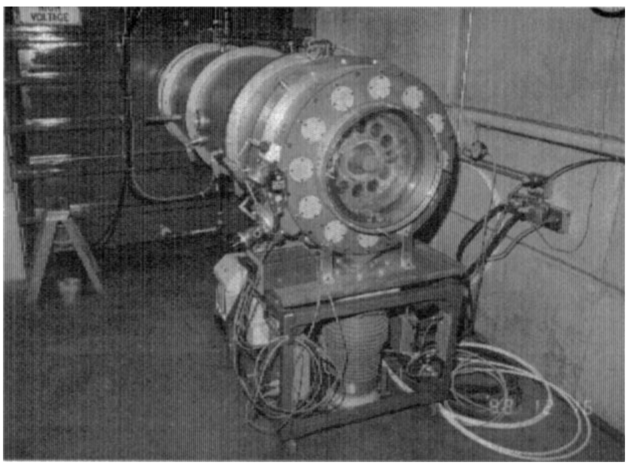

Figure 5. CXS pulseline and transmission diode assembly.

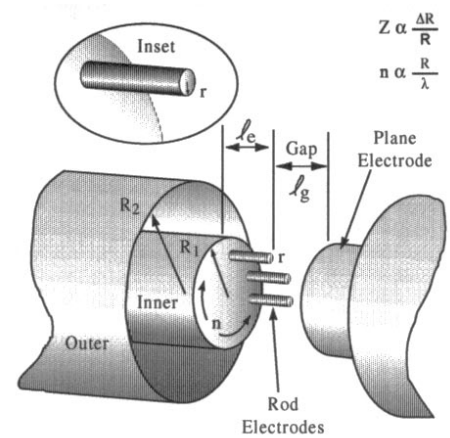


Figure 6. Multi-channel multi-site water switch configuration.

configuration enhancement to produce multi-channel operation. The gap length will be determined by the closure stress to be expected for the effective stress time. The charging time (0 to peak) of the pulseline from the Marx is 500 ns. For closure at peak voltage the effective time would be 208 ns and the gap is the longest. Multi-channel switches on other machines operating at about this effective time are characterized by a closure criteria of $Et_{eff}^{1/3}\, d^{1/6} = 0.23$ and closure stresses of 275 kV/cm. Thus we want a nominal gap of 5 cm at a peak PFL output voltage of 1.5 MV. The gap is decreased for lower voltages. To aid electrode enhancement the total line separation is 10 cm, or a 5 cm electrode "stick out" for a 5 cm gap length. Enhanced field electrode geometry is a truncated cylinder to plane as illustrated in the detail of Fig. 6 showing a multi-channel switch configuration. Switch site-to-site separation is 15 cm, permitting 8 switch electrodes in a 66 cm OD, 3 Ω pulseline. This gives a minimum inductance of 18 nH for closure of all 8 switch sites and an approximate inductance of 28 nH if only 4 sites close. Total switch inductance is due to electrodes and arc channels. Inductance was calculated by Russell's formula [3].

## *C. Prepulse Suppression Switch*

Shunt capacitance of the output switch is almost 1 nF and an appreciable prepulse voltage is developed at the 1.5 Ω output transmission line during charging of the PFL. Prepulse voltage can reach ≈150 kV during the 500 ns charging of the PFL. A prepulse isolation switch in the output line prevents application of this voltage to the diode prior to arrival of the main pulse. The switch must close on arrival of the main pulse without degrading the output pulse rise time. To some extent, depending on input pulse rise time, the prepulse switch can be used to decrease rise time albeit affecting pulse width. Low inductance (≤10 nH) is required and an 8-channel gas dielectric self-breaking switch was chosen. Location of the prepulse suppression switch in the output transmission line was optimized against prepulse voltage and pulse reflections.

Multi-parallelism is achieved by dimensional identity of gaps and electrode field enhancement. The breakdown closure voltage is set by pressure. Gap length was determined by extrapolation of negative point-to-plane breakdown data [4].

The gap design criteria used was $Ft^{1/6}\, d^{1/10} = 120$, resulting in a 1 cm gap for closure at 150 kV at 400 ns with 6 atm air. Air was selected to avoid the cost and compexity of using $SF_6$. Eight prepulse switch sites are embedded in a polyurethane disc insulator which also supports the output transmission line and reacts some of the vacuum load of the diode.

### *D. Marx Generator*

The pulseline is charged by a 13.3 nF, 1.5 MV (15 kJ) Marx generator. The Marx is a 15-stage ± charged m=2 triggered, n=1 coupled standard Maxwell Portamarx, adapted to fit in a 6x6x5 ft oil tank. Charging circuit resonant gain is ≈1.1. Prefire rate at full voltage has been ≈5%. Test bed Marx modules are shown in Fig. 7.

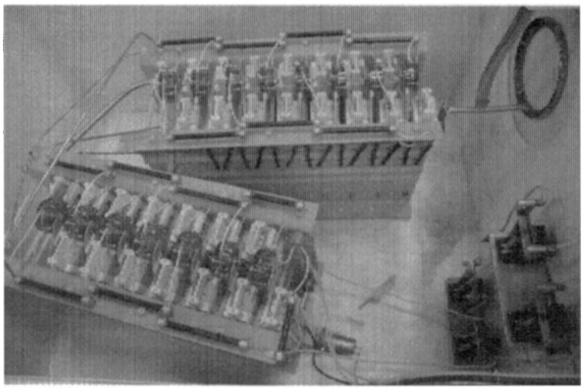

Figure 7. View of 1.5 MV testbed Marx. Pulseline connection is in upper right, ground in lower right.

## III. PULSER PERFORMANCE

Pulsed electrical output performance is primarily affected by the pulseline switches. Control characteristics of output and prepulse switch were determined with initial diode performance in tests up to full rated voltage. Fig. 8 shows pulseline charging and switch-out for 14 shots at 1.5 MV. Performance is consistent with design. Total

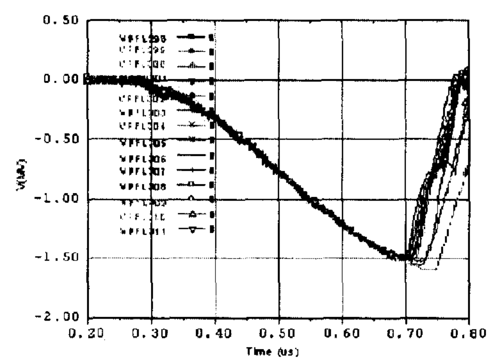


Figure 8. Pulse forming line voltage showing switchout at 1.5 MV with a switch gap of 5.5 cm.

range for all but 3 shots is <25 ns for the self-break output switch. However, three of the shots shown are "1st shot of the day" and closure is at a higher voltage. This phenomenon of higher breakdown strength is observed for the first of a group of shots when more than ≈4 hours has elapsed between shots. The cause of this is not understood but can be managed by reducing the gap for the first shot. Elimination of a 150 kV prepulse is shown in Fig 9.

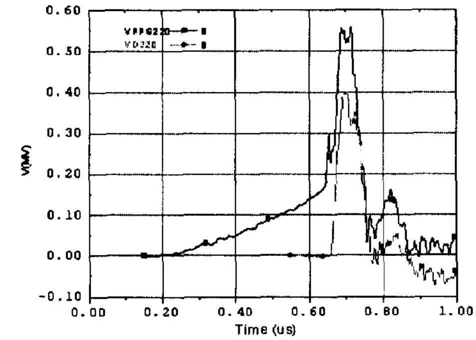


Figure 9. Prepulse suppression switch waveforms showing input and output.

## III. CONCLUSION

The testbed verification of the Compact Simulator pulser components shows performance to design, meeting the radiation specifications required for hardness testing. This validates our code models for diode and pulseline performance prediction and verifies pulsed power component design criteria. A review of initial radiation performance has been presented elsewhere [5].

The transportable prototype is now being constructed. Checkout tests will provide further optimization of pulseline switch and diode parameters plus familiarization with routine operation as a simulator.

## IV. ACKNOWLEDGEMENT

In laboratories around the world there are singular individuals, the "Golden Hands" of pulsed power, who make things work. It is appropriate to acknowledge the efforts of Master Technician Charles Wright in constructing and operating this pulser and his many suggestions affecting its success.

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