# DECADE QUAD WATER COUPLER – ELECTRICAL DESIGN AND PERFORMANCE*

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*Abstract*

The Decade Quad water coupler was designed to pass 10MA into a shorted load and 8MA into a 300ns imploding plasma load. This paper discusses the electrical design of Decade Quad PRS from the water coupler to the load. The coupler structure was modeled using TLCODE. Reliability estimates are made for various components. The electrical design of the coupler diverters and their role in fault mode energy suppression is discussed. The vacuum MITL design is discussed. A detailed circuit model is shown, along with a simpler equivalent circuit model. The predicted electrical performance is compared to recent test data.

## I. GENERAL

The Decade Quad PRS system was designed to drive 200-300ns implosion time Z-pinches. The first stage in this hardware is a set of four marx generators. These drive four separate water transfer capacitors, each of which is switched by six triggered gas switches. Each transfer capacitor drives a 0.5 ohm water coaxial transmission line. These are combined together in a central water coupler, which drives a converging conical triplate water line and then a double vacuum tube stack. On the vacuum side of each tube are magnetically insulated transmission lines (MITL's). The two MITL's are combined together at a post-hole convolute to form a single feed, which drives the load.

This paper discusses the electrical design from the coupler inward. The Marx charge voltage used in the simulations and shots described below is 85kv unless otherwise indicated. See references [1] and [2] for a more detailed physical description of this system.

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## II. CIRCUIT MODELING

### A. TL Circuit Code

The PSD TLCODE [6] electrical simulation circuit code was used to simulate the performance of Decade Quad PRS. In general, such a circuit model consists of transmission lines, resistors (can be time dependent) and their interconnects. Fortran subroutines are used to simulate more complicated physical devices, such as loads or losses in MITL's. All transmission lines are parameterized by an impedance and transit time and can therefore represent a particular inductance or capacitance by using the minimum transit time $\tau$ and noting that $C = \tau/Z$ and $L = Z*\tau$. The TLCODE model uses a constant time step. The time step for the Decade Quad modeling was 0.1ns, equivalent to a distance of about 1/3 of a cm in water or 3 cm in vacuum.

### B. Circuit Model

The detailed circuit model [8] is shown in Figure 1. Each transmission line is numbered. The model simplifies the physical geometry by treating the system from the Marx to the start of the water coupler as one line instead of four parallel lines. All the impedances are therefore one quarter of that of a single Decade module.

Beyond the tapered water coaxes, the circuit model splits into two parallel paths. From the front face termination of the coaxes (the "D" lines - numbers 53 and 63 in the diagram) onward, the front and back sides of the water coupler become distinctly different. These feed the "blades" which are transitions between the front face of the coaxes to a short triaxial waterline, which in turn becomes the front and back water cones, which converge to the tube.

Since the tube plastic is only 0.3ns long, it was modeled as single transmission line in each of the front and back lines. The vacuum flares of the two tubes were modeled similarly.

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14. ABSTRACT
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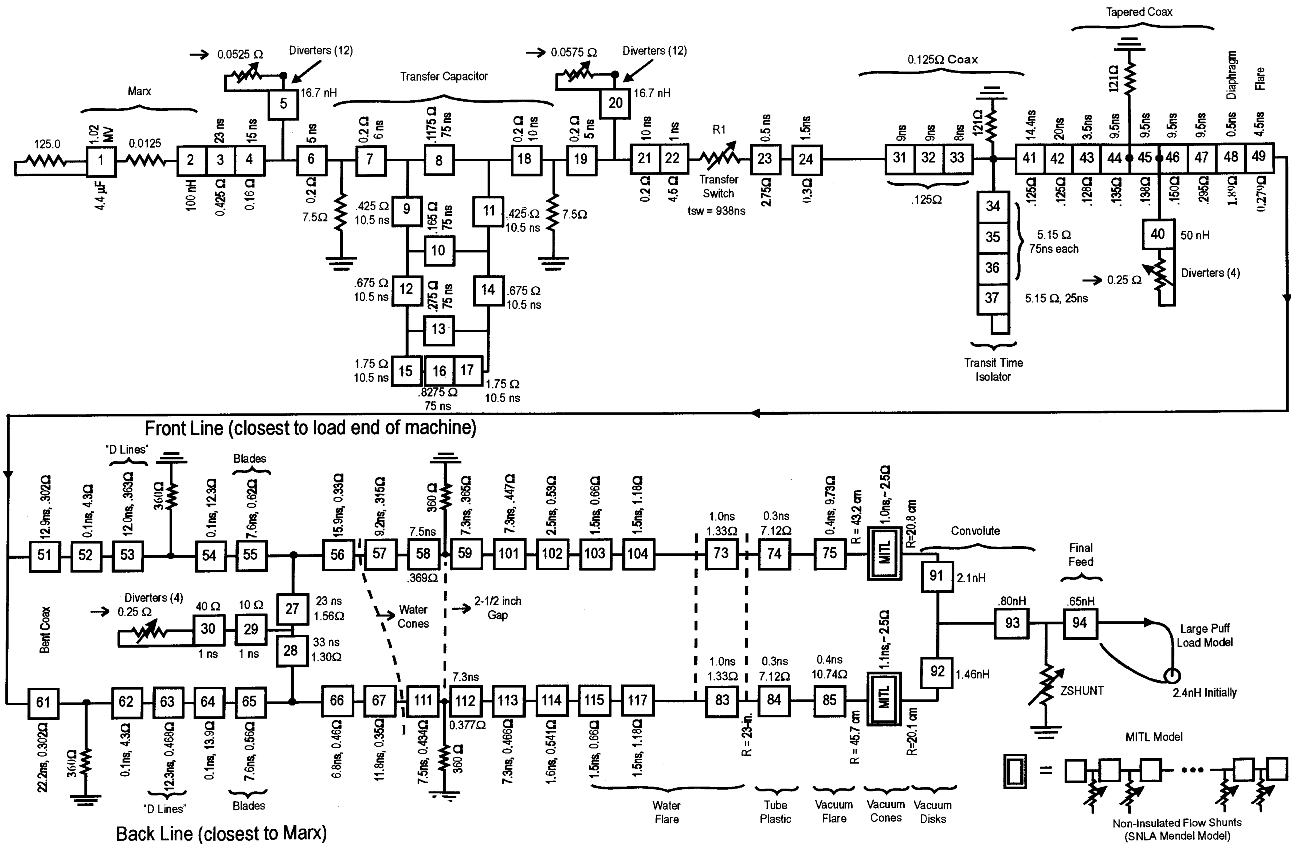



Figure 1. Circuit model (DQ245, 12cm diameter puff load mode).

MITL parameters for both the front and back lines were generated with an automatic line generating subroutine (MGEN7). The advantage of this routine is that variations in the impedance profile can be rapidly made and tried without having to calculate and match individual transmission lines to the geometry. Input parameters include start and stop radius, minimum gap spacing, minimum vacuum impedance, length of an individual transmission line and the mitl angle from the axis. For each transmission line generated, calculated are mean radius, mean gap, mean vacuum impedance, area and length. The object of varying these parameters was to minimize the inductance of the feed without generating excessive shunt and convolute losses.

The individual MITL transmission line elements are connected together through special subroutines that simulate the current loss in the element after emission threshold is reached (here set to 250 kv/cm) and before magnetic insulation begins (determined by local current, voltage and geometry). These were adapted from those used in Sandia Laboratory's SCREAMER code [7].

Magnetically insulated vacuum electron flow in the MITL's is calculated by a subroutine called CTHCUR8. The method is based on electromagnetic pressure balance arguments [4]. The vacuum electron flow is calculated locally for each transmission line in a MITL. The maximum particle current in a particular MITL at a radius smaller than all noninsulated lines is averaged over a time window characteristic of the flow and is shunted at the convolute through a shunt resistive element. This loss current and the local voltage are calculated iteratively to get a self-consistent solution for each time step.

Several loads were simulated. With uniform fill gas puff loads an initial/final radius ratio of 20 was assumed, while with wire loads 10 was assumed. Puff loads used a 2 cm gap between the center of the return current posts and the outer radius of the gas.

The baseline design load was a 12cm diameter, 4cm long uniform fill argon puff with a time from current start (linear regression on waveform between 25% and 75% of peak) to implosion of 300ns. The mass for this load was 3.1mg. A 190ns implosion, 7cm diameter, 4cm long puff load was also simulated. The mass was 1.5mg.

The machine initial checkout load was an Aluminum wire array at a 3cm radius with posts at 3.8cm, a length of 4.0cm and with a mass adjusted to make the time to implosion 300ns. It was designed to imitate the stress on the machine due to the 12cm puff load.

The various loads provided differing inductances to the driving circuit. Therefore, the upstream voltages and breakdown probabilities varied. The 190ns load generated the greatest voltages upstream.

An equivalent circuit model is shown in Figure 2. Total load region inductance is 13.8nH as determined by waveform matching against the full model. This value excludes the initial load inductance between the puff gas and the return posts. An open circuit waveform using a driving impedance of 0.167 ohms is also available.

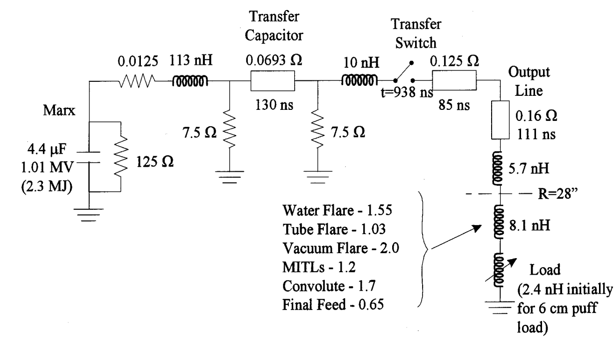



Figure 2. Simple equivalent circuit model (DQEQ7). The excess output inductance of 5.7nH represents extra impedance over the previous 0.16 ohm transmission line.

## III. COMPONENT STRESS

### *A. Water Coupler*

The water coupler reliability (= 1 - probability of water arc) was calculated as part of an overall waterline reliability calculation from the transfer switch forward. The coupler reliability for the 7cm 190ns puff load is 0.93. It is 0.997 for the 12cm, 300ns puff load. Including the waterline back to the output side of the transfer switch, the numbers were 0.91 for the 7cm puff and 0.98 for the 12cm puff.

A number of steps were involved in these calculations. The engineering formula [5] used for calculating the breakdown field (MV/cm) of a waterline is:

$$E_{BD} = k t_{eff}^{-1/3} A^{m} \qquad (1)$$

where $k$ =.23, $m$ = -.058 for a positive surface. $A$ is the area (cm$^2$) experiencing over 90% of peak electric field. The effective time (in microseconds) is often calculated as that duration of the voltage pulse above 63% of peak voltage. Because of the predicted implosion voltage spike, a different form was used:

$$t_{eff} = 1.33 \frac{\int V^3 dt}{V_{\max}^3} \qquad (2)$$

The negative surfaces are over twice as strong as the positive surfaces and in the low impedance geometry of the water coupler, the positive surfaces dominate the breakdown probability.

The breakdown fraction is calculated by taking the ratio of the actual field (obtained via electrostatic plots) to the breakdown field (1). From this fraction the reliability is calculated, using a formula derived from the statistical independence of areas:

$$R = \exp(-0.6(E / E_{BD})^{-1/m}) \qquad (3)$$

This was calculated for each of the transmission lines. The product of the reliabilities is the overall reliability.

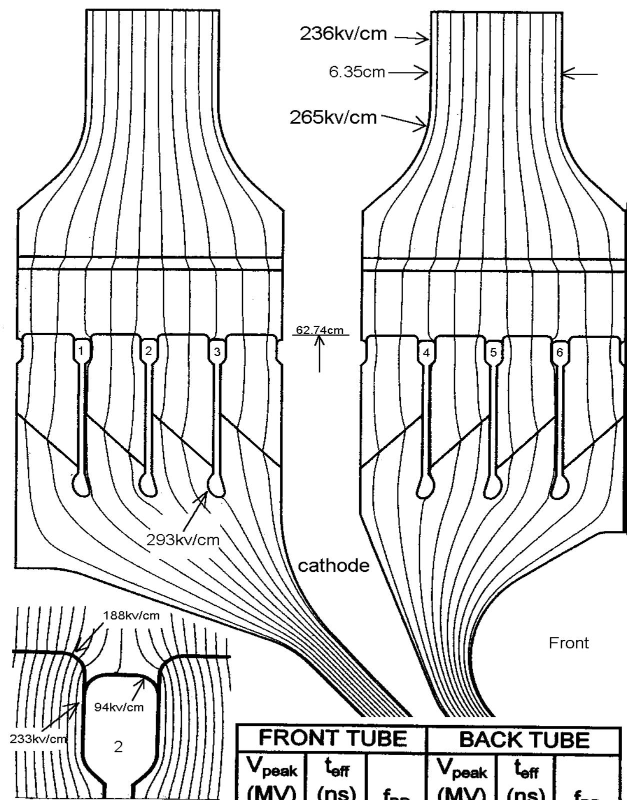
There are three small areas in the water coupler in which the breakdown probability was analyzed separately (and not included in the above reliability numbers). These are the positively enhanced surfaces at the 90 degree corners at the beginning of the blades, the 60 degree corner on the back waterline connecting the coaxial section to the conical section and the 30 degree corner on the back waterline just outside of the tube. Electrostatic plots showed that the greatest problem was the 60-degree corner. The 7cm diameter 190ns implosion reliability was only 0.78. However, by inspecting the waveform at that location, the implosion spike is seen to add a factor of 1.45 to the amplitude of the main pulse. The spike amplitude is the result of an idealized mathematical model of an implosion in which the mass accelerates until it is instantaneously stopped at a chosen final radius. Usually these spikes are not seen outside the tube due to losses, shorting or mechanisms associated with the pinch.

Four water diverters were added to the coupler to help absorb late time energy left in the system. Since the tube might short after the main pulse (on voltage reversal), the coupler diverters needed to be placed a significant distance from the insulator stack. A resistance value of about 1 ohm for all four diverters in parallel damped better than the 0.25 ohms chosen, but the voltage on the diverter resistors would have been excessively large.

### *B. Tube to Load*

The tube is a double stack, designed to accommodate two different insulating materials: Rexolite (crosslinked polystyrene) and polyurethene coated with dendresist[3]. Rexolite is used for the Z machine insulators. Polyurethene has been used extensively on a large variety of machines such as Pithon and Double Eagle at Physics International (now Titan Pulse Sciences Division). This flexibility has made the tube somewhat more inductive than the use of only one material would require. Although the insulator stack height is the same for both tube designs, the Rexolite tube uses four insulators per stack while the polyurethene tube uses three per stack. The reason is that the dielectric breakdown strength of Rexolite is higher than polyurethene, and it was thought that during tube flashover the last insulator to flash may have to hold the full voltage of the tube for a period of time long enough to create breakdowns inside the plastic. The tubes were built with Rexolite.

Figure 3 shows an electrostatic plot of the Rexolite tube with field strengths indicated for 1.5MV. Voltages, effective times and breakdown fractions for the vacuum-plastic interface are also shown. The breakdown fractions and reliabilities are calculated in a manner similar to those of the water section, but with k=0.175, m=-1/10, the effective time being that above 89% of peak voltage and its exponent being -1/6. The breakdown fraction for the vacuum-plastic interface with the 190ns 3.5cm radius load dominates the others. The effective times indicate that the implosion spike dominates the calculation.




| | FRONT TUBE | | | BACK TUBE | | |
|---|---|---|---|---|---|---|
| | $V_{peak}$ (MV) | $t_{eff}$ (ns) | $f_{BD}$ | $V_{peak}$ (MV) | $t_{eff}$ (ns) | $f_{BD}$ |
| 6cm, 300ns puff | 1.10 | 7 | 0.56 | 1.08 | 3 | 0.48 |
| 3.5cm, 190ns puff | 1.84 | 7 | 0.95 | 1.89 | 3 | 0.84 |
| no gas (diode load) | 0.90 | 75 | 0.68 | 0.88 | 94 | 0.69 |

Figure 3. Rexolite tube and grading ring detail. Stress rods are simulated in the electrostatic plot by an area equivalent annulus.

Each tube feeds its own MITL. Each MITL was designed for a minimum gap spacing of 1cm and a maximum impedance of 2.5 ohms. The radius at which constant gap becomes constant impedance is 24 cm.

The convolute sums the current flow from the two MITL's into one line. Its design was based on the parameters of Sandia's Saturn convolute, scaled in radius. The number of posts was scaled linearly with radius. The post center radius with Decade Quad is 13.0 cm and there are 17 posts. The hole geometry is the same as the A and B layers of the Saturn geometry. A minimum of 1cm gap spacing is kept throughout the convolute.

# IV.PERFORMANCE

Experimentally measured waveforms overlaid by circuit model simulations for a 48 wire (1.6mill diameter) array are shown in figure 4. Simulated load and tube (summed) currents are matched to experimentally measured tube (Vac_Curr), MITL and final feed (IfdAn*1.03) currents. Amplitude and shape match fairly well, although the strong implosion current notch predicted by the simulation is not seen. Note that from the similarity of the data traces that large losses were not observed in either the MITL's or the convolute. A shorted shot (#472) was made at 65kv charge, with a shorting plate replacing the puff hardware. Simulated peak tube current measured 7.9MA compared to 7.5MA measured.

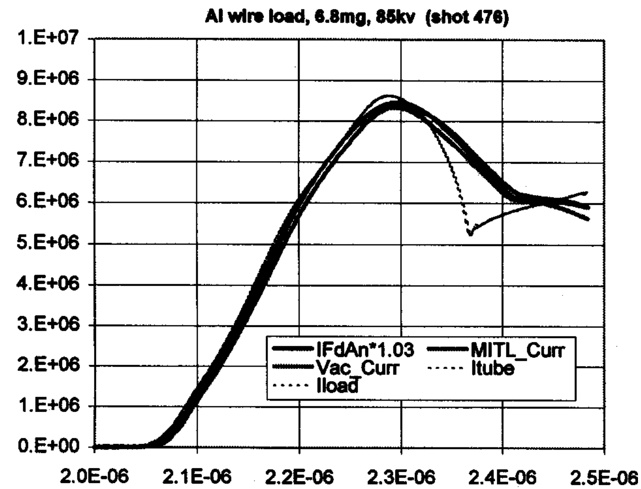



Figure 4. Load region currents, simulation versus experiment. Iload and Itube are simulation.

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