

ANALYSIS OF A DISTRIBUTED PULSE POWER SYSTEM USING A CIRCUIT ANALYSIS CODE

LOTHAR O. HOEFT

AIR FORCE WEAPONS LABORATORY, KIRTLAND AFB, NM 87117 AND
THE BDM CORPORATION, ALBUQUERQUE, NM 87106

Abstract

A sophisticated computer code (SCEPTRE), used to analyze electronic circuits, was used to evaluate the performance of a large flash X-ray machine. This device was considered to be a transmission line whose impedance varied with position. This distributed system was modeled by lumped parameter sections with time constants of 1 ns. The model was used to interpret voltage, current, and radiation measurements in terms of diode performance. The effects of tube impedance, diode model, switch behavior, and potential geometric modifications were determined. The principal conclusions were that, since radiation output depends strongly on voltage, diode impedance was much more important than the other parameters, and the charge voltage must be accurately known.

INTRODUCTION

The prediction of overall performance of complex pulse power devices is required for achieving optimum design, identifying problems that arise during operation, and for evaluating proposed modifications. Rather simple analysis techniques may be used if the transit times of the structure are small compared to the rise time or pulse length. However, in most cases, the rise time/pulse length is comparable to the transit time of the structure and/or its discontinuities. Such systems have been treated as a series of transmission lines with capacitances added at the discontinuities¹. Such techniques are tedious and lack credibility if the structure is complex. With the advent of network

analysis codes such as SCEPTRE, NET-II, etc., the pulse power system designer has a new and powerful analysis tool for predicting the performance of pulse power devices. Conceptually, the pulse power system is modelled with lumped parameter transmission line sections in which the time delay per section is small compared to the time constant of interest in the system. This concept implies that the pulse power system can be represented by a one-dimensional structure; that is, effects due to a change in direction of the electromagnetic wave are ignored. This paper presents the methodology used to construct such a model for a large DC-charged, flash x-ray machine. The use of this model to interpret measured waveforms and evaluate possible modifications is described. Finally, the principal conclusions reached by this analysis are presented.

MODEL DEVELOPMENT

Figure 1 shows a cross-sectional view of the flash x-ray machine. The energy is stored in a 33-foot long high pressure gas insulated transmission line ($Z_0 = 42$ ohms). This line or coaxial capacitor is charged to approximately 10 Megavolts by a van de Graaff generator. A 2-foot

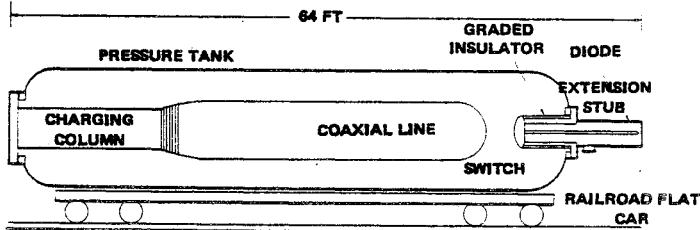


Figure 1. Crossection of Flash
X-Ray Machine

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spark gap is used to switch the energy into the field emission diode via a graded insulator which separates the vacuum and high-pressure regions. The diode is located at the end of a 5-foot long vacuum transmission line. Figure 2 presents the impedance of this system as a function of distance along its axis.

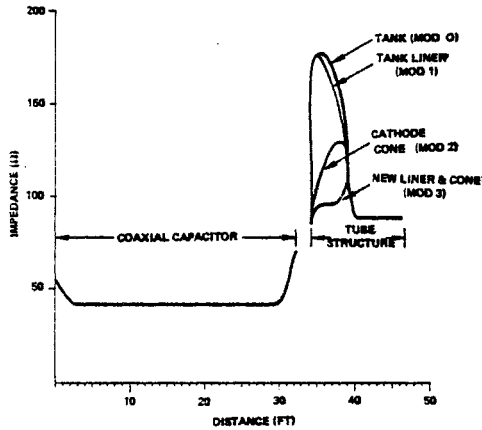


Figure 2. Impedance as a Function of Distance Along Flash X-Ray Machine

Impedance is calculated at each foot or 1-nanosecond segment using the formula $Z = 60 \ln b/a$ where b refers to the outer and inner radii of the line. The charging column is ignored in the analysis since it is highly resistive. The switch area is not modelled as a transmission line because it is only 2 feet long, which is small compared to the expected rise time. Each 1-nanosecond section of the system was modelled by a low-pass constant K , T-section as shown in figure 3. The switch was modelled by a series-connected inductance and resistance. At time zero the voltages on all capacitances associated with the coaxial capacitor were set to 10 megavolts and the voltages on all other capacitors were set to 0.

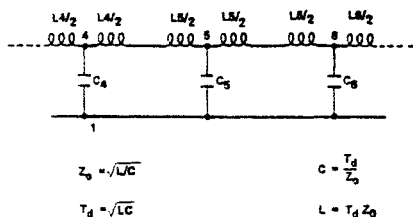


Figure 3. Lumped Parameter Representation of Transmission Line

This physical model was transformed into a network model by identifying each node with a number and specifying the location of each circuit element by pairs of node numbers. Voltages or currents are defined as occurring across a circuit element. One of the advantages of using this type of code is that diagnostic measurements can be specified at places that are normally inaccessible for physical measurements but which are important for understanding the operation of the system. For example, the voltage across the field emission diode can be specified in the code whereas the actual voltage measurement must be made some distance away because of physical limitations.

The SCEPTRE code has a feature that allows simple functions to be calculated as the network is being analyzed. In this case, the instantaneous diode power, total energy, and radiation production were calculated. Radiation production was calculated using the following equation².

$$\text{Dose Rate} = D = 1.09 \times 10^3 V^{2.71} I \text{ (R/sec @ 1 m)}$$

V = Diode Voltage in Megavolts
 I = Diode Current in Amperes

This dose rate was then integrated to give a number that could be compared with measurements made using thermal luminescent dosimeters (TLD's). Since most of the data on the machine was in the form of TLD measurements, this capability was extremely useful in comparing the results of the code with the machine performance.

A number of alternative models for the field emission diode were used. The simplest was a resistor that represented the tube impedance. More complex diode models included several models from the SCEPTRE code as well as a space-charged limited diode representation. In the latter case, the current is given by $I = KV^{3/2}$ where K is the perveance.

RESULTS

Figure 4 shows the waveforms at four different points along the cathode shank. The

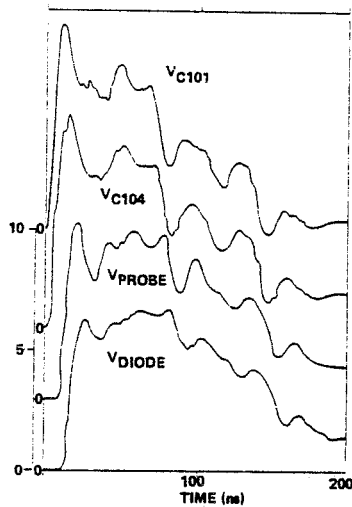


Figure 4. Voltage Waveforms Along Cathode Shank

first waveform (V_{C101}) is at the switch electrode. The second waveform is the voltage that would be present on the cathode shank as it enters the vacuum transmission line. The third waveform is the voltage that would be measured by the capacitive probe located in the transmission line. The final waveform is the voltage across the field emission diode which is modeled in this case by a space-charge limited diode. The ringing associated with a large impedance mismatch at the switch electrode can be seen in the first waveform. This is progressively attenuated as the wave travels to the diode.

Figure 5 shows some of the other waveforms associated with the simulation. Figure 5a shows

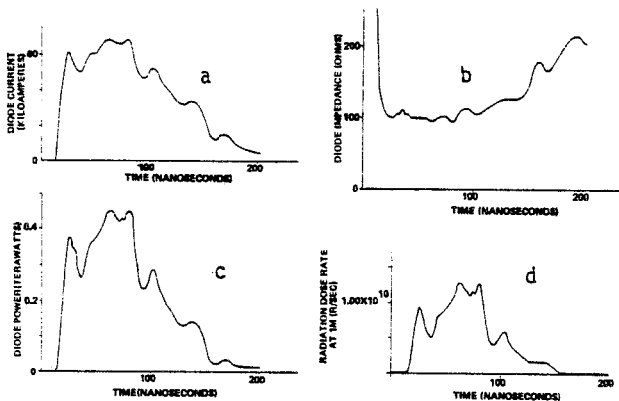


Figure 5. Waveforms Associated With Flash X-Ray Machine Simulation

the diode current which, in this case, is a nonlinear function of the voltage as described above. Figure 5b shows the instantaneous diode impedance as a function of time. Note that the impedance is relatively constant during the main portion of the pulse. Diode power and dose rate are shown in figure 5c and 5d.

The initial calculations performed using this model resulted in waveforms that were similar to those measured on the flash x-ray machine but predicted radiation doses that were three to four times higher than those measured and, in fact, were close to the design values. Therefore, a set of parametric calculations was performed to investigate the effects of varying switch parameters, tube impedance, and geometric modifications. The switch resistance was varied between 0.1 and 10 ohms and the switch inductance was varied between 500 and 1000 nano-henry's. The integrated dose did not change significantly. Consequently, poor switch performance was not considered to be the problem. Next the tube impedance was varied from 25 to 200 ohms and the impedance of the stub or vacuum transmission line was varied between 35.6 and 160.4 ohms, corresponding to cathode shank diameters between 16 and 2 inches. Figure 6 shows the effect of the tube impedance and stub transmission line impedance on the dose at one meter. The dose versus impedance curves for 4, 6, 8, and 12-inch diameter cathode shanks are evenly spaced between the curves for 2 and 16-inch shanks. Not all of the points on the curve are physically realizable. Studies at

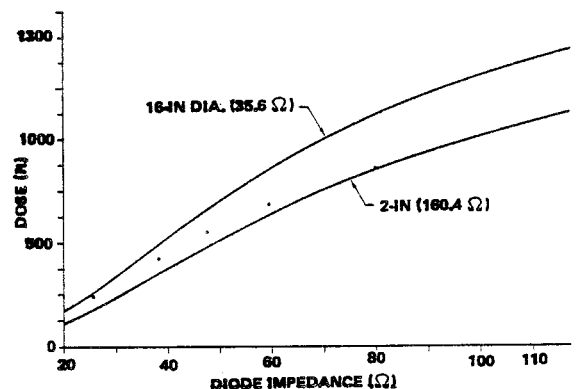


Figure 6. Effect of Diode and Stub Impedance on Dose

Sandia Laboratories³ have shown that the diode impedance is approximately one-half of the stub impedance. The circles shown on figure 6 are the points where the diode impedance is half the stub impedance. In an effort to experimentally optimize performance, cathode shanks that contained sections of different diameters were tried. In fact, one of the highest measured doses used a 3.5-inch diameter shank with a 30-inch long 1-inch diameter section in the diode region. Such configurations would combine the positive advantages of the low impedance stub with those of the high impedance diode. Figure 6 demonstrates that the possible improvement in dose is much greater for variations in diode impedance than for variations in stub impedance.

The effect of stub and tube impedances was also calculated using the space-charge limited diode model. These calculations essentially confirmed the earlier ones using the constant resistance diode model but are more difficult to interpret because of a lack of intuitive understanding of the concept of perveance.

Several modifications to the geometry of the flash x-ray machine were proposed in order to avoid reflections in the region surrounding the graded insulator. The impedance changes for these modifications were shown in figure 2. As the flash x-ray machine was originally built, the impedance could be as high as 175 ohms at the base of the cathode shank. The use of a cone on the cathode shank in combination with a new tank liner could reduce the maximum impedance to about 100 ohms which is close to optimum. The effect of these modifications is shown in figure 7 where the dose is plotted versus tube impedance for the four configurations.

Inspection of the waveforms indicated that these modifications reduced the ringing considerably but the total dose was not significantly changed.

The analysis described above could not identify a reason for the factor of 3 or 4 decrease in radiation output in this flash x-ray machine. One explanation for the low output is that the charge voltage is low. If the diode current is proportional to voltages, and the

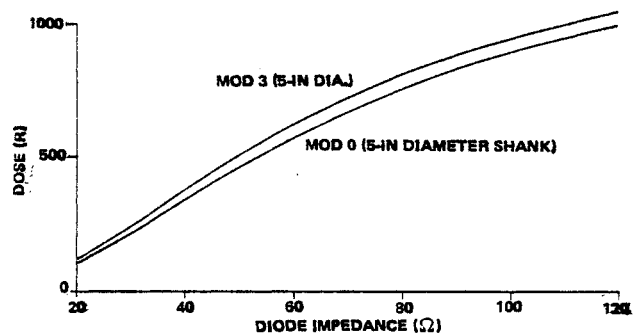


Figure 7. Effect of Geometry on the Variation of Dose With Impedance

radiation output is proportional to $V^{2.71}$, a 25 to 30% decrease in charge voltage reduces the radiation output by a factor of 3 or 4. Subsequent to this analysis, experimental electron beam studies confirmed that such errors probably existed.

CONCLUSIONS

This study has demonstrated that a network analysis code like SCEPTRE can be a very useful tool for gaining an understanding of a complex pulse power device such as a large flash x-ray machine. The effects of the stub impedance, switch behavior, and geometric modifications were of relatively minor importance compared to the diode impedance. Since the radiation output depends on the fourth power of the diode voltage, diode impedance is much more important than other parameters. The major discrepancy between the measured and predicted results could be explained by a 25 to 30% error in the charge voltage calibration.

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