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Plastic Laminate Pulsed Power Development

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ABSTRACT

The desire to move high-energy Pulsed Power systems from the laboratory to practical field systems requires the development of compact lightweight drivers. This paper concerns an effort to develop such a system based on a plastic laminate strip Blumlein as the final pulse shaping stage for a 600 kV, 50ns, 5-ohm driver.

A lifetime and breakdown study conducted with small-area samples identified Kapton sheet impregnated with Propylene Carbonate as the best material combination of those evaluated. The program has successfully demonstrated techniques for folding large area systems into compact geometry's and vacuum impregnating the laminate in the folded systems. The major operational challenges encountered revolve around edge grading and low inductance, low impedance switching. The design iterations and lessons learned will be discussed.

A multistage prototype testing program has demonstrated 600kV operation on a short 6ns line. Full-scale prototypes are currently undergoing development and testing.

INTRODUCTION

The goals of this program are to develop a 600 kV, 50ns, 5 ohm compact pulse shaping driver which is smaller and lighter than comparable coaxial water based systems. The use of plastic laminates forces one to use strip line geometry. Plastic laminates allow for construction of higher average field structures but require dealing with field enhancement at the edges of the flat plates. The plastic laminate technology also requires a higher degree of reliability since breakdowns tend to be fatal to the hardware rather than self healing.

MAIN SECTION

The baseline concept for the pulse shaping section of the driver involves two parallel-stacked Blumlein's of 10 ohms each. Figure 1 shows a diagram of this base configuration.

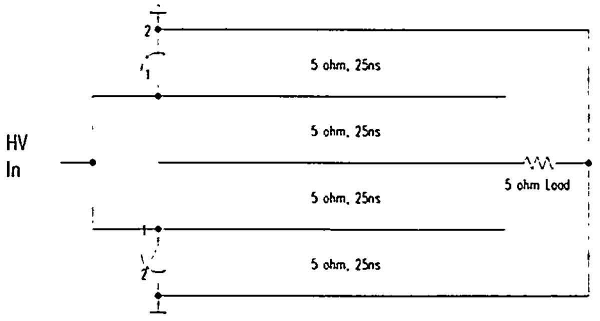

Figure 1

The important performance issues in regards to pulse shape are the switch simultaneity and switch inductance. The reliability and lifetime are driven by the edge fields of the strip line sections. Our program has initially focused on the development of a single Blumlein (i.e. half of the above structure) driving 10 ohms.

Material Selection – A small sample testing program was conducted to determine the best combination of materials with which to construct the lines. Only a few common combinations were tried. Mylar, Polyethylene, and Kapton were tried impregnated with both water and Propylene Carbonate (PC). Lexan impregnated with

water was also tried. The material combination that performed the best was Kapton impregnated with PC. This combination of materials was subjected to over 80,000 shots at fields that averaged 2 MV/cm in the bulk material before eventually breaking down. In addition to the best electrical performance, these materials had the best environmental range, which make them more desirable for field applications. The conductors have been constructed of soft copper and the assemblies have been supported by High Density Polyethylene (HDPE). Both of these materials have shown no adverse effects from the PC.

Test Bed – A prototype test bed has been constructed to explore design issues. The test bed consists of a six stage Marx generator that has been operated as high as ± 80kV per stage. The Marx provides the pulse charge energy for driving the prototype Blumleins. A deionized water and soap solution is used as a resistive 10-ohm load. Each of the major components will be detailed in the following paragraphs. Figure 2 shows a photograph of the testbed hardware.

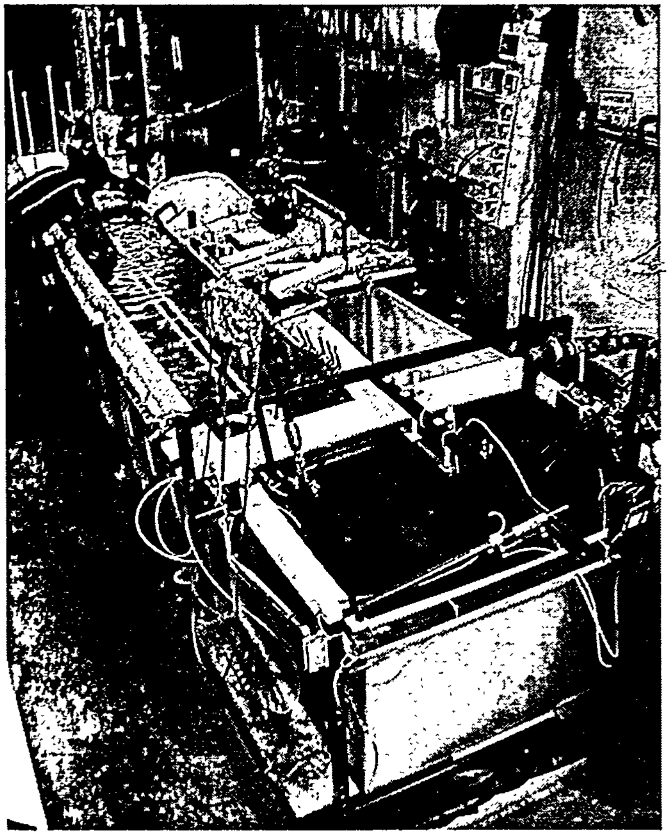

Figure 2 – Prototype Blumlein Test Bed

The small tank in the foreground of Figure 2 is the Marx tank and its associated hardware. The long tank in the background is the prototype blumlein tank. The empty long tank is the Propylene Carbonate storage tank.

Marx Generator – The Marx generator is a six stage, bipolar charged system. The capacitors are .2µf, 100 kV double-ended Maxwell model 35009. The Marx switches are Maxwell model 77073-1 midplane triggered pancake switches. We use a homemade 30 kV spiral generator for a trigger system.

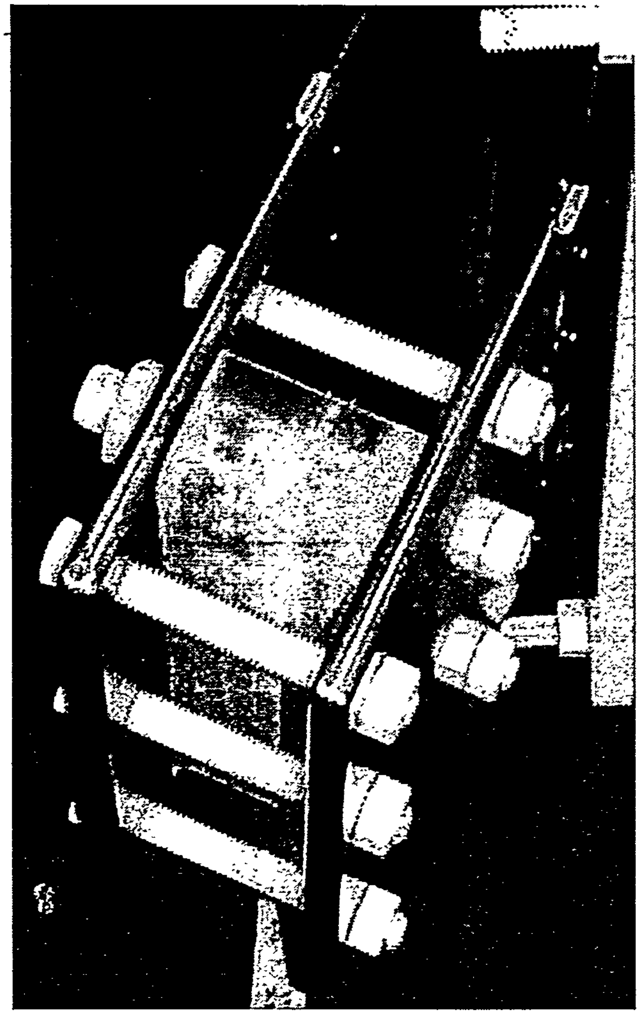

Figure 3 – Load Resistor Assembly

Load – The load resistor assembly is shown in Figure 3. For the prototype testing, we have been working with single Blumleins. The hot and the ground conductor of the erected blumlein clamp into the end of the brass plates shown. The load housing is made of Rexalite ™, which is one of the few structural plastics that is compatible with PC. The cross sectional area of the resistor element is 44 cm^2. The length of the resistor is 6.35 cm. A continuous flow of a 69-ohm cm water and soap solution gives the required 10 ohms to match the system.

Pulse Shaping Section – The pulse shaping section consists of the Blumlein and the Blumlein switch. The original switch concept used three parallel triggered small gap trigatron switches. The program currently uses a single triggered rail switch. Figure 4a shows the three trigatron switch assembly and Figure 4b shows the rail switch.

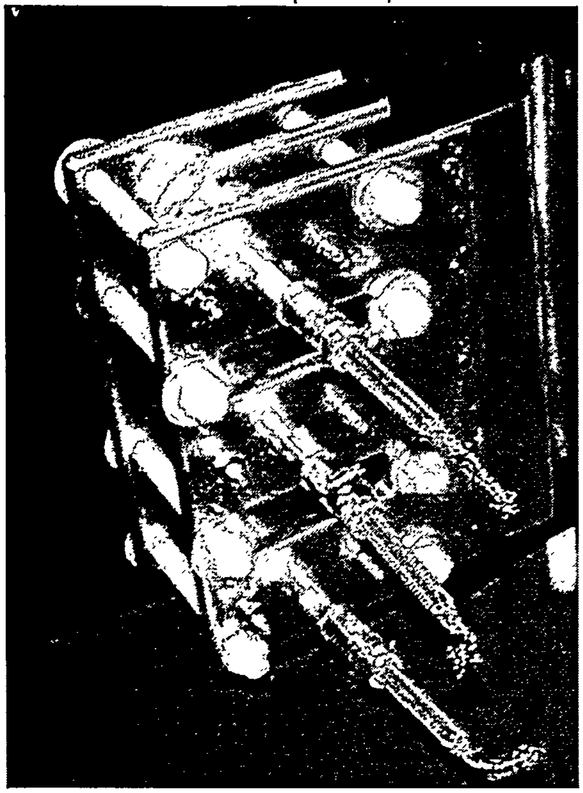

Figure 4a – Switch Assembly Consisting of Three Trigatrons in Parallel

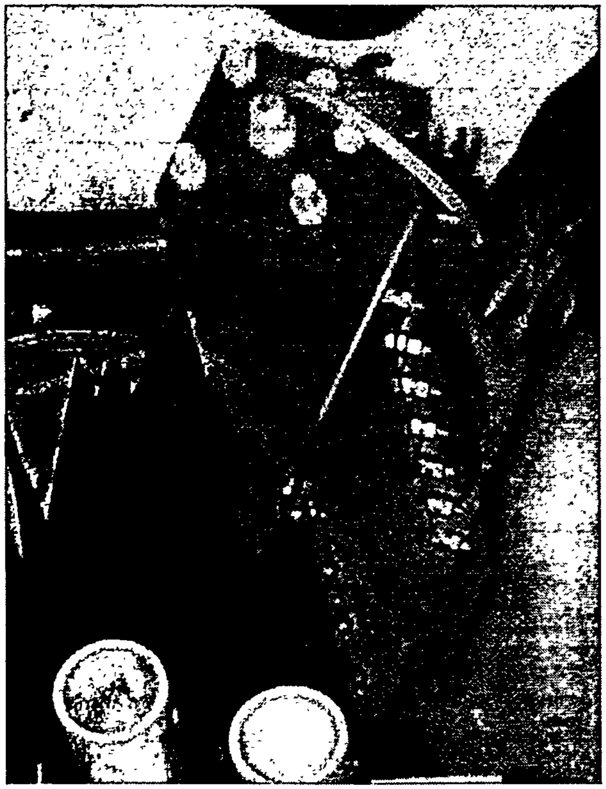

Figure 4b – Switch Assembly Consisting of Rail Gap

A number of switch iterations have been tried and will be discussed in detail in the testing section of this paper. A number of Blumlein configurations have also been tested. All of the configurations are three-conductor strip Blumleins that are 10" in width with 2" Kapton margins. Figure 5 shows a 48-inch blumlein folded into about a 15 inch long assembly. The various Blumlien configurations will also be discussed in detail in the testing section of the paper.

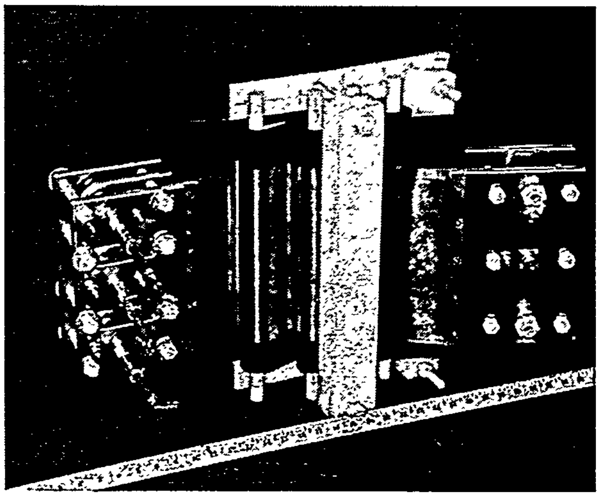

Figure 5

Testing – The initial work on material selection showed that lifetimes of >50k shots at fields as high as 2MV/cm was possible with small-area samples. This small sample test hardware was constructed using large radii and had very little field enhancement at the edges. These tests also involved relatively slow charging and discharging. The need for small compact folded systems has driven us to build prototypes where the edges are very much a part of the problem. The original prototype was a line 3 feet long using .032" thick conductors. A special tool which essentially files or scrapes a full radius on .032" conductors was constructed. The edges were then carefully polished by hand to give a good full radius edge. Each half of the Blumlein needs to have an impedance of 5 ohm line. For a line 10" wide(w) insulated by Kapton, Equation 1 gives a nominal thickness(d) of 0.25". The equation holds true for d/w < 0.1.

Equation 1

$$Z \approx \frac{377 * d}{w * \sqrt{\varepsilon r}} \text{ [ohms]}$$

A line constructed in this manner would give a mean field of 0.944 MV/cm in the bulk material with a charge voltage of 600kV. The edge peak field for a perfect full radius of 0.032" on the conductors would then be 1.58 MV/cm. Figure 6 shows the voltage contours for the edge as calculated by a 2d electrostatic code (Electro™). This figure is shown in order to illustrate the geometry of the edge problem rather than provide data.

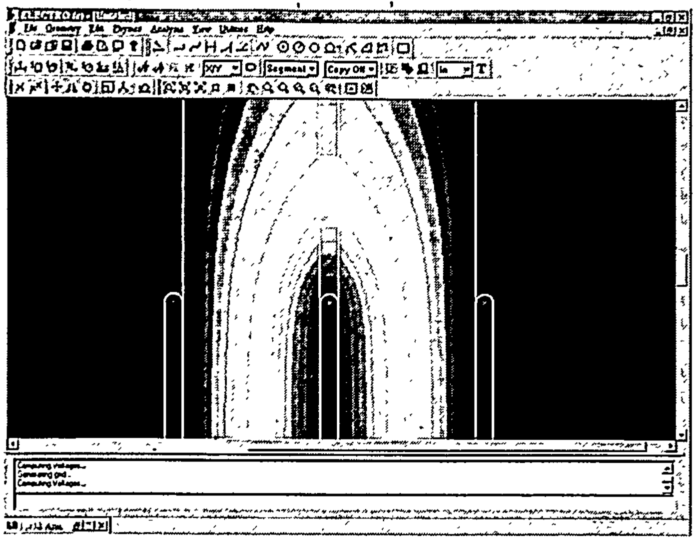

Figure 6 Voltage Contours at the Edges of the Blumlein

The peak field is located on the center conductor at the start of the radius. Based on our data from the material selection tests, this design was believed to have an adequate margin of safety for reliable operation. The initial testing resulted in breakdown of the line at fields of ~1.12MV/cm with lifetimes in the 10's to 100's of shots. A number of modifications have been tried throughout the course of the test program to either raise the breakdown field or lower the field enhancement to achieve reliable operation at the required voltage. Table 1 contains a summary of the insulation failures that have been experienced to date.

Table 1 – Summary of Insulator Failures

Assembly #	Breakdown Field	Comments
1	1.12MV/cm (1.58MV/cm goal)	.032 Brass electrodes Straight 3 ft assembly Punched 4 sheets & surface flashed to edge and across all edges
2	1.38MV/cm (1.58MV/cm goal)	.032 Brass electrodes Straight 3 ft assembly Punched 5 sheets & surface flashed to and across all edges
3	1.38MV/cm (1.58MV/cm goal)	.032 Brass electrodes Straight 3 ft assembly Punched 4 sheets & surface flashed to edge and across all edges
4	1.35MV/cm (1.58MV/cm goal)	.032 Brass electrodes Straight 3 ft assembly Punched all sheets This assembly survived at fields as high as 1.62MV/cm which met our voltage goal.
5	1.27MV/cm (1.58MV/cm goal)	.032 Copper electrodes Folded 4 ft assembly Punched all sheets Lasted ~115 shots
6	1.25MV/cm (1.58MV/cm goal)	.032 Copper electrodes Folded 4 ft assembly modified radius Punched all sheets Survived fields as high as 1.54MV/cm Lasted ~90 shots
7	1.23MV/cm (1.42MV/cm goal) (effects of resistive grading not reflected in these values)	.050 Copper electrodes Folded 5 ft assembly Corona and bubbles Survived ~130 shots Resistive Grading 30kΩ-cm solution
8	1.00MV/cm (1.18MV/cm goal) (effects of resistive grading not reflected in these values)	.125 Copper electrodes Straight 3 ft assembly Minimal corona damage Did not fail after ~430 shots. Switch problems prevented higher field operation Resistive Grading 20kΩ-cm solution
9	1.07MV/cm (1.42MV/cm goal) (effects of resistive grading not reflected in these values)	.050 Copper electrodes Straight 18 in assembly Flashing and corona damage Lasted ~215 shots Resistive Grading 20kΩ-cm solution
10	984kV/cm (1.25MV/cm goal) (effects of resistive grading not reflected in these values)	.050 Copper electrodes .080 diam wire soldered on edge Straight 10 ft assembly in new tanks Bubbles forming from solution
11	1.19MV/cm (1.25MV/cm goal) (effects of resistive grading not reflected in these values)	.050 Copper electrodes .080 diam wire soldered on edge Straight 10 ft assembly in new tanks Bubbles forming from solution

The table shows that we have not been able to operate at fields anywhere near to the fields determined in the small-sample material tests.

After the tests with assembly 6, it was discovered that fine bubbles were being generated in the propylene carbonate well in advance of visible corona or breakdown. Small sample tests were conducted using video to closely examine the edge for bubble formation. The onset field for bubble generation was recorded for three different electrode thickness. Bubbles were generated at 1.03MV/cm ±5% average over all three field enhancements. It was believed that these bubbles were contributing to premature breakdown. It appeared at this point that operating below this field level would be required to achieve reliable operation with reasonable lifetimes.

We then investigated adding salts to the propylene carbonate to adjust the conductivity to produce a resistive grading effect at the electrode edge. In the small sample environment, with a well controlled liquid channel filled with 20kΩ-cm solution the sample was operated with electrode radii, spacing and voltages that would have produced a field of 2.49 MV/cm if not graded. The salt used was Sodium Tetrafluoroborate. Assemblies 7-11 used resistive solutions in an attempt to grade the edges as reported in the table. The large lines that we initially tried did not lend themselves to well controlled channel geometry. Assemblies 7-9 were fabricated using techniques that allowed the Kapton in the edge region to touch and close the channel. Figure 7 shows this geometry. Channel closure caused the field enhancement factor to increase from 1.5 to 1.8. Keeping a consistent open channel is critical to making resistive grading work.

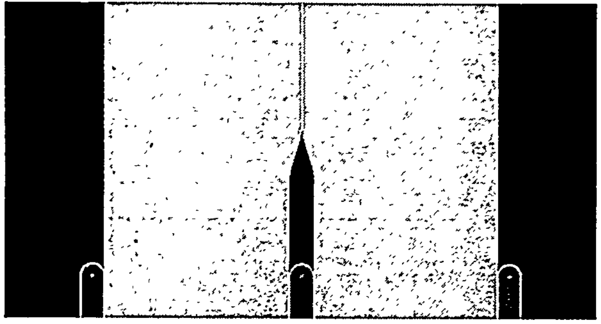

Figure 7 – Closure of Resistive Grading Channel in Edge Region due to Flaring of Adjacent Stacks of Thin-Film Kapton

Assemblies 10 & 11 were built with modified hardware in an attempt to control the channel. Figure 8 shows a cross section of this assembly. The inside channel sheets were extended beyond the 2" margins and tied into the structural components.

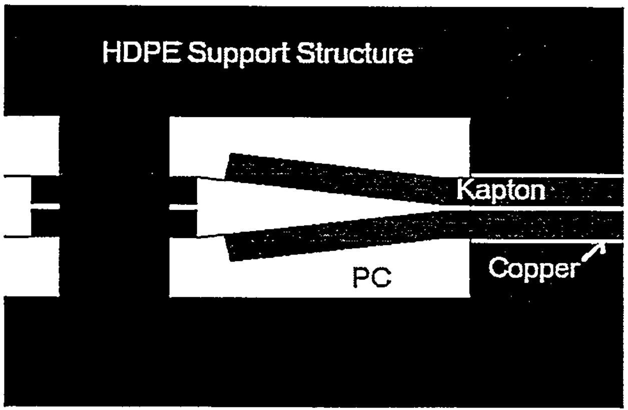

Figure 8 Modified Edge Support to Maintain Open Channel for Resistive Grading

The figure shows the inside layers of Kapton extending to the support bolts with thin nuts to adjust the film outwards to vary the channel width. The actual nuts are much thinner than those drawn, which allow for a narrow channel. The ideal resistive channel has a uniform resistance over the whole length, which drops the voltage uniformly over that length. With the adjusting nuts driven out wide, the highest resistance is near the copper with the resistance dropping rapidly as you go out into the margin. This also produces an enhanced condition, which caused the failure of assembly 10. With the nuts in close to try to get nearly an ideal channel, it becomes difficult to prevent the Kapton from touching in practice with our current hardware configuration on a 10-foot long line. Assembly 11 was able to get very near our voltage goal by adjusting the channel.

Switching - In parallel with the Blumlien development effort, we have also been developing small low inductance switches. The initial switch concept used three parallel high-pressure triggered trigatron spark gaps. These switches were used successfully in other programs within our group at lower voltages. The switches could be operated with sub-nanosecond jitter at about 200kV. Attempts to scale these switches to 600kV did not prove to be successful. Figure 9 shows the self break curve for trigatrons with a 7mm gap.

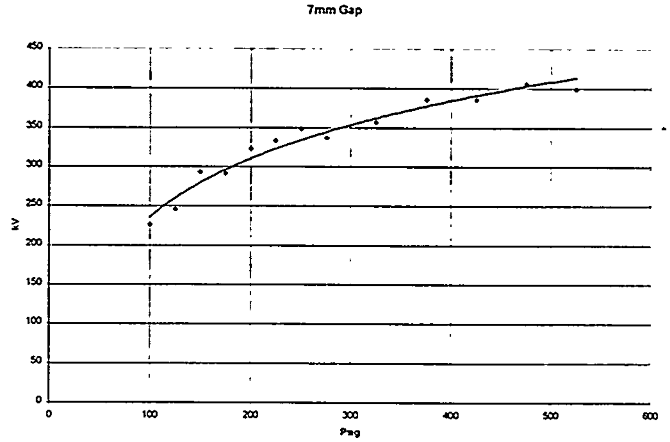

Figure 9 – Self Breakdown Voltage Curve for 7-mm Gap Trigatron Switch

The pressure curve flattens out at about 400kV. Larger gap switches were tried, but the jitter was too high to allow three switches, which were tightly coupled, to operate reliably.

The next switching concept tried was a rail switch. This switch has a single pair of 10" long electrodes with a trigger blade. A cross section of this switch is shown in figure 10.

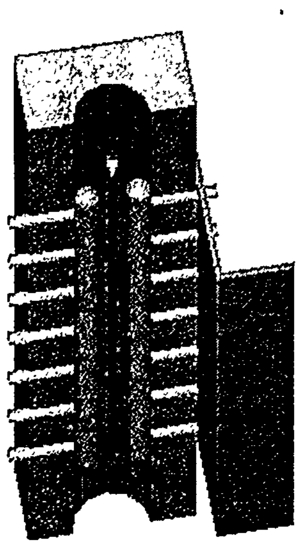

Figure 10 – Cross Section of Triggered Rail Gap Switch

A number of iterations of this switch were tried in order to establish the proper dimensions to prevent the housing from flashing while allowing good triggering performance. The switch is now operating at or near 600kV without flashing. The key feature of this switch is its low inductance when the gap closes with many channels. The ideal switch operation would have an infinite number of channels. Bench top measurements of the ideal inductance were made and determined to be ~50nH. The switch orientation in the testbed does not lend itself to clearly viewing the gap profile to determine the actual number of channels experimentally. The electrodes exhibit uniform discharge sites over their whole length and comparisons of the data with circuit models using 50 nH of switch inductance indicate the switch is indeed operating with many channels and approximates an ideal switch. Figure 11 shows a comparison of the actual data and the circuit model for assembly 11.

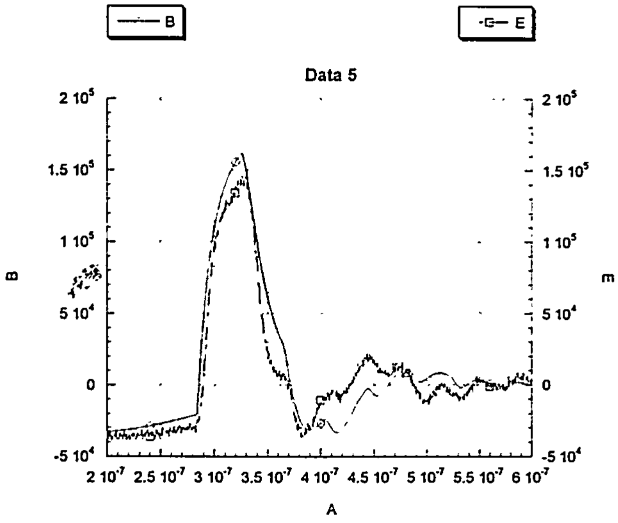

Figure 11 – Predicted and Measured Output Pulse for Assembly #11

The solid line is the model prediction and dashed line is the measured data. The circuit model does not take into account all the stray capacitance or the distributed nature of the losses along the line. The circuit for assembly 11 is shown in Figure 12.

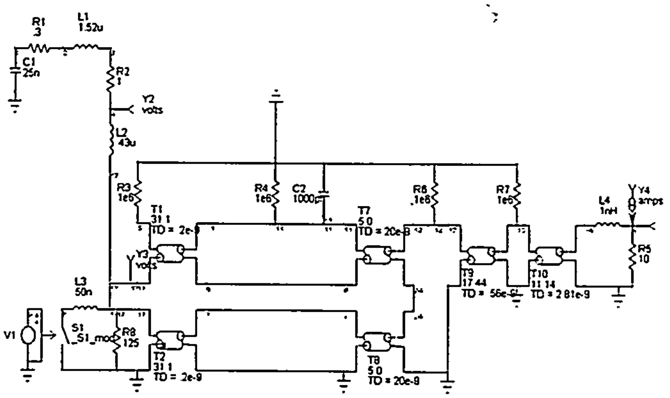

Figure 12 – Circuit Model for Assembly #11

CONCLUSION

Compact high power drivers for field systems are possible using plastic laminate lines. Breakdown problems due to field enhancement in the edge region of the lines can be reduced by using conductors with larger edge radii and/or by incorporating resistive grading channels in the edge margin region. Wider line geometry can also be used to allow for greater insulation thickness for a given operating voltage and line impedance. Successful implementation for field applications will require careful tradeoff of the parameters that drive system size, weight, energy efficiency, and operational life.

ACKNOWLEDGMENTS

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Electro is a registered trademark of Integrated Engineering Software

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