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FERRITE-FREE, OIL-SWITCHED, FOUR-STAGE, HIGH-GRADIENT MODULE FOR COMPACT PULSED POWER APPLICATIONS

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FERRITE-FREE, OIL-SWITCHED, FOUR-STAGE, HIGH-GRADIENT MODULE FOR COMPACT PULSED POWER APPLICATIONS*

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Abstract

We describe the design and present initial experimental results of a novel, high-gradient, compact pulsed power module. Our application focus is linear accelerators but our technology is easily applicable to a wide range of pulse-power applications. Our design incorporates and combines for the first time a number of our recently developed, enabling technologies including: a novel, bipolar pulse-forming line allowing module stacking without ferrites, very compact and fast oil-filled switches, novel high-dielectric constant insulator/ energy storage material, and a novel method for reducing edge enhancements in the pulse forming structure. The combination of these technologies enables us to design a very compact stackable module that will deliver high-gradient (5-10 MV/m) voltage at 5-10kA to arbitrary loads.

Our prototype is comprised of four stages. Each stage is designed to operate at 300kV producing 1.2-MV into 120 Ohms. The pulse length is 25-ns and the pulse-shape is rectangular. We present initial experimental results up to 75 kV per stage with the switches operating in self-break mode.

I. INTRODUCTION

A growing number of pulsed power applications require technologies that allow compact design. In this paper, we present initial experimental results from a prototype pulsed power generator that combines several technologies to achieve compact size. These technologies include: a stackable pulse forming architecture that is grounded at the switch-end and requires no ferrite, tightly integrated switches without separate housings, and use of a high dielectric constant, solid material for high stored energy density.

In our previous work, we presented various aspects of these enabling technologies. In [1], we presented 3D, time domain, electromagnetic modeling of the pulse forming line (PFL) architecture. We showed that our novel PFL allows for multi-stage voltage stacking at the output end while keeping the switch-end at ground. We further showed that it is possible to configure a linear accelerator without ferrite core between the stages using this PFL.

In [2], we showed that by immersing a PFL in liquid-dielectric, the liquid serves a dual purpose by insulating the exterior of the PFL while also serving as the switch media. We achieved very high gradient in this experiment of 106 MV/m using a film-insulated, planar Blumlein.

In [3], we demonstrated a two-stage pulse generator using a high dielectric constant (ε_r=10.2) solid material (Rogers 3210) to achieve a 25ns pulse in a line only 1.2m long.

The four-stage device discussed in this paper also employs the Rogers 3210 as an initial material. However, we know from extensive high-voltage testing that this material will not achieve the design goal of 300 kV per stage (23.6 MV/m charge stress). Later in this paper we will discuss our plans to achieve full voltage.

In the present work, we combine our novel PFL with liquid immersion, tightly integrated switches, and high dielectric constant material to produce a very compact pulse generator that may be scaled to many more stages.

II. PFL ARCHITECTURE

The pulse forming line architecture is derived from a line originally presented by Smith [4]. Our line is electrically equivalent and trades improved switch access for net gradient. Our PFL architecture is shown in Figure 1. Three versions of the line are shown. In all three diagrams, the dashed lines represent the charged electrode, the solid lines are other metal electrodes at DC ground, and the switch is indicated schematically on the left-side. In Fig.1a, we show the version of the PFL discussed and modeled in [1]. In this version of the PFL, the uncharged, shorted-line is split into two lines. During our tests in the laboratory, we found that because the switch is not ground referenced, a negative feedback tended to inhibit switch closure. Fig. 1b shows an alternant version of the PFL where the shorted line is realized as a single line (not split) and the switch is ground referenced. We plan to use this version of the PFL the future. As a short term fix, the data presented in this paper was taken with the configuration shown in Fig. 1c where we simply shorted the lower line at the switch-end. This ground referenced the switch but left the shorted line with an impedance too low by a factor of two. This reduced the generated voltage levels from the ideal design.

This PFL has a number of important characteristics.

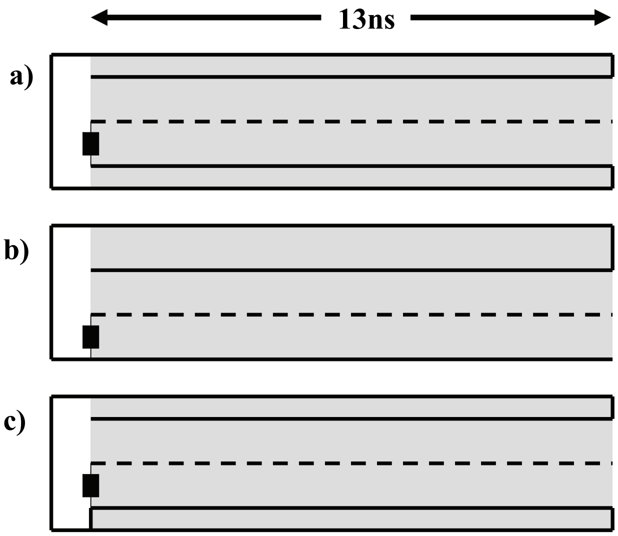

Figure 1. a) original version of the bi-polar ZIP line, b) an alternant, electrically equivalent version of the bi-polar ZIP line that ground references the switch, and c) a modified version of (a) as implemented in the data presented here

The output waveform is a bi-polar or zero-integral pulse (ZIP). To achieve perfect matching, the first half cycle is open circuited at the load end while the second half cycle is matched at the load end. This "switched load" can occur naturally in an accelerator application if the beam appears right at the zero-crossing to load the line. A computer model of the ideal waveform is shown in Figure 2a while Figure 2b shows the effect shorting the switch end of the lower shorted-line. The pulse amplitude is reduced and rings since the matching is imperfect.

The switch-end is encased in a grounded boundary (the back-short). This feature keeps multiple, stacked stages from erecting at the switch end. This makes it practical to charge multiple stages and also provides a ground reference for any trigger that may be employed for the switches. Pulse currents flow on the inside of the back-short, but not the outside. When many stages are stacked, the back short also provides a grounded surface that may be use to mount the stack in a laboratory.

The net result of using this PFL is that multiple stages add only at the output end without the use of ferrite cores while the switch-end stays at ground.

III. EXPERIMENTAL DESIGN

We built a four-stage experimental device to test the integration of our PFL and switching technologies. As mentioned above, we originally built the stack using the split-ZIP PFL as shown in Fig. 1a and subsequently converted to the configuration shown in Fig. 1c. A photograph of the assembly (out of the oil-filled tube is

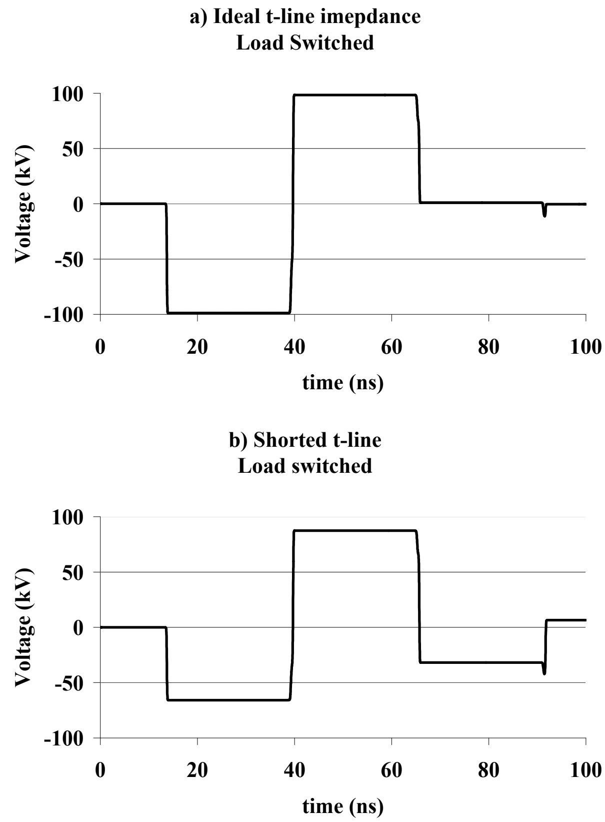

Figure 2. Expected waveforms for a single stage charged to 100kV. a) the ideal case where all line impedances are correct and the load switches exactly at the zero-crossing b) waveform for configuration in Fig. 1c.

shown in Figure 3 while a close-up of one of the switches is shown in Figure 4. The dielectric material is Roger 3210 and the line length is 1.2m giving an expected pulse duration of 26ns. The Line width is 10.16cm and the line thickness is 1.26cm. This yields a line impedance of approximately 15Ω, and stage impedance of 30Ω and a net output impedance for the four stages of 120Ω. We monitor the voltage of each stage with a separate, resistive voltage monitor. The signals from these monitors show the charging and switching of each stage. A fifth resistive probe monitors

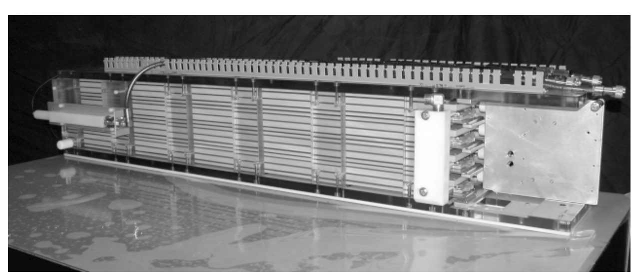

Figure 3. A photograph of the four-stage experimental apparatus.

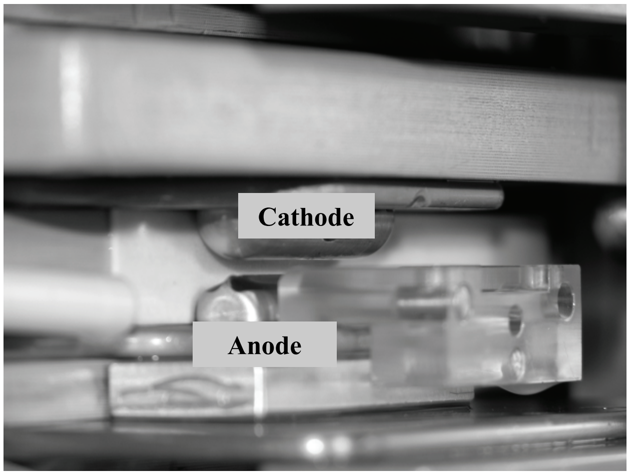

Figure 4. Photograph showing a close-up view of one of the switches. The gap shown here is 1.5mm and operates at 75-80kV.

the signal at the stack output.

We charge the stack with a three-stage Marx bank (not shown). Each stage is isolated from the Marx generator by an inductor.

The switches are brass rails where the anode side is contoured to provide higher electric field to promote positive streamer formation. We also incorporated a Xenon flashlamp that illuminates the switch region. We operate the flashlamp with a 10 μs current pulse which is relatively slow compared to the charging and switching time for the PFL stages.

The entire assembly is immersed in an oil filled plastic tube. We are currently using a silicone oil. An external pump flows oil through the switch region.

The output load consists of a bank of water-solution resistors. We have incorporated a variable-gap switch between the load and the stack output. This output switch allows us to operate the stack with no load (open circuit), constant load (no gap), or switched load. This output load switch and the four individual stage switches use the ambient oil in the experimental tube as the switch medium.

IV. EXPERIMENTAL RESULTS

Our focus during initial operation was synchronizing the four switches. Due to the limited dielectric strength of the Rogers 3210 material, we limited the charging voltage to <100kV per stage. We operated the switches in both triggered and self-break modes. In the self-break mode we set the switching voltage by machining the electrodes with a particular gap. We have accumulated hundreds of shots in various configurations. The shots vary with respect to switch-scatter (time between first and last switch firing) and to a lesser degree switch break-down voltage. Generally we achieved our best results with the following conditions: self break switches, field-enhanced anode shape, and flashlamp illumination. One example of a shot is shown in Figure 5. In the shot the load was connected for the entire waveform (no output switch gap). We present the data essentially in raw form (no post processing) except for amplitude calibration factors. We can see the four charging waveforms and the bi-polar output pulse. In this shot, the switch scatter was 6.4ns. The switch scatter can be seen to increase the pulse rise-time. For the conditions on this shot (configuration in Fig. 1c and load not switched) we expect a voltage of 208kV in the negative cycle which is about the observed value.

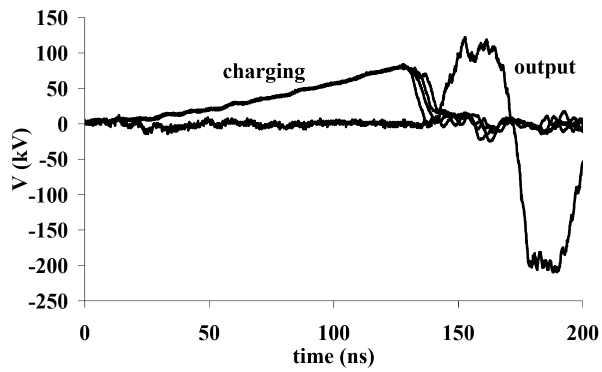

Figure 5. Shot with four stages firing with a switch-scatter of 6.4ns. The output voltage is in good agreement with expected value.

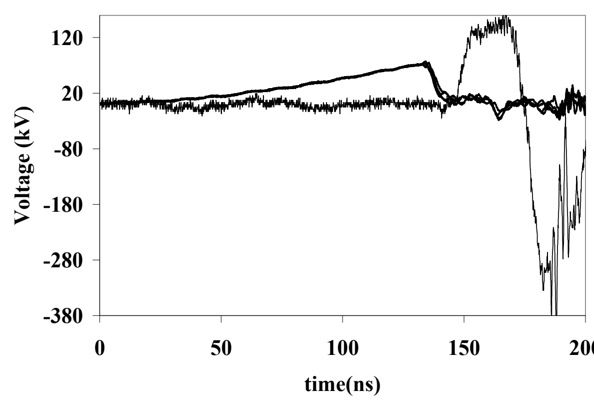

Figure 6. A shot with an excellent total switch scatter of only 1.4ns and the out put switch closing in the negative cycle.

We show another shot example in Figure 6. In this case, we opened up the output switch with a gap of 2mm. The gap was a little big in this case because the output switch closes a little late; after the negative cycle has started. The switch scatter for this shot was very good, only 1.4ns

We show a zoomed in view of the switching and positive cycle for this same shot in Figure 7. We modeled the conditions of this shot including the late-closing output switch using XFDTD to help predict the

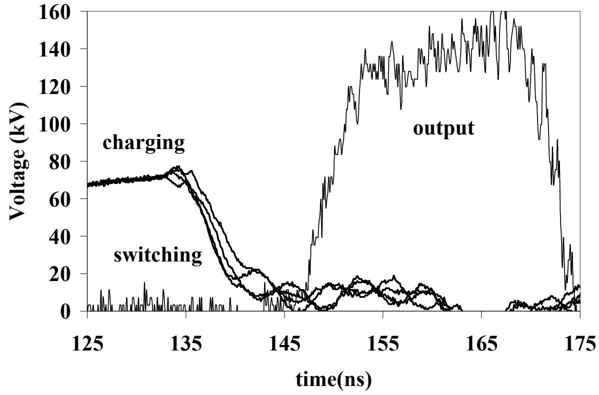

Figure 7. Zoomed in view of a shot showing details of switching (1.4ns switch scatter) and output pulse.

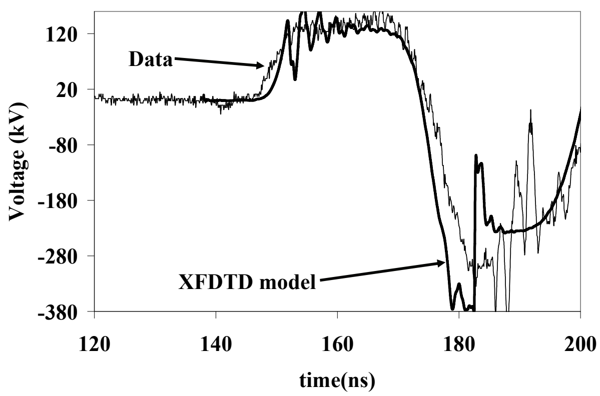

Figure 8. Overlay of actual output pulse with a model generated with XFDTD.

expected voltage values. We overlay the actual output pulse with the XFDTD model result in Figure 8.

As mentioned above, we employ flashlamp illumination to improve the switch scatter. We found in our previous work with self-breaking gas switches, that this method reduced switch-scatter. Our data suggests that the method works in oil filled switches as well. We pulse a single flashlamp before we trigger the Marx bank to charge the stack. The flashlamp current pulse is on the order of 10 s. When viewed on the timescale of charging and switching, the flashlamp current is essentially constant. It is therefore not a trigger. The light from the lamp illuminates the entire switch region including the oil and the electrode surfaces. We make no claim as to the mechanisms at work but the data indicate generally less switch scatter when the lamp is used in a shot. Figure 9 shows a plot of switch scatter for a number of consecutive shots. During the series of shots, we alternated lamp-on and lamp-off.

V. CONCLUSION AND NEXT STEPS

In this paper, we have presented initial results from a four-stage, compact, ferrite-free pulse generator. We are in the process of implementing this device on the existing ETA II accelerator at LLNL. For this implementation, we will be replacing the Rogers 3210 dielectric material with a proprietary cast material[5] that will operate at the full design voltage of 300 kV. We are also working to improve the switches to reduce the average switch scatter.

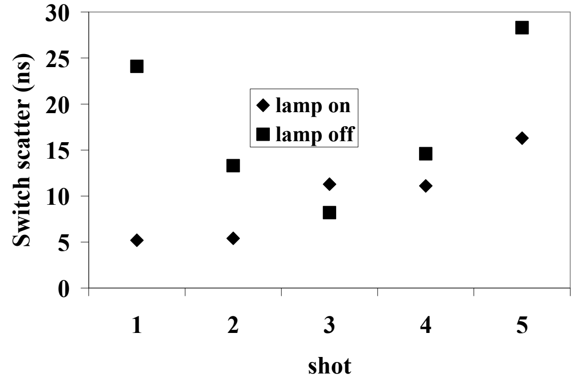

Figure 9. Total switch scatter for a series of shots showing the affect of flashlamp illumination

VI. REFERENCES

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[3]gas switched paper

[4] smith paper

[5] D. Sanders, S. Sampayan, G. Caporaso, M. Rhodes, J. Watson, "Development of a Low Loss, High Dielectric Strength Microwave Substrate," UCRL-CONF-222059 and 27th International Power Modulator Symposium, 2006.

[6] XFDTD

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