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Design and Test of a Low Jitter Metal to Metal Contact Solid Dielectric Switch

Edward Ernest Domning
(M.S. Thesis)

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MASTER

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Design and Test of a Low Jitter Metal to Metal Contact Solid Dielectric Switch

By

Edward Ernest Domning

B.S. (University of California, Davis) 1984

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

The image shows three horizontal lines with handwritten signatures written over them. The signatures are in dark ink and appear to be cursive. The first signature is the most prominent and spans across the first two lines. The second and third signatures are written below it, each spanning across its respective line.

Committee in Charge

1992

Design and Test of a Low Jitter Metal to Metal Contact Solid Dielectric Switch*

By

Edward Ernest Domning

Abstract:

A low jitter metal to metal contact solid dielectric switch was designed and tested. A metal to metal contact solid dielectric switch with a jitter of less than 25 ns is required for the 150 kJ experiment. Since this is one fourth the 100 ns jitter reported using exploding bridge foil (EBF) triggers, experiments to optimize this trigger were performed. A jitter of 25 ns was achieved using the EBF trigger and it was also achieved using a new type of trigger called the magnetic push trigger. This trigger uses the magnetic force between the two plates of a parallel plate transmission line to push the dielectric. It was found to be better than the EBF trigger because it was easier to design, easier to implement and did less damage to switch components.

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Chapter One: Introduction

The purpose of this work was to develop a trigger with jitter under 25 ns for the 150 kJ bank's metal to metal contact solid dielectric switches. To do this an exploding bridge foil (EBF) trigger was designed on a computer code and then tested on a specially constructed test stand. Using the results of these tests a better EBF trigger and a new trigger called the magnetic push trigger was designed and tested. This dissertation covers the work performed designing and testing these triggers.

The first chapter of this dissertation gives a summary of the different types of solid dielectric switch triggers, presents the 150 kJ bank specifications and describes how the triggers were optimized. Chapter two describes the modeling and implementation of the triggers and gives the layout of the experimental test stand. Chapter three presents the results of the experiments and Chapter four

uses those results to find the differences between the two triggers. Chapter five concludes by recommending which trigger to use on the 150 kJ experiment.

Brief history

Solid dielectric switches use a solid instead of a gas or liquid as the dielectric that stands off the voltage between anode and cathode. The high dielectric strength of this solid allows the switch to have a small anode to cathode spacing that will, with a correct design, result in low switch inductance. Low switch resistance can also be achieved by designing a trigger that can push a metal plate across the small anode cathode gap forming a metal to metal contact.

To engage the switch, a trigger ruptures the solid. The solid, being unable to reform, must be replaced before the switch is operated again. This makes the solid dielectric switch (SDS) too unwieldy to use for most pulsed power experiments. Typically it is only used on pulsed power experiments that require low switch inductance or low switch resistance.

The earliest work with solid dielectric switches was performed by J.C. Martin¹ in 1962. He designed a fast acting switch with very low inductance for use on a high voltage surge generator. He chose a solid to hold off the high voltage because its high dielectric strength allowed him to design a switch with low inductance. The high dielectric strength of the solid allows the anode and cathode to be very close together. This anode cathode spacing dictates the switch inductance.

To operate this switch, he placed a sheet of polythene that had been stabbed to a preset depth with a number eight Singer sewing needle within the

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¹J.C. Martin, "Notes on Some Dielectric Switches," (1962).

switch's anode cathode gap. The switch was then pulse charged to a high voltage forcing the dielectric to break down and close the switch. By controlling the depth of the holes created by the needle, he was able to control the breakdown voltage to within 2 to 3 %.

Solid dielectric switches were also used extensively in the late sixties and early seventies as crowbars on high current coils used in thermonuclear experiments (James, Dokopoulos -- "A Combined Arc....," Nunnally, Skelton, Dike, Call). These experiments used a low resistance switch to crowbar the coil at peak current. The coil then slowly discharged through the switch, maintaining a relatively high current, and increasing the duration of the high magnetic field within the coil. The switches designed by these experimenters used the force of the trigger to drive a metal plate through the solid dielectric making a direct metal to metal connection from anode to cathode. The resistances of these switches were in the microohm range.

More recently solid dielectric switches have been used in EBF driven, high velocity projectile impact experiments (Carpenter, Ricketts). Solid dielectric switches allow the experimenter to minimize the resistance and inductance of the capacitor bank. This maximizes the rate of rise of the current making the exploding foil work more efficiently. This means more energy is dissipated in the foil giving the projectile pushed by the EBF a higher velocity. The 150 kJ experiment is an EBF driven projectile experiment. It will use a coaxial EBF to accelerate 'chunky' projectiles.

Solid dielectric switches do have some distinct advantages over other types of switches. The foremost is low inductance. While all the solid dielectric

switches referenced here have relatively low inductance, the better designs have inductance values of 1-3 nH.^{2 3 4 5}

The low resistance is also an advantage. The resistance of a well-designed metal to metal contact SDS can be much lower than the resistance in other switches. Resistance values in the 5 $\mu\Omega$ range^{6 7 8} have been reported by some experimenters. Some other advantages of solid dielectric switches include lower electrical noise and a wide range of operating voltages.

The greatest disadvantage of the solid dielectric switch is the labor required to replace the dielectric after every shot. It is possible to build automatic dielectric feed systems, but it is only practical to do so on a large experiment. Even with an automatic feed system, it is still much easier to use a gas or liquid switch than a solid dielectric switch.

A summary of the different types of triggers used in solid dielectric switches

To operate the SDS, the solid dielectric is ruptured by a trigger allowing an arc or metal plate to pass through. This forms the current conducting path. The different types of triggers that have been used to rupture the dielectric include field distortion, laser induced breakdown, exploding bridge foil, chemical detonator, auxiliary arc, magnetic push, and tack.

Papers that describe the use of these different types of triggers are given in the bibliography. To investigate the field distortion trigger read Dokopoulos: "A

²H.J. Huber, "Wide Voltage Range High Energy Solid Dielectric Switch,"(1964), p. 1068 .

³J.C. Martin, "Notes on Some Dielectric Switches," (1962).

⁴R.S. Dike and R.W. Kewish, "The Development of a High-Explosive Driven Crowbar Switch," (1974), p. 658.

⁵R.A. Richardson, W.R. Cravey, D.A. Goerz, "Performance of a 10 kV, 625 kA, 85 kJ Energy Discharge Module Utilizing a Solid Dielectric Switch," (1991), p. 2.

⁶R.S. Dike and R.W. Kewish, "The Development of a High-Explosive Driven Crowbar Switch," (1974), p. 658.

⁷P.G. Carpenter, "An Automatic Multi-Megamp Metal to Metal Crowbar Switch," (1977), p. 3.

⁸I. Henins, J. Marshall, "Fast Metallic Contact Solid Dielectric Switch for High Voltage and Current," (1968), p1483.

Combined Arc...," Dokopoulos: "Fast Multichannel Field...," Gerasimov, Martin, Nunnally, Ramrus and Ricketts. To investigate the laser induced breakdown trigger read Babalin, Guenther and Ury. To investigate the exploding bridge foil trigger read Call, Carpenter, Dokopoulos: "A Combined Arc...," Dokopoulos: "Fast Metal...," Henins, Huber, Skelton and Richardson. To investigate the chemical detonator trigger read Dike, Ford, Weinmaster and Chau. To investigate the auxiliary arc trigger read Alston, Andrezen, James. The magnetic push and the tack switch have not been referred to in any of the papers the author has been able to find.

The field distortion trigger uses a high field to overvoltage the dielectric, causing it to breakdown. This is typically done by pulsing a wire or metal strip built into the dielectric with a high voltage pulse. The field distortion trigger has the advantage of having a fast turn on time and low jitter. A turn on time of 10 ns and jitter of 3 ns has been reported⁹ for the field distortion trigger.

The laser trigger uses a burst of laser light to induce free electrons in the dielectric. When enough free electrons are generated an avalanche breakdown occurs within the dielectric. This causes it to rupture. This trigger has a jitter of 1 ns and a turn on time of 15 ns¹⁰.

Exploding bridge foil triggers use the pressure of a hot plasma generated when a foil is vaporized by a high current¹¹ to cut the solid. Typically, the plasma pushes the dielectric against a cutting edge installed in one of the electrodes. A turn on time of 300 ns and jitter of 50 ns has been reported¹² for EBF triggers.

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⁹P. Dokopoulos, "Fast Multichannel Field Distortion Foil Switch for 500 kV," (1971), p. 303.

¹⁰A.H. Guenther, D.M. Strickland, J.R. Bethis, "Low Jitter, Low Inductance Solid Dielectric Switches," (1979) p. 1488.

¹¹J.E. Osher, et al., "Operating Characteristics and Modeling of the LLNL 100-kV Electric Gun," (1989), p. 392.

¹²H.J. Huber, "Wide Voltage Range High Energy Solid Dielectric Switch," (1964), p. 1068.

The auxiliary arc trigger works in the same way as the exploding foil trigger except that it uses the plasma produced by a breakdown across a gap.

Chemical detonator triggers use the pressure of the hot gases generated by explosives to push the dielectric. A turn on time of 1.01 μs and jitter of 78 ns has been reported¹³ for auxiliary arc triggers and a turn on time of 11 μs and jitter of 300 ns has been reported¹⁴ for chemical detonator triggers.

The tack trigger uses a tack driven by some type of mechanical system to rupture the dielectric. This method usually cuts the dielectric slowly, producing a high jitter. No reference to this type of switch was found in the literature.

The magnetic push trigger uses the force generated on a high current running in a magnetic field (the Lorentz force) to push the dielectric into the cutting surface. This is done by running a high current in a parallel plate transmission line that is designed to maximize the magnetic field between the plates. This causes a large force to be generated on the current running in the plates which in turn causes the plates to move which in turn pushes the dielectric.

The main advantage of using this type of trigger over the other types of mechanical push triggers is the reduction in damage to associated switch parts. This is due to its use of a relatively low pressure magnetic push instead of the high pressure hot gas or plasma. Experiments showed that switch components in direct contact with this trigger could be used 4-5 times while those not in direct contact would last indefinitely. In contrast, the parts in direct contact with the EBF triggers needed to be replaced with every shot and the parts not in direct contact needed to be replaced after about 10 shots.

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¹³L.L. Alston, et al., "Some Experiments on a High-Power Closing Switch with Polythene as the Main Dielectric," (1965), p. 1427.

¹⁴R.S. Dike and R.W. Kewish, "The Development of a High-Explosive Driven Crowbar Switch," (1974), p. 658.

Switch specification for the 150 kJ capacitor bank

The 150 kJ experiment will be used to perform hypervelocity impact studies with 'chunky' projectiles on a variety of targets. It consists of four capacitor modules each connected to a center transmission line by a SDS (Figure 1). When the four solid dielectric switches are closed, the four capacitor modules discharge into a coaxial exploding bridge foil mounted at the center of the transmission line. The energy from the exploding foil is used to accelerate the projectile.

The coaxial EBF is attached to an assembly that is mounted in the middle of the center transmission line. In the middle of this assembly is a tube made of an insulator with a conducting surface on the outside connected at one end to an EBF plated on the inside. The tube is connected to a mounting plate such that when the mounting plate is clamped in place, it electrically connects the top conductor of the center transmission line to the tubes outer conductor and the return conductor of the center transmission line to the EBF. The EBF will then short the capacitors when the switches are turned on. The coaxial assembly is shown in Figure 2.

Figure 1: Layout of the 150 kJ experiment

Figure 2: Layout of the 150 kJ experiments coaxial assembly

The experiment is operated by charging the modules to the operating voltage (the maximum operating voltage is 60 kV) and then triggering the solid dielectric switches. This causes the capacitors to rapidly discharge a high current through the coaxial EBF inside the tube. The high current causes the EBF to explode¹⁵, generating a high pressure directed towards the center of the tube.

¹⁵J.E. Osher, et al., "Operating Characteristics and Modeling of the LLNL 100-kV Electric Gun," (1989), p. 392.

The pressure generated by the plasma is augmented by the pressure from the Lorentz force that is generated by the current running in the tubes outer conductor. This pressure vaporizes the foam installed inside the tube, causing it to jet down a vent tube that is blocked by the projectile. The projectile is then accelerated to a high velocity (10-15 km/s) into the target under study.

Each capacitor module has four 5.2 μF , 20 nH capacitors connected in parallel to a feed transmission line. This gives each module a total capacitance of 20.8 μF and a total inductance of about 5 nH.

To achieve the desired projectile velocities, modeling indicates that the current in the bank must rise to 6 MA in 1.1 μs . To achieve this, the system inductance must be approximately 6 nH. Given that the coaxial EBF inductance is about 4 nH and the parallel inductance of the modules is about 1 nH, the total parallel switch inductance cannot be greater than about 1 nH. This means that each switch must have an inductance of less than 4 nH.

The 1.1 μs rise also requires the system resistance to be less than 1 m Ω . The major contributors to resistance are the coaxial foil, the capacitors and the switches. The foil contributes a resistance of about 0.4 m Ω and the capacitors contribute about 0.5 m Ω . This implies that each switch must have a resistance less than 0.4 m Ω .

The fast rise of the current is not useful if the current in the coaxial EBF is not uniform. Uniformity ensures that the foam is crushed radially, ejecting the gas jet at the center so the projectile is pushed with maximum force. This means the modules must be switched onto the center transmission line within 50 ns of each other. This implies that the SDS must have a jitter of less than 25 ns.

The 150 kJ bank was designed with a metal to metal contact SDS to meet the low resistance, low inductance requirements. Since no existing mechanical push trigger had a jitter of 25 ns, this study was performed to create the required

trigger. The two trigger types developed in this study are the EBF and magnetic push triggers.

The test stand layout

Figure 3 shows a schematic layout of the experimental test stand built to test the triggers. It consists of two capacitor banks: the capacitor discharge unit (CDU) and the test module. When the tack switch in the CDU closes, the high energy capacitors in the CDU discharge through the trigger. This causes the trigger to rupture the SDS dielectric, discharging the test modules capacitors through the SDS into a shorted transmission line.

The trigger engages the SDS by converting the energy dissipated in it by the CDU into mechanical action. Since the trigger is supported by the cathode, the mechanical action of the trigger pushes the sacrificial plate and dielectric against a cutting edge in the anode. The dielectric probably breaks down shortly before the sacrificial plate reaches the anode, but if the dielectric is traveling at a high velocity the amount of time the current is conducted in an arc would be small.

Figure 3: Test stand electrical layout and cut away views of the SDS

Operation of the EBF trigger

The EBF trigger converts the electrical energy from the CDU into mechanical action by vaporizing a thin metal foil. This is done by the high current rapidly heating the foil through the solid and liquid phases, and into the vapor phase. When the foil becomes a vapor, its resistivity increases rapidly causing a rapid dissipation of energy within the foil.

If the EBF is designed correctly, the current density at the start of the vapor phase is high and most of the energy in the circuit is stored in inductance. The circuit can then maintain the high current density by converting the energy in the inductance into energy in the vapor. This results in a large voltage spike across the EBF. Eventually enough energy is put into the vapor to ionize it, causing a rapid decrease in its resistivity.

This large energy dissipation in the EBF during the short vapor phase can cause the vapor to generate pressures and shock waves equal to or greater than those of a chemical explosive giving it the name exploding bridge foil. These shock waves and the expansion of the plasma are what accelerates the metal and dielectric package against the cutting surface.

The velocity of the material above the EBF cannot be determined analytically because the resistivity of foil in the vapor phase is very nonlinear. In this study an EBF modeling code called CONFUSE¹⁶ was used to calculate velocity of the 'flier' (the material that is pushed by the EBF). CONFUSE is a one dimensional, magneto-hydrodynamic code that calculates the burst characteristics of an exploding foil for various circuit configurations. It was written by I. Lindemuth at Los Alamos National Laboratory.

The operation of the magnetic push trigger

The magnetic push trigger uses the expansion of a stripline due to the Lorentz force to move the metal and dielectric package against the cutting surface. The position and velocity of this flier are calculated by integrating the acceleration due to the Lorentz force acting on the pushing segment.

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¹⁶I.R. Lindemuth, et al., "A Computational Model of Exploding Metallic Fuses for Multimegajoule Switching," (1985).

For a push segment of thickness h , width w and length l conducting a current $I(t)$, the magnetic field is

$$B(t) = \frac{\mu I(t)}{w + 2h}. \quad (1)$$

The Lorentz force on the segment is then

$$F(t) = I(t)B(t)l = \frac{\mu l}{w + 2h} I^2(t). \quad (2)$$

Given m as the sum of the mass of the conductor and mass of the flier, the position of the front of the conductor is then

$$x(t) = \int_0^t \int_0^t \frac{F(\tau)}{m} d\tau dt = \frac{\mu l}{m(w + 2h)} \int_0^t \int_0^t I^2(\tau) d\tau dt. \quad (3)$$

Equation (3) implies that the time it takes to cut the dielectric can be changed by modifying the pushing segment's geometry and current. It also implies that accurate control of geometry and current should produce low jitter.

Chapter Two: Experiment Description

The development of the triggers on the test stand took the following steps: modeling, testing, remodeling and then final testing. Initially, the EBF trigger was chosen as the trigger to be optimized in this study. The initial modeling was done on this trigger type. Its jitter was assumed to be due to thickness variations in the dielectric it was pushing. The modeling produced an EBF geometry that reduced the time to cut the dielectric after EBF burst to under 445 ns. From calculations shown later, this corresponds to a jitter of 10 ns.

When this trigger was tested on the test stand its jitter was found to be in the 100 ns range. It was determined that this trigger deviated from the model because of a poor estimate of the CDU circuit parameters, a poorly designed switch clamping structure and the magnetic movement of the EBF before the foil burst.

The EBF trigger was then redesigned and remodeled with reduced magnetic movement. This was done on CONFUSE using realistic CDU parameters. The magnetic push trigger was also designed and modeled at this point. Before testing these new triggers, an improved switch clamp was installed on the test stand. The final tests of these triggers showed that both met the jitter requirements.

This chapter begins by presenting the CONFUSE modeling and the physical layouts of the four different trigger types. This is followed by a description of the physical layout of the CDU and the test module. It concludes with a presentation of the estimated circuit parameters for each trigger type and brief description of the test module and CDU diagnostics.

Initial EBF trigger design

The goal of the initial modeling was to find a reasonable EBF geometry and CDU capacitance such that a 0.001 inch variation in the thickness of the dielectric would contribute less than 10 ns to the jitter of the switch. Assuming the dielectric is 0.022 inch thick, the thickness used in the 150 kJ bank, and that it is under constant acceleration from the trigger, it would have to be cut in less than 445 ns to achieve this jitter. The final velocity of the dielectric would be greater than 2.5 km/s.

The modeling was an iterative process that involved choosing an EBF geometry, modeling it over as set of CDU capacitances and using the results to make improvements in the next geometry. CDU capacitance values of 2.8, 5.6, 5.4, 10.8, 10, 20, 14 and 28 μF were used in these models since they reflected the possible capacitance values given the capacitors that were available. Inductance and resistance values were initially estimated and kept the same

through out the initial modeling. The EBF material was chosen as copper since the triggers could be quickly constructed from strips cut from copper sheets.

The different EBF geometries used in the models are shown in Table 1. Table 2 shows the time to cut (t_{cut}) for each model. The time to cut is the time it takes to move the front of the EBF the dielectric thickness (0.022 inches) minus the time it takes the EBF to burst. The EBF bursts when the voltage across it reaches its peak value.

EBF type	width (inches)	length (inches)	thickness (inches)	Charge Voltage (kV)
EBF1	0.125	0.25	0.0005	10
EBF2	0.125	1.00	0.0005	10
EBF3	0.125	1.00	0.0005	20
EBF4	0.125	1.00	0.0010	20
EBF5	0.125	1.00	0.0020	20
EBF6	0.125	1.00	0.0040	20
EBF7	0.125	1.00	0.0030	20

Table 1: Geometry of the originally modeled EBF triggers

C (μ F)	L (nH)	R (m Ω)	t_{cut} EBF1 (ns)	t_{cut} EBF2 (ns)	t_{cut} EBF3 (ns)	t_{cut} EBF4 (ns)	t_{cut} EBF5 (ns)	t_{cut} EBF6 (ns)	t_{cut} EBF7 (ns)
5.4	48	75	480	-	-	-	-	-	-
10.8	38	63	455	1010	620	460	340	340	
2.8	48	75	525	-	-	-	-	-	-
5.6	38	63	470	1070	625	460	400	2500	
14	48	75	470	-	-	-	-	-	-
28	38	63	465	1000	615	430	330	290	330
10	48	75	485	-	-	-	-	-	-
20	38	63	460	1030	610	435	350	300	345

Table 2: Comparison of times to cut of the EBF triggers

While geometry EBF1 did not meet the goal, its results did indicate a direction to take in the design. They showed that the low inductance CDUs performed the best. Only those CDUs were used on the rest of the models. The 30 kV voltage spike predicted for geometry EBF1 also indicated that an electric field of 120 kV/inch would be developed across the 0.25 inch long foil. In reality this field would cause an arc to form around the EBF before it burst, negating the burst action. To be able to hold off this voltage, the length of the EBF in geometry EBF2 was increased to 1.0 inches. This would lower the field to 30 kV/inch.

Since the results from geometry EBF2 indicated that none of the CDUs had enough energy to explode the increased EBF mass, the energy in each of the CDUs was increased in geometry EBF3. This was done by increasing the CDU charge voltage to 20 kV. The results from geometry EBF3 showed times to cut that were much slower than the goal of 445 ns. This indicated that the EBF needed more energy dissipated in it.

It is reasonable to assume that there is an optimal EBF cross sectional area where energy is most efficiently coupled from the CDU into the EBF motion. Before the first current peak, an increase in the EBF cross sectional area will lead to an increase in the current at EBF burst and more than likely the energy at burst. If the increase in the energy at burst is greater than the increase in mass, then the EBF will move with a higher velocity. It is not unreasonable for this to happen since the relationship between the energy dissipated in the foil and the current at burst is non-linear. In the following models, variations in the cross sectional area were made until a reasonable geometry was found.

The cross sectional area of geometry EBF4 was doubled by making it twice as thick as geometry EBF3. This is a thickness of 0.001 inches. While the results of this model did show that the cut time improved, it still did not meet the goal.

Foil thicknesses of 0.002, 0.004 and 0.003 inches were then tried on geometries EBF5, EBF6 and EBF7. Each of these models produced a time to cut that met the 445 ns goal.

While the results for geometry EBF6 operated by the 28 μF capacitors gave the best cutting time, the current waveform showed that its EBF burst after the first current peak. According to empirical results, exploding bridge foils tend to work best when they burst before the first current peak. The second best cutting time is that of geometry EBF7 operated by the 28 μF capacitors. Its EBF geometry was chosen to be used on the initial trigger.

When laying out the trigger, it was decided that it would have two EBFs to generate two points of contact in the SDS. This was to lower SDS inductance and resistance. The two EBFs have the same cross sectional area as geometry EBF7 but have half its length. This trigger layout is shown in Figure 4. It is referred to as the two EBF trigger.

The next step was to build the CDU, the test module and the trigger. When constructing the CDU, it was discovered that the inductance of its 14 μF capacitors was twice as high as expected. This would increase the estimated inductance of the CDU to 48 nH. To lower the inductance back to the models 38 nH, the inductance of the CDU was lowered by 10 nH. This was done by making the dielectric in the trigger and in the transmission lines thinner. Unfortunately, this also limited the CDU charge voltage to 15 kV.

After the construction of the CDU, test module and trigger, the trigger was tested. The results indicated that the CDU inductance was about 30 nH and the CDU resistance was about 20 m Ω . Modeling with these realistic values gave an estimated time to cut of 335 ns. The results of this more realistic model are shown in Figure 5.

Figure 4: Layout of the two EBF trigger

Figure 5 : CONFUSE modeling of the two EBF trigger

Modified EBF design

When tested on the test stand, the two EBF triggers produced a jitter of 135 ns. Close examination of the first of the two EBFs showed that it was shorting through the trigger insulation to the return line on the other side. It is possible that this was due to the combined voltage of the two EBFs at burst.

The burst voltage can be cut in half by removing one of the EBFs. To try this without building a new trigger, the end EBF was removed from a set of two EBF trigger and copper shorts were soldered in their place. They were then tested on the test stand. The implementation of this trigger is shown in Figure 6. It is referred to as the one EBF trigger. The CONFUSE modeling of this trigger is shown in Figure 7.

Figure 6: Layout of the one EBF trigger

Figure 7 : CONFUSE modeling of the one EBF trigger

Trigger redesign

While the jitter for the one EBF trigger shots was reduced to 90 ns, it still wasn't good enough to meet the jitter specifications. This was unexpected because the EBF bursts looked similar from shot to shot. Upon closer inspection of the modeling results it was found that the EBF moves before the burst of the foil due to magnetic push. This made it seem that the dielectric was moving faster than it really was. As it turns out, half the movement of these triggers was due to magnetic push. This means the dielectric is moving much slower than anticipated.

To increase the speed of the dielectric, the EBF triggers were redesigned with very little magnetic movement. Since the magnetic force on a conductor is inversely proportional to its width, the width of the EBF was increased to 0.3125 inches. The length was also chosen as 0.3125 to cover the 0.25 inch diameter cutting edge.

Given the 0.3125 inch square EBF geometry, models with thicknesses of 0.001, 0.002, 0.003 and 0.0005 inches were run on CONFUSE. Table 3 shows the results of these models. Circuit parameters derived from experimental results were used in these models.

The implementation of the model with the fastest time to cut, the 0.001 inch thick EBF, is shown in Figure 8. This trigger is referred to as the wide EBF trigger. It is estimated that the amount of movement due to magnetic force at the time to cut for this trigger is 0.004 inches. The CONFUSE modeling of this trigger is shown in Figure 9.

Foil Thickness (inches)	t_{burst} (μs)	t_{on} (μs)	t_{cut} (ns)
0.001	0.625	0.995	370
0.002	0.900	1.335	435
0.003	1.400	1.780	380
0.0005	0.380	0.830	450

Table 3: Calculated times to cut for various thicknesses of the wide EBF trigger

Figure 8: Layout of the wide EBF trigger

Figure 9 : CONFUSE modeling of the wide EBF trigger

After seeing the amount of movement generated by the magnetic field on the two EBF triggers, it became apparent that the magnetic movement could be used to trigger the SDS. The magnetic push trigger was designed to maximize the amount of magnetic force on a small segment that would push the SDS dielectric into the cutting surface without allowing the segment to melt. This means that the push segment must be narrow for high magnetic force, thick enough to keep from melting and short enough to keep the trigger inductance low. The push segment width was chosen to be 0.0625 inches and its length was chosen to be 0.3125 inches. Using these values, the push segment was modeled on CONFUSE with thicknesses of 0.005, 0.007, 0.01 and 0.015 inches. The results of these models are shown in Table 4.

The push segment with a thickness of 0.010 inches was chosen because it had the fastest turn on time of the segments that burst after they cut the dielectric. The implementation of this trigger is shown in Figure 10. It is referred to as the magnetic push trigger. The CONFUSE modeling of this trigger is shown in Figure 11.

Push Segment Thickness (inches)	t_{burst} (μs)	t_{on} (μs)
0.010	1.140	0.960
0.015	1.690	1.055
0.005	0.635	0.790
0.007	0.810	0.865

Table 4: Calculated times to cut for various thicknesses of the magnetic push trigger

Magnetic Push Foil

Figure 10: Layout of the magnetic push trigger

Figure 11 : CONFUSE modeling of the magnetic push trigger

Test stand and CDU layouts

Figure 12 contains photographs of the test stand built to test the triggers. The CDU is the capacitor bank upon the wooden stand and the test module is the capacitor bank upon the metal stand. The CDU tack switch is located under the relay hanging from the wooden beam above the CDU. The SDS is located under the C-beam clamp. A description of the test module SDS and CDU are given below.

The test module was constructed out of a spare 150 kJ bank module upon which several modifications were made. The first was the installation of only two of the four 5.4 μF capacitors to limit test module energy. The next was the addition of a shorted copper transmission to ensure a reasonable current (about 300 kA) when operating the test module.

The biggest change was the rebuilding of the original 150 kJ SDS. The old switch clamp transmission line was removed and a new one was installed. New switch components were also designed and built. A new C-beam clamp was installed above the switch allowing the switch components to be inserted and aligned easier. The new clamp put more pressure on the switch in order to remove the air gaps between switch components. Figure 13 shows an exploded view of the test module SDS.

Figure 12: Test stand layout

Figure 13: Exploded view of the test module switch

At the bottom of the SDS assembly is the anvil plate. It is placed on alignment pins that are screwed in to the shorted transmission line. The alignment pins are to hold the anvil plate in position when the anvil plate is aligned to the cutting plate.

The anvil plate is made of 6061 aluminum and has slots for the backing plate and trigger milled in it. The backing plate is a 0.25 inch thick piece of stainless steel that is placed right behind the active region of the trigger to keep the high pressures created by the trigger from damaging the anvil plate. The slot for the trigger is only 0.015 inches deep so that the trigger protrudes slightly

above the anvil plate. This allows the full force of the clamp to be on the trigger, reducing air gaps in the switch package above the trigger. This ensures good coupling of the force of the trigger into the switch package.

All the triggers are made of copper laminated within kapton. The lamination contains the burst of the EBF, isolates the upper and lower conductors and isolates the trigger from the anvil and sacrificial plates. All the triggers have a one inch wide feed line, an active region(s) and a one inch wide return line. The return line runs directly under the feed line for low trigger inductance.

The next piece is the sacrificial plate. It is placed over the trigger such that it makes a good electrical contact with the anvil plate. It is pushed by the trigger action through the dielectric to make electrical contact with the cutting plate closing the switch. A 0.005 inch thick aluminum sacrificial plate was chosen to keep the mass of the material pushed by the trigger low.

The solid dielectric that holds off the anode to cathode voltage is constructed of four 0.005 inch thick sheets of mylar that are laminated into a single 0.022 inch thick sheet. This is the thickness needed to hold off 60 kV. The dielectric is slid into position after the anvil plate, backing plate, trigger and sacrificial plate are all put into position. The final piece, the cutting plate is then slid in position on top of the dielectric.

The cutting plate is made of stainless steel to absorb the high pressures and temperatures of the triggers. The cutting surface is placed in a groove milled in the cutting plate. Recessed screws installed at 90 degrees to the groove (Figure 13) clamp the cutting surface in position.

The first cutting surface used on the experiments was a shick injector blade clamped by brass holders. Since the razor was difficult to align and install, it was replaced on the redesigned trigger experiments with a piece of tool steel

milled with a 0.25 inch diameter hole. Diagrams of the cutting surfaces are shown in Figure 14.

Figure 14: Cutting surfaces

Once the cutting plate is in position, the alignment tool is used to align the cutting plate to anvil plate before clamping the switch package. The switch dielectric is slid into the groove in the alignment tool and the alignment tool is pushed into a position such that one parallel edge is in contact with the front of the anvil plate. The cutting plate is then held against the other edge while the clamp is tightened down. The alignment tool is then removed.

The clamp transmission line is made of copper and makes contact between the capacitor transmission line and the cutting plate. The pressure is applied to the switch components by pushing on this plate with a piece of acrylic that is pushed by three 0.625 inch diameter screws set in an aluminum C-beam. The C-beam is connected to supports that are in turn connected to the base of the module. A three inch diameter acrylic tube installed between the return line of the test module and the module base supports the backside of the switch.

The amount of torque on the bolts corresponds to the pressure on the clamp. Initially a torque value of 50 inch-lbs was chosen. The torque was increased to 120 inch-lbs on shots 13-19 to improve switch performance. After inspecting the triggers from those shots, it became clear that this higher pressure was causing the trigger to breakdown. The torque was then reduced to 20 inch-lbs on the rest of the switch shots.

After operating the bank for 12 shots, a set of plates (Figure 15) was added to the C-beam to give it more rigidity. The clamp screws were causing the C-beam to deflect limiting the pressure on the switch.

Starting at switch shot number 13, DC4 vacuum grease was added to improve trigger pressure coupling. A coating of grease was added below the backing plate, under the trigger, above the trigger and above the sacrificial plate. When the switch was clamped together the grease extruded, forming a thin layer of material that excluded air gaps and coupled the motion of the materials. Other experimenters reported that adding this grease would improve transfer of shock waves between dissimilar media separated by air gaps.

Figure 15: Test module with added support

The CDU was constructed out of a capacitor bank that was used for experiments on high explosives. Originally this bank had four $14\ \mu\text{F}$ capacitors connected in parallel to a capacitor feed line. The feed line was connected to a chemical detonator SDS that was in turn connected to a feed transmission line.

The bank was modified by removing two of its four capacitors, the chemical detonator SDS and the feed transmission line. The tack driven SDS replaced the chemical detonator SDS and, when switched on, connected the capacitor feed line to the transition transmission line. The transition line was tapered from eight inches at the SDS end to one inch at the trigger connection. Figure 16 shows an exploded view of the CDU tack switch.

Figure 16: Exploded view of the CDU tack switch

The tack is a sharpened piece of all thread that is screwed into a modified Ross high voltage relay. When the relay is energized, it pushes the tack through the hole in the upper plate and into the sacrificial plate. It then drives the sacrificial plate through the dielectric and into the anvil plate, closing the switch. The capacitors are then discharged into the trigger.

The circuit that describes the linear operation of the CDU and the test module is the series LRC circuit shown in Figure 17. For the CDU at high current the resistance of the foil changes dynamically making the circuit nonlinear. Analysis in this case is usually done using EBF modeling codes. The circuit is operated by first charging the capacitor to the desired voltage and then closing the switch. The capacitor then discharges through the inductor and resistor. The current in the circuit is either a damped sinusoid (underdamped) or a decaying exponential (overdamped) depending on the inductance and resistance values. The CDU at low current and the test module are both underdamped.

Figure 17: Circuit of the test module and CDU

The current in an underdamped LRC circuit with the capacitor charged to a voltage V_0 oscillates by the following formula:

$$I(t) = \frac{V_0}{\omega L} e^{-t/\tau} \sin(\omega t) \quad (4)$$

where

$$\omega = \sqrt{\frac{1}{LC} - \frac{1}{\tau^2}} \quad (5)$$

and

$$\tau = \frac{2L}{R}. \quad (6)$$

The derivative of the current and the time to first current peak of this circuit is:

$$\frac{dI(t)}{dt} = \frac{V_0}{\omega L \sqrt{LC}} e^{-t/\tau} \cos(\omega t + \phi) \quad (7)$$

$$\phi = \tan^{-1}\left(\frac{1}{\omega \tau}\right) \quad (8)$$

$$t_{\text{peak}} = \frac{\tan^{-1}(\omega \tau)}{\omega}. \quad (9)$$

For an actual experiment, the values ω and τ can be calculated from measurements of the time between two consecutive zero crossings of the current and the magnitude of two current peaks separated by a half period. The equations are:

$$\omega = \frac{\pi}{T_H} \quad (10)$$

and

$$\tau = \frac{T_H}{\ln\left(\frac{I(t_1)}{I(t_1 + T_H)}\right)}. \quad (11)$$

The value T_H is the half period determined from zero crossings of the current and t_1 is the time at the first current peak. The inductance and resistance of a LRC circuit, given the capacitance, can then be calculated using Equations (5) and (6).

Estimates of CDU and test module circuit parameters

The circuit parameters of the CDU and test module¹⁷ were estimated using their physical dimensions. The results of these calculations are shown in Table 5. This was done to check the values that are calculated from the experimental data. A large deviation between the experimental and calculated values would indicate a problem with the calculation, capacitor bank or trigger. Deviations larger than 25 % warrant further inspection.

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¹⁷E.E. Domning, "Improving the Jitter of the 150 kJ Experiments Solid Dielectric Switches" (1993), pp 50-53.

Configuration	Inductance (nH)	Resistance (mΩ)	Capacitance (μF)
Test module	28.9	8.4	10.7
CDU with no trigger	27.4	8.2	29.2
With two EBF trigger	34.6	21.4	29.2
With one EBF trigger	32.2	17.0	29.2
With wide EBF trigger	32.3	16.0	29.2
With magnetic push trigger	34.0	12.5	29.2

Table 5: Estimates of the circuit parameters of the test module and CDU

Diagnostic system

The diagnostics used on the test module and the CDU gathered information about the timing of the banks, the operation of the trigger and the operation of the SDS. They measured the derivative of the current (IDOT) in the CDU and the test module. The turn on time of each bank was taken as the time of the initial rise of each IDOT signal. The burst time was measured from the CDU IDOT signal. The circuit parameters of the test modules were calculated using the test module IDOT signal.

The IDOT in the CDU and the test module were monitored with Rogowski¹⁸ belts installed on the return side of the capacitor feed transmission lines. Rogowski belts output a voltage that is proportional to the IDOT running the conductor it surrounds.

A current viewing resistor (CVR) was also installed in the return side of the CDU's capacitor feed line. This was used to calibrate the Rogowski belt in the CDU. The voltage across the trigger was monitored by a voltage divider that is

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¹⁸R.E. Hebner, "The Measurement of High Current and Voltage Pulsed." (1982), pp.33-36.

isolated from the data acquisition system by a balun. In a balun differential voltages from a transducer, in our case from resistors measuring CDU voltage, are fed into the primary of a transformer. The measured signal is then output on a secondary giving DC isolation between the signals and a disconnect between the differential and signal grounds. A layout of the diagnostics is shown in Figure 18.

Figure 18: Diagnostic system for the one and two EBF experiments

The screen room provides isolation and shielding from noise generated by the high currents used in this experiment. The electric company ground is removed before the shot so that the system has a single point ground at the ground stake located at the test module.

Chapter Three: Experiment Results

Two types of experiments were performed on the test stand: ringdown shots and switch test shots. The ringdown shots were performed to test the operation of the CDU tack switch and to get the circuit parameters of the CDU. The switch test shots tested the performance of the two EBF, one EBF, wide EBF and magnetic push triggers. The results of all the different types of shots are summarized in this chapter.

Ringdown test results

The goal of the ringdown shots was to get the circuit parameters of the CDU and the triggers. This was done by putting the trigger under test in the CDU, charging the CDU to a low voltage and then closing the tack switch. Since the CDU discharges with a low current, the resistance of the trigger remains

constant, and the current in the CDU "rings" through the trigger according to Equation (4). Given the CDU capacitance, the inductance and resistance of the CDU and trigger can be calculated. The circuit parameters of the trigger are obtained when circuit parameters calculated for the CDU without a trigger (shorted) are subtracted from values calculated for the CDU with a trigger.

Twenty-two ringdown shots were performed on the CDU. The first 16 were used for tuning the data acquisition system and improving the performance of the tack switch.

Ringdowns 17 to 20 had a short put in place of the trigger to get the circuit parameters of the CDU without a trigger. In ringdown 21 a 2 EBF trigger was installed and in ringdown 22 a wide EBF trigger was installed. The data from these shots were used to determine the circuit parameters of these two triggers. The waveforms for a typical ringdown shot is shown in Figure 19.

A large change in inductance was found to occur in the CDU and test module during the first 200 to 600 ns after they turned on. This nonlinearity means that Equation (4) cannot be used to calculate the circuit parameters. The next chapter covers difference equations used in a computer program to estimate the CDU and test module circuit parameters from ringdown and test module results.

Figure 19 : Experimental data for ringdown shot # 20

Two EBF switch test results

After 21 ringdown shots, nine switch tests were performed using the two EBF triggers. The switch times for these shots are shown in Table 6. Of these shots, only 4, 6, 7, 8 and 9 can be used to calculate switch jitter; shots 1 and 2 had the CDU charged to 10 kV instead of 15 kV, shot 3 was not constructed properly and shot 5 had a short in the CDU transmission line. The average switching time using these shots is $1.008 \pm 0.142 / - 0.128 \mu\text{s}$ for these shots. This is a jitter of 135 ns.

Shot	CDU Charge (kV)	Bank Charge (kV)	Torque (in-lbs)	Switch time (μs)
1	10.2	11.2	50	1.530*
2	10.1	10.9	50	1.455*
3	15.2	16.4	50	1.300*
4	15.2	16.7	50	0.880
5	15.2	16.7	50	2.975*
6	15.1	16.6	50	1.010
7	15.2	16.8	50	1.095
8	15.6	16.8	50	0.905
9	15.2	16.1	50	1.150

*Not useful data, see text.

Table 6: Switch times using the two EBF triggers

Inspection of the triggers after the shots indicated that the EBF closest to the CDU had more energy dissipated in it than the one furthest from the CDU. This was unexpected since the two EBFs operate with the same current and are of the same geometry. They should have burst with the same amount of energy. Closer inspection of the damage under the first EBF indicated that a breakdown occurred in the dielectric beneath it. This could have been caused by the high voltage spike generated in the EBFs at burst. The short would shunt current

away from the EBFs during burst reducing the amount of energy dissipated in them. It would also make it seem that the first EBF burst with more energy because the damage from the arc would look the same as the damage from the EBF.

This also means that the dielectric above the first EBF is pushed by both the exploding foil and the breakdown arc. The pushing from the arc would cause some jitter in the turn on time of the SDS since the turn on time of the arc and the amount of energy dissipated in it would vary from shot to shot. The results of a typical two EBF trigger shot is shown in Figure 20.

Figure 20 : Experimental data for switch shot # 9 (two EBF trigger)

One EBF switch test results

To reduce the voltage spike at burst, a set of two EBF switches were modified by removing the second EBF and putting a short in its place. These switches were then tested on the test module. Their switch times are shown in Table 7.

During these shots, the SDS clamping structure was found to be flexing when tightened down and was reinforced after shot 12. The jitter of the shots 10 to 12 and the jitter of shots 13 to 16 must be calculated separately because of the difference in clamping pressure. Shots 10 to 12 had an average switch time of $1.077 \pm 0.108 / - 0.097 \mu\text{s}$. This is a jitter of 103 ns. Shots 13 to 16 had an average switch time of $1.1 \pm 0.045 \mu\text{s}$. This is a jitter of 45 ns. Shots 13 to 16 also had DC4 grease applied between switch components. The results of a typical one EBF trigger shot is shown in Figure 21.

Shot	CDU Charge (kV)	Bank Charge (kV)	Torque (in-lbs)	Switch time (μs)
10	15.1	16.8	50	1.065
11	15.1	16.5	50	0.980
12	15.1	16.8	40	1.185
13	15.1	17.1	100	1.055
14	15.1	16.4	120	1.145
15	15.0	16.6	120	1.055
16	15.2	16.9	120	1.145

Table 7: Switch times using the one EBF triggers

Figure 21 : Experimental data for switch shot # 13 (one EBF trigger)

Magnetic push switch test results

The magnetic push trigger was designed after the discovery of the magnetic expansion problems on the one and two EBF triggers. It was designed to use the magnetic expansion to move the SDS package. The switch times for this trigger are shown in Table 8. The average switch time for these shots is $0.869 \pm 0.011/-0.034 \mu\text{s}$. This is a jitter of 23 ns. The results of a typical magnetic push trigger shot is shown in Figure 22.

Shot	CDU Charge (kV)	Bank Charge (kV)	Torque (in-lbs)	Switch time (μs)
21	15.3	16.8	20	0.880
22	15.7	18.5	20	0.870
23	15.4	18.5	30	0.835
24	15.0	16.9	20	0.875
25	15.1	16.7	20	0.875
26	15.1	16.5	20	0.870
27	15.1	16.6	20	0.880

Table 8: Switch times using the magnetic push triggers

Figure 22 : Experimental data for switch shot # 25 (magnetic push trigger)

Wide EBF switch test results

The wide EBF trigger was designed after the discovery of the magnetic expansion problems on the one and two EBF triggers. It was designed so that most of its movement comes from the EBF explosion and not magnetic force. The switch times for the wide EBF shots are shown in Table 9.

Switch tests 30 and 33 both had shorts in the trigger lead transmission line, indicating a problem in the construction of the trigger. Since this a problem of trigger construction and not the explosion or expansion of the EBF, excluding them from the switch time calculation would give a more accurate indication of jitter due to strictly the EBF factors. The average switch time for this trigger is then $0.860 \pm 0.025 / -0.020$ ns. This is a jitter of only 23 ns. The results of a typical wide EBF trigger shot is shown in Figure 23.

Shot	CDU Charge (kV)	Bank Charge (kV)	Torque (in-lbs)	Switch time (μ s)
28	15.1	16.5	20	0.840
29	15.1	16.8	20	0.850
30	15.1	16.5	20	0.755*
31	15.1	17.2	20	0.885
32	15.1	16.7	20	0.865
33	15.1	16.9	20	0.925*

*Not useful data, see text.

Table 9: Switch times using the wide EBF triggers

Figure 23 : Experimental data for switch shot # 29 (wide EBF trigger)

Summary of the average switch times of the different trigger types

The timing of the different types of triggers is summarized in Table 10.

Switch type	Mean switch time (ns)	Upper bound (ns)	Lower bound (ns)	Spread (ns)
2 EBF	1008	142	128	270
1 EBF: old clamp	1077	108	97	205
1 EBF: new clamp	1100	45	45	90
Magnetic Push	869	11	34	45
Wide EBF	860	25	20	45

Table 10: Jitter Summary for the different types of triggers

Chapter Four: Analysis

This chapter covers the analysis performed to determine whether the wide EBF or magnetic push trigger would be implemented on the 150 kJ experiment. To perform this analysis, the circuit parameters of a LRC circuit with a non-linear resistance and an initial inductance fall needed to be calculated. The first section of this chapter covers the derivation of difference equations to model a LRC circuit that includes this fall. It also covers the programming of a computer model that, given the LRC circuit parameters, estimated the IDOT in this circuit. This modeled IDOT could then be compared to the actual data to see if the input parameters were correct. The circuit parameters were calculated for both the CDU and test module.

The next section compares, for each trigger, the estimated circuit parameters of the CDU to those calculated in Chapter 2. A reasonable match will indicate

that the CDU is working correctly. The next section compares estimated and calculated test module circuit parameters for each trigger. A difference between these parameters indicates that the trigger interferes with the operation of the SDS.

In the next section the performance of each trigger is compared to that predicted by the CONFUSE code discussed in Chapter 2. A deviation from the predicted performance could indicate a problem with that trigger. This is followed by a section in which the source of jitter between the two trigger types is investigated. This will indicate other area of improvements in the trigger. The last section gives a comparison of the damage to switch components for the two switch types.

Estimating circuit parameters with nonlinear computer model

Attempts to fit Equation (4) to the ringdown waveforms quickly showed that there was a non-linearity during the initial rise of the current in the CDU. Closer inspection of the waveforms revealed that the inductance fell by about 10 nH after the turn on of the tack switch. This fall in inductance is attributed to a widening of the discharge channel or metal contact through the cut in the tack switch dielectric. This inductance fall also occurred in the test module SDS. This seems to indicate that it can be expected in any mechanically driven SDS. The decay time of the inductance is probably influenced by the rate of rise of the current and the velocity of the dielectric.

To get the circuit parameters of the CDU, a model was constructed in the LabVIEW application that included a heated foil and a decaying inductance in a set of difference equations set up for a LRC circuit. The inductance in the circuit was assumed to be the sum of the final inductance and the decaying inductance given by the following formula:

$$L(t) = L_f + \Delta L e^{-t/\alpha}. \quad (12)$$

An exponential decay of the inductance difference was chosen empirically to match the quick decay of the inductance. It seemed to fit the data well.

The resistance is just the sum of the resistance of the capacitor, the transmission lines and the heated foil. The resistance of the heated foil changes with temperature because its resistivity changes with temperature. The metal resistivity ($\rho(t)$) before melt can be calculated from temperature (T) from:

$$\rho(t) = \rho_0 (1 + \alpha(T(t) - T_0)). \quad (13)$$

The temperature in the foil can be determined by setting the electrical energy dissipated in the foil equal to the heat energy in the foil. Thermal radiation is ignored. This energy balance gives the following equations:

$$mC_v T(t) = \int_0^t I^2(\tau) R_{\text{foil}}(\tau) d\tau \quad (14)$$

$$\frac{dT}{dt} = \frac{I^2(t) R_{\text{foil}}(t)}{mC_v}. \quad (15)$$

The resistance of the foil can then be calculated given the skin depth δ and using one of the following resistance equations. The resistance of a rectangular foil of length l and width w that is thicker than the skin depth with is:

$$R_{\text{foil}}(t) = \frac{\rho(t)l}{w\delta}. \quad (16)$$

The resistance of a trapezoidal foil of length l , initial width a , and final width b that is thicker than the skin depth is

$$R_{\text{foil}}(t) = \frac{\rho(t)l}{\delta(b-a)} \ln(b/a). \quad (17)$$

The resistance of a foil thickness h that is thinner than the skin depth for both rectangular and trapezoidal regions is

$$R_{\text{foil}}(t) = \frac{\rho(t)l}{w\delta \left(1 - e^{-\frac{h}{\delta}}\right)} \quad (18)$$

$$R_{\text{foil}}(t) = \frac{\rho(t)l}{(b-a)\delta(1 - e^{-h/\delta})} \ln(b/a). \quad (19)$$

The charge in the capacitor of a LRC circuit is found by setting the voltage across the capacitor equal to the sum of the voltage across the inductor and the resistor. Given that L is that given by Equation (12), the charge in the nonlinear circuit is:

$$Q(t) = L(t)C \frac{dI(t)}{dt} + R(t)CI(t). \quad (20)$$

Using Equations (20) and (15), difference equations for current, derivative of the current, temperature, charge in the capacitor for a time step T can be formulated. They are shown below.

$$I_n = \frac{CL_n I_{n-1} + Q_{n-1} T}{L_n C + R_n C T + T^2} \quad (21)$$

$$T_n = T_{n-1} + \frac{I_n^2 R_{\text{foil}_n}}{m C_v} T \quad (22)$$

$$Q_n = Q_{n-1} - I_n T \quad (23)$$

It is important to note that L_n is the current inductance value calculated from Equation (12), R_{foil_n} is the current value of the foil resistance given by Equations (16) to (19) and that R_n is the sum of the circuit resistance and the foil resistance. Skin depth and resistivity would also have to be recalculated each time step using the current temperature, resistance and inductance values.

A code was set up in the LabVIEW application using these equations. The user inputs a set of circuit parameters and it outputs files containing estimated current and IDOT values. These files are then read into the IGOR application where they are compared to the collected waveforms. The circuit parameters for a waveform can be estimated by varying the parameters input to the LabVIEW code and until the estimate fits to the data.

Circuit parameters of the CDU

Table 11 shows the inductance and resistance values calculated for the different trigger types using this model. Notice that the one EBF and magnetic push parameters were determined from switch shots, not from ringdown shots. Their inductance decay times are much less than those taken from the ringdown shots. Figure 24 shows the curve fits of ringdowns 20, 21 and 22 plotted against the experimental data. Figure 25 shows the curve fits switch tests 14 and 25 plotted against the experimental data.

Shot	Foil Type	Initial Inductance (nH)	Final Inductance (nH)	Delta L (nH)	Decay factor (ns)	Resistance (mΩ)
Ringdown # 20	none	33.0	27.2	5.8	600	9.1
Ringdown # 21	2 EBF	44.2	33.6	10.6	600	20.3
Switch test # 14	1 EBF	40.8	30.4	10.4	350	20.3
Ringdown # 22	Wide	40.9	30.3	10.6	650	17.3
Switch test # 25	Magnetic	44.6	34.0	10.6	425	12.5

Table 11: Estimated Inductance and resistance values of the CDU for the different types of triggers

Figure 24 : Curve fits to the ringdown data

Figure 25 : Curve fits to the switch test data

Table 12 shows the comparison of the circuit parameters estimated with LabVIEW compared to the calculated circuit parameters. Note that these values match fairly well.

Foil type	Calc. L (nH)	Calc. R (mΩ)	Est. L (nH)	Est. R (mΩ)	Diff in L (nH)	Diff in R (mΩ)
Bank Only	27.4	8.2	26.9	9.1	0.5	1.1
2 EBF	34.6	17.2	33.6	20.3	1.0	3.1
1 EBF	32.2	15.0	30.4	20.3	1.8	5.3
Wide	32.3	14.5	30.3	17.3	2.0	2.8
Magnetic	34.0	11.5	34.0	12.5	0.0	1.0

Table 12: Comparison of the circuit parameters from LabVIEW to the calculated values

Circuit parameters of the test module

Estimates of the circuit parameters of the test module were calculated using the LabVIEW application. Table 13 shows the averages of this data for the different trigger types. Figure 26 shows the curve fits of the test module plotted against the experimental data for all the different trigger types. Note that for shot 13 the estimated curve fits to the actual data for the first three microseconds and then deviates after that. This was true for all one EBF shots. This is due to the trigger causing a variation in either the switch inductance or resistance.

It is also important to note that when the magnetic push and wide EBF triggers were used on the test module, the test module's resistance went up by 2 mΩ and inductance went up by 0.5 nH. This indicates that an arc, not metal carried the current in these switches. It is possible that the sacrificial plate needs a surface to mold into to make a direct contact. The cutting edge used in these

shots (the barrel) did not have one. Also note that there is little difference between the circuit parameters of the wide EBF and those of the magnetic push triggers.

Foil Type	Initial Inductance (nH)	Final Inductance (nH)	Delta L (nH)	Decay factor (ns)	Resistance (mΩ)
2 EBF	39.1	29.0	9.9	203	6.9
1 EBF	40.8	28.7	12.1	200	6.3
Magnetic	40.0	29.5	10.5	191	8.4
Wide	40.0	29.6	10.4	217	8.9
Estimate		28.9			8.4

Table 13: Average test module circuit parameters for the different types of triggers

Figure 26 : Curve fits for the test module IDOT signals

Comparison of trigger performance to model

Table 14 shows the difference between the experimental and modeled switch times. The burst time of the EBF triggers shown in Table 14 are greater than the modeled burst times because the non-linear inductive rise was not included in the CONFUSE models. The same is also true of the difference between the experimental magnetic push switch times and the CONFUSE model. Figure 27 shows plots of the modeled data against the experimental data.

The experimental time to cut of the wide and 2 EBF triggers are much less than the modeled time to cut. This indicates that the dielectric is probably being pushed with more energy than just the explosion of the foil. It is possible that an arc due to the short behind the EBF is also pushing the dielectric, causing it to cut sooner than the EBF alone.

Switch type	Actual t _{on} (μs)	Actual t _{burst}	Actual t _{cut} (μs)	Modeled t _{on} (μs)	Modeled t _{burst}	Modeled t _{cut} (μs)
2 EBF	1.008	0.845	0.163	1.138	0.804	0.334
1 EBF	1.100	0.770	0.330	1.032	0.744	0.288
Magnetic Push	0.869	?	-	0.960	1.140	-
Wide EBF	0.860	0.665	0.195	0.995	0.625	0.370

Table 14: Comparison of experimental and modeled switch times

Figure 27 : Comparison of the CONFUSE models and the experimental data

Reliability of the magnetic push and wide EBF triggers

An important factor to consider in selecting a trigger is its reliability. More specifically, it is important to know if the jitter will remain small enough when the trigger is used on the 150 kJ bank. An analysis of the cause of the jitter in magnetic push and wide EBF triggers would indicate whether the jitter would vary if the trigger was applied elsewhere. It would also point out other areas that could be improved in that trigger.

If the switch is tightly clamped, the factors that effect the magnetic push triggers are just those factors that effect $x(t)$ in Equation (3). These are: the mass of the material moved, the geometry of the push segment and the CDU current. The effect of these different factors can be seen from the analysis of the results of the magnetic push triggers.

The position of the dielectric for each shot was calculated by using Equation (3). The mass of the flier is found by summing the mass of the switch package with the weight of the copper push segment. Table 15 shows the calculated time to cut for all the magnetic push shots.

Shot #	Measured time to cut (ns)	Push segment thickness (inches)	Calculated time to cut (ns)
21	880	0.0095	884
22	870	0.0110	861
23	830	0.0095	834
24	875	0.0095	884
25	875	0.0095	882
26	870	0.0095	863
27	880	0.0110	867

Table 15: Calculation of the time to cut 0.022 inches of mylar for the magnetic push shots.

Two discrepancies were found during this analysis: the first, shown in Table 15, is the variation of the thickness of the magnetic push triggers between 0.011 and 0.0095 inches, the second was slightly higher currents in shots 22, 23 and 27. This higher current was probably influenced by the decaying inductance described earlier.

Since shots 22, 23 and 27 have higher current, they would be expected to have a faster turn on time. This is true of shot 23, but not of in shots 22 and 27. This is due to their higher push segment masses.

In contrast, shots 21, 24, 25 and 26 have the same push segment thickness and virtually the same current. Their jitter is only 5 ns. This seems to indicate that by controlling the thickness of the copper push segments and improving the CDU switch, a much lower jitter can be achieved.

Quantifying the source of jitter in the wide EBF trigger is more difficult than the magnetic push trigger. The highly non-linear nature of the EBF makes it possible for small variations in tamping, foil impurities and foil geometry to cause large variations in burst energy. Studying the effect of these parameters require a new set of tests that are beyond the scope of this study.

There is also the effect of the high voltage spike at burst. This spike caused the breakdown of the trigger leads in shots 30 and 33. It is also possible that it is causing a short behind the wide EBF foil. While the breakdowns could be eliminated with a thicker trigger dielectric, the thicker dielectric would change the performance of the EBF. This indicates that while a low jitter EBF trigger has been found, it is still not refined enough to be used on the 150 kJ bank. Some more testing still needs to be performed to remove some of its other problems.

Damage to switch components

The EBF trigger generates high pressures and temperatures causing much more damage to switch components than the magnetic push trigger. The stainless steel backing plate underneath the EBF was deformed on every shot by about 0.015 inches. The pounding of the EBFs from shot to shots was slowly deforming the anvil piece until it was unusable after 8 to 10 shots. The pounding was also slowly deforming the transmission line under the anvil piece.

The cutting plate was also being damaged. The EBF pressure was pressing the cutting piece into its holding groove with such force that it had to be pounded out with a hammer after every shot. This slowly deformed the holding groove in the cutting plate, shortened the plates life to about 30 shots. Each EBF trigger also created so much residue due to the burning of the dielectric and sacrificial plate that the switch area had to be thoroughly cleaned after every shot.

The magnetic push triggers on the other hand produced very little damage. The backing plates were only slightly indented from the magnetic force and the anvil plate had no damage at all. While the magnetic push strip was completely molded to the cutting piece, the cutting plate was not damaged. The cutting piece was easily removed from its groove. The magnetic push triggers also left much less residue than the EBF trigger.

Chapter Five: Summary

This report covered the development of low jitter triggers for the metal to metal contact SDS that will be used on the 150 kJ experiment. These triggers were tested on an experimental test stand from which data was collected and analyzed to find the best trigger. This chapter concludes this dissertation by recommending a trigger for the 150 kJ bank, describing how to apply it and giving recommendations for future work.

Trigger selection

It is clear from the analysis of the two triggers that the magnetic push trigger would be a better trigger to use on the 150 kJ experiment. This is due to its design simplicity, higher reliability and low switch damage.

Magnetic push triggers are simpler to model, construct and operate than the EBF triggers because they use a simple magnetic force to convert the energy stored in the capacitor bank into movement of the dielectric. This simplicity also makes the magnetic push trigger reliable, since the factors that affect jitter can be easily eliminated by careful trigger construction and careful CDU operation. The magnetic push operation also means that excess energy is not generated as heat and pressure limiting the damage to SDS components.

The magnetic push triggers are also attractive because the version designed for this study wasn't optimized. There are areas where they can be improved. Two improvements that immediately come to mind are decreasing the dielectric thickness and changing the material to aluminum. The dielectric thickness can be cut in half since magnetic push segments generate no high voltage spikes. This reduces the trigger inductance by two, increasing the rate at which the current rises. This change, as well as changing the push segment material to the lighter aluminum, would increase the velocity of the push segment, and decrease the jitter.

Applying the trigger to 150 kJ experiment

The 150 kJ experiment consists of four capacitor banks each switched by a SDS to a center feed line. Each SDS is switched by a trigger that needs a high current pulse to operate. This current can be provided by two methods: four CDUs, one for each trigger, or a single CDU connected to all the triggers. Since the four CDUs would have to be switched with low (<5 ns) jitter, they could not have a metal to metal contact SDS. Since a metal to metal contact SDS is required in the CDU, the only option is the single CDU.

The test bed CDU could be used as the single CDU if the other two 14 μF capacitors were added, the trigger inductance was lowered, and the charge voltage was increased to 30 kV. With the trigger inductance cut in half by the thinner dielectric, the current in each trigger would be about that used in the test stands CDU.

The CDU tack switch would have to be modified to handle 800 kA and the dielectric in the CDU would have to be increased to handle 30 kV. A symmetrical feed transmission line would need to be built to distribute the current to the four triggers and a new clamping system would also have to be installed on each of the four capacitor modules.

Recommendation for future work

Before operating the 150 kJ bank a few problems need to be solved. The first is the elimination of the high resistance barrel cutting edge. A short study of cutting edges on the test module could be done to find one that forms a good low resistance contact while still being easy to install.

Another problem is that the CDU required for 150 kJ bank is large and will be difficult to install and operate. With magnetic push triggers that operate at a lower current, a smaller CDU could be used. Before operating the 150 kJ bank, a short study looking at different capacitors, charge voltages, and push segment configurations can be performed on the computer. Some of the better configurations can then be tested to determine a more optimal design.

Another possible trigger design is to combine the magnetic push and EBF actions such that the jitter due to the energy variations in the EBF would be reduced. This design would initially move the dielectric via magnetic push until right before the dielectric cuts. The pusher, being an EBF, would burst at this

point giving the dielectric a higher velocity at cut. This would lower the jitter from thickness variations in the dielectric without a large contribution from the EBF. Of course this type of switch would be more sensitive to construction and would cause more damage to switch parts.

Summary

The goal of this study was to develop a trigger for a metal to metal contact solid dielectric switch that would have a jitter of less than 25 ns. During the process of improving a EBF trigger, the magnetic push trigger was created. While both were found to have a jitter of less than 25 ns, the magnetic push trigger was also found to be easier to develop and more reliable than the EBF trigger.

While this trigger was designed for the 150 kJ bank, it also would be a good choice for experiments that need a low jitter trigger for a metal to metal contact SDS. It would also be a good replacement for chemical detonator, auxiliary arc and EBF triggers on experiments that do not require a low jitter trigger because the magnetic push trigger does such a small amount of damage to SDS components. The cost of personnel and parts for operating the bank would be reduced. The reduced cost would eventually pay for the upgrade

It is also important to note the inductive decay at the turn on of the tack, EBF and magnetic push switches. While this effect may just be an artifact of this switch design, it is more likely that this effect occurs on all solid dielectric switches that cut the dielectric mechanically. It has not been noticed until now because the time scale for most experiments that used this type of switch is much larger than that used on these experiments. It would be important to reduce this effect when it may affect the experiment the SDS is used in.

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