

High Voltage Pulse Generator for a Capillary Discharge

X-ray Laser

A Thesis

Presented to the

Department of Physics

Brigham Young University

In Partial Fulfillment

of the Requirements for the Degree

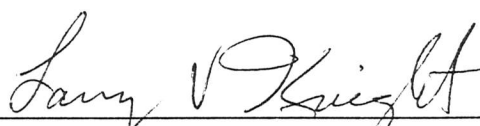
Master of Science

by

Bryan Royce Olsen

December 1996

This thesis by Bryan Royce Olsen is accepted in its present form by the
Department of Physics of Brigham Young University as satisfying the thesis
requirement for the degree of Master of Science.



Larry V. Knight, Committee Chair



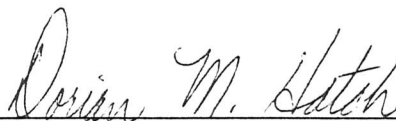
David D. Allred, Committee Member



James M. Thorne, Committee Member

Nov. 25, 1996

Date



Dorian M. Hatch, Department Chair

This work is dedicated to my wife, Kristine Marie Kipp Olsen. She always loved me, supported me and encouraged me through all of the set-backs and frustrations that are so common to experimental science. She believed in me even during the periods when I did not believe in myself.

Acknowledgment

I would like to thank A. Richard Miller who gave freely of his time, vast experience and knowledge to teach me the art of pulsed power systems. Without his invaluable assistance in working out the engineering details, the capillary discharge device that now stands in the laboratory would probably be little more than a concept.

I would also like to thank Larry V. Knight, David D. Allred and James M. Thorne who served on my thesis committee and helped me determine the parameters of my research. Thanks should also go to R. Stephen Turley who helped me understand the data gathered by various diagnostics that monitor the performance of the discharge device.

Much of the success of this project is due to the efforts of Wes Lifferth who took my incomplete drawings and turned them into beautifully machined components for the device.

I am especially grateful for my wife, her parents and my parents who encouraged me through the long process of completing this work.

Funding for this project was provided by the Department of Defense through a SBIR contract awarded to Moxtek, Inc.

Table of Contents

List of Figures	vii
1. Introduction	1
1.1 History	1
1.2 X-ray Laser Research at BYU	2
2. Design	4
2.1 Waveform Parameters	4
2.2 Basic Discharge Circuit	6
2.3 Basic Concept	10
3. Components	12
3.1 Insulation Requirements	12
3.2 Capillary	13
3.3 Transmission Line	13
3.4 Transmission Line Switch	17
3.5 Marx Generator	19
3.6 Resonant Charge Inductor	26
4.1 Tests And Diagnostics	28

4.1 Static Breakdown Tests	28
4.2 Visible Light Data	32
4.3 Copper Sulfate Voltage Probe	34
4.4 Rogowski Coil	43
4.5 High Pass Filter	46
4.6 Current Data	51
5. Conclusions	57
5.1 Objectives Achieved	57
5.2 Directions For Further Research	58
Appendix A Copper Sulfate Resistivity Data	63
Appendix B Notes on Solid Dielectric Switches	66
Appendix C Operating Procedures for the Capillary Discharge	80
References	85
Bibliography	88

List of Figures

2.1-1 Current waveform in the capillary	5
2.2-1 Original circuit concept for the discharge driver	8
2.2-2 Basic discharge circuit used for the pulse generator	9
2.3-1 Simplified diagram of the discharge device	11
3.2-1 Design of the capillary	14
3.3-1 Schematic of the transmission line mated to the capillary	18
3.5-1 Three common Marx generator circuits	20
3.5-2 Circuit diagram of the specific Marx generator used in the discharge device	22
3.5-3 Cable pulser used to trigger the Marx generator	24
3.5-4 Physical arrangement of the capacitors in the Marx generator	25
4.1-1 Results of the static breakdown tests of the spark gap switches	29
4.1-2 Operating voltage curves for the spark gap switches	30
4.1-3 Operating voltage curve provided by the switch manufacturer	31
4.2-1 Temporal behavior of the visible light produced by the discharge	33
4.3-1 Schematic of the copper sulfate voltage probe	36

4.3-2 Output voltage of the Marx generator	38
4.3-3 Voltage output of the transmission line	39
4.3-4 Leading edge of the transmission line voltage waveform	41
4.4-1 Position of the Rogowski coil relative to the capillary	44
4.4-2 Schematic of a typical Rogowski coil	45
4.5-1 Output of the Rogowski coil during one discharge of the capillary	47
4.5-2 Generalized Butterworth type low pass filter	50
4.5-3 Generalized high pass filter	50
4.5-4 Schematic of the completed high pass filter	52
4.6-1 Rogowski coil output with the high pass filter installed	53
4.6-2 Rogowski coil output with the trigger level adjusted to show just the leading edge of the transmission line discharge	54
4.6-3 Rogowski coil output with 15 traces averaged together	55
5.2-1 Single channel operation of the transmission line switch	59
5.2-2 Multi-channel operation of the transmission line switch	59
5.2-3 Details of a solid dielectric switch	61
A-1 Copper sulfate resistivity data	65

1. INTRODUCTION

1.1 History

Since the development of the ruby laser in 1960, significant effort has been expended to improve this valuable tool. Currently, lasers are available with power ratings from a fraction of a milliwatt to thousands of watts and operating at wavelengths from the infra-red through the visible spectrum and into the ultra-violet. In recent years, attention has turned to the development of laser systems that operate at soft x-ray wavelengths (500Å-30Å). Researchers at Lawrence Livermore National Laboratory first conclusively demonstrated x-ray amplification in 1984. The LLNL laser is an "exploding foil" device. In this first experiment, green light (532 nm) from the Nova laser -- with incident intensity of $5 \times 10^{13} \text{ W cm}^{-2}$ -- was line focused onto a 750 Å thick selenium foil. The intense laser radiation exploded the foil creating a cylindrical plasma of neonlike selenium atoms. The energy in the plasma was sufficient to collisionally excite x-ray laser transitions at 206 Å and 209Å.¹ Since the first demonstration of an x-ray laser, LLNL has demonstrated lasing in both collisional and recombination schemes. The highest output powers have been observed in neonlike collisionally pumped systems. Neonlike x-ray lasers have been demonstrated using elements from titanium ($Z = 22$) to silver ($Z = 47$). Currently, a yttrium x-ray laser, which operates at 15.5 nm, holds the record for the brightest XUV source.² Unfortunately, the expense of operating the Nova laser severely limits the number of x-ray laser experiments that can be carried out using this system, but enough

work has been done to demonstrate the potential value of x-ray lasers in many fields such as non-linear optics and biological imaging.

In an attempt to develop relatively inexpensive, "table-top," x-ray lasers, various research groups have begun experimenting with capillary discharge devices. In such a device, the x-ray producing plasma is generated from a gas confined in a small capillary. Typical capillary dimensions are: in 1-4 mm diameter and 1-12 cm long. The main advantages of capillary devices are the homogeneous plasma conditions which result from the capillary geometry and the lower energy requirements due to the plasma being produced from a gas rather than a solid. Various techniques are used to excite the plasma in the capillary. Rhodes' group in Chicago, for example, uses a high power optical laser to pump their x-ray laser device.³ Of particular interest, is the work carried out by J.J. Rocca and colleagues at Colorado State University. Rocca reports gain at 469Å in a neon like argon plasma excited by a high power electrical discharge. In these experiments, a 700 kV Marx generator is used to produce a high power electrical pulse which is fired through the capillary.⁴ In this system, the plasma becomes the current conductor and is excited sufficiently to generate the x-ray laser pulse. Without doubt, Rocca's device represents a vast improvement in terms of size, complexity, and cost efficiency over the LLNL x-ray laser. Construction, maintenance and operation of a Marx generator based system such as Rocca's is within the capabilities of most large laboratories, but more work is still necessary before x-ray lasers are feasible for widespread applications.

1.2 X-ray laser research at BYU

For the past several years, researchers at Brigham Young University have been involved in

the development of a compact soft x-ray laser system. The project's goal is to develop a capillary discharge, soft x-ray device pumped by a high power electrical discharge that is small and simple enough for widespread application in industry and research. Traditionally, capillary discharge experiments, such as Rocca's have used a "brute force" approach, in which huge Marx generators are used to drive very large current pulses through the capillary. With this approach, most of the available energy is wasted so the group at BYU has looked carefully at the theoretical requirements to induce lasing to design a device that requires a much less powerful driver. The first generation discharge device is nothing more than a high voltage capacitor which is discharged through the capillary by means of a low inductance, coaxial circuit. This simple discharge device produces pulses approximately 200 ns wide with an amplitude of 12 kA. Although this system has been a valuable test bed for developing diagnostic equipment, it has proven unsuccessful in producing the requisite plasma conditions for lasing. The main shortcomings of this device are the relatively long pulse rise time and the low power level in the discharge. To remedy the failings of the first system, a second generation system has been designed and constructed that is faster and much more powerful than the first generation system.

2. DESIGN

2.2 Waveform Parameters

The most important parameter of the device is the shape of the discharge pulse. Theoretical models of the plasma behavior⁵ predict that conditions favorable for lasing are most likely to be produced when the pump pulse has the shape shown in Fig. 2.1-1. The flat portion of the waveform, labeled I_{pre} , is approximately 200 ns in duration and serves to ionize the gas and begin heating the plasma. One essential function of I_{pre} is to establish a low impedance channel through the gas in the capillary. This channel, then, insures that the fast, high current portion of the pulse travels through the plasma instead of along the capillary walls. The duration of I_{pre} is not critical--the only requirement is that it needs to be long enough to produce an equilibrium in the plasma. If Rocca's conditions are to be reproduced accurately, then this portion of the pulse is limited to 20-30 Amps. Otherwise, I_{pre} can be raised to a sizable fraction of the maximum current. The portion of the waveform labeled I_{pulse} has an amplitude of 20 kV and is primarily responsible for driving the laser transition. Theoretical calculations indicate that the optimal rise time for the pump pulse (I_{pulse}) is on the order of 100 ps.

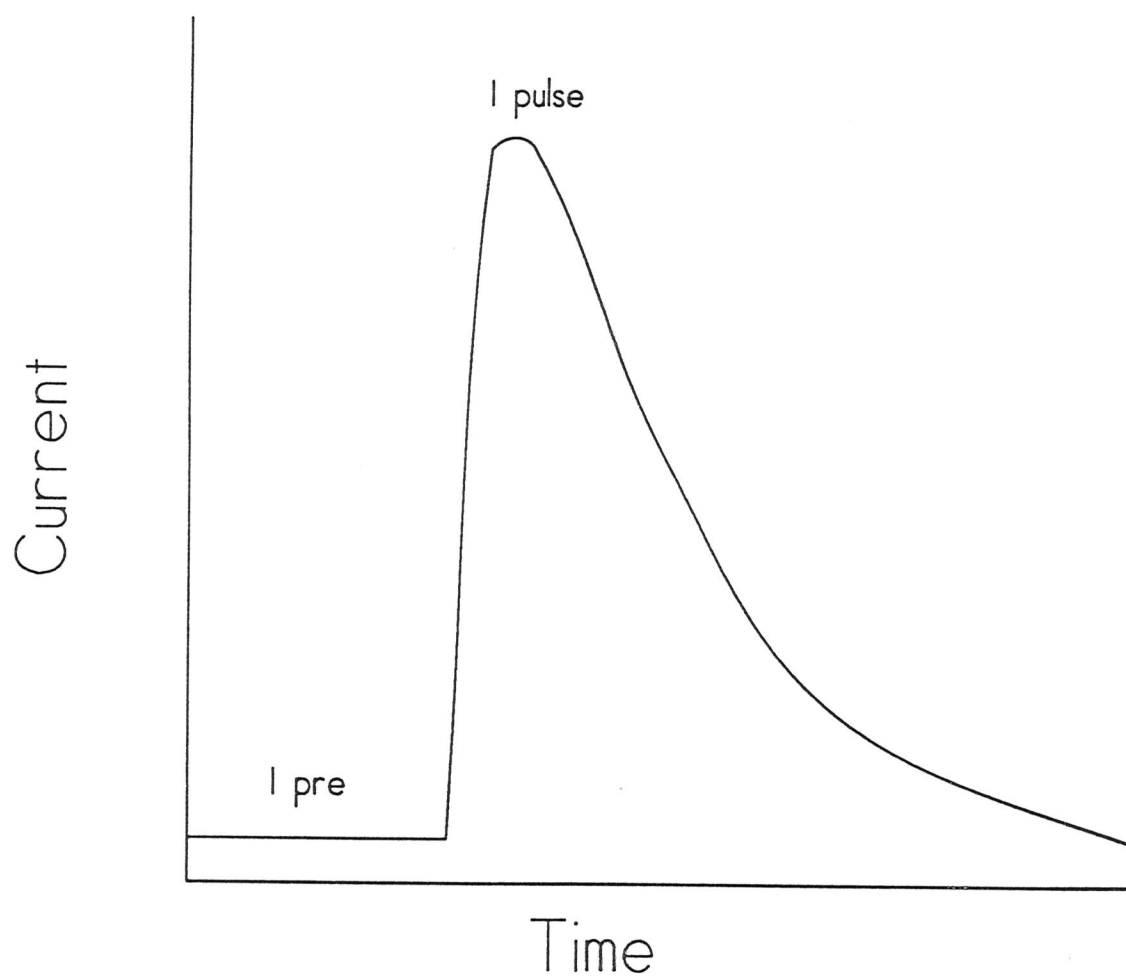


Fig. 2.1-1 The basic shape of the current waveform predicted by theoretical models of the plasma behavior

The dI/dt requirements for such a pulse are⁶

$$\frac{dI}{dt} = \frac{20 \text{ kA}}{0.1 \text{ ns}} = 2 \times 10^{14} \frac{\text{A}}{\text{s}} = 200 \frac{\text{kV}}{\text{nH}} \quad (2.2-1)$$

Based on the results of Eq. 2.2-1, a charge voltage of 1.2 MV would be required to produce 100 ps rise times pulses in the capillary, since the inductance of the capillary is estimated to be 6 nH. Unfortunately, 1.2 MV is well beyond the feasible operating voltage of a small system. In order to meet the design goal of building a compact system, it is necessary to relax the dI/dt requirements. If the pulse rise time is increased to 1 ns, then

$$\frac{dI}{dt} = \frac{20 \text{ kA}}{1.0 \text{ ns}} = 2 \times 10^{13} \frac{\text{A}}{\text{s}} = 20 \frac{\text{kV}}{\text{nH}} \quad (2.2-2)$$

A rise time of 1 ns can, therefore, be achieved in the capillary with 120 kV, which is not an unreasonably large voltage for a compact device. Experimental results, such as Rocca's, indicate that the 1 ns rise time, while not optimal, should still be fast enough to excite lasing. In view of these calculations, the design specifications for the pump pulse are: rise time of 1 ns, amplitude of 20 kA and pulse width (FWHM) of 10 ns.

2.2 Basic Discharge Circuit

Due to the fact that I_{pre} and I_{pulse} have very different parameters, it is necessary to design a

two stage discharge device. The pre-stage (to produce I_{pre}) can be as simple as a capacitor discharge. The pulse-stage, however, has to be very fast so a transmission line is chosen as the energy store for this stage. The original concept called for the circuit depicted in Fig. 2.2-1. With this circuit, once the capacitor, C_1 , is fully charged, switch S_1 closes, discharging the capacitor through the capillary. This discharge serves to both ionize and heat the plasma (I_{pre}) and to charge the transmission line. Switch S_2 then closes, causing the transmission line to fire the second, fast, pulse (I_{pulse}) back through the capillary. There are two serious flaws in this design. First, the current through the capillary would not be constant during the I_{pre} stage. Clearly, the current in the capillary would fall to zero just before S_2 closes to discharge the transmission line. Also, it would be very difficult to charge the transmission line sufficiently to produce the necessary rise time and peak current in the I_{pulse} stage. Of more minor importance, this circuit would cause the current in the capillary to reverse between the two stages.

A better discharge circuit is shown in Fig. 2.2-2. In this circuit, once the capacitor, C_1 , is charged, switch S_1 closes discharging the capacitor through R_{pre} into the capillary to provide I_{pre} while simultaneously charging the transmission line in parallel with the capillary. Switch S_2 then closes, discharging the transmission line into the capillary. The most important advantage of this circuit is that the transmission line can be charged to the requisite voltage without significant difficulty. The pre-stage current through the capillary remains constant in this circuit with the additional advantage that the pre-stage current can be adjusted by changing the value of R_{pre} . Further, the current through the capillary does not reverse between the stages.

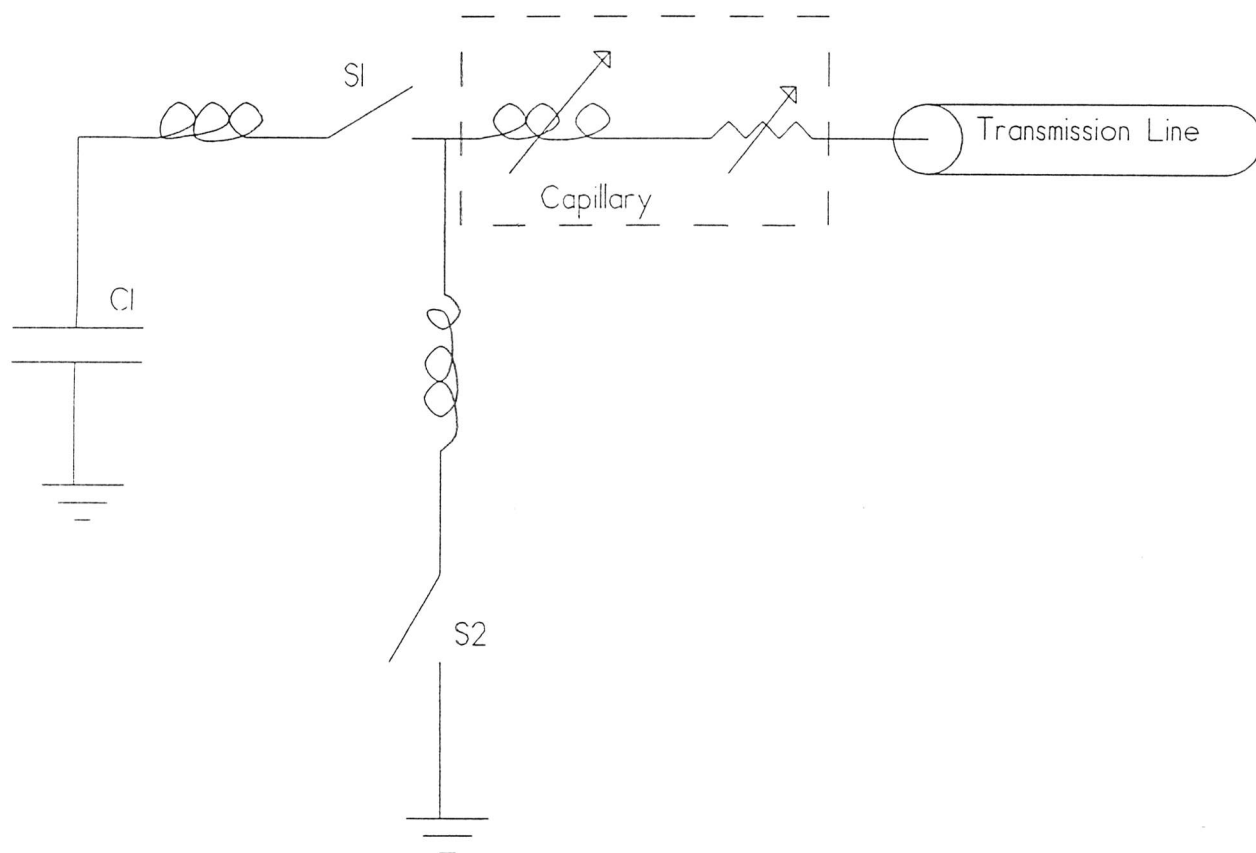


Fig. 2.2-1 Schematic of the original circuit concept for the discharge driver

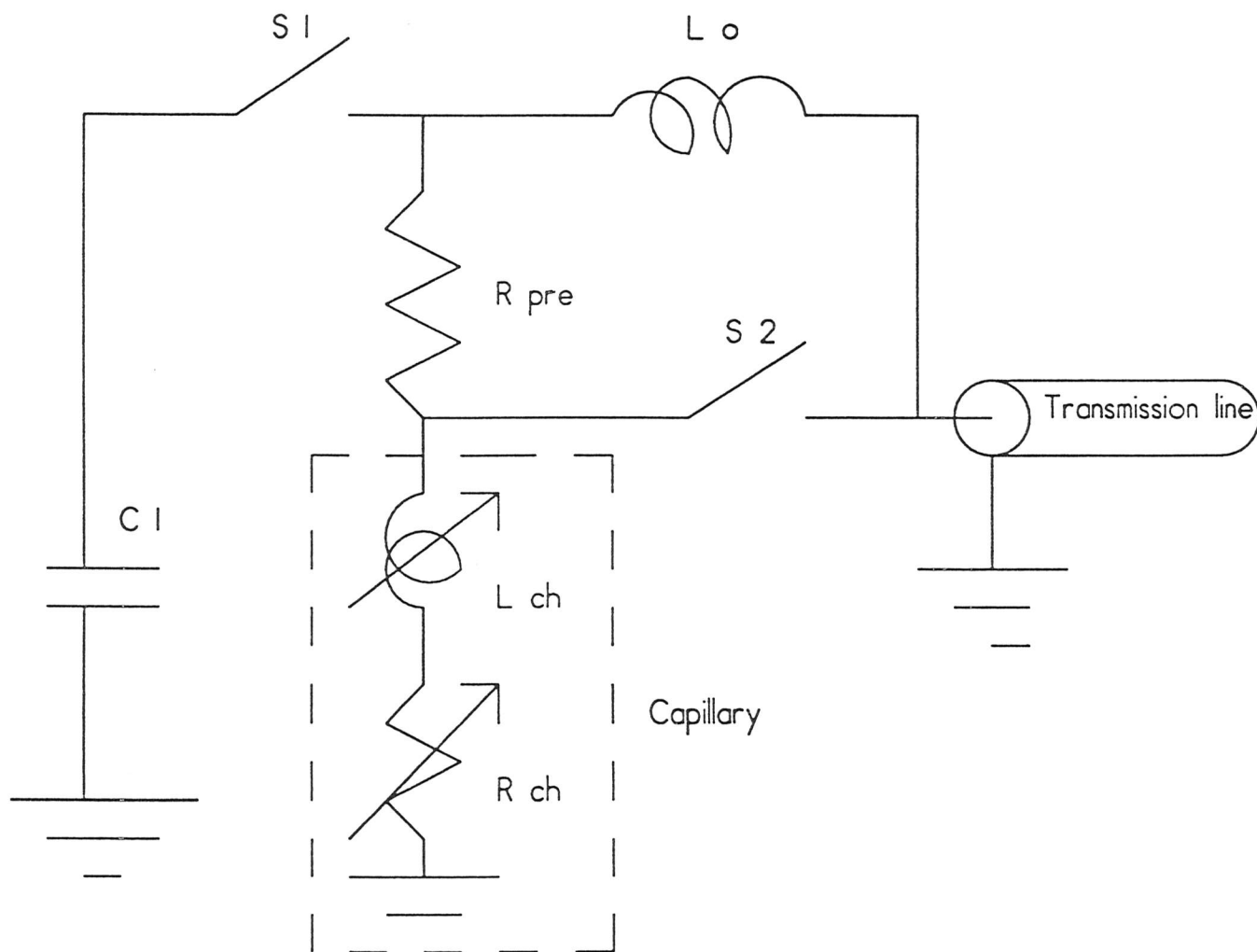


Fig. 2.2-2 Schematic of the basic discharge circuit used in the capillary discharge device

2.3 Basic Concept

The circuit diagramed in Fig. 2.2-2 is quite simple conceptually, but many details have to be carefully worked out before an actual device can be constructed. For example, care must be taken to insure the insulation is sufficient to prevent break-down at when operating at 200 kV. At the same time, however, the device must be small enough that the inductance of the transmission line / capillary interface is minimal in order to achieve the fastest possible rise time for the pump pulse. Since the capillary is cylindrical, coaxial geometry is the obvious choice for the transmission line. Fig. 2.3-1 shows a simple diagram of the device. For ease of comparison, the components in Fig. 2.3-1 have been labeled to correspond to the circuit diagram in Fig. 2.2-2. It should be noted that switch S2 is a self- breaking switch that is built into the transmission line, rather than being a separate component as might be assumed from the circuit diagram. The design of each component is discussed in detail in the following sections.

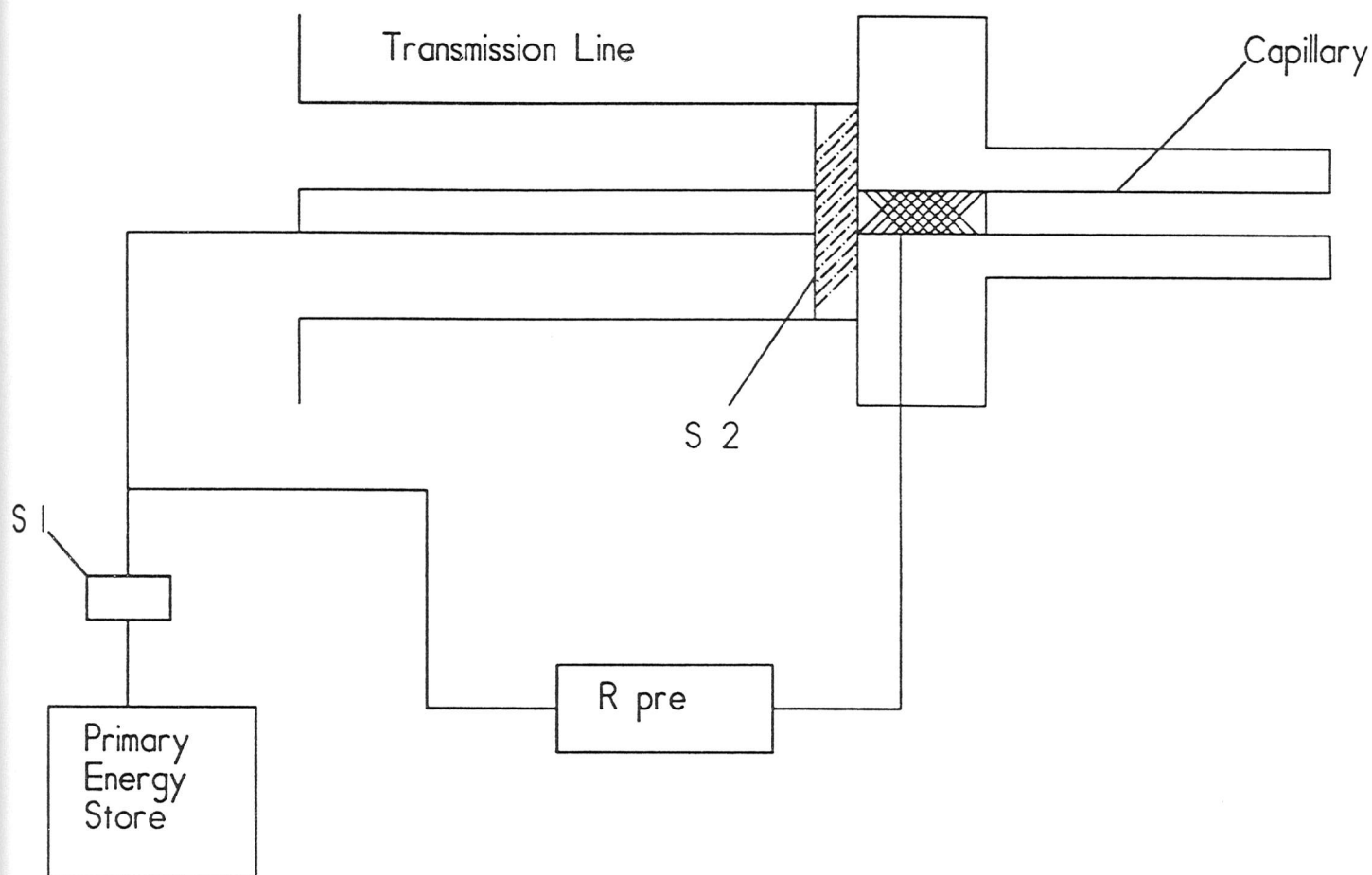


Fig. 2.3-1 Simplified diagram of the capillary discharge device

3. COMPONENTS

3.1 Insulation Requirements

One of the first considerations when designing high voltage equipment is the insulation required to prevent electrical breakdown (arcing). First consider the voltage placed on the capillary during the ionization pulse, I_{pre} . When switch S_1 closes, the voltage across the capillary will begin to rise towards the first stage output voltage which is 100 kV. As the argon gas in the capillary ionizes, however, the channel resistance falls to a few ohms or less. As a result of the low plasma resistance, the voltage across the capillary should stabilize at a few 10's of volts. Furthermore, the channel resistance should drop rapidly enough that the voltage on the capillary is no more than a few 10's of kV transiently. Next, consider the voltage stresses during the fast pulse stage. When switch S_2 closes to discharge the transmission line, the channel resistance is already very low as a result of the ionization pulse. As a result, the voltage at the "hot" terminal of the capillary should still not exceed a few 10's of kV unless the device goes open circuit. In summary, the insulation requirements for the capillary are only 10's of kV instead of 100's of kV. The capillary is machined from a block of polyacetal plastic which has a dielectric strength of 20 kV/mm. If the conductors are separated by at least 5 mm of plastic, then the insulation requirements should be adequately satisfied.

3.2 Capillary

It is convenient to design the capillary first and then size the transmission line and other components to match. The important parameters of the capillary are its length and inside diameter. In view of the plasma conditions necessary for lasing, the capillary is chosen to be 2 cm long and have an inside diameter of 2 mm. The simplest capillary design is a cylinder with a 2 mm diameter hole drilled through the center. In order to minimize the capillary inductance, the outer diameter of the capillary should be kept small. Unfortunately, the insulation requirements at the high voltage terminal of the capillary necessitate a relatively large outer diameter. A tapered capillary, such as the one shown in Fig. 3.2-1, gives the best balance between low inductance and sufficient insulation. The inner and outer conductors of the capillary at the high voltage terminal are separated by 5 mm which corresponds to a breakdown strength of 100 kV, which is significantly greater than the expected maximum voltage stresses.

3.3 Transmission Line

Having established the dimensions of the capillary, the next step is to design the transmission line which is responsible for launching the fast pulse into the capillary. De-ionized water is the best choice for the transmission line dielectric since it can be stressed with very high energy densities without breaking down, which, in turn, allows the device to be quite compact. The first step in designing the transmission line is to specify the length of the line. Those familiar with basic

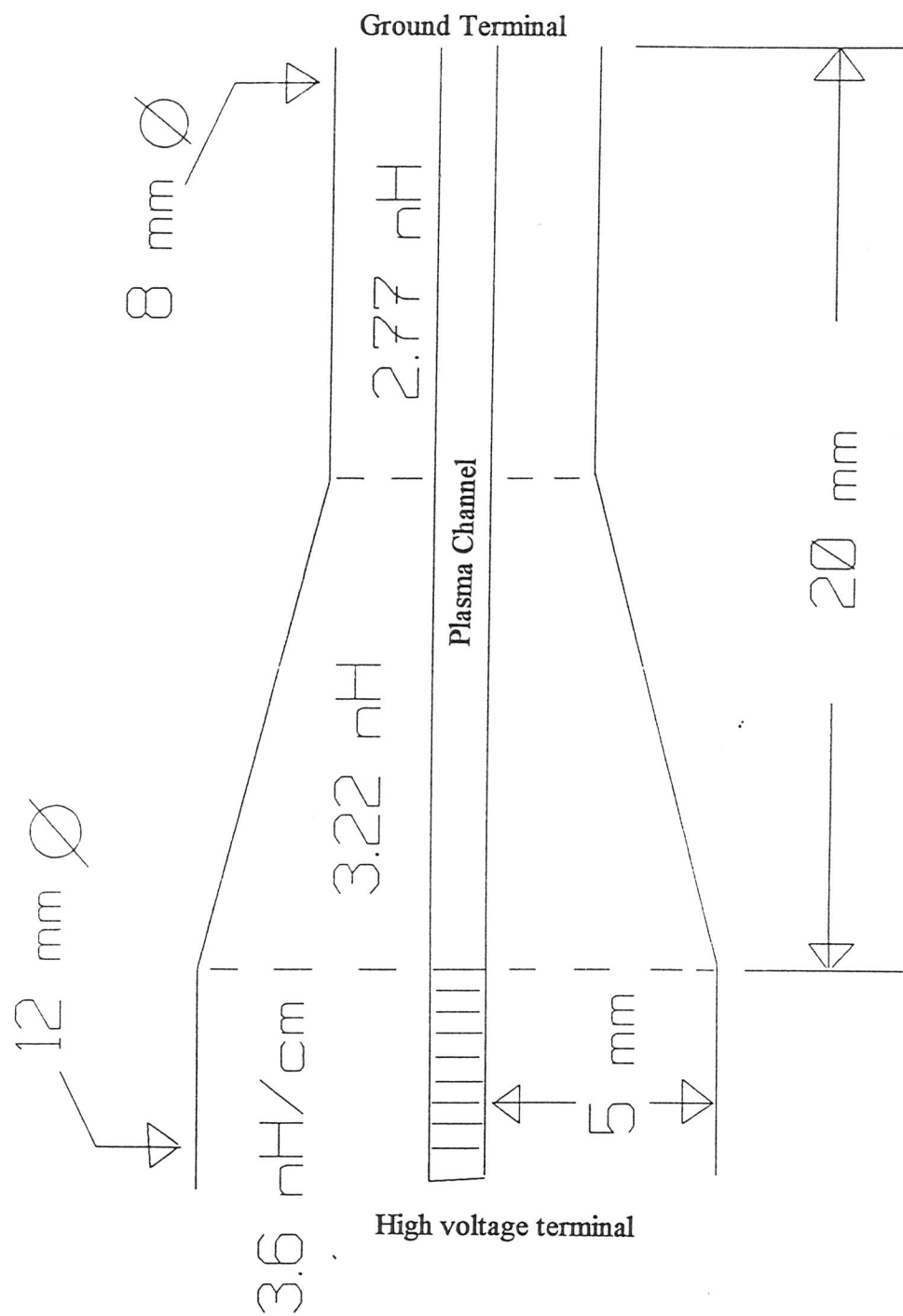


Fig. 3.2-1 Design of the capillary, showing the taper of the capillary and the approximate inductance of each segment

transmission line theory know that the width of a pulse produced by a transmission line is twice the transit time of the line. Therefore, specifying the length of the line is a simple matter of multiplying the half-width of the desired pulse by the speed of propagation in the transmission line. The length of the transmission line, L , is then⁷

$$L = \delta \frac{c}{\sqrt{\epsilon_r}} \quad (3.3-1)$$

where δ is the pulse half-width and ϵ_r is the dielectric constant of the insulator in the transmission line and c is the speed of light. For de-ionized water, the dielectric constant is about 80.⁸ To allow for rise time loss and to give the pulse generator a little more flexibility, choose a pulse width of 12 ns. From Eq. 3.3-1 it is easy to calculate the necessary length of the transmission line to be 20 cm.

The next step is to calculate the electric stress on the transmission line when it is charged to its full operating voltage. For convenience in matching the transmission line to the capillary, the inner conductor has a radius, r_i , of 0.5 cm while the radius of the outer conductor, r_o , is 2.24 cm. The surface area of the inner conductor, A_i , is 64 cm² and the area of the outer conductor, A_o , is 280 cm². The breakdown relation for water with a positive applied field is⁹

$$E_{Pos} = \frac{0.23}{t_{eff}^{\frac{1}{3}} A^{0.058}} \quad (3.3-2)$$

and the breakdown relation for a negative applied field is¹⁰

$$E_{neg} = \frac{0.557}{t_{eff}^{\frac{1}{3}} A^{0.069}} \quad (3.3-3)$$

In both equations, t_{eff} is the length of time (measured in μs) the system is above 63% of breakdown.

If the electrode area, A , is measured in cm^2 , then the critical field strengths will be in units of MV/cm.

For this system, t_{eff} is estimated to be about 0.25 μs so the critical field strengths are

$$E_{pos} = 0.262 \frac{MV}{cm} \quad E_{neg} = 0.687 \frac{MV}{cm} \quad (3.3-4)$$

One interesting consequence of Eq. 3.3-4 is that water has a greater resistance to breakdown when a negative voltage is applied than when positive voltage is applied. To take advantage of this fact, the center electrode (which will have the strongest surface field) will be charged to a negative potential.

To calculate the surface fields at the two conductors of the transmission line, use the relation¹¹

$$E = \frac{V}{r \ln \frac{r_2}{r_1}} \quad (3.3-5)$$

where V is the applied voltage, r_2 is the radius of the outer conductor and r_1 is the radius of the inner conductor. Eq. 3.3-5 reduces to

$$E = \frac{0.133}{r} \frac{MV}{cm} \quad (3.3-6)$$

when the voltage is 200 kV. From Eq. 3.3-6, the surface fields are

$$E_{outer} = 0.06 \frac{MV}{cm} = 0.23 E_{pos} \quad (3.3-7)$$

and

$$E_{inner} = 0.266 \frac{MV}{cm} = 0.39 E_{neg} \quad (3.3-8)$$

At 200 kV, the electrode surface fields will be less than 50 % of the breakdown strength of the water dielectric which will allow for higher operating voltages if required. Fig. 3.3-1 is a drawing of the transmission line mated to the capillary assembly.

3.4 Transmission Line Switch

A simple water breakdown switch is used to switch the energy out of the transmission line and into the capillary. This switch is nothing more than a small, water filled gap between the center conductor of the transmission line and the capillary electrode where the breakdown voltage is controlled by the distance between the two electrodes. To calculate the approximate electrode spacing, use the relationship¹²

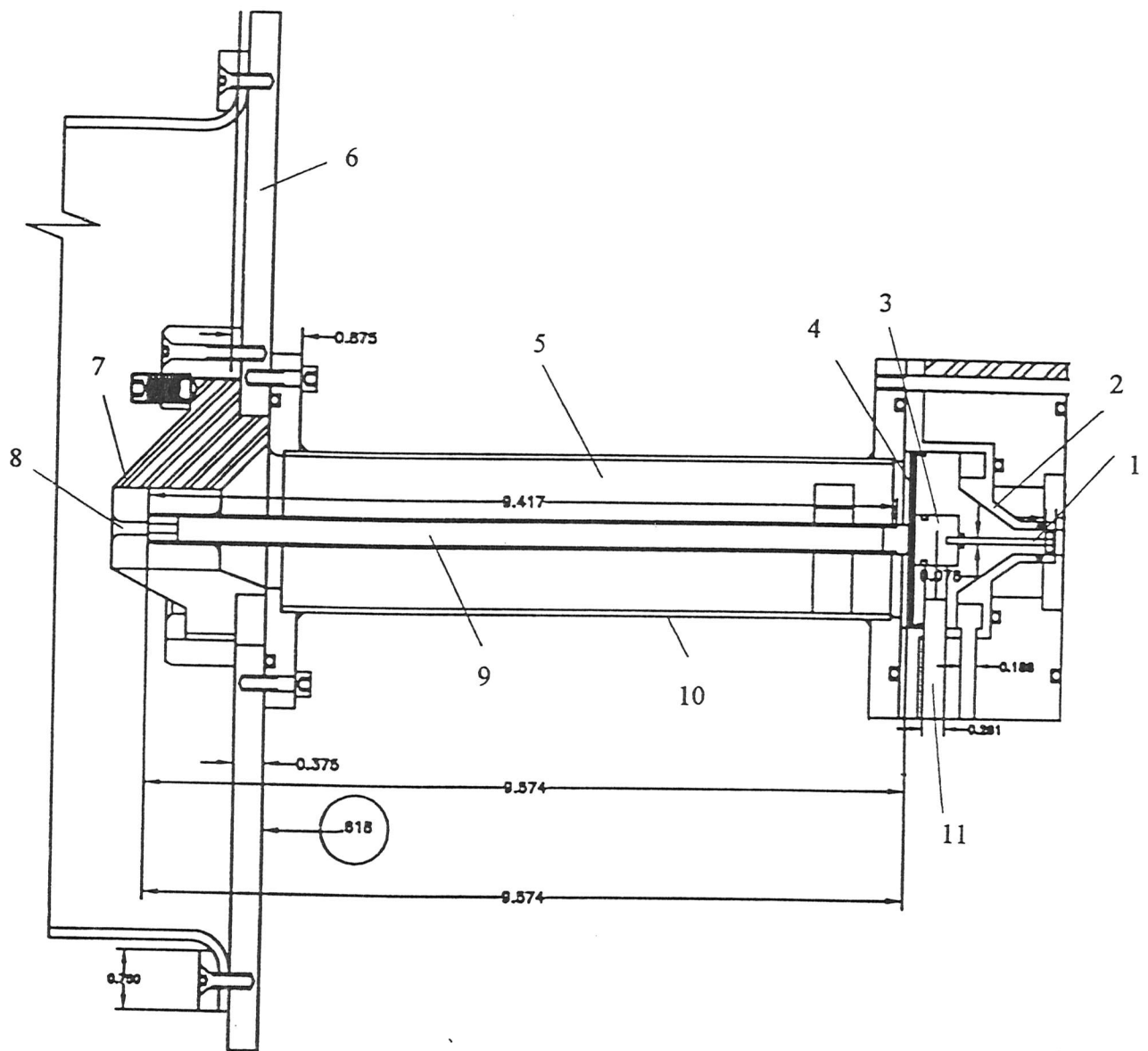


Fig. 3.3-1 Schematic of the transmission line and capillary assembly: 1) capillary, 2) current return path, 3) capillary electrode, 4) switch S2, 5) DI water, 6) steel plate that serves as ground connection, 7) support for center conductor, 8) attachment point for Marx generator, 9) transmission line center conductor, 10) transmission line outer conductor, 11) access for cable carrying I_{pre} (dimensions are in inches)

$$E \sqrt{t_{eff}} = 0.1 \quad (3.4-1)$$

where E is the electric field in MV/cm and t_{eff} is the same quantity as in Eq. 3.3-3. Eq. 3.4-1 can be rewritten as

$$\frac{V}{d} \sqrt{t_{eff}} = 0.1 \quad (3.4-2)$$

where V is the voltage in MV and d is the electrode spacing. Using Eq. 3.4-2 and specifying the voltage as 200 kV yields an electrode spacing of 1 cm. For a switch operating with a single breakdown channel, the switch inductance is about 15 nH/cm of channel length. Therefore, the water gap is not the fastest possible switch that could be used in the transmission line, but it is the simplest and it allows the device to be fired repetitively without any adjustments being made to the switch. Section 5.2 discusses two additional switching schemes that would allow faster switching.

3.5 Marx Generator

A compact Marx generator is used as the primary energy store for the capillary discharge. This generator serves two purposes. First, it provides the constant current pulse through the capillary which ionizes the plasma prior to the fast pulse, and, second, the Marx generator pulse charges the transmission line. The Marx generator was invented in 1923¹³ as a means of generating very high voltage. Shown in Fig. 3.5-1¹⁴ are three common Marx generator circuits. Looking at Fig. 3.5-1a, it is possible to understand the basic operation of a Marx generator. Assume the charge voltage of

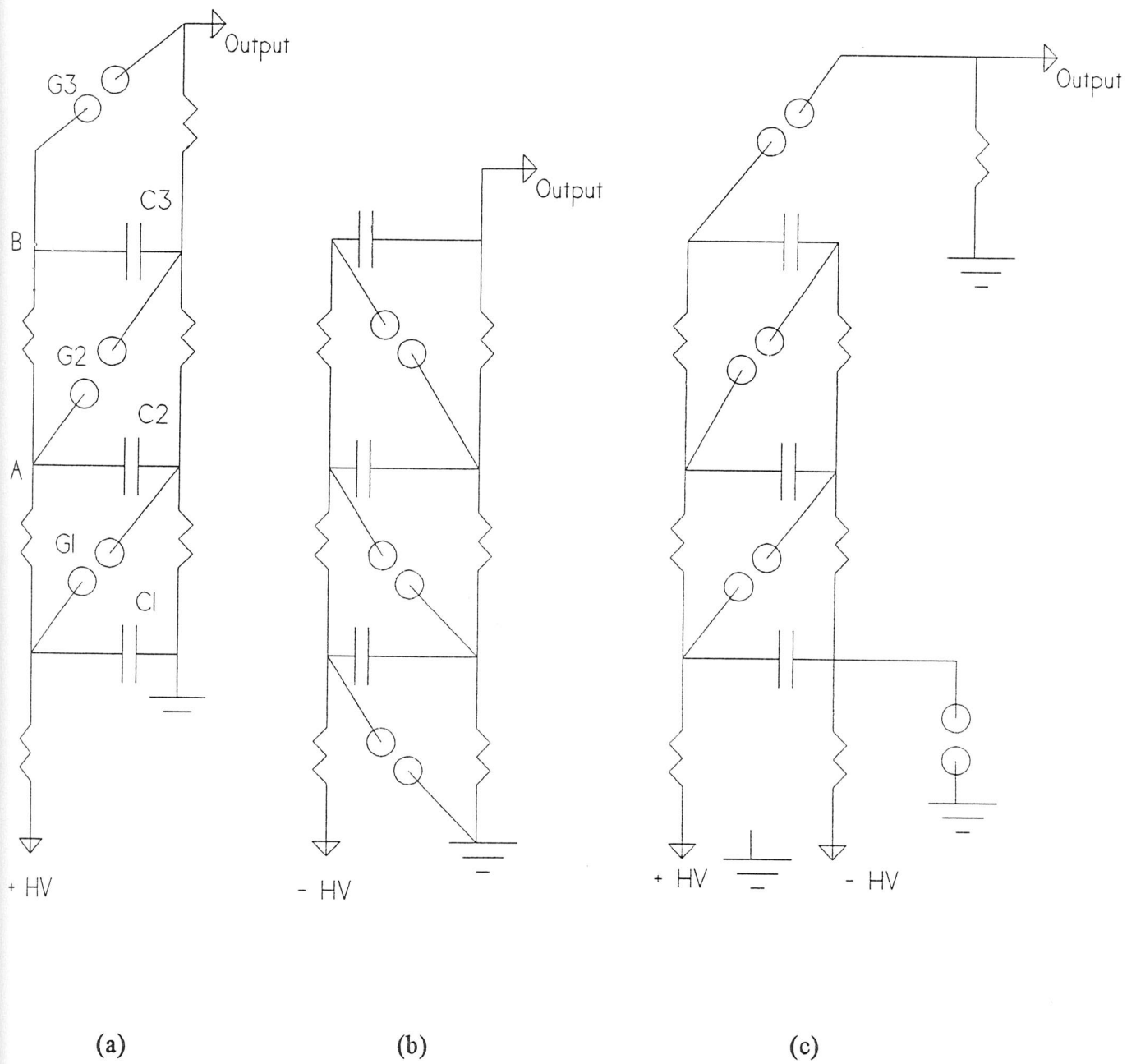


Fig. 3.5-1 Three common Marx generator circuits

the generator is specified as V volts. Each of the spark gap switches (G_1 , G_2 , G_3) is set to withstand V volts and then the capacitors are charged in parallel to V . After charging, all of the parts on the left of the generator are at a potential of V volts while the components on the right side are at ground potential. Switch G_1 is now triggered, connecting capacitors C_1 and C_2 in series. Since the voltage dropped by the arc across the spark gap is very small, the potential at point A rises rapidly to $2V$. Switch G_2 can only withstand V volts, however, so it breaks down, connecting capacitor C_3 in series with the other two. The potential at point B rises to $3V$ which in turn breaks down G_3 , switching the energy out of the generator.¹⁵ Clearly, the output voltage is three times the charge voltage. In general, it is possible to build a Marx generator with any number of capacitive stages. The resulting output voltage is always NV , where N is the number of stages and V is the charging voltage. In Fig. 3.5-1, circuit 3.5-1b is essentially the same as 3.5-1a except for the fact that the output voltage has the opposite polarity of the charge voltage. Circuit 3.5-1c uses a bipolar charging unit which can reduce corona problems in very high voltage applications.

Fig. 3.5-2 shows a schematic of the specific Marx generator for the x-ray laser driver. Since the driver is only designed to operate at 200 kV, it would be possible to make do with a single capacitor and save the cost and complexity of building a Marx generator. Using only a single capacitor, however, would require charging the capacitor to its maximum operating voltage which greatly reduces the service lifetime of the capacitor. The Marx generator not only reduces the stress on the capacitors, but it allows much greater flexibility in the output voltage.

One difference between the actual design and the theoretical circuits in Fig. 3.5-1, is the spark gaps. In this case all three switches are triggered which allows for more reliable operation of the generator than when two of the gaps are self-breaking. The switches in the Marx generator each have

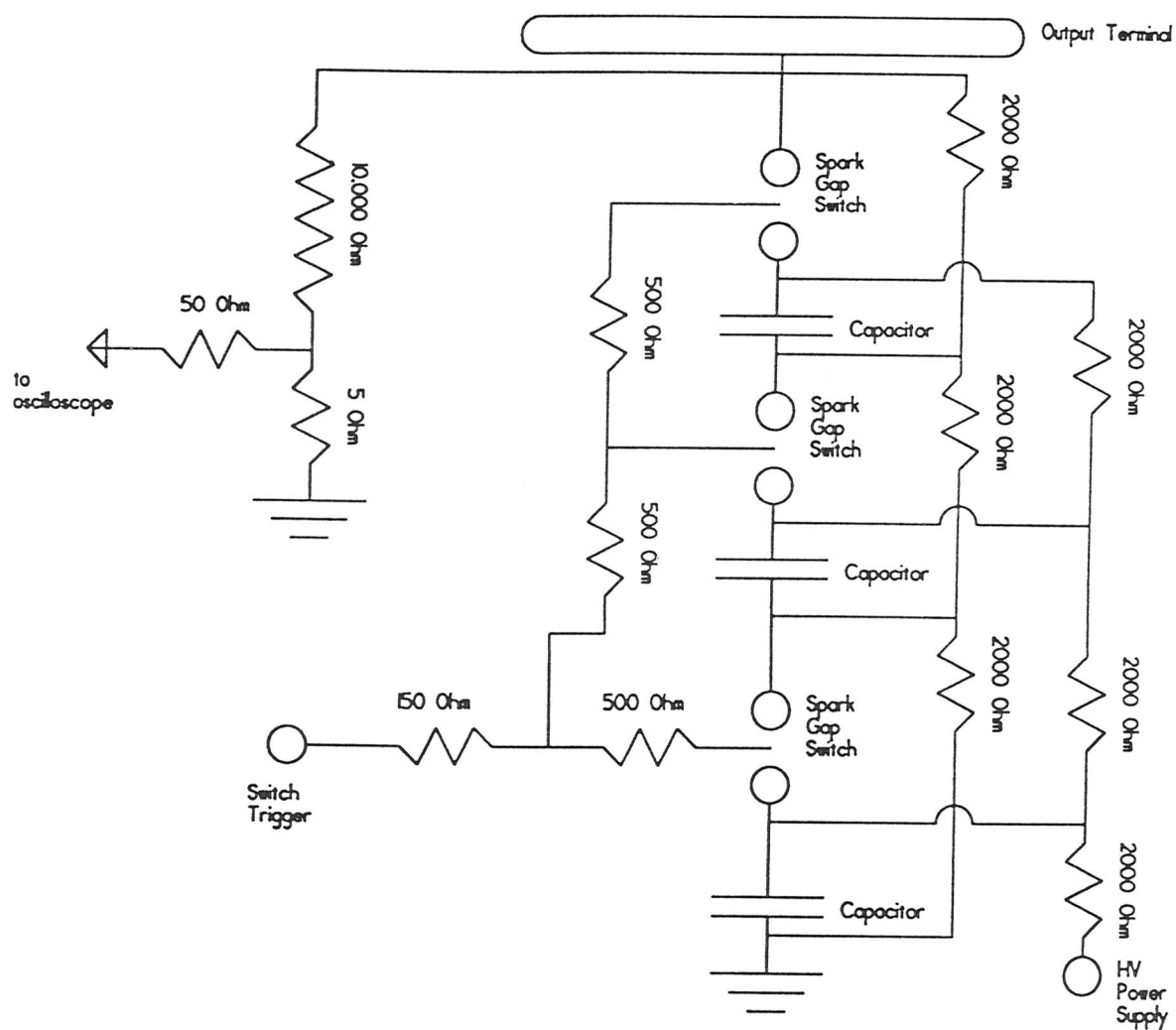


Fig. 3.5-2 Circuit diagram of the specific Marx generator used in the pulse generator

a trigger plate between the main electrodes as indicated in Fig. 3.5-2. The circuit is arranged so that the top switch electrode is at ground potential, the trigger plate is at $-V/2$ and the bottom electrode is at $-V$, where V is the charge voltage of the capacitors. The switches trigger when a short positive high voltage pulse is applied to the trigger plates. Also indicated in Fig. 3.5-2 is the attachment for the trigger pulse generator. The trigger pulse is produced by a simple cable pulser which is shown schematically in Fig. 3.5-3. The trigger line is charged simultaneously with the Marx capacitors to a voltage of $-V$. When the center cable conductor is shorted to ground using a large Ross relay for a switch, a voltage pulse of $+2V$ is applied to the trigger plates. This trigger generator is fairly crude, but it has been shown to trigger the Marx generator reliably. Although it is not shown in Fig. 3.5-2, the resistor that controls the ionization current (I_{pre}) also attaches to the output plate of the Marx generator. Currently, this resistor is a 1000Ω high power resistor so I_{pre} is limited to 100 A.

It is important to note that while the internal voltage in the capacitors is the charge voltage, the fields from the capacitors to ground are determined by the erected voltage of the generator. As a result, it is very important that the generator components are adequately insulated from ground. The most convenient physical arrangement of the components to maintain the insulation requirements is to stack the capacitors vertically as shown in Fig. 3.5-4. In this configuration, plates can be affixed to the sides of the capacitor supports to allow the attachment of the various resistors. All of the supporting hardware is made from a suitable insulating plastic. Care must be taken during construction to avoid sharp corners, wire ends etc. that will provide field enhancement points that may lead to arcing.

The high voltage capacitors used in the Marx generator are manufactured by CSI Capacitors, model number 100W329. Each capacitor has a capacitance of 35 nF and is rated for operation at

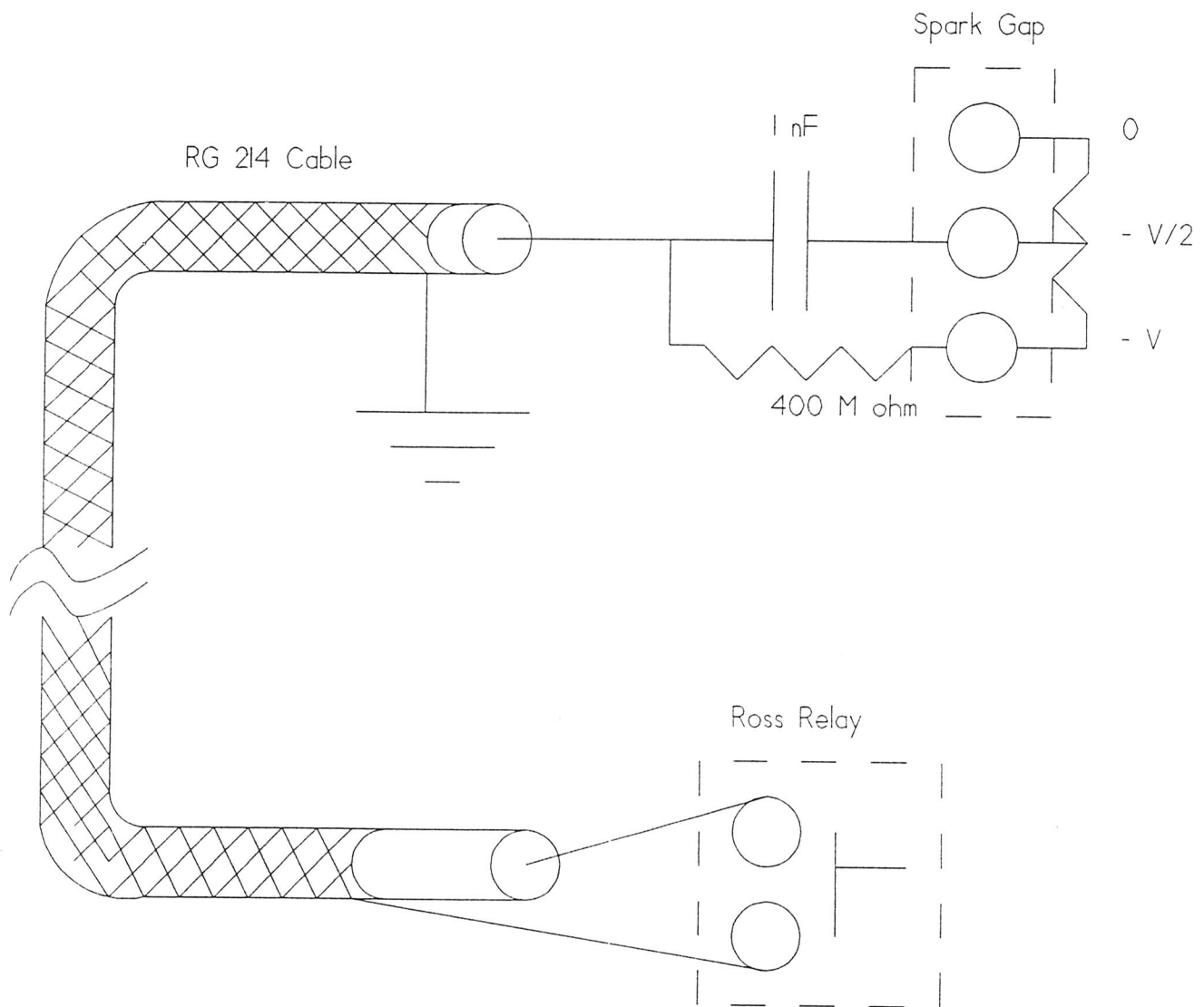


Fig. 3.5-3 Cable pulser used to trigger the spark gap switches in the Marx generator

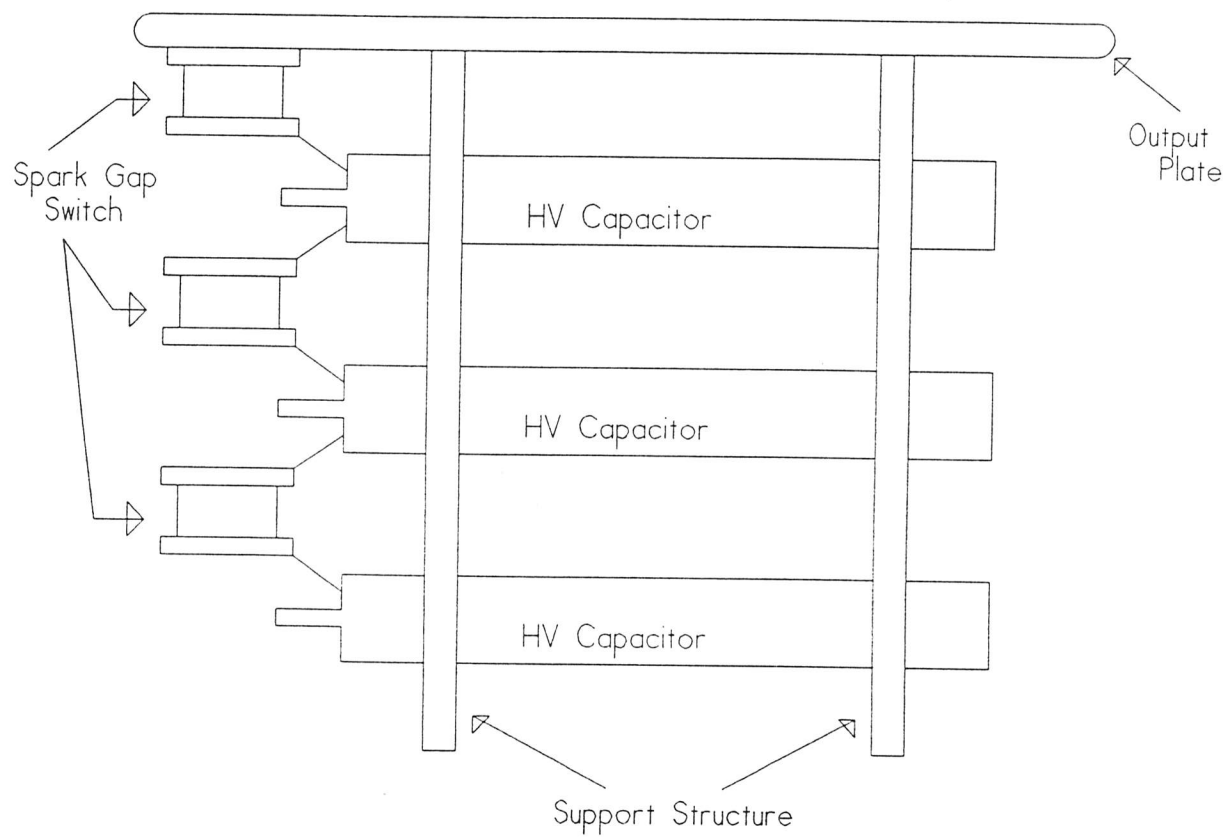


Fig. 3.5-4 Physical arrangement of the capacitors in the Marx generator

charge voltages up to 100 kV. The spark gap switches are from Maxwell Laboratories, Inc., model number 40264. The switches are designed to operate reliably at charge voltages from 25 kV to 100 kV. The maximum peak current rating of the switches is 100 kA. The resistors used in the Marx generator are non-inductive bulk ceramic power resistors manufactured by Cesiwid, Inc. It is important that the resistors are non-inductive since the total inductance of the pulse generator needs to be as small as possible.

3.6 Resonant Charge Inductor

The Marx generator is connected to the transmission line through a large inductive coil. This coil serves two purposes. First, it decouples the Marx generator from the transmission line discharge and, second, it allows resonant charging of the transmission line to approximately twice the output voltage of the Marx generator. In order to allow time for the preionization pulse to begin ionizing the plasma in the capillary, the inductor is constructed to have an inductance of about 50 μH . A 50 μH inductor causes the charging time of the transmission line to be 0.5 μs . The inductor is constructed from RG-8 coaxial cable with the outer insulation and braid removed. The inductor is 30 cm long, 20 cm in diameter and has twenty turns. Using a formula for the inductance of a solenoid,¹⁶

$$L = \frac{\mu_0 n^2 A}{d} \quad (3.6-1)$$

where n is the number of turns, A is the area of each turn, d is the length of the coil and μ_0 has the

value 1.26×10^{-6} H/m, the inductance of the coil can be calculated to be 50 μ H. The actual measured inductance of the coil is 48 μ H.

4. TESTS AND DIAGNOSTICS

4.1 Static Breakdown Tests

Once the driver was constructed, static breakdown tests were performed to determine the operating pressure for the spark gap switches since the operating voltage of the switches depends directly on the gas pressure in the switch. In a static breakdown test, the pressure in the switch is set and the voltage across the switch is slowly increased until the switch breaks down without being triggered. These breakdown tests were performed with the switch pressure set at 0, 5, 10 and 15 PSIG. Repeated tests at each pressure confirmed that the breakdown characteristics of the switches are very reproducible. Fig. 4.1-1 shows the results of the static breakdown tests and a plot of breakdown voltage (in kV) versus internal switch pressure (in PSIG). Once the static breakdown tests are complete, the breakdown data is used to plot an operating curve for the switches. The operating voltage of the switches is

$$V_{\text{operating voltage}} = \frac{V_{\text{static breakdown}}}{M} \quad (4.1-1)$$

where M is typically chosen to be about 1.5. Fig. 4.1-2 shows the operating voltage curve calculated

Switch Pressure (PSI)	Breakdown Voltage (kV)	Average (kV)
0	23	23
5	31, 30, 30, 31	30
10	38, 37, 37, 37	37
15	46, 46, 46	46

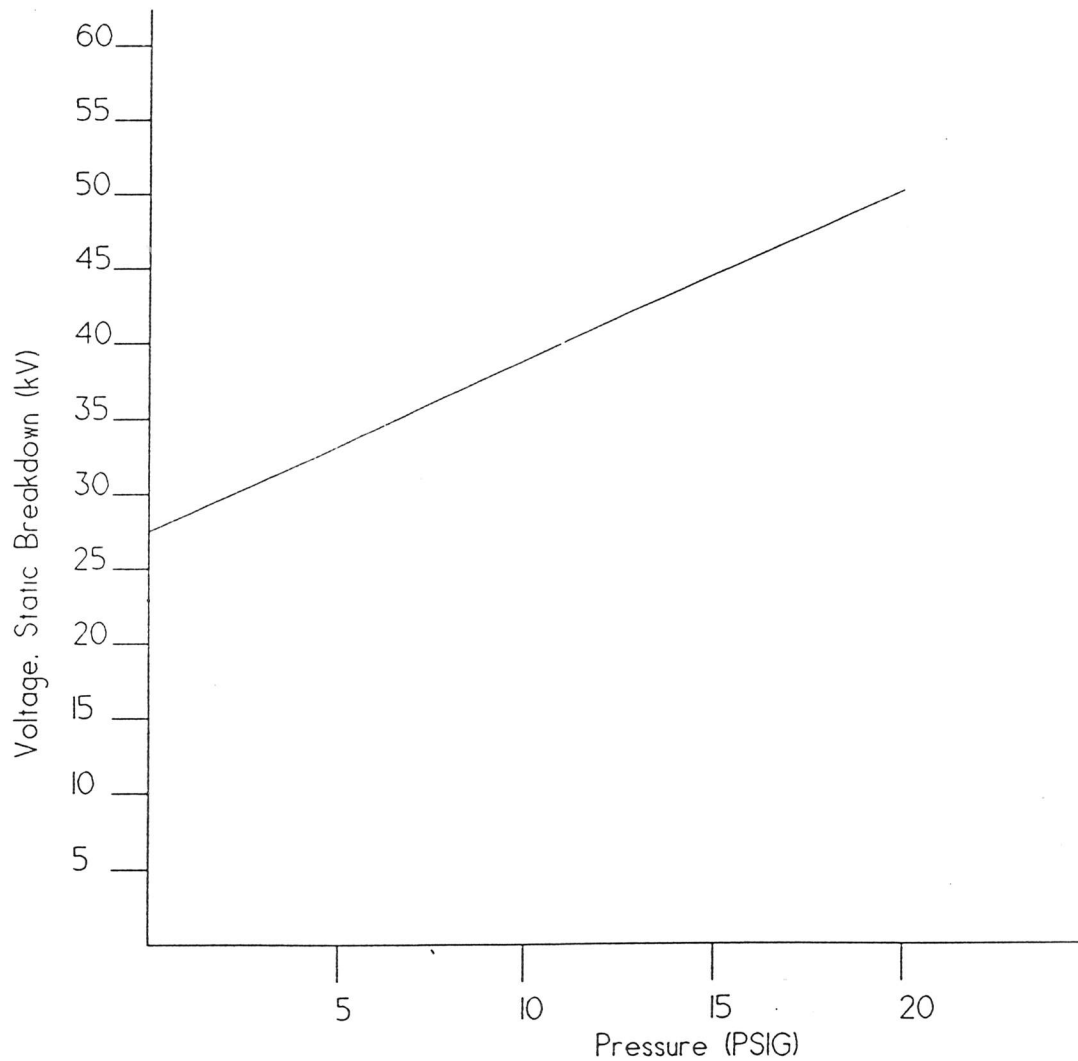


Fig. 4.1-1 Results of the static breakdown tests of the spark gap switches

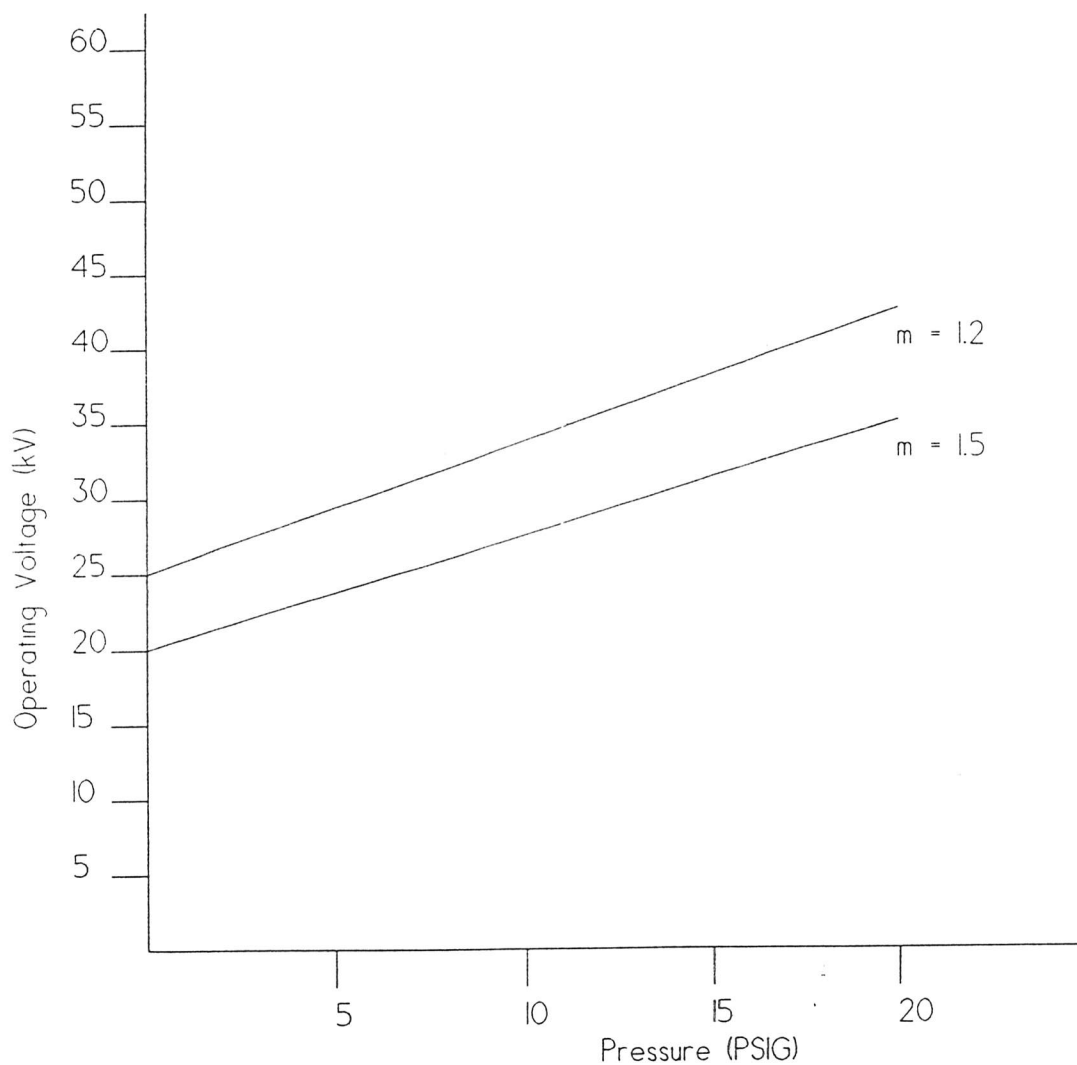


Fig. 4.1-2 Operating voltage curves for the spark gap switches calculated for $M=1.2$ and $M=1.5$



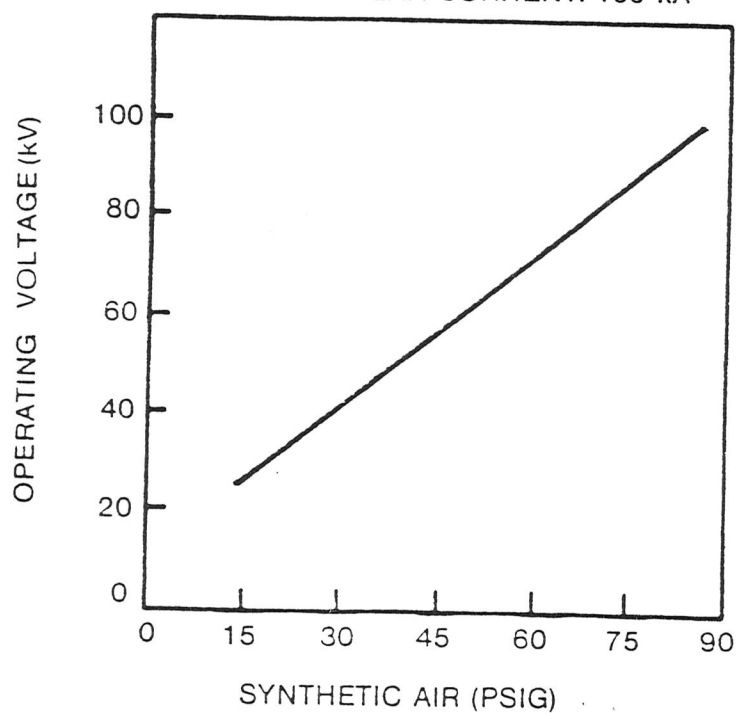
HIGH VOLTAGE SPARK GAP SWITCH

MODEL #40264

RATINGS

VOLTAGE: 25 to 100 kV

MAXIMUM PEAK CURRENT: 100 kA



OPERATING CURVE $M = 1.5$

Fig. 4.1-3 Operating voltage curve provided by the switch manufacturer

from the breakdown test data for $M=1.2$ and $M=1.5$. The operating curve for $M=1.5$ in Fig. 4.1-2 agrees closely with the operating curve, shown in Fig. 4.1-3, provided by the manufacturer of the switches, Maxwell Laboratories.

4.2 Visible Light Data

The capillary produces an intense pulse of purple light when the current pulse is discharged, so one obvious test of the system is to study the visible light output. A photomultiplier tube was used to look at the temporal behavior of the visible light. Fig. 4.2-1 shows the output of the tube for one discharge of the capillary and is representative of all of the data of this nature. The very large, narrow peak at the beginning of the waveform is not "real" data, but rather an electrical transient caused by the discharge of the Marx generator and the transmission line. An attempt was made to shield the photomultiplier tube electrically, but it proved impossible to block out this transient. Conclusive evidence that this pulse is not part of the visible light output is provided by completely blocking the end of the tube and then discharging the capillary. In this case, the oscilloscope records this same sharp, narrow pulse and then nothing else.

At first glance, the visible light data seems to conform very well to the expected current waveform since the intensity drops to a low plateau and then falls rapidly to a large negative value. (Note: Due to the nature of the PMT, high light intensities correspond to large, negative voltages.) Unfortunately, careful consideration reveals that this visible light data is highly misleading. The long time scale of this data indicates that there is a very low probability that the light output has any direct correlation with the current waveform since the entire current pulse is unlikely to last more than 10ns.

26-Sep-96
15:33:54

M1
.1 ms
10.0 V

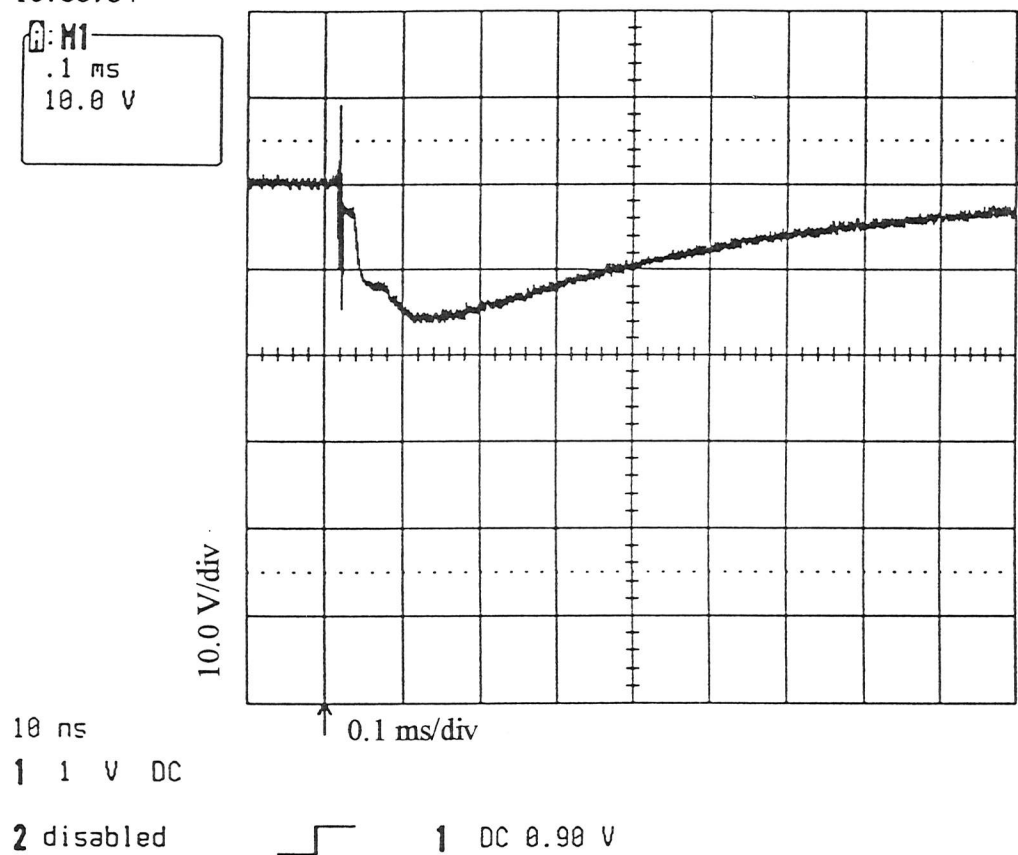


Fig. 4.2-1 Output of the photomultiplier tube showing the temporal behavior of the visible light produced by the discharge

A possible explanation of the data is that the current pulse travels through the capillary and excites the atoms in the plasma to very energetic states. Then as the atoms begin to relax, the x-ray and hard ultra-violet transitions occur, but are not detected by the photomultiplier tube. Then the visible light transitions, with their much longer transition times, begin to occur producing the intensity peak detected by the tube. Most of the visible light detected by the PMT is actually produced a relatively long time after the current pulse passes through the capillary. An attempt was made to look at the ultra-violet light produced by the capillary using a PMT that is sensitive to light with 100 to 400 nm wavelengths. Unfortunately, the electrical noise produced by the discharge prevented meaningful data about the leading edge of the current pulse from being collected, since the noise drowned out any signal that might have been seen by the PMT. One solution to the noise problem, is to move the PMT far away from the discharge and feed the signal to it using a fiber optic. It would be necessary to find a phosphor with a sub-nanosecond response time that would fluoresce in the visible spectrum when exposed to UV light to perform such an experiment, however, since fiber optics attenuate UV light too strongly to be of use alone.

4.3 Copper Sulfate Voltage Probe

As originally designed, the Marx generator was fitted with a simple voltage divider to monitor the output voltage. This divider consisted of a high power 10,000 Ω resistor and a 5 Ω resistor in series with the oscilloscope attached between the two resistors. This arrangement should provide a 10,000 : 1 voltage division so that the 100,000 V output of the Marx generator would be shown as 10 V on the oscilloscope. Unfortunately, this device proved to be unacceptably noisy so

it was replaced with a copper sulfate voltage probe. Fig. 4.3-1 is a schematic of the copper sulfate probe. As can be clearly seen in the figure, the center conductor of the output connector is attached to the high potential plate of the small gap while the outer conductor is attached to the ground terminal of the entire probe. As a result, the voltage measured by the oscilloscope is the voltage across the small gap. The voltage across the small gap depends both on the overall length of the probe and the resistivity of the copper sulfate solution. The resistivity of the copper sulfate solution depends, of course, on the concentration of the solution. Possible resistivities range from 4600 Ω -cm down to 57 Ω -cm.¹⁷ Appendix A contains detailed information on the resistivity of copper sulfate solutions.

The resistance of the probe can be calculated from the solution resistivity using the formula¹⁸

$$R = \frac{\rho L}{A} \quad (4.3-1)$$

where ρ is the resistivity of the solution, L is the length of the gap and A is the area. The small gap of the probe is 0.15 cm long and has an area of 3.08 cm². The main portion of the probe is 40.6 cm long and has an area of 5.06 cm². Therefore, for a given solution resistivity, the resistance of each gap can be calculated and then the voltage measured across the small gap can be approximated by treating the probe as a simple voltage divider. The actual voltage across the small gap depends, however, not only on the resistance, but also on the capacitance of the gap. As a result, it is necessary to calibrate the probe before it is used. The probe used in the discharge device has a resistivity of 500 Ω -cm and is used in series with a 10,000 Ω high power resistor to further reduce the voltage measured by the oscilloscope attached to the probe. The probe was calibrated using the

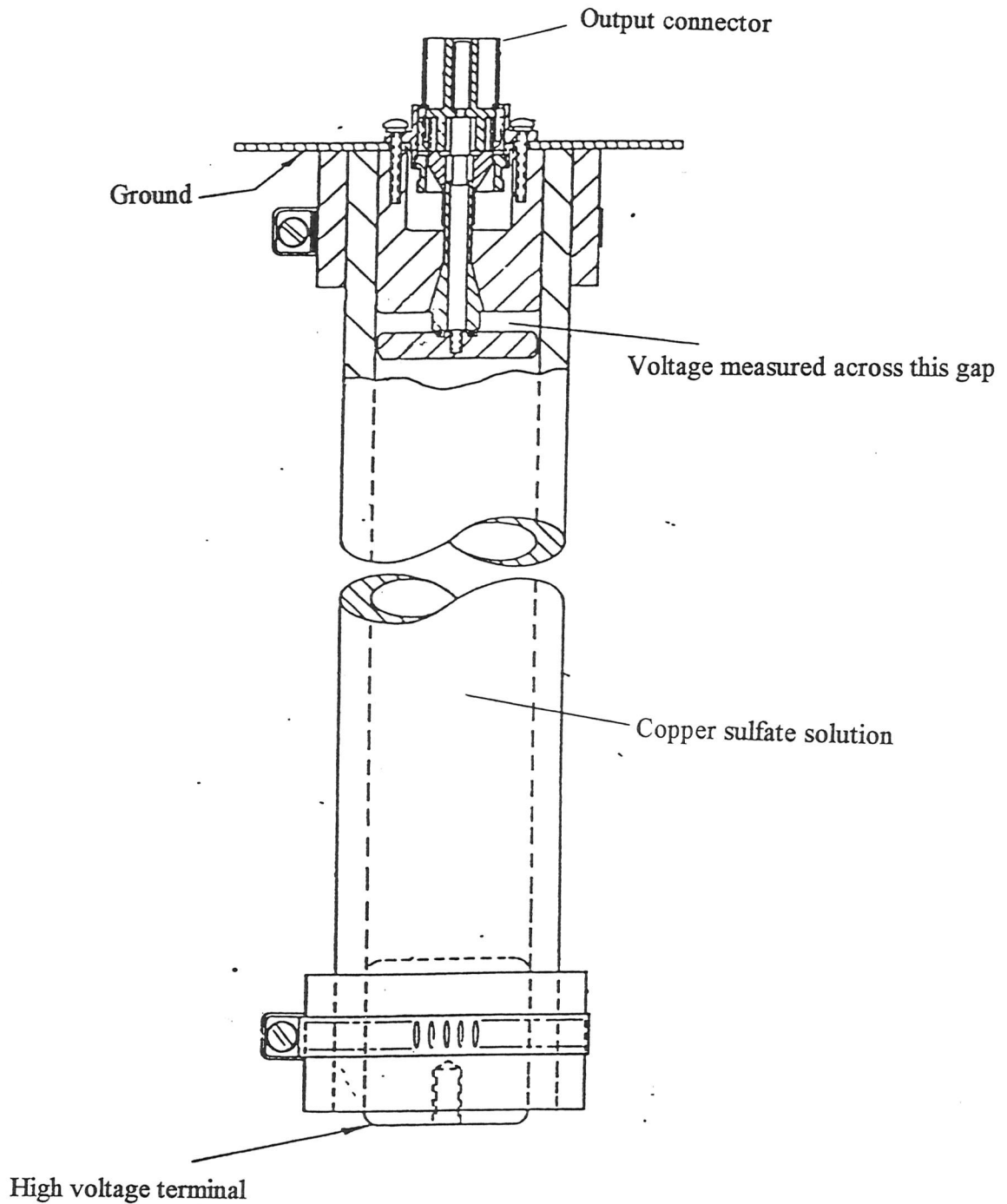


Fig. 4.3-1 Schematic of the copper sulfate voltage probe

output of the Marx generator, since the output of the Marx is three times the charge voltage and the charge voltage is known for each discharge. The response of the probe is completely linear over a wide voltage range and its calibration function is

$$V = 1.33(S + 26) \quad (4.3-2)$$

where V is the voltage (in kV) applied to the probe and S is the voltage (in volts) measured by the oscilloscope.

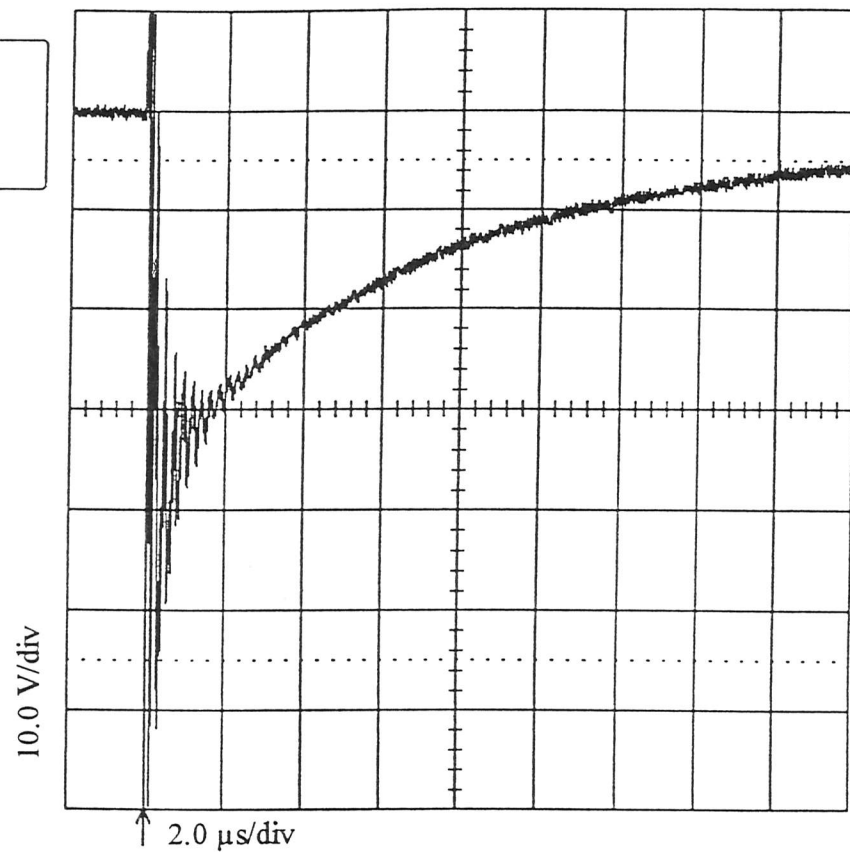
Fig. 4.3-2 shows the voltage waveform produced when the Marx generator is fired without the transmission line attached. In this case, the voltage probe was attached to the output plate of the Marx generator. The overall shape of the waveform is as expected, that is the voltage rises sharply to a maximum (in this case negative) value and then decays exponentially back to zero. Clearly there is some ringing at the beginning of the pulse and the voltage seems to over shoot the expected value as the Marx erects, but it is easy to extrapolate the general form.

The voltage waveform of the Marx generator has little value beyond showing that the generator is working as expected. What is interesting is the voltage waveform measured at the transmission line. Fig. 4.3-3 shows the output of the voltage probe when it is connected to the center conductor of the transmission line during a discharge. In this trace, the point corresponding to zero voltage is very near the top of the display, so the long voltage drop at the left edge of the trace is clearly the charging phase of the transmission line. In this particular trace, the voltage drops to -70 volts which corresponds to -130 kV. The charging time for the transmission line is seen to be about 0.5 μ s which is what it was predicted to be when the device was designed. After the voltage is fairly constant for a short time, the transmission line switch breaks down, causing a very sharp rise in the

25-Oct-96

10:01:33

M1
2 μ s
10.0 V



2 μ s

1 10 V DC

2 disabled



1 DC -4.6 V

Fig. 4.3-2 Output voltage of the Marx generator with the transmission line disconnected

25-Oct-96

12:21:09

M1
.2 μ s
10.0 V

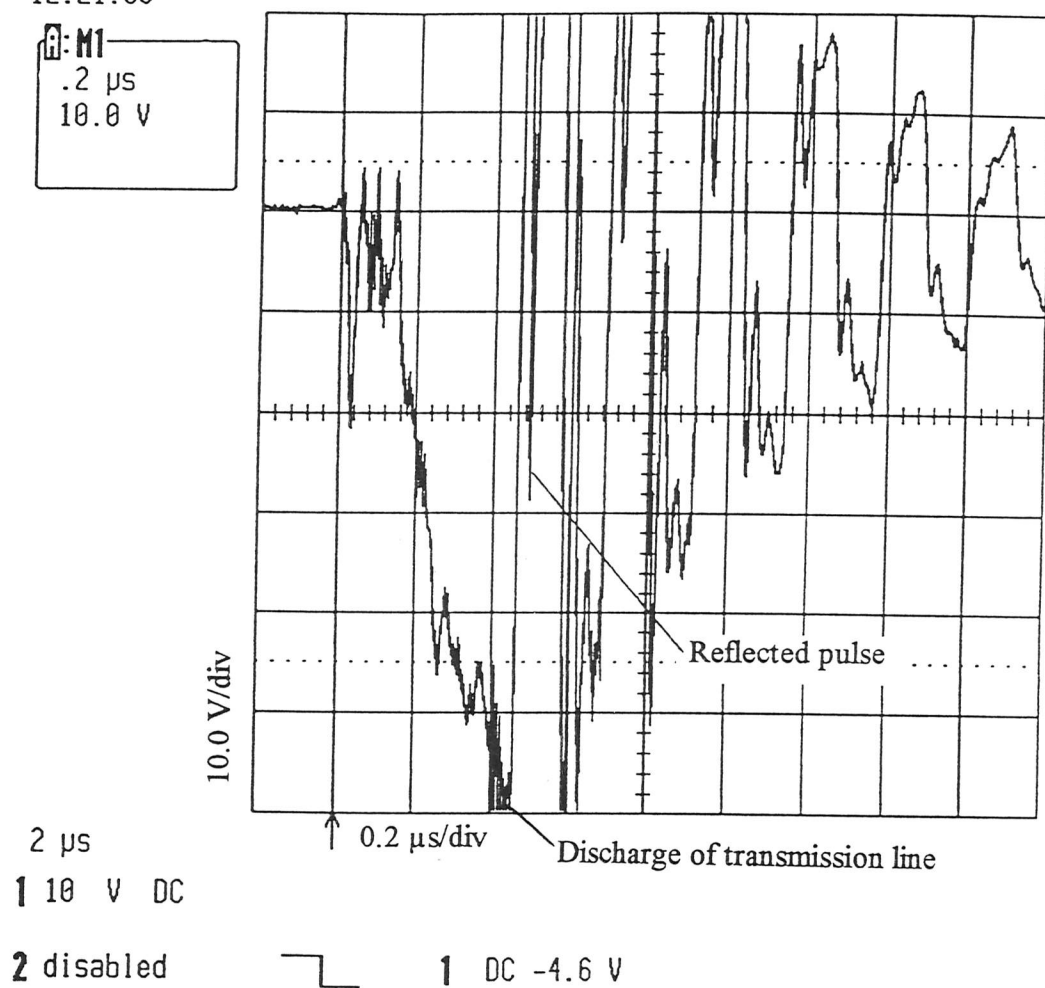


Fig. 4.3-3 Voltage output of the transmission line

voltage as the transmission line discharges through the capillary. Approximately 30 ns after the transmission line switch closes, a small negative pulse is seen. This pulse is energy that has traveled the length of the transmission line, and reflected back since the capillary is not terminated. Since the transit time of the transmission line is 12-15 ns, the delay between the discharge of the transmission line and the arrival of the reflected pulse is exactly what would be expected. The large repeated pulses that follow the discharge and seem to decay exponentially are due to the ringing in the Marx generator which can also be seen in Fig. 4.3-2. When viewing this data, it is clearly important to determine that the sharply rising edge following the charging phase is really the discharge of the transmission line and not just an artifact of the ringing in the Marx generator. If the trace is expanded as in Fig. 4.3-4, the rise time of this edge is seen to be about 3 ns while the rise time of the ringing in the Marx is 30-40 ns. Clearly, this sharp edge is a real effect as is the reflected pulse 30 ns later since both are too fast to be from the ringing.

Knowing that the time required to discharge the transmission line is 3 ns, it is possible to calculate the current through the capillary using the relationship¹⁹

$$I = \frac{dQ}{dT} \quad (4.3-3)$$

once the charge stored in the transmission line is known. To find the stored charge, first calculate the capacitance of the transmission line. Since the transmission line has coaxial geometry, its

25-Oct-96
12:23:17

M1
10 ns
10.0 V

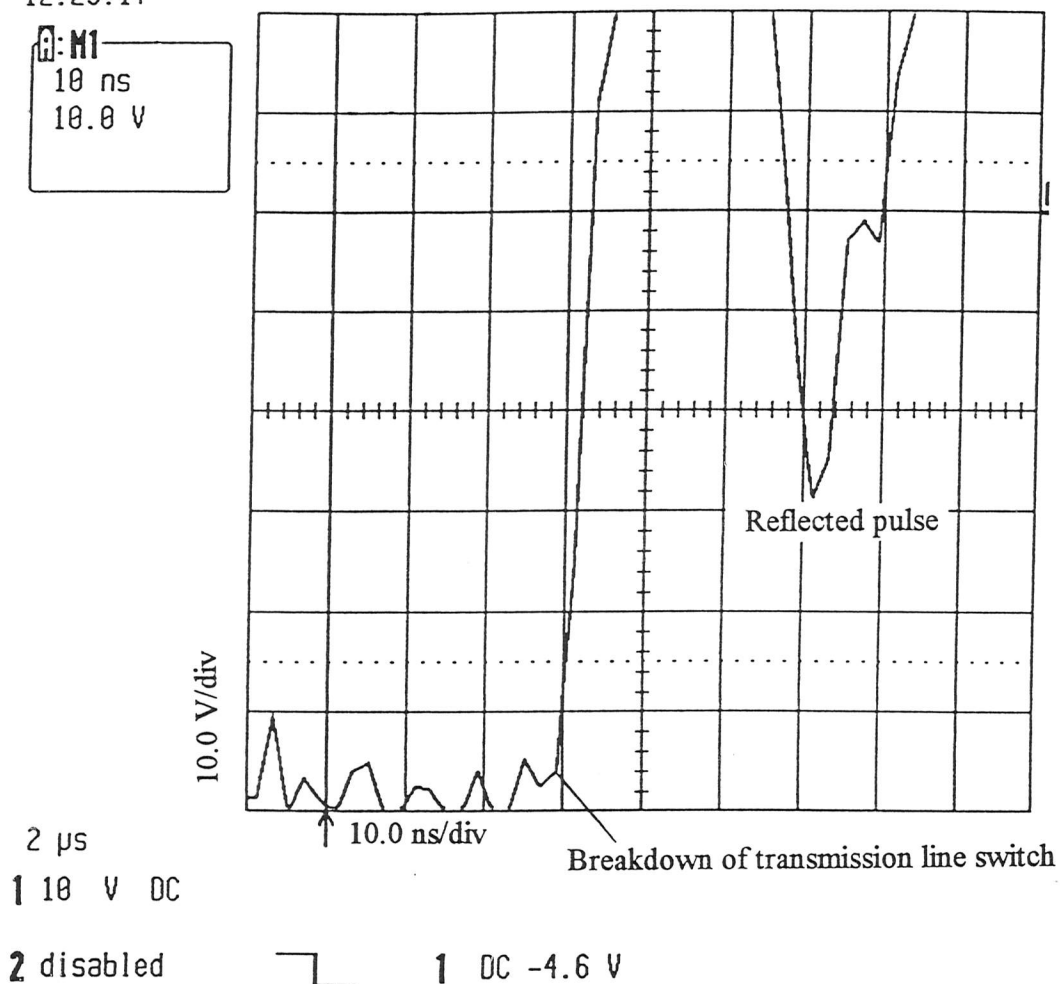


Fig. 4.3-4 Leading edge of the transmission line voltage waveform expanded to show the discharge time

capacitance is²⁰

$$C = \frac{2\pi K \epsilon_0}{\ln\left(\frac{r_2}{r_1}\right)} L \quad (4.3-4)$$

where L is the length of the line, r_2 is the radius of the outer conductor, r_1 is the radius of the inner conductor, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m and K is the dielectric constant for water. The dimensions of the transmission line are: $L = 20$ cm, $r_1 = 0.48$ cm, $r_2 = 2.4$ cm and $K = 80$ so the capacitance of the line is 560 pF. The charge stored in the line can be calculated very easily using²¹

$$Q = CV \quad (4.3-5)$$

where V is the voltage applied to the center conductor. The transmission line charges to 130 kV so the charge stored in the line is 73 μ C. Finally, the current through the capillary is calculated using Eq. 4.2-3 and it is found to be 24 kA. The discharge device was designed to produce a 20 kA current pulse through the capillary when the transmission line is charged to 200 kV. The fact that a 24 kA pulse is generated at only 130 kV indicates that the actual inductance of the capillary is less than it was estimated to be during the design of the device. There is no way to calculate the rise time of the current pulse from this data, but a conservative upper limit for the rise time would be 1.5 ns which fits very well with the design specifications for the device. There is, of course, a very high probability that the actual rise time is considerably less than 1.5 ns.

4.4 Rogowski Coil

When the capillary was constructed, a Rogowski coil was placed inside the device to act as a current diagnostic. Fig. 4.4-1 shows the position of the Rogowski coil relative to the capillary. Notice, that the coil is placed so that it has the largest possible diameter. This large diameter serves two purposes. First, it would be very difficult to construct a small coil with sufficient turns to accurately measure the current. Most importantly, however, if the coil was very close to the capillary, the magnetic field from the coil would couple with the capillary fields and change the discharge parameters. Fig. 4.4-2 shows a schematic of a typical Rogowski coil.²² A Rogowski coil operates on the principle of magnetic induction. When current passes through the center of the coil, a changing magnetic field is produced which induces a voltage in the coil which can then be measured using an oscilloscope. The sensitivity of the coil depends on the diameter of the coil, the diameter of each turn and the number of turns. The measured voltage does not depend, to any significant extent on the coil shape, the shape of the turns or the position of the coil relative to the current path. The coil in the discharge device is 4 cm in diameter, has 90 turns and each turn is 1 cm in diameter. The self-inductance of the coil can be calculated using the relationship

$$L = \frac{\mu_0 N^2 A}{l} \quad (4.4-1)$$

where N is the number of turns, A is the area of each turn, l is the length of the coil and μ_0 is equal to 1.26×10^{-6} H/m. Using Eq. 4.4-1, the self inductance of the coil around the capillary is found to be 6.3 μ H. One nice feature of Rogowski coils is that they have a very linear response over a very

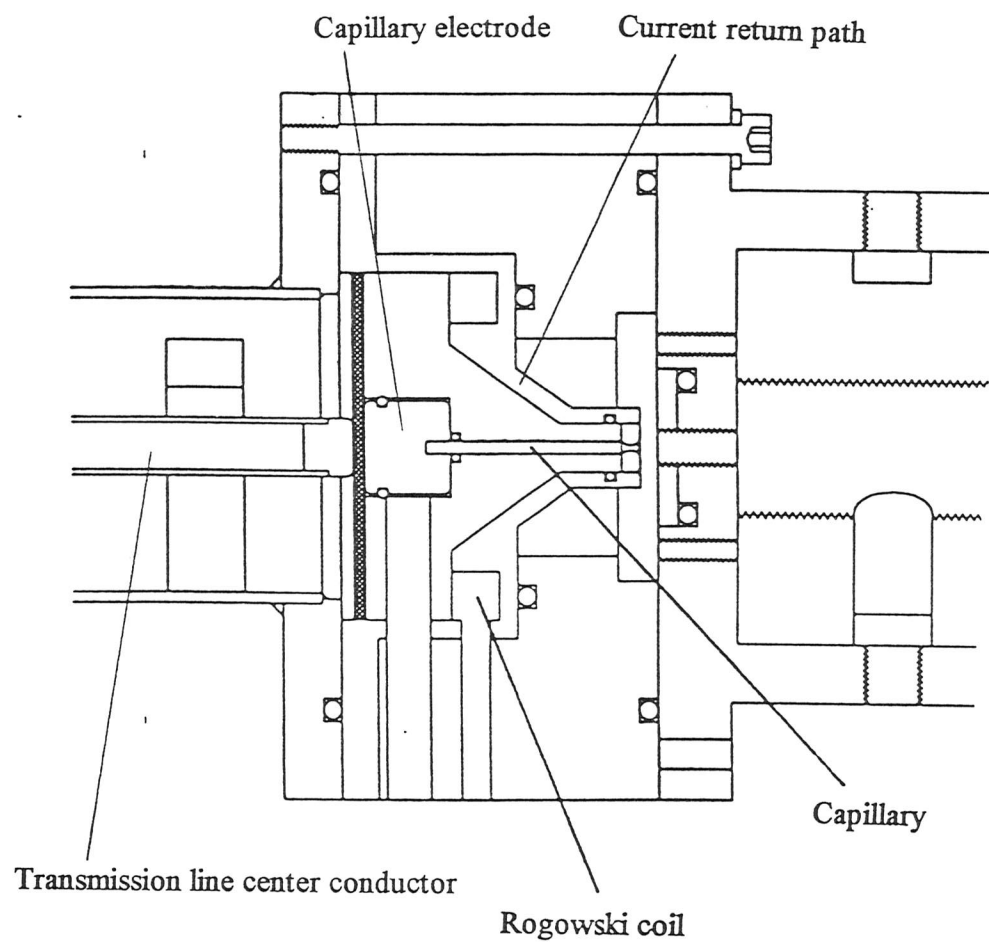


Fig. 4.4-1 Position of the Rogowski coil relative to the capillary

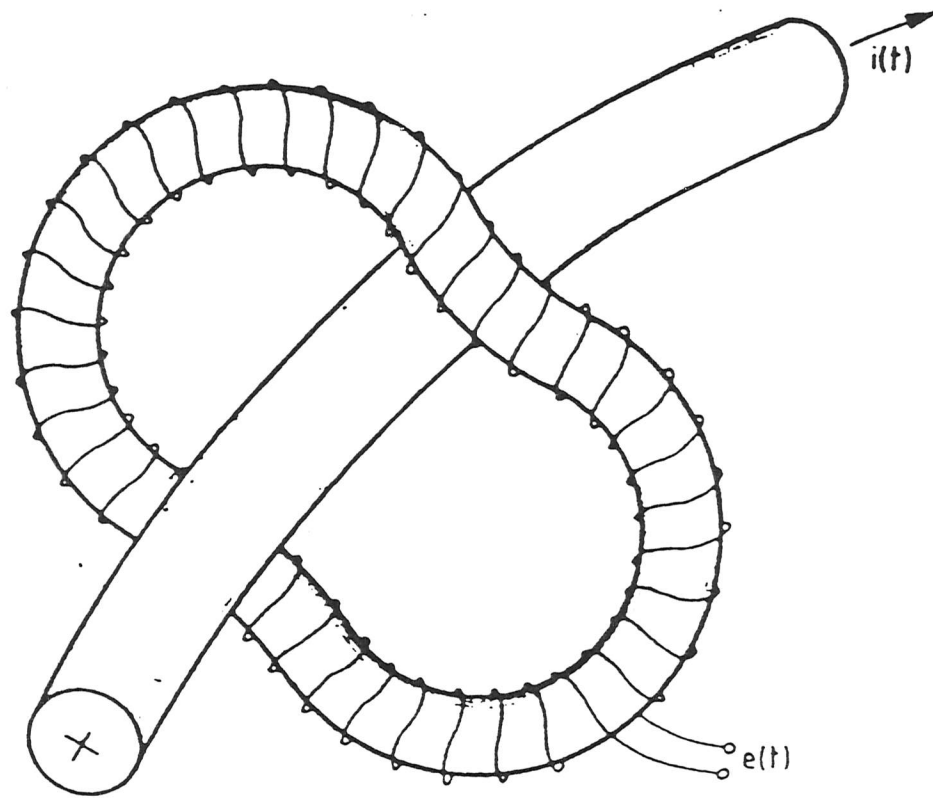


Fig. 4.4-2 Schematic of a typical Rogowski coil

wide current range. As a result, a coil can be calibrated using a relatively small current and be used to measure large currents. This coil was calibrated using a simple capacitive discharge and comparing the results to a previously calibrated coil.²³ The calibration factor for the coil is approximately 1770 A/V, meaning that the current through the capillary can be found by multiplying the voltage recorded by the oscilloscope by 1770.

Another feature of Rogowski coils is that they can be either integrating or differentiating depending on the ratio of inductance to resistance. With a self integrating coil, the output voltage of the coil is directly proportional to the current through the coil. When L/R is greater than the temporal width of the current pulse being measured, then the coil is self integrating.²⁴ The resistance of the coil in the discharge device is 0.2Ω so $L/R = 31 \mu\text{s}$. As a result, the coil will be self integrating for any pulse less than $31 \mu\text{s}$ in duration. The current pulses in the capillary will only last for nanoseconds so the voltage measured by the oscilloscope will be proportional to the current.

4.5 High Pass Filter

Unfortunately, the Rogowski coil around the capillary is strongly effected by the noise produced when the Marx generator fires. Fig. 4.5-1 is an oscilloscope trace of the Rogowski coil output during one discharge of the capillary. The first pulse in the trace is noise generated by the spark gap switches when they fire while the second pulse contains the data about the current through the capillary and the noise from the breakdown of the transmission line switch. If the noise is studied carefully, it becomes apparent that the predominant frequency of the signal is 125 MHz. In general, one would expect broadband noise to be generated by the spark gaps and transmission line switch,

21-Oct-96

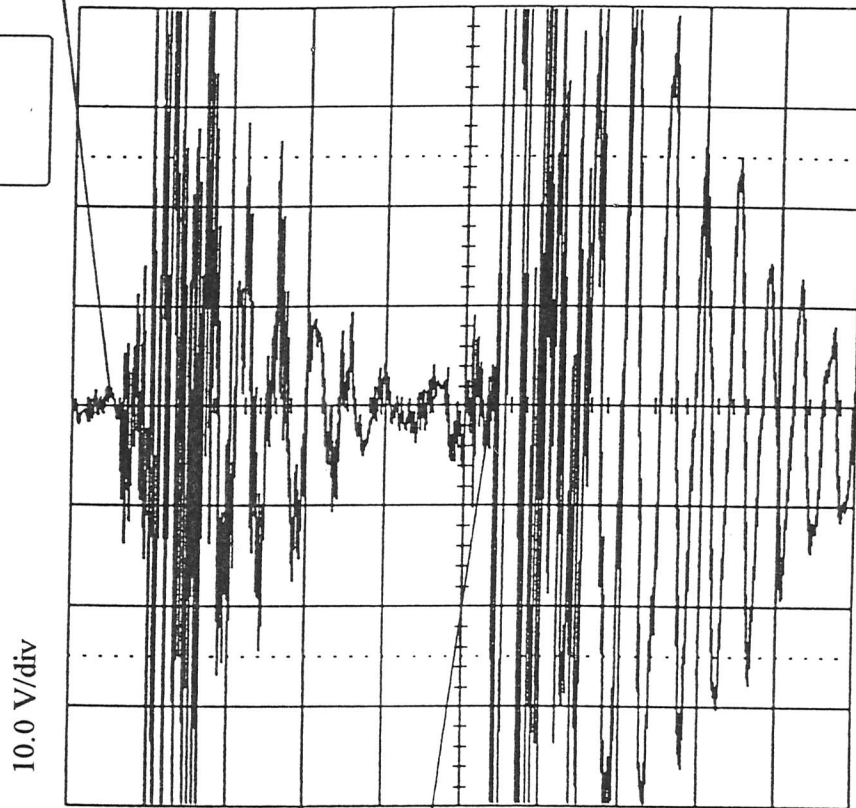
15:01:16

Discharge of Marx generator

M1

.1 μ s

10.0 V



10 ns

1 10 V DC

2 disabled



1 DC -29.0 V

Fig. 4.5-1 Output of the Rogowski coil during one discharge of the capillary

but in this case, the single dominant frequency is due to the fact that the Marx generator is enclosed within a steel cylinder. The broadband noise being generated by the switches is exciting a resonant mode inside the cavity. For any cavity, the wavelength of the allowed resonant modes depends only on the size of the cavity according to the relationship²⁵

$$L = n\left(\frac{\lambda}{2}\right) \quad (4.5-1)$$

where L is the length of the cavity, λ is the wavelength of the resonant mode and n is an integer that indicates the harmonic. Using Eq. 4.5-1 and recalling that the wavelength of an electromagnetic wave is related to its frequency by²⁶

$$c = \lambda \nu \quad (4.5-2)$$

it is possible to calculate that the length of the cavity needed for a 125 MHz resonant mode is 1.2 meters, which is exactly the diameter of the cylinder around the Marx generator.

Clearly, something has to be done about the noise picked up by the Rogowski coil before the current through the capillary can be measured. The obvious solution to the noise problem is to take the Marx generator out of the cavity, but the cylinder provides an essential measure of safety during the operation of the generator so another solution is required. A solution that allows the Marx to remain in the containment vessel is to filter the noise before it reaches the oscilloscope, so a high pass filter has been designed and constructed that attenuates any signal with a frequency below 150 MHz by at least 30 dB and passes any signal with a frequency of 300 MHz or greater with no attenuation. The upper limit was chosen since the expected current rise time through the capillary is 1 ns which

corresponds to 300 MHz.

The basic technique for designing a high pass filter is to find a low pass filter that has the required attenuation and then transform it to obtain a high pass filter. For this filter, the specifications are:

$$f_{\text{pass}} = 300 \text{ MHz}$$

$$f_{\text{stop}} = 150 \text{ MHz}$$

$$\text{attenuation} = 30 \text{ dB minimum}$$

$$\text{impedance} = 50 \text{ Ohm}$$

The first step in the design process is to calculate the steepness factor (A_s) for the filter²⁷ where

$$A_s = \frac{f_{\text{pass}}}{f_{\text{stop}}} \quad (4.5-3)$$

For this filter, $A_s = 2$. The next step is to consult the attenuation curves for the different types of filters and pick a low pass filter that has at least 30 dB of attenuation for values above A_s . In this case, a Butterworth type filter with $n = 5$ gives the desired characteristics.²⁸ Fig. 4.5-1 shows a schematic of a generalized Butterworth type low pass filter. To transform the low pass filter into a high pass filter, each inductor is replaced with a capacitor and each capacitor with an inductor. The values of each new component is the reciprocal of the value of the component it replaces,²⁹ that is

$$C_1 = \frac{1}{L_1} \quad L_2 = \frac{1}{C_2} \quad (4.5-4)$$

Fig. 4.5-2 shows the generalized high pass filter with the transformed component values. The final step in the design process is to denormalize the filter³⁰ using the impedance (Z) = 50 Ω and the

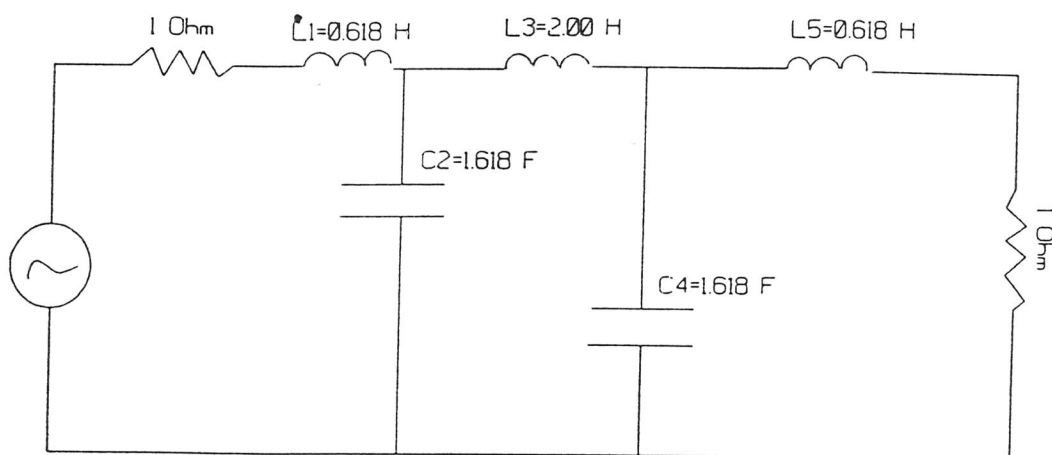


Fig. 4.5-2 Generalized Butterworth type low pass filter

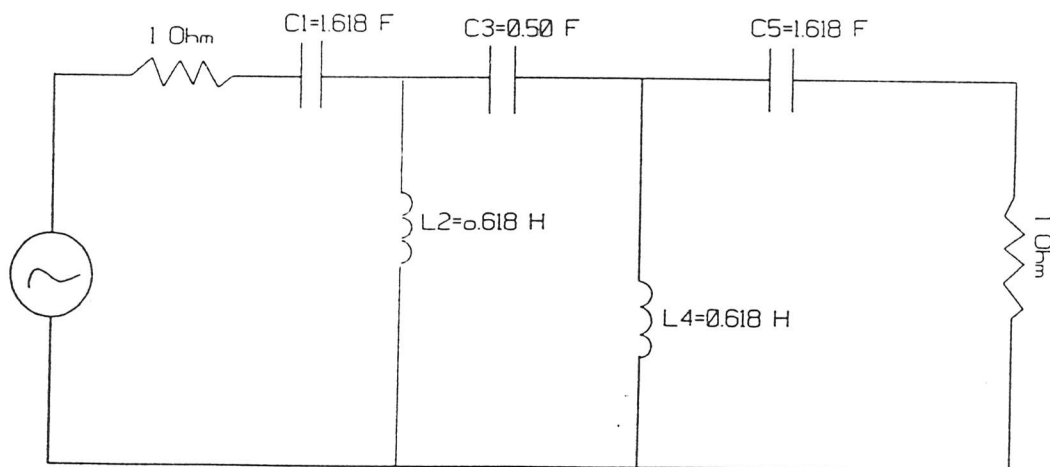


Fig. 4.5-3 Generalized high pass filter

and the frequency factor

$$FSF = 2 \pi f_{pass} = 1.884 \times 10^9 \quad (4.5-5)$$

with

$$c' = \frac{c}{FSF \times Z} \quad l' = \frac{L \times Z}{FSF} \quad 4.5-6$$

Fig. 4.5-3 shows the schematic of the completed high pass filter.

4.6 Current Data

Fig. 4.6-1 is an oscilloscope trace of the Rogowski coil output during one discharge with the high pass filter installed. Even a casual comparison of Fig. 4.6-1 with Fig. 4.5-1 shows the dramatic difference that the high pass filter makes in the recorded signal. One very important advantage of using the high pass filter is that the amplitude of the first pulse has been greatly reduced which allows the oscilloscope to be triggered by the second pulse instead of the first. By setting the trigger level to 29 V, it is possible produce traces such as the one in Fig. 4.6-2 which shows only the leading edge of the signal produced when the transmission line switch breaks down. A second advantage of triggering on the second pulse, is the portion of the waveform that is important (the leading edge of the transmission line pulse) is much more reproducible which allows the data from several discharges to be averaged together to further separate the signal from the noise.

Fig. 4.6-3 shows the result of averaging fifteen waveforms together. In each of the fifteen

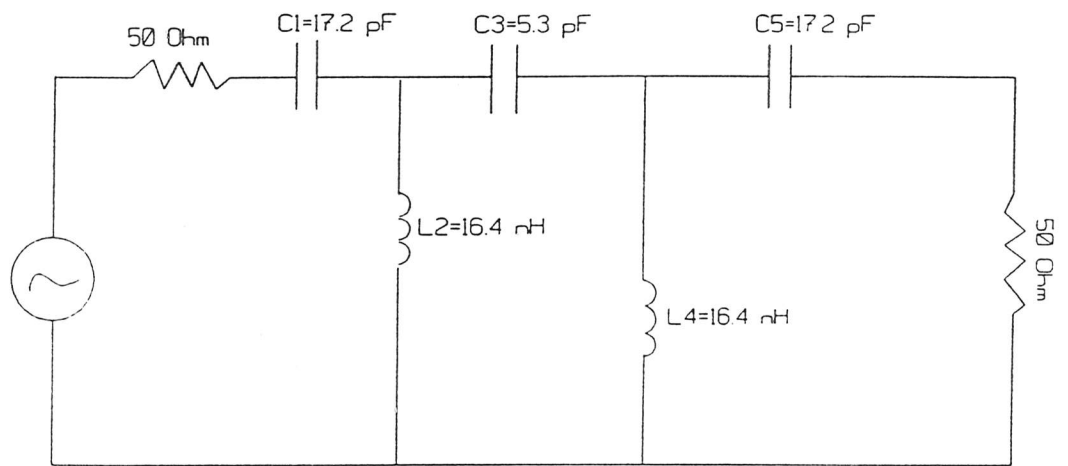
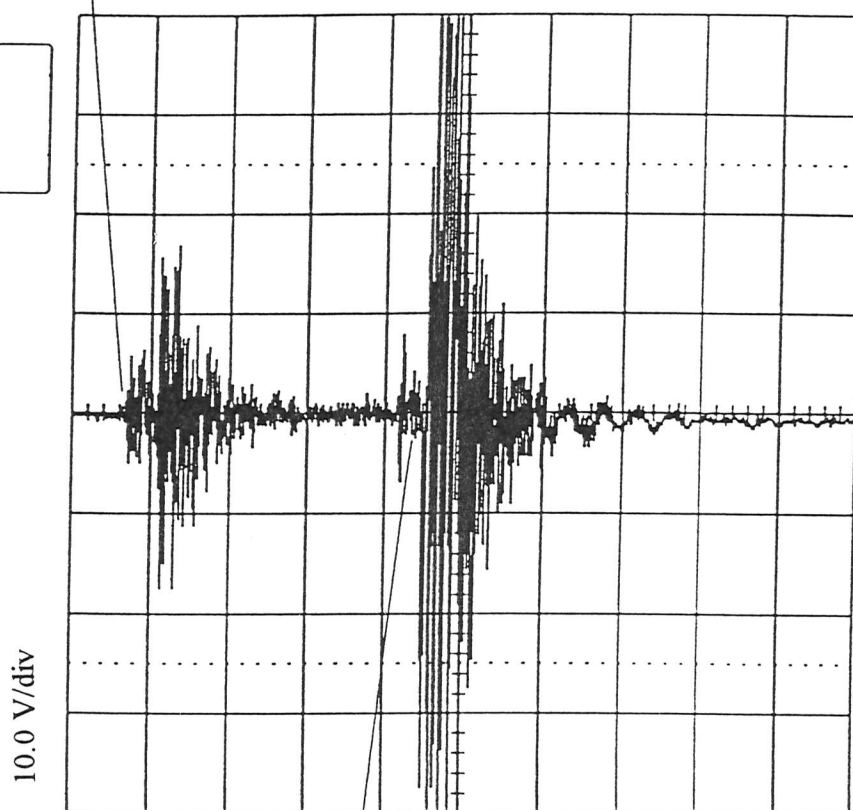


Fig. 4.5-4 Schematic of the completed high pass filter

21-Oct-96
15:02:20

M1
.1 μ s
10.0 V

Discharge of Marx generator



10 ns

1 10 V DC

2 disabled



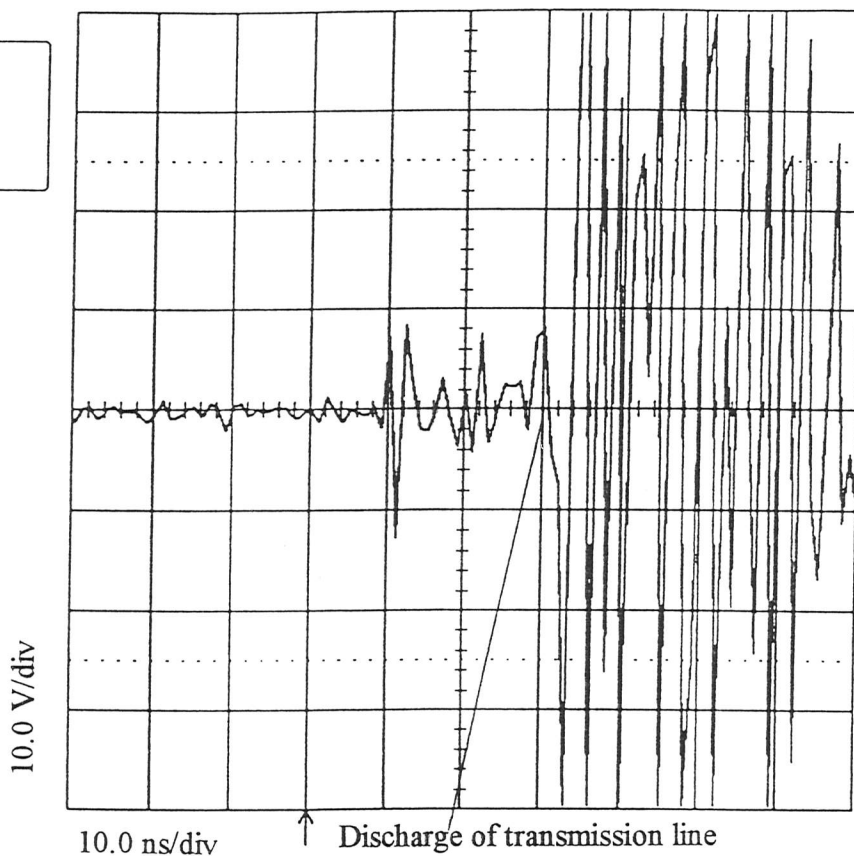
1 DC -29.0 V

Fig. 4.6-1 Rogowski coil output with the high pass filter installed

21-Oct-96
15:03:15

M1
10 ns
10.0 V

10 ns
1 10 V DC
2 disabled



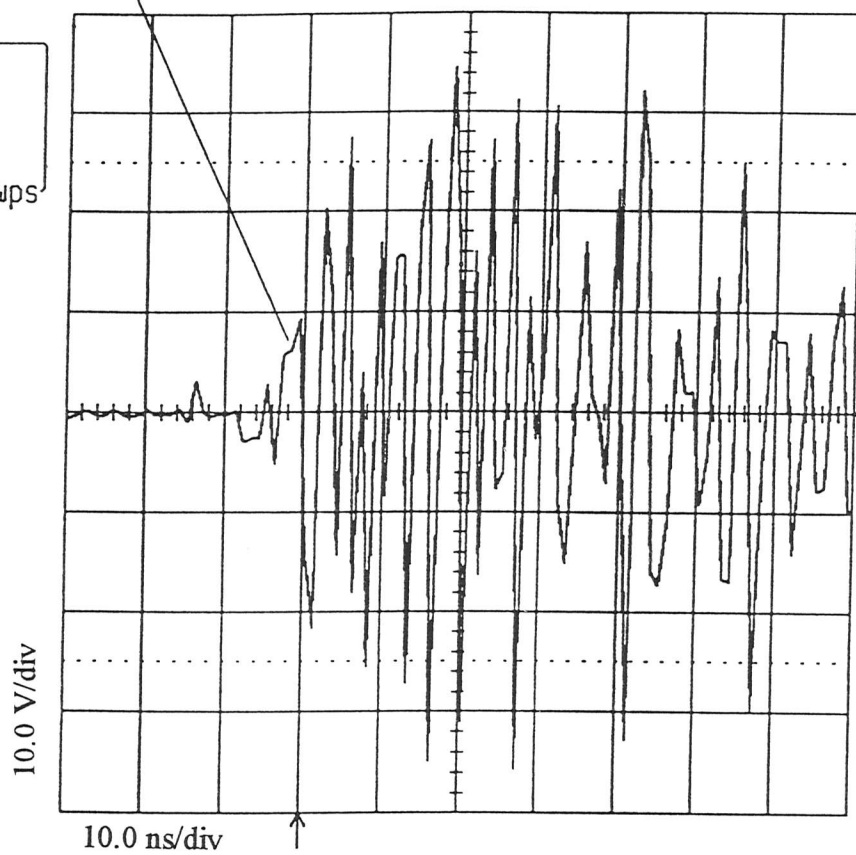
1 DC -29.0 V

Fig. 4.6-2 Rogowski coil output with the trigger level adjusted to show just the transmission line discharge

21-Oct-96
15:05:49

M1
10 ns
10.0 V
15 swps

Possible current pulse through the capillary



10 ns

1 10 V DC

2 disabled



1 DC -29.0 V

Fig. 4.6-3 Rogowski coil output with 15 traces averaged together

shots, the capillary pressure was 100 mT and the Marx generator was charged to 35 kV. Unfortunately, even with the high pass filter in place and with numerous shots averaged together, the noise is still such that it is difficult to determine the current through the capillary with any degree of confidence. It is possible that the first large positive pulse at the left of the trace may be the current through the capillary in which case the rise time of the pulse would be about 1 ns. Clearly, more work will have to be done using more sophisticated techniques before the current waveform through the capillary is well known.

5. CONCLUSIONS

5.1 Objectives Achieved

The original design objectives for the capillary discharge driver, specified a device that would produce a high power electrical pulse through the capillary that peaked at 20 kA, had a rise time of 1 ns and a pulse width of 10 ns. From the voltage probe data, it is possible to calculate the peak current through the capillary to be 24 kA which is better than the expected performance. Since the transmission line discharges in 3 ns, the current rise time is postulated to be 1.5 ns or less. This rise time is also in good agreement with the design specifications. Unfortunately, the current data from the Rogowski coil is drowned out by the noise so it is impossible at this point to measure the current through the capillary directly. The discharge device has also proven to be very robust. Literally hundreds of shots have been fired through the capillary with no discernable failures of the capillary. The capillary electrode, however, has been eroded by the arcs across the transmission line switch and will have to be replaced eventually. This erosion could be significantly slowed if the electrode is machined from stainless steel instead of aluminum when it is replaced.

5.2 Directions For Further Research

Preliminary spectroscopic data indicates that the device, as it stands, is producing x-rays with wavelengths near 325 Å. Three of these lines have been identified as AR VIII lines indicating that the plasma is reaching the correct ionization state. Therefore, before considerable time and effort are expended to measure the current through the capillary carefully, an exhaustive study of the plasma should be undertaken since it is entirely possible that the plasma is lasing with the current driver configuration.

If it becomes important to measure the rise time of the current through the capillary more carefully, one method would be to look at the change in a specific spectral line. If a visible line is chosen, the monochromator and photomultiplier tube could be placed far away from the experiment and the light from the discharge could be carried to the detector using a fiber optic bundle. Hopefully, by moving the PMT away from the discharge, the electrical noise will be attenuated sufficiently that meaningful information can be obtained.

If studies of the plasma indicate that the rise time does need to be shortened, there are a few options that can be incorporated into the device without major modification. The easiest option is to modify the center conductor of the transmission line to allow multichannel breakdown. The current switch configuration in the transmission line is shown in Fig. 5.2-1. In this case, only a single breakdown channel forms in the gap between the capillary electrode and the transmission line conductor. For a switch operating with a single breakdown channel, the switch inductance is 15 nH/cm. The gap between the two electrodes is about 0.4 cm long which results in a switch inductance of 6 nH. If the cap on the end of the transmission line conductor is removed, as is shown

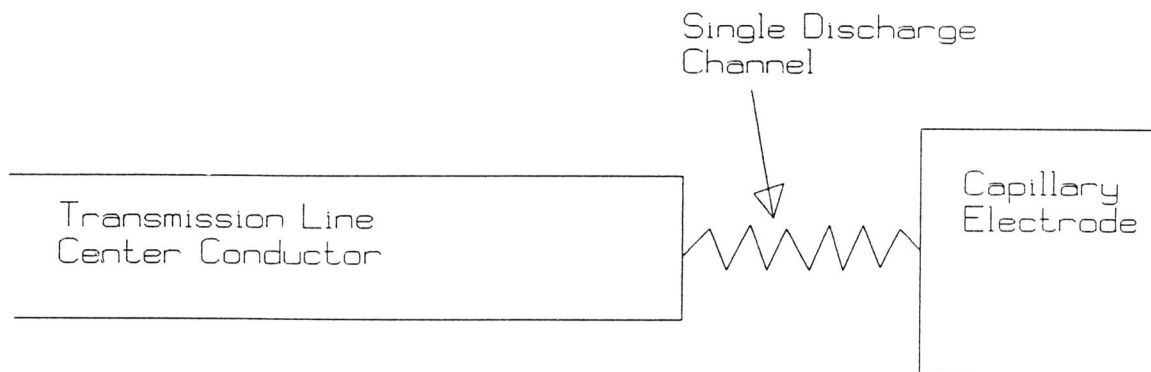


Fig. 5.2-1 Single channel operation of the transmission line switch

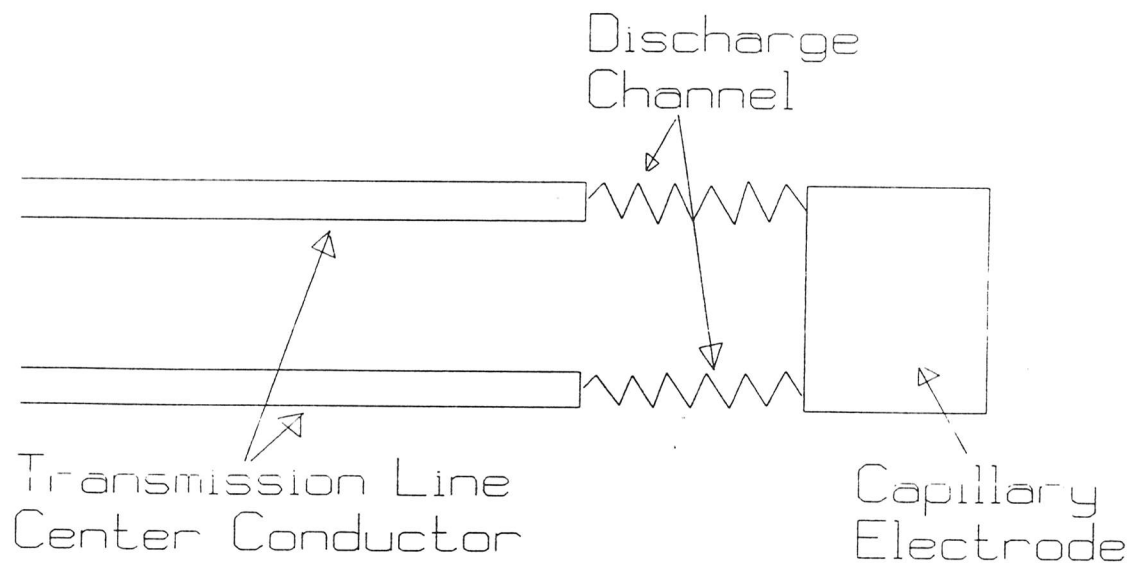


Fig. 5.2-2 Multi-channel operation of the transmission line switch

in Fig. 5.2-2, then multi-channel operation of the switch is possible. When the switch operates with multiple breakdown channels, the inductance of the switch is decreased by a factor of $1/N$, where N is the number of breakdown channels. Clearly, this modification of the switch could bring about significant reductions in the switch inductance which would result in faster rise times. One drawback of multi-channel switch operation, however, is that the device would be less stable. Since there is no way to predict how many breakdown channels will form, the rise time of the current pulse would change from one shot to the next due to fluctuations in the number of channels.

The rise time of the current pulse could also be reduced by replacing the simple water gap switch with a solid dielectric switch. In its simplest form, a solid dielectric switch is nothing more than a sheet of plastic that is stressed until it breaks down and a conduction channel forms. In the early 1960s, J.C. Martin studied solid dielectric switches extensively and showed that the breakdown voltage of the switch can be controlled by stabbing the dielectric repeatedly with a needle. In operation, the voids in the plastic break down first, initiating breakdown in the solid. The deeper the stabs in the plastic, the lower the breakdown voltage. Clearly, multiple stabs give more reliable operation than a single stab. Fig. 5.2-3 shows details of a solid dielectric switch and where it would be placed in the device. By using a mechanical jig to precisely control the stab depth, solid switches can be produced that have a standard deviation of breakdown voltage of only 2 to 3%. Martin's work indicates that the best switches are made from two layers of 1/32" polyethylene sheet sandwiched together. Such a switch can be expected to have an inductance of about 3 nH. The main drawback of solid switches is that the switch is destroyed in the discharge and must be replaced after each shot. For more information on solid dielectric switches, refer to Appendix B which is a copy of some notes written by J.C. Martin.

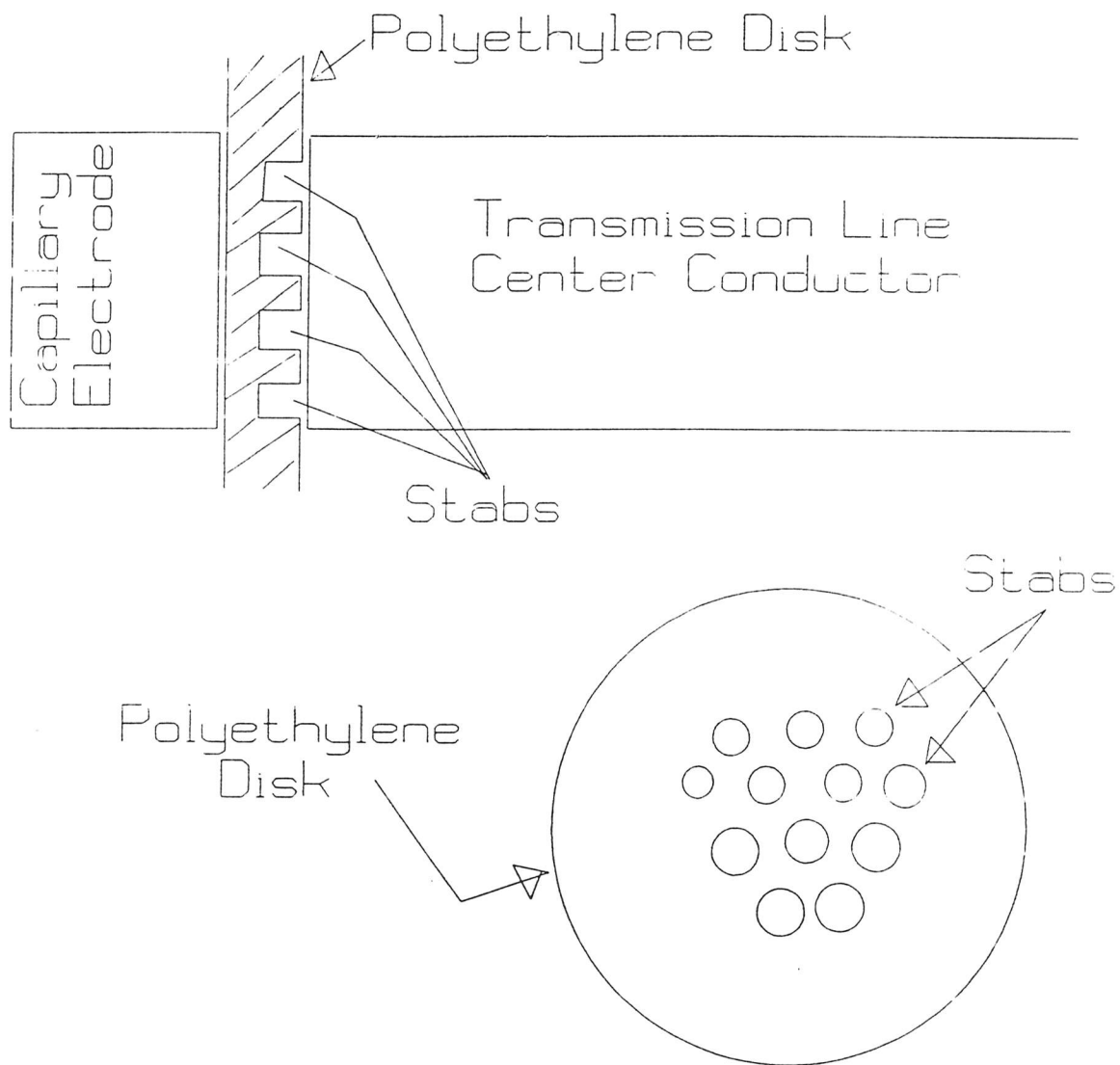


Fig. 5.2-3 details of a solid dielectric switch

A third option for reducing the rise time is to go to higher charge voltages on the transmission line. The Marx generator offers the flexibility to generate output voltages up to 300 kV. Before the voltage can be increased significantly over present levels, however, the support for the transmission line center conductor will have to be redesigned to prevent arcing and some of the components of the Marx may also need to be modified to reduce corona and possible breakdown.

Appendix A--Copper Sulfate Resistivity Data

Method

The method used, simply measured the AC resistance of a known length and cross sectional area of solution. The resistance was measured over a range of applied voltage.

Results

Using copper electrodes and solution dimensions $87 \text{ cm} \times 1 \text{ cm}^2$ and temperature 19°C .

Concentration is given in grams of Copper Sulphate ($\text{CuSO}_4 \cdot 5 \text{ H}_2\text{O}$) dissolved in 100 cm^3 of distilled water.

a) Concentration: $7.7 \text{ g} / 100 \text{ cm}^3 \text{ H}_2\text{O}$

Volts (50 Hz)	3	5.4	10	20	40	80
Amps	0.5	0.95	2	4	8	16
Slope Resistance:	$R = 5000 \Omega$					
Resistivity:	$\rho = 57 \Omega\text{-cm}$					

b) Concentration: $3.58 \text{ g} / 100 \text{ cm}^3 \text{ H}_2\text{O}$

Volts (50 Hz)	2.95	7	15	25	40	60	100
Amps	0.34	0.8	1.7	2.9	4.5	7	11.9
Slope Resistance:	$R = 8600 \Omega$						
Resistivity:	$\rho = 99 \Omega\text{-cm}$						

c) Concentration: 1.92 g / 100 cm³ H₂O

Volts (50 Hz)	2.6	5.2	9.8	15	25	50	100	
Milliamps		0.16	0.34	0.65	0.99	1.6	3.3	6.9
Slope Resistance:	R = 14,700 Ω							
Resistivity:	ρ = 170 Ω-cm							

d) Concentration: 0.96 g / 100 cm³ H₂O

Volts (50 Hz)	4.4	9.4	15	25	50	100	200	
Milliamps		0.16	0.37	0.6	0.99	2	4	8
Slope Resistance:	R = 25,000 Ω							
Resistivity:	ρ = 290 Ω-cm							

e) Concentration: 0.5 g / 100 cm³ H₂O

Volts (50 Hz)	8.8	15	25	39	100	200		
Milliamps		0.21	0.36	0.6	0.95	2.2	4.6	
Slope Resistance:	R = 43,000 Ω							
Resistivity:	ρ = 500 Ω-cm							

f) Concentration: 0.125 g / 100 cm³ H₂O

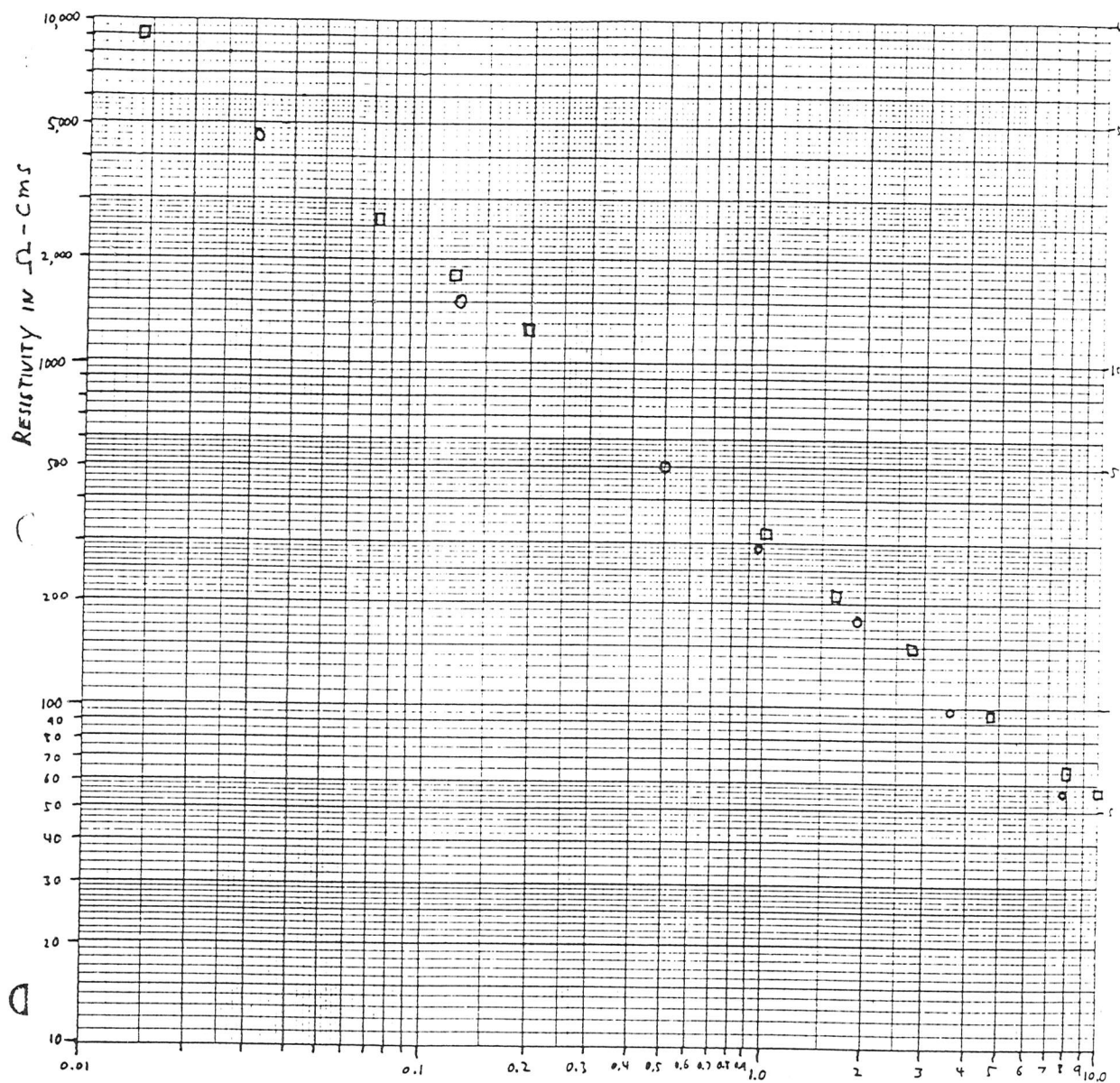
Volts (50 Hz)	13.8	25	54	96	134	250		
Milliamps		0.1	0.19	0.4	0.71	1.0	1.9	
Slope Resistance:	R = 130,000 Ω							
Resistivity:	ρ = 1500 Ω-cm							

g) Concentration: 0.031 g / 100 cm³ H₂O

Volts (50 Hz)	41	81	163	250				
Milliamps		0.1	0.2	0.4	0.61			
Slope Resistance:	R = 400,000 Ω							
Resistivity:	ρ = 4600 Ω-cm							

Notes

Using the result of M.G. Shortland, the saturated solution of copper sulphate has a resistivity of 20 Ω-cm.³¹



O : W.R. BELL 14 JAN '60
@ 19°C

CONCENTRATION, gms $\text{CuSO}_4 \cdot 5\text{H}_2\text{O} / 100\text{cc H}_2\text{O}$

□ : J. OLDENETTEL 4 DEC '72
@ 70°F GIVES 23.5 $\Omega\text{-cm}$ @ 22 gms/100cc
= SATURATED

Fig. A-1 Copper sulfate resistivity data³²

Appendix B--Notes on Solid Dielectric Switches

by
J. C. Martin

S.S.W.A., AERE
Aldermaston, England
31 May 1962

These notes have been typed from a poor copy of a version of the notes that were reproduced from the original document by N. J. Norris (at the Santa Barbara Division of Edgerton, Germeshausen & Grier, Inc.) on December 10, 1963. N. J. Norris indicates that the original copy was nearly illegible, so errors may have occurred in the reproduction.

Bryan R. Olsen
February 1, 1996

1. Introduction

During the development of high voltage, high speed surge generators, it became apparent that switches working in the region of 100kV with a di/dt of 10^{14} amps per second were necessary. Subsequent development made it desirable to achieve rates of current change an order of magnitude higher, and this led to the development of solid dielectric switches which could be triggered with a simultaneity in the nanosecond region. Owing to the fact that the multiplying stages of the surge generator were designed to be pulse charged in times of the order of one microsecond, most of the work has been done with switches where the voltage was applied in this time, although a little work has been done on switches charged in seconds and in times of the order of ten nanoseconds.

The switches are, of course, only good for a single operation, but they are of such simple construction that replacement is cheap and could be mechanized, so that a rate of operation of a few times a second could be contemplated.

While some of the characteristics of the switches have been established, much of the work has only been carried as far as was necessary to satisfy the operational requirements of the surge generators under development, and consequently some of the experiment data lacks the rigor and scope that is desirable. Since this note is intended to help to assess the possibilities of these switches, a fair quantity of speculation has been included, it is hoped that the division between what has been reasonably well established and what is speculative has been made adequately clear.

In actual use the switches have proved surprisingly consistent and reliable and easy to operate, and it is felt that with serious work they could be made to operate in a very satisfactory way.

2. Construction of Typical Dielectric Untriggered Switch and Voltage Working Range

The first attempt to make a solid dielectric switch of reasonably reproducible characteristics was to melt a fine copper wire ($r \sim .005$ cm) half depth into a nominal 1/16" polythene sheet. On

cooling the wire was held firmly by the plastic and when charged on a waveform rising in about 10^{-3} seconds broke at a voltage of about 50 kV with a standard deviation of about 8%. A few tests on voltages rising in about 10 sec., also showed there was a fairly well defined breakdown voltage. In the above tests the wire embedded in the polythene was made positive. When the voltage was made negative in the case of the waveform rising in 10^{-3} the breakdown voltage was 2 to 3 times bigger and considerably more irregular. No tests were done with the wire negative with the slow charging voltage.

Since the construction was rather ill defined mechanically and a bit tedious, the wire was replaced by a small air filled stab made by digging a Singer No. 8 needle into the polythene and then withdrawing it. The author has no reason to believe that the needle has to be manufactured by Singer or to be their product known as No. 8 but it has so happened that nearly all the thousands of switches made in SSWA have been with holes produced by them and we use none other. It was reasoned that the air in the void would break down early in the charging phase at voltage gradients about two orders of magnitude less than that in the polythene and so at the time of closure of the solid dielectric switch, the stab would be equivalent to a wire. This expectation was justified in all but the fastest rising pulses and even here the growth of the conduction channel in the gas is considerably faster than in the polythene. With this alteration it became possible to vary the operating voltage of the switch easily and simply by changing the depth of stab. Figure one shows the breakdown voltage variation of a set of stabs as the depth of stab is altered. Three curves are shown for various rates of application of voltage. The curve labeled DC is where the voltage is applied in about 20 seconds but no difference ($<2\%$) was found when the rate of application was varied from 5 seconds to 2 minutes. The difference between the DC and 10^{-6} curves is very likely to be real,¹ that between the 10^{-6} and 10^{-8} second is not much different from the maximum experimental error and so may not be. All the results shown apply to the case with the joint positive. Some data with joint negative is shown in figure two obtained by Mr. M. Goodman. A few results obtained by the author are given in figure 1. These show that the breakdown voltage is some three or more times greater with the polarity reversed and

¹DC curve goes to pot at higher fields due to glow (probably) at tip. For 55 kV/DC $\sigma = 4\%$

that the standard deviation is poorer.

The original design of the switch was aimed at reducing the highly stressed region of the plastic to as small a volume as possible ($\sim 10^{-8}$ cc) so that there would be no chance of having imperfections, dust, etc. in the high field region to cause breakdown.

It was also intended to use the small radius of the top of the void to give field enhancement factors so that a sufficiently high field would be achieved to cause intrinsic breakdown. With conduction taking place in the plastic, it would not necessarily be the case that the expected increases in field strength would occur, but with the highest rates of application of voltage, very large conduction currents ($\sim 10^2$ amps/cm²) are required to change the applied voltage fields significantly. Similarly physical motion and thermal degradation cannot happen in the time scale of the fast pulses and hence it is likely that the expected voltage field existed in these tests. Unless there are compensating changes in the plastic it seems likely that even on the second time scale the fields at the tip is likely to be that expected. A breakdown curve was calculated using equipotential curves approximating to the smoothed out shape of the hole in the polythene. This is shown in figure 3, which would exist if the tip were smooth. Microscopic examination did not establish that this was so, therefore, there may be a field enhancement factor due to roughness which would increase the figure of 14 MV/cm.

The standard deviation for a single stab was in the region of 10%, but at very early stage the switches were made with many stabs in them. This reduces the spread of working voltages but causes the distribution of voltages to become non-Gaussian. Putting the number of stabs up to 30 or there about decreases the standard deviation to about 0.4 of its previous value. Quite early in the investigations standard deviations of multiply stabbed switches of the breakdown voltage of 5% were obtained. Since then with a mechanized stabber with 50 separated needles, switches have been produced with a standard deviation of 2-3% for stabs less than a third of the depth of the polythene. For deep stabs, i.e. lower working voltages, the standard deviation is a bit worse, probably due to the poorer shape of the void left when the needles are withdrawn from deep holes. The mechanized

stabber was constructed so that the needles could be inserted at a known distance from the top surface of the polythene (for high working voltages) or from the bottom of the plastic (for low working voltages). For a set of about mid depth stabs a standard deviation of 4% was obtained for charging times of tens of seconds.

A small quantity of information has been obtained for 1/32" thick sheets of polythene and also for larger radius tips in 1/16" sheet. In the latter work by Mr. Storr and Mr. Goodfellow, gramophone needles (old type steel ones labeled "loud") were used, but it was found necessary to heat them to avoid bad tearing of the polythene with consequent poor standard deviation. In addition to these there is some data on a very early form of switch working at about 0.5 MV, where a small ball bearing was buried in 1/4" polythene. This crude switch achieved standard deviations of about 8% when the sun was shining.

3. Inductance and Rate of Current Rise in Solid Switches

The switches have copper sheets placed on each side of the polythene and hence the regions of the electrodes most damaged are replaced along with the polythene. At one time it was intended to do some work with liquid dielectrics which could be replaced by pumping, however it was thought likely that the damage to the needles would be so severe that frequent replacement of these would be necessary and hence replacement of the dielectric and electrodes seemed easiest. The switches have been mostly used by building them into the end of a transmission line. Measurements on a series of systems with resistance down to 0.2 ohm have shown that the inductances of the switches are no more than a factor of two up on the calculated value of $2 \times L \times \ln(b/a) \times 10^{-9}$ Henry. Other inductances and integrating effects have prevented the true switch inductance being checked better than this. Few inductance measurements have been made at times less than 10^{-8} second. There is believed to be a resistive phase which is a maximum of a few nanoseconds in duration, this is discussed further in section 4. In one particular experiment, a 1 ohm line was used at 200 kV. The calculated inductance of the switch was 3×10^{-9} and giving rise to an expected e-folding time on the pulse front of 3 nanoseconds. The observed e-folding time of 6 nanosecond contains contributions

from the skin depth increased resistance losses of the line and the band width of the measuring system. Removing these roughly gave a value in agreement with the expected inductance. Thus in this experiment, a rate of rise of current of 7×10^{13} amps per second was probably achieved with one switch. This has since been exceeded by an order of magnitude using multiple switches. The inductance and the time spent on the resistive phase can both be reduced by using a triggered gap when multiple breakdowns can be made to occur. This means that a triggered gap of two sheets of 1/32" polythene can have an inductance about a half of that of a single 1/16" sheet providing a fast enough triggering voltage is provided.

The use of the switches has been restricted to rather short current pulses (since longer ones would require large stores of energy) and the longest unidirectional pulse used has been about 50 nanoseconds. However, systems have rung on for several times this, displaying no more than the expected damping and what is more important, depositing approximately the same amount of energy in the gap as in the case of a switch used with a more or less unidirectional current pulse. If a much longer (i.e. tens of microseconds) current pulse is used, the copper electrodes will vaporize out to a much larger radius than they do at present but work done with a low voltage (20 kV) switch with .001" Al electrodes suggests that a metal plasma forms which carries the current quite comfortably, indeed it is very difficult to see how the inductance of the switch can do anything but stay constant or decrease when very big currents of the [order of] a megamp have established themselves.

4. Duration of Resistive Phase of Solid Switches

A warning should be given that this section is distinctly more speculative than the preceding ones and the results quoted are of rather low accuracy.

The "time of formation" of the spark channel was measured fairly early on by two separate but related methods. One involved increasing the rate of rise of voltage on a single stab switch and measuring the increase of breakdown voltage. As the rate of increase of voltage rose from zero to 1.5×10^{13} volts/sec the mean breakdown voltage of a series of switches increased from about 62 kV

to about 65 kV. However, some of this increase was attributable to the inductance of the measuring circuit. Thus the "time of formation" was 2×10^{-10} seconds or less with a best value of about 10^{-10} seconds. The second method involved increasing the rate of rise of voltage applied to a multiply stabbed switch and observing that when a rate of rise of a few $\times 10^{12}$ volts/sec was reached more than one of the stabs would carry current. The rate of rise of voltage required to make about half the stabs conduct current was determined and from the statistics of breakdown of single stabs, this meant that the voltage had increased about 3 kV after the first stab had started to break down. From this a "time of formation" of about 1.5×10^{-10} seconds was calculated. The "time of formation" measured in the two experiments was not quite the same thing, but it is roughly equal to the time taken to create a conducting channel plus the time taken for its resistance to fall to about 300 ohms at which time the switch was passing tens of amps. Since these experiments difficulties with the triggered have shown that there are resistive phases of durations of about 1 nanosecond during which the impedance may be much greater than that given by the inductance and/or any likely rate of change of inductance. In addition to these observations there is the fact that a rough measure of the energy deposited in some switches leads to estimates of the duration of resistive phase. Also some recent work has measured a time during which energy can be fed into what is probably a plasma in a solid dielectric and this gives a time of about 20 nanoseconds for and 0.14 ohm line feeding an 0.3 cm long arc with an open circuit voltage of 20 kV.

Work on gaseous spark channels has shown that a resistive phase certainly exists in these and that the time history of the voltage across a spark channel fed from a strip transmission line, falls in an approximately exponential fashion (with a time constant t) and that most of the energy is deposited in the channel during a time of the order of t . A rough theory indicates that this time is in accordance with the expected cylindrical explosion of the plasma channel formed. The data obtained for air spark channels is:

$$t = 9 \times 10^{-8} l^{1.4} Z^{-0.3} V^{-1.3} \text{ sec.}$$

where l is the length of the spark (cm), Z is the impedance of the strip line and V is the initial voltage

in units of 10 kV. The energy deposited is then roughly

$$E = 4.5 V^{0.7} l^{1.4} Z^{-1.3}$$

Now the small amount of data, referred to above, where a direct measurement of the duration of the resistive phase has been made gives $t_{\text{solid}} \sim 1^{1.4} Z^{-0.3} V^{-1.3} \times 30 \times 10^{-8}$ using the same powers for want of any other expression.

Taking this and using the values $l = 0.08$ cm (the stabs were about mid depth in the solid) $V = 5$, $Z = 300 \Omega$; $t_{\text{solid}} \sim 1.5 \times 10^{-10}$ in fortuitously good agreement with the early set of observations. With regard to the energy deposited during the early resistive phase

$$E_{\text{solid}} = 15 \times 1^{1.4} V^{0.7} Z^{-1.3} \text{ joules}$$

This gives values in agreement with the energy estimated for various solid gaps with thicknesses of 0.003" as well as 0.060". The energy was measured directly for the thin insulator by using the void blown in plasticene and in the thicker sheet by a rough cross calibration using the diameter of the hole blown in the polythene and comparing this with one produced in circumstances where the energy could also be obtained by the bubble in plasticene method. The energy measurements are not better than a factor three in accuracy but they give answers in reasonable agreement with the formula given above, which suggests that the value of t_{solid} is probably not far out. The energy deposited (typically about 10 joules in a low impedance application of the switch) is only that deposited during the resistive phase of the solid spark channels, more energy may be added with long pulses where extensive vaporization of the electrode surfaces may occur. Where a triggered switch is fired and many breakdown channels (number N) are produced the energy per channel falls as $N^{-1.3}$ and the total energy in the switch as $N^{0.3}$ approximately. This is borne out by the much smaller damage done to a triggered switch by a given passage of energy. The duration of the resistive

phase of a triggered gap may be only 1/3 of a single channel gap.²

With regard to expressions given above for the time of the resistive phase, most of the time the hydrodynamic pressures would appear to be rather greater than the magnetic forces and hence the conclusions of the rough explosion calculations should apply. But for single stab switches fed from very low impedance lines, hydro-magnetics ought to be used and hence the time of growth calculations could be badly wrong.

5. Triggered Solid Dielectric Switches

The simple switches described above have been used in surge generators which were themselves pulse charged in times of the order of a microsecond. Provided the charging system was capable of providing a reasonable degree of overvoltage for the switch, the rate of change of voltage could be of the order of 10^{11} volts per second, and with a standard deviation of 2 or 3% for the switch the standard deviation of time of operation would be 20 or 30 nanoseconds. However since still lower inductive switches were required, triggerable versions of the switches were developed. Such switches were also of use in voltage multiplying systems where a series of lines could be supplied with a switch apiece and the resulting simultaneous pulses added.

Two different versions of triggered switches based on the previously described solid switch have been developed and one has been used extensively. The other version will be mentioned but little work has been done on it after its original tests.

A third different shock-triggered solid dielectric switch has been used once or twice and this will be briefly mentioned at the end of this section. It functions in the region of 10 to 20 kV and can probably be made to work at still lower voltages. The other switches have a useful working range from about 20 to 200 kV and could certainly be made to work at much higher voltages if desired.

²Energy may be deposited in the copper electrodes and this will become important when current density is equal to approx. 10^6 amps/cm approx. for typical fast rise.

Version A (figure 4) is a simple three electrode gap where the pulse for the trigger electrode is supplied by a priming solid switch. The priming and triggered gaps can be in the same or different transmission lines. The middle electrode is held at mid voltage either by resistances or in the case of pulse charged lines simply by keeping the capacities balanced.

The center priming gap is either overvolted on a rising waveform or triggered on a slow waveform by shorting its trigger electrode down to earth with a gas gap. Owing to the slow rate of change of voltage only one stab goes in the priming gap. This however causes the voltage of the trigger electrodes in the main gaps to rise leading to progressive breakdown. When the system is properly balanced, many stabs will go in both sections of the main gaps and by having gaps only a few cm apart on the same line, it was shown from the fact that they carried roughly equal energies that the difference in timing could only be a fraction of a nanosecond. This conclusion is only finally justified by the measurements on the "time of formation" of the solid gaps, which in the experiment referred to was in the region of half a nanosecond.

The proper balancing of the system is quite complicated since, if the inductance between the primary gap and the trigger electrodes is too low, there is a danger that the upper halves of the gaps will not fire, in the case when they are in the same transmission line as the priming gap. On the other hand if the inductance is too high, the rate of change of voltage on the trigger electrode may fall below 10^{13} volts per second and then the number of stabs going in the lower half of the triggered gaps may be small. Also, if the rate of rise of the pulse from the priming gap is not greater than the ringing frequency of the trigger electrodes and connectors, the voltage pulse arriving is considerably reduced and while it might be supposed that it is only necessary to increase the voltage on the lower half of the gap by 30% or so, at these very high speeds of operation the breakdown voltage of the gap rises as is suggested by figure 1. This is possibly due to failure of the air on the stab to become completely conducting, so that the voltage on the bottom of the hole is reduced.

In illustration of some of these considerations, a rough analysis of an existing multigap system developed by Mr. Goodman will be discussed. The system has five gaps driven from one priming

gap. The diameter of all the trigger electrodes is 1" and their capacity 10^{-11} Farad. The connecting leads are 20 cm long and each has an inductance of about 10^{-7} Henry. Thus the impedance of the system viewed from the priming electrode is about 20 ohms and the period of the LC circuits 160 megacycles.

When the total gap is working with about 100 kV on it, the priming gap fires at 50 kV and the "resistive time" of the priming gap is about 1 nanosecond and hence the trigger pulse has an e-folding time of about this time. The trigger electrodes in the main gaps swing up to about E.H.T. voltage in a time on the order of 2 nanoseconds, providing a rate of change of voltage of a bit better than 10^{13} at the time when the lower set of gaps fire. These have resistive times of about 0.3 nanoseconds and lead to a rather faster rate of change of voltage for the upper halves of the gaps. Thus after 1 to 2 nanoseconds, the gaps have fired and the stagger in gap times is probably a fraction of a nanosecond.

In general the stabs in the triggered gaps are set 10% to 15% higher in breakdown voltage than the priming gap. In the case of triggered gaps working in DC or slowly charged systems, the difference between the voltage at which the gaps will not fire prematurely and that at which they will fire in a nanosecond will be greater and hence it will be more important to get the triggering conditions right than in the system described above which was pulse charged. However I do not think there would be any real difficulty and indeed the original work on this gap was done with a DC system.

Version B of the triggered gap is shown in figure 4 and differs from the first type in that the piece of dielectric which has to be replaced is entirely outside the line and this might facilitate changing it under certain circumstances. The outer ring of stabs is back biased by the trigger pulse, however, they will stand much more voltage this way round and indeed can be made to trigger at a quarter of the total volts and not be disturbed by a trigger pulse of up to a half the total volts. Not much work was done on this system but it has certain potentialities and shows some of the freedom solid dielectric switches give to the switch designer.

Switch system C is completely different from the others and was designed to work in the region of 10 to 20 kV not covered by the other switches, but only little experience was gained with it and it is included for completeness. The main line which it is required to provide with several low inductance breaks is made of 0.002" Mylar for 10 kV DC operation. The top electrode is .001" aluminum and on top of this are a series of auxiliary gaps formed from 0.001" Mylar joined by 15 cm of plastic covered wire to a central priming gap. The auxiliary gap top electrodes are 2" in diameter. When the solid dielectric priming gap is closed, a fast pulse causes more than the EHT volts to appear on the 0.001" Mylar and some point under the 2" diameter electrode goes. A few percent of the energy in the condensers formed by the auxiliary gaps (i.e. a few millijoules) is dumped into these spark channels and a strong shock (~ 0.1 megabar) runs out through the aluminum and into the insulation of the main gap. The total transit time of the shock across the main gap is about 20 nanoseconds and the scatter will be less than this. The main gaps fire fast and in experiments the main dielectric has been broken in four places over a width of about 20 cm. The shock that hits the main dielectric is very localized and this may be important since there is slight evidence that a dielectric switch attacked by a flat shock wave from a detonator displayed a long resistive phase. If the attacking shock wave is uniform over a large area the heated dielectric might be able to carry large conduction currents uniformly before eventually going over into small spark channels.

It is important that the original triggering pulse in this gap be fast as the 0.001" Mylar has a fair scatter of breakdown voltages since it is of large area. This could be improved by masking off all but a small area with a second sheet of 0.001" Mylar.

6. Some Practical Details Relating to Solid Switches

This section briefly mentions a few experimental details which have been observed by the team working with the gaps.

At one time it was thought that gaps made several hours previously had slightly different breakdown voltages and some healing of the stabs was postulated. However, more accurate

experiments showed no significant change of breakdown voltage with age of the gaps for times varying from a few minutes to a couple of days.

Variation of the quality of the polythene has sometimes been blamed for small changes in the curve of breakdown voltages but part of the variation is due to the different thickness of nominal 1/16" sheet. As has been explained the effects of this variation can be minimized by selecting the face of the polythene that is used in deciding the depth of the stab, according to whether the intended operating voltage is on the upper or lower band of values. Thickness effects apart, there are changes in the operating voltages of the stabbed gaps some of which can be attributable to the condition of the needle tips in the stabber. There may be an effect of temperature and quality of the polythene on the slight tearing at the bottom of the hole. All of these effects are slight and could be eliminated by some sort of quality control. We, however, have not found it necessary to do any selection of the polythene. Surface markings and finish do not have any serious effect on the operation of the switch in the normal voltage working range.

A few attempts were made to investigate PTFE sheet instead of polythene, but very erratic results were obtained. This was attributed to the obvious granular nature of the samples tried.

If triggered switches are used under water (as they nearly always are in our work) care must be taken to exclude water from the volume between the electrodes and the polythene in the triggered switches otherwise very slow water sparks have to occur before the switch closes and simultaneity is badly affected. We use Evostick adhesive to attach the small copper sheets to the faces of the polythene after it has been stabbed.

7. Incidental Advantages of Solid Dielectric Switches

In addition to providing very fast and very low inductance switches, one of the major incidental advantages of solid gaps is that in a reasonably laid out system, pick-up and interference are greatly reduced. Since the switch is buried in the transmission line, little energy lies outside it and

it is possible to operate quite sensitive equipment near to systems with di/dt in the region of 10^{13} amps per second.

In addition to not causing pick-up, a slight additional advantage comes from the fact that it is easy to prevent the switch spraying the surrounding high voltage insulating surfaces with UV. Operating high voltage pulse equipment such as Marx generators in a flood of UV has not seemed the most logical of procedures to me.

8. Acknowledgments

The work briefly covered in this note has been carried out in SSWA and Mr. Goodman, Mr. Simth, and Mr. Storr in particular, have contributed to many aspects of it, especially in areas relating to the operational characteristics of the switch.

APPENDIX C--Operating Procedures For The Capillary Discharge

C.1 Device Components

The capillary discharge device actually consists of many different components, some of which may be removed from time to time in order to conduct other experiments. The essential components of the device are:

- 1) **Marx generator**--The Marx should only be operated inside its large metal tank since the tank (when connected to ground) serves to prevent potentially lethal electrical shocks and to help shield sensitive electronic equipment in the lab from EMP effects.
- 2) **High voltage power supply**--The power supply should be connected to the Marx generator charging network with RG-214 coaxial cable.
- 3) **Trigger generator**--The trigger generator consists of a high voltage Ross relay inside a copper foil covered box, which is used to shield the relay electrically, and connected to the trigger terminal of the lowest spark gap switch with 6 meters of RG-214 coaxial cable. Since the cable serves as the energy storage for the trigger, the cable cannot be less than 6 m long. Also associated with the trigger is an extension cord wired with a switch that is used to open and close the relay.
- 4) **Transmission line and capillary assembly**--The outer conductor of the transmission line bolts

to the plate welded to the side of the Marx generator tank and the capillary assembly bolts to the flange on the end of the transmission line. The capillary can be fitted with a glass window, the small spectrometer or a photomultiplier tube. The center conductor of the transmission line is installed through the deionized water reservoir inside the Marx generator tank and connected to the output coil of the Marx.

5) **Vacuum pumps**--The capillary assembly should be connected to the small turbo-molecular vacuum pump and a mechanical roughing pump.

6) **Vacuum gauges**--The capillary assembly should be fitted with a thermocouple gauge and a cold cathode gauge.

7) **Deionized water system**--The DI water is used as the dielectric inside the transmission line. The system consists of two ion exchange cartridges, a resistivity meter, a pump to circulate the water and a tank to hold reserve water. Two valves should be arranged so that water can be pumped out of the reserve tank until the reservoir inside the Marx tank is filled. Once the Marx reservoir is full, the reserve tank should be able to be valved off so water is circulated continuously through the transmission line.

8) **Gas supply**--A cylinder of argon gas should be connected through a needle valve to the capillary assembly. Synthetic air must also be supplied to the spark gap switches on the Marx generator. A secondary regulator is used to control the switch pressure from 0 to 15 PSIG. A valve on the outlet of the switches allows the gas flow to be controlled.

C.2 Preparing the system for operation

Before the system can be operated, the transmission line and reservoir must be filled with DI water and the capillary assembly must be under vacuum. The argon and synthetic air lines should also be flushed out. The procedure for filling the transmission line is:

- 1) Fill the reserve tank with tap water if it is not already full
- 2) Open the valve to allow water from the reserve tank to flow into the pump
- 3) Close the return valve from the Marx reservoir
- 4) Check the valve on the cartridge inlet to be sure that it is open
- 5) Start the pump and plug in the resistivity meter
- 6) As the reservoir fills, monitor the resistivity--if the resistivity remains below 1 M Ω -cm then the cartridges must be replaced.
- 7) When the reservoir is filled, slowly open the return valve, allowing the air in the line to be removed gradually
- 8) Once no more air remains in the return line, close the valve to isolate the reserve tank from the system

To pump out the capillary assembly:

- 1) Plug in the controller and the cooling fan for the turbo pump
- 2) Close the high vacuum valve between the capillary and the turbo pump and start the roughing pump
- 3) Slowly open the vacuum valve
- 4) Monitor the pressure using the thermocouple gauge
- 5) Once the pressure falls below 100 mT, turn on the turbo pump
- 6) Plug in the cold cathode gauge when the thermocouple gauge reads zero

7) If the capillary assembly does not reach the 10^{-3} Torr range, check the system for leaks. To flush the argon line, turn on the regulator at the cylinder and loosen the connection at the capillary to allow the gas to flow for a few minutes. To flush the switches and synthetic air lines, turn on the cylinder regulator and open the valve on the switch exhaust line. If gas does not flow, check the secondary regulator to be sure that it is set for at least 10 PSIG.

C.3 Operating the capillary discharge

To operate the discharge device:

- 1) Remove the safety wires that short the capacitors when not in use
- 2) Set the switch pressure based on the operating curves for the switches--for a 35 kV charge, the pressure should be about 10.5 PSIG
- 3) Unplug the cold cathode vacuum gauge
- 4) Close the vacuum valve
- 5) Open the needle valve on the argon line and fill the capillary to the desired pressure
- 6) Remove the sensor from the thermocouple gauge
- 7) Turn the relay control switch to "on", opening the Ross relay
- 8) Turn on the power supply and slowly increase the voltage to the desired charge voltage
- 9) Turn the relay control switch to "off", closing the relay and triggering the discharge
- 10) Purge the spark gap switches (Note: if numerous shots are being done, the valve on the exhaust line can be opened slightly, allowing gas to flow constantly which eliminates the need to purge the switches after each shot)

11) Reconnect the thermocouple gauge and open the vacuum valve

After all the shots have been completed for the day, close the valves on both gas cylinders, turn off the vacuum gauges and pumps, turn off the high voltage power supply, unplug the DI water resistivity gauge and drain the DI water out of the Marx reservoir. It is convenient to drain the reservoir back into the reserve tank.

References

1. D. L. Matthews *et al.* "Demonstration of a Soft X-Ray Amplifier." *Physical Review Letters* **54**(2), 110 (1985).
2. L.B. Da Silva *et al.* "Power Measurements of a Saturated Yttrium X-Ray Laser." *Optics Letters* **18**(14), 1174 (1993).
3. K. Boyer *et al.* "Evidence for Coherent Electron Motions in Multiphoton X-Ray Production from Kr and Xe Clusters." *Journal of Physics B: Atomic, Molecular and Optical Physics* **27**, 4373 (1994).
4. J.J. Rocca *et al.* "Fast-discharge Excitation of Hot Capillary Plasmas for Soft X-Ray Amplifiers." *Physical Review E*. **47**(2), 1300 (1993).
5. E.P. Ivanova *et al.* "Theoretical Investigation of Non-Maxwellian Plasma Electrons in Spectra of Ne-like Ions." *Proceedings of the International Conference Lasers '93* (1993).
6. A. Richard Miller. Private Communication (Oct. 1995).
7. A. Richard Miller. Private Communication (Nov. 1995)
8. Robert C. Weast, editor. *Handbook of Chemistry and Physics, 55th Edition*(CRC Press, Cleveland, OH, 1974), p. E-61.
9. Miller (Nov. 1995).
10. Miller (Nov. 1995).
11. Miller (Nov. 1995)
12. Miller (Nov. 1995)
13. E. Marx. *Deutsches Reichspatent* No. 45593 (1923).

14. Frank C. Creed. *Generation and Measurement of High Voltage Impulses* (Center Book Publishers, Princeton, NJ, 1989), p. 16.
15. Creed, p. 17.
16. David Halliday and Robert Resnick. *Fundamentals of Physics, Second Edition* (John Wiley & Sons, New York, NY, 1981), p.595.
17. W.R. Bell *Resistivity/Concentration Characteristics for nickel Chloride and Copper Sulphate*. (Unpublished research report, 1960), pp. 1-2.
18. Halliday and Resnick. P.507.
19. Hugh D. Young. *University Physics, Eighth Edition*. (Addison-Wesley Publishing Company, 1992), p.715.
20. Young, p.692.
21. Young, p.690.
22. P.N. Murgatroyd *et al.* "Making Rogowski Coils." *Measurement Science and Technology* 2, 1218 (1991).
23. Thomas T. Stark. *Time Resolution of Current and Temperature in a Capillary Discharge Plasma*. 1994.
24. Stark, p.104.
25. Peter W. Milonni and Josehp H. Eberly. *Lasers*. (John Wiley & Sons, 1988), p.10.
26. Milonni, p. 10.
27. Arthur B. Williams and Fred J. Taylor. *Electronic Filter Desigh Handbook, 3rd ed.* (McGraw-Hill, 1995), p. 4.2.
28. Williams, p. 2.37.
29. Williams, p. 4.3.
30. Williams, p.4.3.
31. Bell, pp.1-3

32. Bell. Also includes data from J. Oldenettel. 1972.

Bibliography

- Bell, W.R. *Resistivity/Concentration Characteristics for Nickel Chloride and Copper Sulphate*. Unpublished research report. 1960.
- Boyer, K. *et al.* "Evidence for Coherent Electron Motions in Multiphoton X-Ray Production from Kr and Xe Clusters." *Journal of Physics B: Atomic, Molecular and Optical Physics*. **27** (1994): 4373-4389.
- Creed, Frank C. *Generation and Measurement of High Voltage Impulses*. Princeton, NJ: Center Book Publishers, Inc., 1989.
- Da Silva, L.B. *et al.* "Power Measurements of a Saturated Yttrium X-Ray Laser." *Optics Letters*. **18**(14), 15 July 1993: 1174-1176.
- Halliday, David and Robert Resnick. *Fundamentals of Physics, Second Edition*. New York, NY: John Wiley & Sons, 1981.
- Ivanova, E.P. *et al.* "Theoretical Investigation of Non-Maxwellian Plasma Electrons in Spectra of Ne-like Ions." *Proceedings of the International Conference Lasers '93*.
- Marx, E. *Deutsches Reichspatent* No. 45593. 1923.
- Matthews, D.L. *et al.* "Demonstration of a Soft X-Ray Amplifier." *Physical Review Letters*. **54**(2), 14 January 1985: 110-113.
- Miller, A. Richard. Private Communication, 12 October 1995.
- Miller, A. Richard. Private Communication, 22 November 1995.
- Milonni, Peter W. and Joseph H. Eberly. *Lasers*. New York, NY: John Wiley & Sons, 1988.
- Murgatroyd, P.N. *et al.* "Making Rogowski Coils." *Measurement Science and Technology*. **2** (1991): 1218-1219.
- Oldenettel, J. Unpublished research data. 1972.

- Rocca, J.J. *et al.* "Fast-discharge Excitation of Hot Capillary Plasmas for Soft X-Ray Amplifiers." *Physical Review E*. 47(2), February 1993: 1299-1304.
- Stark, Thomas T. *Time Resolution of Current and Temperature in a Capillary Discharge Plasma*. 1994.
- Weast, Robert C., Editor. *Handbook of Chemistry and Physics*, 55th Edition. Cleveland, OH: CRC Press, 1974.
- Young, Hugh D. *University Physics*, Eighth Edition. Reading, MA: Addison-Wesley Publishing Company, 1992.
- Williams, Arthur B. and Fred J. Taylor. *Electronic Filter Design Handbook*, 3rd ed. New York, NY: McGraw-Hill, 1995.

High Voltage Pulse Generator for a Capillary Discharge

X-ray Laser

Bryan Royce Olsen

Department of Physics

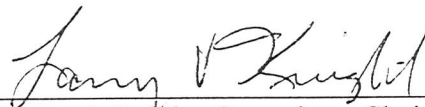
M.S. Degree, December 1996

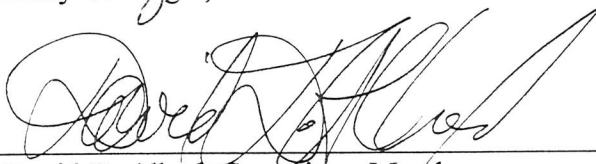
ABSTRACT

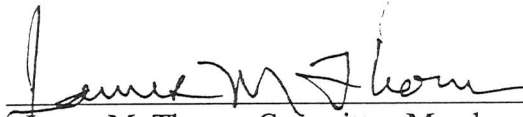
A high voltage pulse generator has been designed and constructed to drive a capillary discharge x-ray laser. The design specifications require that the device produce an electrical pulse through a small capillary with a 1 ns rise time and a peak current of 20 kA. Additionally, the device must be compact and relatively simple.

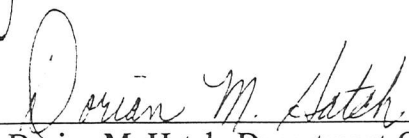
The device was constructed using a three stage Marx generator for a primary energy store and a water filled transmission line to generate the fast pulse. When construction was completed, the device was tested extensively and found to meet or exceed the design criteria. Tests of the plasma excited by the current pulse also indicate that conditions favorable for lasing are being achieved using this pulse generator.

COMMITTEE APPROVAL:


Larry V. Knight, Committee Chair


David D. Allred, Committee Member


James M. Thorne, Committee Member


Dorian M. Hatch, Department Chair