SOME PROBLEMS IN THE DESIGN OF NANOSECOND RISE-TIME HIGH VOLTAGE SOURCES AND ELECTRON GUNS

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In Partial Fulfillment

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Master of Science

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by

Joseph Kirk Thomas

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TABLE OF CONTENTS

I.	ABSTRACT	1
II.	INTRODUCTION	2
III.	EXPERIMENT DESIGN	5
IV.	TRIGGER ELECTRONICS	7
V.	PULSER WAVEFORMS	10
VI.	COAXIAL SPARK GAP DESIGN	11
VII.	COAXIAL SPARK GAP WAVEFORMS	13
VIII.	BIPPIE AND THE ELECTRON GUN	14
IX.	EXPERIMENTAL RESULTS	17
X.	REFERENCES	21

ABSTRACT TITLE

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Abstract

Traditionally, electron beams have been driven by simple capacitive discharge schemes, wherein the cathode of an electron gun was connected in series with a charged capacitor by some type of high voltage switch. Techniques of this sort produced voltage rise times ranging from a few milliseconds to a few microseconds, which was usually quite acceptable for most purposes. Recent developments in laser technology, electron beam-plasma interactions, and so forth, has spurred interest in relatively simple, high voltage, nanosecond rise time electron beam devices. This thesis concerns itself with the problems encountered in the design and construction of fast rise time voltage sources, and the demands such rise times place on measurement circuits, timing circuits, and the electron gun itself. It is shown that charged delay line systems with coaxial spark gaps yield the best waveforms, and that some type of indirectly heated electron gun is best suited for nanosecond operation.

Introduction

The simplest technique for producing a voltage pulse is shown in Figure 1a. A capacitor is charged slowly to the required voltage through a high resistance bleeder resistor. The switch is thrown and the capacitor voltage is applied to the load. If, indeed, the only elements in this circuit were the capacitor and resistor, the output voltage should rise instantaneously to the capacitor voltage and then decay exponentially with a time constant RC. Of course, there are always distributive reactances to deal with. The capacitor itself has an inductance, and there is considerable distributed inductance due to the conductors themselves. Figure 1b then, shows the actual circuit to be a series RLC circuit which will produce, at best, the critically damped waveform shown in Figure 1c. Attempts to reduce inductive effects has led to considerable development of very low inductance capacitors, shorter connections, and to the careful arrangement of conductors in such a way as to partially cancel each other's magnetic fields.

It is clear, however, that very fast rise times are best produced by the use of delay lines, of which coaxial cables are the most readily available. Figure 1d illustrates one such method[1]. A voltage source V is connected through a switch to the center conductor of a coaxial cable whose outer conductor is grounded. The input to the line is terminated by a resistance equal to the characteristic impedance of the cable. Obviously, while the switch is closed, the voltage at both input and output is the supply voltage V. When the switch is opened, the voltage at the input drops to V/2, and a voltage wave of magnitude -V/2 travels down the cable at the propagation velocity, reducing the center conductor's voltage to V/2 at each point it passes. Assuming the input impedance to the load to be quite high, the output is essentially unterminated. The wave is therefore reflected at the output without loss or phase change, and travels back down the cable, wiping out the voltage on the line as it does so. Because the voltage at any point in the line is the superposition of both the transmitted and reflected waves, the voltage at the output is V-V/2-V/2, and therefore falls to zero at $t = t_d$.

Two problems with the above circuit make it totally unsuited for driving an electron gun. Firstly, as shown in Figure 1e, the output is not truly a pulse, but a step function. Prior to opening the switch, the supply voltage is in fact, impressed upon the load, a highly undesirable situation indeed! An even more glaring problem is that, prior to opening the switch, the voltage supply, which for electron guns is usually a few kilovolts, is in series with the resistor Z_o, which is usually a few ohms. The resulting current is quite large, and undoubtedly well beyond the capacity of the power supply. Nevertheless, this circuit does find applications in low voltage laboratory pulse generators.

The above problem can be circumvented by the use of the circuit shown in Figure 1f.[2] Here again, the shield is grounded. The center conductor is connected to a high voltage supply through a high resistance bleeder resistor (typically of several MEG ohms), and the output is developed across a resistance equal to the characteristic impedance of the line. When the switch is thrown, the voltage at the output falls to V/2, sending a wave of magnitude -V/2 down the cable, again reducing the line voltage to V/2 behind it, being reflected from the unterminated end, and wiping out the remaining potential as it propagates back to the output. As shown by the waveforms in Figure 1g, this system does produce a true pulse.

The problem with this circuit is essentially one of switching. During the pulse, neither side of the switch is at ground. ALFANO and YURLINA[3] have used this circuit at voltages as high as 2.5 KV by means of a magnetically actuated mercury switch. For higher voltages, mercury switches are no longer suitable due to arcing, and it becomes necessary to use other switching techniques, such as thyratrons or spark gaps. To avoid high floating potentials, it is advantageous to have one side of the switch at ground.

Figure 1h shows a method for switching ground. The center conductor is connected to ground through a terminating resistor at the characteristic impedance. In contrast to the two previous techniques, the <u>shield</u> is connected to a negative high voltage supply through a high resistance bleeder resistor, and to ground through a normally opened switch. When the switch is open, the shield voltage is at the supply voltage and the center conductor is essentially grounded through Z_0. A negative surface charge appears on the shield, inducing an equal positive charge on the center conductor. When the switch is closed, the shield is grounded. A voltage wave of magnitude V/2 is propagated down the line, where it is reflected at the unterminated output. Since the voltage at any point along the line is the superposition of transmitted and reflected waves, the output voltage is V. Figure 1i shows the wave forms at both input and output.

EXPERIMENT DESIGN

Due to the above stated advantages, the author decided to construct the circuit shown in Figure 1h. A more detailed schematic is presented in Figure 2, and Figure 3 shows the actual physical arrangement of the device. The switch was a Bendix XG-1105 spark gap, pressurized to 15 lbs/in^2 guage pressure of nitrogen. Fifteen meters of RG-8 coaxial cable was used to produce an output pulse width of 80 nanoseconds. This particular cable has a solid polyethelene dielectric, as opposed to similar cables using a cellular polystyrene dielectric, and therefore was capable of withstanding potential differences of up to 30 KV. The cable was tightly wound into a drum 8 inches in diameter and 11 inches high. The drum was encased in the plexiglas structure, with connections to the center conductor and the shield of one end fed through two holes in the bottom plate, and the other end (output) fed through a hole in the top plate. The spark gap was mounted directly underneath the drum. Since the characteristic impedance of this line was 50 ohms, five 10 ohm 2 watt carbon resistors, in series, were connected from the center conductor to the ground plate of the spark gap. Although the inductance would have been much smaller had a single resistor been used, hi voltage corona would have shorted the resistor entirely. Because the output signal from the center conductor must be negative, the outer conductor must be positive prior to switch closure. Therefore, the shield was connected to a positive high voltage supply through a 5 MEG ohm bleeder resistor.

To monitor the output from the delay line, some sort of voltage divider, with an attenuation of about 100:1, was needed. Initial attempts with commercial capacitance dividers proved to be disastrous, as they tended to ring.

It was felt that a coaxial voltage divider would yield a reasonably faithful reproduction of the signal, and therefore the device shown in Figure 4 was constructed. It consisted of a 10 470Ω 2 watt carbon resistors connected in series with themselves and with a single 47 ohm 2 watt carbon resistor at one end. The resistors and the leads between them were coated liberally with high voltage corona dope and then taped with several layers of plastic electrical tape. The shield from a length of RG-8 was slipped over the resistor chain. The end with the 47Ω resistor was connected to ground, the other end to the voltage source to be measured. The 47Ω resistor, in addition to developing a signal 1/100th the input voltage, also nicely terminated a 50Ω RG-58 coaxial cable which went to a 150 MhZ, 2.4 nanosecond rise time Tektronix 454 dual trace oscilloscope. The input to the scope was, of course, also terminated.

When a 10 volt, 10 nanosecond rise time, 100 nanosecond wide test pulse was placed on the divider, the result was somewhat disenchanting, as can be seen in Figure 4a. Surprisingly, when the shield was removed, the divider produced an attenuated version of the input with great fidelity, as can be seen in Figure 4b. At this point, the divider was connected, minus the shield, between the ground electrode of the spark gap and the high voltage output in the naive belief that an adequate nanosecond divider was at hand.

Trigger Electronics

There are two basic requirements for the operation of a standard three electrode triggered spark gap. One is that the trigger signal be of sufficient voltage to produce an arc between the trigger electrode and (usually) the cathode, and the other is that the potential difference between cathode and anode be sufficiently high to sustain a breakdown when triggered. The latter condition can be controlled to a certain extent by the choice of operating gas, gas pressure, and cathode - anode spacing. Most triggered spark gaps have a needle-like trigger electrode which, surrounded by hi-voltage insulator, protrudes up through and flush with the middle of the cathode, which is usually either spherical or hemispherical. A high voltage pulse on the trigger causes breakdown between trigger and cathode, and the resulting ionization causes an avalanche and breakdown between cathode and anode. One would think that a negative pulse on the small radius of curvature trigger electrode would cause breakdown at a lower voltage than a positive pulse, due to field emission of electrons from the trigger. But since the predominate physical process leading to breakdown is the acceleration of existing free ions and electrons in the gas, in practice, the polarity of the trigger pulse is of little importance.

Figure 5 is a schematic of the trigger unit designed and constructed for this experiment. It consists of a 3μfd capacitor in series with an SCR and the primary of an automobile ignition transformer. The output secondary winding goes to the trigger electrode of the spark gap, and the winding is in parallel with a voltage divider consisting of 3 50KΩ resistors in series with a 51Ω terminating resistor. A 50Ω RG-58 coaxial table is connected across this resistor. The attenuation is 3000:1.

The capacitor is charged from a 300 volt power supply through a 15 KΩ resistor. The purpose of this resistor is to limit the current through the SCR after the capacitor is discharged. In its absence, current would flow through the SCR indefinitely, until the supply was shut off, since an SCR, once triggered, remains closed as long as there is sufficient current flowing through it. The 15 KΩ resistor limits the current to a value large enough to charge the capacitor in the repetition period, but too low to maintain SCR closure.

It might be pointed out that the original design of this circuit had the SCR and capacitor interchanged. Operating in such a manner, SCR's burned out at a rate of about one per week. Examination of the problem showed the folly of connecting the cathode of an SCR to an inductive load. The trigger to the SCR is relative to ground. But upon closure, the voltage at an inductor rises rapidly and not only reduces the trigger voltage relative to the cathode, but back biases it. In effect, the SCR attempts to turn itself off, and this tendency can be overcome only by using abnormally large trigger pulses. Once the SCR and capacitor were re-arranged, the problem was solved, and a single SCR has sufficed for many months.

Figure 6a shows the output of the trigger unit when not connected to the gap. The rep rate was about 10 hZ, and the waveform is a negative sinusoid of about -9000 volts amplitude and about 150 μsec duration. Figure 6b shows the waveform when connected to the spark gap trigger. The sharp discontinuity indicates the point where breakdown occurs, here at about -6000 volts.

This discontinuity at breakdown was used to generate a trigger signal for the oscilloscope. The coax carrying the scope signal was interrupted with a T connector mounted on a small metal box. Inside, a 51Ω 1/2 watt carbon resistor terminated the connector, the center connector was connected to a .001μfd disc capacitor in series with a 100Ω resistor, which was then connected to the center of an output connector. This side was also terminated with a 51Ω resistor. This differentiator produced a sharp pulse at the discontinuity which was fed to the external trigger input of the 454.

PULSER WAVEFORMS

Figure 7 shows the high voltage waveforms produced by the pulse forming network. The apparent rise times for the 10 KV, 80 nanosecond pulse was 30 nanoseconds. The waveform is peculiar in there are two pulses present. In this particular trace, the second pulse is significantly smaller than the first. By changing the position of the string of resistors (forming the terminating resistance) relative to the spark gap, and altering the curvature of the string, the relative magnitude of the second pulse could be changed considerably. This indicates that the dual pulse mode is due to reflections in the delay line, which are in turn due to the high frequency resistance of the terminating string being greater than 50 ohms.

COAXIAL SPARK GAP DESIGN

In an attempt to obtain a faster rise time, the author designed and constructed a coaxial spark gap. Delay lines with internal spark gaps or thyratrons are described by FRÜNGEL,[4] and are reputed to have rise times under a nanosecond.

The design of the spark gap is rather involved, and can best be understood by following its schematic in Figure 8. The device was machined out of plexiglas bar stock. The center conductor from the delay line connects to a 50 ohm conical resistor, which screws into a hemispherical cathode, which is held at ground potential by an insulated ground lead. The anode is spherical, attached to a threaded shaft which screws into the anode plate. The anode plate connects to an aluminum foil skin which covers the outside of the switch and is connected to the shield of the coax cable.

The spark chamber itself is 1-1/4 inches in diameter and 2-1/2 inches deep. A slot is cut at its base for an "O" ring, which is held airtight by six 4/32 screws.The chamber is pressurized with nitrogen at 15 psi guage.

The cathode has a 1/16 inch diameter hold drilled along its axis of symmetry. A 1/32 inch diameter hole is drilled about one inch into the conical resistor. The lead was cut from a 1/4 watt carbon resistor and inserted into this hole, being very careful that the wire not touch the walls of the cathode. It is held in place with the insulated trigger electrode screw.

The conical terminating resistor was made by coating the plexiglas member with a layer of Aqua-Dag, a colloidal suspension of carbon in ammonium hydroxide. When dry, the layer had a resistance of approximately 50 ohms. The ends were painted with silver print paint to provide good contact with the aluminum connections. The entire resistor was sprayed with plastic resin to prevent flaking and mechanical damage to the surface.

All metal parts were machined from aluminum, and the metal surfaces were polished mirror bright. The entire switch was enclosed in a 2-1/2 inch O.D. plexiglas tube with plates at each end and holes for the ground and trigger electrodes and the nitrogen feed.

The above spark gap was mounted in place of the Bendix spark gap. In this case, of course, the terminating resistor is built into the spark gap itself. The ratio of outside diameter to inside diameter over the portion containing the resistor was 4.0:1 to preserve the impedance of the line. Because all capacitances and inductances are distributive, it was anticipated that the output from this device should have a much faster rise time than its predecessor.

COAXIAL SPARK GAP WAVEFORMS

The trigger broke down at about -2000 volts. Surprisingly, the output was identical to the waveform produced by the Bendix gap, except that no second pulse was observed. The line had been very closely matched, and the waveform reflected from the unterminated end was therefore completely absorbed.

Closer examination of the rise time problem led to the conclusion that the pulser probably was producing very fast rise time pulses, but that it was not possible to observe them using the voltage divider at hand. When the divider had been tested, the ground side of the divider had been connected to the shield of the 50Ω RG-58 cable from a pulse signal generator, and the other end connected via a wire, which had run parallel to the resistor string, to the center conductor. The area enclosed had been quite small. When connected to the spark gap generator, however, the area enclosed by spark gap, cable drum, and divider had been larger by two orders of magnitude. This had the effect of placing an inductance in series with the divider, which amounted to a series RL circuit whose response was limited by the L/R time constant. To verify this, the divider was removed and tested as before. Increasing the area enclosed by the wire, divider, and coax output indeed increased the observed rise time to the magnitude observed on the spark gap generator.

BIPPIE AND THE ELECTRON GUN

The apparatus with which this experiment was performed is known as BIPPIE, an acronym for Beam Interaction Pulsed Plasma Injection Experiment. It is a long cylindrical magnetic mirror system, a schematic of which is shown in Figure 9. In normal operation, a plasma gun at one end of the system injects a plasma through the loss cone of the first magnet. Thermalization reduces the anisotropy of the distribution function of the plasma emerging from the first mirror to the extent that most of the particle velocities lie outside the loss cone of the second magnet, resulting in trapping. The electron beam is injected from the other end. Properties of the plasma and beam-plasma interactions are studied with diagnostics in the midplane.

The mirror ratio of this system is 1.95:1, with a maximum field at midplane of 1800 gauss when the capacitors are charged to 5 K V. The vacuum is provided by a 6 inch diameter NRC diffusion pump. Typical pressures read 10^{-7} Torr on the ion guage, corresponding to a density of 10^{10} particles/cm^3.

The original electron gun was a conceptually simple affair, consisting of a directly heated tungsten cathode, connected by an isolation transformer to a step down transformer, which was in turn connected to a variable transformer. The anode was a brass plate with a 1/2 inch hole, over which a fine mesh tungsten screen was laid. In past experiments, it had performed satisfactorily with voltage rise times in hundreds of microseconds. When the output from the coaxial spark gap generator was attached to the cathode, however, the signal was lost completely. At nanosecond rise times, pulses were shorted to ground via the interwinding capacitances of the transformers. It therefore became necessary to design and construct a new electron gun where the cathode was indirectly heated and therefore more effectively isolated from ground.

Figure 2 shows the scheme used for driving a tandem electron gun. A tungsten disc was connected to the output of the high voltage pulser, thereby grounding it through a 50 ohm resistor (the terminating resistance). With the directly heated filament held at -2000 volts, electrons impinged upon the disc and were conducted to ground. For the most part, the kinetic energy gained by the electrons in falling through 2000 volts potential was converted to heat at the anode (disc), although, of course, there were some losses due to bremstrahlung. Adjacent to the tungsten disc, on the side opposite the filament, was a grounded brass plate with a hole in it. When the spark gap closed, the disc voltage went from approximate ground to -10 KV or so. Being more negative then than the filament, the electron flow from filament to disc was halted. Being more negative than the ground brass plate, the heated disc served as a cathode and an electron beam emerged through the plate's orfice. The water cooled filament and filament shield from the original electron gun was used to heat the tungsten disc. The disc was mounted in a "paddle," as shown in Figure 10, which was mounted through a brass plate on top of a 3" I.D. glass T. The shaft of the paddle connected to a brass anode plate with a 1/2 inch hole bored into it. The hole was laid with a fine mesh tungsten cloth. Three screws separated the anode from the cathode plate. The disc was held in place with boron nitride, a very high temperature insulator. A 26 guage tungsten wire, held in contact with the tungsten disc by mechanical pressure from two boron nitride plates, was fed through a high voltage insulator in the top plate. The high voltage insulator was connected to the output of the spark gap pulser, and the top plate was grounded.

Events in the system were sequenced electronically. The sequence was initiated by manually firing ignitrons, which discharged capacitors in series with the magnet coils. The magnet circuit was underdamped and began to ring. A peak sensing device fired a crowbar ignitron which shorted the capacitors at the height of the first sinusoid, providing a L/R decay for the coils. The e-folding time was about 150 milliseconds, so the magnetic field was essentially constant over the duration of the electron beam pulse. The crowbar signed was also fed to a Tektronix 161 waveform generator, which produced a ramp. A subsequent Tektronix 162 pulse generator could be adjusted to trigger at any value of the input ramp. The output pulse from the 162 was fed to the trigger electronics, which fired the electron gun and triggered the 454 oscilloscope.

Experimental Results

To reach thermoionic emission temperatures, the tungsten disc had to be heated white hot. This required from 300 to 350 watts. The choice of operating voltage proved to be quite important. At the lower voltage, around 1 KV, the filament temperatures were prohibitively high. The lifetime of the filament was small, and the inside of the glass T became coated with tungsten. The latter necessitated the disassembly of the electron gun, swabbing the glass T with concentrated hydrochloric acid, and sanding the boron nitride and brass clean. Above 2 KV, however, breakdown usually occurred.

Driving the heating electron gun required, then, about 150 to 175 milliamps. The Aqua-Dag terminating resistor proved to be unstable at these current levels. Hot spots would appear on the surface and the resistance would increase, due to the positive resistive temperature coefficient of carbon. Since the impedance of the electron gun was very much greater than 50 ohms, the terminating resistor was essentially connected to a constant current source. Thus, an increase in resistance meant an increase in the I^2R power disipated in the resistor. The situation was obviously unstable, and the coaxial spark gap burned up. A second coaxial spark gap was made, but subsequent experimentation concluded that the Aqua-Dag resistor could not be stabilized without considerable redesign of the spark gap. Since the double pulse structure of the generator using the Bendix spark gap was in no way a problem, it was decided to revert to the original design.

To determine if a beam was present, a grounded beam probe was inserted and moved around in the midplane of the system. Figure 11a shows a succession of traces that the beam probe produced. As the entrance to the beam probe was about 1 cm^2, the current intercepted by the probe was only about 5 milliamps. The probe did serve, however, to verify the existence of the electron beam.

The original beam collector had been a conical "lamp shade" grid device which fit flush with the walls of the T at the end of the system opposite the electron gun. When its output was viewed, nothing could be discerned due to excessive amounts of noise and ringing, which appeared every time the spark gap was fired, whether the electron gun was operating or not. It became apparant that the voltage divider was acting as an antenna and irradiating the collector with signals due not only to the pulse itself but to plasma oscillations in the spark gap, etc.

Figure 11b is a schematic of an improved beam collector. The collector is shielded from RF by copper foil on all sides and copper mesh on the top. The beam is collected by the collector plate, and a voltage signal is developed across a 50 ohm resistor which connects the plate with the foil chasis, which is grounded. The signal is conveyed by RG-58 to the oscilloscope. The collector is laid in the glass T, as shown in Figure 9. The magnetic field at that end is distorted downward due to the presence of iron, from which the diffusion pump is constructed. The electron beam follows the fieldlines fairly well, and impinges on the beam collector.

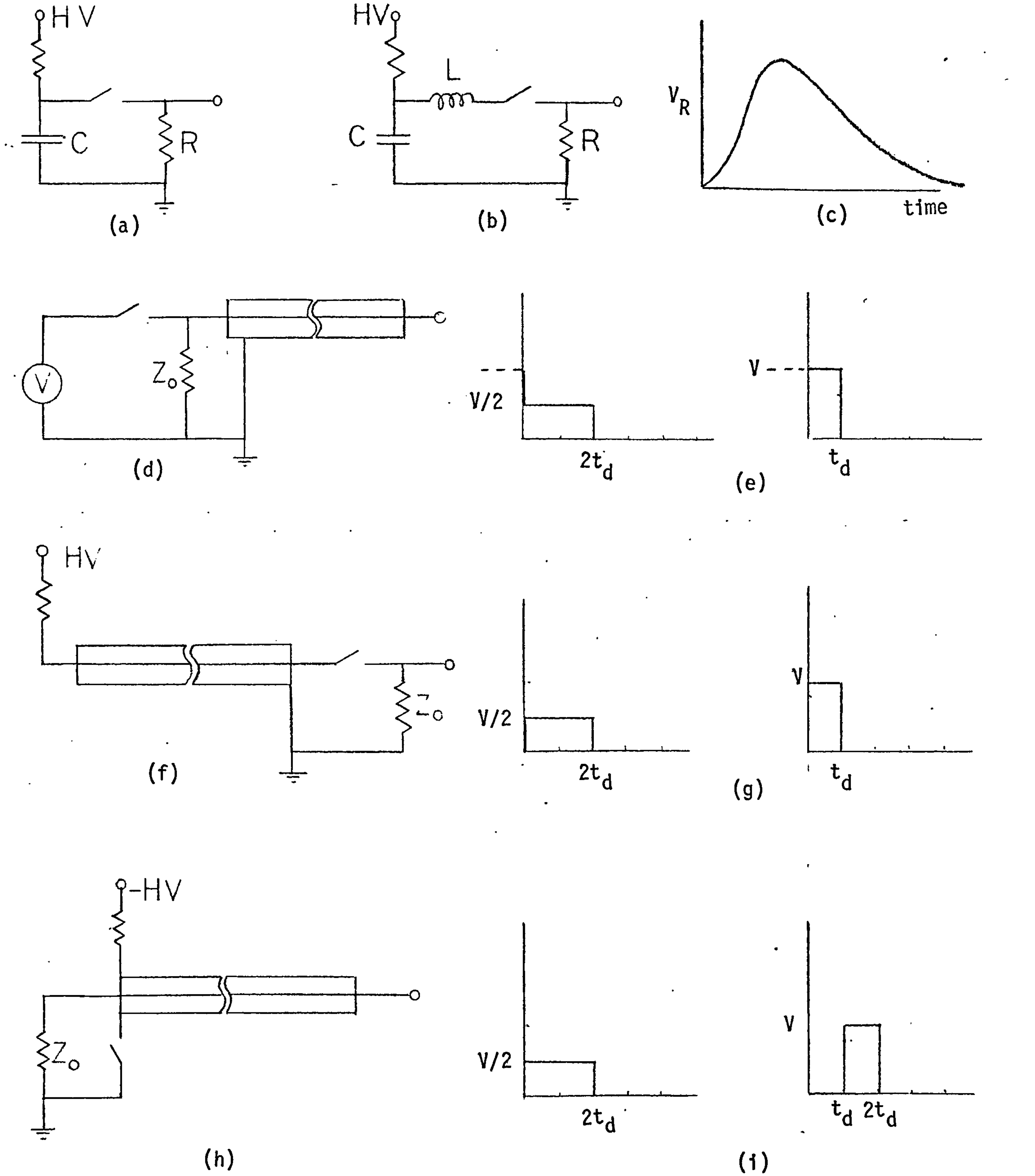
Figure 12 depicts the system in operation. The upper traces are of the voltage pulse placed on the electron gun, and the lower traces are signals from the beam collector. As can be seen, the beam collector waveforms are quite identical to the voltage pulse, with one exception. In Figure 12a, the rise time of the first voltage pulse appears to be about 30 nanoseconds, whereas the rise time for the first pulse, as measured by the beam collector, is immeasurably small at 100 nanosec/cm sweep. This verifies our hypothesis that the pulse generator was indeed producing nanosecond pulses and that the voltage waveform was limited by the divider response.

The length of cable from the beam collector to the scope input was carefully measured to be the same as the cable length from the divider to the scope input. Thus, simultaneous signals at beam collector and divider would produce simultaneous waveforms at the scope. By measuring the lag time between the voltage pulse on the gun and arrival of the beam at the collector (40 nanoseconds), the electron velocity could be computed. Equating the kinetic energy of the electrons to the potential energy lost falling through the potential between cathode and anode, the voltage of the gun was computed to be 7 KV, which compares well with the 8 KV pulse measured by the divider.

The electron beam current can be measured by dividing the signal voltage from the collector by 50 ohms, its terminating resistor. The perveance ($P = (I/V)^{3/2}$) was computed to be approximately 10^{-10} perve with a beam current of 35 milliamps.

CONCLUSION

The problems associated with nanosecond rise-time, high voltage circuits can be summed up as being generation, isolation, and measurement. The method of discharging delay lines is intrinsically superior to capacitor discharge schemes. For voltages above a few KV, spark gaps are the best, and perhaps the only, switching techniques. Coaxial spark gaps probably yield the fastest rise times, since the reactances are distributive about a coaxial terminating resistor, and therefore most accurately terminate the line. Fast rise-time waveforms are easily shorted to ground through interwinding capacitance of transformers used to directly heat filaments, and therefore some method of indirectly heating an electron gun cathode must be used to isolate the voltage pulser. Measuring the voltage waveform itself is a problem. Account must be taken for the circuit loop area and this adds inductance in series with the resistance divider. The divider itself radiates, as does the spark gap, and the electron beam collector must be shielded from this RF interference.



HV
C
R
(a)
HV
L
C
R
(b)
V_R
time
(c)
V
Z_o
(d)
V/2
2t_d
V
t_d
(e)
HV
Z_o
(f)
V/2
2t_d
V
t_d
(g)
-HV
Z_o
(h)
V/2
2t_d
V
t_d 2t_d
(i)

FIGURE ONE

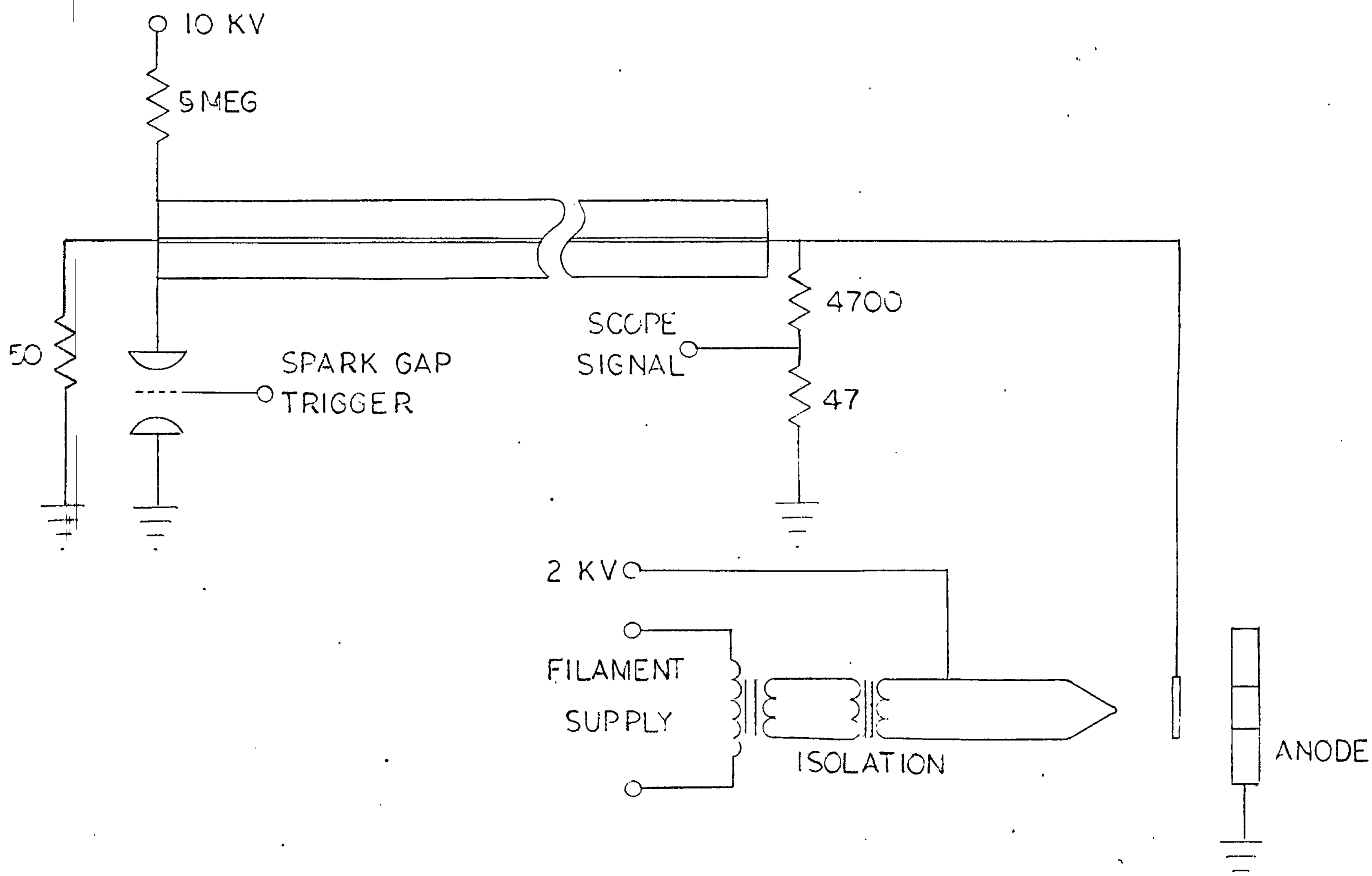

10 KV
5 MEG
50
SPARK GAP
TRIGGER
SCOPE
SIGNAL
4700
47
2 KV
FILAMENT
SUPPLY
ISOLATION
ANODE

FIGURE TWO

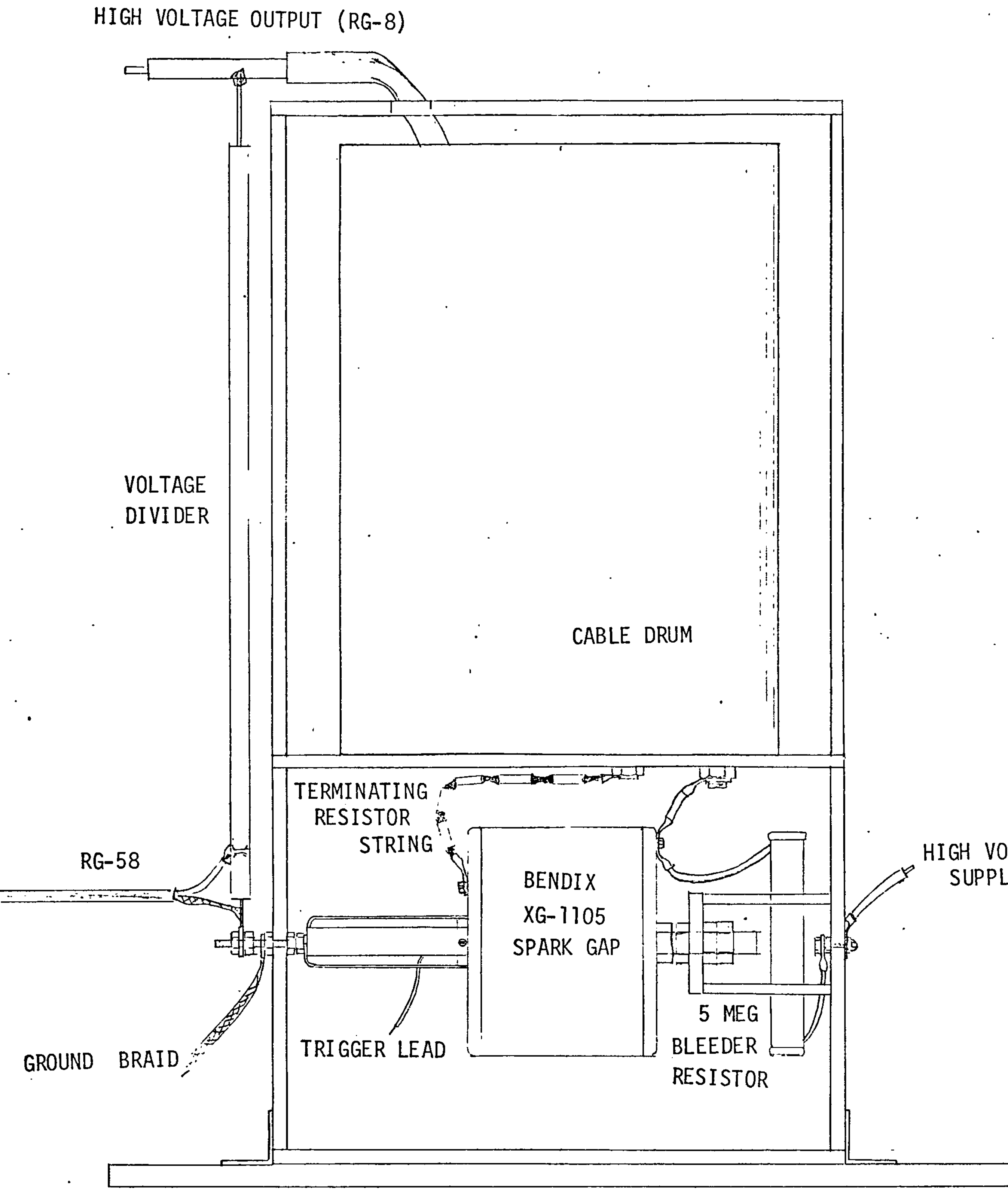
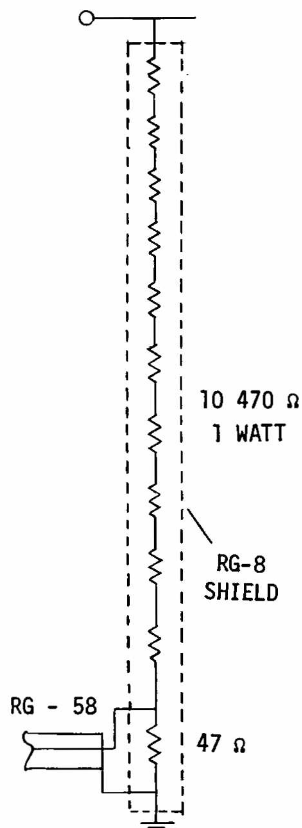


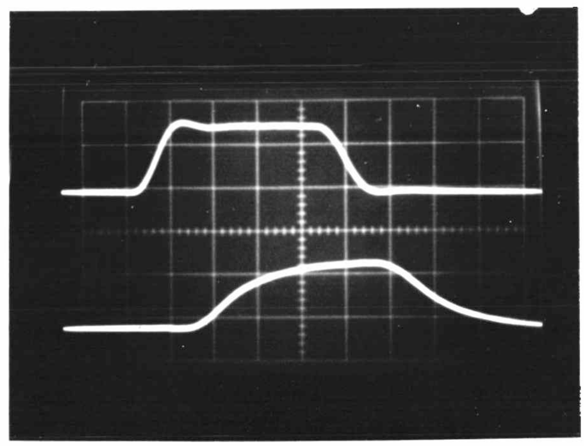
FIGURE THREE

PHYSICAL ARRANGEMENT OF HIGH VOLTAGE PULSER



DIVIDER SCHEMATIC

(a)

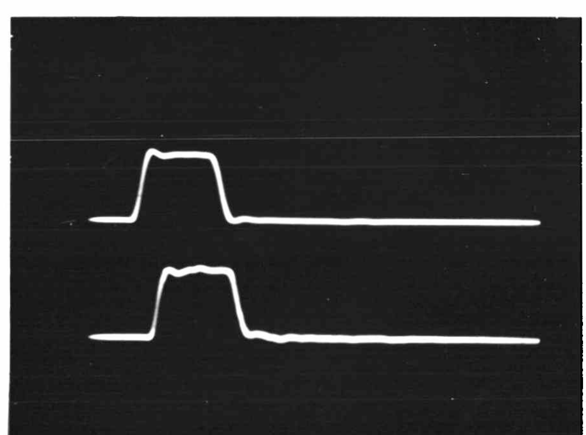


CHANNEL 1 : INPUT WAVEFORM , 10 VOLTS/CM

CHANNEL 2 : DIVIDER WAVEFORM, 0.1 VOLTS/CM

TIME BASE : 20 NANOSECONDS/CM

(b)

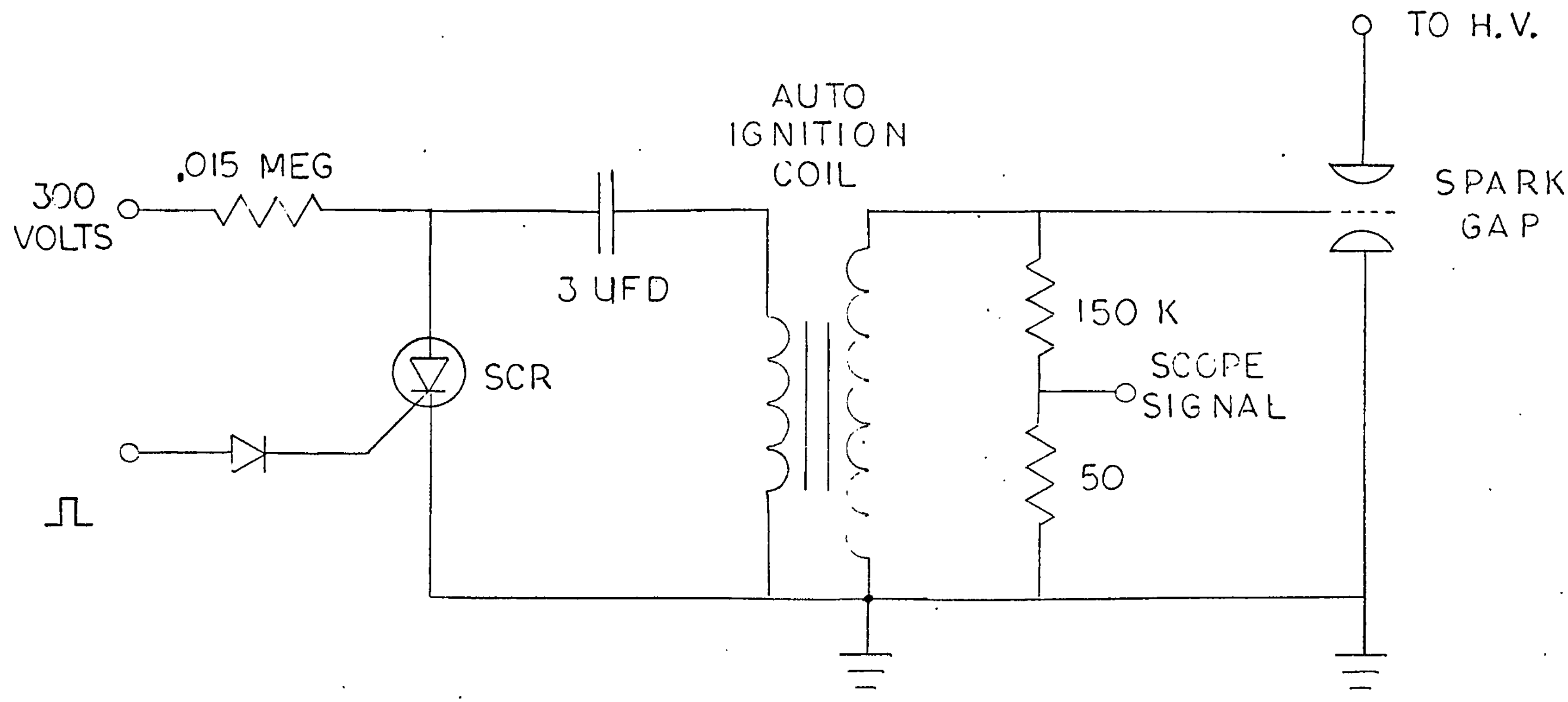


CHANNEL 1 : INPUT WAVEFORM, 10 VOLTS/CM

CHANNEL 2 : DIVIDER OUTPUT WITH THE SHIELD REMOVED, 0.1 VOLTS/CM

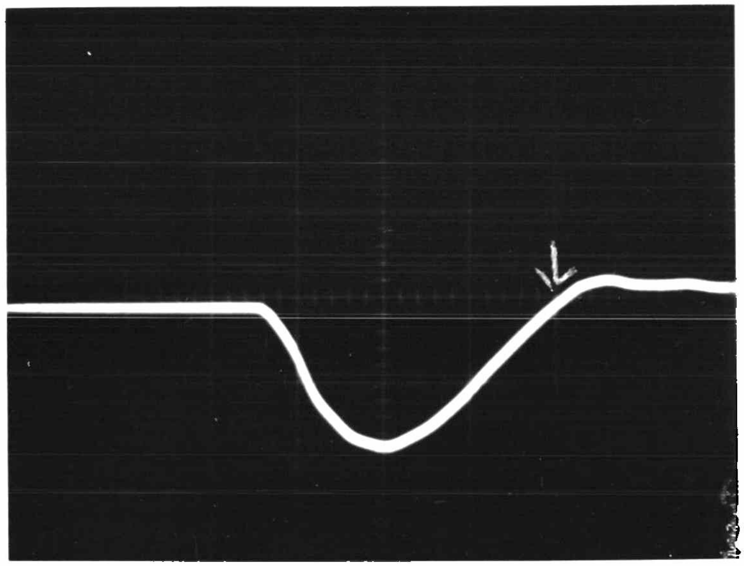
TIME BASE : 50 NANOSECONDS/CM

FIGURE FOUR

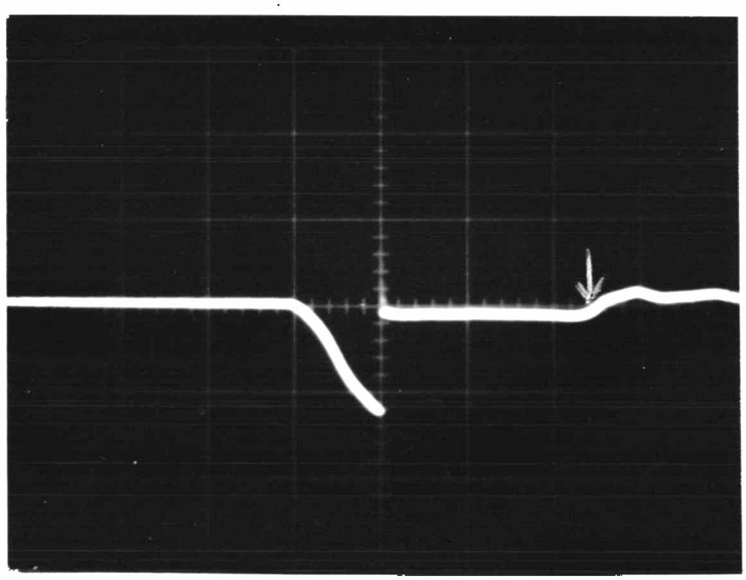


SCHEMATIC OF SPARK GAP TRIGGER UNIT

FIGURE FIVE

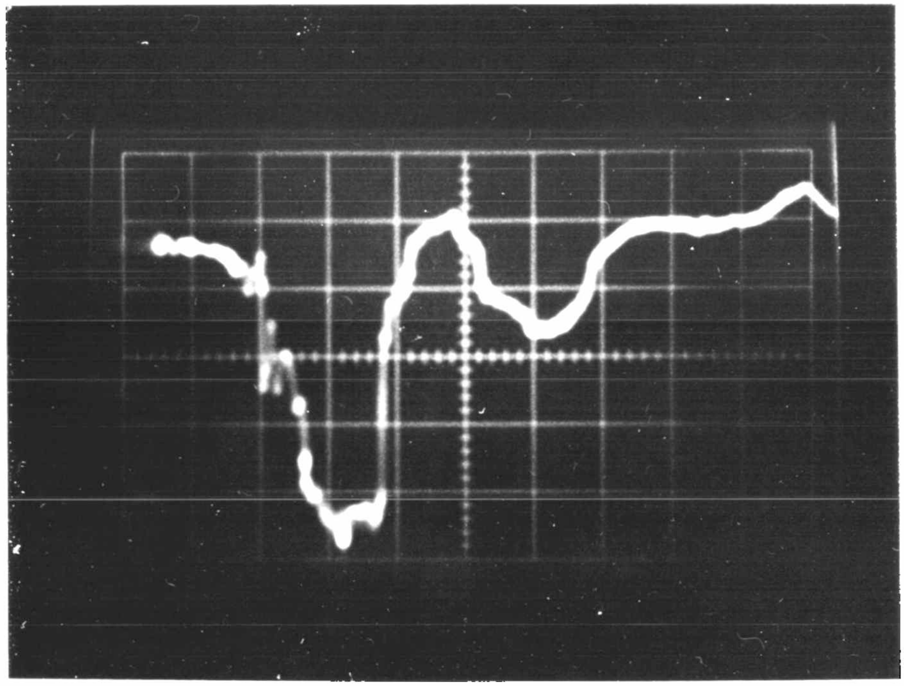


(a) SIGNAL FROM SCR TRIGGER CIRCUIT
TIME BASE : 50 MICROSEC/CM
PEAK VOLTAGE IS -9000 VOLTS, TRIGGER OUTPUT OPEN.



(b) TRIGGER SIGNAL WITH SPARK GAP CONNECTED
BREAKDOWN OCCURS AT -6000 VOLTS

FIGURE SIX



OUTPUT FROM HIGH VOLTAGE PULSER

AMPLITUDE : 10 KV

TIME BASE : 50 NANOSECONDS/CM

FIGURE SEVEN

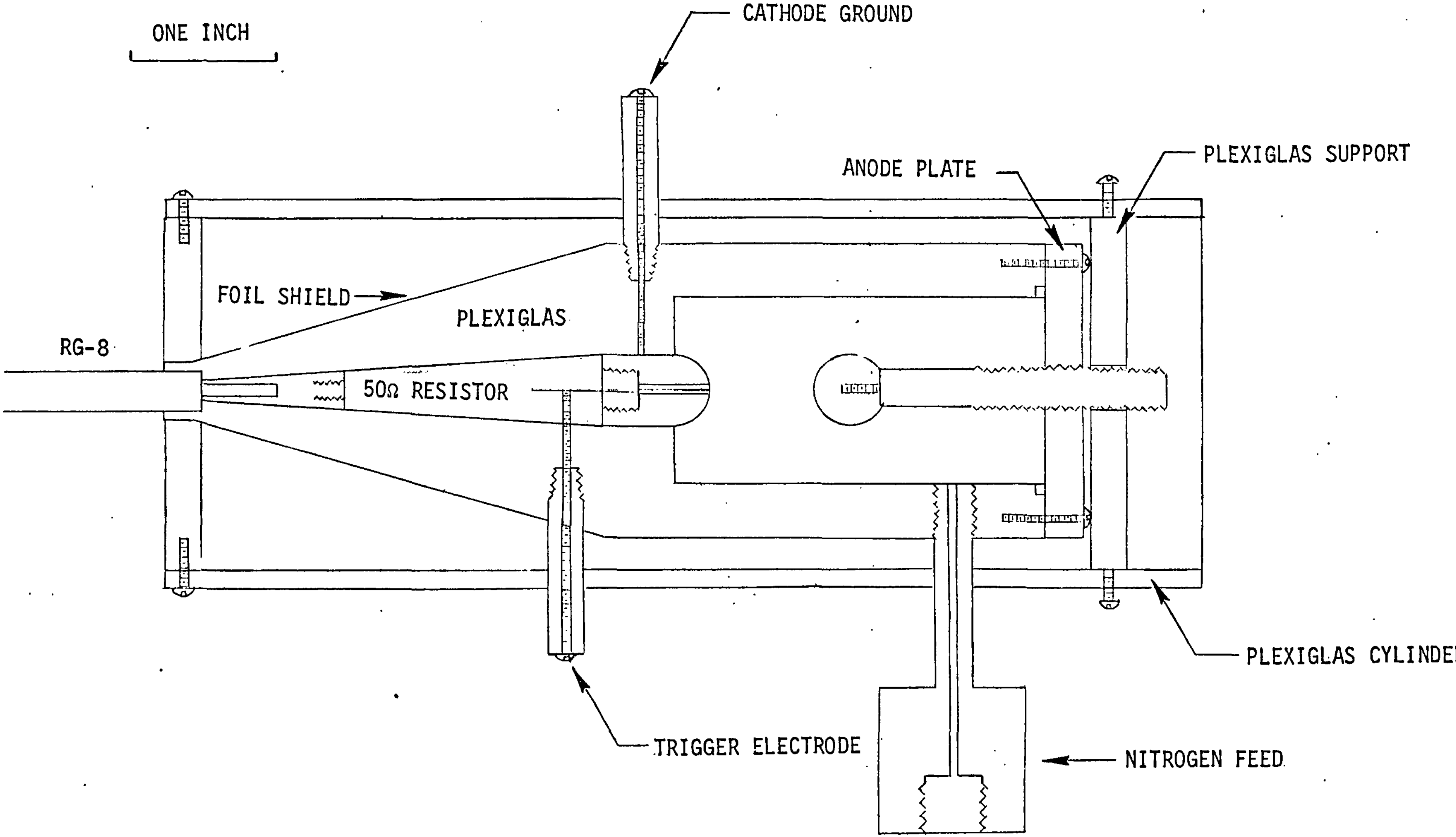
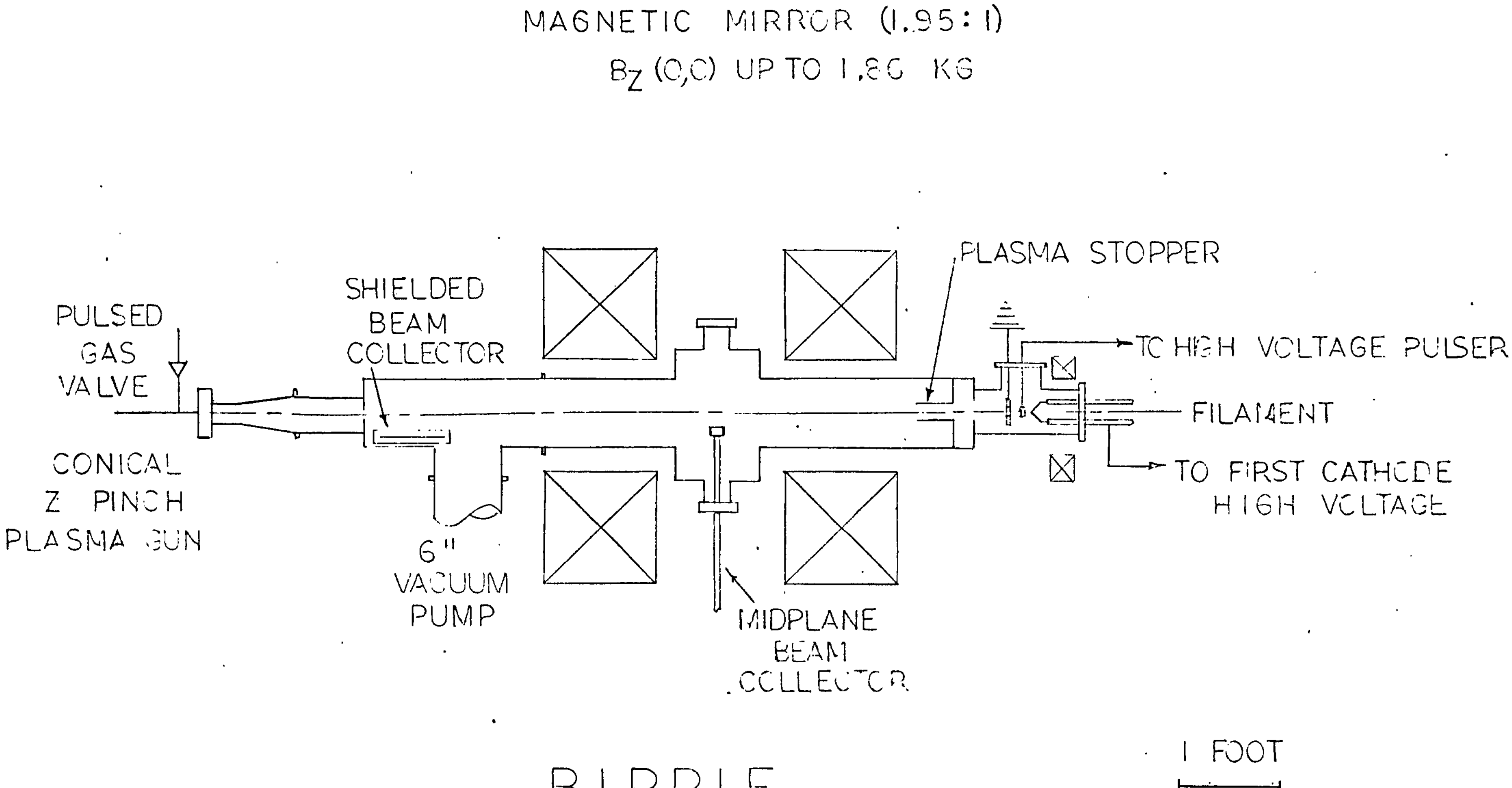


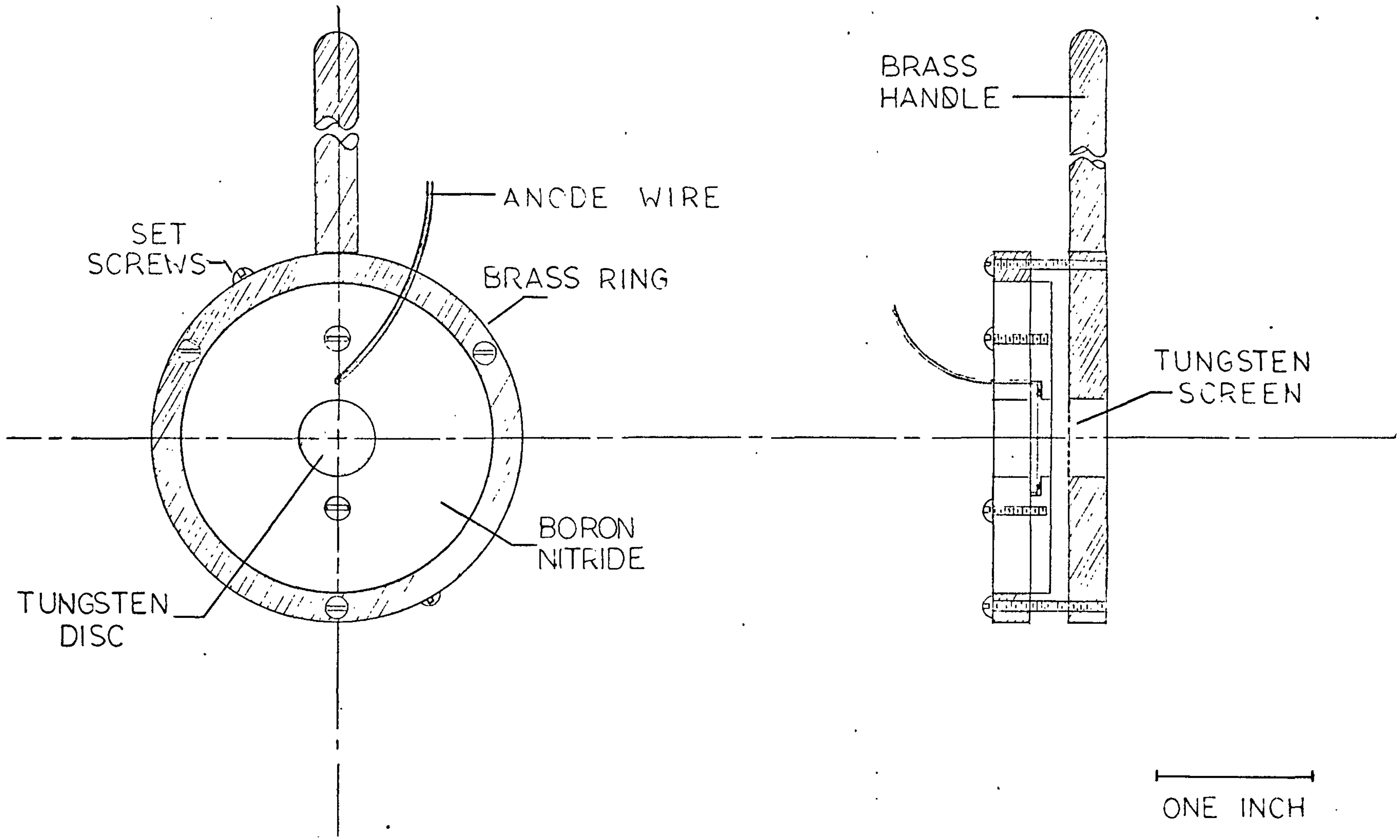
 FIGURE EIGHT. COAXIAL SPARK GAP PULSE GENERATOR



BIPPIE

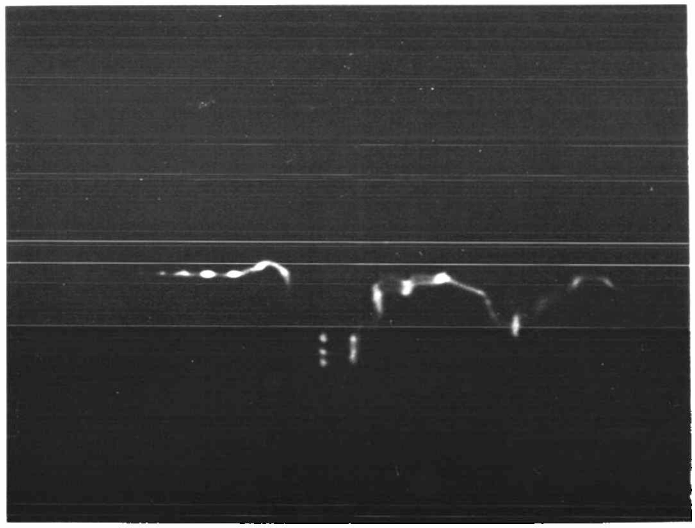
(BEAM INTERACTION PULSED PLASMA INJECTION EXPERIMENT)

FIGURE NINE



ELECTRON-BEAM HEATED ELECTRON GUN

FIGURE TEN



(a) BEAM PROBE SIGNAL
TIME BASE : 50 NANOSECONDS/CM
BEAM CURRENT : 4 to 6 MA

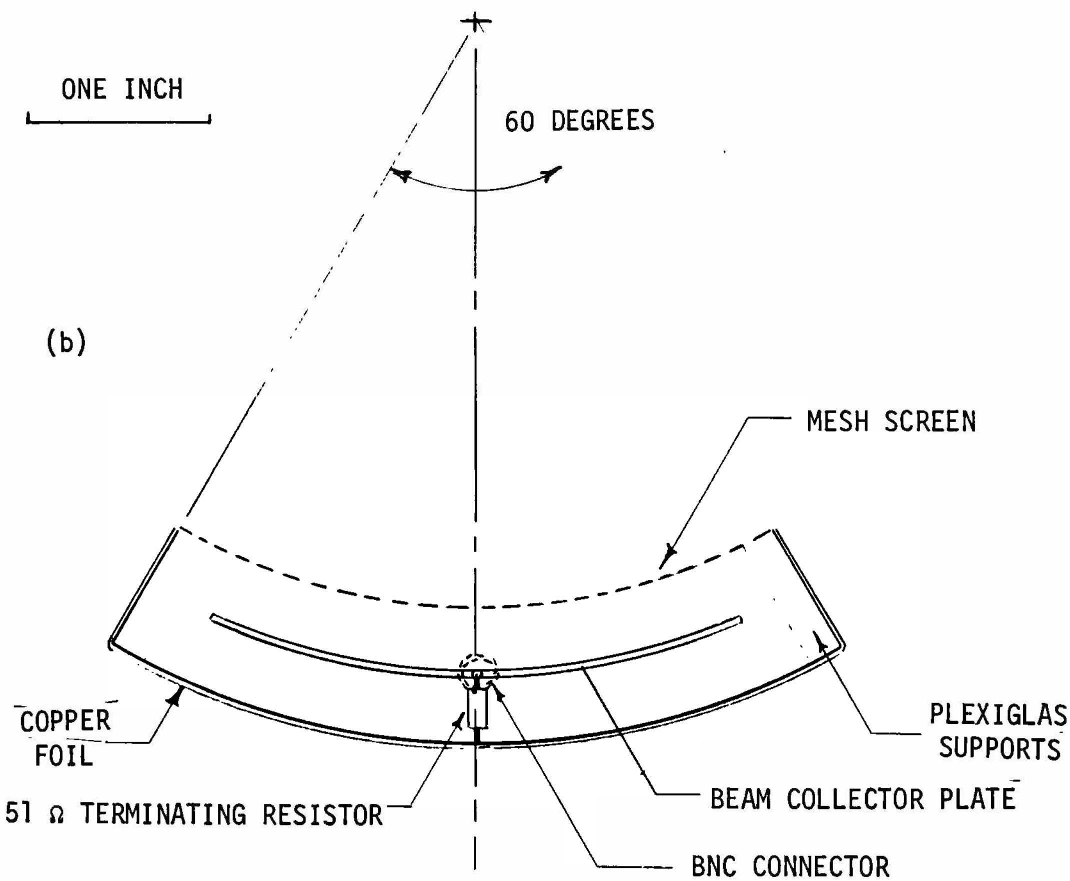
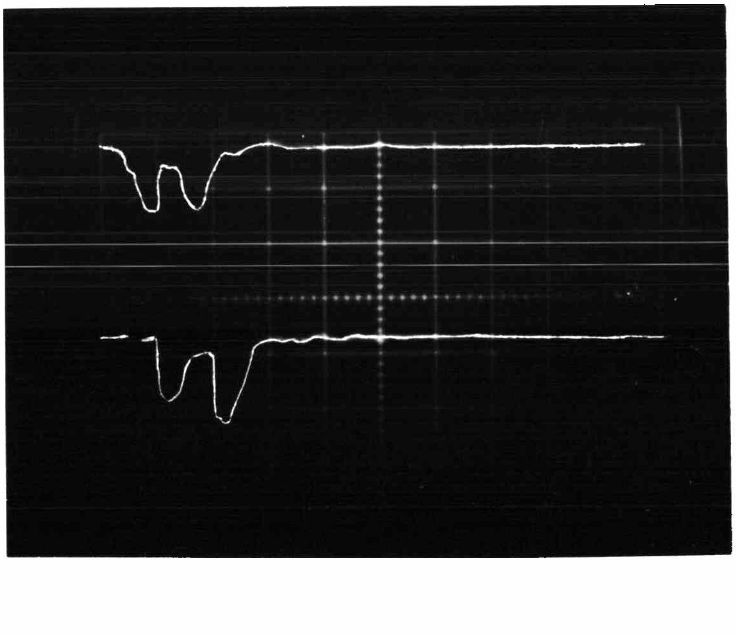


FIGURE ELEVEN

(a)



UPPER TRACES : VOLTAGE WAVEFORMS IMPRESSED ON ELECTRON GUN (8 KV)
LOWER TRACES : BEAM COLLECTOR SIGNALS (MAXIMUM CURRENT IS 35 MA)
TIME BASE : 100 NANOSECONDS/CM

(b)

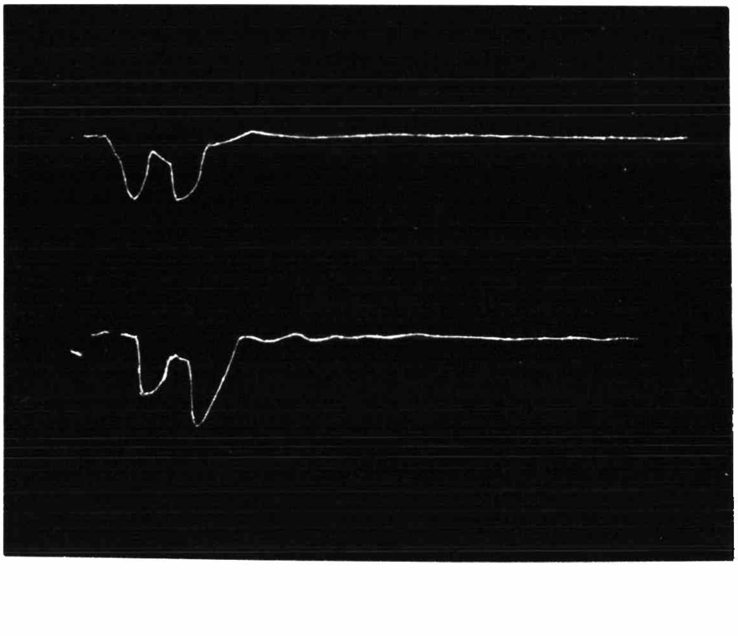


FIGURE TWELVE

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