# A FAST PREIONIZATION SOURCE FOR DIFFUSE DISCHARGES CONTAINING ATTACHERS

by

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# ABSTRACT

Diffuse discharge opening switches and most excimer lasers must operate with gas mixtures containing attachers. In self sustained discharges, preionization is required for arc free initiation of these discharges. The preionizer must have a short rise and falltime and must have an extremely accurate timing system because of the attachers in the discharge gas. Also, this device must have sufficient power to produce large volumetrically uniform electron densities in gases at pressures in the one atmosphere range.

This paper describes the design and construction of such a preionizer and gives an overview of various preionization techniques previously employed. The device presented here consists of eight coaxial cables for energy storage, which are switched through a master spark gap to eight cables terminated by individual multi-spark arrays. The preionizer and the main discharge are triggered by a single laser (with a beam splitter and with a variable optical delay on one of the beams). Experiments showing the influence of the delay, preionization pulse length, jitter, and durability of the spark sources on the main discharge are described.

## LIST OF FIGURES

# CHAPTER I

# INTRODUCTION

In the past fifteen years, the development of and improvement upon TEA (transversely excited atmospheric pressure) lasers has led to a greater understanding of self sustained high pressure volumetrically diffuse discharges and the techniques required to produce them. This type of discharge recently has also become of interest to researchers in the high voltage, high speed switch field because of its low inductance and low electrode erosion and heating rates. Such a "glow discharge" is especially desirable in opening switches because it is not in Local Thermodynamic Equilibrium (LTE). This allows certain control mechanisms to influence the population of individual states. Subsequently, the electron density can be changed in either direction, and with it, the electrical conductivity of the discharge. Therefore, lower electron temperatures and higher discharge volumes than those prevalent in arc discharges are required.

Producing this type of discharge in atmospheric pressure gases requires that certain conditions be present in the discharge chamber. These criteria will be discussed later in this paper. Two developments paved the way to the realization of relatively large volume (greater than 1000 $cm^3$) diffuse discharges, which are able to conduct enough current to be useful for switching purposes. (1) Uniform field electrodes avoid geometrically produced field enhancements at the electrodes which lead to arcing, and (2) volume preionization of the gaseous medium ensures that field fluctuations do not develop statistically in the discharge volume at the time when the discharge is initiated. Preionization also eliminates the statistical delay time associated with all types of breakdown in gases, which is a distinct advantage in systems requiring highly accurate timing for switching.

This paper will discuss the design and construction of a device which produces volume preionization in a diffuse discharge experiment and will give an overview of several other methods to accomplish the same result. Special attention will be given to the requirements for discharge operation in gases containing attachers.

# CHAPTER II

# DISCHARGE PARAMETERS AND ATTACHMENT

## Atmospheric Pressure Diffuse Discharges

The processes which are of interest in TEA laser and opening switch discharges require special discharge conditions. As mentioned previously, these discharges are not in LTE. A cold plasma is desired for these applications. In this case, "cold" means that while the mean electron energy is on the order of several electron volts, the ions and neutral particles present have much lower energies [44]. To be able to influence specific states, it is also required that the heavy particles have a low degree of ionization and dissociation. This is essential for control of the discharge for several reasons. If the conductivity of the discharge is to be influenced by increasing the ionization rate, it is necessary that a large percentage of the atoms and molecules are not ionized [38]. If a high degree of ionization is present, two problems prevent discharge control. The first is the fact that if the gas is already ionized, the conductivity is usually very high, so further ionization would have little effect on it. In addition, the second ionization potential is much larger than first ionization potential.

Because of the low level of ionization, the current density of these discharges is low, even at atmospheric pressures. A typical value for the electron density in a diffuse discharge is $10^{13}$ electrons$\cdot$cm$^{-3}$. This corresponds to a current density of 10 to 100 amps$\cdot$cm$^{-2}$. Thus, for a current of several thousand amps, the discharge must have a cross sectional area on the order of approximately 100 cm$^{2}$.

The production of a diffuse discharge under the E/N (electric field divided by number density of particles) conditions present in switching and laser discharges requires that a certain degree of homogeneously distributed preionization electrons be present [38]. This condition prevents the formation of large space charge fields which produce fast electrons and streamers and subsequently filaments in the discharge. The minimum preionization electron density for most gases at atmospheric pressure has been determined to be on the order of $10^{6}$ to $10^{8}$ electrons$\cdot$cm$^{-3}$ [45].

The voltage applied to the discharge should also have as fast a rise time as possible for switching applications. This minimizes the time that the discharge is in high loss regions of operation. If the discharge is in a lossy region, the plasma absorbs energy which can in turn drive instabilities and produce arcs rather than uniform discharges [41].

## Attachment Processes

Both TEA lasers and diffuse discharge opening switch gas mixtures normally contain electronegative (attaching) gases. An attacher is a gas whose atoms or molecules collide with a free electron to form a negative ion. Two types of attachment must be considered: two body and three body processes. Resonant dissociative attachment is the process which is of interest in the opening switch system to be discussed later in this paper. The reaction for this type of attacher is: $e^- + AB \rightarrow AB^{-*} \rightarrow A + B^-$, where $e^-$ is the free electron, AB is the attacher, A and B are fragments of the molecule AB, and the asterisk indicates that the molecule is in an excited state [46]. The reaction for a three body process is: $e^- + A + B \rightarrow A^- + B$, where A and B can be the same atom (or molecule) or a different atom (or molecule).

Attachers are present in diffuse discharge opening switches to remove electrons from the discharge, and thus lower the conductivity at the time when the control mechanism is activated. This process usually has an e-folding time of under 100ns in these devices, which means the switch will have an opening time of the same order. It also means that any preionization electrons must be produced within 100ns of the ignition of the discharge. This effect is illustrated in [29]. Also, since the control process is implemented within a few hundred nanoseconds after the beginning of the discharge, the preionizer must not produce electrons after the discharge has been initiated. These requirements place restrictions on the timing accuracy and fall time of any preionization device used in this type of switch.

# CHAPTER III

# PREIONIZATION PROCESSES AND TECHNIQUES

Information about preionization experiments and theoretical calculations is widely scattered throughout the various journals dealing with TEA laser research and associated phenomena. A good overview of the subject can be found in [1]. The various types of preionization can be separated roughly into three categories, which are discussed below.

## Ultraviolet Preionization

The majority of TEA lasers use some type of ultraviolet preionization. Several techniques have been used to produce the ultraviolet radiation. These methods can be divided into two basic types which will be discussed below.

### Double Discharge Preionization

The idea of a double discharge is that a predischarge pulse at a certain time in a small portion of the discharge region with a small energy compared to the main discharge can provide preionization in the volume of the main discharge. Three different preionization methods are covered in this section. The first type is a dc corona discharge which is initiated before the main discharge. A typical circuit for this method of preionization is shown in Figure 1(a). In this scheme, $Cs \gg Ct$ and $Cs \gg Cg$, where Cg is the capacitance of the discharge gap, so the voltage across Cs is relatively constant until the main discharge is initiated. When the spark gap S fires, a voltage is applied from point a to ground. The main discharge electrodes are uniform field electrodes, and the trigger wires are small in diameter and closer to the grounded main discharge electrode than the other main discharge electrode. Thus, the electric field strength is much higher around the trigger wires than in the main discharge region and a corona discharge develops between the trigger wires and the grounded electrode. This predischarge acts as a uv preionization source for the main discharge volume. When the capacitor Ct is charged, the voltage between the trigger electrode and the ground discharge electrode decreases, causing the discharge to switch to the main discharge volume. The time delay between initiation of the corona discharge and the main discharge can, therefore, be adjusted by varying Ct, within the constraints given above. This apparatus was used by Reits and Olbertz [3] and Gordiets et al. [4]. A similar setup shown in Figure 1(b) was utilized by Laflamme [2]. This system also operates on the premise that corona discharge will appear at the trigger electrode

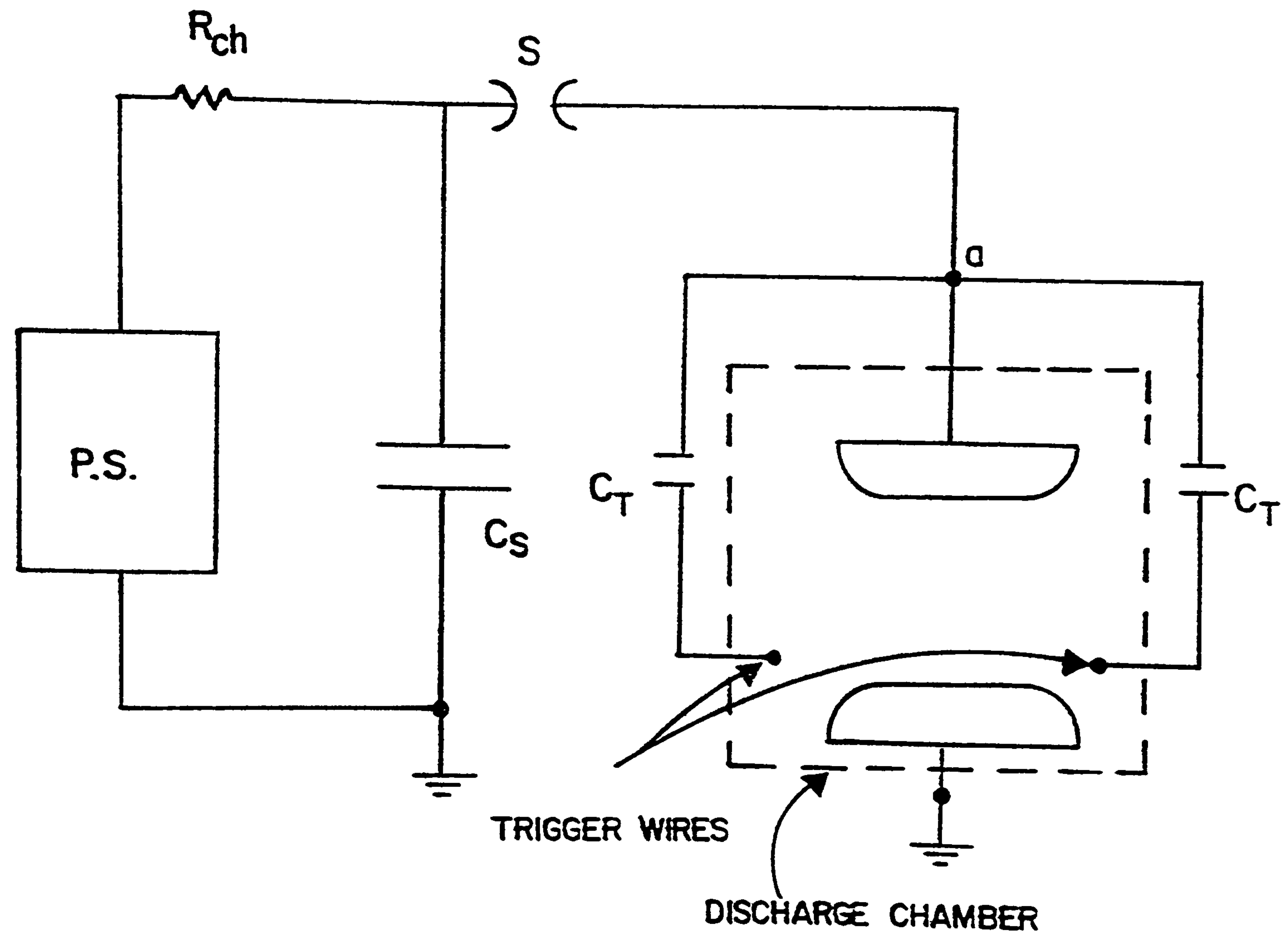


Fig. 1. System using double discharge preionization:
(a) Bare wire preionizer

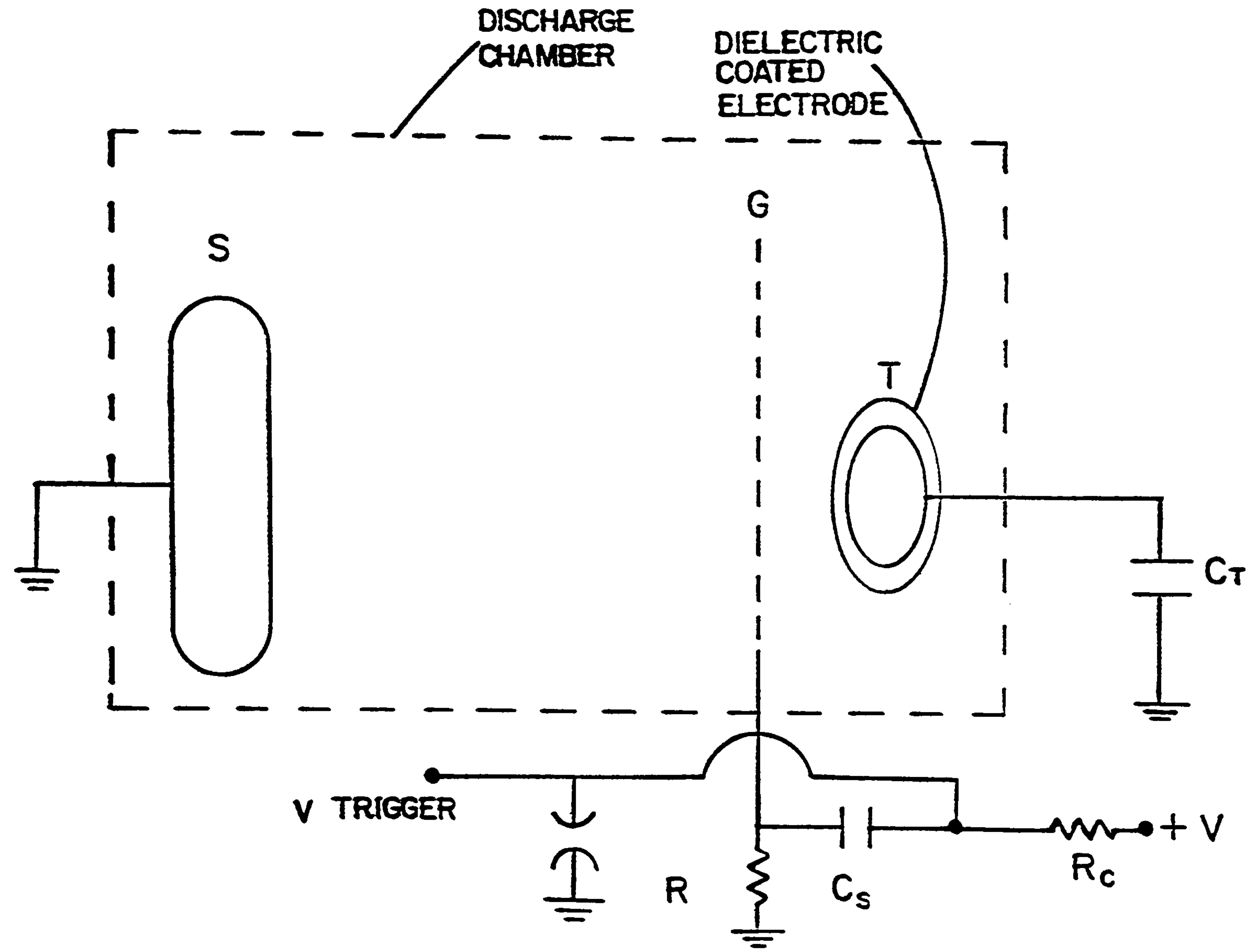


Fig. 1. System using double discharge preionization: (b) Dielectric coated preionizer

before the main discharge fires. The timing can be adjusted by varying Ct as before.

The advantages of a double discharge system are its simplicity, reliability, and independence from complicated timing circuits. An added advantage was thought to be direct electron injection into the discharge volume, but Rickwood [15] and others have shown that the ultraviolet radiation produced by the corona discharge is the important agent for preionization. The disadvantages of such a method are gas degradation, nonuniform preionization, and energy loss to the preionization circuit.

Another double discharge preionization method has been developed by Jain et al. [5] in which a 100 ns pulse of one polarity is applied to the main discharge to break down the gas and, thus, ionize it. At an unspecified later time, the 18 μs main discharge pulse is applied with the opposite polarity. The authors claim this polarity reversal aids in diffuse discharge production. (See [35] for a further discussion of this phenomenon.) The advantages of this scheme are the production of true volume preionization and the possibility for different cathode materials for the main discharge and the preionization discharge. The disadvantages are gas degradation and the need for two pulsers to operate the system.

Rickwood [15] used a semiconductor slab which was aligned such that the slab was parallel to the main discharge volume and came very close to, but did not quite touch, the cathode. This device produced a diffuse discharge from the cathode which was distributed along the length of the semiconductor, producing fairly uniform ultraviolet illumination. The discharge then moved from the semiconductor to the opposite electrode, but stayed uniform. Rickwood reports an improvement in efficiency of 50% over spark arrays.

## Separate Ultraviolet Sources

There are many methods to preionize a discharge volume with a separate ultraviolet source. Some of these methods are discussed below. Taylor et al. reported volume preionization in 5 atm of 1 HCl:5 Xe: 375 He laser mix using a seed gas by using both KrF and ArF lasers as uv sources [16]. (Seeding techniques will be discussed later in this paper.) DuFour et al. [17] reported good results using a xenon flash tube as an ultraviolet source, as did Bvszewski, Enright, and Proud [18]. Because the flash lamps have a transparent envelope which does not pass short wavelength uv light well, a seed gas with a low photoionization threshold must be used in such a volume preionization scheme.

A fairly common method of producing ultraviolet radiation is with a surface discharge, or a number of them, as reported by Richardson, Leopold, and Alcock [19]. Both Beverly et al. [20] and Zaroslcv et al. [21] report that the selection of the surface material has a marked effect on the ultraviolet emission of the preionizing discharge. Zaroslov et al. also performed some studies on doping surfaces to produce a particular desired spectral line. They were able to enhance the emission at 121.5 nm (Lyman α line), which is very useful for $CO_2$ lasers, by doping a substrate with hydrogen. This did produce a higher impedance discharge, however, which lowered the total efficiency of the preionization system.

The most common method of producing ultraviolet light in these devices is by bare sparks. This technique has been used by numerous researchers ([23] - [34]). Many of these researchers ([23], [27], [31], [34]) employed a so-called "seed gas" to increase the uniformity of pre-ionization electrons in the discharge volume, as did some researchers who used surface discharges for preionization. Without a seed gas, the electrons which are produced will be concentrated around the spark due to absorption of the light. Too much seed gas in the discharge volume will have the same effect, so the seed gas is introduced in low concentrations (less than 200 parts per million) and should have little effect on the discharge other than preionization. Seguin et al. [27] showed that typical concentrations of seed gases have only a very small influence on the emission spectra of spark sources. These gases have a low ionization potential so that electrons are easily produced and should be matched to the discharge gases so that there is not a strong absorption peak in the discharge medium at the light wavelength at which the seed gas is ionized. Also, it is desirable to have a spark source with a strong output at that particular wavelength. Two commonly used seed gases are n,n dimethylaniline and tri-n-propylamine. These have ionization potentials of 7.14 eV and 7.23 eV, corresponding to wavelengths for one step ionization of 174 and 172 nm, respectively [1]. For a more complete listing of seed gases, see [1].

The electron density ($n_e$) produced by a spark is the most important preionization parameter, and there is some debate as to what electrical quantity has the largest effect on $n_e$. Judd and Wada [24] claim that the important electrical parameter for good preionization is the total energy dissipated in the arc, while McKen et al. [33] and Babcock, Liberman, and Partlow [25] assert that the peak current is the dominant variable. In any case, the majority of the electrons produced comes from either a seed gas or impurities in the discharge gas. Babcock's group, using spectroscopy of the arc and the surrounding medium determined that at a distance d from the source, the electron density yielded by a spark with intensity $i = I_o d^{-2} e^{-\bar{\alpha} Pd}$ is given by $n_e = n_i \sigma_i i$, or $n_e = n_i \sigma_1 \sigma_2 i^2$ for one and two photon ionization, respectively, where $n_i$ is the number density of ionizable impurities, $\sigma_i$ is the one photon impurity ionization cross section, $\sigma_1$ is the impurity excitation cross section to level 1, $\sigma_2$ is the impurity ionization cross section from level 1, $I_o$ is the intensity of the source at d = 0, P is the gas pressure, and $\alpha$ is the average absorption rate constant for the gas mixture. The equation for electron density produced by a discharging capacitor was found to be:

$$n_e = (4 \times 10^{-4})\ I\ (P\ E\ \mathrm{cap})^{1/2}\ d^{-2} N_e \text{ electrons/cm}^3$$

for diatomic nitrogen, where E cap is in joules, P is in atmospheres, I is in amps, d is in centimeters, and $N_e$ is in (electrons/(cm·steradians/spark)) and is shown for 1 atm of $N_2$ in Figure 2.

Kline and Denes [30] and Mitchell, Denes, and Kline [31] have done studies indicating that the discharge boundaries can be defined by the uv preionization of the medium and that uniform preionization is unnecessary in the direction parallel to the applied electric field. Both of these facts indicate that in large (discharge volume greater than $10^4$cm$^3$) ultraviolet preionized systems, the illumination should be introduced through one electrode rather than from the side of the discharge for best results. However, if the medium is saturated, i.e., if every possible source of electrons is ionized, the positioning of the ultraviolet sources is not an important factor. Since many lasers contain electronegative gases such as $CO_2$, HCl, and $F_2$, several researchers including Hsia [28] and Norris and Smith [29] have been interested in the effect of these attaching gases on the preionization of diffuse discharges. Electron attachment was discussed earlier in this paper. Norris and Smith found

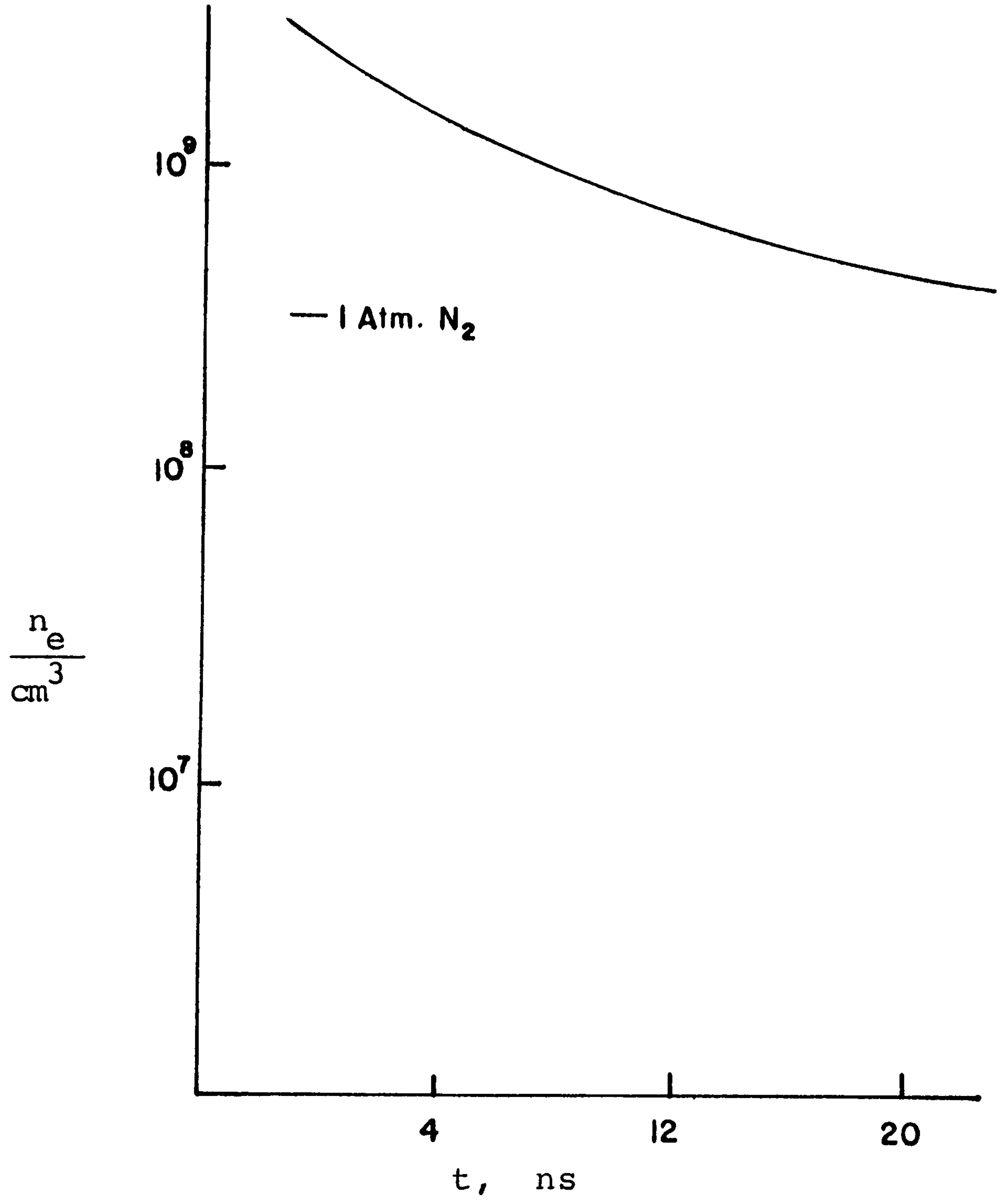


Fig. 2. The number of electrons produced in 1 atm $N_2$ by a spark at a distance d.

that the 1% $O_2$ present in their $CO_2$ laser mix reduced the maximum allowable delay times between preionization and main discharge (versus the same gases with no $CO_2$ present) from 45 μ s to 5 μ s. Hsia determined that the $F^-$ produced by attachment provides a reservoir for easily liberated electrons. The electron affinity of $F^-$ is 3.5 eV, as opposed to the 17.42 eV ionization potential for F [37]. The electrons may be detached from the $F^-$ by photodetachment, electron impact, or collisional detachment, and the decay rate for $F^-$ is much slower than the attachment rate for electrons in this mixture, meaning that under certain conditions, the preionization timing may not be extremely critical. The results of a computer calculation illustrating this process is shown in Figure 3 [41]. The effects of a long preionization pulse (100 ns) and a shorter pulse (10 ns) on the densities of electrons and negative ions in an attaching gas mixture are shown. The calculations were done assuming an ionization rate of $10^4$ $cm^{-3}$ $s^{-1}$, an attachment rate of $10^8$ $s^{-1}$, and an ion-ion recombination rate of $10^6$ $cm^{-3}$ $s^{-1}$. Note that after the light pulse dies out, the electron density decays rather rapidly, but the negative ion density remains relatively constant on the same time scale.

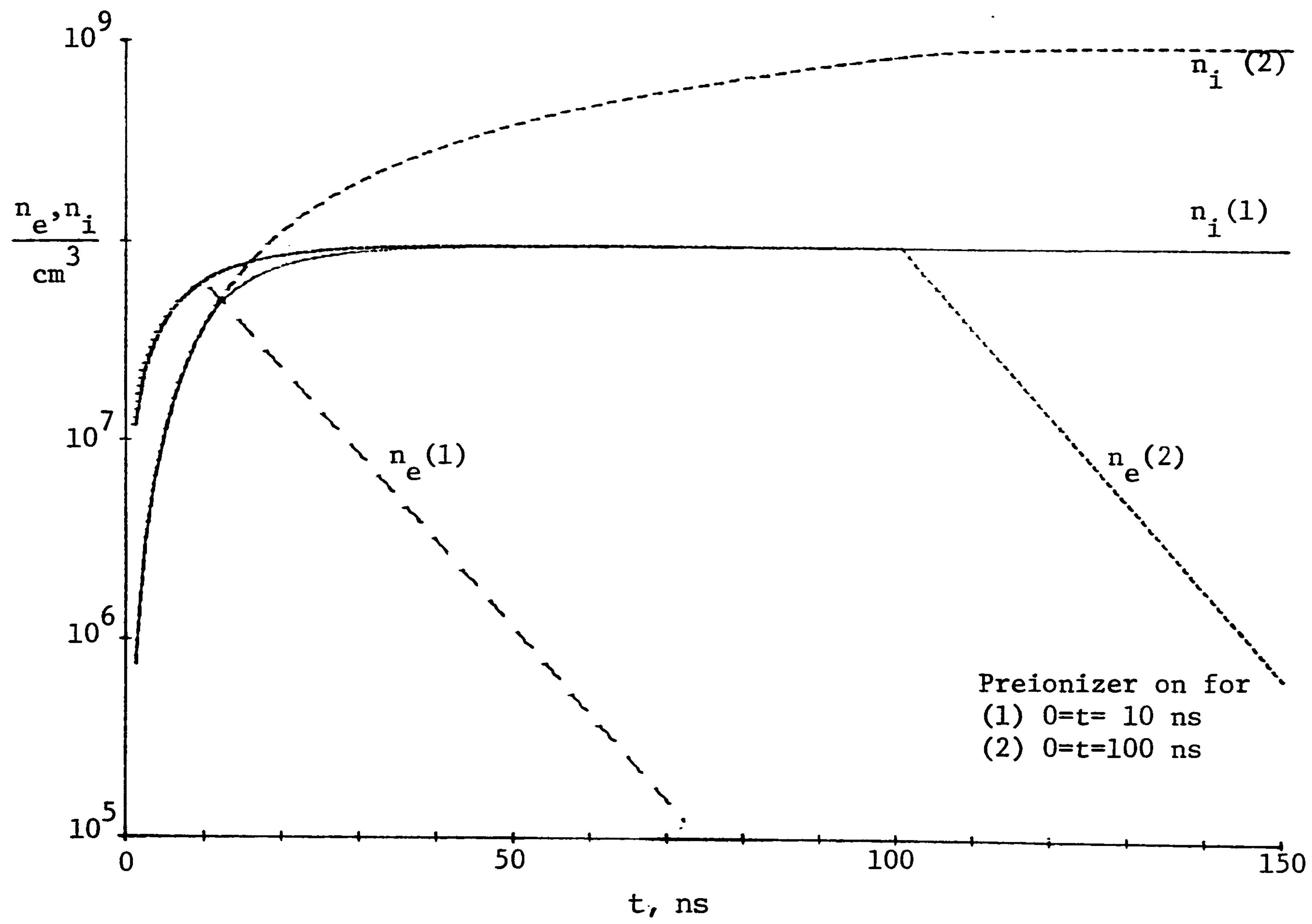
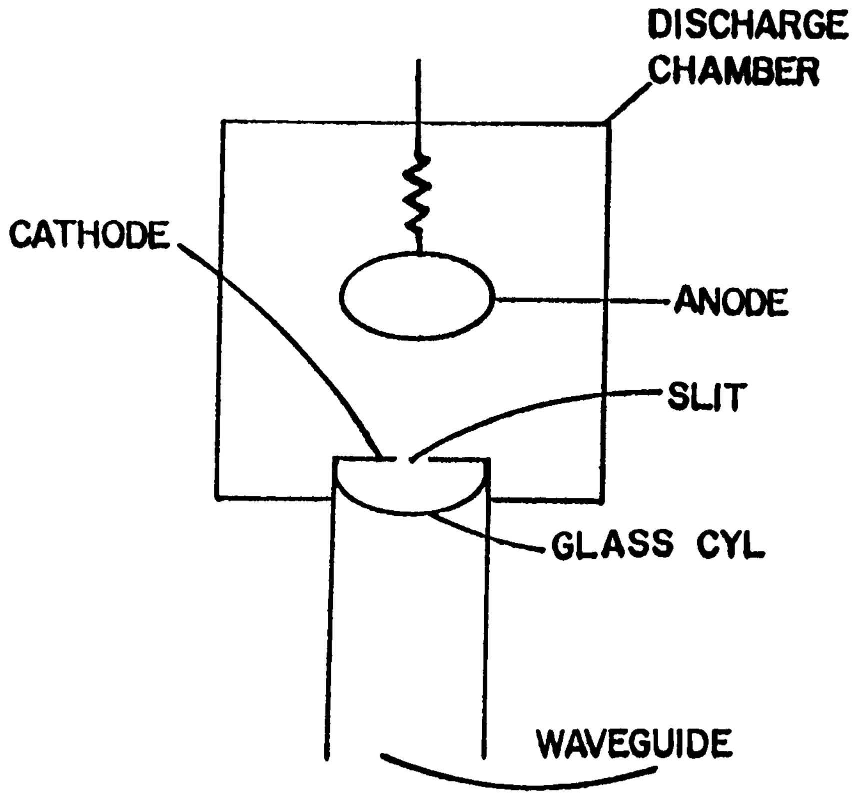


Fig. 3. Electron and negative ion densities as a function of time for different preionization pulse lengths.

### Radio Frequency and Microwave Preionization

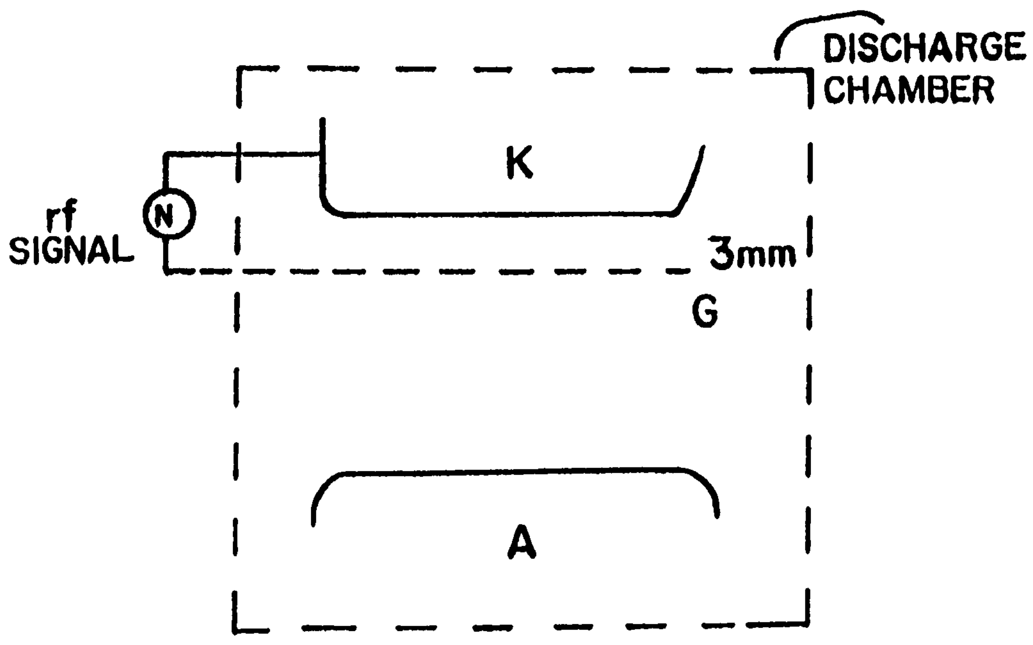
The phenomenon of high frequency breakdown has been investigated for many years, and it is not unexpected that this effect was applied for preionization of a diffuse discharge. One early (1972) application of this technique was described by Nichols and Brandenberg [6]. Their discharge chamber is sketched in Figure 4(a). Five to ten μ s after the 11 MHz rf signal was applied, a discharge formed between the grid G and the cathode K. A voltage of 670 Vrms was required to produce this discharge when the chamber pressure was between 50 and 200 torr of 1 $CO_2$:1 $N_2$:8 He laser mix. The main discharge was initiated 50 μ s after the rf signal was applied.

A system devised by Golovitskii et al. [7] is shown in Figure 4(b). The 10 cm wavelength microwave energy was delivered into the chamber through the waveguide shown in a 50 KW, 2 μ s pulse such that a microwave breakdown occurred across the slit, preionizing the gas. The width and number of slits was varied to provide more homogeneous preionization, but this showed little effect, perhaps because the worst case tried was still an effective preionization. In a later paper [8], Golovitskii et al. claimed that the number density of electrons produced, $n_e$, is linearly proportional to the power dissipated in the microwave discharge. These researchers also reported that at a microwave power close to breakdown, the majority



(b)

Fig. 4. High frequency preionizer:
(a) rf grid type



(a)

Fig. 4. High frequency preionizer:
(b) Microwave discharge type

of the preionization electrons are produced at the first instant of breakdown because only then is the ultraviolet radiation intense enough to provide significant photoionization. This means that the influence of the microwave pulse duration on $n_e$ is small.

Some advantages of this type of preionization are that rf equipment powerful enough to achieve preionization is readily available and that there need not be any preionization device inside the discharge chamber, although both sources cited had devices inside the chamber. One disadvantage is the difficulty in timing the circuit with such a preionization technique.

## High Energy Preionization

This category covers three main methods of preionization. The first is x-ray preionization. This technique has been successfully used by several researchers. Lin and Levatter [9] used a 1.5 μ s pulse of x-ray radiation with photon energies of 60 to 200 keV to produce electron densities of up to $5 \times 10^{11}$ $cm^{-3}$ in one atmosphere of 1 $CO_2$:1$N_2$:3 He laser mix. Shields and Alcock [11] fired 60 keV x-ray photons through a screen electrode into a 5 atm gas medium (3.5 torr HCl, 40 torr Xe, balance of 90% Ne, 10% He). They claimed that since they measured that only 1% of the x-rays were absorbed in the gas, x-ray photo emission from the cathode must be responsible for the preionization. This conclusion is questionable because the penetration depth of x-rays into most metals is on the order of several mm and because 1% absorption of x-rays represents a significant amount of energy loss in the gas which should produce an electron density of approximately $10^{11}$ $cm^{-3}$ according to the results presented in [9]. Sumida et al. [12] used a vacuum spark gap with a tungsten cathode to produce a 400 ns pulse of 20 keV x-rays. This device produced an electron density of $10^{10}$ $cm^{-3}$ in 10 atm of Kr. Also noted were the facts that in this high pressure region, the electron density is a linear function of pressure and that x-ray preionization operates more efficiently with heavier gases at higher pressures. The major advantages of x-ray preionization are that no gas contamination occurs and that larger and higher pressure chambers can be preionized because of the large penetration depth of x-rays. A major disadvantage of x-ray preionization is the short lifetime of flash x-ray devices. This problem can be overcome by use of a continuous wave x-ray source rather than a pulsed source, as was done by Arai, Obara, and Fujioka [10].

Two other high energy preionization sources have also seen limited use. Radioactive sources have been used by Hammond et al. [13], who used an eight microcurie radium 226 source along with a corona discharge for preionization, and by Bigio [14], who used a 300 microcurie americium 241 source. The decay of this source produces 5.5 MeV $\alpha$-particles, which according to Bigio will produce 2.5 x $10^5$ secondary electrons per $\alpha$ event. From this, he calculated a preionization density of 4 x $10^8$ electrons $cm^{-3}$ in 1 atm of He. One advantage to this system is that no timing is required for preionization, but the uniformity of electron density in such a device will be very dependent on the distribution of the sources. Electron beam sources were also investigated for use as preionizers by Bychkov et al. [36]. This type of preionization produces high number densities of electrons and has been used previously in lasers and opening switches to sustain discharges in addition to preionization.

# CHAPTER IV

# DESIGN

## Constraints on Design

The preionizer to be discussed in this paper is a device which was designed to deliver a very fast rising and intense pulse of ultraviolet illumination to a gas with extremely accurate timing. To understand the reasons behind the decisions made in designing the preionizer, a knowledge of the experiment, which the device is a part of, is essential. This experiment is a study of optical control of diffuse discharges, which has direct applications in the area of fast, high voltage opening switches for inductive energy storage. For a complete description of this device and its operation, see [38] and [39]. The gas mixtures used in externally controlled discharges for opening switches must contain fairly high concentrations of strongly attaching gases. This requirement, coupled with the fact that the discharge has to operate in a pressure range on the order of one atmosphere to achieve a sufficiently high hold off voltage, makes it difficult to produce diffuse discharges longer than a few microseconds [31]. In this experimental setup, the discharge time is 100 ns.

The gas mixture for the discharge must be free of impurities. Therefore, so the experimental chamber must be vacuum sealed to allow for removal of these impurities. There is also a possibility that corrosive substances, such as HCl or $F_2$, will be used in this device in the future, so any component which is exposed to the gas mixture must be corrosion resistant.

The conditions of the experiment place several constraints on any device to be used for preionization. Since attachers are present in the gas, the electrons produced will be attached with a time constant dependent on the attachment rate constant and the attacher concentration. It is desirable that an opening switch have an opening time of 100 ns or less. This constraint results in the requirement that the attachment rate constant be on the order of $10^8$ $s^{-1}$ for a gas at atmospheric pressure. If a large electron density is required when the discharge is launched, the preionizer must have the ability to produce that density quickly and must also be triggerable to an accuracy of better than 5 ns. Due to the character of the experiment, it is also desirable that the preionizer have a short and easily varied pulse width to ensure that volume ionization occurs and that no uv radiation is present during the time when the discharge is to be controlled. It must also be possible to introduce the device into a vacuum system without affecting the quality of the vacuum. The device must be inside the experimental chamber because no suitable windows are available which can transmit the highly ionizing uv radiation. The preionizer, therefore, must be rugged enough to perform reliably in the environment inside the chamber. An important design criterion is that the preionizer be able to produce volume ionization in the cylindrical discharge volume of the main experiment. It is also desirable for the light sources to be made as small as possible in order to minimize their effect on the electric field distribution in the chamber.

## General Parameters

The system developed to meet these requirements is described below. A spark discharge best meets the requirements for a light source inside an environment such as the one in the main discharge chamber. There is a relatively large volume of literature on this method of preionization, so information on its effectiveness was readily available. Since a short, variable width ultraviolet pulse is desired, the same type of electrical pulse should be applied to the spark electrodes. A simple method of realizing this is by using a charged transmission line as a pulse forming network. In order to meet the requirement for uniform illumination of the discharge volume, several of these transmission line systems in parallel were used with all the charged lines being the same length. The most accurate method of timing the switching of these pulses to the spark sources, so that all the sources fire simultaneously, is to switch all of the lines through one spark gap. The gap impedance is matched to the sum of the cable impedances in parallel. The pulses are then carried to the spark sources by a set of transmission lines with the same parallel impedance as the charged lines. Obviously, the simplest configuration is to use an equal number of lines with the same impedance per line and the same length. In addition to keeping the spark sources fairly small, an effort was made to design the sources to be impedance matched as closely as possible to the lines connecting them to the pulse source. This aids in maintaining the fast rise and fall times of the pulse. Thus, it is possible to construct this device such that the only jitter introduced between the preionization sparks is due to the inherent jitter in the sources. This jitter can be minimized by charging the system to a voltage high enough to be certain that the spark sources are highly overvolted.

One of the most precise methods of triggering a spark gap is by on axis high power laser triggering. Subnanosecond jitter has been routinely achieved using this technique [40]. Since the main experiment was already triggered using a laser, the same laser was used to trigger the preionizer. This method has not only the advantages of laser triggering, but also makes possible variable timing produced by an optical delay. This passive delay ensures that only uncertainty in firing times between the main experiment and the preionizer is the difference in the delays in firing the two spark gaps. The subnanosecond accuracy possible is well within the 5 ns requirement previously stated. Thus, the entire experiment is triggered at one point, as shown in Figure 5.

## Electrical Design

The design of this preionizer produces requirements for careful impedance matching and close tolerances for the optical triggering system. Since the coaxial cable for the transmission lines was the only component which was obtained from commercial sources, the cable was selected first and the rest of the system was designed around it. The cable chosen was Belden 8870, a special small diameter high voltage cable. This coaxial cable has a characteristic impedance at 75 ohms, and will withstand up to 80 KV dc. The Appendix gives full specifications for this cable. Eight sources placed in a radially symmetric pattern around the cylindrical discharge volume were believed to be enough to provide fairly uniform illumination throughout the discharge region. Therefore, the "master gap" needed an impedance of 75/8 = 9.4 ohms for proper matching. This was accomplished by designing

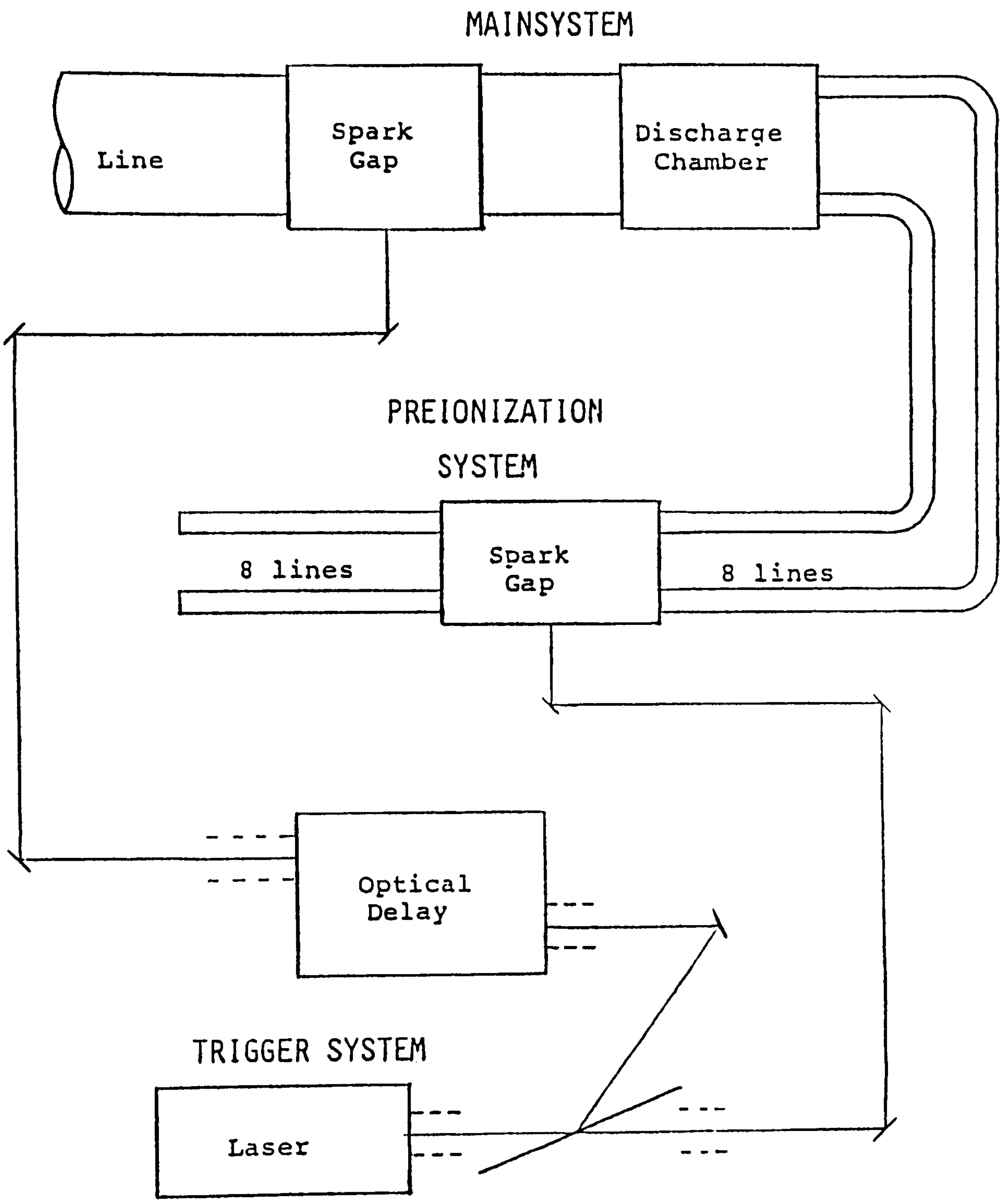


Fig. 5. The laser triggering scheme of the experiment.

what is essentially a 9.4 ohm transmission line with an interrupted center conductor which functions as a spark gap. A sketch of the device is shown in Figure 6. The cables are fed into the master gap in a circular array, with the center conductors of the cables connected directly to the center conductor of the spark gap. The sheaths of the cables are connected to the outer conductor of the spark gap by a plate which presses special connectors onto the end of the spark gap chamber. The plate is electrically connected to the master gap outer conductor and the special connectors are permanently fixed to the sheath of each cable. Note that in Figure 6 the transitions from cables to gap are conical. This is intended to provide the smoothest possible impedance transition.

## Laser Triggering

Figure 6 also shows the arrangement by which the device is laser triggered. The laser light enters the spark gap in the center of the cable array and is focused by the lens through a hole in a one electrode onto a spot close to the surface of the other electrode. This focusing produces a plasma either in the gas or from the electrode surface, depending on where the focal point is, initiating the arc discharge. The electrode on which the laser is incident is slightly conical with a rounded tip. This geometry ensures that the point where the arc forms

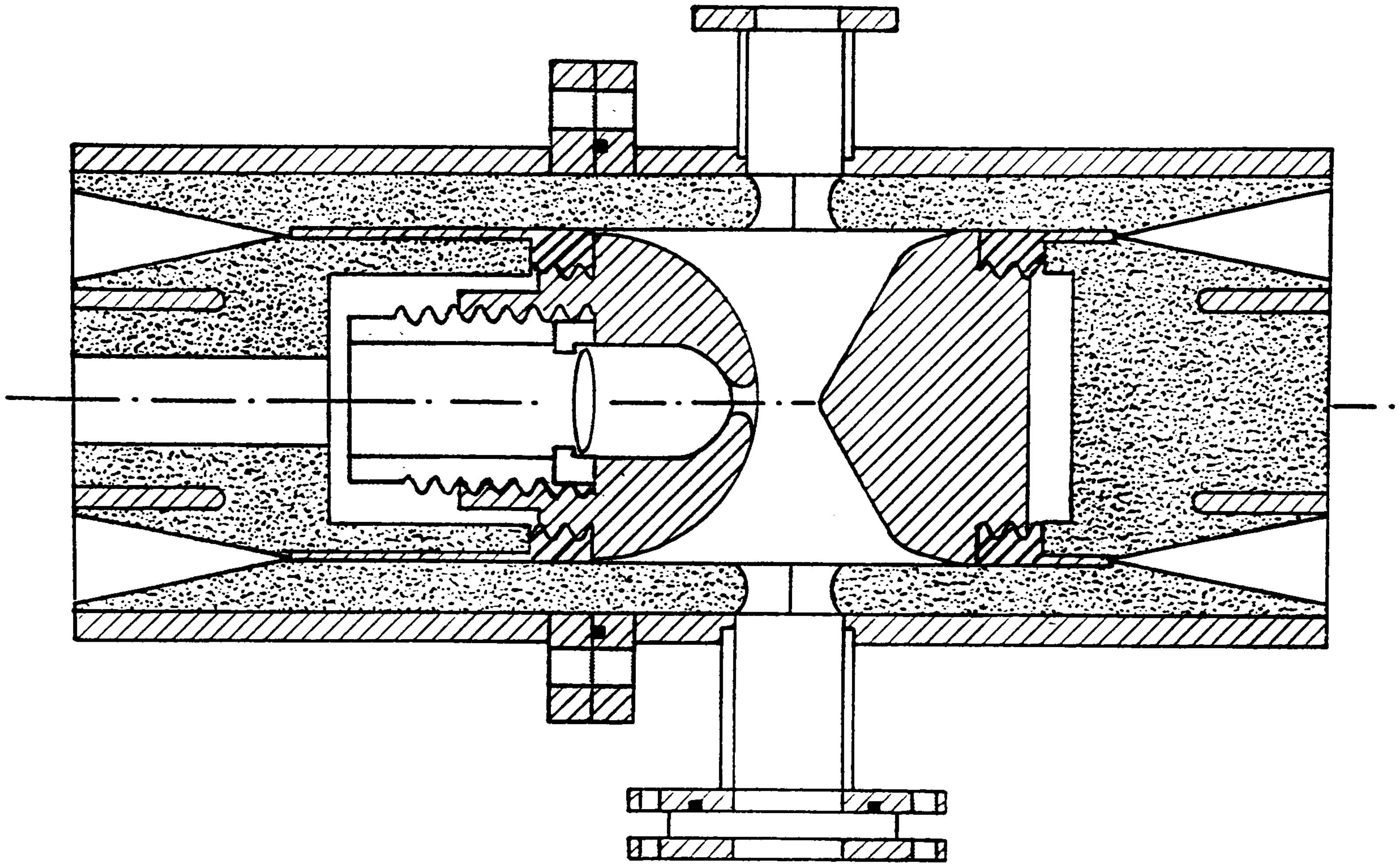


Fig. 6. The master gap.

when the gap is laser triggered is the highest field point, which is the point where self breakdown would occur if the voltage were further increased. It has been shown that this will reduce any jitter that this triggering method for the spark gap exhibits [43]. A system similar to the one described above is reported in [42]. This device switches five 10 kV pulses through a laser triggered spark gap with subnanosecond accuracy.

## Spark Sources

The spark sources were designed to maintain the coaxial geometry of the cables as closely as possible. This ensures that the voltage pulse arriving from the cables will maintain its fast rise time and fall time to the point where it is applied to the spark sources. The spark sources themselves have a novel design, as shown in Figure 7. Each of these devices produce six sparks distributed over a 2 cm spacing. The intermediate electrodes shown are standard 3/16 in ball bearings and the voltage applied to each source is a sufficiently high overvoltage to produce a rapid breakdown.

## Energy Storage and Charging System

The entire system withstands dc charging voltage of up to 40 kV. Using data given in the appendix it can be seen that the energy stored in this device is 0.86 J for 2 m charging cables and 4.30 J for 10 m charging cables. If a significant amount of the energy stored is radiated

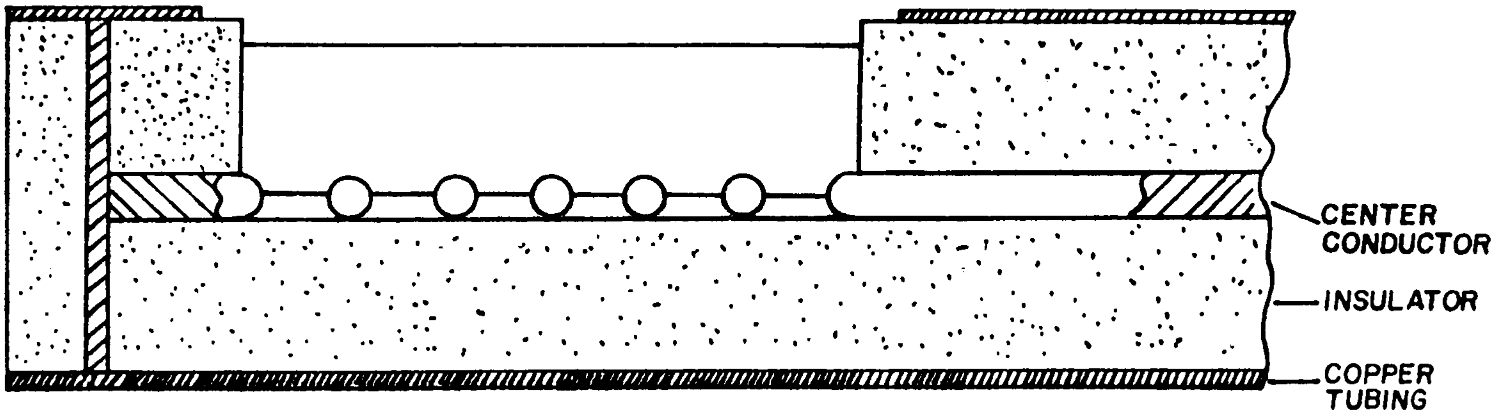


Fig. 7. A cutaway view of one spark source.

from the arc as ultraviolet light, the photon flux should be sufficient to produce a high electron density in the experimental chamber. The charging resistors for the system are divided equally between the high voltage input and the ground input in order to have an electrically "floating" system for pulsed operation. This is necessary because the experimental chamber potential is above ground potential when the discharge is initiated due to the design of the current probe used in the main experiment. The preionizer must be isolated from ground to prevent ground loops.

# CHAPTER V

# CONSTRUCTION

The main components of the system are the cables, the master gap, and the spark sources. The cable characteristics are described in the Appendix.

## Master Gap Construction

The master gap was the most difficult of the major parts of the preionizer to construct. The epoxy insulator shown in Figure 6 was formed in a two step casting process for each side. The first step was to fill the aluminum cups shown in Figure 8(a) with epoxy. Immediately after pouring the liquid epoxy, the piece was placed in a vacuum chamber and evacuated to remove any bubbles in the liquid before it hardened. These bubbles become air pockets which have a lower dielectric strength than the insulator. Therefore, these pockets lower the insulator breakdown voltage.

After the epoxy hardened, the solid aluminum end was drilled out and threaded so that an electrode could be inserted. On the other end eight small holes were drilled into the aluminum lip, as shown in Figure 8(b). These two pieces formed the connections between the cable center conductors and the master gap electrodes. Once these

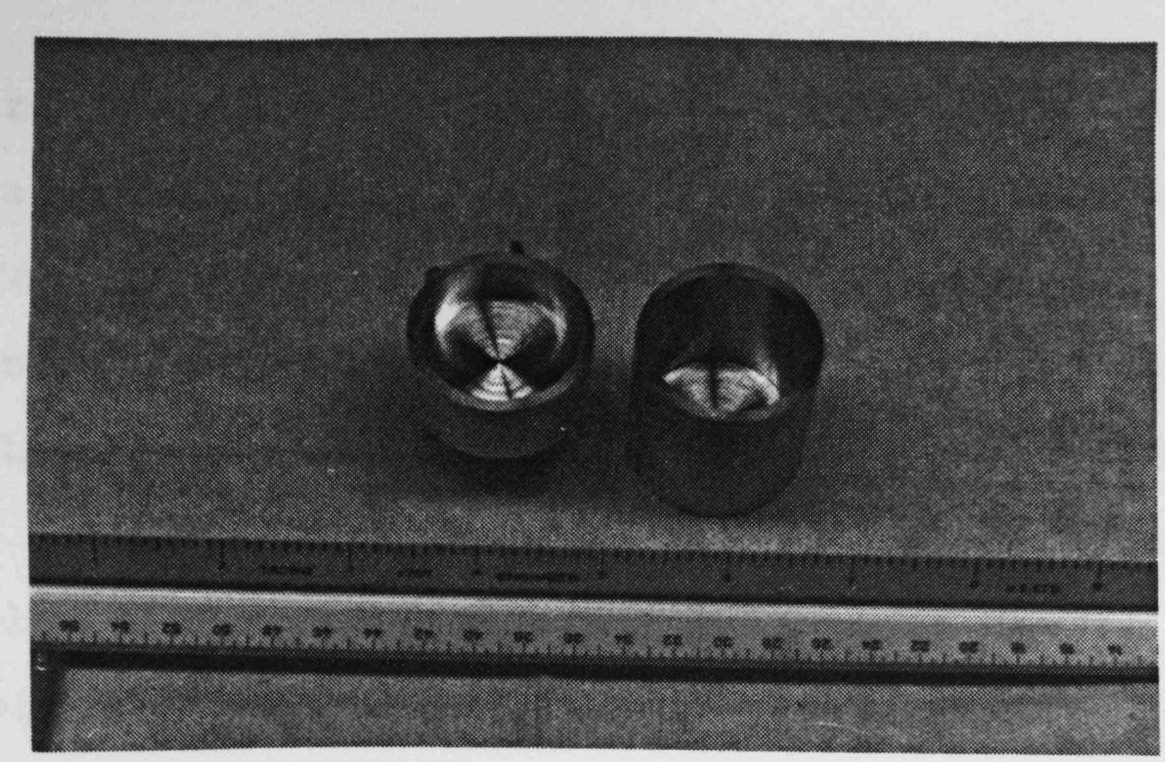


Fig. 8. The master gap center conductors:
(a) Unfilled

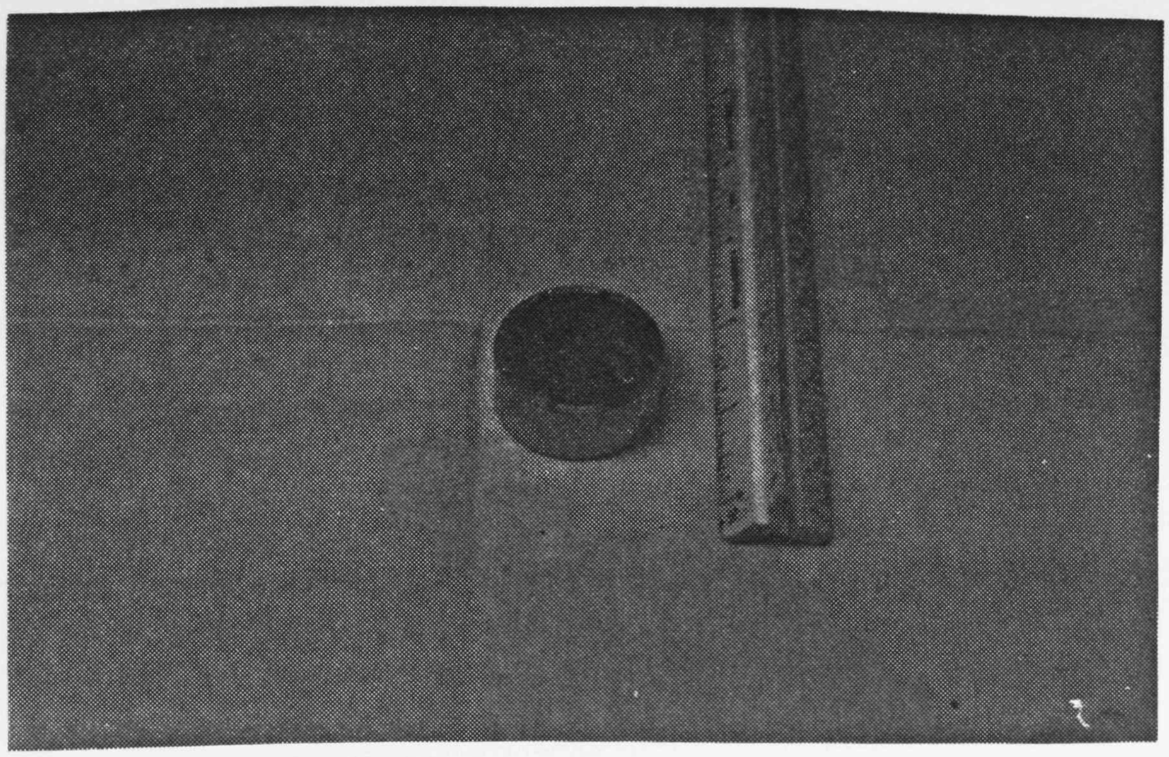


Fig. 8. The master gap center conductors:
(b) Smaller cup filled and tapped for connectors

parts were finished, the rest of the insulation could be cast. Each cup was screwed onto a mold which formed the cavity for the two electrodes. This assembly was then sealed into the outer half shell corresponding to the cup used. The cup and mold were inserted so that the cup was centered inside the shell with the end with the eight small holes facing the outer end of the half shell. Both halves of the outer shell are shown in Figure 9. Each hole in the rear of these shells had a short conical piece of cable inserted through it which also plugged one of the small holes in the cup. The epoxy was then poured into the shell through the eight holes and evacuated as before. The break in the insulator between the two halves is at the farthest point possible from the center conductors to avoid breakdown to the walls. These parts were also constructed for easy removal of both electrodes and cables. This is a distinct advantage because laser triggered spark gap electrodes can erode quickly. Also, one of the original design criteria was that the pulse length, and thus the cable length, be variable. The entire vessel was made with O-ring seals which allow pressurization up to several atmospheres.

## Laser Triggering Assembly

In Figure 6, it can be seen that the lens inside the hollow electrode is held in place by a threaded tube. Originally this device and the main experiment were to be

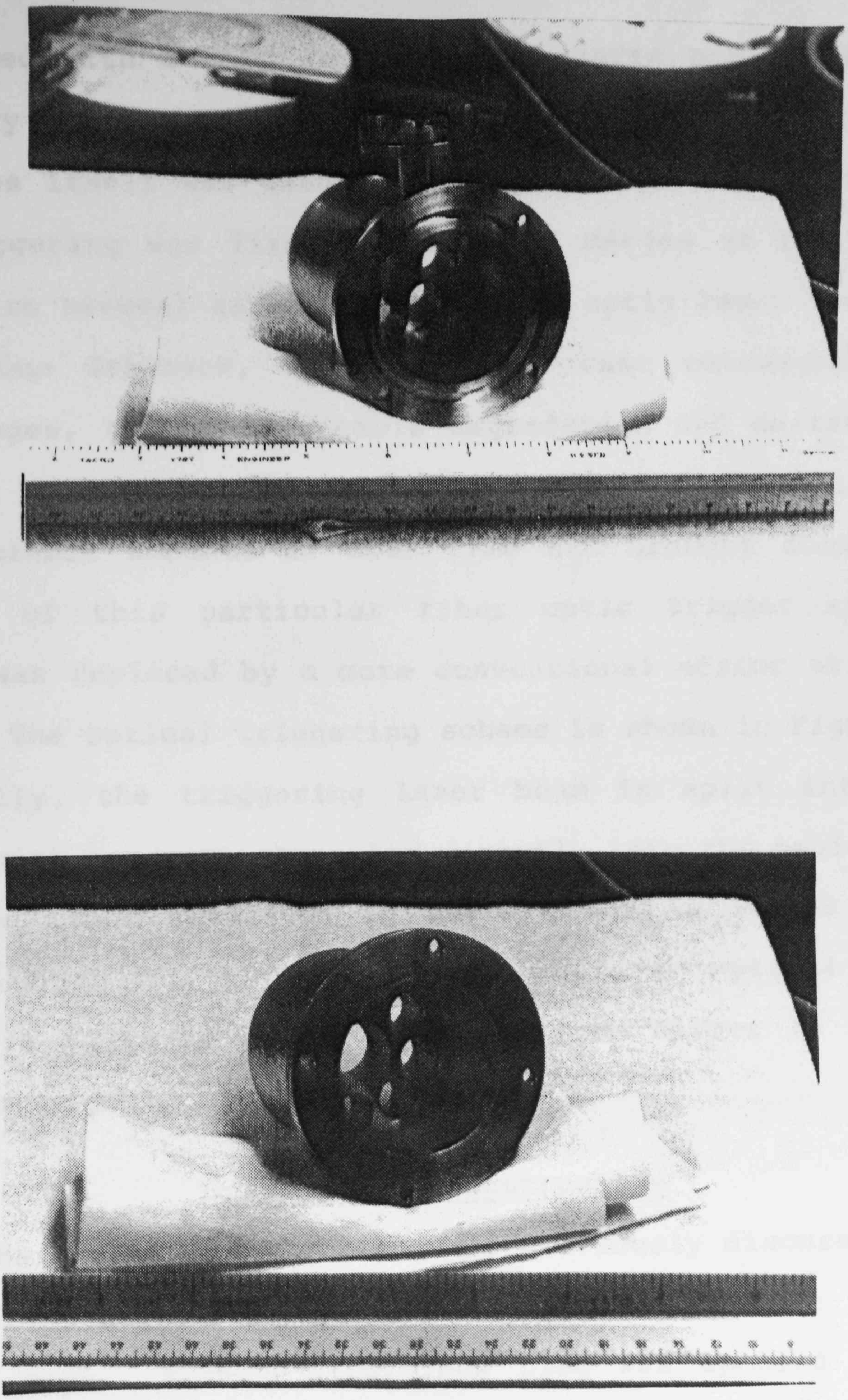


Fig. 9. The outer shell halves.

triggered with a ruby laser, using quartz optical fibers to carry the light pulse from the laser to the spark gap. The tube itself was used as a fiber holder. This method of triggering was first reported by Harjes et al. [43]. There are several advantages to fiber optic laser triggering. One drawback, which in this case outweighed the advantages, is the inevitable degradation and destruction of the fibers by the high power laser. This led to unacceptable amounts of down time and brought about the demise of this particular fiber optic trigger system, which was replaced by a more conventional mirror arrangement. The optical triggering scheme is shown in Figure 5. Initially, the triggering laser beam is split into two parts with one part channeled directly into the preionizer and the other reflected by mirrors onto a longer path. This allows for a precisely controllable optical delay which is adjusted simply by moving one mirror to change the longer path length.

## Spark Source Construction

The preionizer spark sources previously discussed are a simple design. The outer conductor is standard 3/8 in copper pipe. A G-10 fiberglass plug was epoxied inside the 20 cm long tubes about 2 cm from one end using vacuum degassed epoxy. At the same time, a cable form was placed inside the longest side of the tube and surrounded with epoxy to ensure a tight fit for the cable and to give added high voltage insulation. After this stage, a small hole was drilled axially through the center of the cylindrical plug. A 3/16 in slot was then cut from the side exactly halfway into the plug, such that the center hole of the plug was exposed along almost the entire axial length of the G-10. The electrodes on either end of this slot were epoxied into place, followed by the insertion of the ball bearing intermediate electrodes at regular intervals along the G-10 cylinder axis. These end electrodes lead outward to either end of the plug and connect to the transmission cable on one end and the termination on the other. The final step was to insert the termination plate at the end of the source and seal that end with epoxy. Initially, a 75 ohm metal film resistor was placed in a series with each of these shorting plates, but these resistors failed and were replaced by shorted terminations. For short preionizer pluses, this mismatch had a small effect on device performance. The finished product can be seen in Figure 10. This photograph shows that, while these sources produce a reasonably wide angle of illumination, they maintain their coaxial geometry very well. The spark sources were introduced into the experiment through a radially symmetric set of eight commercially available Cajon vacuum fittings. Their placement is shown in Figure 11. The eight brass fittings are plugged with aluminum cylinders in this end-on view of the experimental chamber. These parts allow the sources to be

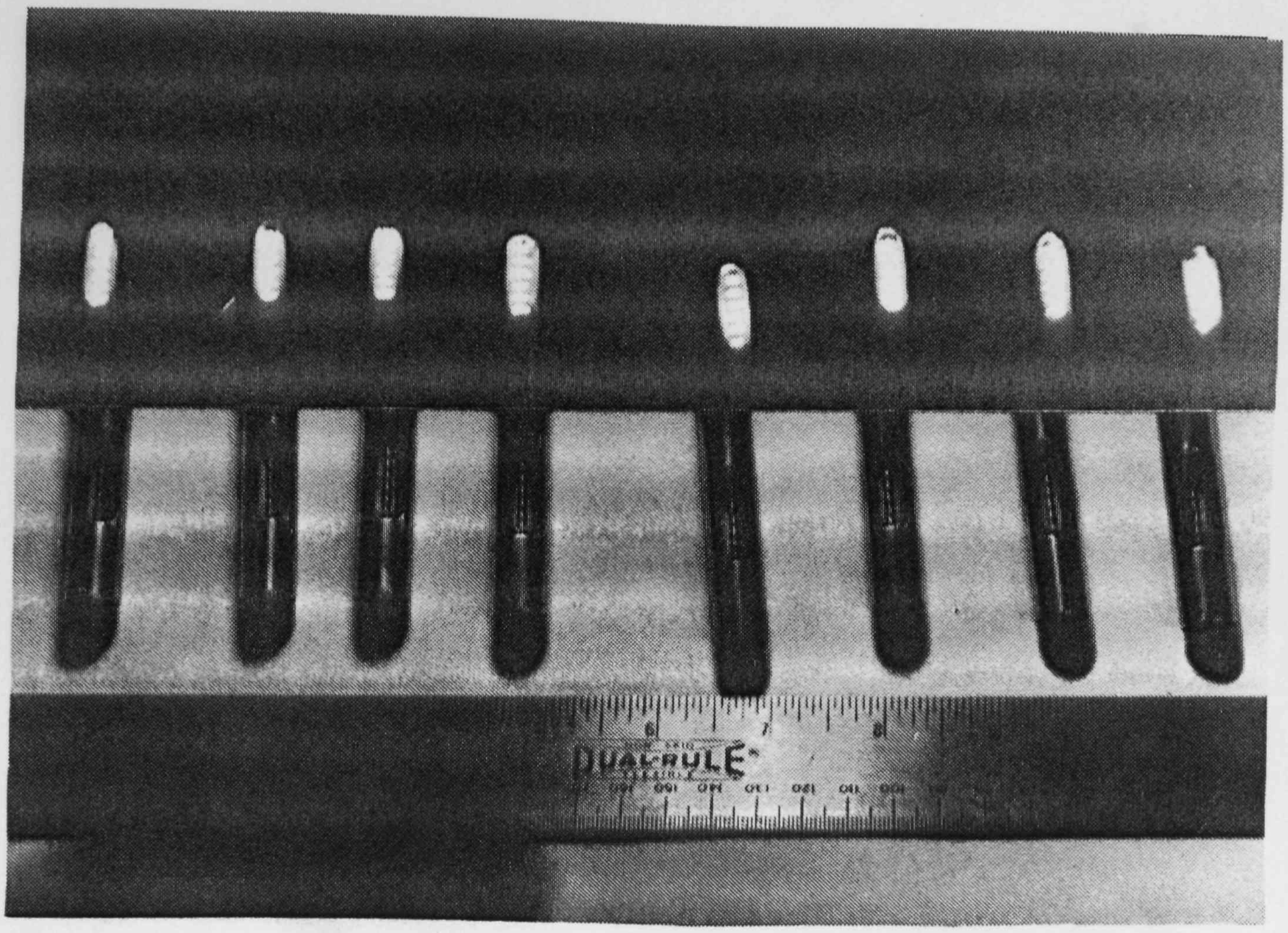


Fig. 10. The spark sources.

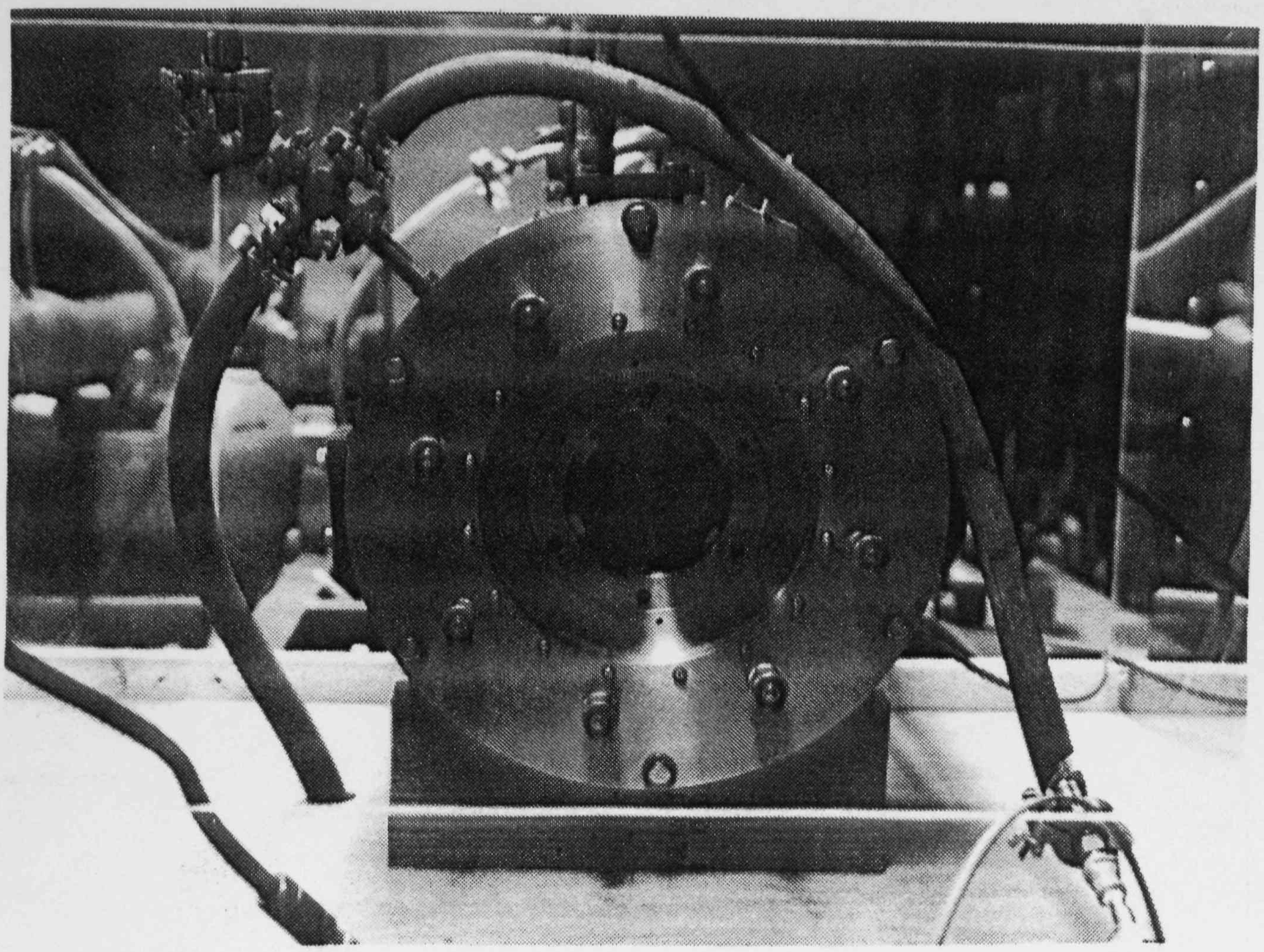


Fig. 11. An end-on view of the experimental chamber.

inserted and positioned without disassembling the chamber, and also provide for adjustments in preionizer position in case the gap spacing in the chamber is changed.

# CHAPTER VI

# RESULTS

Tests were performed to determine the time dependent light emission of the spark sources, the timing of the total system, and the preionizer's effectiveness in the discharge system. Also, a stress test was performed on the ball bearing device. The results of these tests appear below.

## Light Emission

In the first series of test experiments, the light emitted from the multispark sources (operated in air) was monitored using a vacuum photodiode (Hamamatsu R1328). The light outputs as a function of time using 2 m charging cables and 10 m charging cables are shown in Figure 12. Both light pulses have a rise time of under 5 ns and were produced using 20 kV for the charging voltage. The rise time is unaffected by changes in the charging voltage as long as the sources are overvolted by 10% or more. The pulse length is also clearly adjustable by changing the length of the charging cables. The light output observed when all eight spark sources illuminated the photodiode showed no discernible change in the pulse length or shape. In order to obtain a faster fall time, the system should

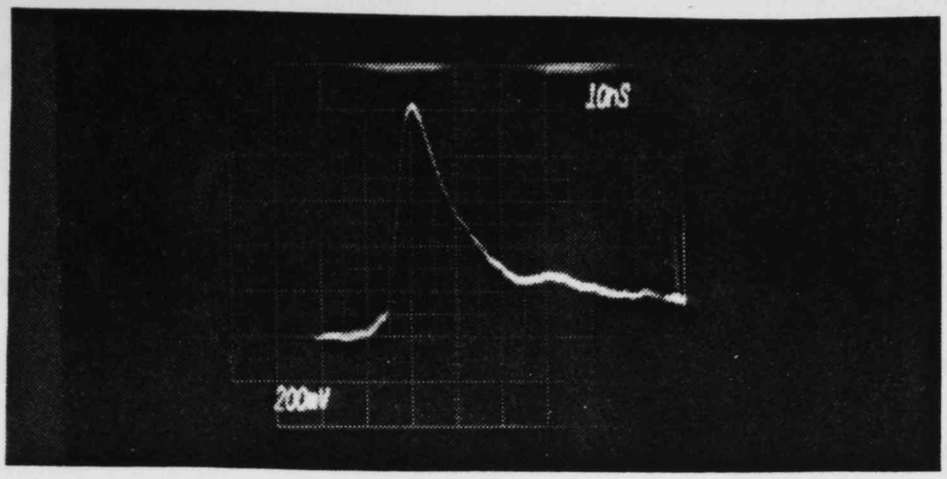


Fig. 12. The light output of the spark sources: (a) 2 m charging cable

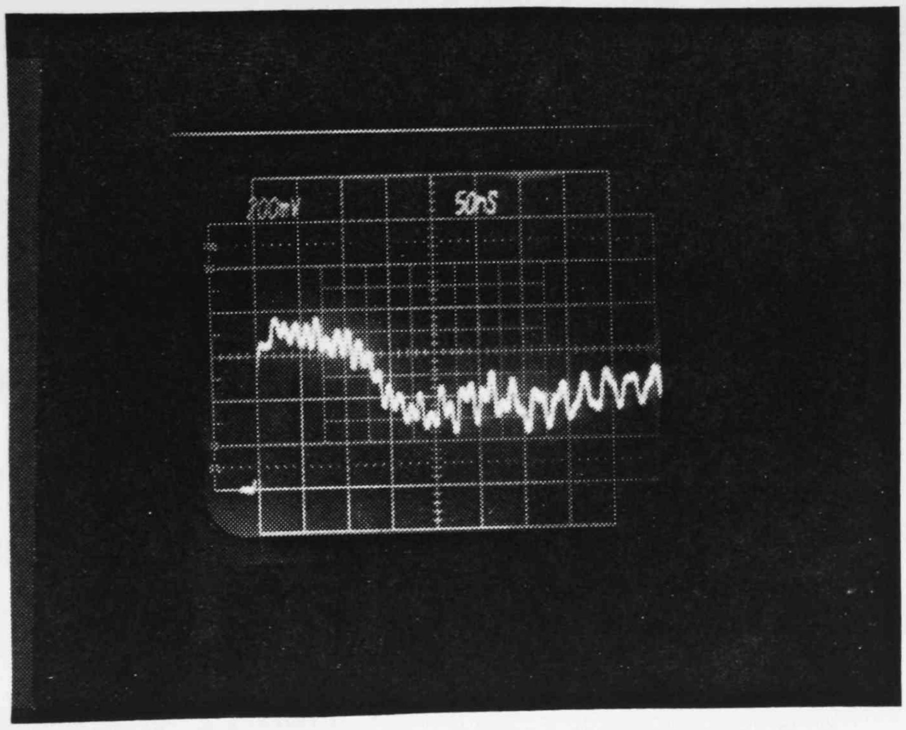


Fig. 12. The light output of the spark sources: (b) 10 m charging cable

be matched at the spark sources. Note that the longer cables produce a much longer fall time of the light pulse than the shorter cables.

## Timing Tests

Experiments were also performed to test the timing characteristics of the main experiment coupled with the preionizer. The results of the test are shown in Figure 13. This picture shows a four shot accumulation, with the first pulse being the light output from the preionizer and the second pulse being the output of a capacitive voltage probe which measures the voltage across the load resistors in the main experiment. The optical delay length in the mirror system was 13.5 m for this test, which corresponds to a calculated delay time of 45 ns between the preionizer and the main experiment. The 2 m charging cables were employed in the preionizer. The oscilloscope trace shows that the jitter between the two signals is on the order of 1 ns or less. Triggering for the oscilloscope in this test was provided by a current probe in one of the preionizer transmission lines.

One sacrifice in attaining this performance is the necessity of using very high power ruby laser pulses. The laser delivers 0.1 J to each gap in a 50 ns FWHM (full width half maximum) pulse. This high power caused the laser to burn holes in the electrodes in both spark gaps even though the focal points were 1 to 2 mm in front of

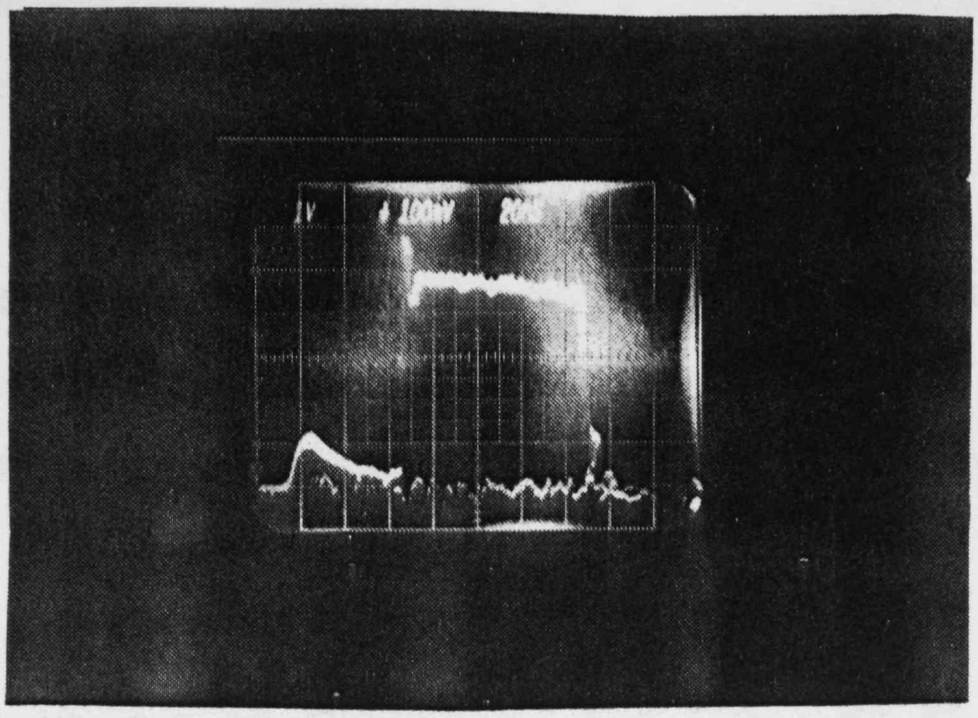


Fig. 13. Timing between the preionizer and the main discharge (4 shots).

the electrode surfaces. After several hundred shots without moving the focal point with respect to the position of the electrode, the jitter increased markedly to approximately 10 to 20 ns. This is due to the fact that when the laser is incident upon a depression in the electrode surface, the power density on the surface is greatly decreased, resulting in a corresponding decrease in triggering precision [40].

## Stress Test of Ball Bearing Device

A stress test was performed on a ball bearing device almost identical to the spark sources used in the actual system. After approximately 100,000 shots on this component, its breakdown voltage rose by less than 10% of the original value. This was the only noticeable change in the device operation throughout the test, so it is expected that the sources will prove to be very durable.

## Total System Test

The preionizer was also fired in the discharge chamber using the 2 m cables to test its effectiveness in its actual working environment. In pure helium, the main experiment produced diffuse discharges at pressures up to 760 torr with preionization, while without preionization the discharges became filamentary at about 250 torr. Because of the high ionization potential of helium, the effectiveness of the preionization was most probably largely due to the ionization of the impurities which are inevitably present. The same tests were also performed using a 3:3:14 $CO_2:N_2:H_e$ laser mix. The preionizer helped to make the discharge less filamentary at higher pressures, but at no test pressure above 100 torr was a completely diffuse discharge produced. This pressure is the lowest pressure at which the preionizer operates properly. This is indicative of a need for addition of a seed gas in this experiment when strong attachers are used in the discharge medium. There was some difficulty operating at the desired voltages without breaking down along the insulator surfaces, but these problems were controlled successfully.

# CHAPTER VII

# CONCLUSIONS

The results discussed above meet or exceed almost all the design specifications mentioned earlier. Using a relatively short 15 ns FWHM light pulse, reasonable volume preionization at atmospheric pressure was shown to be feasible under proper conditions. The performance in attachers was not entirely unexpected in light of past research on preionization under the same conditions. The rise time and fall time of the light pulses are of the order expected and the jitter associated with the trigger system is consistent with results previously reported by others. It can be expected from the results presented that with a seed gas introduced in the gas mixture, this preionizer will perform well in comparison with laser preionizers having a much longer preionization pulse.

Several possible improvements were mentioned throughout this paper, the most pressing of which is the need for higher charging voltages for the system. Since the intensity of the light output is approximately proportional to the peak power input to the spark, and thus to the square of the charging voltage, the importance of this upgrading is obvious. This can be accomplished by simply making the paths between high voltage and ground longer at the critical points. Another proposal for bettering the device's performance is the use of an electrode material more suitable for laser triggering than the easily eroded brass presently in use. It was discovered that G-10 fiberglass is only a fair vacuum material, so a better insulator for use in the spark sources would benefit the whole system by reducing the amount of unwanted impurities in the discharge medium. The use of commercially available copper pipe caused some problems with the vacuum seal due to surface irregularities and the fact that the pipe is not perfectly round. The results of the tests performed with this device show that it is an effective preionizer for diffuse discharges in gases containing attachers.

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# APPENDIX

## Belden 8870 Specifications

# TECH DATA SHEET

## 8870

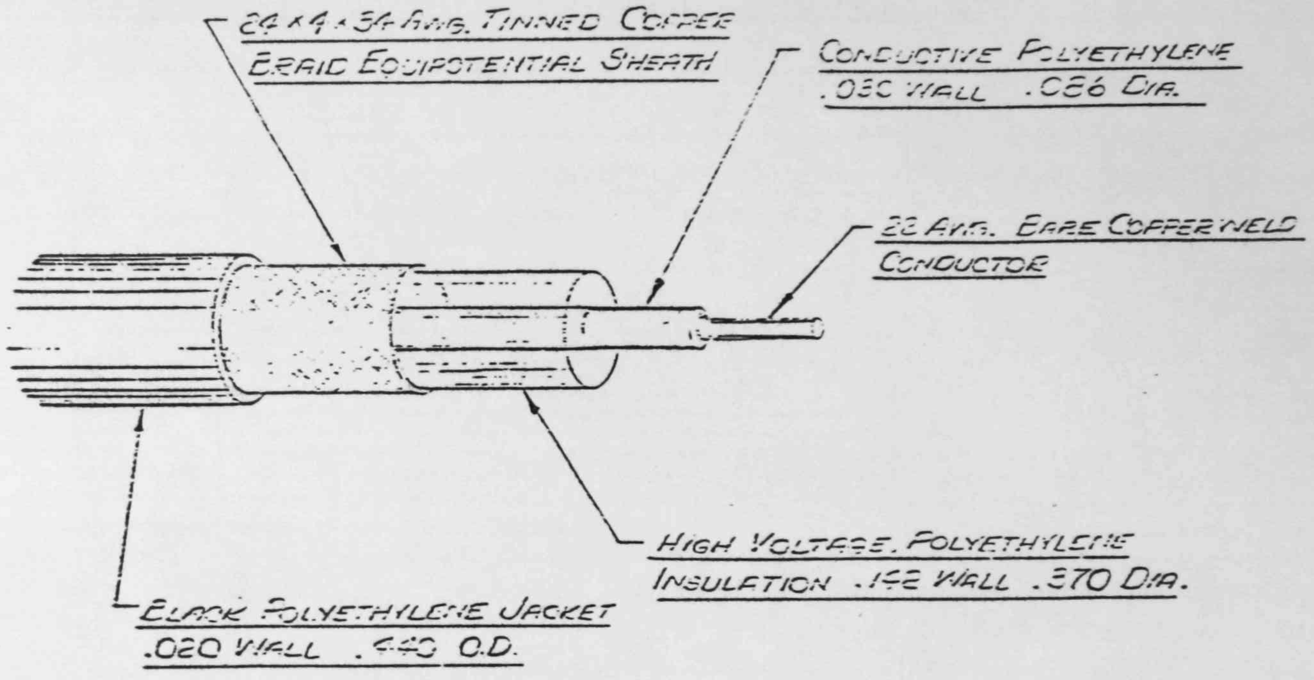
## 80KVDC HIGH VOLTAGE CABLE

| | |
|---|---|
| DC WORKING VOLTAGE | 80KV |
| AC WORKING VOLTAGE | 24,000 Volts * |
| CURRENT RATING 80° (10°C RISE) | 1 Amp |
| CAPACITANCE - BETWEEN CONDUCTOR AND SHIELD | 20.5 pF/ft. Nom. |
| IMPEDANCE | 75.1 OHMS |
| INDUCTANCE | 125.9 NH/ft. Nom. |
| CMA OF BRAID | 3,816 |
| CMA OF CONDUCTOR | 642.4 CM (30% CW-<br>Equivalent Copper<br>CMA = 192 CM) |
| TEMPERATURE RATING | 80°C Max.<br>-50°C Min. |
| MINIMUM BEND RADIUS | 8.80 Inches |
| DC RESISTANCE OF SHIELD | 4.61 OHMS/M' |
| DC RESISTANCE OF CONDUCTOR | 54.3 OHMS/M' |
| UL STYLE | Not Applicable |

* Ratings based on tests at 60 Hz. Does not apply at other frequencies.

This cable is recommended for applications in which the source is power limited so that if a cable failure occurs the source automatically limits the energy transfer to a value less than that required to raise the conductor temperature to 90°C.

G. Dorna
7/23/73



—BELDEN 8870—
HIGH VOLTAGE CABLE
RATING: 80 KV DC

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LIMITS UNLESS OTHERWISE SPECIFIED:
DECIMALS: ± ANGLES: ±
FRACTIONS: ±

CHECKED
APPROVED

BELDEN MANUFACTURING CO.
CHICAGO, ILL — RICHMOND, IND.
DRAWN BY: DATE: 2-4-63
APPROVED: 2C 2-7-63 SCALE:

CUSTOMERS DWG. NO
MACHINE DWG NO
PIECE PART NO 8870

FUSING CURRENT VS. TIME FOR #8870
#22 AWG