LOW JITTER SPARK GAP SWITCH
FOR DENSE Z-PINCH

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DEDICATION

To Val

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I. INTRODUCTION

The Z-pinch experiment at the University of Michigan produces a dense, reproducible plasma which is convenient to study certain aspects of laser-plasma interactions. At maximum compression, a density of over 10^{19} electrons/cm^3[(1)] is obtained, which places the plasma in an overdense regime for the high power CO_2 laser source used for the interaction studies. A principal advantage of this experiment is the production of an overdense plasma independent of the laser source. This facilitates the diagnostic analysis of the laser induced effects on the plasma.

In the present investigation, the study consisted of producing a more reproducible Z-pinch plasma. The principal improvement to the experiment, was the installation of a pressurized, low inductance spark gap and a 100 kV low-jitter pulse generator to trigger the spark gap. A study of the evolution of the Z-pinch plasma is presented as a function of initial helium fill pressure and capacitor charging voltage.

II. EXPERIMENTAL CONFIGURATION

The University of Michigan Z-pinch assembly as it was configured for these experiments, is shown in Figure 1. It consists of a 3 cm diameter quartz tube 15 cm in length, with 4 access holes located symmetrically about the tube midplane. The quartz tube is filled with helium gas, and the Z-pinch plasma is created by the discharge of a 14 μF, 40 nH energy storage capacitor. The current flows through the gas, and returns through a copper tube surrounding the quartz tube, in a coaxial configuration. This coaxial arrangement results in a low inductance electrical circuit which allows the achievement of an electron density of over 10^{19} electrons/cm^3.

The quartz tube was pumped down by a roughing pump to 10-20 mTorr, and back filled with helium, through a precision leak valve to the desired fill pressure. The pressures used varied from 1.2 to 3.0 Torr for a charging voltage of 12.5 kV, and from 1.4 to 8.1 Torr for 13.0 kV. The pressure was set by closing the valve on the input of the roughing pump most of the way, and bleeding in the helium until the desired pressure in the chamber was reached, as read from a mechanical-diaphragm pressure gauge. From the time that the pressure was set until after the capacitor was discharged, the gas was continuously leaked into the chamber, keeping the quartz tube at the set pressure.

Attached to the four access cups of the quartz tube, were stainless steel vacuum fittings secured to the quartz by a hard

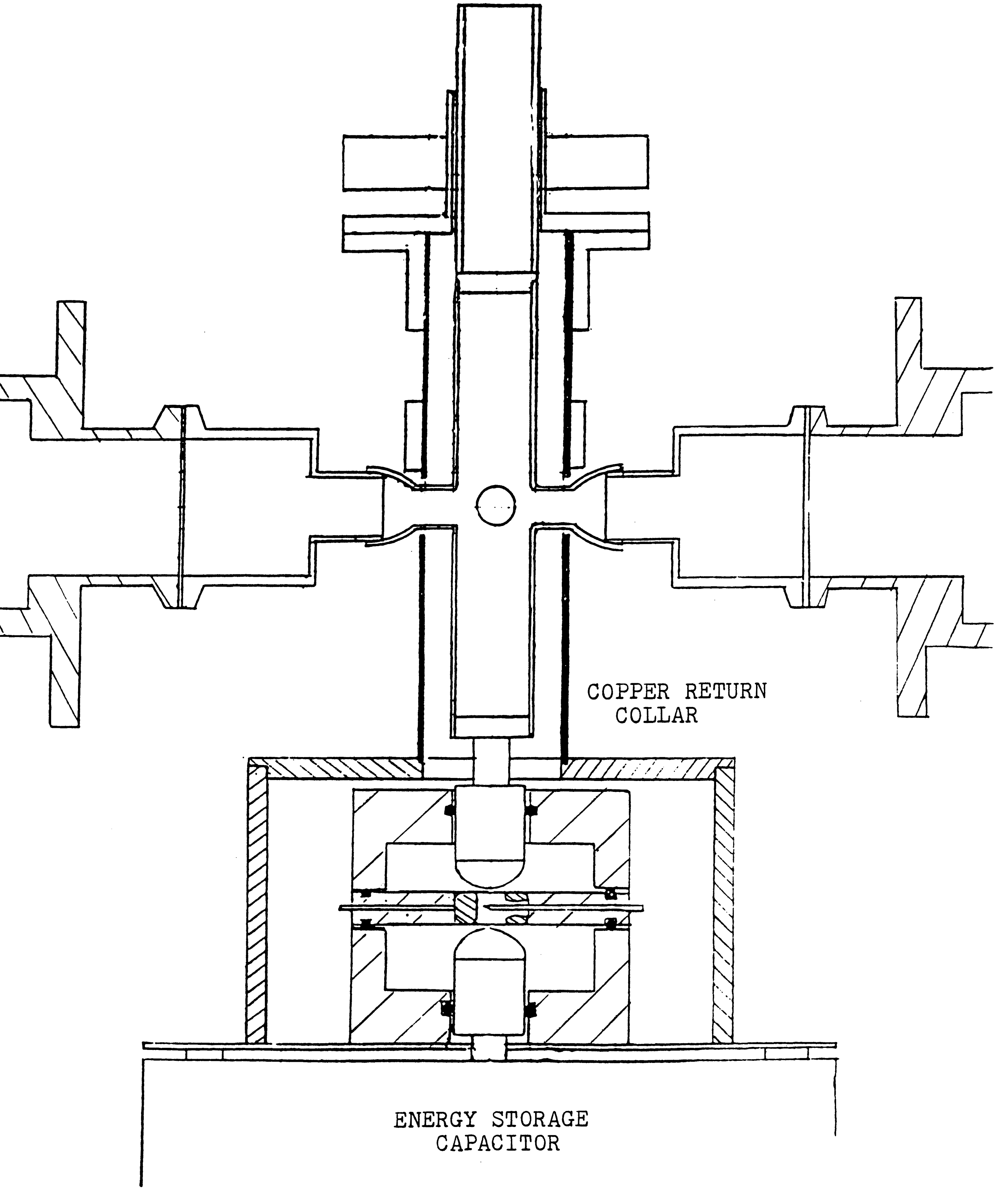
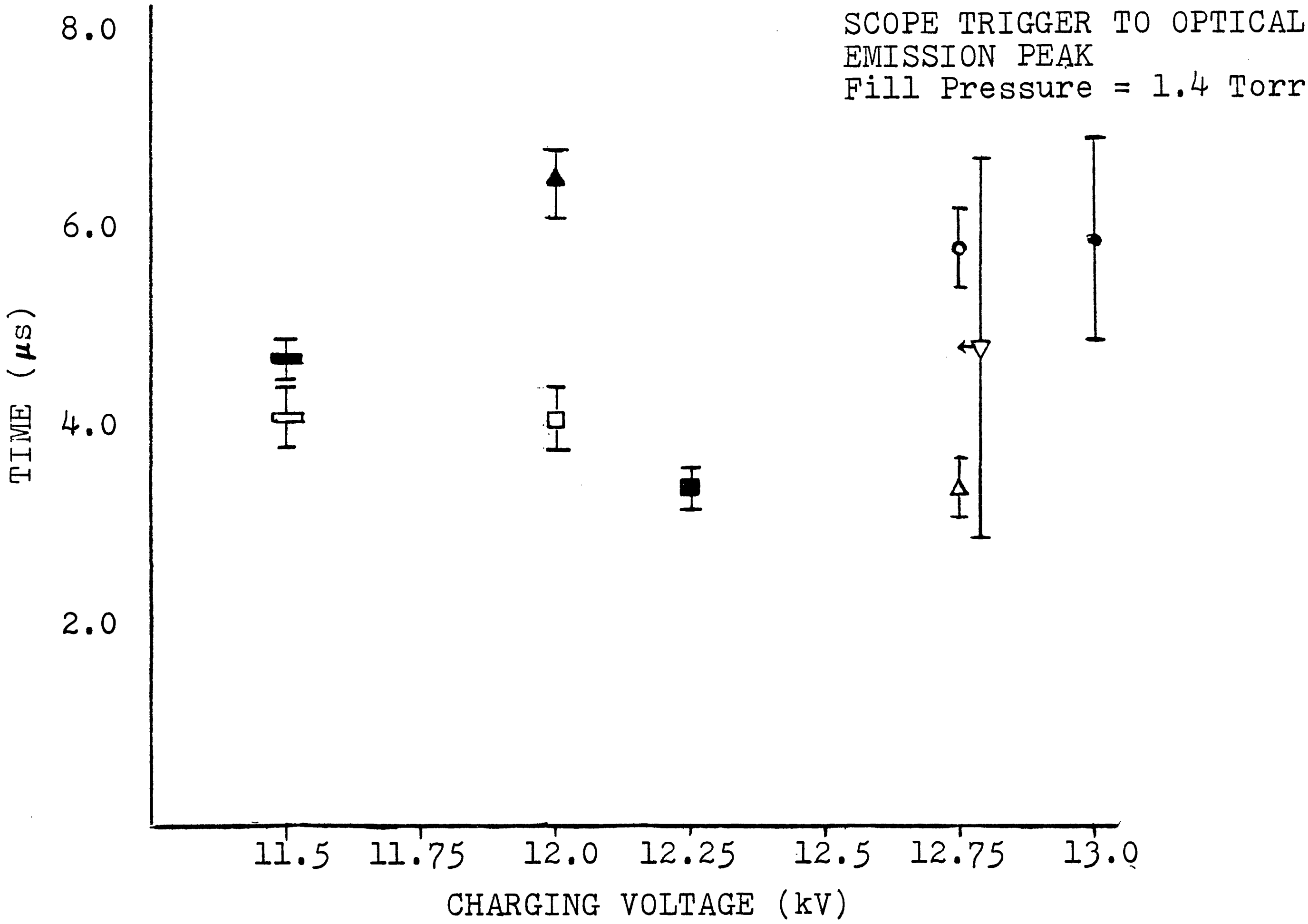


Figure 1. Experimental Configuration.

vacuum wax. Brass bellows which were connected to these fittings, held the windows through which the optical emission measurements are made. These bellows also held zinc selenide windows when laser interaction studies were carried out. These bellows were held in position by small lab jacks, which rested on an aluminum plate attached to the copper ground plane to which the energy storage capacitor was discharged, via the helium gas. An important point to note when putting the bellows in place was to make sure that the bellows did not become grounded. This was done by using plexiglas holders on top of the lab jacks. Should a bellows become grounded, a large portion of the discharge current shunted to it, and a proper pinch did not form. The shunting will show up in the current monitoring diagnostic signal, as a rather spiky waveform rather than the relatively smooth waveform of a good pinch.

In the previous experiments on the Z-pinch, the discharge was triggered by a hydrogen thyratron tube which broke down an open-air pin-trigger spark gap(2). It was found that this method for triggering was unreproducible and had very large jitter. The occurence of the pinch, as shown in Figure 2 for a set experimental configuration, has a timing variation of over ±500 ns, which is intolerable for laser-plasma interactions especially when the CO_2 laser pulse length is 40 ns FWHM.

The open-air spark gap had several factors which lead to the large timing jitter as seen in Figure 2. First, the spark gap was set by adjusting the electrode-to-trigger pin gap and the electrode-to-electrode gap. These settings were difficult to reproduce reliably, and lead to jitter from day to day because of



SYMBOL	DATE	NO. OF SHOTS IN AVERAGE	AVERAGE (μs)
•	7/7/82	5	5.9±1.0
○	7/7/82	9	5.8±0.4
△	7/16/82	2	6.4±0.3
▲	7/27/82	2	4.1±0.2
□	7/28/82	5	5.4±0.2
■	8/2/82	3	4.1±0.3
▭	8/4/82	3	4.7±0.2
▬			
▽	8/6/82	3	4.8±1.9

Figure 2. Timing Results for Open-air Spark Gap.

the length variation involved in breaking down the spark gap. Secondly, since the spark gap was open to the atmosphere, any change in the humidity would change the spark gap breakdown conditions, and effect the day-to-day timing. Thirdly, the spark gap was initiated by an arc from the trigger pin to one or both of the electrodes. The arc provided the ionizing radiation, which broke down the spark gap. Since an arc between two surfaces of differing voltages takes an unreproducible path, the breakdown discharge length would change from shot-to-shot and would lead to shot-to-shot jitter.

For a spark gap to fire reproducibly, both the electrode spacing and the pressure need to be set so that the spark gap is on the verge of self-breakdown under the electric field established when the capacitor is fully charged. In the previous open-air spark gap, this breakdown electric field could only be changed by varying the electrode spacing, which involved disassembly of the experiment. This was a very time consuming and tedious operation, especially since the spark gap breakdown conditions varied whenever the humidity inside the spark gap changed. A better method of setting a spark gap so that it is on the verge of self-breakdown, is to have a sealed spark gap, and vary the pressure. By using dry air from a gas bottle, the spark gap can be set near the self-breakdown condition remotely, and the humidity inside the spark gap is controlled, which will improve the triggering reliability.

III. DESIGN AND DESCRIPTION OF IMPROVED SPARK GAP SWITCH

The purpose of this study was to design, construct and test an improved spark gap switch to reduce the timing jitter encountered in firing the Z-pinch with the previous open-air spark gap. The first choice for the replacement was a commercially available spark gap, but three difficulties were encountered. First, the space available for the spark gap was small, due to the construction of the Z-pinch assembly, and major alterations were undesireable. Second, the inductance of the new switch was required to be close to that of the old switch in order to achieve the same plasma parameters(3). Third, due to the large capacitor used to drive the discharge, a large charge transfer occurred during each shot, at relatively low voltage. Commercial spark gaps typically have a maximum charge transfer rating per shot near the 0.2 C transferred per shot for the Z-pinch(4,5). However, the commercial spark gaps are usually rated for a lower peak current than is encountered during the Z-pinch discharge. Additionally, the large voltage reversal during each discharge, is detrimental to a spark gap, and leads to shortened lifetimes. These considerations pointed to a special design being needed to handle the extreme conditions of each discharge. The new spark gap should be easily disassembled for cleaning as well as easily set for the proper breakdown conditions.

The final design is shown in Figure 1. The spark gap is a three piece design, with the sections being made out of plexiglas, and held together by three nylon bolts. The spark gap is 8.9 cm high and 7.6 cm in diameter. The electrodes are made of copper with elkonite (a copper and tungsten alloy) tips. Elkonite is used to reduce the metal deposited inside the spark gap during each shot. O-rings are used to allow an adjustable electrode spacing, as well to allow pressurization.

The middle section consists of a 2.5 cm brass ring through which a stainless steel trigger pin protrudes. The ring and the pin are connected together through a 47 kΩ resistor, and are charged to half of the charging voltage through a bias resistor before each shot, as shown in Figure 3.

The firing of the spark gap is quite reliable, and very little maintenance is needed. The spark gap has been run for over 150 discharges without premature self-breaking, which is a symptom of a dirty spark gap. As a preventive measure however, when a quartz tube is replaced (approximately every 100 discharges), the spark gap is disassembled and cleaned.

Upon examination after tens of shots, the spark gap is coated with a dark amber coating. This deposit is just the condensation of the vacuum grease from the O-rings, which is vaporized during a discharge. The vapor does not cause premature firing, and can be cleaned using methanol.

IV. HIGH VOLTAGE TRIGGERING CIRCUIT

The second improvement to the reproducible firing of the Z-pinch has been the installation of a Maxwell 40095B pulse generator. The pulse generator is essentially a high voltage

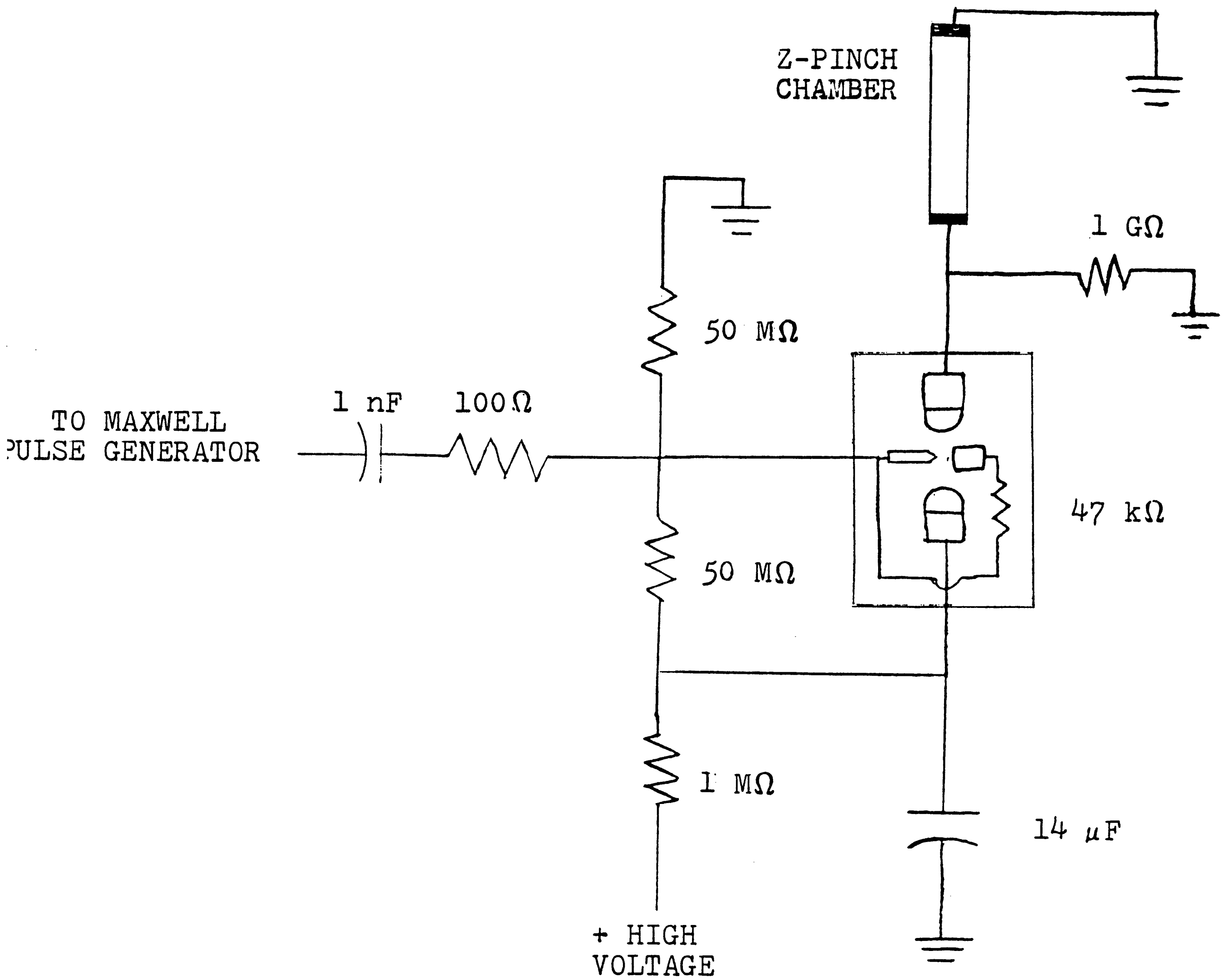


Figure 3. Charging and Triggering Diagram.

pulse transformer and associated pulse shaping network. The pulse voltage generated can be continuously varied from 20 to 100 kV, and lasts for about 300 ns, as shown in Figure 4. The pulse has a fast risetime and a rated shot-to-shot jitter of 7 ns. However, while the pulse voltage is very large, the energy contained in it is very small, and as a result, the pulse transformer must be located near the device to be triggered, and stray capacitance must be kept to an absolute minimum. Initial use of high voltage coaxial cable prevented any breakdown of the spark gap, however removal of the outer shield of the cable reduced the stray capacitance to an acceptable level, so that the spark gap would fire. The pulse transformer was protected from switching transients from the discharge by a 1 nF coupling capacitor and a 100 Ω non-inductive current-limiting resistor.

To trigger the spark gap, typically a 60 kV pulse is used. The pulse goes to the ring and pin, breaking down the small gap separating them by virtue of the voltage drop across the 47 kΩ resistor. This breakdown emits ultraviolet light, which ionizes the dry air in the spark gap. The electrons emitted, provide the seed electrons for the Townsend avalanche of electrons, which breaks down the whole spark gap. Typically, the time from the start of the high voltage pulse to current initiation is 400 ns.

Once the spark gap breaks down, the entire charging voltage is applied across the electrodes of the Z-pinch chamber. Since the helium fill gas is at a few Torr, the chamber acts as an over-volted spark gap, and the entire breakdown process begins.

The current initially flows along the inside walls of the quartz tube, at a rate of 4.3×10^{11} A/s, generating a strong

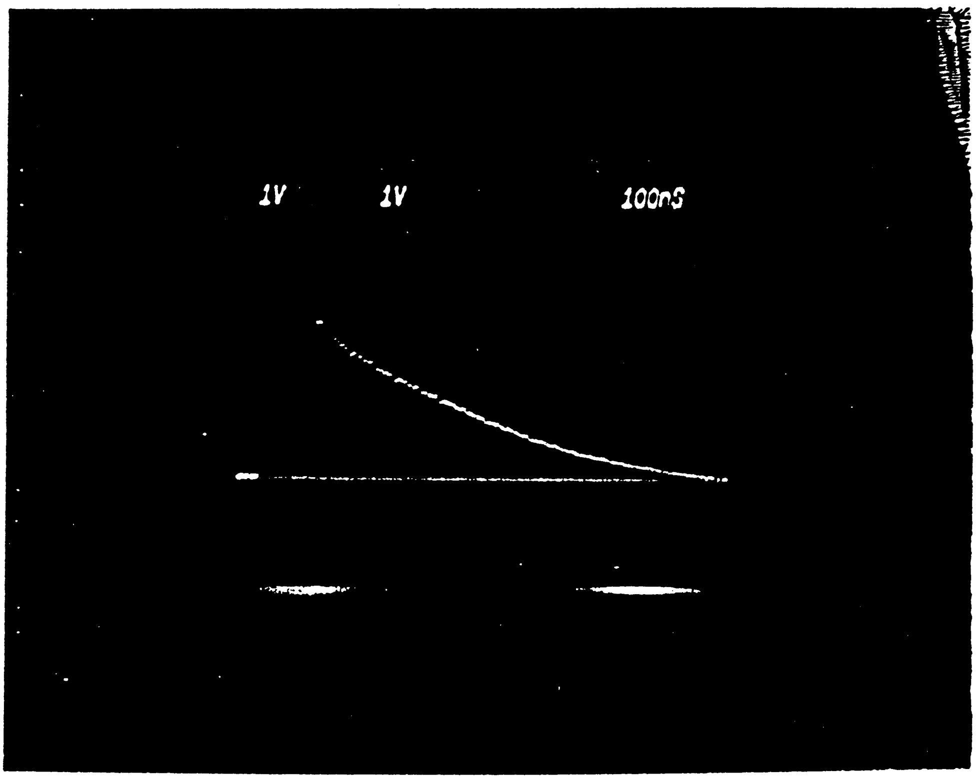


Figure 4. Spark Gap Trigger Pulse.

magnetic field. At a time 400 ns after the current flow begins, the ionized helium gas collapses due to the JxB force. The collapse increases the circuit inductance, and shows up as an upward swing in the signal generated by a Rogowski coil threaded around the copper return collar, as seen in Figure 5. About 600-700 ns after the current initiation, the Rogowski coil signal reaches a maximum, and then returns to the signal of an under-damped electrical circuit. The sharp rise in the signal is an indication of a good compression, and is considered to be a good "pinch".

Another diagnostic used on the experiment is a PIN diode, which measures the optical emission of the plasma. A typical PIN diode signal is shown in Figure 5. At about the time where the Rogowski coil signal was at its local maximum, the optical emission began to increase. The PIN diode signal reaches a maximum 100-200 ns after the Rogowski coil signal maximum. This discrepency lead to some confusion as to what should be the time reference of the pinch. Interferometric measurements by Ackenhusen(1) showed that there was no plasma present at the Rogowski coil signal maximum, while the plasma density was the greatest ($> 10^{19}$ cm^{-3}) near the optical emission peak. The optical emission peak is due to a collisional broadening of transition lines in helium, which is density dependent(2). Therefore, any timing measurements made are referenced to the optical emission peak. The burst of optical emission increases for 150 ns and decreases, monotonically. Due to the inherent instability of a Z-pinch, the plasma breaks up and expands, decreasing the electron density and thus optical emission. The larger and longer optical emission

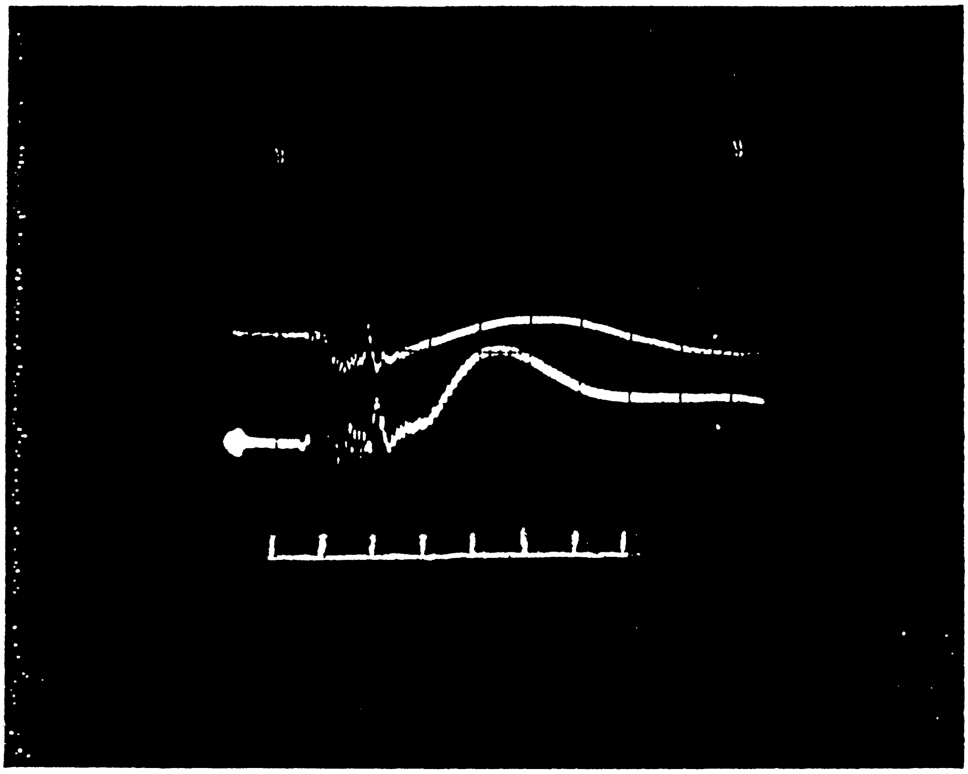


Figure 5. Typical Data Set - Shot # 288
Top : Rogowski Coil 20 V/div Scale 500 ns/div
Bottom : PIN Diode 100 mv/div
Fill = 2.6 Torr Charging Voltage = 13.0 kV

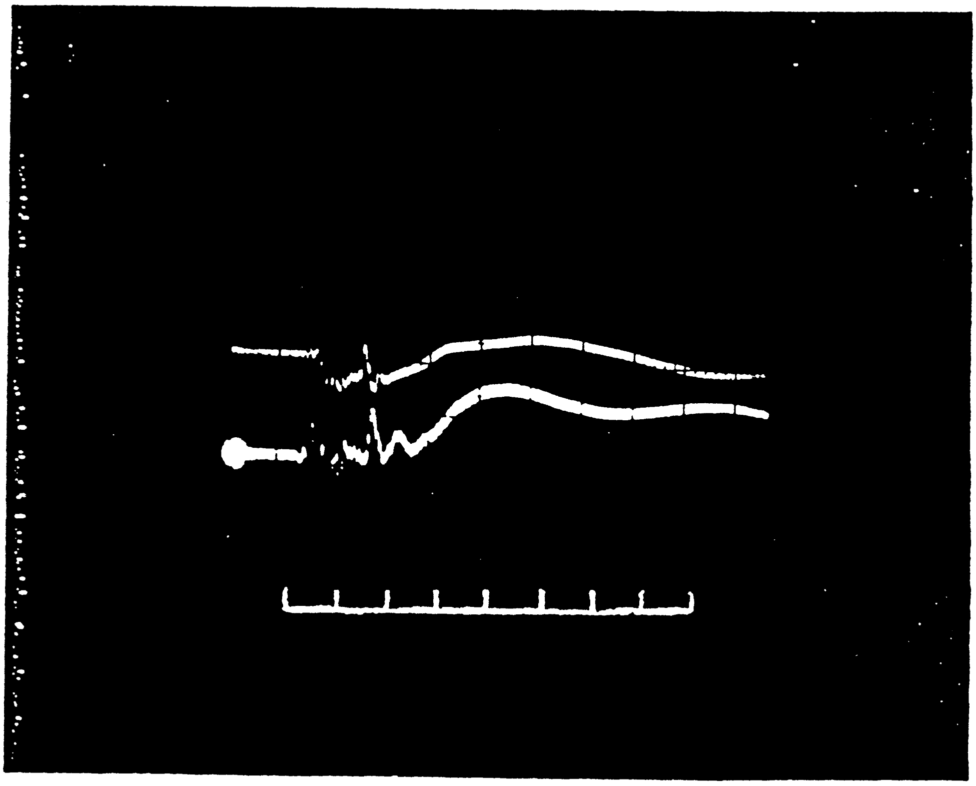


Figure 6. Data Showing Possible Double Pinch Shot # 287
Traces and Settings Same as in Figure 4.
Fill = 2.65 Torr Charging Voltage = 13.0 kV

peak is seen around 5 μs after the pinch and is due to recombination of the helium.

Since the installation of the new spark gap, a number of discharges have exhibited a third optical emission peak, resembling the light emitted by the pinch (Figure 6). This occurs at many fill pressures used, and its origin is uncertain. It may be the occurence of a second pinch resulting from forces generated by the large current still flowing through the plasma. An examination of the Rogowski coil signal does not show another upward swing as with the pinch but it often shows a discontinuous change in the slope of the signal. This phenomenon will be examined using a streak camera, which will measure spatially and temporally resolved light emissions.

V. EXPERIMENTAL RESULTS

The primary investigation performed upon installation of the spark gap was the timing reproducibility of the Z-pinch discharge. The investigation was carried out through the variation of the helium fill pressure and the capacitor charging voltage.

The fill pressure was varied between 1.4 and 8.1 Torr of helium. For pressures of less than 1.8 Torr, the discharge was erratic and unreproducible as indicated by the shape and amplititude of the light emission. The Z-pinch fired well up to a pressure of about 8 Torr, which placed an upper limit on the range of initial conditions. As the fill pressure was increased above a few Torr, the width of the upward swing of the Rogowski coil signal widened. This widening indicated that the evolution of

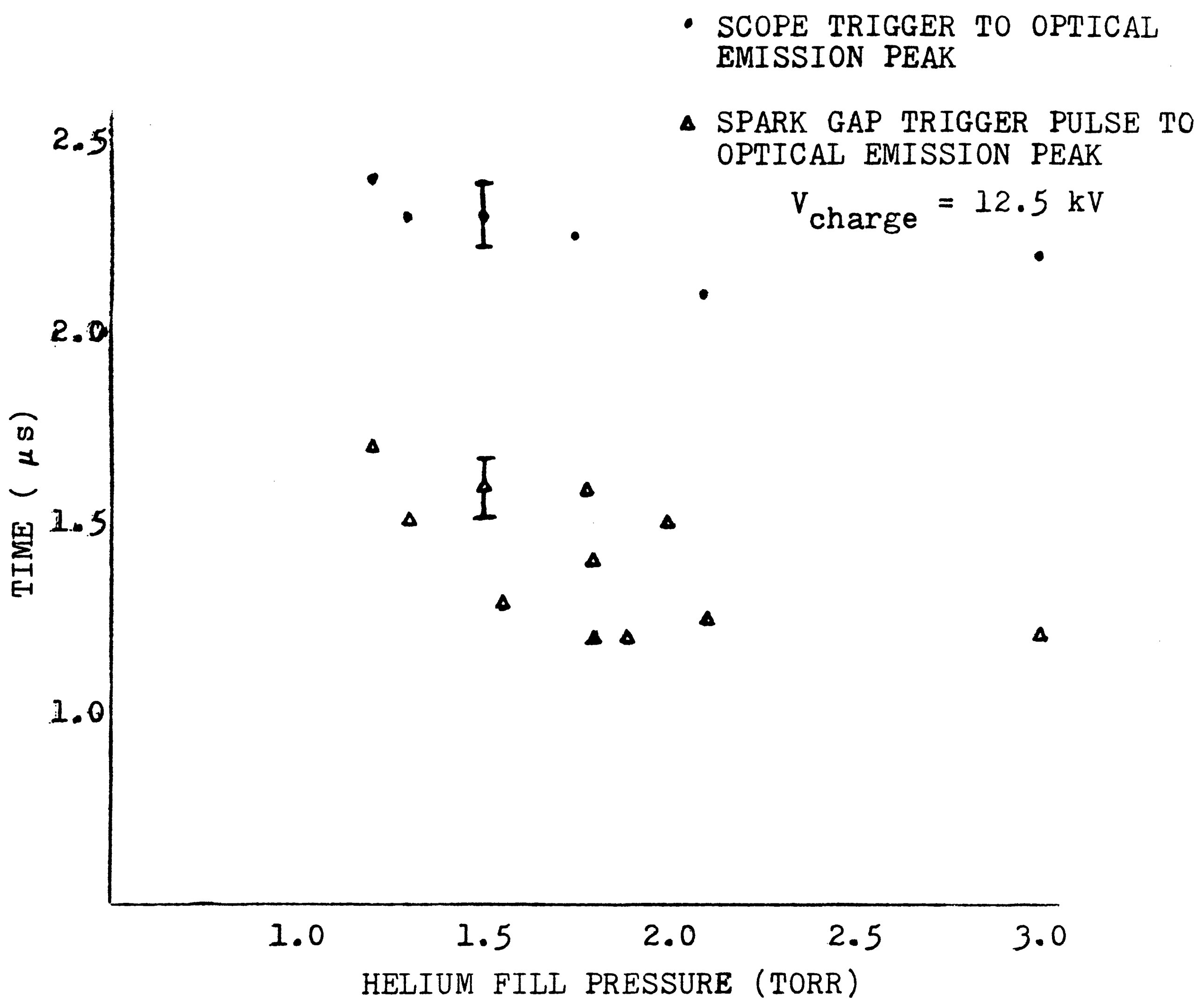


Figure 7. Timing Results for PIN Diode for V_{charge} = 12.5 kV.

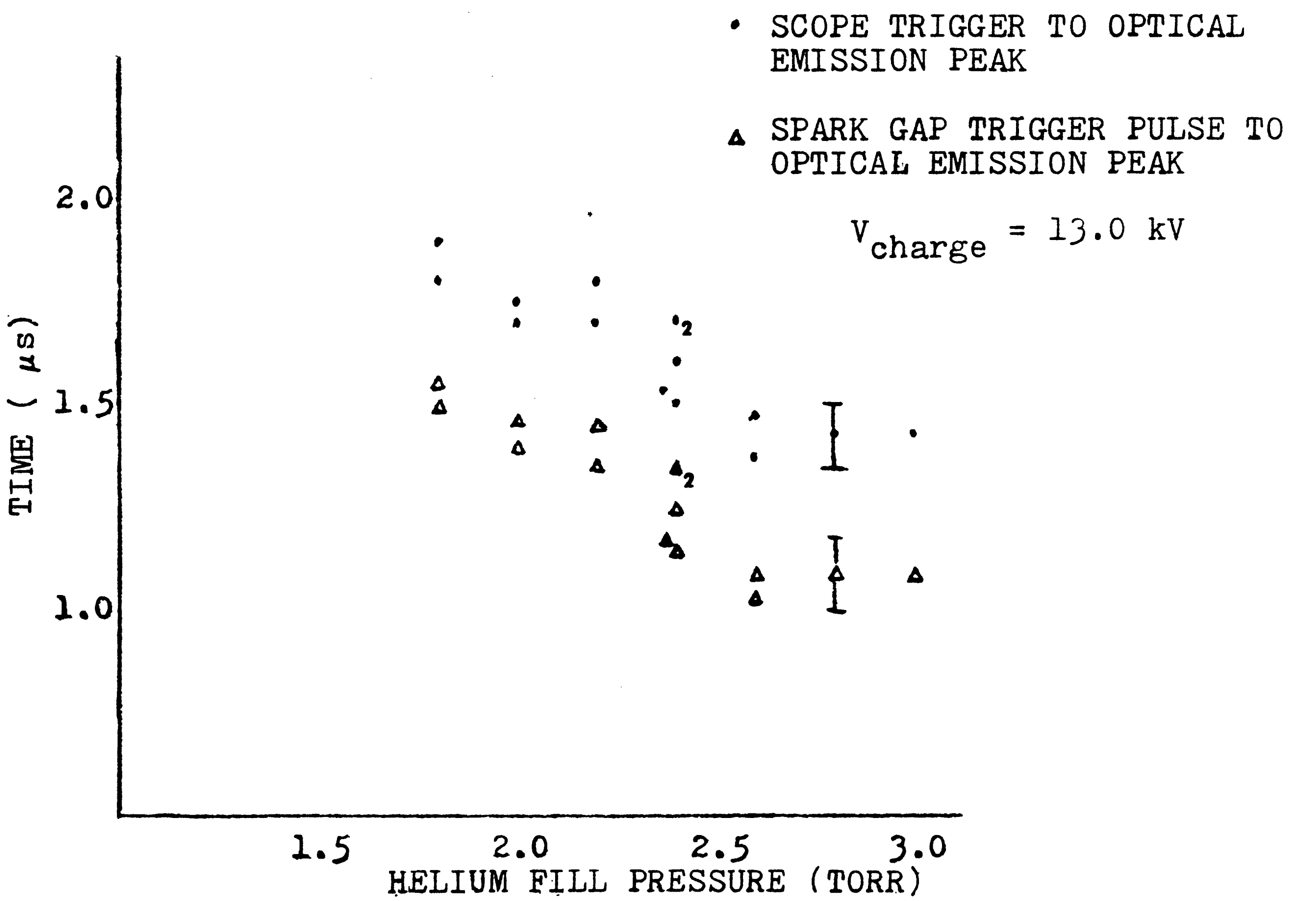


Figure 8. Timing Results for PIN Diode for V_{charge} = 13.0 kV

the plasma was changing, that the compression of the plasma was slower, and that probably the peak density was not as large as at lower pressures(3). As a result, the discharges were run primarily with a fill pressure of 2.4 to 2.8 Torr, and a charging voltage of 13.0 kV. As seen in Figure 7, there is more timing variation in the 12.5 kV results as a function of pressure, than the results shown in Figure 8, for 13.0 kV.

The principle observation that can be made from Figures 7 and 8, is that as the fill pressure is increased, the time between the trigger pulse and the occurence of the optical emission peak decreases. An examination of the Rogowski coil signal, as shown in Figure 9 for 13.0 kV and fill pressures between 1.2 and 3.0 Torr, shows the origin of the timing difference. As the fill pressure is increased, the time that it takes the helium fill gas to breakdown decreases, while the time between the current initiation and the signal maximum is fairly constant.

The reproducibility of the timing was evidenced as the reproducibility of the first optical emission peak, The results from several runs (over a period of 2 weeks) are shown in Figures 7 and 8, for the charging voltages of 12.5 kV and 13.0 kV. The graphs plot the time from the trigger pulse initiation and the scope trigger to the optical emission peak, as read from oscilloscope trace pictures. In these graphs, the typical long term jitter is now on the order of ±100 ns. A large portion of this variation is in judging the optical emission peak from the scope pictures. A larger error occurs in the time

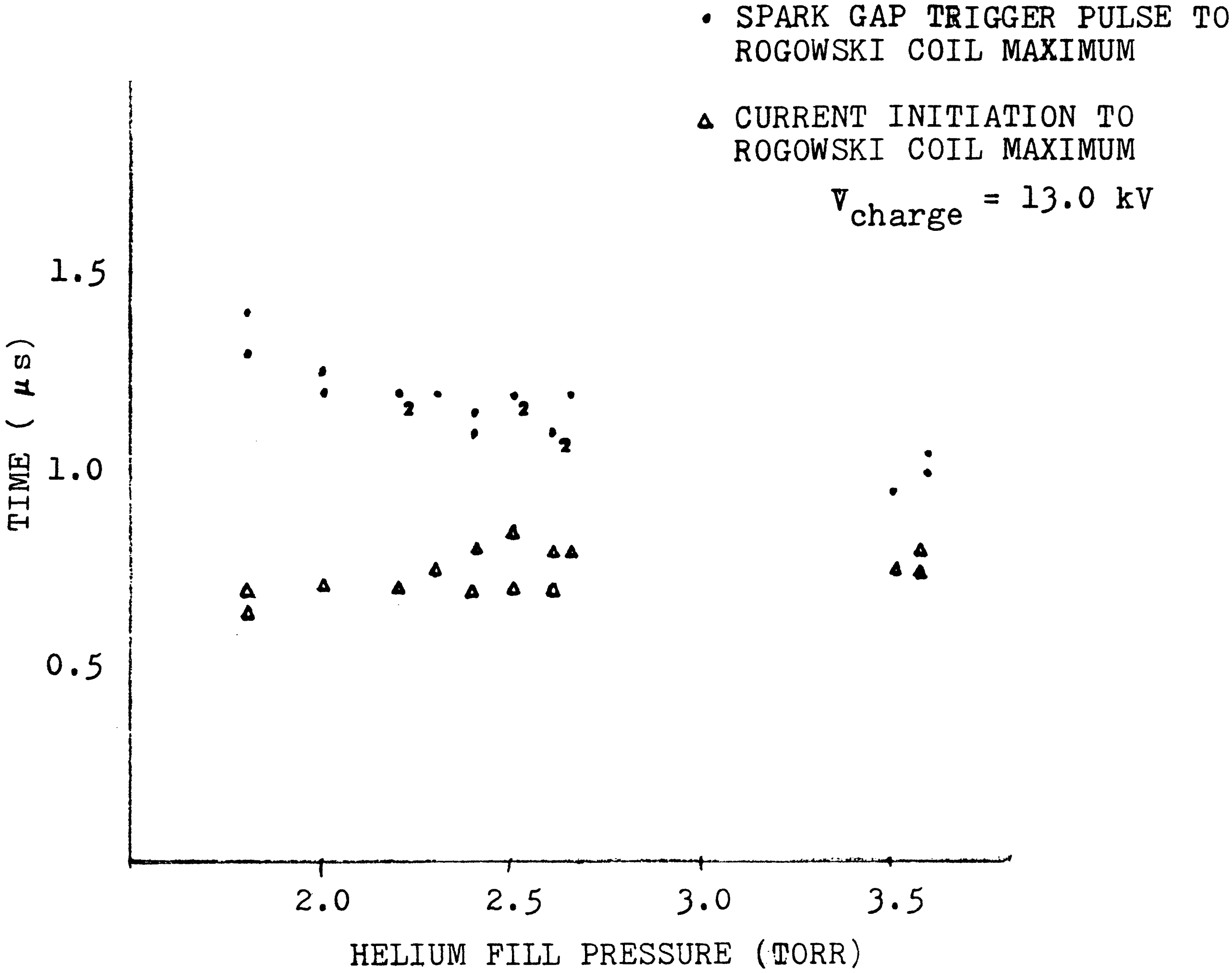


Figure 9. Timing Results of Rogowski Coil for V_{charge} = 13.0 kV.

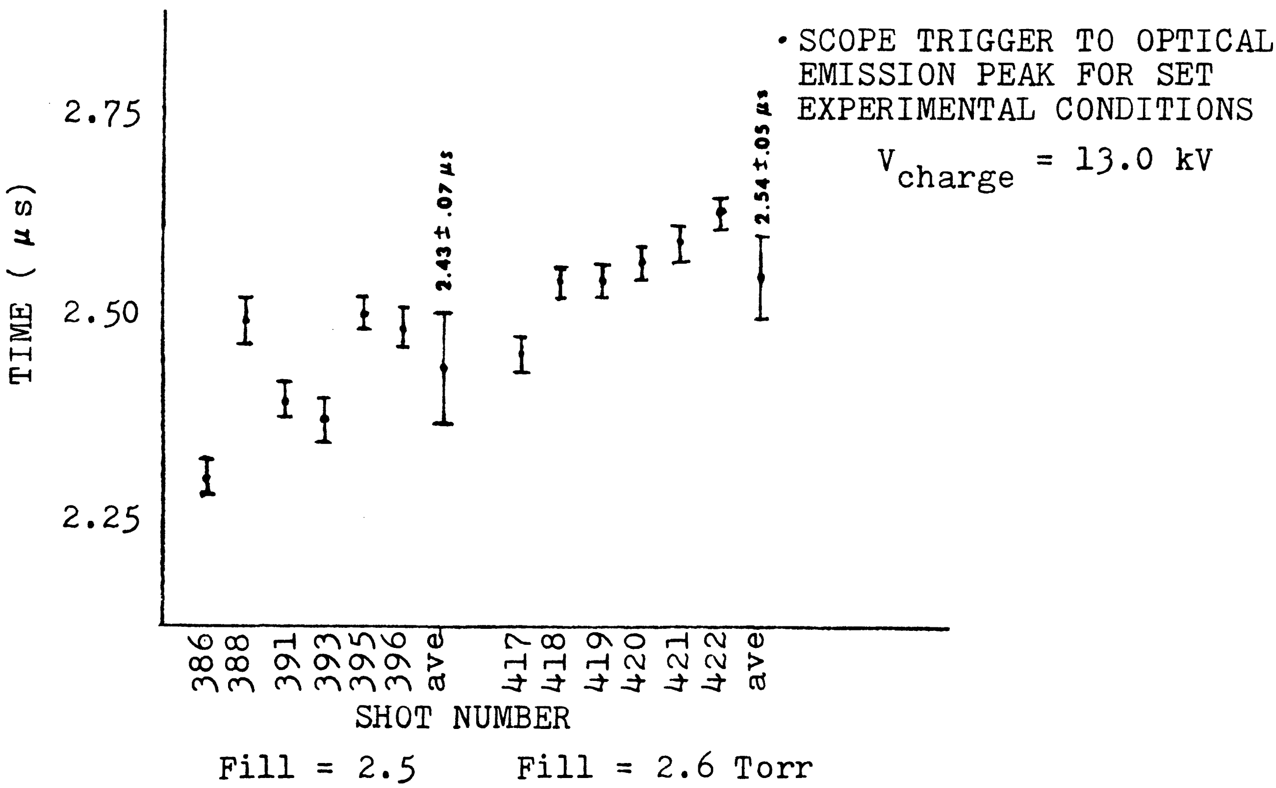


Figure 10. Time Measurements for Optical Emission Peak for Set Experimental Conditions.

measurements from the spark gap trigger pulse to the optical emission peak. This is because the time of the trigger pulse is decided by a burst of noise in the various signal cables. In this case, those measurements may have an error that is larger than ±100 ns.

It is more useful to show the optical peak jitter over one day's run, for set experimental conditions. In Figure 10, the occurrence of the optical peak is plotted for consecutive shots. In this particular mode, the occurrence of the trigger pulse (as evidenced by a burst of noise in the PIN diode signal) can not be seen, and only the time between the scope trigger and the optical peak is shown. In this case, the jitter is even lower, on the order of ±50 ns. The jitter in this case also includes the jitter in the pulse generator, which is used to trigger the scope. When timing is done for laser-plasma interactions, this pulse generator trigger jitter is also included in the laser firing, so that the overall jitter at set experimental conditions may be less.

VI. CONCLUSIONS

The reproducible firing of the Z-pinch discharge has been demonstrated. The improvements made in the system - the pressurized spark gap and the high voltage pulse transformer have reduced the timing jitter significantly. The results show that for set experimental conditions, the Z-pinch will have jitter on the order of ±50 ns or less.

The main observation to be made on the initial conditions of the Z-pinch is that the occurrence of the pinch is more stable as a function of pressure for a charging voltage of 13.0 kV. There is a fairly wide range over which the Z-pinch will function properly, with the range of initial conditons between 2.4 and 2.8 Torr and a charging voltage of 13.0 kV giving the most reproducible timing results.

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