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INVESTIGATION OF A LASER TRIGGERED SPARK GAP

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FOREWORD

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This report was based upon portions of an M. S. thesis submitted by 1/Lt Winston K. Pendleton to the Graduate Engineering School of the Air Force Institute of Technology in August 1964. The paper was presented in part at an American Nuclear Society Meeting in April 1964 at Ann Arbor, Michigan.

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This technical report has been reviewed and approved.

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ABSTRACT

The influence of parameters affecting the laser triggering of a high-voltage electrical sphere-sphere gap has been experimentally investigated. Of primary interest was the delay time between arrival of the laser pulse and current flow across the gap. This delay was studied as a function of total laser beam power (0-80 MW); dielectric gas (SF_6,N_2,air); gas pressure (100-1400 Torr); electrode spacing (0.4-1.5 cm); gap electric field (10-100kV/cm); and focus point location between two 5 cm diam stainless steel spheres. Delay times less than 10 nsec were observed in SF_6 at atmospheric pressure with corresponding low jitter. For the cases studied delay times varied inversely with the electric field, gas pressure, and focus point distance from the anode surface. Above a certain laser beam power the delay time was not a significant function of laser power for the range studied. Applications of laser triggering are discussed with a description of current and future research areas.

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ILLUSTRATIONS

SECTION I

INTRODUCTION

Spark gap conduction initiated by a Q-spoiled laser was first demonstrated by Guenther and Griffin in July, 1963. The investigation of laser triggering of spark gaps was prompted by the requirements for switching extremely high voltage, ultrafast pulsed power systems used to simulate aspects of nuclear detonations in the laboratory. The requirements for an inherently safe, simple, high current, high voltage switch which exhibited nanosecond timing with less than one nanosecond jitter and long life necessitated a novel switching technique. Consequently an experimental research program was conducted to determine the best operating conditions and parameters influencing the delay time between arrival of the laser output and gap conduction.

The results obtained indicate the feasibility of realizing the aforementioned rigorous switching requirements and provide useful data for understanding the mechanism for initiation of current flow across undervoltaged electrical gaps (charged gaps whose electrical field is insufficient to undergo self-breakdown).

An outstanding feature of laser triggering is the absence of electrical coupling between the high gap voltages and the triggering circuit, thereby affording a very safe mode of operation. The technique offers the additional capability for splitting the optical beam to irradiate many parallel gaps where a high degree of switch synchronization is required such as in Blumlein or other field-reversal energy storage systems. The multiple-gap technique has been frequently utilized for reducing both electrode wear and the switch inductance which is occasionally high if only a single gap is employed. One may attempt to reduce the total inductance so as to decrease risetimes of the discharging current. While the speed of the discharging circuit may be increased by reducing the inductance contributed by the gaps it is often offset by inability to initiate all gaps within a sufficiently small time interval, resulting again in undesirably long risetimes.

SECTION II

THEORY

Several previous studies together with inherent laser characteristics indicated the high probability of using lasers successfully as a triggering mechanism. First, visible ionization of gases with focused lasers had been observed and measurements were obtained indicating the production of numerous free electrons.[1] Secondly, in view of the coherence and polarization of the laser beam localized ac electric fields in excess of 10^7 V/cm can be produced at the focal point of a lens.[2] This can be compared to the self-breakdown of an air gap by a dc electric field of $3X10^4$ V/cm (corresponding to the field required for breakdown of an air gap of 5 cm spheres with a spacing of 1 cm at atmospheric pressure). For the 80 MW laser used in these experiments, the power density at the focal point of a 50 mm lens would be on the order of 10^{10} W/cm yielding an ac field of approximately 10^6 V/cm.

The accuracy in timing offered by either rotating mirror or Kerr cell Q-spoiling techniques leads to confidence in the ability to predetermine arrival time of the laser pulse at the gap. It then becomes necessary to determine the delay between arrival of the pulse and initiation of current flow.

While it was not the primary concern of this study to determine the mechanism of laser induced breakdown, it is of interest to summarize the currently proposed model. Inverse bremsstrahlung mentioned by Meyerand and Haught[3] and analyzed extensively by Wright[4] predicts transfer of sufficient photon energy from the laser beam to bound electrons resulting in an exponential growth of the free electron population during the pulse. Since the time for production of electrons by inverse bremsstrahlung is negligible, the statistical time lag,[5] which is of considerable import in the time delay of gap breakdown by overvolting, is relegated to an extremely minor role in the over-all delay. A method of assessing the extent of the contribution of the time lag to the total delay will be discussed later. Numerous workers have performed both experimental and theoretical studies on laser induced breakdown of gases and the reader is encouraged to familiarize himself with their findings.[6-10]

When a laser beam is actually focused on one of the electrodes, it may be necessary to propose a different breakdown mechanism. One such mechanism, proposed by Cobb and Muray,[11] is thermionic emission of electrons from the electrode surface. However, one cannot overlook the observed blowoff of gaseous products from a surface irradiated by a focused laser. These gases would similarly interact with the laser energy as indicated in the previous paragraph. These ejected gases may be composed of electrode material, absorbed dielectric, etc.

A theoretical description of the entire arc formation is certainly not close at hand. The fact that laser triggering becomes easier at higher pressures is one indication of possible discrepancies between normally accepted breakdown mechanisms for overvolted gaps as opposed to the gap behavior encountered here.

In this study, at the powers indicated, no visible breakdown was observed using a 50 mm lens at a pressure of 600 Torr air in the absence of an applied dc electric field. Therefore, this initiation of the discharge, when the laser was focused between electrodes, is probably due to localized field distortion, a mechanism frequently utilized to trigger spark gaps, or local overvolting condition, which is perhaps the most rapid of breakdown initiation techniques. This latter technique is usually limited by the risetime of the high voltage pulse applied. If this is, in fact, the mechanism on which laser triggering operates, we then are fortunate to have a very rapid rising voltage pulse produced by focused Q-spoiled lasers in the <10 nsec pulse widths obtainable.

SECTION III

EXPERIMENTAL

Figure 1 is a diagram of the experimental arrangement with all the major operational and ancillary diagnostic components. To the left of the diagram is the laser system, a Korad Corporation K1Q device, the components of which taken in order are a rear 100% flat reflector, Kerr cell Q-spoiler, polarizer, helical flashtube surrounding a 0.95 cm diam by 9.2 cm long, 0.05% Cr ruby rod, 40% reflecting dielectric mirror to complete the cavity, and necessary power supplies and control equipment. Normal output produces a single symmetric pulse of approximately 0.8 J energy and a half-intensity width of 10 nsec.

The pulse was emitted toward the right and focused between the two 5 cm diam, stainless steel electrodes by a 50 mm lens. These components remained unchanged throughout the experiments. The focal point was always located along a line intersecting the centers of the two spheres. Since gap spacing was kept less than 1.5 cm, a well-defined gap was formed affording an essentially uniform field.*

About 8% of the beam was deflected into a calibrated planar ITT photodiode and the signal displayed on a fast risetime Tektronix 519 oscilloscope. An oscillogram of the trace supplied the laser energy and power information for each pulse. Since the photodiode cathode is not of uniform sensitivity, this is not a completely acceptable technique for power and energy measurements. However, it was sufficient for the purposes here since, as is shown later, the absolute value of the power, if great enough, did not affect the delay time.

As the first oscilloscope was triggered it initiated the sweep of a neighboring ›scope which monitored the sphere gap current via a cable and di/dt sensing coil. The ›scopes were synchronized by simultaneously injecting a pulse into the diode and di/dt cables and adjusting the internal ›scope delays so that each signal was displayed at time "zero." During an experimental run the time delay between arrival at the diode and gap breakdown would result in a di/dt signal displayed at some time during the ›scope sweep. This delayed signal as measured

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*See Ref. 5, pp. 299, 305-315, and Chap. VII.

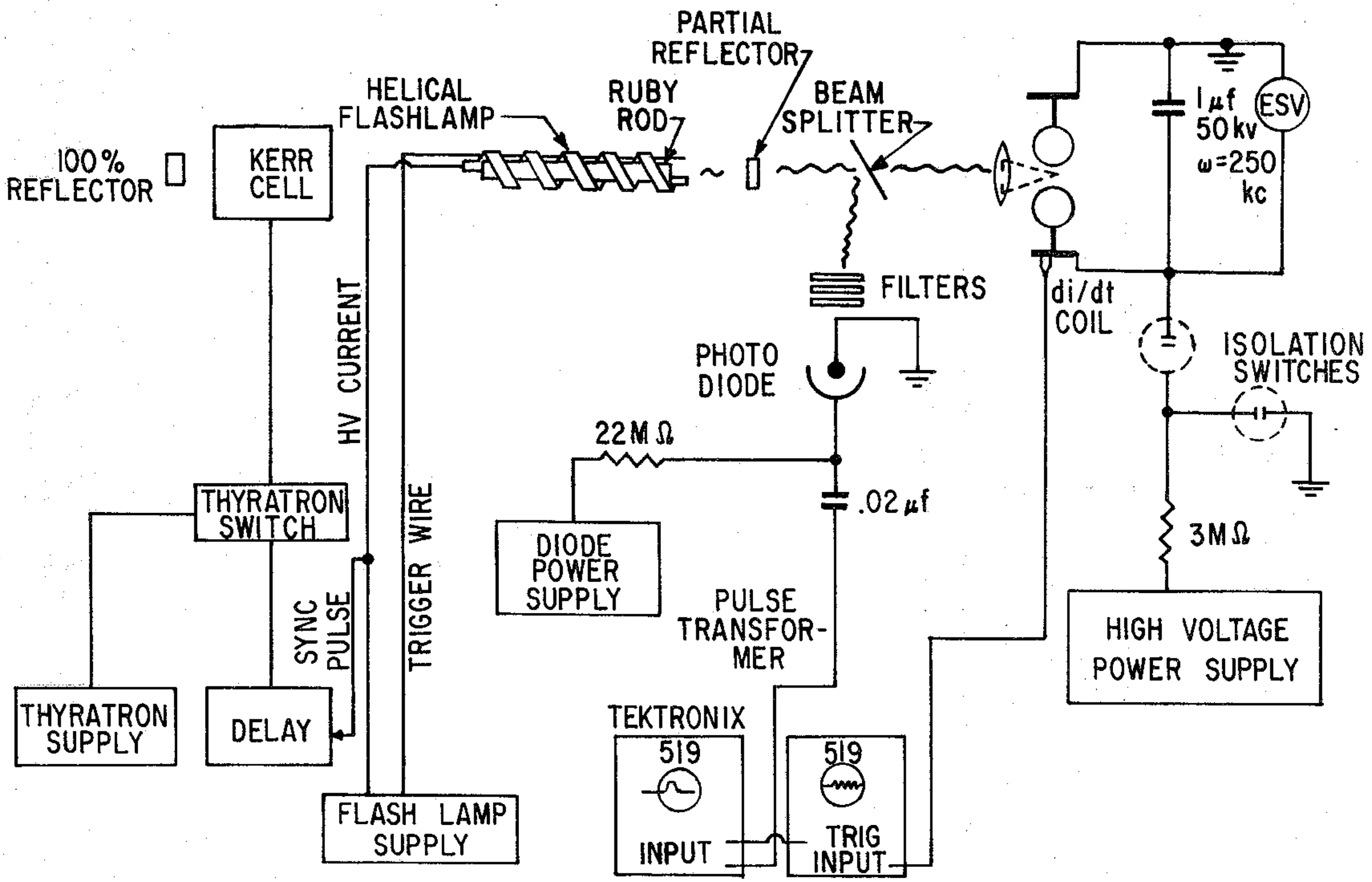

Figure 1. Schematic Depicting Experimental Arrangement for Measuring ΔT_D (nsec) All Important Components are Shown.

on the oscillogram was corrected for diode to gap laser flight time and the result called response time ΔT_D or the time delay between laser arrival at the gap start of current flow. This was the fundamental measurement used to describe the triggering phenomenon under varying conditions. This time delay could be determined to within 5% of the true value. The delay time (<10 nsec) present in the photodiode was not corrected for in the measurements reported on in the next section.

The time delay was correlated with the following parameters with their estimated uncertainties: laser power from 0-80 MW, ~15%; gas pressure from 100-1400 Torr, ~10%; electrode spacing 0.4-1.5 cm, ~5%; gap electric field 10-100 kV/cm, ~5%; laser focus point distance from cathode surface d_n over the range 0-0.335 cm, ~3%; and finally, laser polarization parallel and perpendicular to the gap field. Measurements were performed using SF_6, N_2, and air as the dielectric gas.

SECTION IV

RESULTS

The first study was the variation of ΔT_D as a function of laser power with all other conditions, i.e., gas pressure, electric field, focal point location, etc., held constant. Figure 2 shows the results at low powers and indicates a definite threshold of about 4 MW below which the gap was not triggerable. From this point the delay time decreases with increasing power until about 6 MW when the delay time became fairly independent of the power for a specific E_g/p (gap electric field/gas dielectric pressure) value. This behavior can be seen in Fig. 3 out to the maximum laser power of 80 MW. These beam qualities were not sufficient to cause visible breakdown with a 50 mm lens at a pressure of approximately 600 Torr in air with no field applied. Of course, with an improved laser (brightness) that may produce a spark at a focus of a lens, delays would be shortened still further from those measured here. The only measurements of time delay as a function of incident laser power known to date are those of Tomlinson. These measurements were made in an essentially zero dc electric field at low powers where the time delay is changing rapidly with laser power.

A more meaningful approach is to relate delay time with a standard ratio often used in breakdown studies, i.e., E_g/p. Figure 4 shows the strong dependence of delay upon E_g/p for SF_6. As the electric field is increased toward self-breakdown the delay times shorten. The lowest value observed was estimated to be less than 10 nsec. Figure 5 is a similar plot with N2 as the fill gas. The results are plotted with pressure as the constant parameter. The behavior is similar to SF_6 but the delay times are not as short near the self-breakdown point (short vertical line to the right of each curve). An essentially identical curve is obtained for air as the dielectric medium.

Figure 6 shows an interesting delay dependence upon laser focal point location in the gap. The parameter d_n is defined as the distance from the cathode surface to the laser focal point. Three values of d_n are shown: 0.000, 0.250, and 0.335 cm. The shapes of the ΔT_D vs E_g/p curves are similar but the delay times are considerably shortened as d_n is reduced. The case of d_n=0.000 cm with the laser beam actually irradiating the cathode surface gave the shortest delays for a given E_g/p. In fact, delays were so short (<10 nsec) at the higher E_g/p

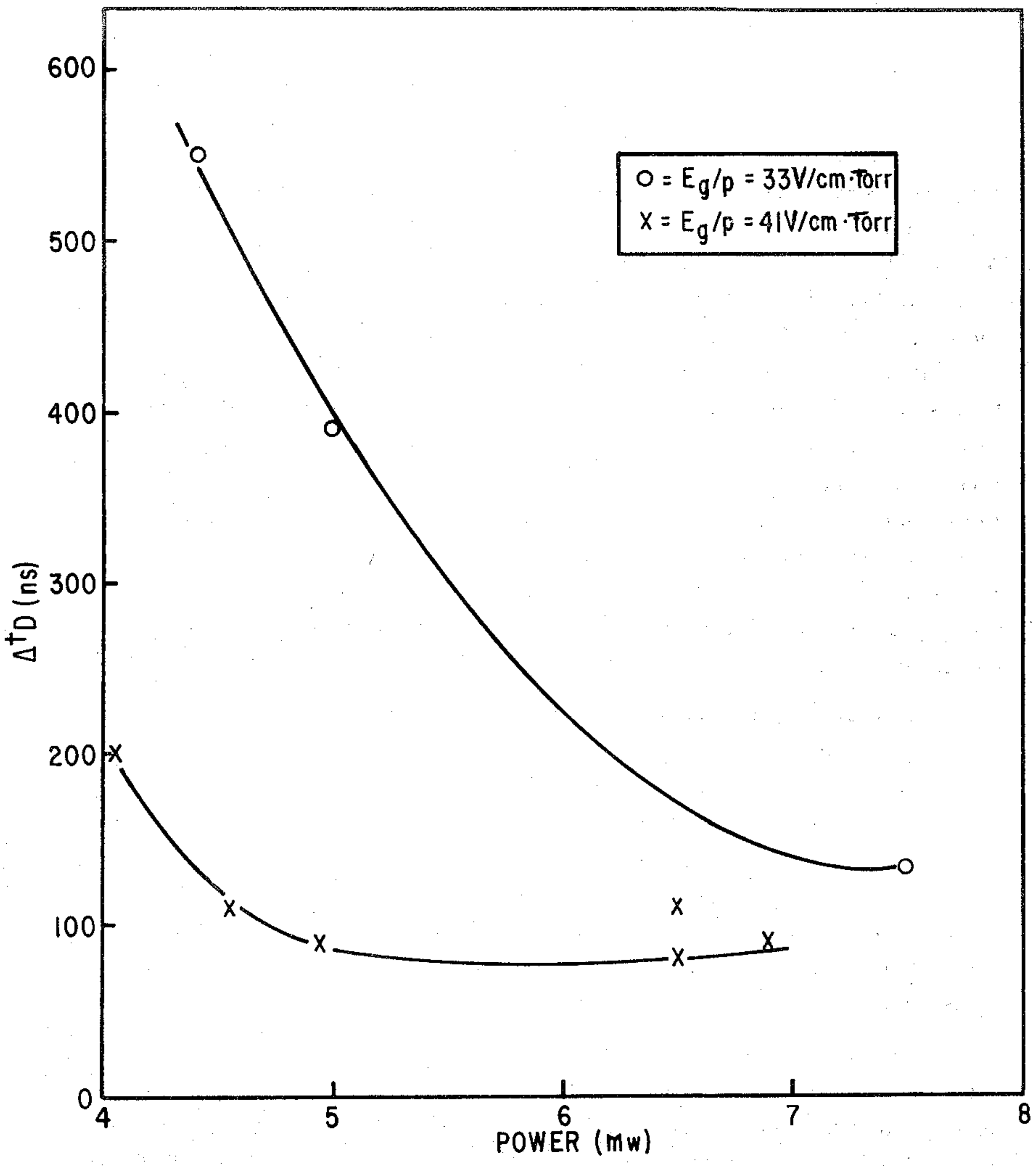

Figure 2. Plot of ΔT_D (nsec) vs Laser Power (MW) Indicating Large Variations of Delay Time at Low Powers.

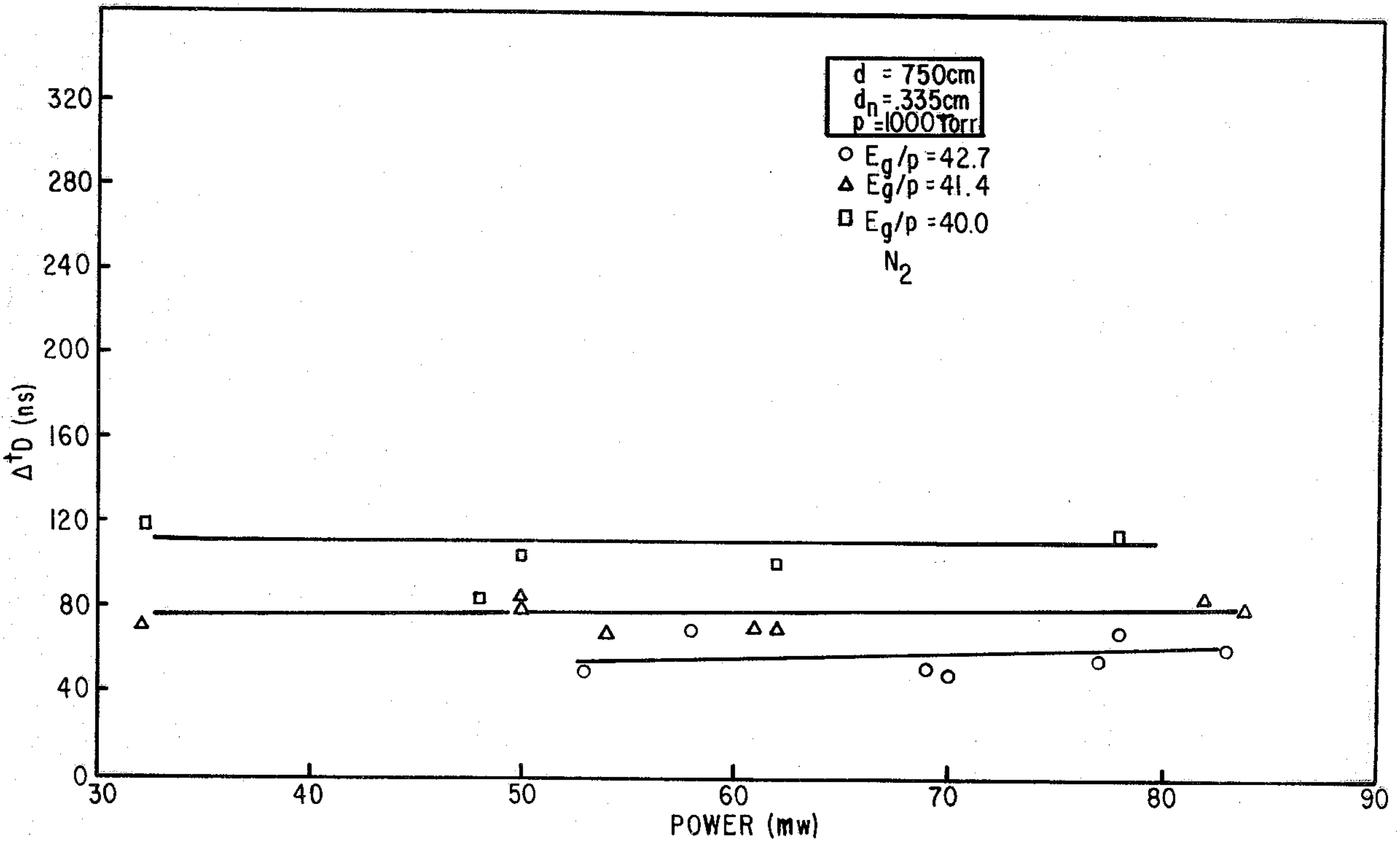

Figure 3. Plot of ΔT_D (nsec) vs Laser Power (MW) Indicating the Essentially Constant Delay Obtained Above Some Minimum Laser Power.

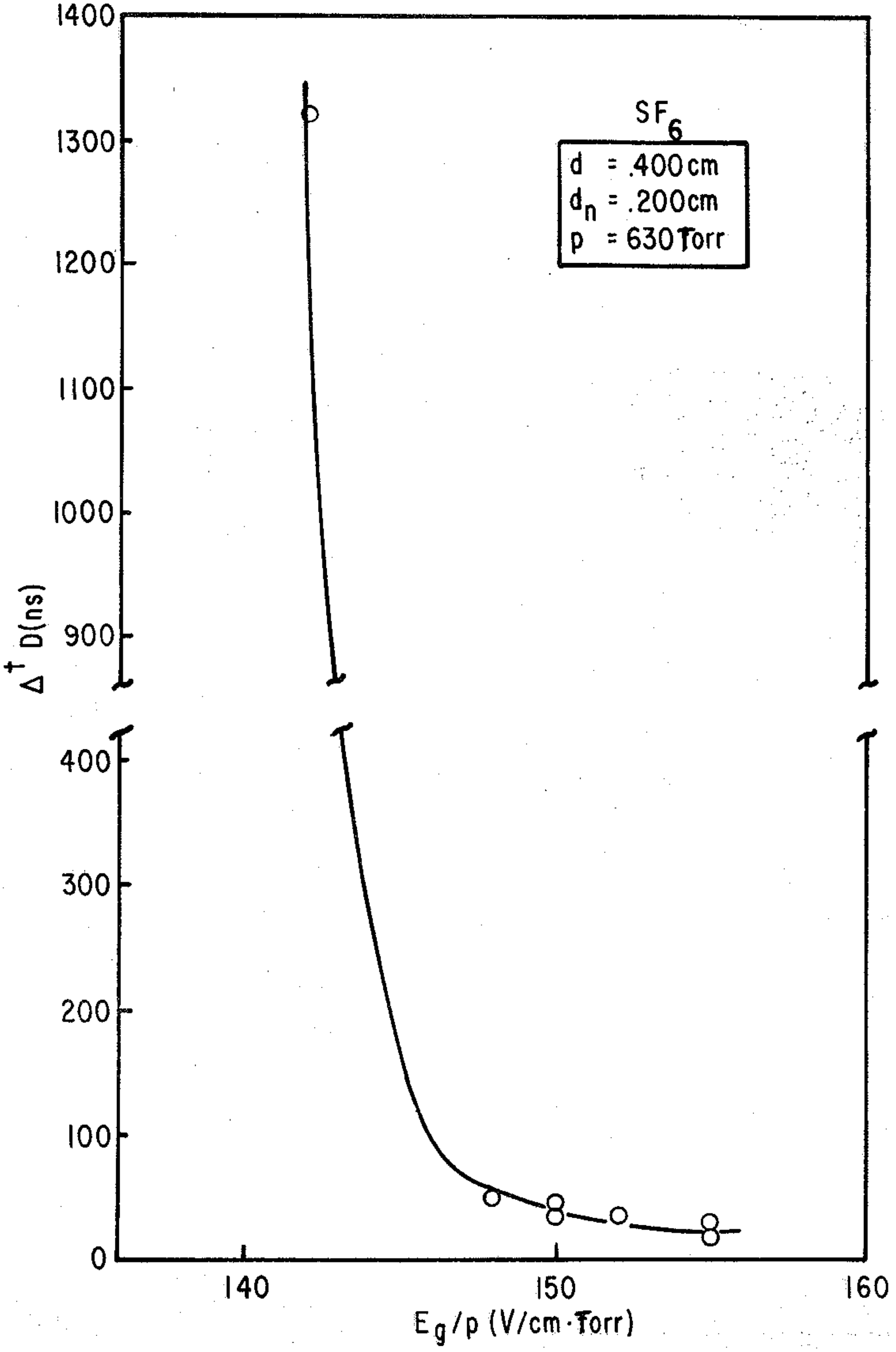

Figure 4. Plot of ΔT_D (nsec) vs E_g/p (V/cm-Torr) for SF_6 Indicating the Strong Dependence of Delay Time Upon E_g/p.

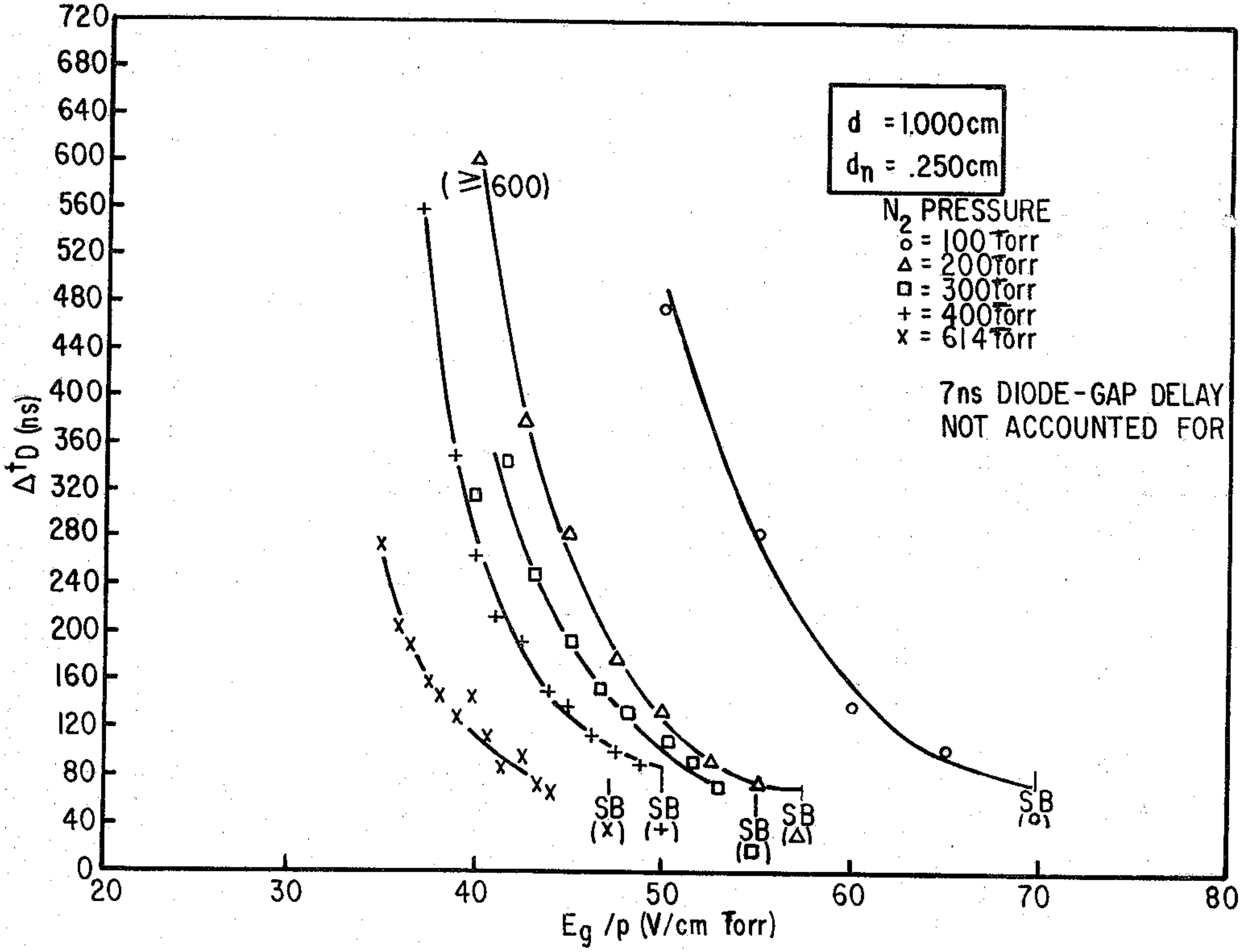

Figure 5. Plot of ΔT_D (nsec) vs E_g/p (V/cm-Torr) for Nitrogen Indicating the Pressure Dependence of Delay Times. SB Indicates Self-Breakdown Point.

values near self-breakdown that they could not be accurately measured. Current research is underway to establish the delay time variations as a function of d_n over the entire range from cathode to anode.

To test the effect of laser beam polarization with respect to the dc gap field, two runs were made, one with the laser field parallel to the gap field and one with the laser field perpendicular to the gap field. As indicated by Fig. 7, no polarization effect is clearly demonstrated under the conditions present. This is to be expected, since the electric field produced by the focused laser beam is orders of magnitude greater than the static field presented by the gap, therefore making it difficult to establish existence of any synergistic or polarization effects. Similar results were obtained when a quartz-jacketed high pressure mercury lamp illuminated the gap during triggering. A more intense source of uv would give conclusive evidence for or against the existence of a statistical time lag component to the total delay.

Figure 8 is a convenient way of plotting switch data. The vertical axis is the gap potential V_g and the horizontal axis is the product pd, gas pressure p times electrode spacing d. The top curve is the Paschen limit relating self-breakdown potential as a function of pd. Any point below this line is an undervoltaged gap and will sustain the voltage. Each of the three lower curves represents the threshold voltages V_T (lowest triggerable gap potential, kV) for which the gap was triggerable for a given focus location. The results clearly show that the triggering region below self-breakdown is a function of d_n. The largest region triggerable is for the case d_n=0.000 cm when the laser actually irradiated the cathode surface. The gap was triggerable when charged 70% below self-breakdown under these conditions.

Figure 9 is similar to Fig. 8 but shows the triggering range for a constant d_n and two values of gap spacing d. There is no apparent difference between a 0.5 and 1.0 cm gap at the same E_g/p value.

A test of reproducibility or jitter was made by measuring the delay times on a series of identical shots with all parameters held constant. For ten shots a mean delay of 70 nsec was determined with a standard deviation of ±5.4 nsec or an uncertainty of about 7%. Under different gap conditions a series of again 10 runs exhibited a 40 nsec mean time delay and the jitter dropped from 5.4 to 4.2 nsec. With better control over the operating parameters and higher power less jitter is to be expected.

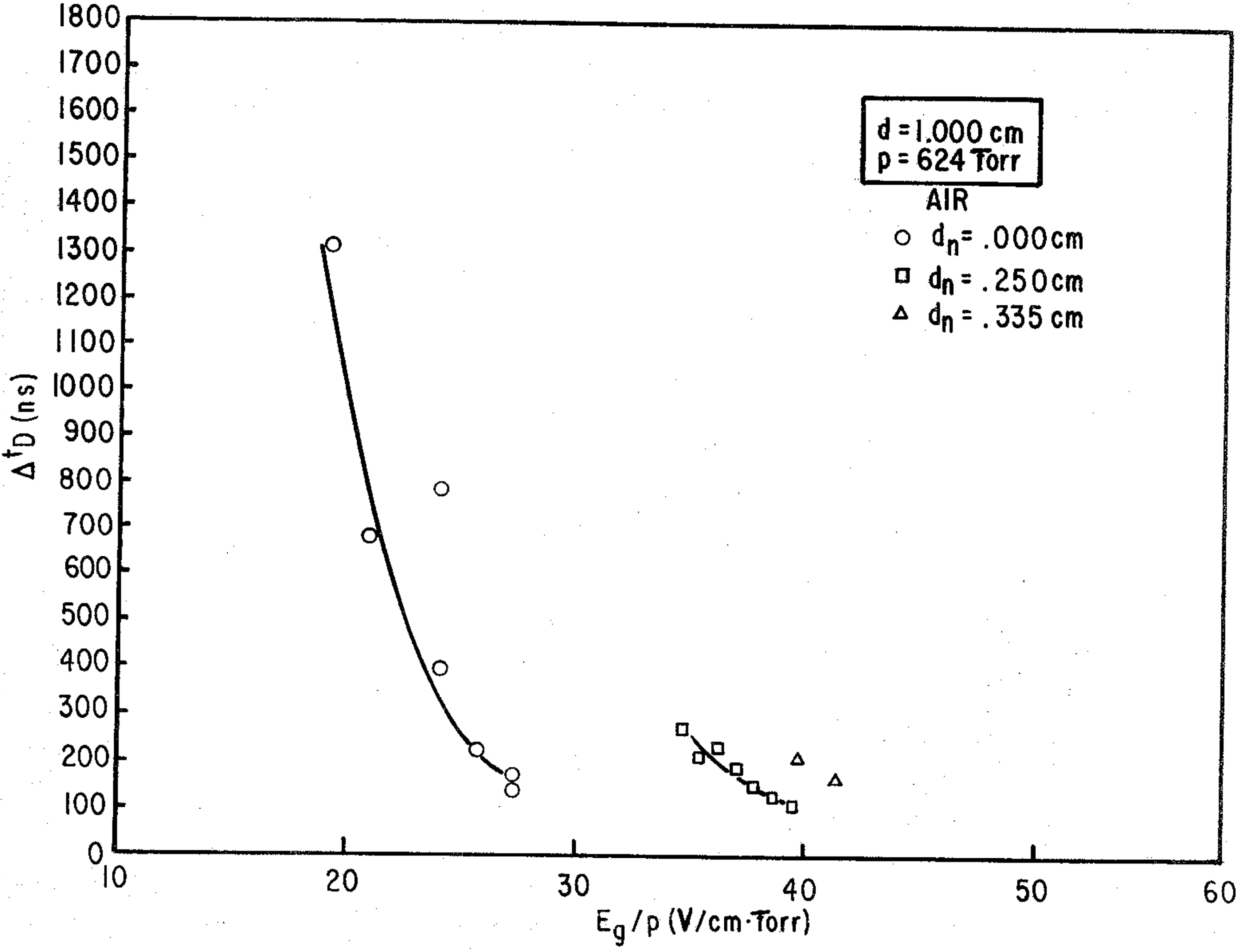

Figure 6. Plot of ΔT_D (nsec) vs E_g/p (V/cm-Torr) for Air Depicting the Dependence of Time Delay on Laser Focal Point Location in the Gap. The Curves are of Similar Shape, but Delay Times are Considerably Shortened as the Focal Point is Moved Toward the Cathode.

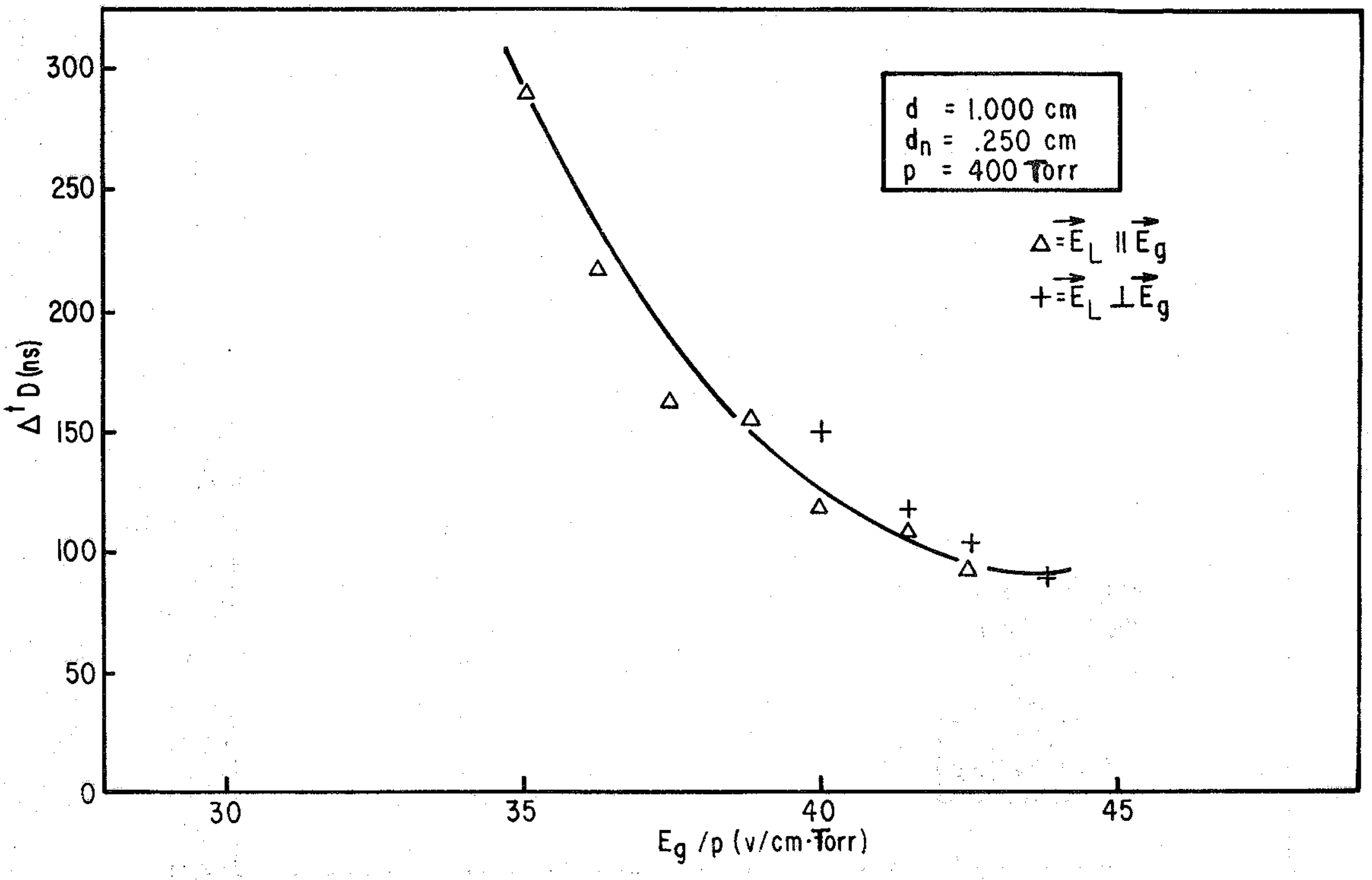

Figure 7. Plot of ΔT_D (nsec) vs E_g/p (V/cm-Torr) Indicating the Lack of the Planes of Polarization of the Laser Irradiation on Delay Times.

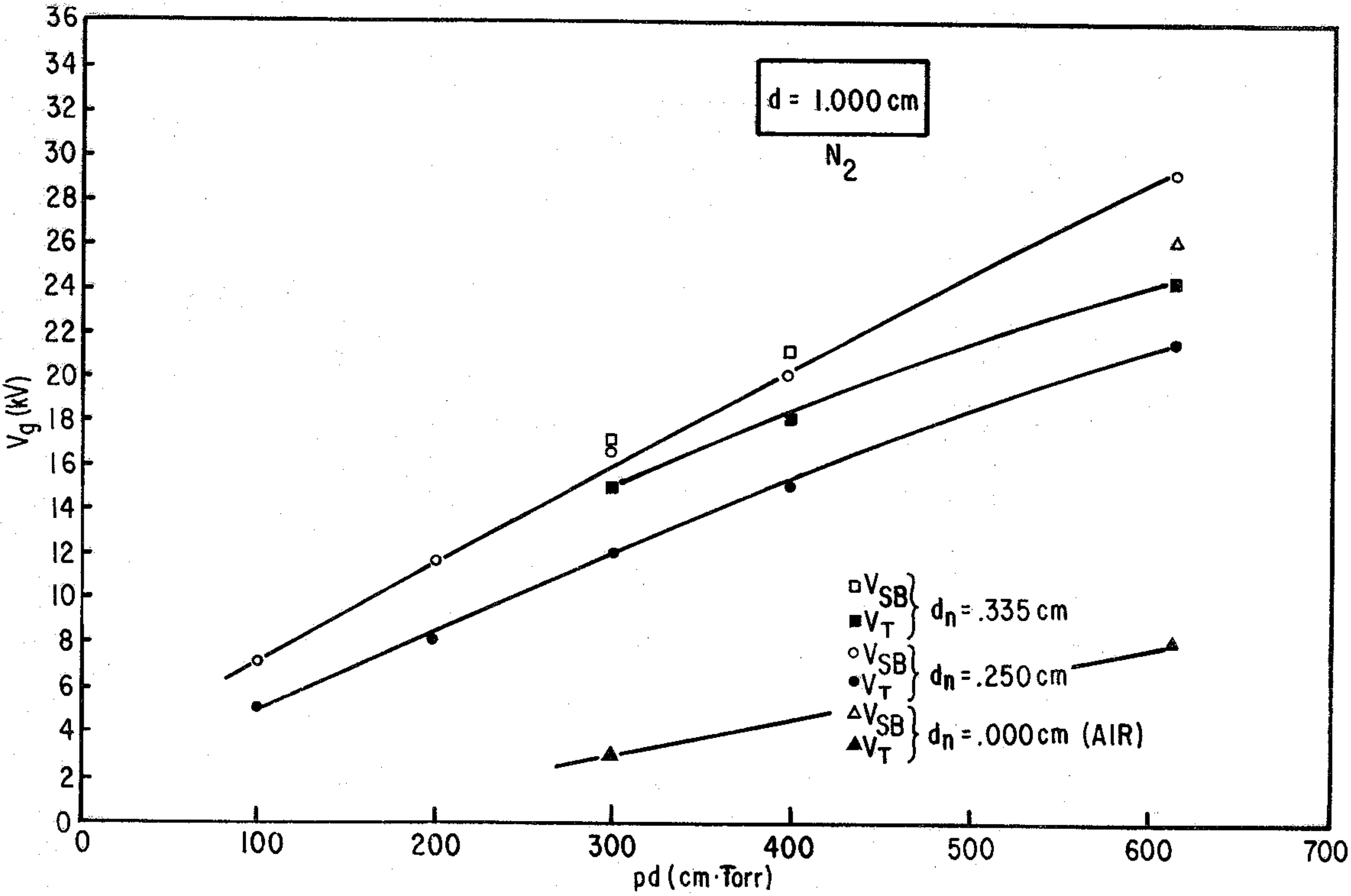

Figure 8. Plot of V_g (kV) vs pd (cm-Torr) Indicating the Range of Triggerability for Various Focal Point Locations.

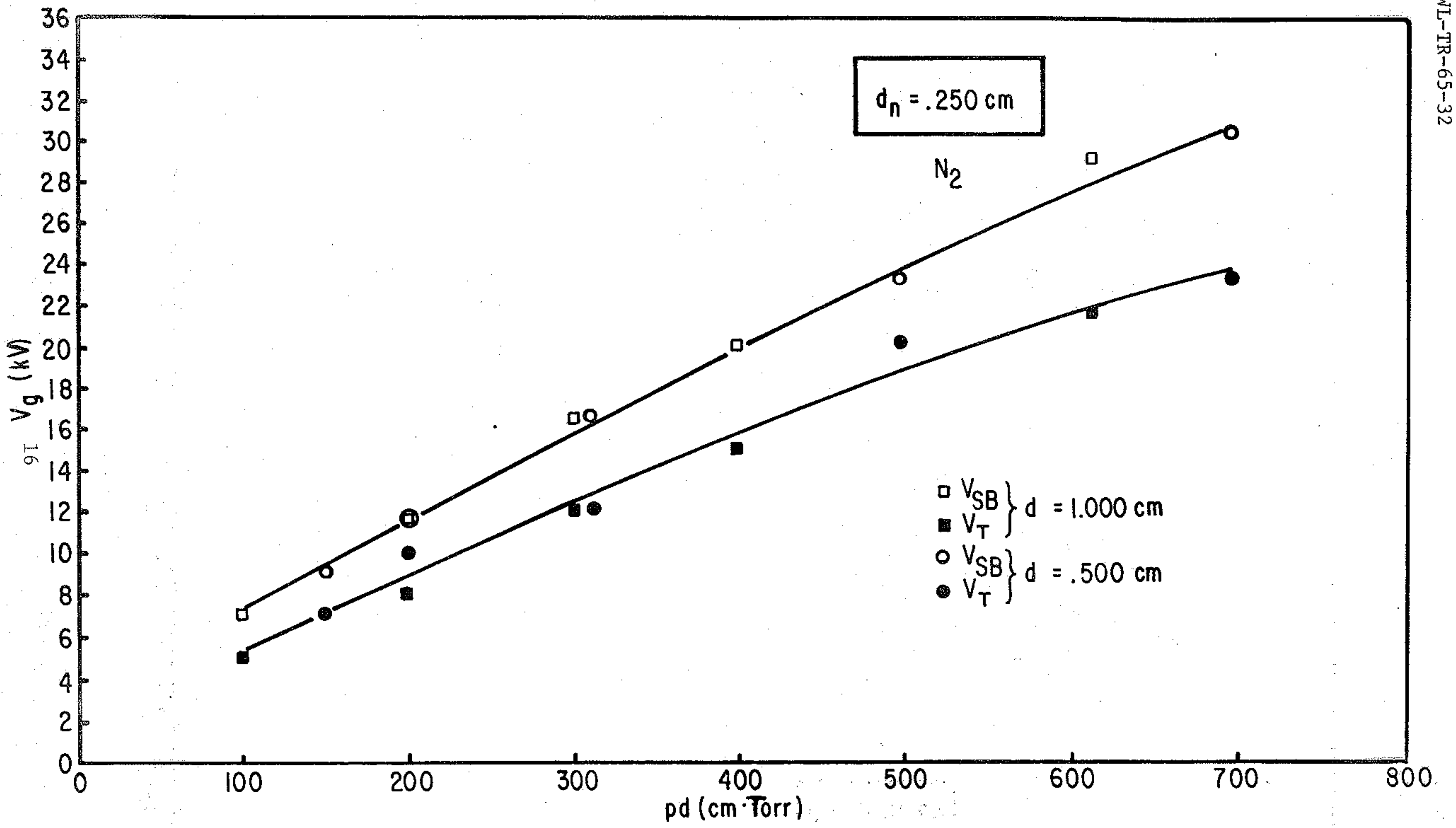

Figure 9. Plot of V_g (kV) vs pd (cm-Torr) Indicating the Triggering Range for a Constant Focal Point Location with Two Different Gap Spacings at Equal E_g/p Values.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The results obtained in this investigation have demonstrated the applicability of laser triggering of a spark gap as a low jitter, short response time, switching technique. The advantages of this switching technique are numerous. The optical coupling to close the switch means that the triggering system is electrically isolated, affording an inherently safe operation. The switching times and reliability make laser switching especially suited to ultrafast energy discharge devices. The power independence of the response time means that a single laser beam could be divided into many beams each capable of triggering a different gap or being focused to different locations in the same gap for the added feature of breaking down long gaps. Unlike many normal triggering schemes where the breakdown is facilitated by a decrease in the pressure, it has been shown that triggering is easier at higher pressures, which in itself is another safety feature that cannot be overlooked.

Much is yet to be done to fully appreciate the usefulness of this technique. From the results presented here natural extensions are obvious. The laser power dependence should be extended as higher powered lasers become available. Higher gas pressure in the gap along with higher electric fields might substantially lower the response time to the subnanosecond region. A study of the behavior at low pressures is indicated as a possible method to gain insight on high vacuum breakdown mechanisms.

The use of solid and liquid dielectrics between the electrodes would introduce a whole new pattern of behavior, probably leading to very low inductance geometries for the switch where the laser beam is directed along the electric field lines. This immediately suggests the possibility of accelerating free electrons across the gap, probably leading to very short closure times.

In addition to research directed toward switch development, the procedures and techniques used in this investigation are well suited to basic studies of the arc discharge mechanism. It is hoped that other researchers will expand on the work begun here. We are presently pursuing research along the aforementioned lines and results will be reported in the near future.

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