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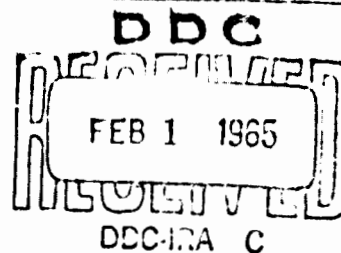
INVESTIGATION OF THE MECHANISMS ASSOCIATED WITH GAS BREAKDOWN UNDER INTENSE OPTICAL ILLUMINATION

PREPARED BY
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SEMI-ANNUAL REPORT
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Report C-920272-2

Semiannual Report Under Contract Nonr-4696(00)
for the Period August 31, 1964, through December 31, 1964

Research Investigation of the Mechanisms Associated with
Gas Breakdown Under Intense Optical Illumination

ARPA Order No. 306, Project Code No. 4730

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SUMMARY

The Research Laboratories of the United Aircraft Corporation are conducting under the subject contract an experimental and theoretical investigation of the physical mechanisms involved in the electrical breakdown of gases under intense optical illumination. Experimentally, the focused high-intensity optical frequency beam from a Q-spoiled laser is used to cause electrical breakdown in a test gas, and the ionization produced is examined as a function of gas pressure. These phenomena have been observed in a number of gases using both ruby and neodymium laser irradiation. Of the gases studied, breakdown in air required the highest field strengths, with lower field strengths required in helium and in argon.

Studies have also been conducted of the attenuation of the laser beam by the breakdown plasma. With either ruby or neodymium incident radiation, it is observed that more than half of the laser beam energy can be absorbed in the plasma produced by the breakdown and that over 90% attenuation of the laser beam can occur at later times in the optical pulse.

Preliminary measurements have been made of the effects of diffusion loss on the breakdown threshold by varying the focal volume within which the breakdown is formed. These data show that, in argon at atmospheric pressure, the breakdown threshold electric field strength is inversely related to the dimensions of the breakdown region; i.e., breakdown within small focus volumes requires a greater optical frequency electric field than is necessary with a larger focus region. This implies that, over the range of breakdown volumes studied, at atmospheric pressure diffusion losses play a significant role in the development of optical frequency breakdown.

INTRODUCTION

The interaction of extremely high-intensity optical frequency electromagnetic radiation with gas atoms has been accessible for experimental study only with recent development of high-powered lasers. Studies of gas breakdown by optical frequency radiation were initiated under Corporate sponsorship early in 1962. These Corporate sponsored investigations demonstrated that breakdown at optical frequencies occurs in many gases at field strengths which can be easily achieved by optical lasers. A pulsed ruby laser was used in these studies, and the optical field strength required for breakdown was investigated as a function of gas pressure in argon and helium. It was determined that field strengths of the order of 10^7 volts per centimeter were required for breakdown and that electron densities greater than 10^{17} electrons per cm^3 were produced in the resulting breakdown plasma. Under the joint sponsorship of the Advanced Research Projects Agency, the Office of Naval Research, and the Department of Defense (Contract Nonr-4299(00)), gas breakdown studies in air were undertaken. The field strengths required for breakdown in air were larger even than those required for helium or argon, indicating that gases of a molecular nature possess energy loss mechanisms in addition to those characteristic of monatomic gases. It was also observed that a significant attenuation of the optical beam, in many cases exceeding 50%, may be produced by the breakdown plasma formed. Direct electron stripping of electrons from atoms, single or multiple photon absorption, Compton collisions, or conventional microwave breakdown theory do not adequately account for the breakdown phenomena observed, and it is believed that the quantum mechanical process of inverse Bremsstrahlung is the mechanism responsible for breakdown at optical frequencies. These results have been reported in the Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, France, July 8-13, 1963; Physical Review Letters, Vol. 11, No. 9, November 1963; Physical Review Letters, Vol. 13, No. 1, July 1964; and the Final Report C-920088-2, under Office of Naval Research Contract Nonr-4299(00).

Under the present subject contract, further studies of the threshold electric field strength required for breakdown as a function of pressure in different gases, the effect of spot size on threshold field strength, the frequency dependence of the breakdown threshold, and the attenuation of the laser radiation by the breakdown plasma are being conducted to more fully define the nature of the breakdown mechanisms at optical frequencies.

DISCUSSION OF RESEARCH PROGRAM AND RESULTS

Frequency Dependence of Breakdown Threshold

During this report period, experimental studies of gas breakdown have been carried out using the visible ($.69\mu$) and infrared (1.06μ) radiation from high-intensity, Q-spoiled ruby and neodymium lasers, respectively. Breakdown at these frequencies has been obtained in air, argon, and helium over a range of pressures from atmospheric pressure to 2000 psi. With either ruby or neodymium laser irradiation, argon is the most easily ionized with helium and air, in that order, progressively more difficult.

Two Q-spoiled laser systems have been used in these gas breakdown experiments. The two laser systems each have the configuration shown in Fig. 1. In the ruby system, the laser element is a $\frac{1}{2}$ -inch diameter, 6-inch long ruby rod, while the neodymium laser employs a $\frac{3}{4}$ -inch diameter, 12-inch long rod. In each system the laser rod is pumped by four E. G. & G. xenon flash lamps, each lamp individually powered by a 1200μ F capacitor bank. A polarizer-Kerr cell shutter is used to alter the Q of the laser cavity, resulting in a single giant pulse of optical radiation from the laser. The giant pulse emitted by the laser is incident on a lens which forms one window of a cell containing the test gas. At the focus of the lens, breakdown of the test gas by the focused laser beam is observed for suitable conditions of beam energy and gas pressure. As shown in Fig. 1, a photomultiplier and calorimeter are used to observe a known fraction of the irradiating laser beam and monitor the laser output at all times. Both the photomultiplier and the calorimeter are calibrated with respect to the radiation which reaches the focusing lens and measure, respectively, the wave shape and beam energy for each pulse.

Measurements have been made of the breakdown threshold in argon and helium over the pressure range from atmospheric pressure to 500 psi using the giant pulse output from the ruby and neodymium laser systems. As in the ruby laser experiments carried out under Contract Nonr-4299(00), the breakdown threshold electric field for neodymium laser radiation is observed to decrease with pressure, varying approximately as $\frac{1}{\sqrt{P}}$. During the next period, these measurements will be extended to pressures up to 2000 psi. In addition, an absolute calibration of the 1.06μ data will be made and compared with the earlier $.6943\mu$ ruby results to determine the frequency dependence of the breakdown threshold.

Attenuation of Laser Beam by Breakdown Plasma

In the course of the gas breakdown studies carried out under Contract Nonr-4299(00), it was observed that when breakdown occurs the transmitted ruby laser radiation is severely attenuated during the later portions of

the laser optical pulse. Studies of this attenuation were carried out, and it was established that the energy removed from the optical beam was not scattered at the laser frequency or reradiated by excited atoms but instead was truly absorbed by the breakdown plasma.

Under the present contract, investigations have been made of the attenuation of 1.06μ neodymium laser radiation by the breakdown plasma using the apparatus shown in Fig. 2. As in the breakdown threshold experiments, photomultiplier A and the calorimeter are used to monitor the wave shape and beam energy of the laser radiation for each shot. A second photomultiplier (B) is used to record that portion of the incident radiation which is transmitted through the breakdown plasma formed at the focus of the lens. When no breakdown occurs; i.e., operating just below the threshold, the transmitted light has the same wave shape and intensity as the incident radiation. However, when breakdown does occur, the laser is significantly attenuated as shown by the lower trace in Fig. 3. These results parallel those observed previously with ruby irradiation and show that at incident powers slightly above the breakdown threshold of the argon test gas over one-half of the incident neodymium radiation can be absorbed by the breakdown plasma.

As observed in Fig. 3, during the later portions of the giant optical pulse, the attenuation of the incident radiation can exceed 90%; i.e., less than 10% of the incident radiation is transmitted through the breakdown plasma. To examine this attenuation at times subsequent to the incident giant laser pulse, preliminary studies have been made of the attenuation of $.6328\mu$ helium-neon laser radiation by the breakdown plasma formed by a ruby laser pulse in argon at atmospheric pressure. Using the optical arrangement shown in Fig. 4, a helium-neon laser beam was directed through the breakdown plasma at right angles to the incident giant pulse beam, and the transmitted fraction of the helium-neon beam detected by a photomultiplier filtered to record only $.6328\mu$ radiation. The measurements obtained show that the breakdown plasma transmits no more than 10 to 20% of the helium-neon laser radiation for times of the order of milliseconds after the incident giant pulse. Additional experiments are planned to observe this afterglow attenuation in gases other than argon and over a range of pressures from atmospheric pressure to 2000 psi.

Effect of Diffusion Losses on Breakdown Threshold

Preliminary studies of the effects of diffusion losses on the breakdown threshold have been made by varying the focal volume within which the breakdown is formed. The focal volume of the laser beam is determined by the divergence of the laser radiation and the focal length of the focusing lens. The divergence of the ruby laser beam has been measured and is essentially constant for every pulse. As a result, the focus volume is conveniently varied by using

different focal length lenses to focus the incident laser radiation, and a series of measurements have been carried out to determine the breakdown threshold laser power in argon at atmospheric pressure as a function of lens focal length. From these measurements, the threshold power density can be obtained as a function of the surface-to-volume ratio of the breakdown region. Experimentally, the breakdown threshold electric field strength is inversely related to the dimensions of the focus region; i.e., breakdown within small focus volumes requires a greater optical frequency electric field than is necessary with a larger focus region. This implies that, in the pressure-volume regime studied, diffusion losses play a significant role in the development of optical frequency breakdown, an important result in determining the mechanisms responsible for breakdown at optical frequencies. Further experimental studies of diffusion loss effects are planned and involve an investigation of the breakdown threshold electric field in argon and other gases over a wider range of breakdown volumes and at a series of pressures from atmospheric pressure to 2000 psi.

Theoretical Investigations

Theoretical calculations have been carried out examining in detail the quantum mechanical picture of optical energy absorption. These results show that at optical frequencies an electron exchanges energy with an impressed electromagnetic field in increments of the photon energy, a result which differs in kind from that given by microwave breakdown theory.

According to classical microwave breakdown theory, an electron oscillates in response to the applied electromagnetic field and during a collision gains an increment of energy from the field proportional to the oscillation energy of the electron. This oscillation energy varies directly as the intensity of the applied field and, while a function of the microwave frequency, is unrelated to the energy of a quantum of the radiation. At field strengths corresponding to the breakdown threshold at microwave frequencies, the oscillation energy is 10^{-3} to 10^{-2} eV, much larger than the 10^{-6} eV energy of a microwave photon. At optical frequencies, the breakdown threshold electron oscillation energy, according to the same classical picture, is also 10^{-3} to 10^{-2} eV. This "oscillation energy," however, is small compared with the 1 to 2 eV of an optical frequency photon, and a classical view of energy gain from the applied electromagnetic field is no longer valid. As part of a parallel Corporate sponsored program, Prof. L. Brown and Dr. P. Mallozzi of Yale University, acting as consultants to the Research Laboratories, have developed a detailed quantum mechanical theory for the case of optical frequency irradiation; i.e., where the photon energy is greater than the classically calculated electron oscillation energy.

The theory shows that during a collision an electron exchanges energy with the applied field in increments equal to the photon energy. This result differs in kind from that given by classical microwave theory as applied to optical frequencies and has important implications in developing an understanding of the physics of the optical frequency breakdown process. It should be noted that the quantum mechanical analysis applied to the case of microwave irradiation, in which the photon energy is much less than the electron "oscillation energy," leads to a result identical with that given by the classical microwave breakdown theory, and thus the quantum mechanical analysis carried out is valid over the entire microwave-optical frequency regime.

Physically, in an optical frequency field, an electron gains energy by making a free-free transition during a collision, absorbing a photon of the applied field in the process. An electron may also lose energy during a collision by stimulated Bremsstrahlung, and the net rate of energy gain is determined by the relative magnitudes of these two processes. For a thermalized electron energy distribution in which the average thermal energy per particle is substantially greater than the photon energy of the applied electromagnetic field, the two processes are comparable in magnitude, and the quantum mechanical energy absorption rate is numerically equal to that obtained from the classical picture. During the early stages of the breakdown, however, the electrons will not make sufficient collisions with other electrons or with atoms in the gas to become thermalized, and a highly non-equilibrium electron energy distribution may be produced. It is possible, for example, that, while most of the electrons gain and lose energy in successive collisions, a few experience a series of predominately energy gain collisions and receive sufficient energy to cause the ionization of a neutral atom. The average rate of energy gain by the electrons may be small, but, because of the large increment of energy transfer to the electrons from the field and the highly non-thermal conditions existing early in the breakdown process, the rate of ionization in the gas may be very large. During the next report period, additional calculations will be made to determine whether this process can account for the rapid development of breakdown observed experimentally.

SIX-MONTH STATUS EVALUATION

Studies of gas breakdown by optical frequency radiation have been carried out in argon and helium over the pressure range from atmospheric pressure to 500 psi using the $.69\mu$ and 1.06μ radiation from high-intensity ruby and neodymium lasers, respectively. With either ruby or neodymium laser irradiation, the breakdown threshold electric field is observed to decrease with pressure, varying approximately as $\frac{1}{\sqrt{P}}$. Measurements have

been made of the attenuation of the irradiating neodymium laser beam by the breakdown plasma produced. It is observed that over one-half of the incident laser energy can be absorbed by the breakdown plasma and that the attenuation of the incident beam can exceed 90% during the latter portions of the giant pulse. Preliminary measurements of the attenuation of a helium-neon laser beam by the breakdown plasma have been made, and it is observed that attenuations of 80 to 90% are present for times up to several milliseconds following the incident laser pulse. Preliminary measurements of the effect of diffusion losses on the breakdown threshold have been carried out by varying the volume within which the breakdown is produced. These results show that the breakdown threshold is inversely related to the dimensions of the focus volume, indicating that diffusion losses are important in the development of optical frequency breakdown.

During the next six months of this contract, an absolute calibration of the 1.06μ breakdown threshold electric field strength will be made and compared with the previously obtained results for $.6943\mu$ radiation to determine the frequency dependence of the breakdown threshold. The measurements of the attenuation of optical frequency radiation by the breakdown plasma following the incident giant pulse will be extended to gases other than argon and to pressures up to 2000 psi. Additional studies of the effect of diffusion losses on the breakdown threshold will be carried out in argon and other gases over a wider range of breakdown volumes and at a series of pressures from atmospheric pressure to 2000 psi.

LIST OF FIGURES

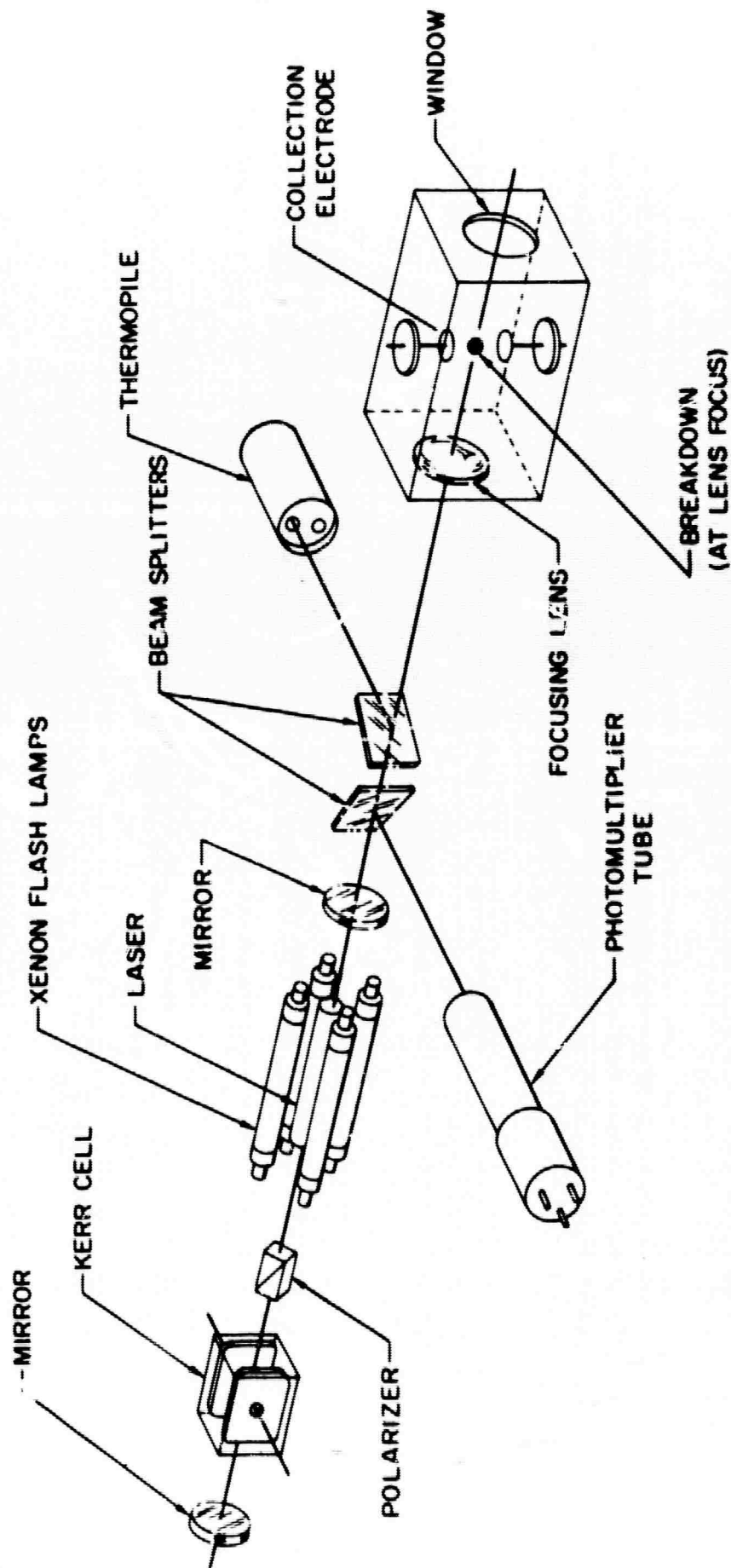
Fig. 1 - Gas Breakdown Q-Spoiled Laser System

Fig. 2 - Attenuation by Breakdown Plasma

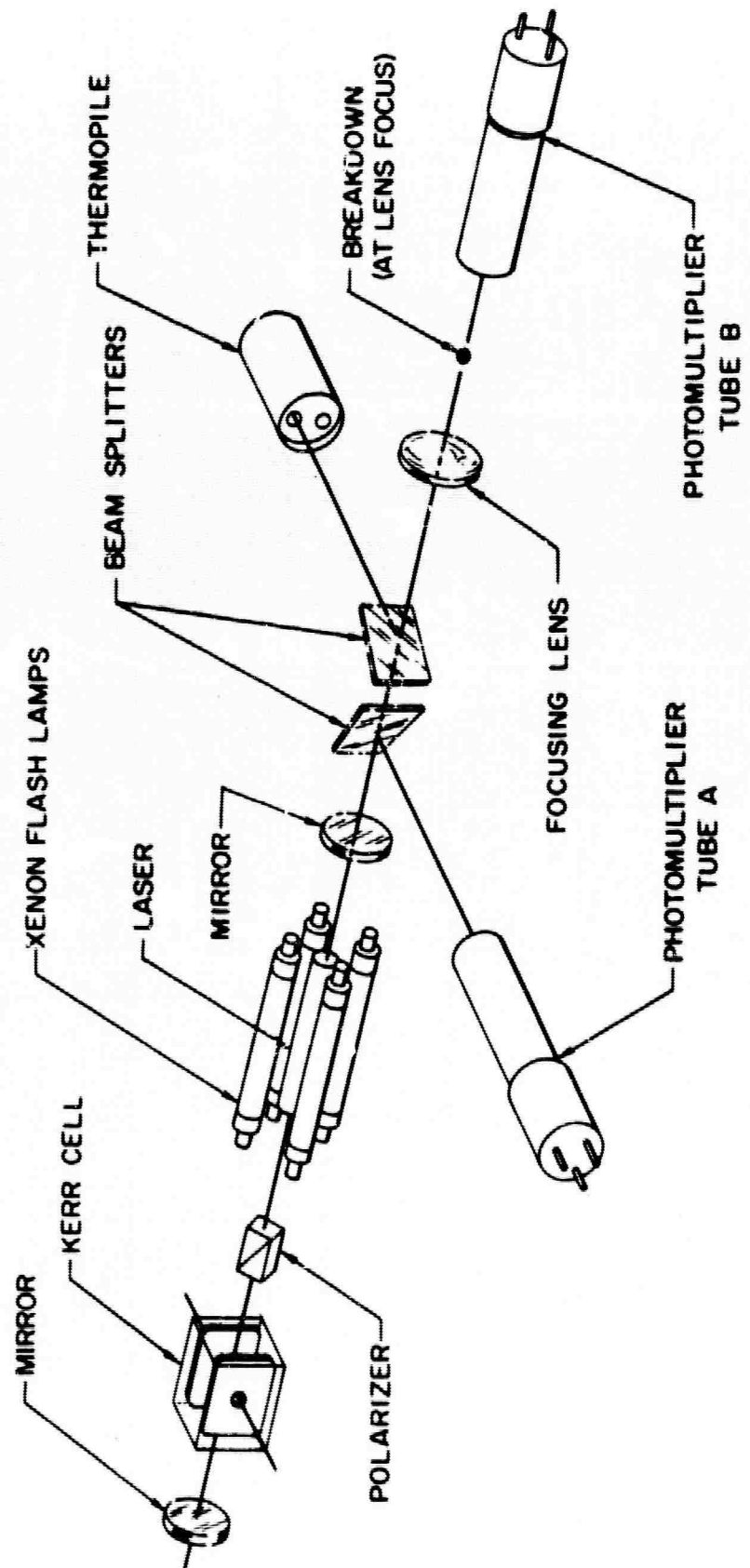
Fig. 3 - Attenuation of 1.6μ Laser Beam by Breakdown Plasma

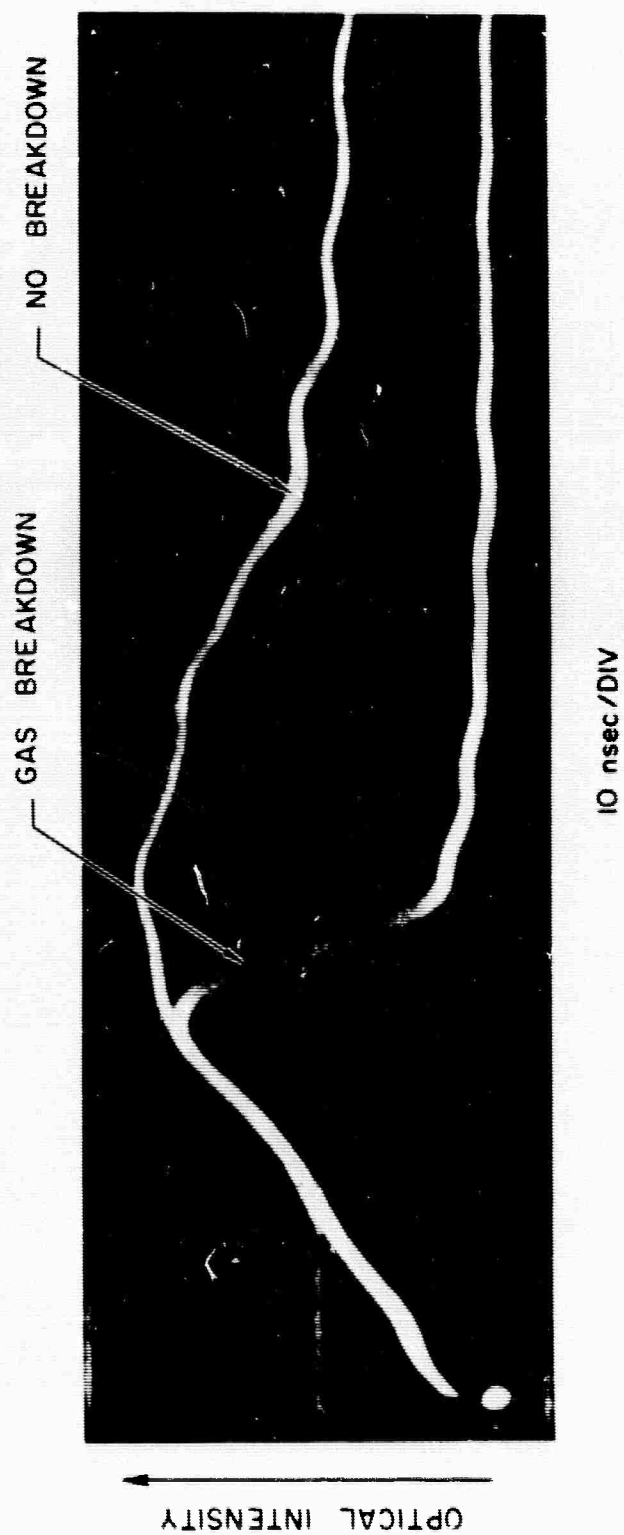
Fig. 4 - Attenuation by Afterglow Plasma

GAS BREAKDOWN Q-SPOILED LASER SYSTEM

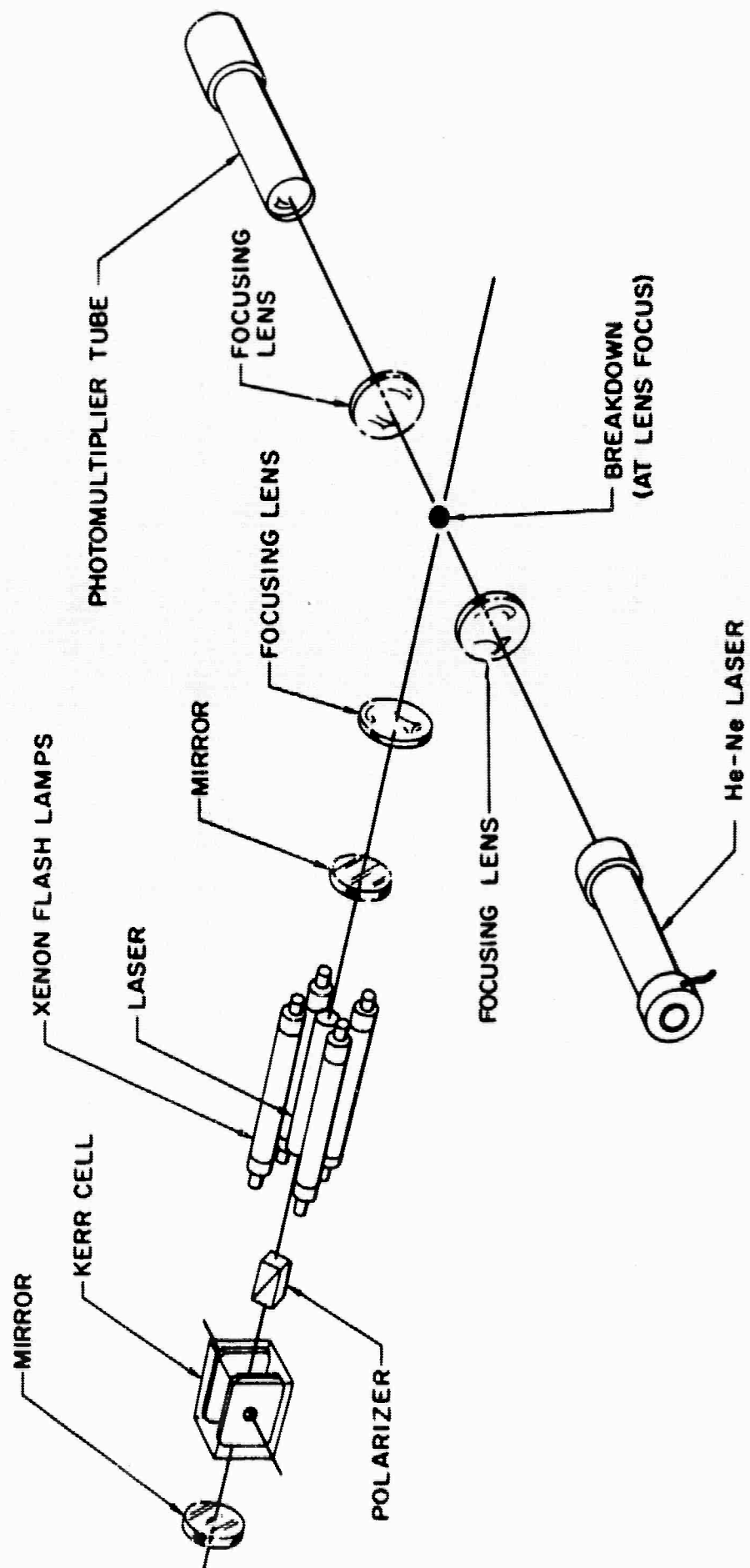


ATTENUATION BY BREAKDOWN PLASMA



ATTENUATION OF 1.06μ LASER BEAM BY BREAKDOWN PLASMA

ATTENUATION BY AFTERGLOW PLASMA



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