THE ABSORPTION OF LASER RADIATION BY A LASER PRODUCED PLASMA

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THESIS

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ABSTRACT

Intense, Q-switched, neodynium laser pulses (1-9 joules), were focused into a vacuum chamber containing 5 mil and .5 mil Mylar targets to investigate the absorption of laser radiation by the subsequent plasma produced. Absolute measurements of the incident and transmitted laser energies were obtained for various background pressures and incident beam intensities. The data show that the absorbed energy for both the 5 and .5 mil targets is linearly dependent on the input energy. At the same time, however, the percentage of energy absorbed is greater in the 5 mil target (78-90%) than in the .5 mil target (44-73%). Increased plasma temperatures both at higher input energies, and from the .5 mil targets may partially account for these observed results. Time resolved measurements of the incident and transmitted laser power pulses were also taken in order to determine the time dependent behavior of the absorption process. The results of these measurements substantiated that greater percentages of energy were absorbed by the 5 mil target. In addition, the measurements revealed a decrease, followed by an unexpected increase, in the transmitted power which would indicate that optimum absorption conditions exist relatively early during the expansion of the plasma.

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I. INTRODUCTION

The experimental and theoretical work dealing with plasmas produced by focusing high power laser pulses onto solid surfaces has been the subject of extensive research for the last decade. With many unresolved problems still remaining, the work in this field continues to progress in search of a feasible solution to the fusion dilemma.

This study was undertaken to examine the absorption process of laser radiation by a thin Mylar target, in conjunction with simultaneous investigations of the self-induced magnetic fields by Leslie McKee. The principle aim of this project was to investigate the dependance of the absorption process on the energy of the incident laser beam and on the background pressures. This was accomplished by taking absolute energy measurements with a laser radiaometer, and by photographing time resolved displays of the input and transmitted laser power pulses.

II. THEORY

A. LASER SOLID INTERACTION

The vaporization of solid matter is easily accomplished by means of high intensity laser radiation. It is important to note, however, that vaporization produced by normal pulsed lasers is quantitatively different from that produced by Q-switched lasers. Therefore, since the laser utilized in the experiments was a Q-switch, neodynium laser, attention will be focused only on the latter case.

To begin with, consider the mechanism of energy transfer when laser light of power densities well below those required to melt the solid impinges on the surface of the solid. A portion of the light energy is reflected while the remainder is absorbed by the electrons in the material. These excited electrons transfer their energy through collisions with lattice phonons and other electrons. Many of these collisions, which also govern heat transfer, occur during times on the order of the duration of the laser pulse. Consequently, the optical energy is essentially transferred into heat at the point of interaction, and subsequently thermally conducted into the solid. For Q-switched lasers this occurs so rapidly that local equilibrium is also established during the length of the pulse.

The mechanism of optical energy transfer to and subsequent heat transfer in the solid are essentially understood.

So also is the case of the interactions between solids and lasers which are of sufficient power densities to cause vaporization of the solid material. Prior to summarizing the mechanisms describing the dynamics of this process, a rough determination will be of approximate order of magnitude required of laser fluxes to bring about this unique phenomenon.

1. Vaporization of a Solid

An estimate of the energy flux, ϕ, required to induce vaporization of solid matter by a nanosecond laser pulse can be determined roughly by insuring that the sublimation energy of all the solid particles within a thermal wavelength of the surface is provided within a time not exceeded by the laser pulse, τ, that is,

$$\phi\tau \geq \ell\rho\lambda_o$$

where ℓ, the thermal wavelength in the case of optical wavelengths is approximately equal to $(\kappa\tau/C)^{\frac{1}{2}}$; κ is the thermal conductivity; C is the heat capacity per unit volume; and λ_o is the sublimation energy per unit mass. Unfortunately the thermophysical properties of Mylar, the target material in the experiment, are not readily available. However, for metals the sublimation energy per unit mass is typically 10^{11} erg/gm, similarly κ/C is 10^{-1}cm^2/sec, and ρ is on the order of 10 g/cm^3. Therefore, for nanosecond pulses, the threshold flux density, ϕ, for typical metals is approximately 10^{13} erg/cm^2-sec or 10^6 W/cm^2. Since this calculation was

based on parameters characteristic of metals, one can expect the threshold for Mylar to be no greater than this value. The flux densities provided by the K-1500 laser system used in this study were well above this value, with operational fluxes ranging between 1 x 10^9 W/cm^2 and 4 x 10^9 W/cm^2. For energy flux densities well below the threshold value no vaporization of the solid occurs and the previously mentioned situation results, that is, the absorbed optical energy is thermally conducted into the solid, thus heating the solid, but brings about no phase change to the vapor state.

2. Creation of a Plasma

In the range of flux densities slightly greater than that required for vaporization the temperature of the vaporized matter is small in comparison with those at which significant ionization occurs. Since the important process under investigation was the laser-plasma interaction, i.e., the absorption of optical energy by the plasma, only the dynamics for the case of laser flux densities which are well in the excess of threshold densities will be treated.

The high flux densities of interest not only cause the breaking of the atomic bonds in the solid material, thereby forming a vapor, but also result in such sufficiently high temperatures so as to cause ionic and atomic excitation, and thus the creation of a highly ionized plasma. This highly ionized plasma in turn absorbs the electromagnetic energy of the laser beam.

Because of the very high flux densities a small amount of solid material is vaporized early in the Q-switched

laser pulse. The blow-off material is further heated by the absorption of the incoming laser radiation becoming thermally and multiphoton ionized, and opaque to the incident light. Because the vaporization and ionization energy is small compared to the high energy contained in the laser beam, most of the energy in the pulse will be absorbed by the plasma created, thereby increasing the temperature of the plasma which in turn thermally radiates. The end result is the creation of a high temperature plasma with a high electron density. The details of the interaction of the laser beam with this plasma will be considered in II.B.

A relatively clear physical picture of this unique method of plasma development can be obtained from a model proposed by Caruso [Ref. 1]. A brief summary of his model, without introducing the mathematical details of his theoretical predictions, is appropriate.

Essentially, three processes are involved. The first of these is the absorption of the intense laser energy flux within a thin absorbing layer, F. Here the electron collision frequency is sufficiently high enough that even a small percentage ionization causes the layer to become opaque to the beam thus resulting in the absorption and transformation of the optical energy to thermal energy. The second process is characterized by the expansion of an extremely fast and hot plasma jet, J, from the surface of the solid with a velocity v_2. The third process is the resulting propagation of an ordinary shock wave, S, into the solid with a velocity

v_1. This stage insures the conservation of momentum, and shock heating of the target material. The densities of these phases are characterized by ρ_1 and ρ_2 as shown in Fig. 1.

Notwithstanding the somewhat simplistic model, it provides some insight into the physical dynamics of what in reality is a truly complicated process. Also many of the characteristics of this model may be applied to this study. To begin with, the physical properties of the target material are of little relevance since the light is completely absorbed in a very thin surface layer after a brief period during which a small volume of target material is ionized. A second applicable characteristic is that the absorption of light in the plasma is a self-regulating process, in that a considerable amount of energy reaches the target surface and the plasma produced remains near transparency. Since flux densities of 10^9 W/cm^2 to 10^{14} W/cm^2 were assumed by Caruso, ionization phenomena which would apply to lower flux densities, and light reflection and radiation pressure which would apply to higher flux densities were neglected in evaluating the regulating dynamics of the vaporization process. A third applicable characteristic of this model, one which was observed during the experiments, is that the plasma expands normal to the target surface.

The details of the mathematical treatment of the evaporization process can be found in works by Afanasév, et al. [Ref. 2], Anisimov [Ref. 3], and Ulyakov [Ref. 4]. Such treatment is not included here as primary attention

is focused on the laser-plasma interaction discussed in the next section.

B. LASER-PLASMA INTERACTION

The dynamics and physical state of the plasma jet created are quite complex. Any thorough treatment of this problem would entail consideration of many phenomena such as: the gas dynamics, the plasma characteristics, the absorption mechanism, the thermal and multiphoton ionization, and plasma radiation. Any such treatment is beyond the scope of this study and therefore will not be attempted. Instead, a basic discussion of the absorption process will be presented.

1. Absorption

In order for absorption of light and subsequent heating of a plasma to occur free electrons are necessary. Initially the electrons are freed from the atoms by a multi-quantum photoelectric effect which is made possible by the intense radiation at the focus of the laser beam. Ionization will occur in times much less than the duration of the laser pulse, therefore allowing the plasma to absorb the light in the remainder of the pulse. This absorption of energy from the beam will occur predominantly by the inverse Bremsstrahlung process which involves the absorption of a quantum of photon energy by a free electron. The electron is raised to a higher energy state within the field of an ion in order that momentum be conserved. The transition is referred to as a free-free transition, or inverse Bremsstrahlung.

Now consider the absorption process in terms of the interaction between an electromagnetic wave and the plasma electrons. The dispersion relation for the propagation of an electromagnetic wave with frequency, ω, and propagation vector, $\vec{k}$, in a plasma characterized by a plasma frequency, ω_p, is

$$(ck/\omega)^2 = 1 - (\omega_p/\omega)^2 \left[1+i(\nu_c/\omega)\right]^{-1}$$

where ν_c is the electron-ion collision frequency for momentum transfer. The absorption coefficient, K, can be determined from the imaginary part of the complex wave number, k, from the relationship

$$K = 2\text{Im}(k)$$

For the case of $\nu_c \ll \omega$ in a underdense plasma, i.e., $\omega_p < \omega$, the absorption coefficient is

$$K = \nu_c/c\sqrt{\varepsilon}\ (\omega_p/\omega)^2$$

For the case of $\omega \gg \nu_c$, which applies to optical frequencies, the classical absorption coefficient is obtained using the Boltzmann equation and treating the electric field of the electromagnetic wave as a small perturbation in a plasma which is in equilibrium with a temperature, T. The absorption coefficient in this case is given by Spitzer [Ref. 6] and Ready [Ref. 7] as

$$K = 4/3(2\pi/3\kappa T)^{\frac{1}{2}}\ (n_e n_i Z^6 \ell^6/hcm^{3/2}\nu^3)(1-\exp(\tfrac{-h\nu}{\kappa T})) \qquad (1)$$

The term $[1-\exp(-h\nu/\kappa T)]$ takes into account the reduction of the absorption coefficient by induced emissions, i.e., Bremsstrahlung. For neodynium laser light this term is approximately one for $T \ll 10^4 {}^\circ K$ and $h\nu/\kappa T$ for $T \gg 10^4 {}^\circ K$. Therefore, for the latter case, i.e., high temperature plasmas, the absorption coefficient becomes

$$K \simeq 4/3(2\pi/3)^{\frac{1}{2}}(1/m\kappa T)^{3/2}(n_e n_i Z^2 \ell^6/c\nu^2) \qquad (2)$$

Notice the fundamental difference between equations (1) and (2) lies in their functional dependence on the plasma temperature and frequency of the light.

The requirement for efficient heating of the plasma is that the plasma be of dimensions on the order of 1/K, otherwise if larger, heating will not be uniform, and if smaller, the plasma will be partially transparent and energy will be lost. One of the most difficult aspects of trying to test the classical absorption coefficient against the plasmas created during this study is of course the problem of matching the continuously changing plasma properties to obtain a valid absorption coefficient.

Before light can even penetrate into the plasma, the frequency of the light must be greater than the plasma frequency, ν_p, which is given by, $\nu_p = 8.9 \times 10^3\ n_e^{\frac{1}{2}}$, where n_e is in electrons/cm^3. In the case of neodynium laser light, $\lambda = 1.06\ \mu m$ or $\nu = 2.83 \times 10^{14}\ sec^{-1}$, therefore the critical electron density is on the order of 10^{21} electrons-cm^3 which is only an order of magnitude lower than the electron

densities of typical solids. Plasmas of higher electron densities will reflect the incident laser light and greatly reduce the probability of penetration into the plasma. Because of the rapid expansion of the plasma (typically about 10^7 cm-sec^{-1}), the electron density will quickly drop below the critical density, allowing propagation and absorption to readily take place.

After the absorption of light energy by the electrons subsequent transfer of energy to the ions occurs via collision. The equilibration of the ion and electron temperatures in a plasma where Maxwellian velocity distributions are assumed is governed by the following relaxation equation

$$dT/dt = T_e - T_i / t_{eq}$$

where t_{eq}, the time of equipartition in seconds is given approximately by Ready [Ref. 7] as

$$t_{eq} \cong 252 \; AT^{3/2} / n_e Z^2 \ln\Lambda$$

where A is the atomic weight of the ions, T is the temperature in Kelvin, Z is the effective ion charge, and n_e is the electron density in cm^{-3}. For a Q-switched laser pulse of about 20 nsec the equipartion time will be much shorter than the laser pulse. Consequently the assumptions may be made that transfer of energy between the electrons and ions effectively occurs during the laser pulse, and that the ion and electron temperatures are equal.

The foregoing presentation of the absorption mechanism is different in principle from non-linear anomalous

absorption, which has been experimentally observed only in the microwave region [Ref. 9]. Theoretical predictions by Pustovalov [Ref. 10] and Silin [Ref. 11] along with a numerical computer treatment by Kruer, et al. [Ref. 12] indicate the existance of anomalous absorption in the optical frequencies. The use of weakly turbulent plasma theory results in an anomalous absorption coefficient which is proportional to the square of the electric field intensity of the electromagnetic wave. Anomalous absorption results when electric field intensities above specified threshold values interact with the plasma. Although very high degrees of absorption were observed in this experiment, as much as 90% of the input energy, no conclusive statement may be made regarding this mode of absorption.

By considering the conservation of energy,

$$\frac{dE_{ABS}}{dt} = \frac{dE_{ION}}{dt} + \frac{d(\kappa T_e)}{dt}$$

that is, the rate of energy absorbed from the laser beam is equal to the rate of ion energy increase plus the temperature rise of the electrons, Dawson [Ref. 8] has solved this problem with the use of several simplifying assumptions, such as, a spherically symmetric plasma with a constant number of particles of homogeneous spatial density and particle temperature. The assumptions used in his calculations may not be fulfilled by the plasmas produced in this study. Regardless of the angle of incidence of the laser beam to the surface, the plasma expands normal to the surface, and the

density gradient is large near the surface during the pulse. Because of the greater complexities involved in the plasma production from large surface targets, a similar mathematical approach to this problem would be extremely difficult.

2. Radiation and Scattering

Consider next, two processes which might have affected the absorption measurements in this experiment, namely plasma radiation and scattering. Since in the case of neodynium laser light E = hω = 1.17 eV, the photon energy is much less than the electron rest mass (.511 MeV), the classical total cross section for scattering of a photon by an electron can be applied. It is given by

$$\sigma_s = 8\pi/3 \left(\frac{\sigma^2}{m_e c^2} \right) = 6.65 \times 10^{-25} \text{ cm}^2$$

Therefore, with the mean free path given by

$$\lambda = \frac{1}{n\sigma}$$

for a plasma at the critical electron density, the Thompson scattering mean free path is about 15 meters so that scattering can be considered entirely negligible in comparison with the absorption process.

Similarly the plasma radiation may also be neglected. To show this, it is assumed that the plasma radiation is black body radiation for frequencies for which the absorption length is less than the plasma radius, and Bremsstrahlung for frequencies for which the absorption length is greater than the plasma radius. Black body conditions exist

early during the heating of the plasma, when the surface area and temperatures are small ($T < 10^6$°K). The radiated power under these conditions are negligible when compared to the laser input power. Later in the heating and simultaneous expansion process, the plasma becomes transparent to its own radiation and the significant radiation is due to Bremsstrahl-ng losses. These losses are governed by the equation

$$P = 1.42 \times 10^{-34} Z^3 n_i^2 T^{\frac{1}{2}} \text{ W/cm}^2$$

where n_i is in cm^{-3} and T in degrees Kelvin.

In order to determine an order of magnitude of these radiated power losses, estimates must be made of both the density and temperature since these plasma parameters were not measured in the experiments. To begin with, based on the hole sizes left in the 5 mil Mylar targets, the average volume of material removed was approximately $9 \times 10^{-14} cm^3$. Therefore, assuming the target density to be 10^{22} cm^{-3}, approximately 9×10^{18} atoms were removed from the target. Next, data obtained from the self-induced magnetic field measurements were used to estimate the effective plasma volume at the peak of the laser pulse. The volume was determined to be about 4×10^{-1} cm^3. Assuming the ions to be doubly ionized, i.e., Z = 2, implies a plasma electron density, n_e, of about 2×10^{19} cm^{-3}. The temperature, T, roughly calculated using $E = N\kappa T$, where E is the energy absorbed by the target, and N is the number of electrons and ions, was estimated to be about 2×10^4°K. For the .5 mil

targets the hole diameters, for similar energies, were approximately equal to those in the 5 mil targets. Therefore, the temperatures in the plasmas produced from the thinner Mylar are greater by a factor of ten. Both estimates of n_e and T are in good agreement with measured values obtained in several similar experiments [Ref. 7]. Using these values the radiated power is approximately 10^5 W. Therefore, assuming the radiation to expand spherically with a $1/R^2$ attenuation, the effect on the absorption measurements, when compared to the laser powers used in the experiments (300 MW), is negligible.

III. APPARATUS

A. LASER SYSTEM

The high power, nanosecond light pulses required were provided by the Korad Model K-1500 laser system. The components of this system include the K-1 laser head (oscillator), the K-2 laser head (amplifier), a Pockels cell, a closed cycle cooler, a 5 kilovolt and 10 kilivolt console housing the energy storage capacitors for the K-1 and K-2 laser heads respectively, and finally the necessary optical coupling components. Typical operational ranges and characteristic outputs of the laser during the experiments were:

Energy	1-9 Joules
Peak Power	400 MW
Pulse Width (at half maximum)	23-26 nsec
Wavelength	1.06 μm

A photograph of the laser heads and pockels cell is shown in Fig. 2.

1. Pockels Cell

The Pockels cell functions as an adjustable optical Q-switch after the firing of the flashlamp. The time may be adjusted to correspond to the maximum inversion of the doping ions in the laser crystal. Plane polarized light emerging through the Brewster stack from the neodynium rod in the K-1 laser head is incident on the Pockels cell. When the crystal is unbiased this light proceeds through the crystal

(Potassium Dihydrogen Phosphate crystal), with no change in its polarization, and strikes another polarizing stack normal to its preferred plane for transmission. It is therefore reflected and not transmitted through to the reflecting mirror. On the other hand, when a one-half wavelength longitudinal electric field is applied to the crystal, the polarization is retarded by 90° by the crystal, enabling the light to pass through the polarizing stack to the reflecting optical mirror behind the Pockels Cell. The reflected light passes back through the crystal, undergoing an additional 90° retardation of the electric field vector, and returns to the neodynium laser rod thereby completing the Q-switching of the optical cavity.

2. <u>K-1 and K-2 Laser Heads</u>

With few exceptions the K-1 and K-2 laser heads are structurally and functionally similar. The essential components of the laser heads are a helical, Xenon gas filled flashlamp, a Pyrex ultraviolet light shield, a cylindrical aluminum reflector, and a neodynium glass doped laser rod. A cross-sectional view of the K-2 laser head is shown in Fig. 4.

Firing of the laser K-1 head is initiated by discharging up to 5,000 volts (10,000 volts for the K-2) from the K-1 power console through the Xenon lamp which results in a peak current flow of several thousand amperes, causing the gas to be heated to temperatures of about 6000°K. The resultant optical energy from the lamp is then absorbed by

the neodynium laser rod resulting in the required population inversion for lasing. The ultraviolet shield reduces the possibility of absorption of short wavelength radiation which can cause damage to the rod, while the reflecting aluminum surface enhances the absorption probability of the flashlamp energy. Both the flashlamp and the laser rod are submerged in circulating deionized water to provide effective cooling, reduce rod damage, increase lamp life, and maximize optical coupling between the laser rod and the lamp energy.

B. TARGET CHAMBER

The target chamber was designed by Leslie L. McKee specifically for the purpose of studying laser produced plasmas. It is constructed of aluminum and contains six ports which can be used for viewing or diagnostic instrument insertion. During this experiment all six ports were utilized. With the target mounting device, approximately twenty-four separate shots could be made on the same target. The target holder was capable of being rotated by an external knob. The entrance port for the laser beam contains an adjustable lens which allowed the laser beam to be focused onto the target. In addition the chamber is connected to a vacuum system capable of maintaining pressures of about 10^{-2} microns to one atmosphere. The target chamber is shown in Fig. 3.

C. RADIOMETER

The RN-1 Laser Radiometer, developed by Westinghouse, was utilized to obtain absolute energy measurements of the

transmitted laser pulse, as well as to calibrate the photodiode which monitored the input laser pulse.

The radiometer consists of a bolometric calorimeter which is part of a conventional Wheatstone bridge circuit. The bolometer element contains a bundle of fine insulated copper wire. When placed in the path of the laser beam, the copper wire absorbs the beam energy thus heating the wire and raising its resistance. The change in resistance of the wire is proportional to the energy absorbed and essentially independent of the distribution within the wire. Being an integral part of the Wheatstone bridge circuit, the change in resistance results in a change of balance of the bridge. A measurement of this change of balance yields an indirect measurement of the beam energy. Use of the Kiethly Model 149 microvoltmeter to measure this imbalance enables the following empirical formula to be used to calculate the energy of the beam:

reading in microvolts x (1/625) = laser beam energy in joules

One caution had to be observed to insure that energy densities of 2.5 $j\text{-}cm^2$ were not excluded, in order to avoid possible damage to the insulation on the fine copper wire.

The main advantage of using the radiometer detection system over that of the available Korad calorimeter was that it was unnecessary to obtain temperature equilization, thus eliminating waiting for extended periods between laser firings. Another advantage was that the lighter, more compact

bolometer element was the most compatible for use in the limited laboratory arrangement.

D. PHOTODIODES

Critical to the monitoring of both the incident and transmitted power pulses were two fast photodiodes. One was the Korad K-D1 and the second was a unit developed in the NPS Plasma Facility by Hal Harriman primarily for use in this experiment (see Fig. 5).

The K-D1 system is designed to yield both the power and integrated power (energy) signals. Its utilization in this experiment was solely limited to the monitoring of the input laser beam. In order to insure that the sensitive photodiode was not damaged by the high laser flux densities, attenuation of the beam was necessary. Since at the same time high powers were required for plasma production, the input beam was monitored with the aid of a beam splitter, a neutral density filter and a magnesium oxide diffusing plate (see Fig. 6). The beam splitter was positioned between the laser and the target chamber to reflect about one percent of the input laser beam while allowing the remainder of the beam to pass through to the target. This reflected beam was further attenuated by reflecting it from the diffuse reflecting surface of the magnesium oxide plate. The power reaching the photodiode from this surface is

$$P = P_{in} \cos\theta \frac{A}{\pi D^2}$$

where θ is the angle between the normal to the surface and the photodiode; A is the area of the photodiode, and D is the distance from the photodiode to the diffusing surface. This approximation is valid when D is larger than either the diameter of the beam or the detector, which was the case in the experimental set up. Finally, two neutral density filters with a combined index of 3.0 was inserted in front of the photodiode to further attenuate the beam by 10^{-3}.

By insuring that the components of the beam monitoring arrangement remained fixed throughout the experiment made possible the calibration of the K-D1 photodiode system, thereby eliminating the necessity for less accurate theoretical calculations of the input powers and energies. The K-D1 output was calibrated by plotting the integrated power, or energy, signal against the energy of the beam as measured with the RN-1 radiometer described earlier.

Several circuit design precautions were necessary in the set up for photodiode produced laser pulse displays. Because of the fast nanosecond pulses the output impedance of the photodiodes had to be carefully matched into the oscilloscopes, otherwise energy reflections and troublesome ringing distorted the signals. Cable lengths had to be minimized to reduce the stray capacitance which also distorted the desired photodiode signals.

The nanosecond response times of the fast photodiodes and broadband oscilloscope were easily lost in poor design

of load and input circuitry. This prompted the design and construction of the photodiode system shown in Fig. 5 for use in observing the transmitted laser pulse.

IV. EXPERIMENTAL PROCEDURE

The K-1500 laser system was used to focus one to nine joule pulses, with widths at half maximum power of twenty-three to twenty-six nanoseconds onto five mil and one half mil Mylar targets.

Each input laser pulse was monitored by inserting a beam splitter in the path of the beam between the laser and the target chamber. Approximately one percent of the input beam was reflected onto the magnesium oxide diffusing plate into the Korad K-D1 photodiode. The photodiode output was calibrated and monitored using a Textronix 564B storage oscilloscope. The laser beam entered the vacuum chamber, which was maintained at pressures ranging from 10^{-2} millitorr to one atmosphere, at an incident angle of thirty degrees from the normal to the target surface.

A. PLASMA RADIATION, SCATTERING, AND TARGET REFLECTION MEASUREMENTS

In order to investigate the significance of possible plasma radiation and scattering, the first measurements were taken using both the radiometer and photodiode systems. These elements were placed opposite each of the viewing ports on the target chamber. No significant observations were recorded by any of these devices of any light coming from these ports, indicating little or no reradiation or scattering by the plasma. Included in these measurements

were those taken from the port which was at the same angle from the normal to the target as the incident angle of the incoming laser beam. Negative observations from this particular port indicated no loss of the laser beam due to reflections from the target surface. As a further check, a bandpass filter corresponding to the wavelength of the neodynium laser light (λ = 1.06 μm) was inserted in front of the photodiode. The traces obtained showed the same percentages of transmitted energy thereby supporting the assumption that reradiations would not affect the absorption measurements.

B. ABSOLUTE ABSORPTION MEASUREMENTS

Absolute energy absorption measurements were obtained by placing the radiometer opposite the rear port of the target chamber which was located behind the target, in line with the laser beam. The experimental arrangement for absorption measurements is shown in Fig. 6. Measurements were obtained in order to determine the functional dependence of the absorbed energy on the incident laser beam energies, and on the background pressures. The results of these measurements are discussed in the next section.

C. TIME RESOLVED POWER MEASUREMENTS

In order to investigate the time dependent behavior of the absorption process, two different procedures were utilized. Both methods employed the photodiode systems explained previously. The first method entailed the placement of a

magnesium oxide diffusing block behind the rear port of the target chamber. The fast photodiode was used to observe the reflection of the transmitted beam off the diffusing block after it had passed through the target. The output of the photodiode was recorded and photographed on a Textronix 7709 oscilloscope. A second shot was then made by removing the target. The photodiode output was again photographed or superimposed over the first, thus recording both the "incident" and transmitted laser pulses. The oscilloscope monitoring the photodiode was triggered externally by the input laser pulse to insure a standard, uniform trigger so that the corresponding time frames for both signals were identical. Care was also taken to include only those exposures in which both laser pulses were of equal energies. The second method of obtaining time resolved displays of the input and transmitted pulses utilized both photodiodes and two independent oscilloscopes. After calibrating the two photodiode outputs simultaneous traces were made of the incident and transmitted laser pulses, with the results being replotted onto one graph. Because of the difficulties in calibrating both the time and vertical scales of the two different oscilloscopes, and the inherent errors in transposing these results to one plot, it was found that the first method produced the more reliable results.

V. RESULTS AND CONCLUSIONS

Typical examples of the high temperature plasmas formed from the Mylar target during this study are shown in Figs. 7a and 7b.

The measurements taken to determine the significance of scatter, reflection and reradiation of the laser beam energies were so insignificantly small that at times there was no detectable registration on the microvoltmeter, thereby confirming theoretical predictions that these processes would have negligible effects on the absorption measurements. The background pressures of 10^{-2} microtorr to one atmosphere also had no effect on the absorption measurements. This was expected since in the short times of the laser pulse the expansion dynamics of the plasma would not be altered by such low background pressures. This may not be the case, however, at much greater pressures.

Figures 8a and 8b show the results of the absolute energy absorption measurements for both the 5 mil and .5 mil Mylar targets. Both targets were similar in that the absorbed energies displayed a linear dependence on the incident laser beam energy (Fig. 8a). It is interesting to note that within the energy ranges examined the slope of both graphs are essentially identical. At the same time, however, the percentage of energy absorbed in the case of the .5 mil target was much lower than that for the 5 mil

target (Fig. 8b), the percentage of energy absorbed in the 5 mil target ranging between 78-90%, while the percentage of energy absorbed by the 5 mil target fell between 44-73%. The percentage absorption for the 5 mil target dropped off sharply for energies less than five joules. This could result from the transparency of the plasma due to decreased ionization levels at the lower power densities. The linear dependence of the absorbed energy on the incident energy is unknown. However, one possible explanation for the increase in the absorbed energy might be that the absorption coefficient is increased. Throughout the experiment the hole size was observed to increase with increasing laser energies. This meant a greater number of target atoms were converted into the plasma which in turn could cause a decrease in temperature. Assuming the absorption coefficient to be inversely proportional to the temperature, as is the case for the classical absorption coefficient, a decrease in temperature would lead to an increase of the absorption coefficient. Implied in this reasoning is that the absorption occurs at densities near the critical densities. This same explanation may also account for the observed decrease in the amount of energy absorbed by the thinner, .5 mil target, in comparison with the 5 mil target at equal incident beam energies.

The time resolved plots of the absorption process (Figs. 9a and 9b), using the first method described earlier, clearly substantiate the higher percentage absorption of laser

energies by the 5 mil target and the lesser degree of absorption in the .5 mil target as determined by the absolute energy absorption measurements. Of particular interest is the confirmation of the peculiar double peaked nature of the transmitted pulse, as reported by Tuckfield and Schwirzke [Ref.13]. Note that, because of the high plasma densities early in the formation, the plasma is opaque to the incident laser light. After the first five to fifteen nanoseconds, when the plasma has expanded sufficiently to drop the particle densities below the critical density, the plasma transmits and absorbs the energy of the incident beam. It is conjectured that the unexpected behavior of the transmitted pulse, that is, the first decrease in the transmitted pulse, is due to optimal absorption conditions in the plasma which result in a decrease in the transmitted pulse in spite of the increasing incident pulse.

Unfortunately, only qualitative explanations may be given in analyzing the results of this study. In order to derive more quantitative results from similar absorption studies, the critical plasma parameters, such as species density and temperature distributions, must be determined. Therefore, likely extension of this work would entail plasma diagnostic studies of the plasmas produced by this unique method. Such investigations would, in turn, provide more meaningful insight into the qualitative results obtained in this study.

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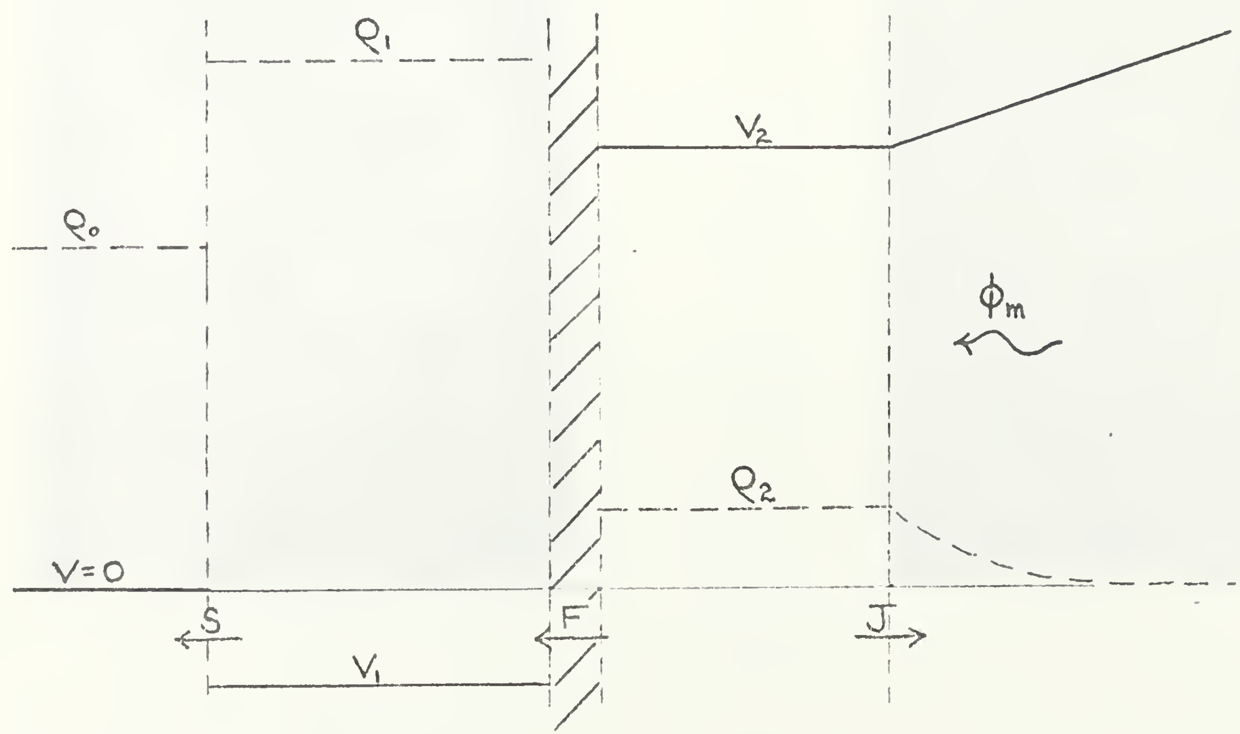

Figure 1. Caruso's Plasma Formation Model.

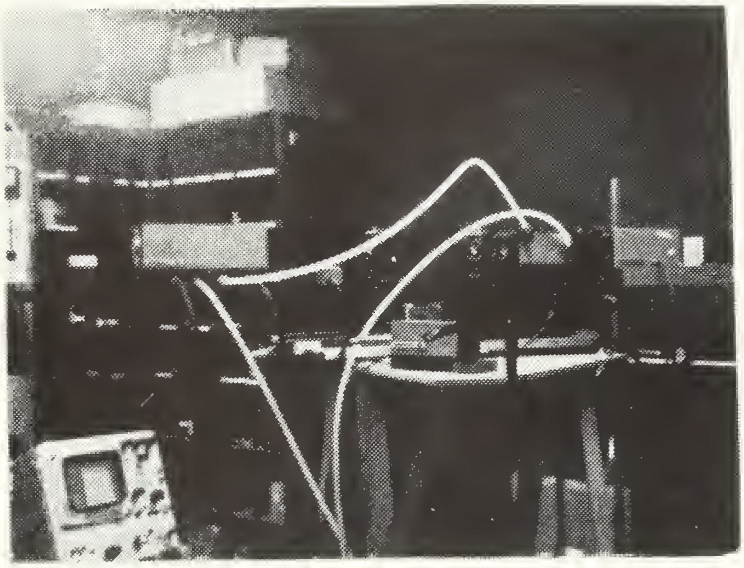

Figure 2. Pockels Cell, and K-1, K-2 Laser Heads.

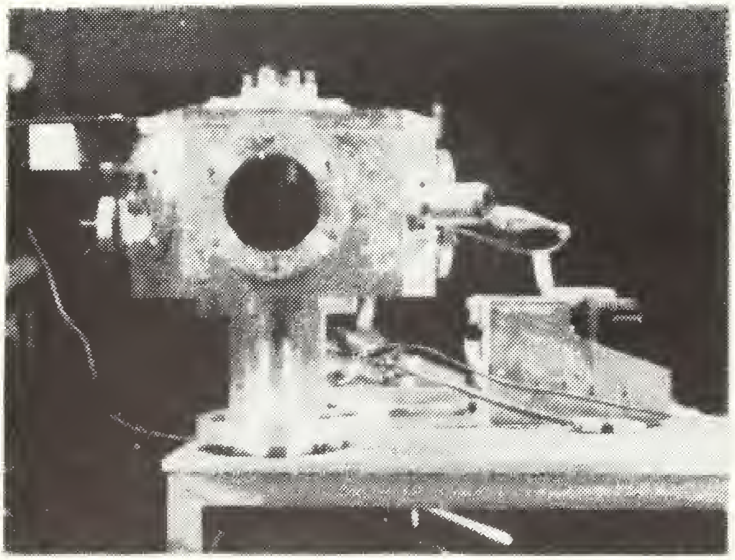

Figure 3. Target Chamber.

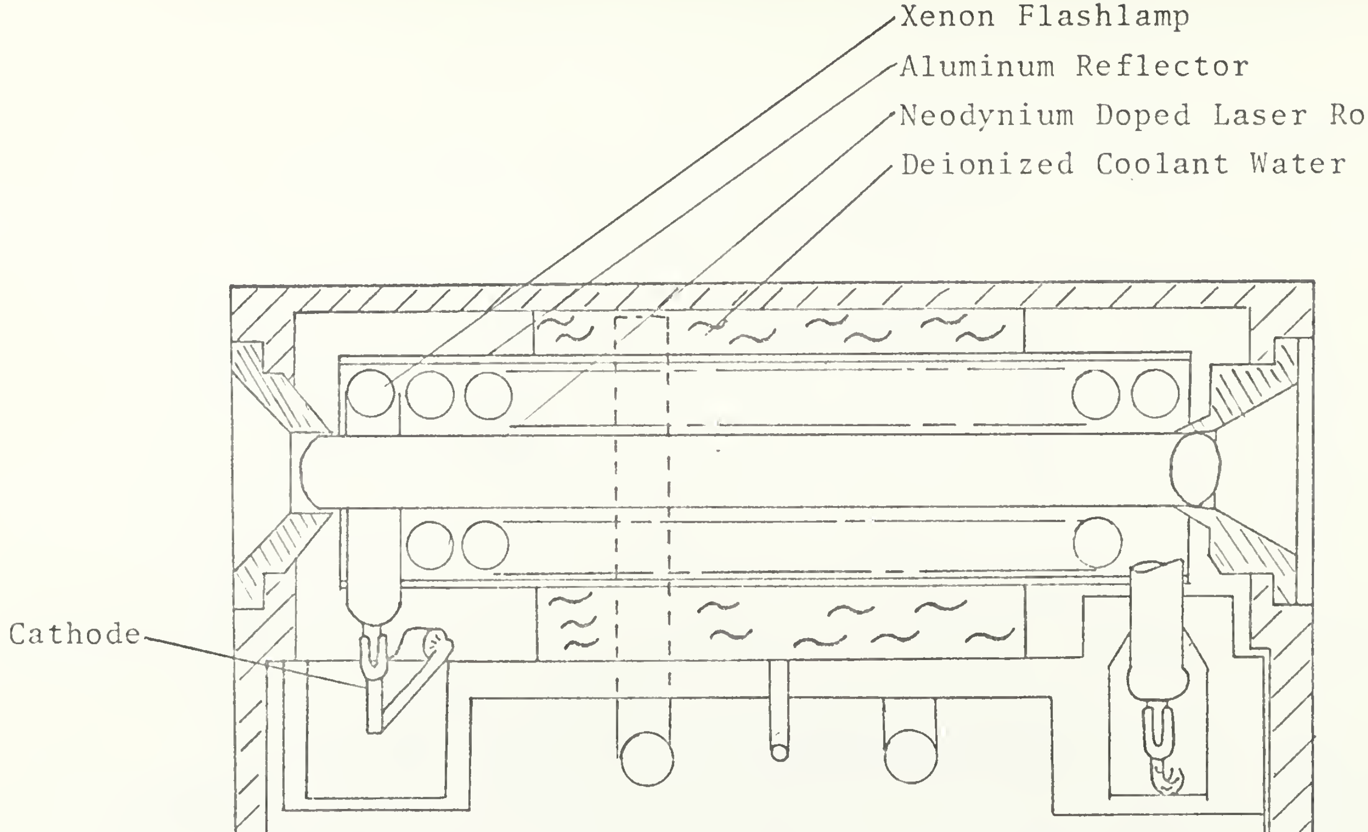

Figure 4. K-2 Laser Head (sectional view).

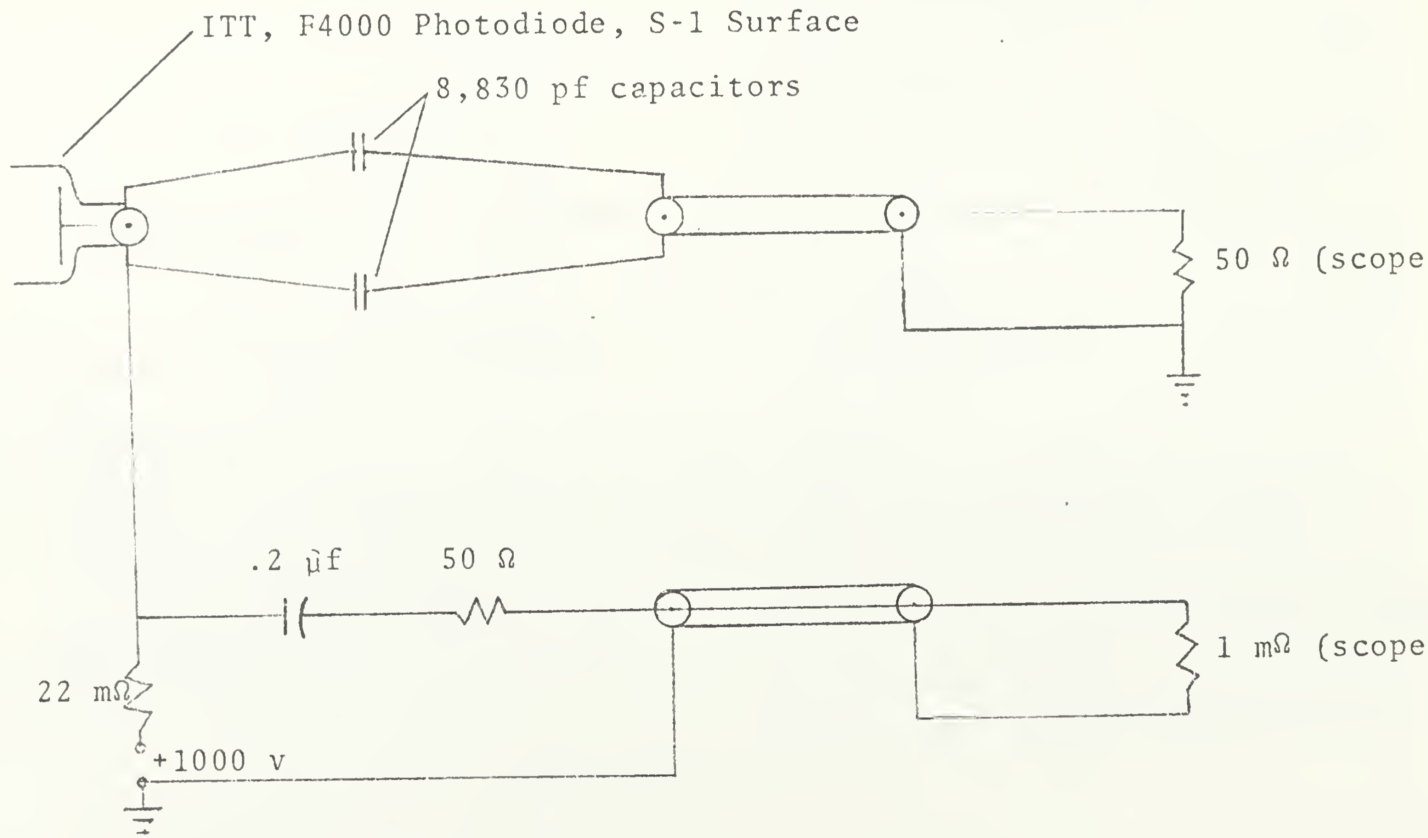

Figure 5. Photodiode Circuit Diagram.

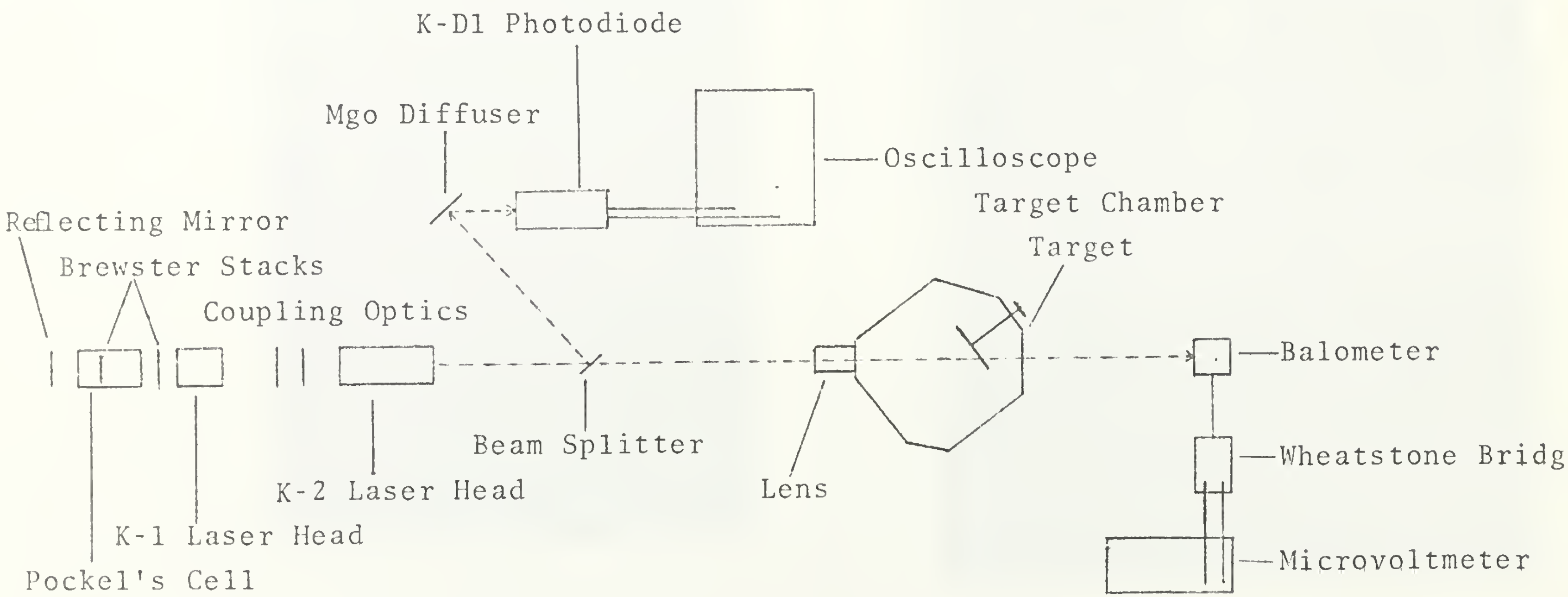

Figure 6. Experimental Arrangement.

Figure 7a. Plasma Formation, Pictured with a Magnetic Probe.

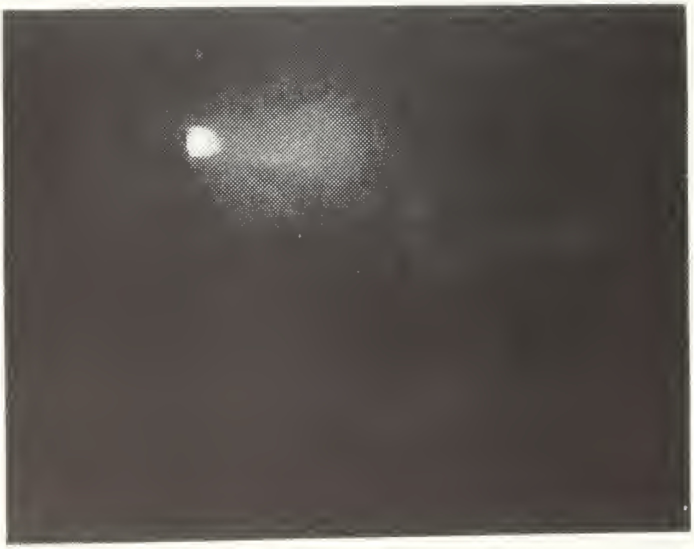

Figure 7b. Plasma Formation.

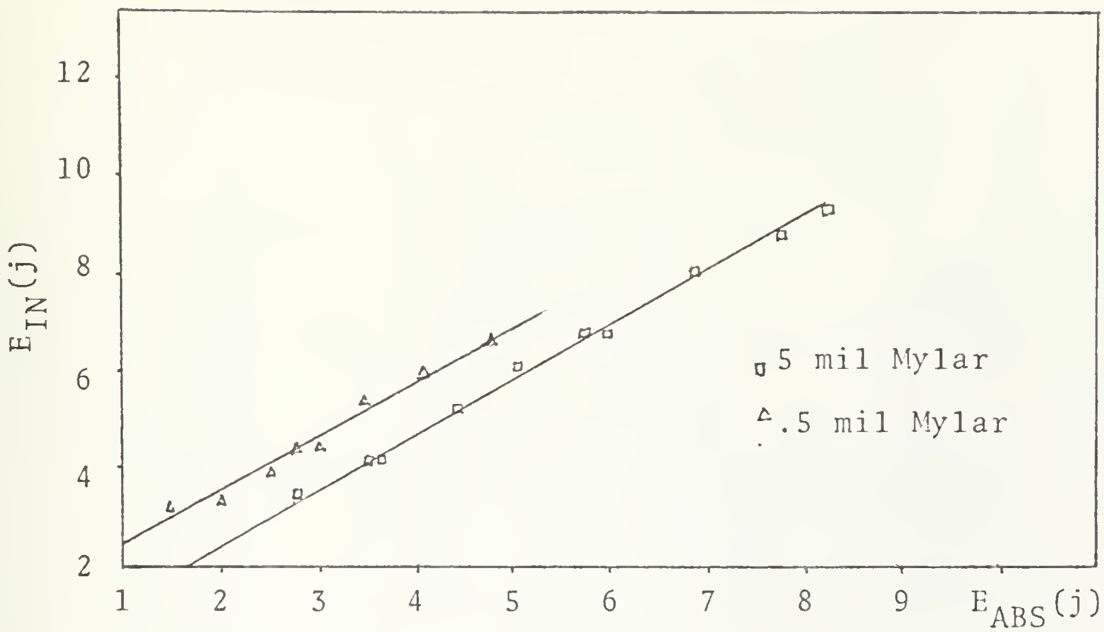

Figure 8a. Input Energy vs Absorb Energy.

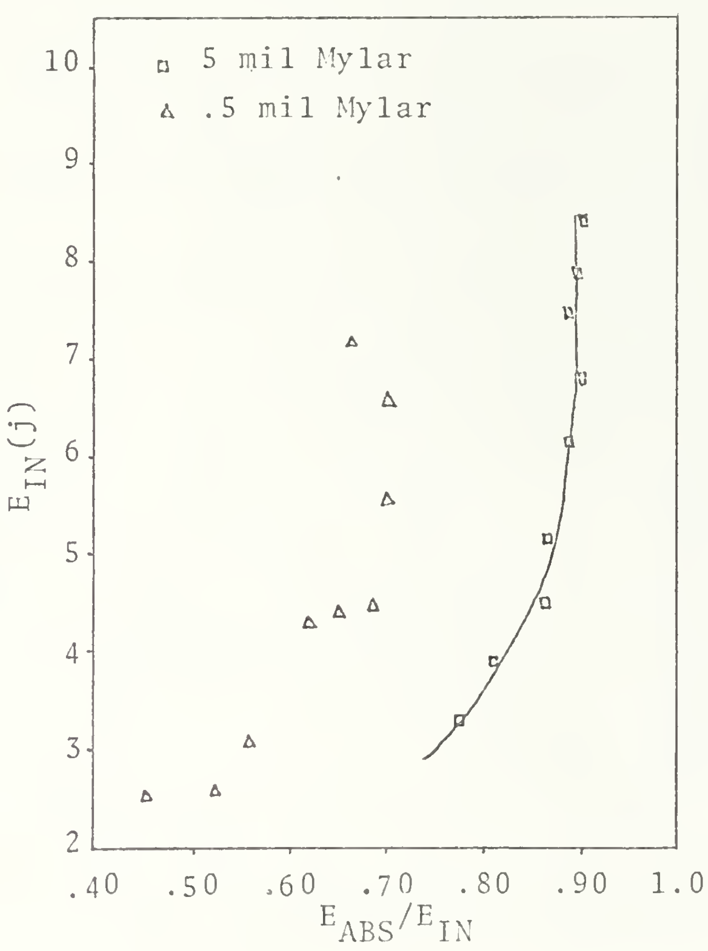

Figure 8b. Input Energy vs E_{ABS}/E_{IN}.

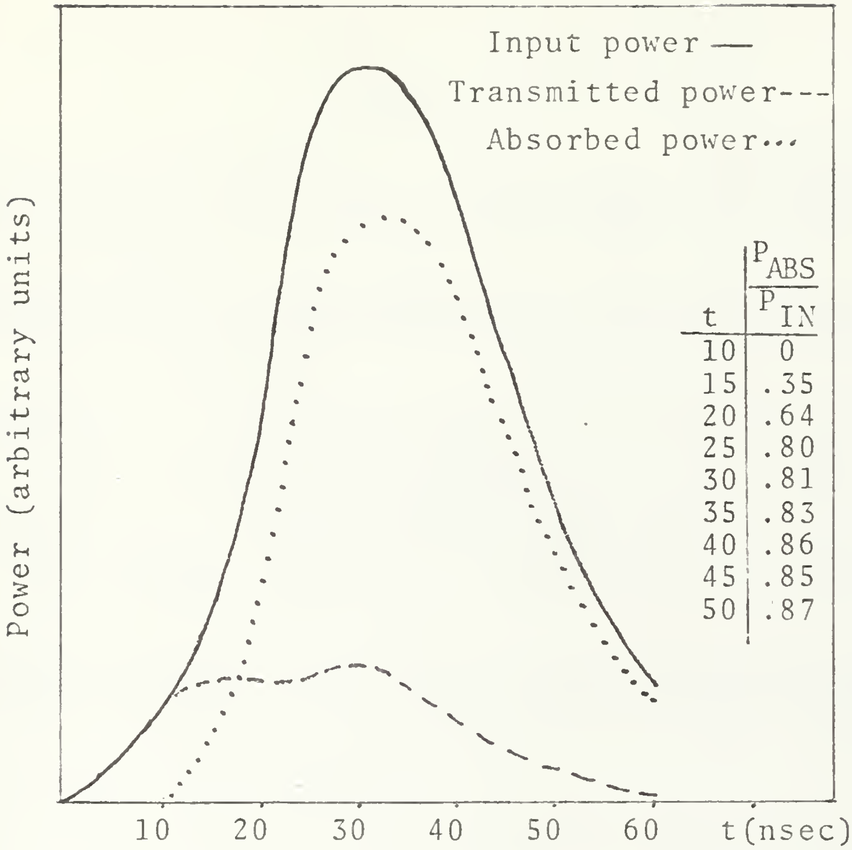

Figure 9a. Input and Transmitted Power Measurements (5 mil Mylar).

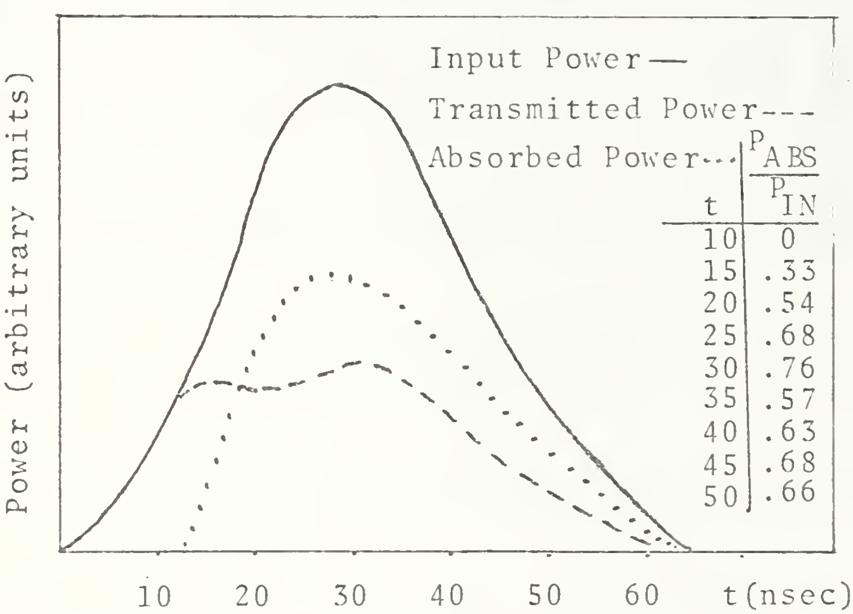

Figure 9b. Input and Transmitted Power Measurements (.5 mil Mylar).

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13. ABSTRACT

Intense, Q-switched, neodymium laser pulses (1-9 joules), were focused into a vacuum chamber containing 5 mil and .5 mil Mylar targets to investigate the absorption of laser radiation by the subsequent plasma produced. Absolute measurements of the incident and transmitted laser energies were obtained for various background pressures and incident beam intensities. The data show that the absorbed energy for both the 5 and .5 mil targets is linearly dependent on the input energy. At the same time, however, the percentage of energy absorbed is greater in the 5 mil target (78-90%) than in the .5 mil target (44-73%). Increased plasma temperatures both at higher input energies, and from the .5 mil targets may partially account for these observed results. Time resolved measurements of the incident and transmitted laser power pulses were also taken in order to determine the time dependent behavior of the absorption process. The results of these measurements substantiated that greater percentages of energy were absorbed by the 5 mil target. In addition, the measurements revealed a decrease, followed by an unexpected increase, in the transmitted power which would indicate that optimum absorption conditions exist relatively early during the expansion of the plasma.

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