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# INVESTIGATION OF NONLINEAR PROPAGATION AND CHIRPING OF SHORT CO2 LASER PULSES

Paul J. Berger, et al

United Aircraft Research Laboratories

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13. ABSTRACT

Under the sponsorship of the Office of Naval Research, United Aircraft Research Laboratories have been carrying out an experimental program to generate short pulses at the 10.6 μ wavelength, to study the propagation and interaction of these pulses with amplifying and absorbing media, and to investigate flowing metal-vapor lasers as sources of radiation in the blue-green portion of the spectrum. The selection of a single pulse from a train of mode-locked $CO_2$ laser pulses based on the attenuation and reflection of a gas breakdown has been explored. The most important feature of this selection technique is the sharpening of the leading edge of selected pulse because of the rapid "turn-on" of the reflectivity of a breakdown plasma. Work with several "low temperature" metal vapor lasers, and with a variety of configurations for operation at higher temperatures, had led to the practical design for copper vapor laser operation utilizing fast closed-cycle transverse vapor flow. A small laser of this type has been operated at repetition rates of an excess of $5 \times 10^4$ pps - about an order of magnitude greater than rates reported prior to this work. Although the present demonstration model laser is small and relatively inefficient, the design appears to be readily scalable for increased power and efficiency.

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| Single Pulse Selection | | | | | | |



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## Section 1

## INTRODUCTION

Under the sponsorship of the Office of Naval Research, United Aircraft Research Laboratories have been carrying out an experimental program to generate short pulses at the 10.6 μ wavelength, to study the propagation and interaction of these pulses with amplifying and absorbing media, and to investigate flowing metal vapor lasers as sources of radiation in the blue-green portion of the spectrum. In the early work under this contract new methods of Q-switching and mode-locking conventional low pressure $CO_2$ lasers were developed and pulses as short as 10 nsec were produced. In the course of this work, basic studies of the $CO_2$ laser, such as the influence of diffusion on the saturation intensity and the velocity dependence of the gain, were performed and lead to a better understanding of $CO_2$ laser dynamics. The advent of the electrically pulsed atmospheric pressure $CO_2$ laser increased the available bandwidth from 60 MHz to 2-3 GHz, leading to the possibility of subnanosecond pulse generation. Self-mode-locking was extensively studied; and, realizing that reproducible pulse generation would require an active modulator, a low insertion-loss Brewster angle acousto-optic modulator was developed. Pulses of 1.2 nsec duration and peak powers in excess of 20 MW were generated. For the detection of these pulses a fast photon-drag detector was developed. A single pulse selection from the mode-locked train based on gas breakdown in a pair of cells was explored during the current contract year. Research on metal vapor lasers has concentrated on a transverse evaporation-condensation cycle and culminated during the current year with the development of a small copper vapor laser with a fast closed-cycle transverse vapor flow. Pulse repetition rates in excess of $5 \times 10^4$ pps have been demonstrated, representing about an order of magnitude increase over rates reported prior to this work. The flow technique employed appears to have general applicability to a class of condensable gas laser media, especially when sealed-off laser operation is required.

Sections 2, 3, and 4 present a discussion of the research carried out during the current year on short pulse detection, single pulse selection, and metal vapor lasers, respectively. Details of the work carried out during the first three years of this contract may be found in the Annual Reports, issued in April 1971 and May 1972. A brief summary of this work as well as the current year's work is given in Section 6. A listing of the technical publications and reports issued under this contract may be found in Section 5.

# Section 2

# SPATIAL RESOLUTION OF SHORT PULSES WITH PHOTON-DRAG DETECTOR

## 2.1 Introduction

The previous annual report (Ref. 1) described the construction of a photon-drag detector which was demonstrated to have a circuit response of 0.3 nsec, equal to the fundamental response time of a 2.5 cm long detector element. Due to its fast response time the display of a mode-locked train of 1.2-nsec pulses with this detector did not show the ringing found with slower detectors. Unfortunately, the sensitivity of photon-drag detectors is low (~0.2v/MW) and the output voltage saturates at approximately 0.3v. In order to display short pulses on a Tektronix type 519 oscilloscope (~0.3 nsec response time) signal levels on the order of 1-10v are required; therefore, an amplifier limits the resolution to approximately 1 nsec. The actural pulse width of mode-locked pulses must be inferred from a deconvolution of the measured pulse width and amplifier characteristics. As a result various indirect schemes have been proposed for resolving subnanosecond duration pulses, employing the photon-drag effect (Ref. 2, 3) and other non-linear schemes (Ref. 4). Recent studies (Ref. 5, 6), however, indicate some renewed hope for direct detection.

Three types of indirect pulse measurement schemes are briefly described below. Of the three the earliest method, proposed by Patel in 1971 (Ref. 2), has not been experimentally demonstrated and under this contract an attempt has been made to put this method into practice. The design considerations and the construction of such a device are discussed below. Final testing of the device has not been carried out yet. In comparison to the other photon-drag techniques (Ref. 3), this method appears completitive.

## 2.2 Indirect Pulse Measurement Techniques

The first of the indirect schemes employing the photon-drag effect was proposed by Patel in 1971 (Ref. 2) and is illustrated in Fig. 1. The laser output is split into two beams of equal intensity, which are directed onto the detector element from two opposite directions. The key to this detector scheme is that the sign of the photon-drag voltage depends on the direction of propagation of the pulse through the detector. When the probe is centered in the optical bridge, position 1, the pulses traveling from the right and the left overlap in the detector, complete cancellation of the opposing voltages occurs, and a null output is observed. As the detector is moved to the left, position 2, the right traveling pulse arrives earlier and the positive voltage signature occurs at a time 2t = 2d/c earlier than the negative voltage signature. Cancellation is now incomplete. For a short pulse the resulting signature is too fast to be displayed directly on an oscilloscope and the success of the scheme relies on being able to rectify the compound signature with a fast full wave rectifier in order to integrate and display the output with a slow oscilloscope. The peak voltage is then inversely related to the degree of overlap. By varying the probe position the method allows the degree of spatial overlap, and hence the pulse width, to be measured. A disadvantage of this method is that shot-to-shot variations in the operation of the laser cannot be distinguished.

The second technique employs both a photon-drag detector and two nonlinear absorbers in an optical bridge, as shown in Fig. 2. The photon-drag detector is centered in the optical bridge to give a null output when the movable nonlinear absorber is far off-center. The two ideally identical, nonlinear absorbers must have a response time substantially shorter than the pulse widths to be measured. Gibson, et. al., (Ref. 3), used polished slices of p-type germanium set a Brewster's angle as the nonlinear absorbers. When the movable nonlinear absorber is far off-center the two pulses arriving at the photon-drag detector have equal intensity and a null output is seen. As the movable absorber is moved toward the center, the pulses from the right and the left overlap in this absorber and increase the absorption of the later portions of the pulse from the left. In this way the two pulses arriving at the photon-drag detector are not identical, the degree of mismatch increasing as the movable absorber moves toward the center of the bridge, and a non-null output is seen. From an analysis of this method, Gibson, et. al., show that the pulse width for either a gaussian or a $\sin^2 x/x^2$ pulse is given by

$$\frac{1}{1.41} \quad \frac{4\ell}{c} \tag{2.1}$$

where $\ell$ is the distance the movable absorber must be moved from the mid-point of the bridge to reduce the out-of-balance signal by a factor of 2. Apparently an exacting allignment procedure is required to keep the two beams coincidently focussed on the movable nonlinear absorber, an essential requirement for the success of the method. In addition the physical restriction on how closely the optical assembly containing the nonlinear absorber and the focussing lenses can be placed next to the photon-drag detector is a limitation on this technique. Exact coincidence of the two beams in the photon-drag detector is not essential, so that the first method discussed above, offers operational advantages, providing a fast full-wave diode bridge can be realized in practice.

A third indirect technique for measuring short pulses at the 10.6 micron wavelength has recently been reported (Ref. 4), wherein the electric field from a high power laser is used to produce birefringence in carbon disulfide, which in turn can modulate visible or near-infrared radiation. The modulation of the probe beam can be detected with the fast sensitive detectors for this spectral range which have response times on the order of 100 nsec. Since the response time of the molecular Kerr effect in carbon disulfide is reported to be 2 psec (Ref. 7), the detection of even shorter pulses could be carried out with streak cameras having picosecond response times. This technique has been demonstrated (Ref. 4). using a mode-locked train of pulses from a TEA laser to induce birefringence in a 1.5-cm long carbon disulfide cell which is placed between crossed polarizers. The modulation of a c.w. He-Ne beam was detected by a photomultiplier and displayed on a 7904 oscilloscope along with the output from a photon-drag detector. A comparison of the traces shows that the strongest pulses in the mode-locked train give rise to a strong modulation of the He-Ne beam, but that signal-to-noise problems exists for the weaker pulses. Improvements in the detection schemes are expected through the use of a pulsed probe beam and a 10-psec streaking camera. Of the three techniques considered here this one appears to have the greatest promise since it has the highest ultimate response time and provides a pulse width measurement on a single pulse.

2.3 Design Considerations

Of the three devices considered above, the first one had not been demonstrated; and, since it appeared to be the only available technique a year ago, the decision was made to construct a device of this type. The design of such a device involved considerations of the detector element itself, the diode circuit, and the optical systems.

High speed microwave diodes have fairly low impedance allowing some flexibility in the resistance of the detector itself. A 30-ohm detector having dimensions of 4 mm x 4 mm x 2.4 cm was constructed from 2 ohm-cm p-type (Ga doped) germanium. The hole concentration for 2 ohm-cm p-type germanium is $1.8 \times 10^{15}$ $cm^{-3}$ and from the absorption cross-section of holes at 10.6μm (Ref. 8) an absorption coefficient of 1.08 $cm^{-1}$ is calculated. Thus, with a 2.4 cm sample length, 97% of the radiation is absorbed. The faces of the detector were optically polished but not antireflection coated so that a front surface loss of 36% is expected. Using this information and the measured detectivity of photon-drag detectors (Ref. 9) a sensitivity of 0.250 v/MW is predicted.

The key element in this design is the full wave rectifier bridge capable of operating at the high frequencies contained in the short pulse. Low-loss x-band diodes are available for such an application. The diodes used in this design are Alpha D5018A beam lead Schottky barrier mixer diodes. These diodes have a 0.3-v forward turn-on voltage and typically a 3-v breakdown voltage, giving an operating range of 1.2 MW to 12 MW for the incident power of the optical pulse. Since the impedance of the diodes is indeterminate there is no sense in attempting to match the impedance of the detector element itself and the diode bridge in order to reduce circuit reflections. To keep the time response of the circuit as fast as possible, the design illustrated in Fig. 3 was used. The detector element was fixed to the top of a 0.025-in ceramic substrate. Picture frame aluminum contacts were diffused into the germanium detector. The tapered planar gold conducting paths on the bottom side, as well as conducting pads on the top surface and over the edges, were produced photo-lithographically. The diodes were ultrasonically bonded to the conducting pads and to the output posts tabs. One post is connected to the BNC output jack, and the other one provides a ground point, if necessary, or can be used to bias the diodes.

The optical system is also shown in Fig. 3. It consists of a pair of 5-in focal length lenses to focus a 0.5-in optical beam onto the 4 mm detector surface. The high index of refraction of germanium converts this focused beam into a nearly parallel beam within the detector.

This device was tested with a 1.5 MW beam of 200 nsec duration (non-mode-locked) entering only one side of the detector. In this configuration an output similar to the usual photon-drag detector should have been seen. Instead a large ringing signal was observed. This may be due to the fact that the power in the beam was not sufficient to overcome the forward turn-on voltage, or that additional electrostatic and electromagnetic shielding is required. Both of these possibilities are presently under study.

## 2.4 Summary

The limitations of direct detection schemes have been considered briefly and three indirect schemes for measuring the pulse width of short mode-locked pulses at 10.6μm have been described. Of the three schemes, one had not been studied previously and the design of such a device was initiated. Testing of the device is currently being pursued.

Section 3

# PULSE SELECTION BASED ON GAS BREAKDOWN

## 3.1 Introduction

The technique illustrated in Fig. 4 was proposed as a method of selecting a single pulse from a train of mode-locked pulses. The electrically pulsed $CO_2$ laser is placed in a ring resonator, together with the acousto-optic modulator and a two-lens gas breakdown cell. The laser is forced to operate in a clockwise direction by means of a unidirectional element. With no breakdown occuring in the cell, the pulse train illustrated in trace (A) would be seen. By adjusting the pressure in the cell, breakdown can be made to occur on one of the most intense pulses in the train. Then the pulse illustrated in trace (B) is reflected from the plasma, exiting in the counter-clockwise direction. One advantage of this scheme is that the synchronization problems encountered with the use of electro-optic switches can be eliminated. For this method to be useful the plasma reflectivity must be sufficiently high, the beam quality of the ejected beam must be good enough to allow the pulse to undergo subsequent stages of amplification and the ratio of the amplitude of the selected pulse to the background level must be high. There is very little data available on the reflectivity of plasmas produced by $CO_2$ laser radiation. A reflectivity in excess of 10% was inferred by Karlov, et. al., (Ref. 10), from the modulation of a 10-$\mu$sec TEA laser pulse by an intracavity plasmoid; however, this relatively stationary plasma differs from the transient one considered in the present study. With a 200-nsec pulsewidth Offenberger and Burnett (Ref. 11) have measured a reflectivity of 2% from a hydrogen breakdown plasma at a pressure of 150 Torr. The optical quality of the reflected pulse depends on the growth of the breakdown plasma. Streak photographs of the luminosity from a breakdown plasma indicate (Ref. 12) a smooth growth in both the radial and axial directions; therefore, a reasonable beam quality is expected. Finally, the background radiation level prior to the ejection of the pulse will be small if a truly unidirectional operation can be achieved and if the scatter of the partially reflecting mirror is small, both conditions being reasonably easy to achieve in theory. However, after the desired pulse is ejected from the cavity the signal-to-noise level may be degraded as follows: The leading portion of the pulse generating the breakdown is transmitted through the focal region and after a cavity round trip is incident once again on the breakdown cell. If, after the round trip time, approximately 50 nsec in a typical laboratory setup, the plasma is still highly reflecting, another pulse will be ejected from the cavity. However, if the plasma expands rapidly during the 50 nsec and is sufficiently cool, the reflectivity may be reduced by several orders of magnitude. This problem as well as the previous ones must be subject to experimental scrutiny.

A fundamental advantage to this pulse selection technique is the possibility of sharpening of the leading edge of the pulse by the rapid "turn-on" of the plasma reflectivity. Neglecting losses the index of refraction, $\mu$, of a plasma is given by (Ref. 13)

$$\mu^2 = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \tag{3.1}$$

$$\omega_p = \sqrt{\frac{n e^2}{\epsilon_o m}} = 56.4 \sqrt{n} \quad (n \text{ in } m^{-3}) \tag{3.2}$$

where $\omega$ is the radian frequency of the field, $\omega_p$ is the plasma frequency, n is the electron concentration and e and m are the electron charge and mass, respectively. The reflectivity of the plasma is given by

$$R = \frac{(\mu-1)^2}{(\mu+1)^2} \tag{3.3}$$

For 10.6 micron radiation the radian frequency is $1.79 \times 10^{14}$ $sec^{-1}$ and the plasma frequency is equal to the radian frequency at an electron concentration of $10^{19}$ $cm^{-3}$. At this point the index of refraction becomes purely imaginary within the framework of this simple model and the plasma is 100% reflecting. However, at an electron concentration of $10^{18}$ $cm^{-3}$, the index of refraction deviates from unity by only 0.05 and the plasma reflectivity is approximately $6 \times 10^{-4}$. Thus a factor of ten growth in the electron concentration results in a dramatic increase in the plasma reflectivity.

Estimates of the electron growth can be obtained by recent computer calculations of clean-air breakdown (14). In these calculations a square laser pulse and an initial electron concentration of $10^3$ $cm^{-3}$ are assumed, and the growth of the electron temperature and concentration are solved in a self-consistent manner, taking into account the various energy losses. Results for two different field values are shown in Fig. 5. For the threshold field of $1.1 \times 10^6$ v/cm, the electron temperature achieves an equilibrium value of $3.7 \times 10^4$ °K after approximately 0.5 nsec but the electron concentration does not start to grow until the electron temperature reaches $3 \times 10^4$ °K; thereafter, it grows exponentially with a time constant determined by the rates appropriate to the steady-state electron temperature. Although this curve does not extend beyond a concentration of $10^6$ $cm^{-3}$ it appears that a time constant on the order of 0.5 nsec results in a ten-fold increase in the electron concentration. For the higher field of $1.47 \times 10^6$ v/cm, the steady-state electron temperature is reached after 0.06 nsec and the growth of the electron concentration starts at 0.04 nsec, when the electron temperature is once again approximately $3 \times 10^4$ °K. The ensuing exponential growth proceeds at the higher rate determined by the correspondingly higher electron temperature. For a ramping pulse typical of experimental conditions it can be argued that the electron temperature will initially increase at a slower rate and that the electron concentration will not start to grow until the temperature is on the order of $3 \times 10^4$ °K. Now since the intensity continues to rise, a steady-state electron temperature will not be realized; rather, the temperature will continue to increase and the time constant for the electron growth will be progressively faster. For a fast ramping pulse of nanosecond duration, the time required for the electron concentration to grow from $10^{18}$ $cm^{-3}$ to $10^{19}$ $cm^{-3}$ will be substantially shorter than 0.5 nsec. A correspondingly sharp growth of the plasma reflectivity is expected from the preceeding discussion.

### 3.2 Exploration of the Ring Laser Concept

A ring laser was set up to explore this concept. Power output with this geometry was found to be comparable to that obtained with the standard Fabry-Perot type structures. There was speculation that the ring laser might run in only one direction without the use of a unidirection element, because of radiation scattering or inhomogenous excitation of the laser medium. This did not prove to be the case. On each firing of the laser, more-or-less equal outputs were obtained in the two beams. An attempt was made to force the laser to run in one direction by placing a partially reflecting mirror in one of the exit beams, redirecting a portion of that beam through the gain medium. Even with 80% feedback it was not possible to quench the second beam. Another possible technique, which has recently been demonstrated but not tried at the time, is the use of a c.w. probe beam to injection lock the pulsed laser (Ref. 15). Thus, it appeared that a unidirectional element is required.

At the 10.6μ wavelength, a unidirection element can be formed with a CdS quarter wave plate and an InSb Faraday rotator. The principal axis of the quarter wave plate is set at $45^{o}$ to the desired polarization direction. By adjusting the magnetic field to give a $45^{o}$ rotation in the Faraday element the net rotation of a clockwise wave is $0^{o}$ whereas the rotation of a counter-clockwise wave is $90^{o}$. The counter-clockwise wave will suffer 7.6% reflection losses at each air-Brewster salt interface and 77.5% losses at each air-Brewster germanium interface, resulting in a 96% loss per pass. CdS quarter wave plates are commercially available, and anti-reflection coatings have been developed with 98% transmission and c.w. power tolerances of 200 $W/cm^2$ . An InSb Faraday rotator has been constructed at UARL under a separate corporate sponsored program. The free carrier concentration of the element is $5 \times 10^{16}$ $cm^{-3}$ giving a rotation of 7.[illegible] $\times 10^{-20}$/gauss-cm; however, to reduce free carrier absorption, the element must be operated at 77 $^{o}$K. Permanent magnets are mounted inside the nitrogen dewar and provide a nearly uniform magnetic field of 4 kgauss over the sample aperture of 5 mm. With a field of 4 kgauss a smaple thickness of 1.5 mm gives the required $45^{o}$ rotation. Bulk absorption and 3% losses at the anti-reflection coated surfaces give a net transmission of 80%. The 5 mm aperture of the presently available rotator is a severe restriction, making difficult the allignment of optical components, already complicated by the lateral shift introduced by the Brewster angled modulator. As a result, the ring resonator approach was abandoned for the present time in favor of a more direct technique, employed external to the laser cavity.

### 3.3 Two Cell Method

The two cell method is illustrated in Fig. 6. The mode-locked train of pulses, illustrated in trace (A), is incident from the left and causes breakdown in the first cell which, eliminates all subsequent pulses, as shown in trace (B). This cut off pulse train is incident upon a partial reflector and a portion of it goes on to a second breakdown cell. If the focal lengths of the second lens is judiciously chosen (or the pressure in the cell correctly adjusted) breakdown can be made to occur on the leading edge of the last pulse in trace (B). The reflected pulse, trace (C), exits at an angle to the incident beam. To reduce the background, the leading portion of the pulse, which is transmitted through the focus, is prevented from reflecting back through the optical system by using a light dump. Thus, the breakdown in the first cell eliminates the trailing portion of the pulse train, and the breakdown in the second cell eliminates the leading portion of the pulse train. leaving only the desired pulse which is also shortened by the two breakdown processes. With this technique the ratio of the reflected pulse to the background radiation level depends exclusively on the quality of the optical components, in particular, on the anti-reflection coatings of the last lens.

. At this point it is useful to digress briefly and discuss some recent measurements of air breakdown thresholds (Ref. 16). The predicted threshold for STP air breakdown is $3 \times 10^9$ W/cm$^2$ (Ref. 17), independent of beam size for diameters sufficiently large that the diffusion of free electrons out of the breakdown region can be neglected; however, until recently measurements of air breakdown thresholds have shown an inverse focal spot size dependence, similar to that shown in curve (B) of Fig. 7 with a threshold for large beam diameters two orders of magnitude lower than predicted. It is now recognized that particulate matter of micron and submicron dimensions present in the atmosphere at typical concentrations of $10^{3}$-$10^{4}$ $cm^{-3}$ initiate breakdown at these lower intensity levels. Canavan (Ref. 18), has presented an explanation of the inverse diameter dependence in terms of the probability of finding a particle in the focal volume, with larger particles assumed to initiate breakdown at lower intensity levels. For particulate initiated air breakdown a very weak pressure dependence is found (Ref. 19). To measure clear-air breakdown, ultra-pure bottled air was used, and particulate matter was removed by passing the gas through a 0.025-micron filter. A thoroughly scrubbed breakdown cell was used and a fresh gas fill was used for each laser firing as particulate matter is driven from the lens and the cell walls by the impinging radiation. The laser used in these measurements was constrained to fundamental mode operation to avoid the large spatial fluctuations found with multi-mode beams. Lenses of various focal lengths were used to focus the radiation in the breakdown cell and the focal spot size is taken to be $F\theta$, where F is the focal length and $\theta$ is the full angle divergence of the laser beam. Under these conditions the data shown by curve (A) are measured. For the largest beam diameter a threshold in agreement with the predicted clean-air threshold is observed. For smaller focal spot sizes the threshold increases and a diffusion-like fit to the data can be made; however, the diffusion constant is an order of magnitude larger than expected for free electron diffusion, for which no explanation is available. With the 70-nsec pulse width used in these measurements the threshold is found to increase linearly with decreasing pressure; however, above atmospheric pressure, only a weak pressure dependence is observed. A stronger pressure dependence would be expected for pulses of nanosecond duration (Ref. 20).

For clean air the occurence of breakdown is a steep function of intensity, going from a 0% probability (<1 out of 10 identical firings of the laser) to 100% (10 events out of 10 shots) for a 10% increase in the intensity, indicative of a true threshold behavior. Since only the average pulse energy was recorded in this series of measurements it is believed that even this small scatter can be accounted for by shot-to shot fluctuations in the laser output and that the threshold is extremely sharp. In contrast to this the breakdown probability of laboratory air is more gradual, increasing from 1% to 100% for a three-fold increase in the intensity.

The success of the pulse selection method requires reproducible settings for the breakdown thresholds in the two cells; therefore, from the preceeding discussion it is clear that clean air conditions are essential.

In the experiments to be described below two combination of lenses were used. In the first combination, a pair of 3.7-cm focal length lenses are used in the first cell, followed by a 2.5-cm lens in the second cell. In the second combination, a pair of 6.4-cm lenses are used in the first cell, followed by a 3.7-cm focal length lens in the second cell. For a laser with a 1 mrad beam divergence, the required intensities for clean-air breakdown are $1.03 \times 10^{11}$ W/cm$^2$., $6.2 \times 10^{10}$ W/cm$^2$, and $2.3 \times 10^{10}$ W/cm$^2$ in order of increasing focal length. The required laser power levels are 0.5 MW, 0.67 MW, and 0.74 MW, respectively.

### 3.4 Experimental Measurement of the Plasma Reflectivity

This method was tested by using the self-mode-locked pulse train from a 3-m long helical pin-type TEA laser. The laser cavity consisted of 6-m radius of curvature totally reflecting mirror and an 80% reflecting flat output mirror, with an 8 mm aperture directly inside the flat mirror for mode selection. With this configuration a pulse energy of 0.04 J and a beam divergence of 1 mrad is obtained. The pulsewidth is 200 nsec, giving a peak power of 0.2 MW. As discussed above this intensity is too low to produce breakdown in clean gasses; therefore, the first experiments were carried out with laboratory air in the breakdown cells.

The first experiment was conducted without the first cell in order to measure the plasma reflectivity. Typical results are shown in Fig. 8. The first trace shows the incident pulse as monitored at position 1 (see Fig. 6). The second trace shows the reflected pulse seen by the detector at position 2. This trace on a 50 nsec/cm scale, shows the self-mode-locked structure on the pulse train and the abrupt "turn-on" of the plasma reflectivity, the actual "turn-on" being limited by the response of the detector (~2 nsec, 10-90 risetime) and the 150 MHz bandwidth of the oscilloscope (~2.4 nsec, 10-90 risetime) giving a combined risetime of approximately 3.1 nsec. The magnitude of the plasma reflectivity can be estimated from these traces. The incident pulse was transmitted through the 50% beam splitter and a 90% attenuator was placed in front of the detector to prevent saturation. Thus

$$\begin{aligned}(0.5)\,(0.1)\,P &= 1.5 \text{ volts} \\ P &= 30 \text{ volts}\end{aligned} \tag{3.4}$$

The pulse incident upon the breakdown cell and the reflected pulse undergo a 50% reflection loss at the beam splitter, thus

$$\begin{aligned}(0.5)R\,(0.5)\,P &= 0.3 \text{ volts} \\ R &= \frac{0.3}{(0.25)\,(30)} = 4\%\end{aligned} \tag{3.5}$$

By carefully adjusting the position of the detector, a reflection signal level approximately twice that shown in the trace could be obtained; thus the 4% value is low and 8% may be more appropriate. This 4-8% reflectivity is smaller than the previously reported value of 10% (Ref. 10). Under the tightly focussed conditions of this experiment, the curvature of the expanding breakdown plasma may not be perfectly matched to the optics and so only a portion of the reflected radiation is re-collimated by the focussing lens. The use of longer focal length lenses, other types of gas, or higher pressures may result in an improved reflectivity. In Fig. 8, trace B, a small signal level (~0.02v) is seen prior to the plasma reflectivity, giving a signal-to-noise for the present arrangement of approximately 15. This background signal level is apparently due to non-perfect anti-reflection coatings on the lens and could be reduced by specifying more exacting tolerances for the anti-reflection coatings, designing a lens with surface curvatures which would provide a minimum reflected signal in a collimated beam, or replacing the lens with an off-axis paraboloid.

If the reflected beam is to be useful it must have a beam quality comparable to that of the incident beam. It was argued that if the breakdown plasma expands uniformly one would expect the reflected beam to have a beam quality comparable to the incident beam. A test of the quality of the reflected beam was carried out as follows. Using a flat mirror in place of the lens it was possible to locate the detector 2.5 meters away from the breakdown cell. Since the beam reflected from the plasma was not perfectly coincident with this allignment beam a 4-in focal length mirror was used to focus the radiation onto the detector element. The reflected signal was clearly picked up in this manner and signal levels as high as 3 volts were measured when the detector was properly centered. Scanning the detector, the signal was found only over a 3-mm range, equal to the diameter of the detector element. Thus the focussed spot size of the reflected beam must be less than 1 mm and hence its divergence is inferred to be less than 10 mrad. This test has shown that the reflected signal can be propagated over a 2.5-m path and that the divergence is less than 10 mrad. Further work will be required to see whether the divergence is equal to the 1 mrad divergence of the incident beam.

When the first breakdown cell was placed in the optical train the following observations were made. Breakdown occured in the first cell approximately 50% of the time and breakdown in the second cell likewise occured 50% of the time, but the simultaneous occurence of breakdown in the two cells was only about 1 out of 50. Breakdown at these flux levels requires a particle for its initiation, and in either cell the probability of finding a particle of the required size is only 50%; however, when breakdown does occur in the first cell it most often occurs at an intensity sufficiently below the peak that the transmitted pulse is no longer intense enough to initiate breakdown in the second cell. Increasing the pressure in the second cell to 130 psi made no difference since at these small focal spot sizes the threshold is relatively independent of pressure. Thus the success of the proposed method requires clean breakdown, as discussed earlier, and the output beam must be amplified to reach the desired flux levels.

## 3.5 Pulse Selection by the Two Cell Method

The experimental arrangement used to study the pulse selection method with clean gases is shown in Fig. 9. The single mode output from the helical pin-type laser is amplified by a double passage through a solid-cathode double-discharge laser of 75-cm active length. At this point the first breakdown cell is introduced, having two 6.4-cm focal length lenses separated by 12.7 cm. The leading portion of the pulse, which is transmitted through the breakdown cell, is then redirected through the amplifier and incident upon the 50% beam splitter, followed by the second breakdown cell. A 3.7-cm focal length lens is used in this cell. The reflected beam is propagated over a 2-m path before being received by the detector. The Santa Barbara gold-doped germanium detector and the Tektronix 454 oscilloscope were enclosed in a shielded box to prevent r.f. pickup from the pulsed lasers. The 10-m radius of curvature mirror and the 1:1 telescope of the first breakdown cell combined to keep the beam confined to a diameter of 1 cm or less over the 7-m optical path.

The expected amplification per pass can be estimated from the following expression developed for a two-level system (Ref. 21).

$$E_o - E_1 = \tfrac{1}{2} g_o L E_s - \tfrac{1}{2} E_s \ln \left( \frac{1 - \exp(-2E_o/E_s)}{1 - \exp(-2E_1/E_s)} \right) \qquad (3.6)$$

where $E_o$, $E_i$, and $E_s$ are the output, input, and saturation energy fluxes, respectively, $g_o$ is the small signal gain, and L is the length of the amplifier. The 0.04-J input beam, with an approximately 4 mm diameter, has an input energy flux of about 0.5 J/cm$^2$, equal to the saturation energy flux. Using the expression above, first and second pass amplifications of 3 and 1.6 respectively, are expected for a $g_o L$ product of 4, typical of the solid-cathode double-discharge operation, giving a combined amplification of 4.8. In the actual case, modifications of the above expression are expected since the beam profile is gaussian, rather than the uniformly illuminated case treated analytically, and the beam is expanding slightly as it proceeds through the amplifier. Experimentally, a first pass amplification of 2-3 was found. Following breakdown in the first cell the energy flux in the beam is reduced to approximately 40% of its two pass value, that is to 1 J/cm$^2$, so that a third stage amplification of 2 is expected.

After two stages of amplification, the power incident upon the first cell is approximately 1 MW. Since the breakdown of clean air at atmospheric pressure in this cell requires 0.74 MW, the beam has enough power to allow a certain margin for shot-to-shot variations in the operation of the oscillator and the amplifier. Breakdown in this cell was observed better than 90% of the time, the misses being caused by erratic performance of the pin-type laser. Breakdown in this cell produces a saw-tooth pulse of 0.74 MW peak power and 100 nsec base. Neglecting pulse sharpening in the amplifier, the factor of 2 gain in the third pass compensate for the 50% reflection loss of the beam splitter and the above described saw-tooth pulse is incident upon the second cell. Breakdown in this cell requires a power of 0.67 MW and should occur at the 90 nsec mark on the saw-tooth, resulting in a reflected pulse of 10 nsec duration. Breakdown in this cell was also observed better than 90% of the time and with few exceptions, if breakdown occured in one cell, it occured in the other. In practice the self-mode-locked structure on the output pulse and shot-to-shot variations in the performance of the amplifier modifies the arguments presented above. Approximately 60% of the reflected pulses consist of a 20-50 nsec slice of the incident pulse and contains several self-mode-locked pulses of nearly equal intensity. In the remainder of the cases, a single pulse is reflected from the cell. Typical reflected pulses are shown in Fig. 1[illegible]. In trace (A) a single mode-locked pulse is extracted and from the ringing observed on the trace it can be inferred that the actual pulse is considerabley faster than [illegible] nsec response time of the detection system. Traces (B), (C), and (D) show [illegible], 20, and 50 nsec slices from the incident pulse. These traces also exhibit the fast "turn-on" of the plasma reflectivity.

Greater control over the width of the selected pulse could be achieved by the following modification to the two-cell arrangement. Basic to the change is the elimination of the third pass through the amplifier, since it introduces an undesirable variability in the intensity of the pulse incident on the second cell, due to shot-to-shot and spatial variations in the operation of the present amplifier. If four passes are made through the amplifier the 0.04-J pulse should be amplified by a factor of 12 and the peak intensity increased to 2.4 MW. Then, using a pair of [illegible]-cm lenses in the first cell, a peak intensity of $4.9 \times 10^9$ W/cm$^2$ would be obtained, whereas $4.5 \times 10^9$ W/cm$^2$ is required for clean air breakdown. The peak intensity of the transmitted pulse is 2.2 MW and, after reflection from a 50% beam splitter, 1.1 MW would be available for breakdown in a second cell. Breakdown in a second cell with a 13-cm lens would require 1.07 MW. Hence with truly clean air breakdown a good control over the pulse selection should be possible with this arrangement. Fine tuning, if required, could be obtained by making use of the weak pressure dependence at these focal spot sizes.

### 3.6 Summary

This section has presented a discussion of pulse selection based on gas breakdown. An exploratory study was made of the proposed scheme based on breakdown in a unidirectional ring laser, which indicated that additional optical components would be required to achieve the desired unidirection operation. The feasibility of the method was then examined using a two-cell arrangement external to the laser cavity and the following characteristics were determined.

(1) The plasma reflectivity of air at atmospheric pressure was 4-8% for a laser pulse of ~100 nsec duration.

(2) The reflected beam could be propagated several meters and appeared to have a divergence comparable to the incident beam.

(3) The ratio of the signal to the background level was 15:1. The background level was controlled by the reflectivity of the lens in the second cell. Methods of reducing this level are discussed.

(4) The reflected pulse exhibits a sharp leading edge, faster than the time response of the detection system. A simple analysis indicates that the reflectivity should increase three orders of magnitude in one generation time. This time is at least 0.5 nsec and may be shorter for a fast ramping pulse of nanosecond duration.

Reproducible operation of the two-cell method requires clean gasses in the breakdown cells and an oscillator-amplifier arrangement is used to achieve the required flux levels. Single pulses of nanosecond duration have been extracted from the self-mode-locked output pulse; however, due to shot-to-shot variations in the operation of the oscillator and the amplifier, control over the width of the extracted pulse is not yet possible.

Additional study of this attractive pulse selection technique will be carried out. The suggested modification to the two-cell method should allow a greater control to be exercised over the width of the extracted pulse. This arrangement will also be studied with mode-locked pulse trains using the acousto-optic modulator developed earlier under this contract. Other gases will be used to examine the plasma reflectivity with a view to obtaining a higher reflectivity than the present 4-8%. Finally, having established the validity of the concept, consideration should once again be given to the proposed ring laser arrangement. The most important feature of this pulse selection technique is the sharpening of the leading edge because of the rapid "turn-on" of the plasma reflectivity, a feature which may find application in laser-induced fusion. As a result, an effort will also be made to use one of the methods discussed in Section 2 to resolve the selected pulses.

Section 4

# METAL VAPOR LASERS WITH CLOSED-CYCLE VAPOR FLOW

## 4.1 Introduction

Metal vapor lasers have attracted considerable interest by virtue of their potential efficiency and high peak power output in the visible part of the spectrum, particularly in the blue and green regions of interest for underwater applications. The copper vapor laser, for example, has exhibited efficiency in excess of 1% with tens of kilowatts peak power at a wavelength of 5106 Å. However, the copper laser, like most other metal vapor lasers with comparably high potential efficiency, is of the cyclic type in which laser action is self-quenching due to termination of the lasing transition in a long-lived metastable state. In such lasers it is necessary to substantially remove the metastable population resulting from a previous output pulse before lasing can again be initiated. This requirement sets an upper limit on the pulse repetition rate and thus on the average power attainable for these lasers. For example, experimental evidence suggests output degradation at pulse rates greater than about $10^4$ Hz in typical lead vapor lasers, about $10^3$ Hz in copper, and $10^2$ to $10^3$ Hz in thallium. On the assumption that these limits are imposed primarily by insufficient interpulse metastable depopulation, it can be expected that enhancement of the metastable depopulation rate should significantly increase the attainable repetion rates. It is thus of interest to consider the possibility of using rapid vapor flow across the laser channel as a means of enhancing metastable removal rates, and thus maximum laser pulse rates.

### 4.1.1. Description of Evaporation-Condensation Flow Cycle

In the case of materials, including metals such as thallium, lead, mercury and copper, which evaporate from and condense to a liquid state at conveniently attainable temperatures, a particularly attractive method of obtaining rapid vapor flow is one involving a continuous evaporation-condensation cycle such as is used in ordinary diffusion-type vacuum pumps. In essence, the cycle involves heating a liquid to produce vapor which streams rapidly to a cool surface, where it condenses. The condensate then returns to the heater, e.g. via gravity flow, for re-evaporation.

One way of applying such a cycle to flowing vapor in a laser is to use a laser discharge tube having a hot sidearm (evaporator) at one end and a cool sidearm (condenser) at the other end, with the sidearms connected by a liquid return path. However, such a longitudinal flow configuration has the disadvantage of requiring gas to flow the entire length of the laser tube before it is actually removed from the optical path. Flow velocities must then be inordinately high to achieve useful removal rates. This problem can be overcome by flowing the vapor transverse to, rather than parallel to, the optical path. If a narrow discharge channel is used, rapid gas removal can be effected by means of relatively low flow velocities.

One method of obtaining transverse vapor flow is to place the working material (lead, copper, etc.) on the bottom of a simple cylindrical laser tube and then to heat the bottom of the tube, while cooling the top, as indicated in Fig. 11. The material melts and evaporates from the bottom, with the vapor rising to and condensing at the top, and the condensate flowing down the tube walls for re-evaporation.

In estimating the flow rates to be expected in configurations of the type shown in Fig. 11, it is useful to consider the case of an evaporating plane surface separated from the condensing surface by a distance not significantly larger than the mean free path of the vaporized metal atoms. In the case of copper, which is of interest because of its green radiation and high efficiency, strong laser emission has typically been observed at copper pressures as low as $10^{-1}$ Torr, corresponding to a mean free path of the order of 1 centimeter. Under these conditions, the mean free path criterion stated above is approximately satisfied for evaporator-condenser spacing of the order of 1 cm, and the rms velocity ($V_{rms}$) of atoms moving from evaporator to condenser is determined simply by the temperature of the evaporating surface in accordance with the expression (Ref. 22)

$$V_{rms} = 2(kT)^{\frac{1}{2}} \quad m^{-\frac{1}{2}} \tag{4.1}$$

where k is the Boltzmann constant, m the atomic mass, and T the evaporation temperature. For a temperature of about $1420^{\circ}C$, corresponding to the assumed $10^{-1}$ Torr copper vapor pressure, Eq. (4-1) gives $V_{rms} \approx 10^5$ cm/sec. Thus, for an evaporator-condenser spacing of 1 cm an atom spends typically about $10^{-5}$ seconds in the laser, i.e., the gas in the laser is changed at a rate on the order of $10^5$ times per second. In this case, the maximum laser repetition rate without output degradation should approach $10^5$ pps, an increase of about two orders of magnitude over the rates suggested by available data for non-flowing copper vapor lasers. It should be noted that vapor pressures in excess of $10^{-1}$ Torr, which may be required for maximum laser efficiency, may reduce the flow effectiveness, due to collisions between atoms in the vapor. However, the operation of the evaporation-condensation cycle remains essentially unchanged.

### 4.1.2 Review of Experiments with Low Temperature Metal Vapor Lasers

Although lead is inherently less efficient and spectrally less desirable (red and blue laser outputs) than copper (green output), its low evaporation temperature made it a more practical vapor for initial work with the evaporation-condensation flow cycle. A laser configuration was designed and constructed making use of the desired transverse vapor flow along with other features such as multiple low inductance transverse discharges, and high temperature materials resistant to thermal shock and to cracking by solidification of the molten metal. With lead as the laser medium, proper operation of the flow cycle was confirmed and laser repetition rates in the low kilohertz range were obtained, limited only by the de-ionization rate of the spark gap used in the discharge pulsing circuit. Problems with synchronization of the multiple transverse discharges were largely over come by use of separate, simultaneously switched capacitors driving the individual discharge electrodes.

Thallium was found to lase better in the above apparatus than in a conventional, non-flowing, longitudinal discharge configuration. Reliable data could not be obtained with thallium, however, due to rapid coating of the electrode insulators with a conductive deposit which short circuited the discharge pulses. This was not as severe a problem with lead, which produced a non-conducting deposit consisting of small separate droplets.

Attempts to obtain laser action in bismuth and antimony, neither of which has yet been reported to lase, were unsuccessful, probably due at least in part to the polyatomic nature of their vapors, in contrast to the monatomic vapors of usual metal vapor lasers.

In work with the "low temperature" metals indicated above, it became apparent that large differences in both physical and atomic characteristics of the various metals would make it difficult to achieve a single optimum laser design for all metals. Consequently, it seemed reasonable at this point to proceed directly toward work with copper vapor, which is presently the most promising candidate for efficient, high power operation.

### 4.2 Copper Vapor Laser Development

Initial work with copper, using apparatus similar to that used with the low temperature metals, provided additional evidence that subsequent work should be concentrated on development of a laser configuration for use specifically with copper. For example, it was found, among other things, that copper was even worse than thallium in forming conductive deposits on the electrode insulators, and that the surface wetting characteristics of liquid copper caused it to creep up and out of metal boats of the type used with lead and thallium. Consequently, it was necessary to make major alterations in the earlier laser design.

#### 4.2.1 General Design Considerations

The basic design problem in the present work is to achieve a laser configuration incorporating all of the following features:

(1) Rapid closed-cycle copper vapor flow transverse to the laser axis, making use of a continuous evaporation-condensation flow cycle.

(2) Means for introducing a reasonably uniform, spatially confined, rapidly pulsed electrical discharge in the flowing vapor.

(3) Provision for passage of the laser beam through the electrically excited vapor without allowing copper to escape from the flow cycle.

(4) Protection of hot materials from oxidation and from other effects of atmospheric constituents.

The problem is somewhat similar to that of designing a $CO_2$ laser with closed-cycle transverse flow, but with the added complexities associated with use of vapor which readily condenses to an optically dense and electrically conductive coating at any temperature lower than about 1500°C, and which tends to react with, melt, or otherwise degrade many ordinary optical and constructional materials at higher temperatures.

In developing the flowing copper vapor laser configuration it has been convenient to consider the vapor source and the laser channel as somewhat independent entities. The vapor source consists of a container (boat) for the molten copper and a heater to evaporate the copper. Provision is included for passage of vapor from the source and for return of condensate to the heated region. The laser channel comprises a region bounded by walls sufficiently cool to ensure condensation (but not solidification) of copper vapor entering the region from the vapor source. This results in essentially unidirectional vapor flow to the channel wall and thus provides the desired rapid removal of spent atoms from the active laser volume. The channel walls are shaped to induce gravity flow of the liquid condensate back to the source and must also provide for the introduction and confinement of a suitable electrical discharge and for through passage of the optical beam. This is to be accomplished without allowing loss of copper vapor or condensate and without permitting excessive discharge penetration into the vapor source region. The entire assembly of vapor source and laser channel is to be suspended in an evacuable chamber provided with optical access ports, electrical feedthroughs, vacuum and gas backfilling facilities, etc.

4.2.2 Vapor Source Design

Of primary importance in developing the vapor source is the choice of material for containment of the liquid copper. Since the copper is to be evaporated from this container, the material must withstand a minimum of 1500 to 1700°C without reacting with or dissolving in the copper. Attempts to use readily available refractory metals such as tungsten, molybdenum and tantalum have resulted in attack and eventual destruction of the refractories by the copper. High temperature ceramics appear to better withstand the molten copper, but the hard ceramics such as alumina (and also quartz, though its melting point would at best be marginal for this application) are apparently wet sufficiently by the copper to cause cracking of the ceramic as the copper solidifies and contracts on cooling. In addition, the hard ceramics are not well suited for laboratory fabrication into any but the simplest forms. Of the readily available materials, only boron nitride and graphite have exhibited adequate resistance to the molten copper and to cracking during cooldown, while also providing good machinability and ease of fabrication. Boron nitride has the advantage of being a better thermal conductor and better electrical insulator than graphite, making it easier to obtain uniform heating of the boat and to prevent short circuiting of heating element. These factors, along with the fact that molten copper seems to fall away more cleanly from walls of boron nitride than from those of graphite, have made BN the material of choice for the evaporating boat. Also important in the vapor source design is choice of a method for heating the copper. Only resistance heating techniques have been investigated to date, although electron bombardment, induction heating, etc., might be reasonable alternatives to consider. Since direct resistance heating of the copper would require very large currents, it has been more convenient to use some form of indirect heating with either graphite or tungsten as the resistive heating element material. The problem then is to find a suitable means of transferring sufficient heat from the heater to the liquid copper. Several approaches tried to date are discussed below.

It was hoped earlier that the surface wetting action of copper on solid metals (the action causing copper to creep out of some metal boats) would allow use of refractory metal wicks to draw molten copper from a reservoir to the heating element. This would have required only the heating element to reach evaporation temperature, with the rest of the laser remaining just hot enough to prevent solidification. Attempts were made to employ this technique using a tungsten rod heater in conjunction with twisted wire wicks of tungsten, molybdenum, or tantalum. Of these wick materials tungsten and molybdenum provided adequate wicking action and resulted in successful laser operation using multiple transverse discharge excitation. In each case, however, not only the wick, but also the adjacent heater material was rapidly eroded away by the hot copper. Erosion was substantially less for tantalum wicks, due largely to the reduced degree of surface wetting and the resultant lack of adequate wicking action.

Heat transfer somewhat similar to that provided by the wick technique can also be obtained by using heater elements which directly touch the molten copper. In this case the contact area must be small and each contact point must be associated with an electrically separate pool of copper in order to prevent short circuiting of the heater. Alternatively the heater might be coated with a high temperature, electrically insulating coating with high thermal conductivity and a thermal expansion coefficient matching that of the heater. However, such a coating has not yet been found. Tests with the direct contact heater technique suffered from problems in addition to the required complex multiple-pool boat configuration. For example, the relatively low thermal conductivity of graphite heaters and minimal graphite surface wetting by the copper, coupled with the necessarily small contact areas made it difficult to transfer sufficient energy from heater to copper. Tungsten heaters on the other hand have high thermal conductivity and are easily wet by copper, leading to good heat transfer characteristics. However, the tungsten was again rapidly eroded by the copper and the wetting action also caused copper to creep out of the reservoir along the heater surface.

The multiple copper pools required for direct contact heating can be avoided by placing the heater just above the liquid surface, but still internal to the vapor source, thus preventing direct short circuits while still providing good heat confinement. However, heating must then be accomplished by radiation (rather than conduction) from heater to copper, and this requires substantially higher heater temperatures unless large heater surface areas are employed. Tests with tungsten heaters in this geometry have suffered again from heater erosion and creep-out of copper, especially where drops of condensate fall back on and wet the heater. Graphite heaters seem not to be limited by these problems, and in fact have produced adequate vapor for laser action. However, as was indicated in the last reporting period prolonged graphite heater operation resulted in a thin carbon coating on liquid copper surfaces. This coating appeared to retard evaporation of copper from the vapor source and to increase its tendency to collect on interior surfaces of the vapor source and the laser channel, leading eventually to blockage of the vapor flow and of the laser optical path.

In the present reporting period these problems have been overcome by replacing the internal graphite heater with an external, resistively heated tungsten strip. Earlier tests of external heaters had resulted in rapid heater failure. However, this was due primarily to lack of sufficient heater area, necessitating very high temperature operation in order to provide the desired heat flux. In the present design the effective heater surface area is comparable to the external surface area of the vapor source, and the vapor source is at least several times larger than in earlier designs. This results in radiative transfer of at least an order of magnitude larger heat flux, at temperatures low enough that no heater failures have yet been observed in normal operation. The increased size of the present vapor source makes heat shielding more important, though not unreasonably difficult. Adequate shielding is obtained using four to six layers of thin refractory metal sheets (e.g. tungsten) around the vapor source assembly. The geometry of the redesigned boat, as in previous designs, has been chosen to satisfy three basic criteria. First, the depth from vapor port (at top of source) to the liquid copper surface should be at least comparable to the source width. This restriction ensures essentially upward directed vapor flow into the laser channel, simplifying the prevention of copper loss from the channel. Second, the surface area of copper in contact with the boat must be large enough to provide adequate heat transfer to the copper at reasonable values of heater temperature. Third, the top port, through which vapor enters the laser channel and condensate returns to the source, should be small enough to concentrate vapor outflow in the central region of the laser channel but large enough to simultaneously allow return of molten copper to the evaporator. The boat wall must be reasonably thin, to maximize through-wall heat conduction to the copper.

### 4.2.2 Laser Channel Design

As in the case of the vapor source, the material of construction for the laser channel should: (1) exhibit high resistance to hot copper vapor and liquid.

(2) be moderately easy to fabricate, and (3) have relatively high thermal conductivity, to improve distribution of vapor-borne heat to outer radiating surfaces of the channel. It was initially thought that the channel material must also be electrically insulating, to simplify proper containment of the electrical discharge; and boron nitride appeared to be the material of choice. However, experimental tests with boron nitride showed its thermal conductivity to be marginal for this application. In addition copper was found to condense as drops and blobs on the boron nitride, often falling or blowing (due to the high velocity vapor flow) through or even out of the laser channel, and occasionally blocking the optical path entirely. These problems have now been obviated by the empirical discovery that discharge confinement is not greatly affected by use of non-insulating channel materials. It is in fact found that sheet tungsten or molybdenum promotes uniform condensation into a sheet of molten copper which returns smoothly along the channel walls to the boat; and the relatively high thermal conductivity, especially of tungsten provides much improved heat transfer charcteristics.

Since the laser channel is to act as a condenser for the copper vapor, it is made of a separate piece of material, relying then on a joint of relatively high thermal impedance between source and laser channel to minimize heat conduction from source to channel. Under these conditions the channel is heated almost entirely by condensation of the copper vapor and can be dimensioned such that heat radiated from the outer surface of the channel balances that delivered by the vapor at the desired vapor flow rate and laser channel temperature.

As indicated earlier, the interior of the laser channel is contoured to promote gravity flow of condensate back to the vapor source. The channel is basically cylindrical (parallel to the optical axis of the laser) but with a downward slope of the bottom surface from both ends toward the central vapor source. Lack of high temperature optical window materials compatible with liquid and gaseous copper dictates that the cylinder be open at both ends to allow through passage of the laser beam. However, since the channel surfaces are cool enough not to re-evaporate copper, it is possible to minimize copper loss by utilizing the directional flow charcteristics of a relatively deep and narrow vapor source, as previously indicated.

With this approach most vapor hits the channel surface directly above the vapor port, immediately condenses on the surface, and eventually slips down the contoured surface into the source for re-evaporation. Refractory metal wicks are found to assist the return of condensate to the boiler, but these have not been necessary in the present work. Experimental tests indicate that relatively little copper is lost from the channel ends with this type of configuration.

One of the problems in designing the laser channel is that of introducing and confining an electrical discharge suitable for laser excitation. Discharge electrodes must be introduced in such a way that most of the discharge energy goes into the central, optically accessible region of the laser channel, and such that condensation of copper on the electrode insulators does not short circuit the discharge. Experimental tests suggest that axial (longitudinal) discharges provide more effective excitation than do multiple transverse discharges in copper vapor lasers of the type considered here. For the axial discharge, satisfaction of the discharge confinement requirement is facilitated by letting the laser channel walls provide confinement at the top and sides of the discharge. At high laser pulse repetition rates the directed flow of copper vapor tends to carry residual discharge products upward, providing effective confinement at the bottom of the discharge. However, at low repetition rates the residue from each pulse disappears before the next pulse arrives, and some other means of bottom confinement is needed. In experimental tests it has been found that such confinement requires relatively little in the way of a physical barrier. In fact there appears to be little discharge penetration into the vapor source as long as the entrance (vapor port) to the source is somewhat smaller than the overall laser channel diameter and as long as the channel diameter is not too small compared to the interior dimensions of the vapor source.

Two methods of preventing insulator failure (due to copper condensate) have been tried experimentally. The first relied on the use of shields over electrode insulators to interrupt the anticipated straight line flight of copper atoms under low vapor pressure conditions. However, this approach was only partially successful, even at low copper vapor pressures, due to the presence of residual gas atoms which may evolve from the hot laser materials or may enter the enclosing vacuum chamber via small leaks, gasket outgassing, etc. Direction-changing collisions of copper atoms with the residual gas atoms resulted in eventual copper coating of even the best shielded insulators. At higher copper vapor pressures where the assumption of straight line atomic flight is no longer valid, even in principle, insulator coating was so rapid as to make even brief laser operation impractical.

The second, and more successful, approach to the copper condensate problem is based on the experimental observation that (at least on some substrates) the usual uniform vapor-deposited copper film tends to break into separate droplets if the substrate temperature is sufficiently above the copper melting point. Boron nitride and, to an apparently greater extent, quartz are among the substrates showing this behavior. As a result it is possible to prevent formation of conductive coatings on insulator surfaces by keeping the temperature well above the melting point of copper, but still below the evaporation temperature. The relatively good droplet forming and droplet shedding characteristics, along with the ready availability and relative chemical inertness of fused quartz, initially made this the material of choice for electrode insulators. However, boron nitride has since been found to perform satisfactorily with a longer service life. The electrodes have been inserted either through the top wall or through the open ends of the laser channel, with the former technique usually having the advantage of obscuring less of the laser channel cross-section. In either case impinging copper vapor provides adequate heating to promote the desired droplet formation on the insulator surfaces.

### 4.2.4 Design Details of Operational Copper Vapor Laser

Evolution of the foregoing design ideas, based on construction and test of a variety of experimental units, has resulted in development of a practical, operational copper vapor laser with closed cycle transverse vapor flow. The laser, shown schematically in Fig. 12, includes an externally heated, heat shielded boiler, and a radiatively cooled laser channel with roof-mounted electrodes. Photographs of the laser are shown in Figs. 13 and 14.

The boron nitride boiler is 2.5 cm square by 7.5 cm deep, with 0.25 cm thick walls and with a slightly constricted top opening to direct vapor into the channel. The external resistance heater is a 5 mil thick by 2.5 cm wide tungsten strip mounted close to, but not touching, the boiler walls. The heater-boiler assembly is heat shielded by several layers of refractory metal sheet. Tungsten appears to be best, although molybdenum and tantalum have also been used.

The laser channel consists of a boron nitride base, tapered inside to promote flow of condensate to the boiler, and a refractory metal roof serving as the condensing surface. Tungsten appears to be the best roof material in terms of resistance to attack by the copper and of high heat conductivity. However, molybdenum is more readily worked, and more available, and offers adequate performance for laboratory purposes. Tantalum is too rapidly attacked to be useful here. The laser channel assembly is about 6 cm long, with 1 to 2 cm transverse dimensions. Machined boron nitride electrode insulators protrude a few millimeters through the channel roof, spaced by 2.5 cm. The electrodes are of tungsten wire, pointed and flush-mounted in the insulators to minimize the electrode surface exposed to copper vapor. The minimal surface exposure prevents large drops of copper condensate from hanging on the electrode tips.

The entire laser assembly is mounted in a vacuum tight, water cooled chamber equipped with electrical feedthroughs and with gas filling and evacuation ports. Brewster angle windows in the chamber walls opposite the ends of the laser channel provide access to external reflectors comprising the laser resonator. Energy for the electrical discharge laser excitation is stored in a capacitor external to the chamber and is supplied to the laser electrodes through a spark gap switched, low inductance discharge circuit.

### [illegible] Copper Vapor Laser Operation

In operation, the boiler is typically half-filled with copper, argon buffer gas is admitted to the chamber at a pressure somewhat less than one Torr, and the copper is heated until a bright liquid copper sheet has condensed on the interior of the laser channel roof. Typical roof temperature during operation is about 1[illegible] °C.

with a boiler temperature of about 1700°C. The external resonator mirrors are aligned by conventional methods and the discharge capacitor is then charged. This capacitor is discharged into the vapor filled laser channel through a triggered or overvoltaged spark gap. Laser operation has been achieved for a wide range of capacitance values (several hundred to several thousand picofarads), charging voltages (3 to 30 kv), and output mirror reflectivities (4 to 99 percent) however, most observations have been made with a capacitance of 500 pf, charging voltage of about 7 kv, and output mirror reflectance of 33 percent. In spite of the short active discharge region (2.5 cm) and the small discharge energies employed (of order $10^{-2}$ joule), laser output normally occurs on both the green 5106 Å and the yellow 5782 Å copper transitions; predominantly in the green. However, either wavelength can be obtained alone by usual prism or diffraction grating selection techniques. Typical output pulses at 5106 Å exhibit peak powers of order $10^{2}$ watts, with a pulse duration (FWHM) of 20 to 30 nsec, thus yielding pulse energies up to a few microjoules. The output beam is uniformly illuminated over an area corresponding to the transverse cross-section of the laser channel, and exhibits a half angle beam divergence slightly larger than one milliradian.

It is observed that the laser output energy decreases significantly and monotonically as the laser resonator length is increased beyond the 60 cm mirror spacing presently employed. Mechanical constraints in the present apparatus prevent substantial reduction of the resonator length; although it appears clear that such reduction would appreciably increase the laser output. This resonator length dependence is largely due to the fact that long resonators limit the number of passes light can make through the laser during the short electrical excitation pulse. For example, the 4 nsec round-trip transit time for light in a 60 cm resonator allows only a few passes through the active medium during the 20 nanosecond excitation pulse presently employed. In future designs, laser efficiency can be increased by reducing the resonator length and/or by increasing the length of the active medium. In either case light would be amplified to higher intensity during the excitation pulse and would thus extract more of the available energy from the active medium.

Vapor loss from the laser channel ends is relatively small, since the boiler walls direct the vapor toward the channel roof, where it condenses and returns as liquid to the boiler, rather than undergoing rapid gaseous diffusion out the channel ends as in conventional "oven-tube" lasers. As a result, the laser can be operated for short periods of time even with no buffer gas. However, it is found that addition of a small amount (less than one Torr) of argon buffer gas provides a significant additional reduction of out-diffusion. This small amount of buffer gas appears to have negligible effect on the copper vapor flow as long as the copper vapor pressure is sufficient to displace buffer gas from the flow region. Even with buffer gas, it is observed that vapor diffusion begins to noticeably cloud the laser windows within a few hours. However, this can be prevented by circulating the buffer gas slowly past the window surfaces. In the present work this has been accomplished by slow infusion of argon across the windows while pumping on the chamber to maintain an equilibrium buffer pressure of about 0.75 Torr. However, it is felt that simple convective buffer flow would probably be adequate in a suitably designed chamber.

With buffer gas flushing the windows as indicated above, the laser can be operated for periods of at least eight to ten hours without attendance. At the end of this time no clouding of the windows is apparent, and the laser output exhibits no noticeable degradation. The copper level in the boiler has usually dropped significantly during this period, however, and is replenished at the end of the run. Lifetime of the laser itself is now limited by pitting of the external boron nitride boiler surface, which results in loss of copper through the boiler walls after a few tens of hours operating time. It is felt that a better grade of boron nitride (commercially available but considerably more expensive) might increase this service life significantly. Alternatively the boiler and heater surface areas might be increased to permit adequate heat transfer with lower heater temperatures, thus reducing thermal gradients in the boiler walls.

Based on the transverse dimensions (1 to 2 cm) of the laser channel and on a copper vapor temperature of about 1700$^{\circ}$C, the time required for substantial purging and vapor replenishment in the laser channel is estimated at 10 to 20 microseconds.

Thus the flow should be sufficient to prevent laser pulse degradation at repetition rates to nearly $10^5$ pps. As a test of repetition rate capability, the laser was double-pulsed by means of two identical, parallel-wired capacitor discharge circuits with independently triggered spark gaps. The delay time between pulses was variable over a range corresponding to repetition rates from zero to more than $10^5$ pps. Oscilloscope displays of the laser output showed that up to a rate of at least $5 \times 10^4$ pps the two electrical pulses produced virtually identical laser output pulses of about 25 nsec duration (FWHM), with pulse energies up to a few microjoules. Even at somewhat higher rates the laser pulses appeared to be identical when both pulses were recorded. However, at these higher rates the second laser pulse was seldom observed at all, due apparently to discharge of the second electrical pulse into the metallic laser channel roof. It is thought that ions carried to the electrode insulators by vapor flow following the first pulse, are not fully recombined when the second electrical pulse arrives, so that these ions guide the second pulse along the insulators to the roof. These observations appear to be consistent with the vapor replenishment rate estimated above.

An attempt was also made to run the laser continuously at high repetition rates using a single free running spark gap discharge circuit. Due to deionization limitations of the spark gap (even with gas blast assistance), operation was not reliably achieved at pulse rates higher than $10^4$ pps. Up to this rate, however, no degradation of peak pulse power or pulse duration was observed. An oscilloscope photograph of a typical output pulse is reproduced in Fig. 15.

The laser described here has been operated on the 7229 Å laser transition of lead, as well as on the 5106 Å and 5782 Å copper lines, although the thermal design is far from optimum for the relatively low melting and boiling points of lead. It is thus anticipated that the vapor flow technique used here should also be applicable to other gaseous laser media which condense readily to the liquid state.

## 4.4 Summary

Work with several "low temperature" metal vapor lasers, and with a variety of configurations for operation at higher temperature, has led to a practical design for copper vapor laser operation utilizing fast closed-cycle transverse vapor flow. The flow is produced by means of an evaporation-condensation cycle with gravity return of the condensate. A small laser of this type has been operated at repetition rates in excess of $5 \times 10^4$ pps--about an order of magnitude greater than rates reported prior to this work. Service life of the laser is limited to a few tens of hours due to degradation of the vapor source. However, improved materials now available may prove more durable. Although the present demonstration model laser is small and relatively inefficient, the design appears to be readily scalable for increased power and efficiency.

It may be noted that the closed-cycle evaporation-condensation flow cycle employed here is also applicable to other gaseous laser media which condense readily to the liquid state. The technique is especially appropriate for applications where sealed-off laser operation is required.

Section 5

# PUBLICATIONS AND TECHNICAL REPORTS

The papers and reports listed below have resulted from research investigation sponsored by the Office of Naval Research under the present contract.

<u>1969</u>

Smith, D. C. and J. H. McCoy: Effects of Diffusion on the Saturation Intensity of a $CO_2$ Laser. Appl. Phys. Letters <u>15</u>, 282 (November 1, 1969). (UAR-H218).

Marcus, S.: Two Saturable Absorbers for Extending the Wavelength Limits of a Passively Q-Switched $CO_2$ Laser. Appl. Phys. Letters <u>15</u>, 217 (October 1, 1969). (UAR-H234).

McCoy, J. H.: Continuous Passive Mode Locking of a $CO_2$ Laser. Appl. Phys. Letters <u>11</u>, 353 (December 1, 1969). (UAR-H230).

Smith, D. C., S. Marcus and J. H. McCoy: Semi-Annual Status Report Under Contract N00014-69-C-0308 for period April 1, 1969 to September 30, 1969. (UAR-F920832-1).

<u>1970</u>

Marcus, S. and J. H. McCoy: Self-Mode Locking and Saturation-Pulse Sharpening in a Rotating-Mirror Q-Switched $CO_2$ Laser. Appl. Phys. Letters <u>16</u>, 11 (January 1, 1970). (UAR-H263).

McCoy, J. H.: Passively Q-Switched $N_2O$ Laser. J. of Quantum Electron. <u>QE-6</u>, 5 7 (September 1970). (UAR-J17).

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<u>1971</u>

Smith, D. C. and F. J. Berger: Mode-Locking of an Atmospheric Pressure Cross-Excited Electrically Pulsed $CO_2$. IEEE J. Quantum Electron., <u>QE-7</u>, 172 (April 1971). (UAR-J247).

Smith, D. C.: Velocity Dependence of the Gain of a $CO_2$ Laser. IEEE J. Quantum Electron., QE-7, 459 (September 1971). (UAR-J279).

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1972

Berger, P. J., and D. C. Smith: Gas Breakdown in the Laser as the Limitation of Pulsed High Pressure $CO_2$ Lasers. Appl. Phys. Letters 21, 167 (August 1972). (UAR-L44).

Flynn, J. T. and P. J. Berger: Acoustic-Optic Modulator Design for a High Power Mode-Locked $CO_2$ Laser. Proceedings of Electro-Optics '72 East, (December 1972). (UAR-L157).

Berger, P. J. and D. C. Smith, C. M. Ferrar, J. T. Flynn, and F. K. Cheo: Annual Summary Report Under Contract N00014-69-C-0308 for period April 1, 1971 to March 31, 1972. (UAR-L920832-4).

Flynn, J. T. and P. J. Berger: Acoustic-Optic Modulator Design for a High Power Mode-Locked $CO_2$ Laser. Interim Report Under Contract N00014-69-C-0308, November 1972 (UAR-L920832-5)

1973

Ferrar, C. M.: Copper Vapor Laser with Closed Cycle Transverse Flow. Submitted for publication in IEEE J. Quantum Electronics, March 1973.

# Section 6

## RESEARCH SUMMARY

The research carried out under the present Office of Naval Research Contract has resulted in nine journal publications, and these as well as other results are reviewed briefly in this section.

### Two New Passive Q-Switching Agents

Q-switching the laser cavity with a saturable absorber is an efficient method of obtaining short, high-power $CO_2$ laser pulses. Prior to the work done under this contract, sulfur hexafluoride and boron trichloride had been reported in the literature as being efficient passive Q-switiching agents for several $CO_2$ laser lines. In the present program two new gases, chlorotrifluoroethylene ($C_2F_3Cl$) and difluorodichloromethane ($CF_2Cl_2$, commonly known as Freon-12), have been discovered for passive Q-switching of the $CO_2$ laser can be passively Q-switched. Further, passive Q-switching on the P-branch of the 9.4 micron band was achieved for the first time. These new Q-switching agents are not only useful in the experiments carried out under the present contract but will also prove of value in high resolution investigations of transient phenomena in absorbing media. This paper appeared in the October 1, 1969 issue of Applied Physics Letters.

### Q-Switching in $N_2O$

Simultaneous laser action of $CO_2$ and $N_2O$ molecules in a $CO_2$-$N_2$ mixture gas laser has been reported in the literature (Ref. 23). Much additional work is needed to determine the feasibility of obtaining substantial power simultaneously from two different molecular gases in a common discharge. By using a segmented discharge tube, however, the two gases can be isolated and the mixtures adjusted for optimum operation. Simultaneous oscillation on $N_2O$ and $CO_2$ offers a possible increase bandwidth through the intermix of $N_2O$ and $CO_2$ lines which do not compete, as do the lines of the individual molecules. Since $N_2O$ has not been subjected to the extensive investigations given $CO_2$, there is little information available on its pulsing behavior. In view of this, a preliminary study of the pulsing behavior of $N_2O$ has been initiated. Using $SF_6$ and Freon-12, passive Q-switching of a $N_2O$ laser has been observed for the first time. Phase-locking of two transverse modes during Q-switched operation of the $N_2O$ laser has also been observed for the first time. A paper entitled "Pressure Q-Switching in $N_2O$" has been published in the September 1970 issue of the Journal of Quantum Electronics.

## Continuous Passive Mode-Locking

Under the present contract, mode-locking has been investigated as a means of obtaining short, high intensity pulses at the 10.6-micron wavelength. Mode-locking of the $CO_2$ laser has been reported in the literature using $SF_6$ as a bleachable absorber (Ref. 24). In their studies, optical cavities of up to 16 meters in length were used to reduce the axial mode frequency separation. In this manner, three or four axial modes were above the oscillation threshold. The $CO_2$ laser at a pressure of 10 torr has a half-intensity line width of 50-60 MHz and, except in very long cavities, only a few axial modes are contained within this bandwidth. It is of interest to determine the effect of locking more than a few axial modes of a $CO_2$ laser, and pursuant to this objective, an optical delay line was constructed and incorporated in the laser resonator, producing a 45-meter-long cavity. With this cavity length the axial mode-spacing was 3.3 MHz, and it was anticipated that 10 or more axial modes could be locked in phase. Because of the increased cavity losses due to reflections in the delay line, only a few of the modes near line center were observed to oscillate. These modes were locked in phase producing 60 nsec half-width pulses at 300 nsec spacing. Contrary to previous experiments, this laser was mode-locked on a continuous basis, producing a continuous train of uniform amplitude mode-locked pulses. The difference between this experiment and previous ones is that the several modes locked in phase in this experiment lie on the relatively flat portion of the gain profile near the center of a gaussian line and are simultaneously above the oscillation threshold, thus enabling the laser to continously mode-lock. With shorter laser cavities, as, for example, those used by Wood and Schwarz (Ref. 24), the modes are farther from the line center where the gaussian gain profile drops off sharply and Q-switching is required to increase the gain of the modes above the oscillation threshold. This research is described in detail in the December 1, 1969 issue of Applied Physics Letters in a paper entitled "Continuous Passive Mode-Locking of a $CO_2$ Laser."

## Self-Mode-Locking

In addition to the passive mode-locking with bleachable absorbers, self-mode-locking of a $CO_2$ laser has also been observed. This was achieved with a rotating mirror Q-switching laser and the resulting 10 to 12 nsec pulses were the shortest $CO_2$ laser pulses directly observed to date. The decrease in pulse length below the normal $CO_2$ line width limit of about 20 nsec is attributed to a saturation broadening of the pulse spectrum. The laser output consisted of a train of pulses in a Q-switch-type envelope, each pulse separated by the round trip cavity transit time. Cavity lengths from 5.5 to 19 m were used. The initial pulse in each train was about 25 nsec wide. The subsequent pulses were observed to decrease successively in width until a minimum width of about 10 nsec was reached.

The evolution of the pulse train can be explained in the following manner: During the time in which the laser is misaligned, a high population inversion builds up in the normal manner. As the mirror comes into alignment, the gain of several modes is above threshold due to this large inversion. If the cavity length is such that the modes are properly positioned on the gain profile, then a mode-locked pulse, whose width is determined by the oscillating mode spectrum, will develop due to the mode interactions in the laser medium itself. As the pulse intensity increases, it becomes sufficiently high within the cavity so that the leading edge begins to deplete the available inversion as it is amplified. Since the pulsewidth is shorter than the rotational relaxation time, the available inversion is only that of the single transition on which the laser is oscillating. The trailing edge of the pulse thus sees a much smaller inversion and is only slightly amplified, resulting in pulse narrowing. Sufficient time exists between pulses for the restoration of a population inversion by energy transfer from the

half-width of 5 nsec were obtained with a gas pressure of 450 torr and a 2.2 meter cavity length. These pulses represent the shortest self-mode locked $CO_2$ pulses that have been observed to date. More detailed data is contained in the United Aircraft Research Laboratories Report J247. A paper entitled, "Mode-Locking of an Atmospheric Pressure Cross-Excited Electrically Pulsed $CO_2$ Laser," was published in the April, 1971, issue of the IEEE Journal of Quantum Electronics.

## Effects of Diffusion on Saturation Intensity

The capabilities of a laser oscillator or amplifier can be specified by the small signal gain and the saturation intensity of the laser medium. Measurements were made of these two parameters in a flowing gas, electrically excited $CO_2$ laser amplifier. It was determined that the saturation intensity (i.e., the intensity required to reduce the gain by a factor of two) was strongly dependent on the size of the beam, a result which was not expected nor predicted by an existing theoretical model. From these measurements it was shown that the increase in saturation intensity with decreasing beam size was due to molecular diffusion of excited $CO_2$ molecules. The diffusion of molecules was sufficiently fast to be important in maintaining the laser inversion in the presence of stimulated emission. A simplified theoretical model was developed which took into account molecular diffusion and explained qualitatively the dependence of saturation on beam size. The details of the measurements and the theoretical model are contained in the published paper "Effects of Diffusion on the Saturation Intensity of a $CO_2$ Laser," in the November 1, 1969 issue of Applied Physics Letters.

## Velocity Dependence of the Gain of a $CO_2$ Laser

Experiments were carried out to examine the effects of gas flow velocity, both the direction and magnitude, on the gain of a cw $CO_2$ laser beam. The gas velocity was varied between $\sim 0$ and 10 m/sec in a 2.5 meter long, 2.5 cm diameter dc electrically excited $CO_2$ laser amplifier; and the gain of a 0.25 cm diameter stable probe laser was measured as a function of the input intensity. The measurements yielded the small signal gain and saturation intensity of the laser as a function of gas velocity. The small signal gain increased with increasing gas velocity whereas the saturation intensity decreased. The optimum output of the laser is proportional to the product of the small signal gain times the saturation intensity, and this product was found to be independent of velocity within the experimental error of the measurements. The most interesting results were obtained for the intermediate flow velocity where the gain was observed to be a function of the direction of propagation of the oscillator beam with respect to gas flow. Effectively, the saturation intensity was greatest for propagation in the direction of flow. The velocity dependence of the gain is attributed to the dissociation of $CO_2$ into CO and $O_2$. For dwell times in the laser of $\sim$ one second, there is an axial gradient in CO which leads to an axial gradient in saturation intensity. It is most efficient to propagate in the direction of increasing saturation intensity which is the flow direction. Details of the experimental results and their interpretation are contained in the technical report, "Velocity Dependence of the Gain of a $CO_2$ Laser," which was published in the IEEE Journal of Quantum Electronics, Vol. QE-7, September 1971.

## Atmospheric Pressure Argon and Freon-12 Lasers

A cross-excited electrically pulsed discharge has been used successfully to obtain laser action at atmospheric pressure with two different gas mixtures: a 9 to 1 mixture of He and Ar lasing at a wavelength of 1.79 μm and a 9 to 1 mixture of He and Freon-12 at 1.59 μm. The pulses have a shape similar to the gain switched atmospheric pressure $CO_2$ pulses. For He-Ar, the pulse width is 0.2 μsec, and the peak power is measured to be approximately 10 kilowatts, much higher than previously reported values for the pulsed Ar laser. For the He-Freon-12 mixture a peak power of 0.5 kilowatts is measured. This represents a considerable power increase over the cw lasing of Freon-12, which has been power limited to less than 1 milliwatt with low pressure (<1 torr) discharges. The gain of these mixtures is found to be comparable to the gain measured with the $CO_2$-$N_2$-He mixtures at atmospheric pressure.

## Metal Vapor Lasers

Conventional copper vapor lasers employ more or less uniformly heated refractory discharge tubes in which copper evaporates slowly from small pellets and diffuses throughout the tube interior. Inert buffer gas at a pressure of several Torr carries the electrical discharge to the evaporation region and slows vapor diffusion, to minimize copper loss and coating of the laser end windows. Most attempts to increase the average output power of such lasers by increasing the pulse repetition rate have apparently been hindered by inadequate interpulse removal of long-lived metastable atoms. These metastables absorb the laser radiation, causing self-termination of each pulse and preventing immediate initiating of the next pulse. Repetition rates on the order of $10^3$ pps are typically reported (Ref. 26) and it is found that the peak pulse power tends to drop rapidly above a few thousand pps (Ref. 27) even when care is taken to ensure that vapor pressure, temperature, and electrical excitation characteristics remain constant.

Under the present contract, UARL has recently demonstrated extended pulse rate capability in excess of $5 \times 10^4$ pps, without degradation of peak output power. This has been accomplished by developing a laser shown schematically in Fig. 12, in which copper vapor flows transversely to the laser channel, sweeping metastable atoms rapidly from the discharge region. The flow is provided by a continuous evaporation-condensation cycle similar to that employed in diffusion vacuum pumps. Refinements of laser channel geometry, electrode configuration and construction materials allow reliable, repeatable, laser operation for periods of up to eight hours without maintenance, after which replenishment of the copper supply is usually required. Lifetime of the laser channel and evaporator appears to be typically several tens of operating hours. This laser has also been successfully operated with lead vapor (7229 Å) as the active medium, although the thermal design is poorly suited to the relatively low temperatures associated with lead.

The present laser was designed solely for the purpose of demonstrating feasibility of pulse rate enhancement by means of transverse vapor flow. Consequently it is small, and relatively inefficient, with peak pulse powers typically in the 10 to 100 watt range. However, it appears that the design should be scalable to considerably larger size, with a corresponding increase in output power and efficiency. A paper based on this work has been submitted for publication in the IEEE Journal of Quantum Electronics.

## Forced Mode-Locking

Forced mode-locking of the atmospheric pressure $CO_2$ laser was accomplished with a germanium acousto-optic modulator, giving a measured pulse width of 1.5 nansec and a peak power of 18 Megawatts. The pulse resolution is limited by the bandwidth of the amplifier chain and the actual pulse width is estimated to be 1 nanosecond with a peak power in excess of 25 Megawatts. Previous forced mode-locking experiments (Ref. 27, 28, 29) were limited to peak powers of 3-4 Megawatts because of the high insertion loss and low damage threshold of the anti-reflection coated modulators. The modulator used in this work was a Brewster angle modulator which had a power insertion loss of only 50% and withstood the full intracavity intensities without damage. Special design considerations were required to simultaneously satisfy the Brewster angle and the Bragg requirement for acousto-optic modulation. This work was presented at Electro-Optics '72 East and has appeared in the proceedings of this conference.

## Photon-Drag Detector

A high speed photon-drag detector was developed for the measurement of the mode-locked $CO_2$ pulses. From a study of the properties of doped germanium a selection of 5 ohm-cm p-type material was made for optimum sensitivity and the dimensions were chosen to give a 50 ohm element. Matching the detector to 50 ohm transmission line was accomplished through a low inductance coaxial design and time domain reflectomery measurements showed a circuit response of 300 psec.

The sensitivity of the detector was calibrated and found to be 150 millivolts/ Megawatt. Although the speed of this detector is inherently 0.3 nsec, the low sensitivity require- the use of an amplifier in order to display the mode-locked pulses on a fast Tektronic 519 oscilloscope. This limits the direct measurement of pulsewidths to approximately 1 nsec. Patel (Ref. 2) has suggested an indirect pulse measurement technique, employing a photon-drag detector and a fast rectifier bridge. The sign of the photon-drag signal depends on the direction of propagation of the pulse through the detector. If a mode-locked pulse is split into two equal intensity pulses and the pulses are incident upon a detector from both sides, the measured voltage depends upon the degree of pulse overlap, as shown in Fig. 1. The instantaneous voltage waveform occur on a time scale too fast for direct display: however, if the output is rectified, the net voltage can be displayed on a slow oscilloscope and used to measure the spatial extent of the pulse. Patel's suggestion has not been reduced to practice, to our knowledge, and in the past year we have designed and constructed this type of detector. The key elements of the design are a low inductance configuration and fast microwave diodes, which have a sufficiently low turn on voltage. Fabrication of the initial devices is complete and testing will proceed in the near future.

## Double Discharge Laser

A solid-cathode double-discharge laser has been constructed which has an extremely uniform discharge, high specific output of 20 joules/liter, and a gain of 4%/cm. The key elements of the design are a low inductance discharge circuit, a pair of uniform potential electrodes, and a pair of trigger wires through the electrode mid-plane which produce a short-lived intense current discharge and a desirable preionization prior to the main discharge. Up to [illegible] joules of single pulse energy have been extracted from the laser with a peak power in excess of 4[illegible] Megawatts. The pulse shape depends on the cavity details but in general is characterized by a leading spike of 100 nsec full width followed by a lower intensity 2 μsec long tail. Various cavity arrangements and unstable resonator configurations have been used to obtain a desirable output beam divergence. The peak gain of the 75 cm long discharge at a high excitation level is [illegible], that is a gain per unit length of 4%/cm. This high gain and short length, together with the uniform volume excitation, are advantageous for ultra-short pulse generation.

## Thin Film Modulators

The high modulation frequencies, required for the generation of ultra-short $CO_2$ pulses, present technological problems for bulk modulators but can be conveniently achieved in theory with thin film wave guide structures. An exploratory research program was initiated on GaAs epitaxial thin films grown on $n^+$ substrates. The coupling of radiation into the films was demonstrated with germanium prisms giving coupling efficiencies as high as 40%. Under development is a phase grating coupler, which will be required to launch radiation into thin films with a low index profile. The characteristics of TE and TM modes in guides of different thickness and index profile were studied both analytically and experimentally. It was found that the modes are most strongly attenuated in the presence of metal electrodes, which are required for active manipulation of the optical radiation. The simultaneous excitation of two orthogonal guided modes of equal amplitude was demonstrated, a step toward the realization of a polarization modulator.

## Gas Breakdown Limit on High Pressure $CO_2$ Lasers

Gas breakdown inside the active laser medium has been observed with the double-discharge laser and it was recognized that this would present a fundamental limit on the use of high pressure lasers for short pulse generation. The gas breakdown threshold of typical laser mixtures was measured as a function of beam diameter and gas pressure. For pulses shorter than 0.1 $\mu$sec and beam diameters larger than 0.2 cm the breakdown of the active laser medium is decribed by an energy flux of 5 joules/cm$^2$ and it decreased with increasing pressure. The saturation energy of the laser mixture is 0.5 joules/cm$^2$ and increases with increasing pressure. These competing trends indicate that a maximum pressure will exist above which gas breakdown will cause a termination of the laser pulse developing in the laser medium. From a study of the amplification of short pulses, it is predicted that for efficient operation the pressure must be limited to 2-4 atmosphere. This is a severe limitation on the use of $CO_2$ lasers for short pulse generation and amplification. A paper based on this work was published in August 15, 1972 issue of Applied Physics Letters.

### Pulse Selection Based on Gas Breakdown

The standard method of selecting a single pulse from a mode-locked train employs an electro-optic shutter; and precise timing circuitry, such as the use of a laser triggered spark gap, is required for the selection of a single intense pulse. As an alternative to this approach, a novel method employing gas breakdown in a pair of cells has been demonstrated under this contract. The focal lengths of the two cells are chosen to give nearly coincident breakdown thresholds. The first cell is used in transmission; the beam reflected from the second breakdown plasma is the desired pulse. Thus, the first cell clips the trailing portion of pulse and the second cell eliminates the front portion of the pulse, leaving a single pulse in the case of a mode-locked pulse train or the central slice of a pulse in the case of Q-switched pulse. In the study of this technique it was found that a plasma reflectivity of 4-8% holds for atmospheric pressure air with $\sim$ 100 nsec pulses, the reflected beam has good beam quality, and a signal-to background ratio of 15 was typical but could be improved with a better optical design. With clean gasses in the cells the breakdown thresholds are extremely sharp, a necessary condition for the success of this method. The pulses selected by this method ranged from a single pulse extracted from a self-mode-locked train to a 50 nsec slice out of the Q-switched output pulse of the TEA laser. Modifications to the existing arrangement are under study to allow a greater control to be exercised over the width of the selected pulse.

The pulse reflected from the breakdown plasma have an extremely sharp leading edge, faster than the time response of the detection system ($\sim$3.1 nsec). A simple analysis indicates that the plasma reflectivity increases 3 orders of magnitude in one generation time, approximately 0.5 nsec for a long duration square laser pulse at threshold. A considerably faster growth time would be expected for a fast ramping pulse of nanosecond duration. This is the most important feature of the present pulse selection technique, and further study is of the risetime is planned.

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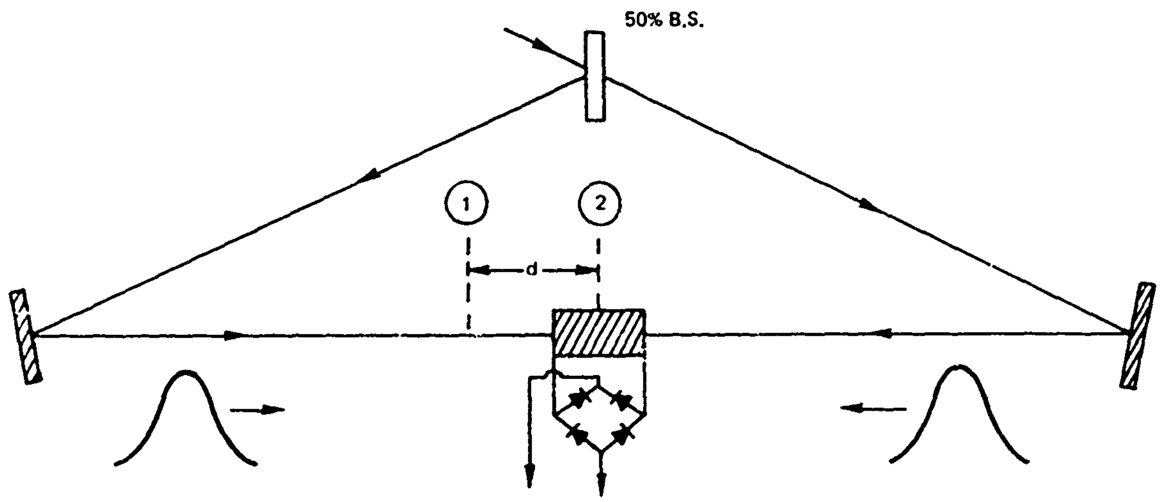
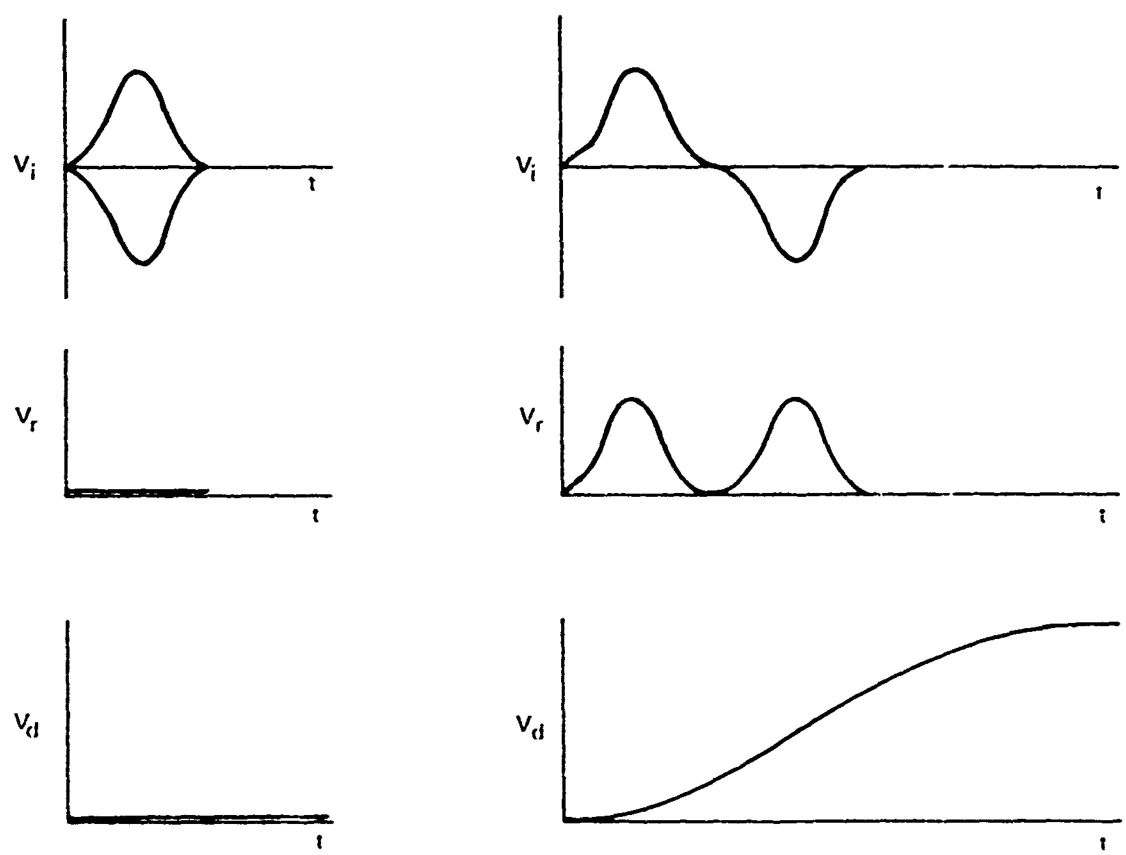
## LIST OF FIGURES

**SPATIAL – OVERLAP PHOTON – DRAG DETECTOR**




a) OPTICAL BRIDGE AND DETECTOR CIRCUIT




b) INSTANTANEOUS, RECTIFIED, AND INTEGRATED VOLTAGES SEEN AT THE TWO PROBE POSITIONS

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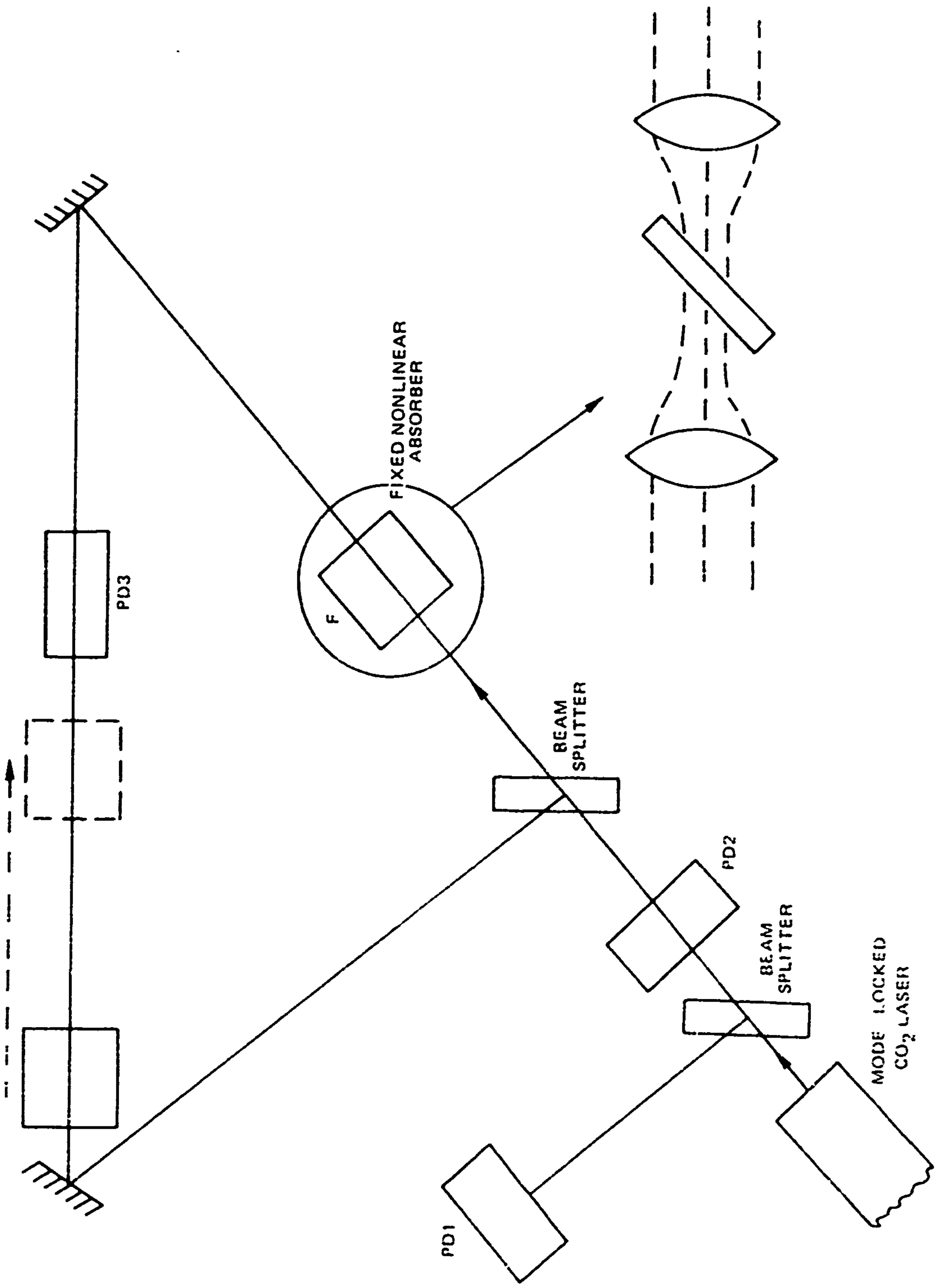
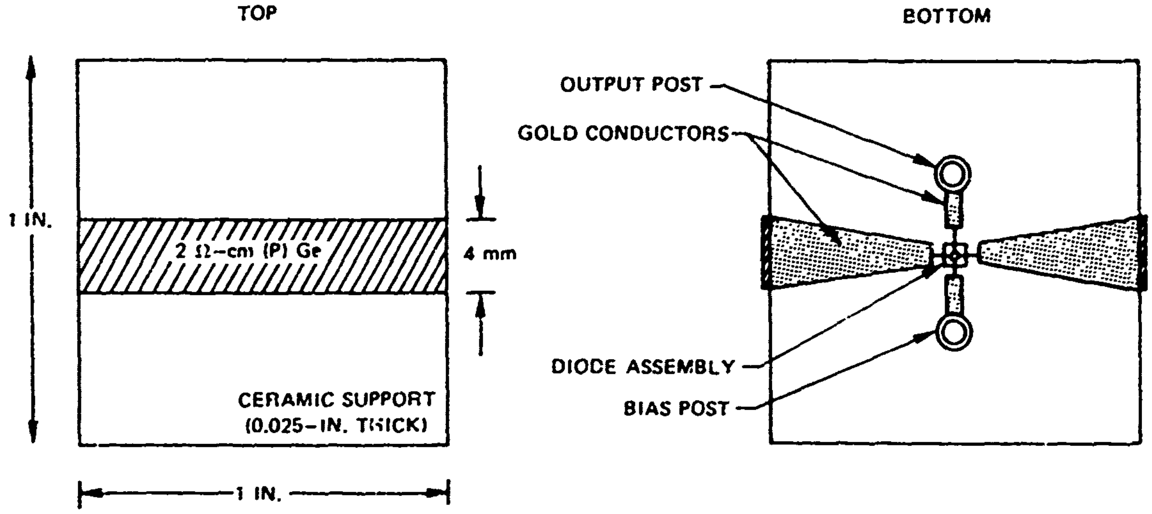
FIG. 2

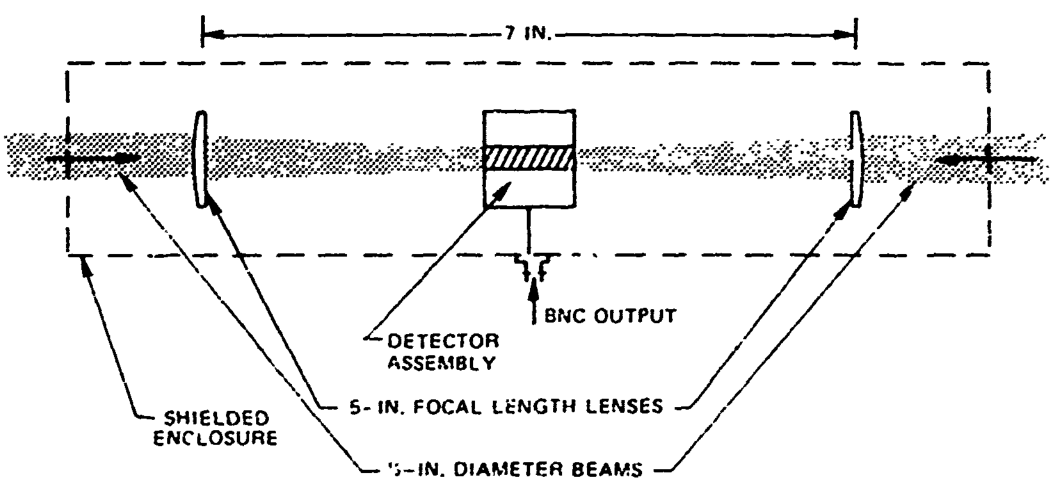
OPTICAL BRIDGE METHOD USING A PHOTON–DRAG DETECTOR AND TWO NONLINEAR ABSORBERS
(AFTER GIBSON, et al)



## DETAILS OF SPATIAL OVERLAP DETECTOR



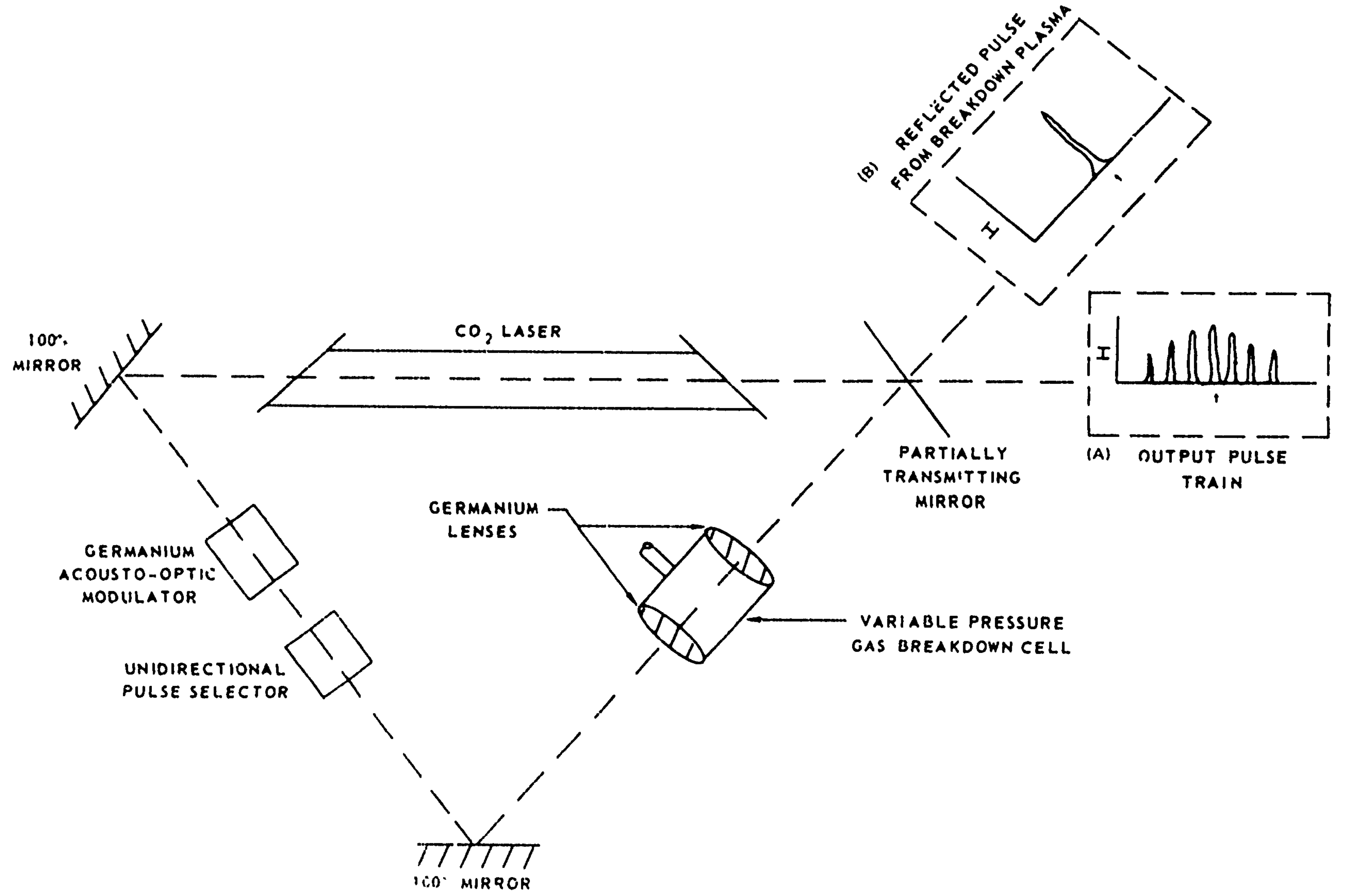

(A) LAYOUT OF DETECTOR AND DIODE BRIDGE



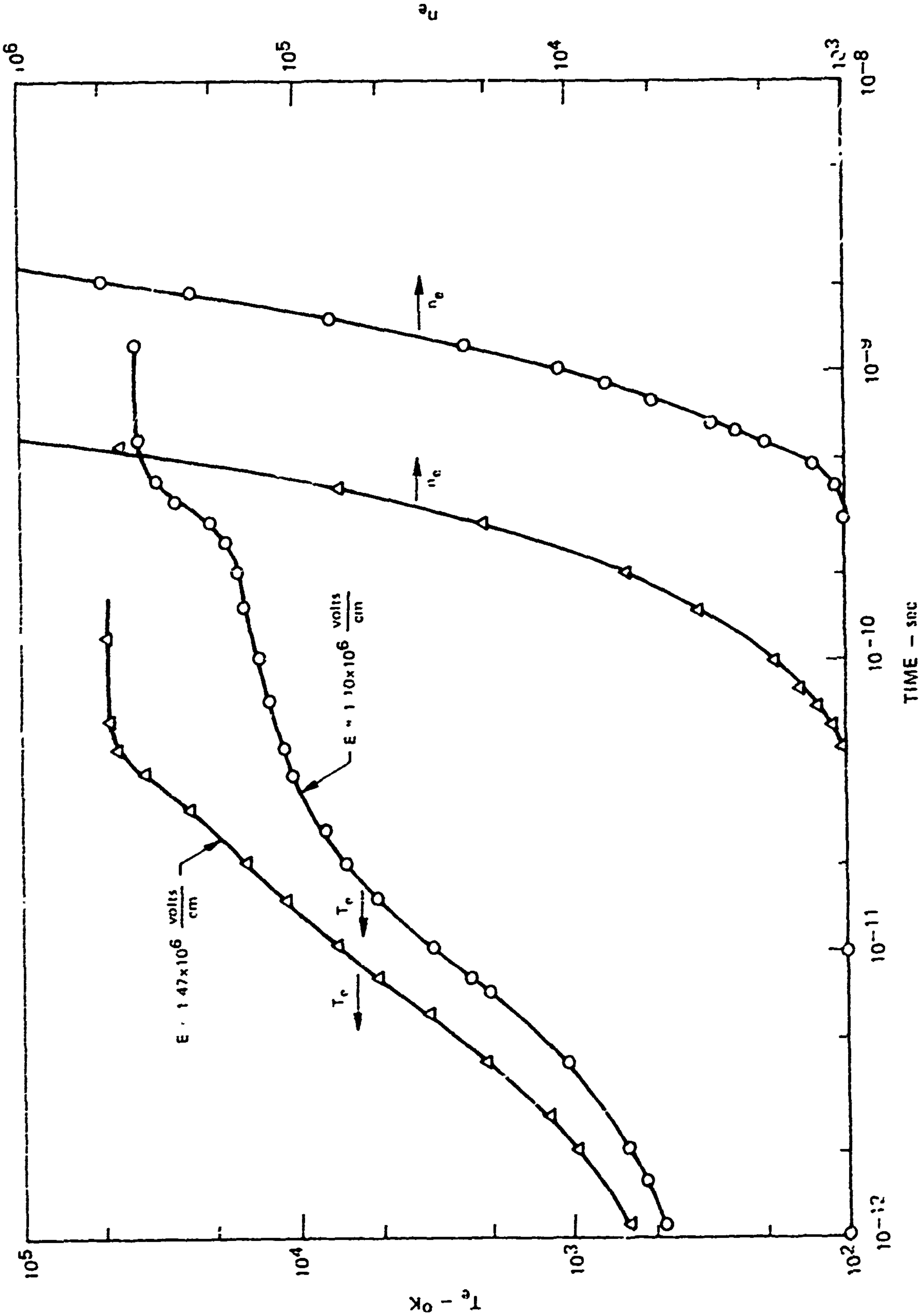

(B) DETECTOR AND OPTICAL PACKAGE

FIG. 4

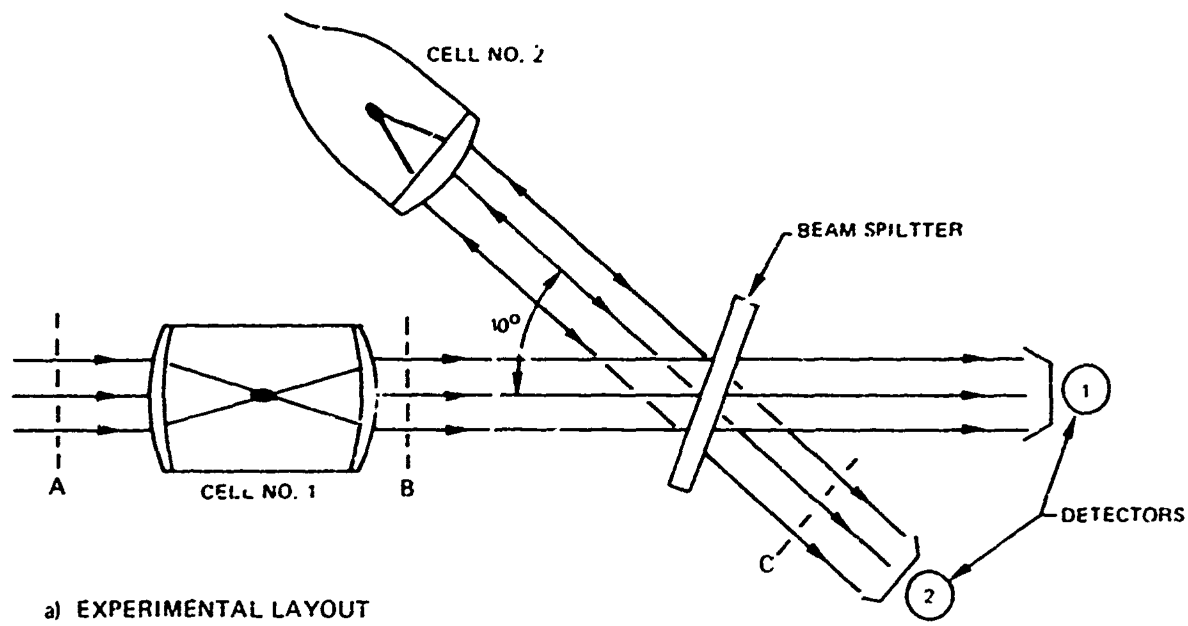
# SINGLE PULSE SELECTION SCHEME BASED ON GAS BREAKDOWN



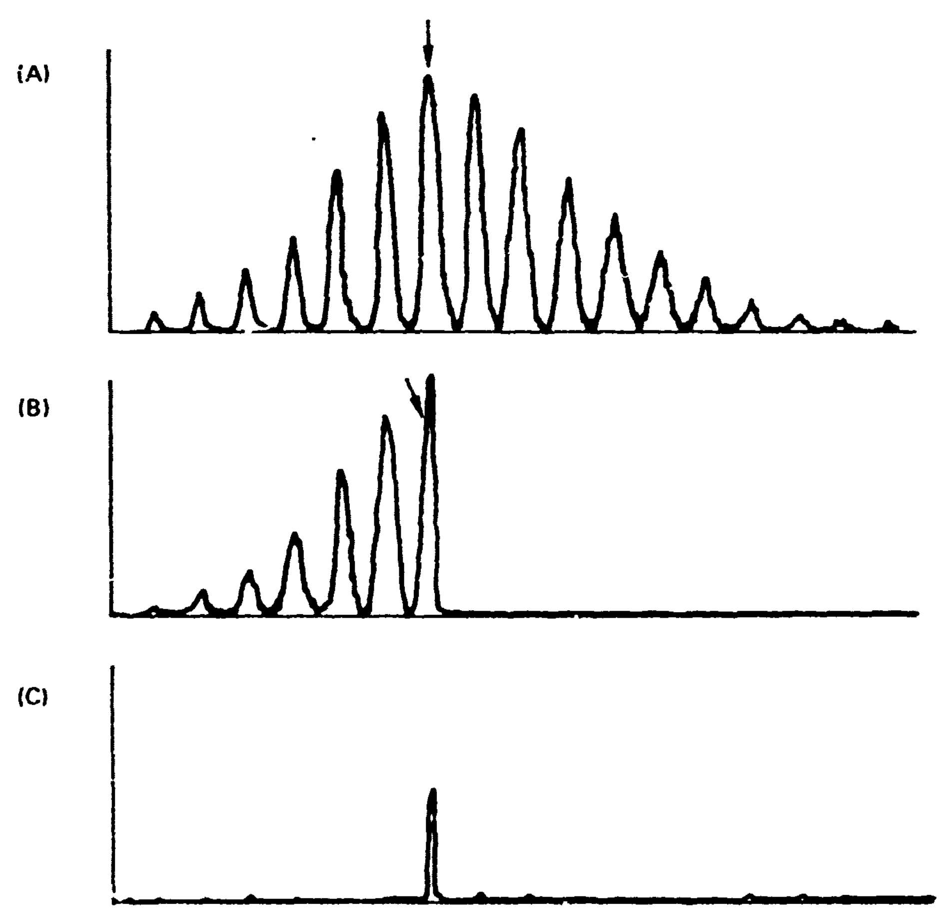
GROWTH OF ELECTRON TEMPERATURE AND CONCENTRATION WITH SQUARE LASER PULSE



# TWO- CELL PULSE SELECTION METHOD

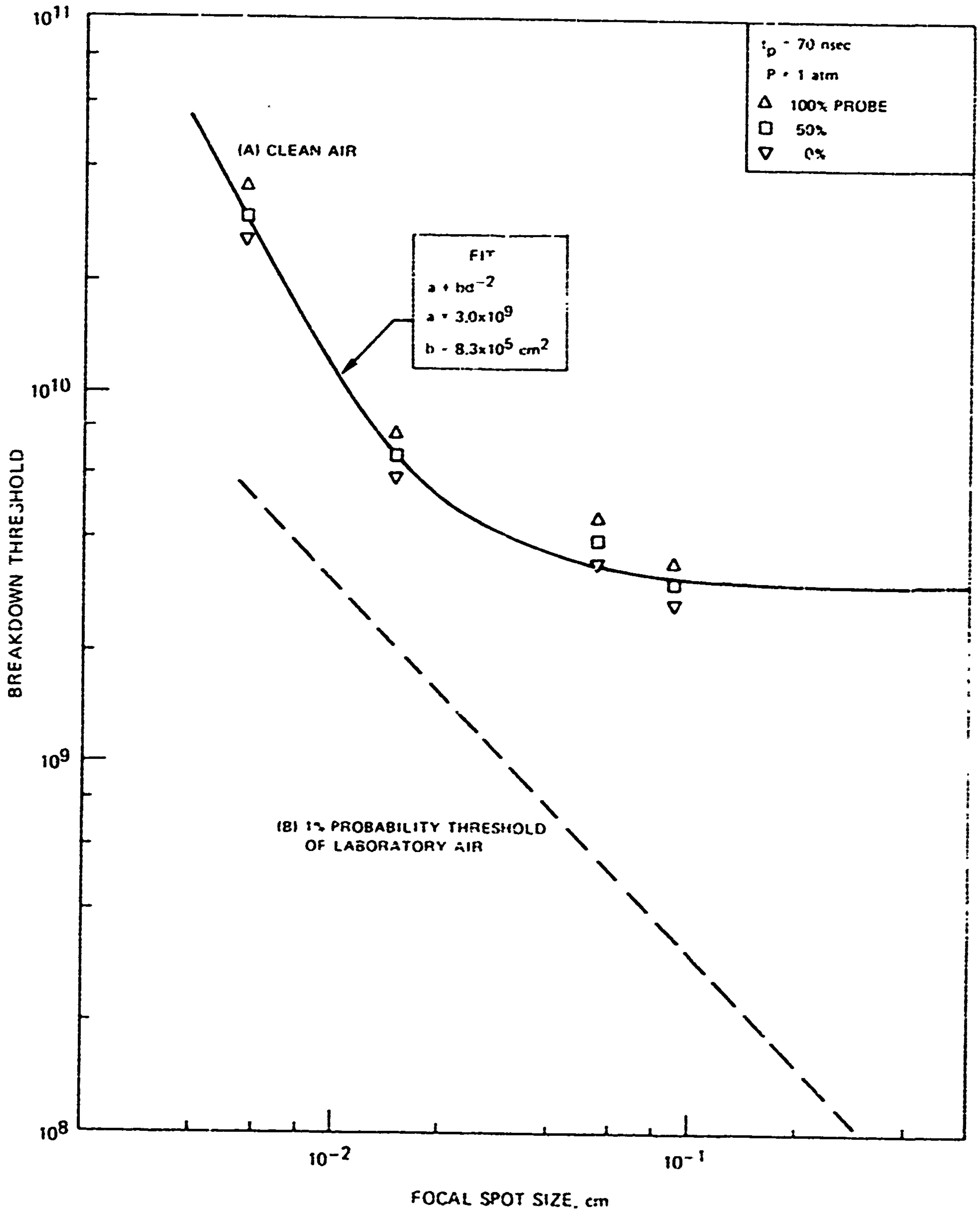



a) EXPERIMENTAL LAYOUT

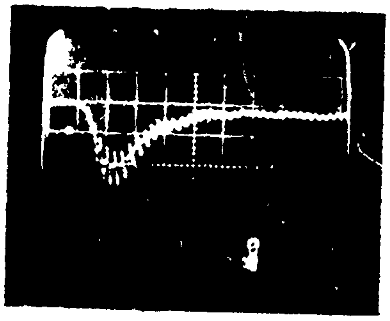



b) PULSE TRACES AT POSITIONS A, B, AND C

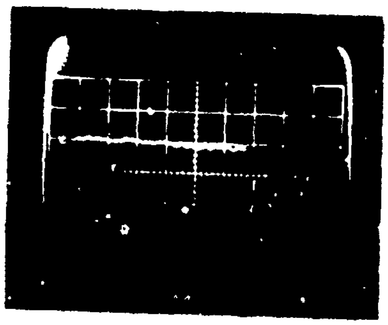
## AIR BREAKDOWN THRESHOLD VS BEAM SIZE



PULSE REFLECTED FROM BREAKDOWN PLASMA



(A) INCIDENT PULSE: 0.5 V/div, 100 nsec/div
(ATTENUATED 10x)



(B) REFLECTED PULSE: 0.2 V/div, 50 nsec/div

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FIG. 9

# EXPERIMENTAL ARRANGEMENT FOR PULSE SELECTION

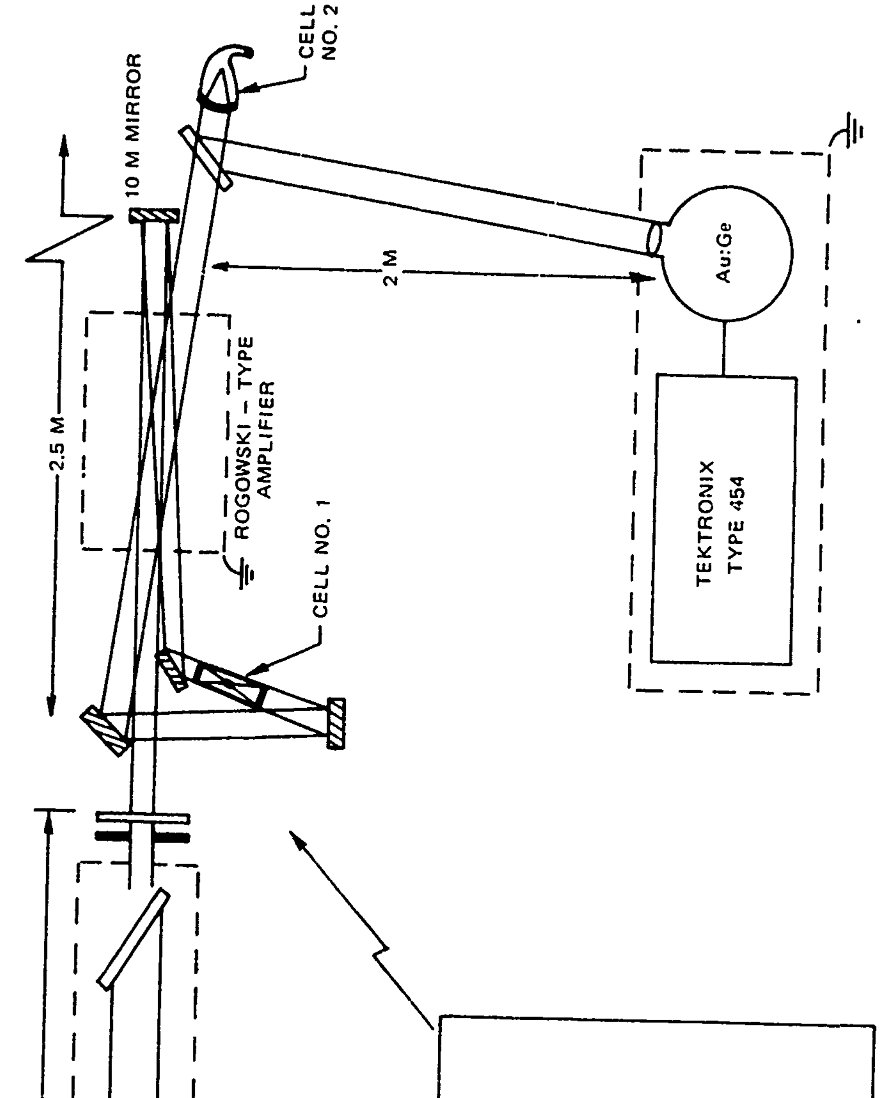
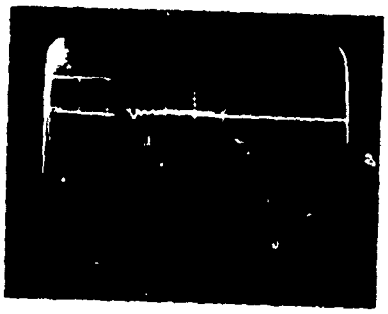


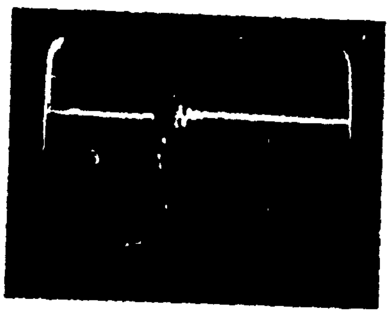
FIG. 10

# PULSES SELECTED BY TWO CELL METHOD

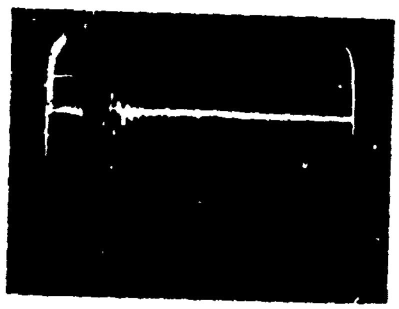


(A)

(B)



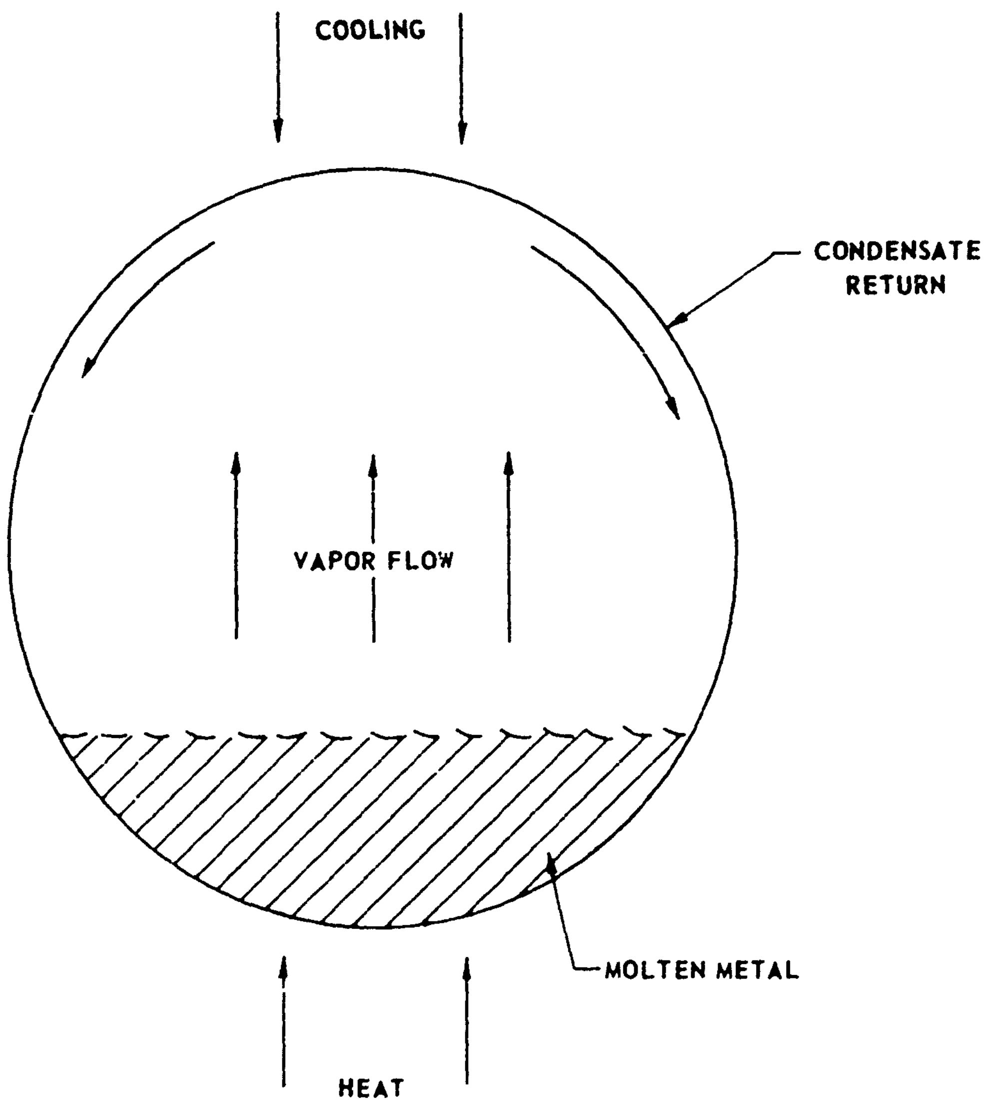
(C)



(D)

ALL TRACES 50 NEC DIV, 0.2 V DIV

TRANSVERSE FLOW EVAPORATION-CONDENSATION CYCLE



FLOWING COPPER VAPOR LASER ASSEMBLY

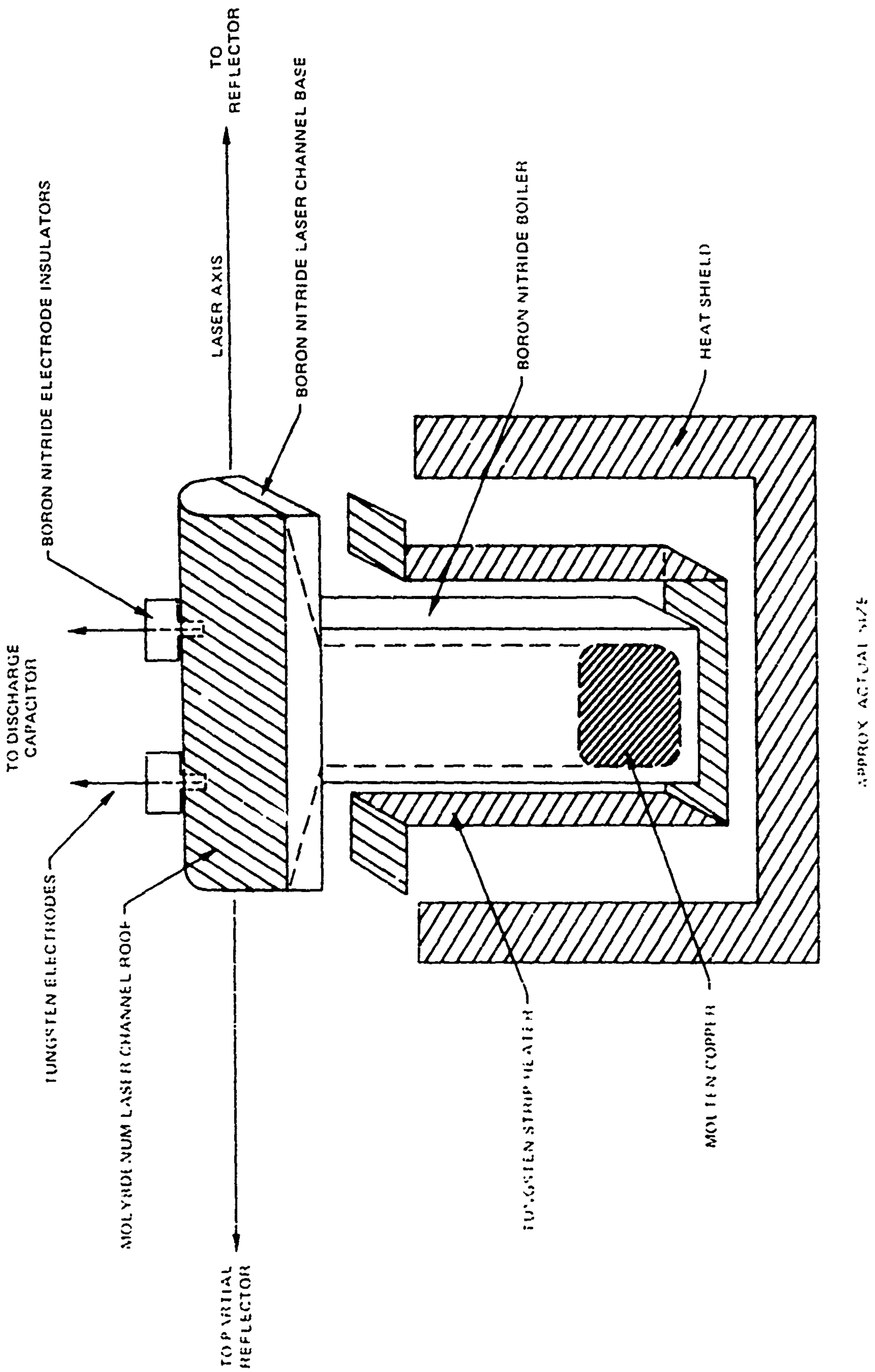
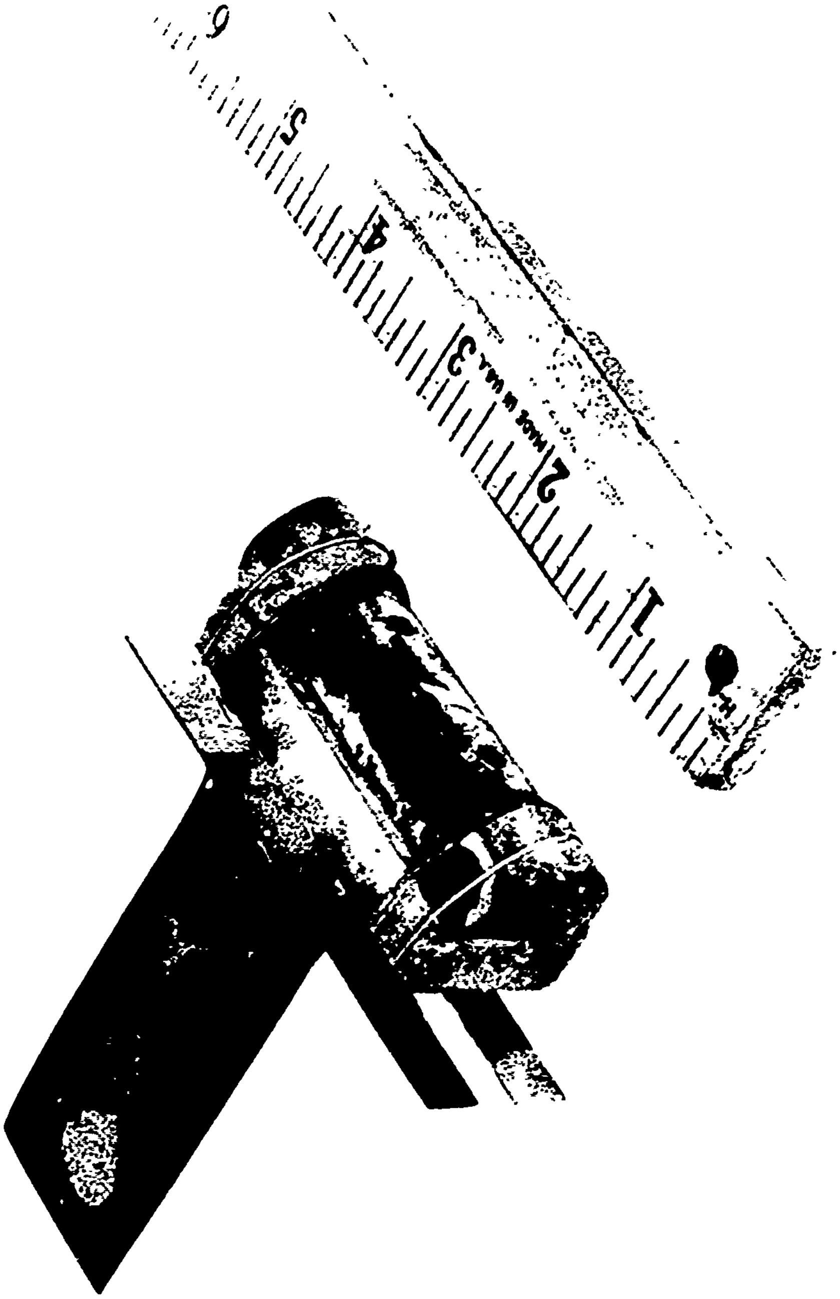
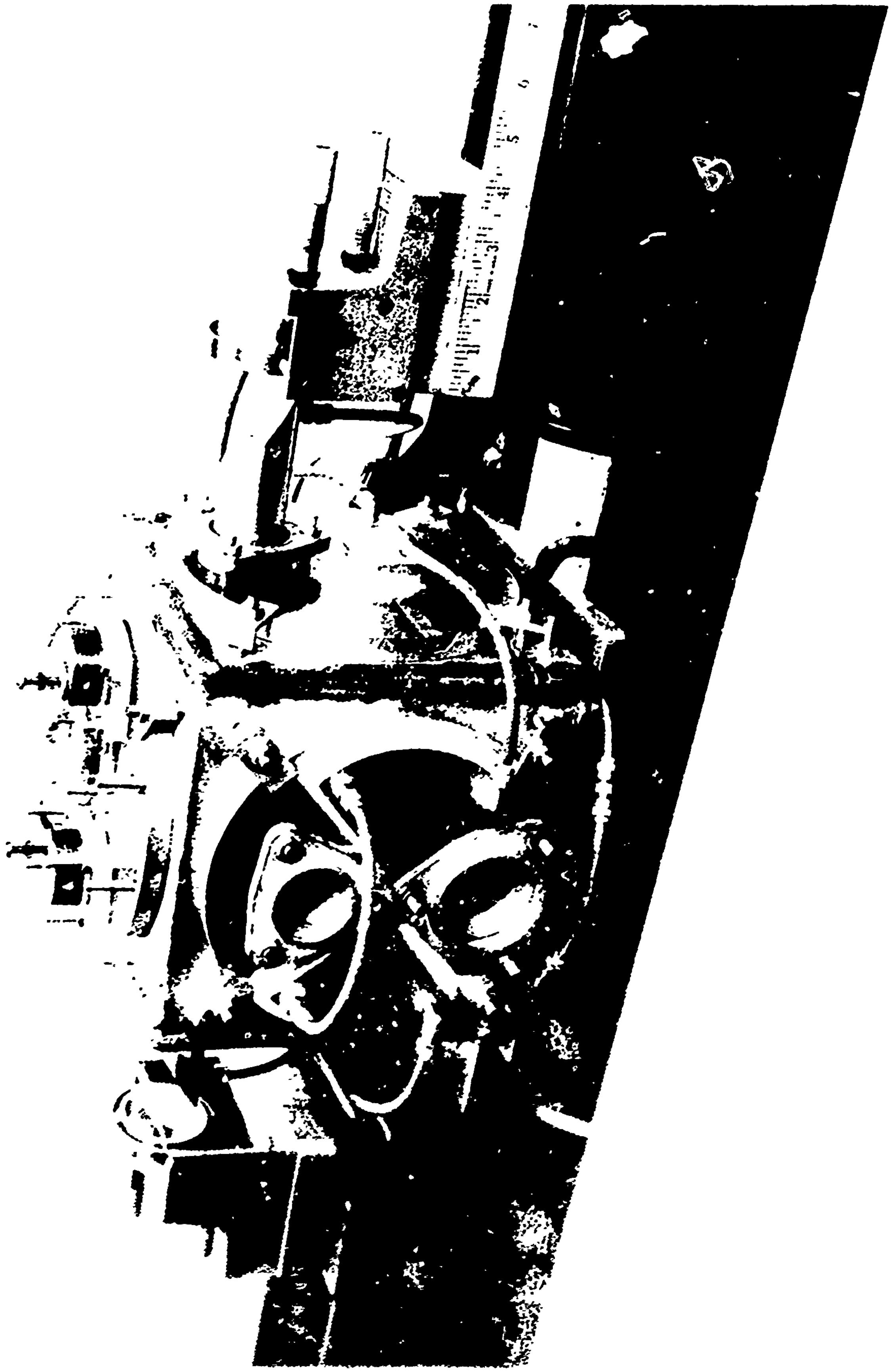


FIG. 13



INTERNAL COPPER VAPOR LASER ASSEMBLY

FIG. 14



OUTPUT PULSE FROM COPPER VAPOR LASER