NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Technical Memorandum 33-730*

# *Ionizing Mechanisms in a Cesium Plasma Irradiated with a Ruby Laser*

*K. Shimada*

*L. B. Robinson*




JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

June 1, 1975

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Technical Memorandum 33-730*

# *Ionizing Mechanisms in a Cesium Plasma Irradiated with a Ruby Laser*

*K. Shimada*
*L. B Robinson*

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

June 1, 1975

## PREFACE

The work described in this report was performed by the Applied Mechanics Division of the Jet Propulsion Laboratory.

Dr. L. B. Robinson is a consultant for the Jet Propulsion Laboratory. His permanent address is the University of California, School of Engineering and Applied Science, Los Angeles, California 90024.

CONTENTS



TABLES



FIGURES

## ABSTRACT

A cesium filled diode--laser plasmadynamic (LPD) converter was built to investigate the feasibility of converting laser energy to electrical energy at large power levels. Experiments were performed with a pulsed ruby laser to determine the quantity of electrons and cesium ions generated per pulse of laser beam and to determine the output voltage. A current density as high as 200 amp/cm$^2$ from a spot of approximately 1 mm$^2$ area and an open circuit voltage as high as 1.5 volts have been recorded. A qualitative theory has been developed in order to explain these results.

In the operation of the device, the laser beam evaporates some of the cesium and ionizes the cesium gas. A dense cesium plasma is subsequently formed to absorb further the laser energy.

Results suggest that the simultaneous absorption of two ruby laser photons by the cesium atoms plays an important role in the initial ionization of cesium. Inverse bremsstrahlung absorption appears to be the dominant mechanism in subsequent processes. Recombinations of electrons and cesium ions appear to compete favorably with the simultaneous absorption of two photons. A better understanding of charge particle transport mechanism is required to improve further the LPD energy conversion.

# IONIZING MECHANISMS IN A CESIUM PLASMA IRRADIATED WITH A RUBY LASER

## I. INTRODUCTION

A cesium-filled diode, laser plasmadynamic (LPD) converter was built to investigate the feasibility of converting laser energy to electrical energy at large power levels ( >1 $kW/cm^2$). Any energy conversion device requires simultaneous generation of output voltage and output current which, in the LPD converter, is carried by cesium ions and electrons.

A schematic diagram of the LPD converter is shown in Fig. 1. The diode is formed with a cup-shaped electrode (emitter) containing cesium liquid and a semi-spherical electrode (collector) above the emitter. The diode is enclosed in a stainless cylinder which is provided with: (1) sapphire windows, one for the laser beam and the other for an optical observation, (2) an eight-pin lead-through for connection to collector electrode, collector heater and a thermocouple. The collector material is stainless and a sheathed heater is brazed on it. The collector, which has a dome radius of 0.794 cm, has a hole with a diameter of 0.476 cm through which the incident laser beam is introduced, striking the center of the cesium reservoir at a 45-deg angle. The cesium reservoir is made of copper which is externally connected to a temperature-controlled copper block. To avoid undesirable condensation of cesium at places except the reservoir, the reservoir is kept at the coldest temperature (≃50°C) in the system.

Experiments were performed with a pulsed ruby laser to determine both the quantity of cesium ions and electrons generated per pulse of laser beam and the output voltage. The principle of the converter operation is to: (1) generate high-density cesium vapor at or near the focal spot of the laser, (2) photoionize the gas, and (3) separate ions and electrons by two electrodes that are at two different work functions.

Since it is appropriate to use coulomb-volt curves for pulsed operations, such curves have been obtained under various laser inputs and collector temperatures. The circuit used for these measurements is shown in Fig. 2, and typical oscillographs are shown in Fig. 3 in which the input laser pulse (upper trace) and the output current (lower trace) are indicated. Note that the change of current polarities occurred as the polarity of voltage was reversed. Also the current tended to saturate at an applied voltage on the order of a volt, confirming the low level of energy possessed by generated charge carriers. The electron current (in negative quadrant) showed faster response time compared with that of the ion current. A close examination showed practically a one-to-one correspondence between the laser pulse and the electron current spikes. However, this type of relationship was not observed in the ion current. Note also that the curve moved to the right, i.e., there was a positive current when the device was shorted, which occurred when the collector was heated to 950°K. This was expected since the collector work function should be higher than that of the emitter (cesium reservoir) and the collector tended to reject electrons and collect ions. However, the quantity of current or the voltage was still much less than what was expected. Possible causes are the use of a ruby laser whose wavelength is not small enough for a one photon ionization process, the pulsed operation, or the large interelectrode gap of this LPD converter. A partial analysis of the cesium ionization is described below.

## II. THEORETICAL CONSIDERATIONS

It is evident that the following events occur when the laser radiation is incident upon the pool of cesium. The laser beam evaporates some of the cesium with ionization to form a dense plasma; this is followed by absorption of the laser energy in the plasma. The ionization can be one, two, or three photon processes. Eventually ionization will occur. A part of the generated electrons are accelerated by the inverse bremsstrahlung mechanism so that they excite cesium neutrals and subsequently ionize excited species. Recombinations between cesium ions and electrons also occur in the plasma. Coincident with all of these competing processes, net current is produced by the passage of

the ions and electrons in the appropriate electrode under the influence of the field in the interelectrode region. Some consideration will now be given to the relative importance of the above processes, based on the available data and theory.

Table 1 provides a guide as to processes which are energetically possible. Some of the important transitions from the ground state to excited states are shown. We see that the work function of cesium is very close in magnitude to the energy of the laser photon. The simultaneous absorption of two photons corresponds to a transition from the ground state to the 9D level. Only a fraction of an eV separates this state and the ionized state.

It has been determined experimentally that the excitation of the $6S_{1/2} \rightarrow 9D_{3/2}$ transition in cesium has been induced by intense light from a ruby laser[1]. The $9D_{5/2,3/2}$ levels have term values which are twice the frequency of the ruby photons.

Ionization of cesium atoms can occur in several possible ways. Likely ones are: (a) simultaneous absorption of three photons, (b) simultaneous absorption of two photons, followed by ionizing collisions with energetic electrons, (c) excitation of neutrals by energetic electrons followed by simultaneous absorption of two photons, (d) sequential excitation of neutrals by energetic electrons followed by absorption of one photon, (e) sequential excitation of neutrals by energetic electrons followed by ionization by electrons. Results obtained so far can rule out some of the above processes as being unlikely, but no single process has been identified to be a dominant one.

## III. EXPERIMENTAL RESULTS

Some of the results obtained so far are shown in Figs. 4 and 5. Figure 4 shows the results of two different experiments, performed in essentially the same manner. Different values of the input laser energy were used as shown on the graph. The results shown in Fig. 5 were obtained when the collector electrode

was heated to approximately 950°K. The results show that (1) a few hundred microcoulombs represent the typical saturation current collected (Fig. 4), and (2) as much as one to two thousand microcoulombs were collected with the special operating conditions (Fig. 5).

Table 2 lists some conversion factors which are important in the following discussion.

## IV. ANALYSIS OF RESULTS

B. A. Tozer[2] developed the following expression to account for the production of $N_o$ electrons in laser pulse time T by the simultaneous absorption of $N_\nu$ photons in volume V irradiated by the laser beam:

$$N_o = \frac{VNT}{t} \exp(-n_\nu \sigma t) \left[ \frac{(n_\nu \sigma t)^{N_\nu}}{N_\nu !} \right] \tag{1}$$

where N is the number of atoms $cm^{-3}$ in volume V, t is the reciprocal of the photon frequency $\nu$, $n_\nu$ is the photon flux (no $cm^{-2}$ $sec^{-1}$) and $\sigma$ is the cross section for the excitation of the atom by the simultaneous absorption of $N_\nu$ photons.

First we shall consider the possibility of a three photon process, i.e., $N_\nu = 3$. If we select the number 800 μC to represent the total number of electrons typically collected in the experiments, and with $\sigma = 10^{-16}$ $cm^2$, a value often quoted,[3] one sees that for a pulse of 100 μsec duration, the product VN must be about $10^{32}$ in order to obtain $N_o = 5 \times 10^{15}$ electrons, corresponding to 800 μC. If one considers that recombinations have some effect, the product VN must be larger. A produce of $VN = 10^{32}$ is equivalent to a plasma atom density of $10^{29}$ $cm^{-3}$ throughout a liter volume. This is highly unlikely. Therefore, one can rule out any significant contribution from a three photon process in the present experiments.

If we consider the two-photon process, we note that in Eq. (1) the required VN produced is reduced by a factor of about $10^9$ from the previous case. This present result corresponds to a plasma atom density of $10^{20}$cm$^{-3}$ throughout a liter volume. Under any circumstances, the required VN product is less by a factor of $10^9$ for the two photon process than for the three photon process. The conclusion is that one would expect the simultaneous absorption of two ruby laser photons to play a significant role in the ionization mechanism.

With the two photon absorption process, one could have pre-excitation of the cesium atoms or post-ionization. In order to determine the relative importance of the above two processes, one needs the excitation (by electrons) cross section from the ground state, the ionization cross section from excited states, and the lifetimes of excited states.

Whenever plasma electrons are exposed to laser radiation, it is likely that energetic electrons will exist in profusion. The absorption of photons by the inverse bremsstrahlung mechanism is a highly probably process. R. D. Kerr et al.[4] state "It is likely that when ionization is appreciable, conventional inverse bremsstrahlung absorption will take over as the main heating (and hence ionizing) mechanism." Preliminary calculations in the present case indicate that the above assertion is borne out.

In the present case an appropriate expression for the inverse bremsstrahlung absorption coefficient,[5] $K_\nu$ is

$$K_\nu = 3.69 \times 10^8 \frac{n_e^2}{\nu^3 T_e^{1/2}}, \qquad (2)$$

where $n_e$ is the electron density, $T_e$ the electron temperature, and $\nu$ the laser photon frequency. $K_\nu$ has the dimensions of cm$^2$/cm$^3$ or cm$^{-1}$ and is

like a mean free path. We can calculate $K_\nu$ for assumed electron temperatures and densities, and hence obtain an equivalent cross section $\sigma_e$ for the process according to the following equivalence relationship:

$$K_\nu = \frac{1}{n_e \sigma_e} . \tag{3}$$

In Eq. (2), if we take

$$n_e = 10^{16} \text{ cm}^{-3} \text{ and } T_e = 2000°\text{K}$$

as being typical, we obtain

$$K_\nu = 1.012 \times 10^{-5} \text{ cm}^{-1}$$

and $\sigma_e$, the effective cross section for inverse bremsstrahlung absorption, is given by,

$$\sigma_e = 10^5 \times 10^{-16} \text{ cm}^2$$

With such an enormous cross section, this mechanism is likely to take over.

Finally, something needs to be said about recombinations. C. J. Chen et al.[6] measured recombination coefficients as a function of electron temperature and density for cesium plasma. The recombination coefficient, $\alpha$, in $\text{cm}^3 \text{ sec}^{-1}$ is defined in the following equation:

$$\frac{dn_e}{dt} = -\alpha n_e^2 . \tag{4}$$

$\alpha$ and the recombination cross section, $\sigma_r$, are related as follows

$$\alpha = \sigma_r \bar{v}, \tag{5}$$

where v means electron speed and the bar means average. If we take the average speed to be about $2 \times 10^7$ cm/sec, a rough calculation gives $\sigma_r$ to be about $5 \times 10^{-16}$ cm$^2$, a significant cross section. They[6] measured values of $\alpha$ at 2000° K in the range of $n_e$ from $10^{12}$ to $10^{15}$ cm$^{-3}$. We have extrapolated the measured value of $\alpha$ at

$$T_e = 2000° K, \quad n_e = 10^{16} cm^{-3}.$$

The extrapolated value of $\alpha$, thus determined, is $10^{-8}$ cm$^3$ sec$^{-1}$.

Recombinations compete rather favorably with the two-photon ionization process. However, the presence of an electric field in the interelectrode region would tend to keep the ions and electrons separated and make the recombination process more difficult.


## ACKNOWLEDGMENT

The authors would like to acknowledge the able assistance of Paul Cassell in performing experiments with the converter that he fabricated.


## V. CONCLUSIONS

The analysis shows that the plasma density would have to be unreasonably high for a three photon absorption process to be important in accounting for the results obtained. Also the absorption of one photon quantum does not correspond to any energy level difference in cesium. Therefore, the simultaneous absorption of two ruby laser photons appears to be one of the important mechanisms in the ionization process; from Table 1 it is evident that this type of

absorption will produce cesium atoms excited close to their ionization levels.

The excited cesium atoms become ionized as a result of subsequent collisions by energetic electrons. The cross section for inverse bremsstrahlung interactions of electrons and ruby photons is large enough so that energetic electrons will exist in abundance. It is likely that collisions of the energetic electrons with cesium atoms, particularly the excited ones, are an important step in the final ionization mechanism.

Table 1. Energies Involved in Absorptions in Cesium

| Property | Energy(ev) |
|---|---|
| Work function of CS | 1.81 |
| 1st excitation potential of Cs $6^2S \rightarrow 6^2P$ | 1.43 |
| $6^2S \rightarrow 9^2P$ Transition in Cs | 3.43 |
| $6^2S \rightarrow 10^2P$ | 3.57 |
| $6^2S \rightarrow 9^2D$ | 3.58 |
| $6^2S \rightarrow 11^2P$ | 3.65 |
| $6^2S \rightarrow 16^2P$ | 3.81 |
| Ionization potential of Cs, with respect to ground state | 3.86 |
| Energy per photon of ruby laser light | 1.79 |

Table 2. Conversion Factors

| | |
|---|---|
| $6.250 \times 10^{12}$ | electrons per microcoulomb |
| $3.490 \times 10^{18}$ | photons per joule in ruby laser light |
| $3.490 \times 10^{22}$ | photons per joule per second for a 100 - μsec pulse |
| $3.490 \times 10^{24}$ | photon flux (no $cm^{-2}sec^{-1}$) for photons crossing 1 $mm^2$ area |

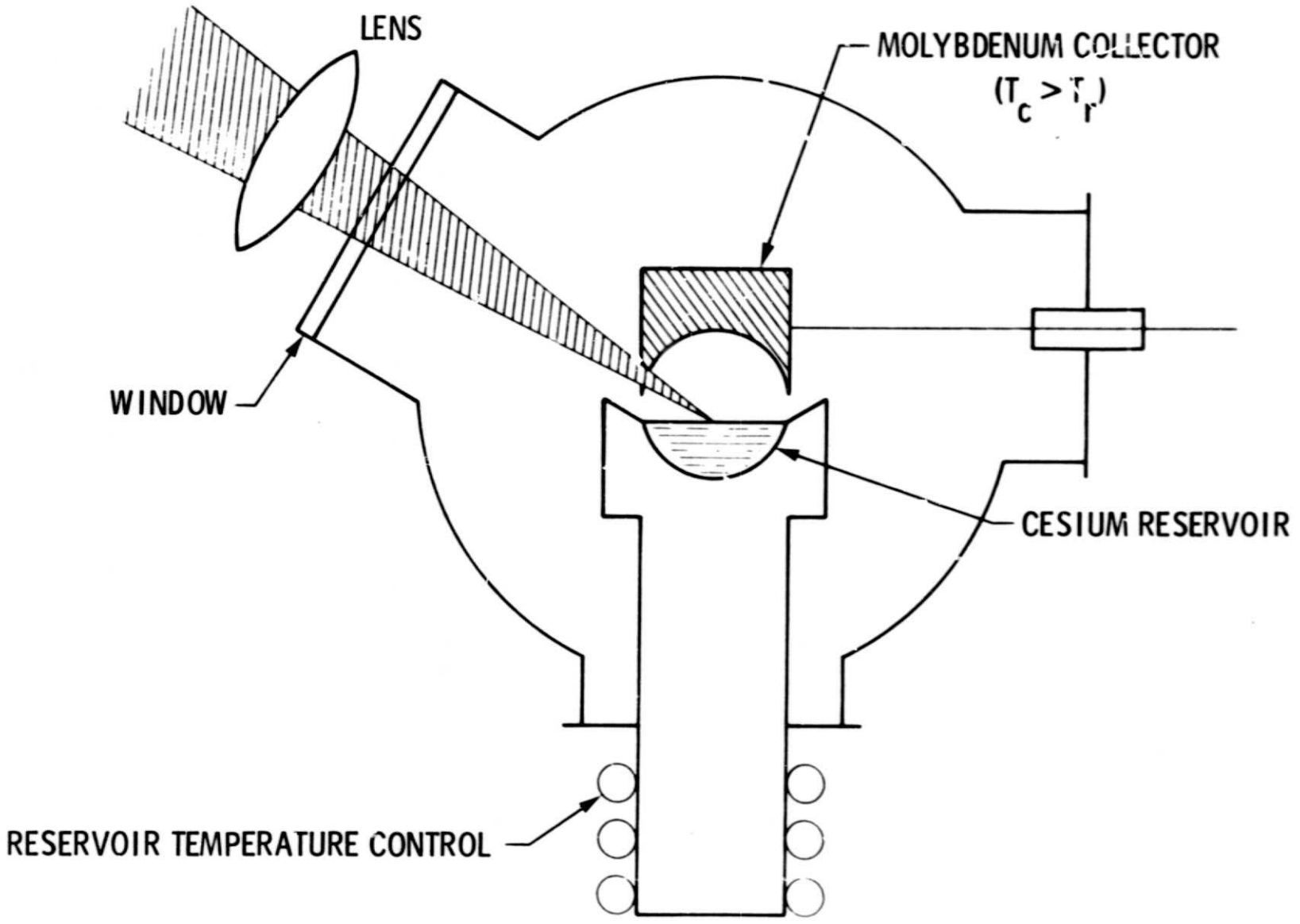



Figure 1. Schematic Diagram of the LPD Converter

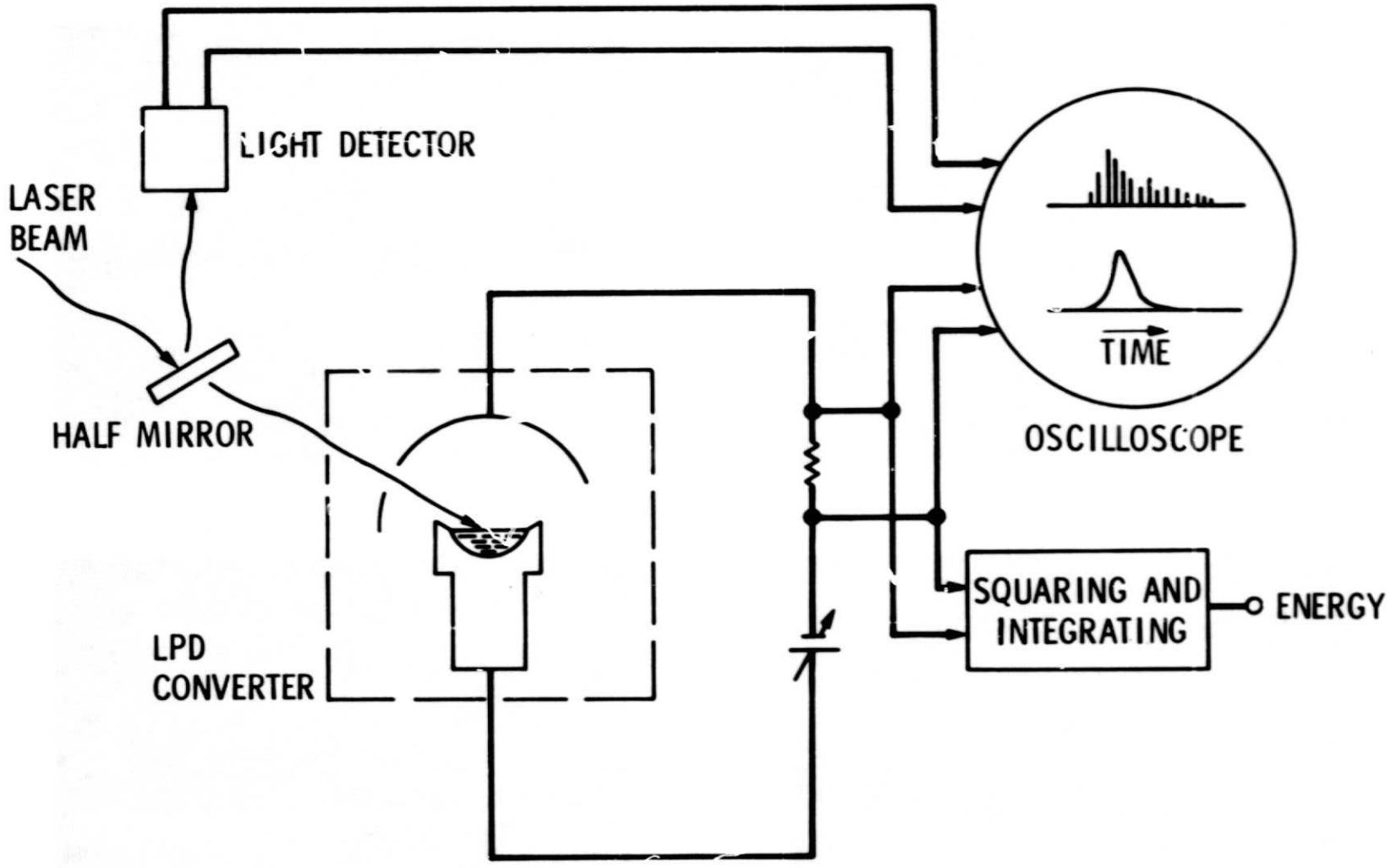
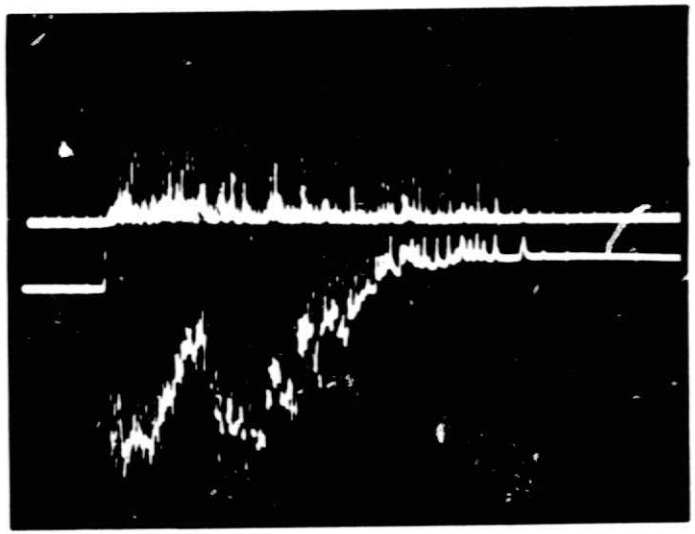
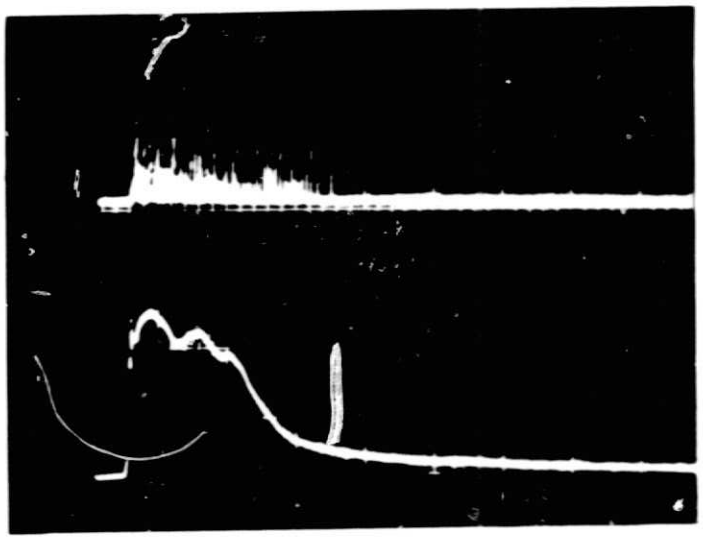


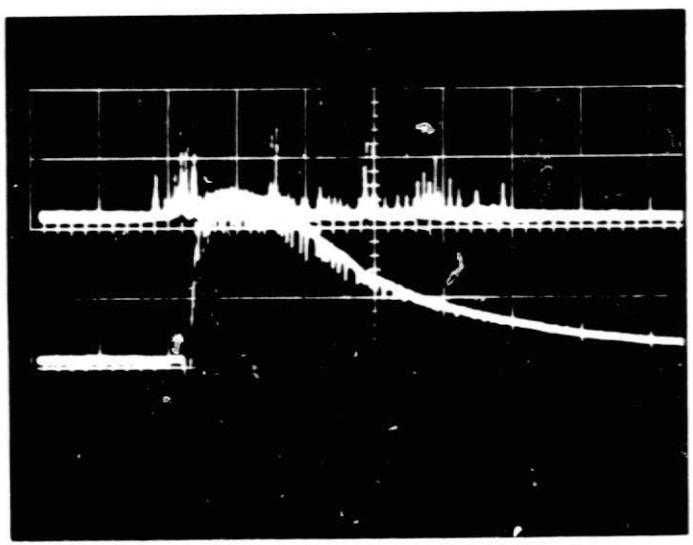

Figure 2. Measuring Circuit



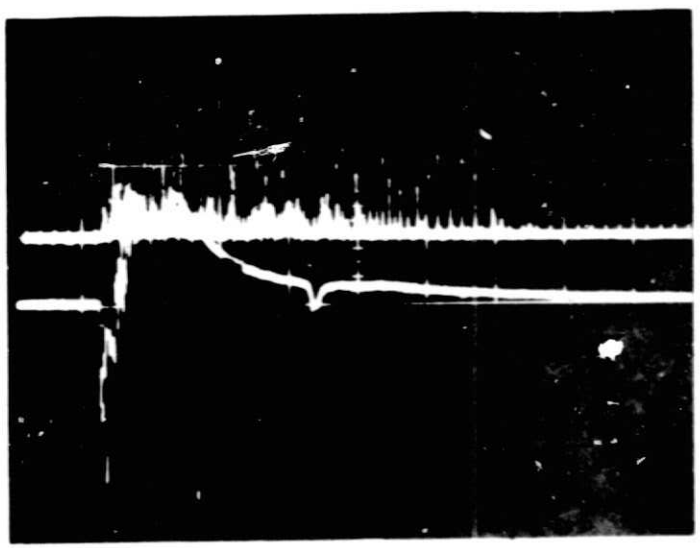
APPLIED VOLT = +0.5V
CURRENT SCALE 0.2A/cm



APPLIED VOLT = -2.0V
CURRENT SCALE 0.5A/cm



OPEN CIRCUIT VOLT
VOLTAGE SCALE 0.1 V/cm



SHORT CIRCUIT CURRENT
CURRENT SCALE 0.1 A/cm

Figure 3. Oscillographs Showing the LPD Output

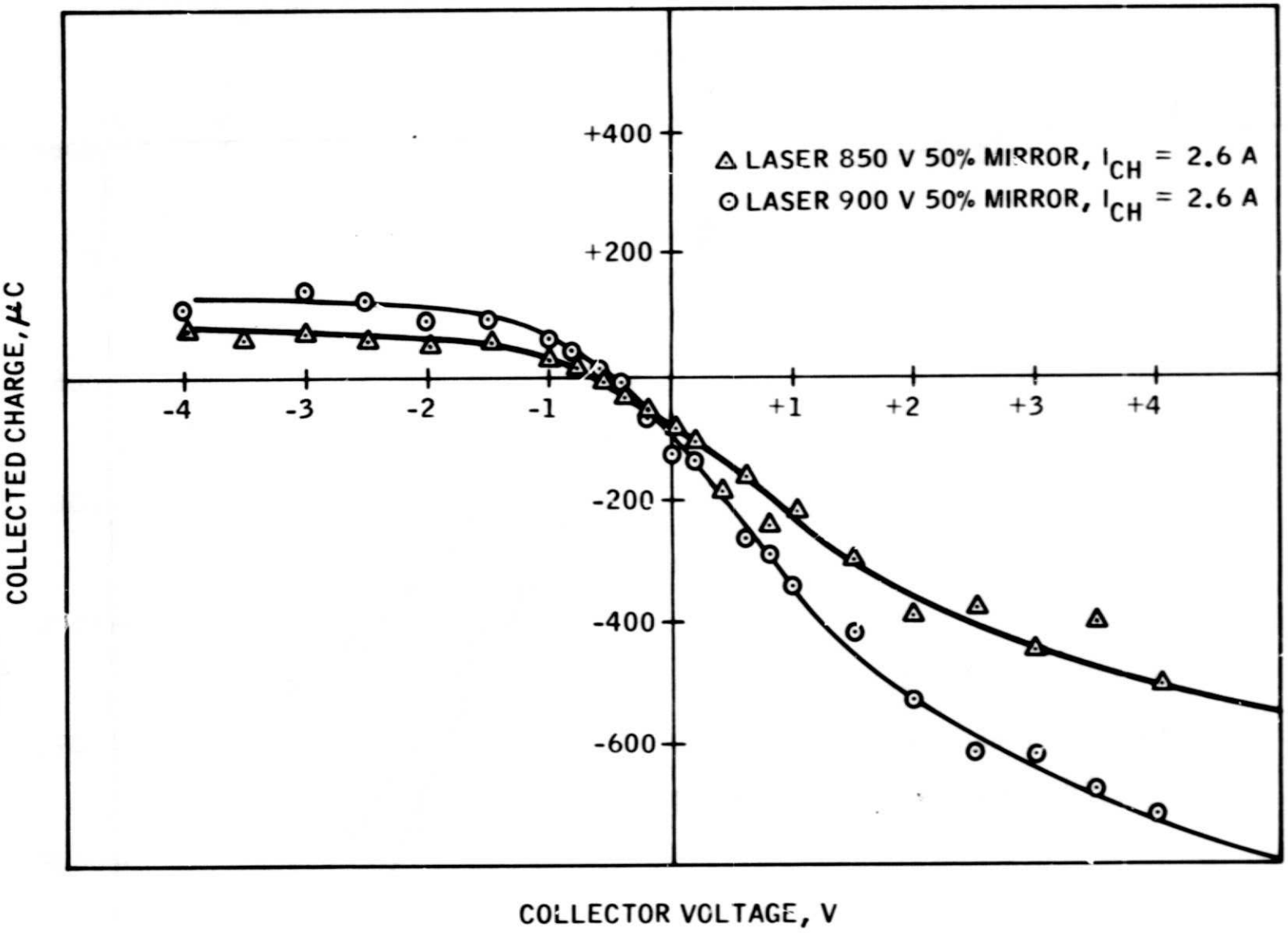



Figure 4 Collected Charge vs Collector Voltage At Low Collector Temperatures with Collector Heat Current $I_{CH}$ = 2.6 A

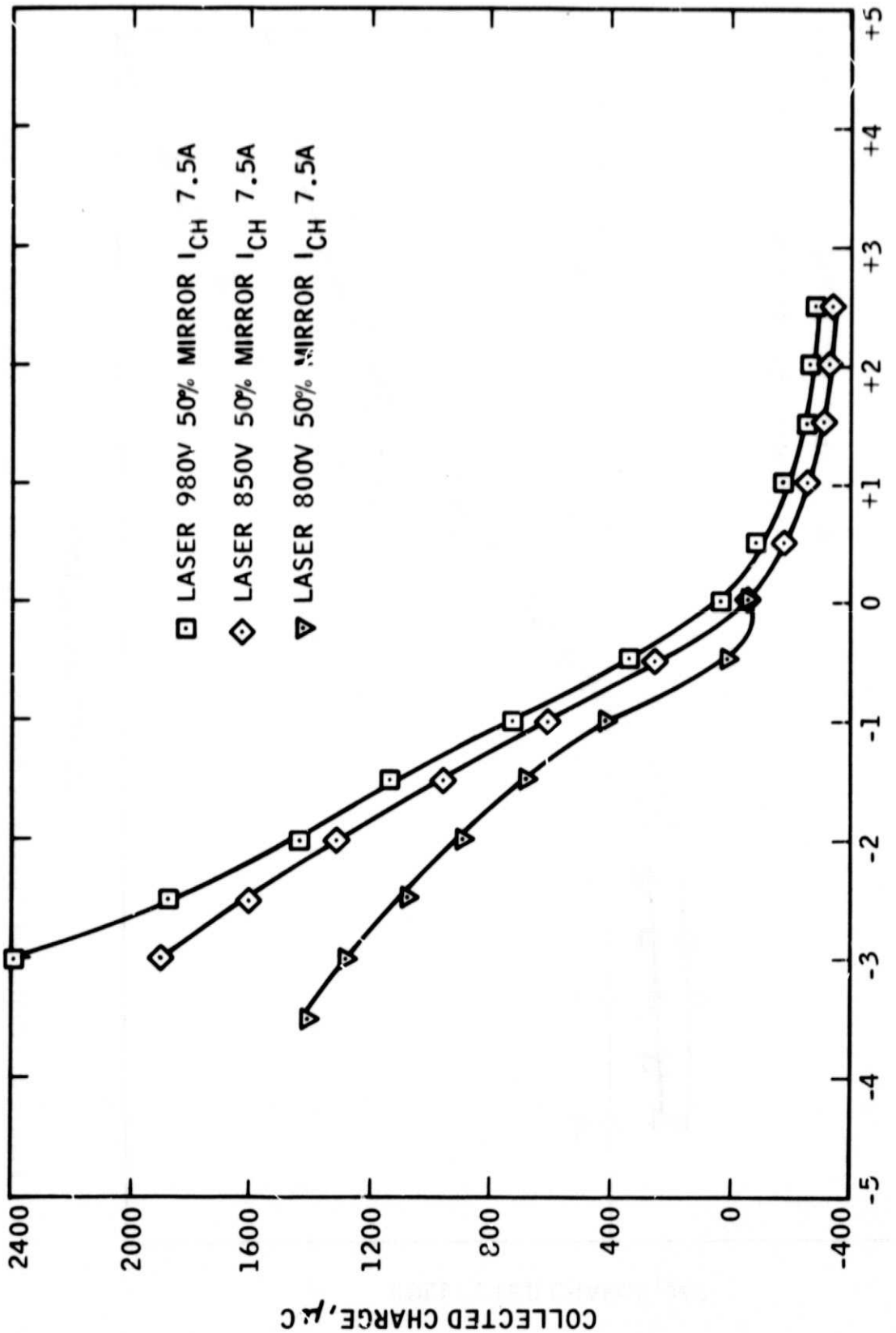



Figure 5. Collected Charge vs Collector Voltage with $I_{CH}$ = 7.5 A (Collector Temperature ~ 950°K)

## REFERENCES


1. I. D. Abella, Physical Review Letters 9, 453 (1962)
2. B. A. Tozer, Physical Review, 137, A1665 (1965)
3. B. A. Tozer, Op. cit.
4. R. D. Kerr, P. R. Smy, and A. A. Offenburger, Jour. Appl. Phys. 44, 3063 (1973)
5. L. Spitzer, Jr., Physics of Fully Ionized Gases, 2nd Revised Edition, P148. Interscience Publishers, New York (1962)
6. C. J. Chen, J. M. Wu, F. T. Wu, and D. T. Shaw, Jour. Appl. Phys. 44, 3052 (1973)




NASA–JPL–Coml., L. A. Calif.