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The NRL One Kilojoule CO₂ Laser

R. E. PECHACEK, J. R. GREIG, M. RALEIGH and S. R. ROD

*Experimental Plasma Physics Branch
Plasma Physics Division*

September 1977

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THE NRL ONE KILOJOULE CO₂ LASER

INTRODUCTION

This report describes an ultra-violet preionized, CO₂ laser head that was developed at the Naval Research Laboratory for use in plasma production experiments. A 1000 Joule CO₂ laser, consisting of four of these heads is to be used with a 100 J Nd-glass laser to produce a large, moderately warm plasma ($N = 3 \times 10^{19}$ ions, $T \approx 50$ eV), which is to be studied in a variety of magnetic field geometries. A pulsed high energy CO₂ laser head is essentially a device that produces a very uniform electrical discharge of very large cross-sectional area in a gas mixture of the proper constituents. There are two types of devices in wide use for achieving this large uniform discharge in a CO₂ laser mixture: In one type a high voltage electron beam provides the ionization in the laser gas mixture, and the electron acceleration that results in excitation collisions with CO₂ molecules is provided by a separate and relatively low voltage applied across the electrode gap. By relatively low, it is meant that the applied voltage is not high enough to cause electron multiplication.

In the second type of laser head a relatively high voltage is applied across the gas mixture and a uniform discharge is insured by having previously slightly preionized the gas mixture by ultra-violet radiation. The u-v preionization provides only enough electrons to ensure a uniform discharge. Ionizing collisions in the applied electric field provide the bulk of the electrons for the high current discharge.

The laser head described in this report is of the second type and is a scaled up version of the CO₂ laser head developed at the National

Note: Manuscript submitted August 30, 1977.

Research Council in Ottawa and reported in reference 1. A photograph of the four laser heads arranged in tandem is shown in Figure 1. The entire laser is about 11 meters long and stands about 1.6 meters high.

OPERATING CHARACTERISTICS

The CO₂ laser when connected as an oscillator followed by three amplifiers, produces one kilojoule pulses of 10.6 μ m radiation. The pulses consist of 70 nsec, FWHM, initial spike followed by a 1.0 μ sec tail. The spike contains 30% of the laser pulse energy and it attains a peak power of 4.3 GW. The lasing gas mixture corresponding to these values is a 1:1:8 mixture of carbon dioxide, nitrogen and helium. An oscillograph recording of the laser output and the corresponding pumping current are shown in Figure 2.

The firing rate for the laser is one shot every 6.5 minutes. Of this interval 1.25 minutes is required for charging the laser Marx generators, 0.25 minutes to complete the firing cycle, and five minutes is used to bleed a fresh gas mixture into the laser heads and to exchange the gas in the Marx generator switch columns. As of June 1977, the laser has been fired about a thousand times at an output energy of one kilojoule per pulse.

The area of the output beam is 300 cm². The divergence of the laser beam, as measured by recording damage patterns, from multiple reflections through a germanium wedge is about 1.2 mrad. Those measurements were made using a 1.0 m focal length lens and a bismuth film target. The 1.2 mrad value for the divergence is about 20 times larger than the diffraction limit. Table 1 is a summary of many of the characteristics of the laser.

LASER HEAD MECHANICAL DETAILS

An entire laser head assembly is shown in Figure 3. The laser head discharge chamber sits above the four capacitors and the switch column of the Marx generator. The entire assembly rests on a hydraulic table that raises and lowers the Marx generator out of and into the high voltage transformer oil in the 400 gallon polyethylene and epoxy-fiberglass plating tank. Maintenance on the Marx generators would be nearly impossible without the hydraulic tables. The high voltage electrode is situated in the bottom of the plexiglass vessel and is barely visible behind the white dust cover. The grounded electrode is at the top of the chamber. Unlike the high voltage electrode, which is smooth and solid on its face, the face of the ground electrode is a perforated screen, behind which is the ultra-violet preionizing spark board. The four vertical copper tubes extending downward from the chamber cover are the Marx generator ground return conductors.

The four capacitors and the laser head are supported by insulating cast epoxy blocks, that in turn are supported on vertical aluminum rods. The blocks were cast from a 10:6 mixture of Hysol R-2039 casting resin and TH 3888 hardener. Besides its strength, this material has two desirable features: It has very low shrinkage ($<1\%$) and it hardens very slowly, such that all bubbles rise out of the mixture before it hardens. This latter quality is important if an epoxy is to have a high dielectric strength.

Figure 4 contains two cutaway views of the discharge chamber. This figure shows the Rogowski profile of the electrodes and the extent of the hole in the ground electrode. The high voltage electrode is raised above

the bottom aluminum cover plate to allow a greater high voltage creepage path between the cover plate and the surface of the transformer oil.

The Rogowski electrodes were designed by using the equations of Cobine², and the resulting surface is given by

$$y = b - \frac{a}{2} \cdot \frac{a}{\pi} \left(\frac{\pi(|x| - w)}{e^a} + \frac{\pi(|z| - l)}{e^a} \right),$$

where

$$a = 16 \text{ cm}$$

$$b = 18.16 \text{ cm}$$

$$w = 24.46 \text{ cm}$$

$$l = 72.43 \text{ cm.}$$

A plot of one octant of this equation is presented in Figure 5. It should be noticed that looking from the top, i.e., in the - y direction, the outline of this electrode is nearly square. This is in contrast with other designs that have semicircular ends. The sharper corners of the square electrode, however, have never caused any arcing. The casting patterns were made from templates cut on a tape-fed mill using the above equation. The electrode material is aluminum casting alloy #195.

The surface of the electrodes is rough-sanded or filed to remove bumps or obvious irregularities. The first pair of electrodes that were cast were also heat treated in the mistaken belief that the heating/hardening process should improve the machinability of the metal. Not only was the opposite true, but the castings sagged during the heating process and quite a bit (1/8" to 1/4" cuts) of milling followed by hand filing was required to remove a central low spot in the face of the high voltage electrode. The ground electrode did not sag as much because it is cast with a large rectangular hole in its face that will later be covered with a perforated

metal screen. The remaining three pairs of electrodes were machined as cast and more nearly approach the Rogowski than the first pair.

As mentioned before, the ground electrode is cast with an approximately 110 cm x 21 cm rectangular hole in its face. To prepare the casting for the perforated screen, the casting is milled flat around the hole and then a step, 1.25 cm wide, and as deep as the thickness (~ 1 mm) of the perforated screen, is milled around the hole. The perforated screen is then bolted into this inset with flat head screws. The screen was cut from a standard sheet of perforated stainless steel having .386 cm diameter holes spaced .462 cm apart, and transmitting 55% of normally incident light. It is difficult to cut and bolt this material without bending its edge, which prevents the sheet from lying flat on the milled surface of the electrode. It was later found that, at not much more expense, custom perforated sheets could be fabricated that had a solid border that resulted in a much smoother electrode surface. The drawback of the custom material is that while the hole size is the same, the minimum hole spacing available is .56 cm resulting in a 37% transmission efficiency. The decreased efficiency necessitated a 50% increase in preionizer capacitor bank energy, but the increased smoothness eliminated the only spots on the electrode surfaces that received repeated arcs.

The ultra-violet preionizer spark gaps are located in the ground electrode, 5.7 cm from the perforated screen. The 5.7 cm distance is the minimum distance at which there is no arcing between preionizer and screen. The pre-ionizer consists of an array of 800 surface sparks between stainless steel washers that have been glued onto a nylon sheet. The array consists of 16 rows of 50 washers each, as shown in Figure 6. The first washer of

each row is connected to the preionizer high voltage source through a vacuum feed-thru. The last washer is connected to ground. The washers (#6S) are etched in hydrofluoric acid and glued to the 1.5 mm thick sanded nylon sheet with Eastman 910 glue. The nylon sheet is bonded (also with Eastman 910) to an approximately 3 mm thick brass sheet that serves as the ground plane. After the washers have been glued onto the nylon and the glue has hardened, the bonding is checked by running a screwdriver along each row, like running a stick along a picket fence. Out of 800 washers two or three may pop loose under this test, and are replaced. Once they pass this "screwdriver" test, the washers are permanently in place.

As mentioned earlier, the last washer is connected to ground and this is accomplished simply by a screw threaded into the brass ground plane through the last washer. The sixteen first, or high voltage, washers are actually the heads of custom made $\frac{1}{4}$ " brass bolts. The bolt shaft passes through the ground plane and the aluminum cover plate to the exterior of the vessel, where it is connected to a coaxial cable and the u-v preionizer capacitor bank. The brass bolt is insulated from the aluminum top plate by a $\frac{1}{2}$ " o.d., 1/8" wall, nylon sleeve. As shown in Figure 7, this nylon tube extends to the brass ground plane where it meets the 1.5 mm nylon sheet. Breakdown at the seam between the tube and the sheet is avoided by the use of a compressed silicone washer. The washer is a vacuum seal as well as a "voltage seal". Aluminum sleeves around the nylon insulators provide a low inductance return path for the preionizer current, provide a vacuum seal between the gas chamber and the outside, and are a structural element against which the brass bolts are tightened to compress o-ring seals. Two nuts are screwed on each brass bolt. The uppermost compresses the o-rings mentioned

above, and the lower nut compresses the nylon sleeve into the silicone washer. The result is a vacuum tight, coaxial feed-thru that provides more than 30 kV insulation.

ELECTRICAL DETAILS

There are two capacitor discharge systems associated with the laser head: the u-v preionizer capacitor bank and the main discharge Marx generator. These are shown schematically in Figure 8. This section consists of a discussion of the preionizer circuit followed by a discussion of the Marx generator.

The electrical characteristics of the preionizer are summarized in Table 2. The preionizer consists of sixteen identical rows of 50 stainless steel washers glued to a nylon sheet with a ground plane backing. (See previous section.) The driving voltage is applied to the innermost washer of each row and a surface arc propagates outward, washer to washer, to the outermost washer, which is connected directly to the ground plane. Figure 6 is a photograph of the u-v preionizer, showing the sixteen rows of washers and the sparks between the washers.

A streak camera photograph of the chain of washer-to-washer sparks, as shown in Figure 9, permits a qualitative picture of the sparks' propagation. The sequence of events when the high voltage end of the washer row is energized, is as follows: A very dim streamer is propagated from the high voltage washer to the ground washer at a speed of 3×10^8 cm/sec. When the streamer reaches the grounded washer, a return stroke is immediately initiated in the opposite direction, that first extinguishes the streamer light and then emits more strongly. This return stroke propagates at a speed of 1.2×10^9 cm/sec. The light from the return stroke persists for

about 150 nsec and then dims. Fifty nanoseconds later the intense light from the high current discharge begins. This intense light starts in the middle of the washer row and propagates outwardly at a speed of several times 10^9 cm/sec. The dark spaces recorded on the streak photos correlate with nulls in the applied current.

The electrical characteristics of the Marx generator are summarized in Table 3. It is a four stage generator with the capacitors arranged as shown in Figure 10. The capacitors have steel cases as one terminal and high voltage bushings as the other. In a Marx generator, of course, the capacitors are charged in parallel and discharged in series. During discharge, the lower right capacitor as shown in Figure 10 is closed to ground, followed in series by the lower left and then the upper right. The case of the upper right capacitor is connected directly to the high voltage electrode. This configuration permits all of the charging resistors to be located on one side of the switch column, and the clamping resistors on the other side. In Figure 10, it is the charging resistors that are visible. The resistors consist of CuSO_4 solution filled Tygon tubing with #4/0 wire lugs sealed into the ends with nylon clamps. The lugs have been sealed with solder to make them water tight. The resistance values are 1.0 k Ω for the clamping resistors.

The switch column consists of four 1.25 cm spark gaps between 3.75 cm diameter electrodes. The gaps are optically coupled by u-v radiation. The gap to gap spacing is 10 cm. The spark gaps are connected in series with the capacitors during erection, and the ground side spark gap is a triggered gap, using a Pharos type trigger pin electrode. The trigger is generated by

a .01 μ f capacitor charged to 23 kV. The electrodes are mounted on opposite sides of a square plexiglass cylinder, that is filled with about 5 psig of a $N_2:SF_6;95:5$ mixture for operation at a 68 kV charging voltage.

OPTICAL CAVITY

The entire laser consists of an oscillator head and three amplifying heads, and is shown schematically in Figure 11. All heads are joined by bellows and the oscillator mirrors are connected to the oscillator head by bellows. This scheme reduces the number of transmitting optical parts to a partially transmitting mirror and an output window.

The length of the optical cavity in the oscillator is 291 cm, of which 112 cm is active length. The cavity is terminated at one end by a gold plated plane laser mirror ($\sim 99\%$ reflectivity @ 10.6μ) and at the output end by a plane germanium window. The surface of the output window that is interior to the cavity is uncoated, and provides a reflectivity of 36%. The exterior surface of the output mirror is coated for high ($\sim 99\%$) transmission at 10.6μ . The output area of the beam is 300 cm^2 , and the shape of the output cross section is given by the intersection of the 21.6 cm diameter output window and a 15 cm wide horizontal strip centered about the circle. This 15 cm strip is the projection of the gap, between the discharge electrodes, on the output window.

The mirrors are mounted internal to the cavity, that is, the mirrors are used to seal the gas chamber and are exposed directly to the discharge. The mirrors are mounted in gimbaled mirror mounts, that are connected to the gas chamber by stainless steel bellows. The bellows are flexible enough to

allow the mirrors to be aligned. During the electrical discharge that pumps the laser gas mixture, about 166 joules/liter are dissipated in the gas. This sudden heating causes a shock wave of about 0.5 atm amplitude to strike the mirrors on each shot. To prevent wear and tear on the gimbal bearings, the mirror mounts are themselves mounted on four steel leaf springs in such a way that small axial motion of the mirror produces no change in mirror orientation (See Figure 12). This method of mounting mirrors has been used for some time in a variety of optical systems. It was first analysed and studied experimentally by R.V. Jones³ and first used in an optical interferometer by D.J. Bradley.⁴

Since both cavity mirrors are opaque to visible light, mirror alignment cannot be accomplished in the usual ways, and the following device and method are used. The alignment device shown schematically in Figure 13 and pictorially in Figure 12, consists of a silvered right angle prism, that has been selected for accuracy of the angle, mounted at the output end of an autocollimator with its 90° apex toward the autocollimator. Adjusting screws permit the prism to be oriented such that the autocollimator beam is reflected from the prism sides into two oppositely traveling but co-linear beams. This device, autocollimator plus prism, is mounted in a sliding vacuum feed-thru on a modified gimbaled mirror mount. The alignment procedure is as follows: The external surface of the germanium mirror is oriented to a desired position using a He-Ne laser. The autocollimator prism assembly is inserted radially into the cavity via the sliding vacuum feed-thru and oriented such that the beam that reflects from the germanium mirror is focussed on the autocollimator cross-hair. The gold

mirror is then oriented such that the reflection of the other beam is also focussed on the autocollimator cross-hair. The cavity is then considered to be aligned and the autocollimator is withdrawn from the cavity.

The laser heads are usually (always for purposes of this report) operated at a capacitor charging voltage of 68 kV and with a mixture consisting of 10% CO₂, 10% N₂, and 80% He. To this mixture is added 0.1 cm³ of tripropylamine, (C₃H₇)₃N, (ionization potential < 7.5 eV) to insure a diffuse discharge. This volume of liquid tripropylamine per head produces a molecular number density of $8 \times 10^{14} \text{ cm}^{-3}$. The 68 kV charging voltage and 15 cm electrode spacing produces a nominal initial electric field of 18 kV/cm, and a pumping energy input density of 181 Joules/liter. Under these conditions the small signal gain of the heads is about $.018 \text{ cm}^{-1}$, and a function of position on the output cross section as shown in Figure 14a and 14b. The dip in gain along the center-line of the heads is believed to be due to a spurious oscillation, generated in a mode that reflects from the corner (in the manner of a roof top reflector) produced by the Plexiglass tube and the salt window that was installed at either end of the gas chamber for the small signal gain measurements.

For a 10% CO₂, 10% N₂, 80% He mixture the cross section for stimulated emission at P(20) is $1.6 \times 10^{-18} \text{ cm}^2$. From this number and the small signal gain, $.018 \text{ cm}^{-1}$, the density of excited CO₂ molecules can be calculated : $N = 1.25 \times 10^{16} \text{ cm}^{-3}$. The total available energy stored in the gas is the product of N, the discharge volume $V = 35000 \text{ cm}^3$, the energy per lasing transition, and a factor of 15, as there are approximately that many excited vibrational levels. (In the small signal gain measurement we expect to have

measured the population of only one level {say $P(20)$ } but when the laser fires ~ 15 levels can contribute simultaneously.) The result is a total energy of 110 Joules, which is reasonably close to the energy in the initial 70 nsec wide spike of the oscillator output pulse. The magnitude of the laser head gain as a function of time is shown in Figure 14c.

Acknowledgments

The authors wish to acknowledge the initial suggestion and continued interest of Dr. A. E. Robson for this project. Also we wish to acknowledge many discussions with Dr. B. H. Ripin particularly concerning the measurement of the laser beam divergence. The technical assistance and many practical suggestions of Edward Laikin are also appreciatively acknowledged.

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2. J. D. Cobine, Gaseous Conductors, pg. 179, Power Publications, New York (1958).
3. R. V. Jones, J. Sci. Instrum. 28, 38 (1951).
4. D. J. Bradley, J. Sci. Instrum. 39, 41-45 (1962).

Table 1 -- Laser Head Characteristics

Electrode Type	Rogowski Profile
Electrode Dimensions	56 cm x 152 cm
Electrode Gap	15 cm
Gas Chamber Volume	$3.9 \times 10^5 \text{ cm}^3$
Beam Area	300 cm^2
Discharge Area	$112 \text{ cm} \times 21.5 \text{ cm} = 2408 \text{ cm}^2$
Peak Current Density	52 A/cm^2
Peak Electric Field	$\sim 18 \text{ kV/cm}$
Ionization Method	UV Pre-ionized
Ionization Discharge Energy	1.1 kJ
Discharge Volume	36 liters
Input Energy Density	181 J/liter
Output Energy/Discharge Volume	11 J/liter

Table 2 -- Laser Head u-v Preionizer Characteristics

Stored Energy	10^3 J
Capacitance	$4 \mu\text{f}$
Charging Voltage	23 kv
Current Risetime	$2 \mu\text{sec}$
Total Peak Current	$.9 \times 10^5 \text{ A}$
Configuration	16 Parallel Rows of 50 Gaps Each
Current/row	5.7 kA

Table 3 -- Marx Generator Characteristics

Type of Marx Generator	$m = 2$
Number of Stages	4
Number of Triggered Gaps	1
Gap Coupling	Optical
Type of Capacitor	0.7 μ F, 100 kV Aerovox Inc. PX480D63
Charging Voltage	68 kV
Stored Energy	6.5 kJ @ 68 kV
Ring Frequency (in situ)	0.33 MHz
Total Inductance (in situ)	1.5 μ H
Capacitor Inductance	30 nH ea.
Peak Current	1.3×10^5 amps
Current Risetime	0.6 μ sec

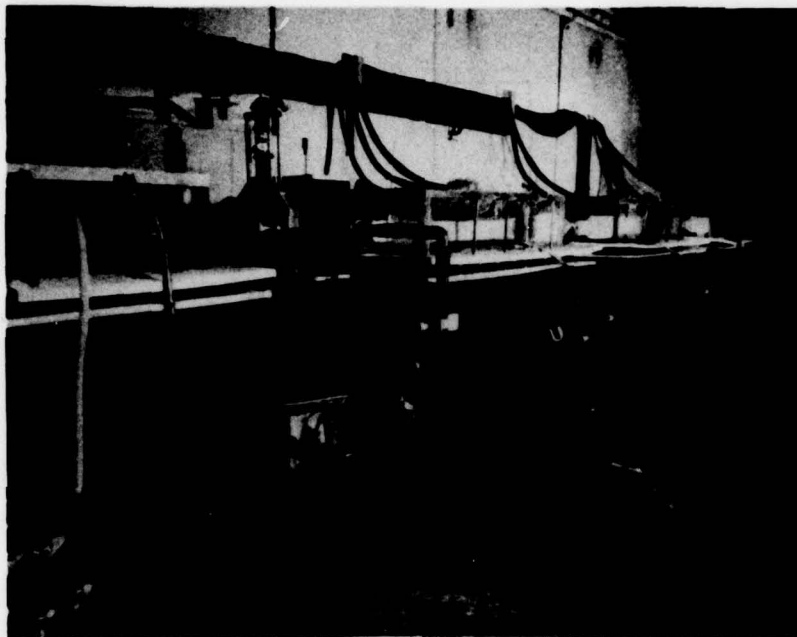


Fig. 1 — Photograph of the NRL one kilojoule CO₂ laser. Part of the oscillator is shown at the far left and the third amplified is at the far right.

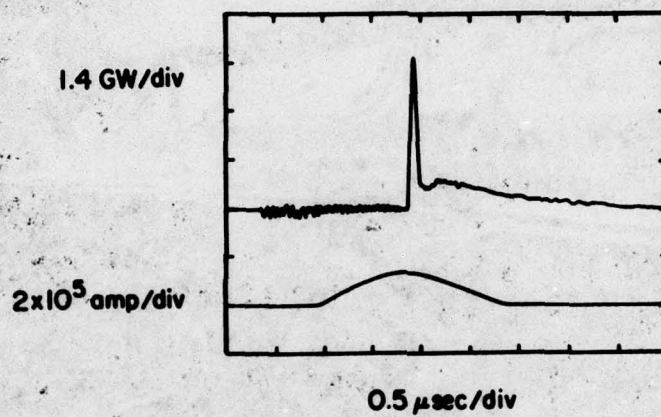


Fig. 2 — Oscilloscope recordings of the laser output, as detected by a photon drag detector, and the laser pumping current.

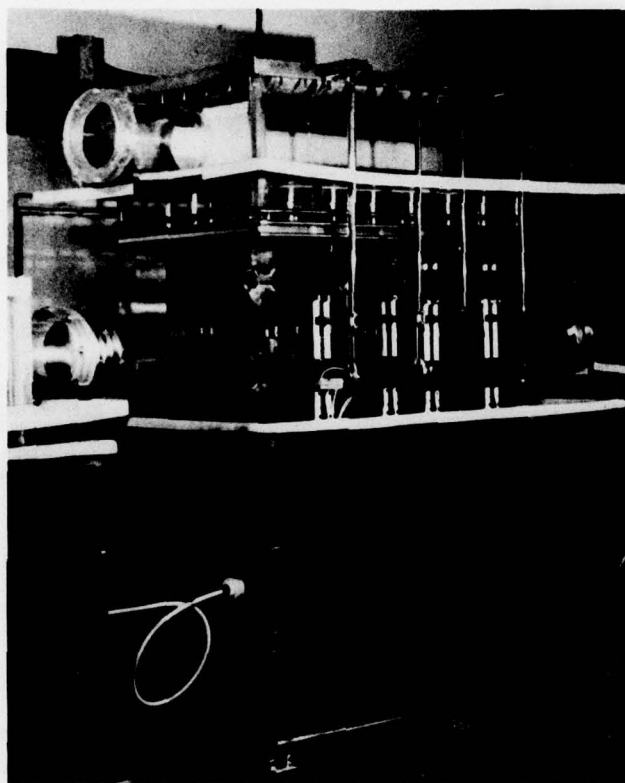


Fig. 3 — Photograph of a 35 liter atmosphere CO₂ laser head. The Marx generator has been raised out of the oil tank by means of a hydraulic table situated permanently in the tank.

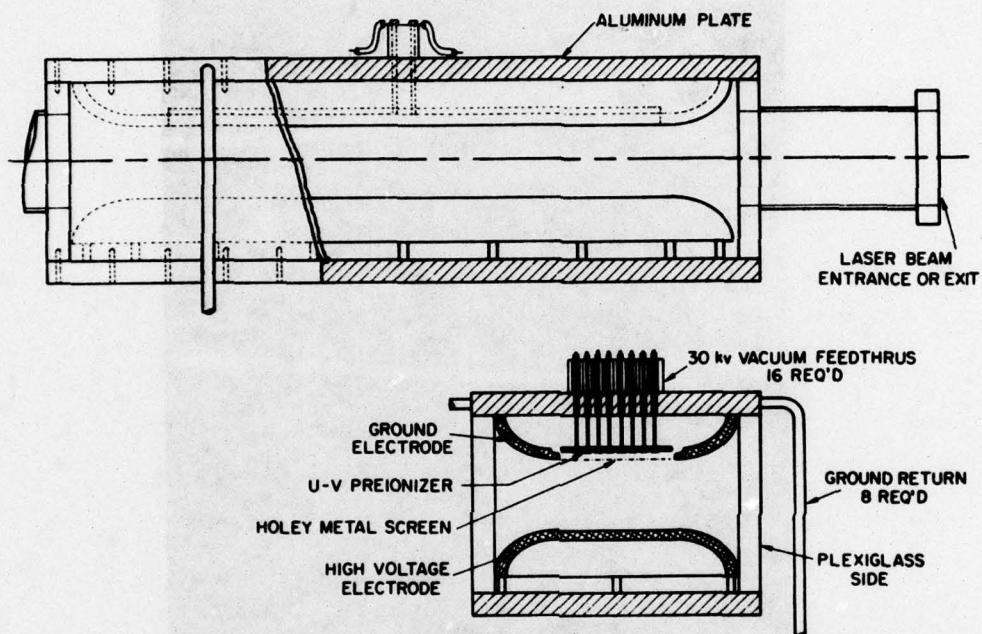


Fig. 4 — A cutaway line drawing of the 35 liter atmosphere CO₂ laser head.

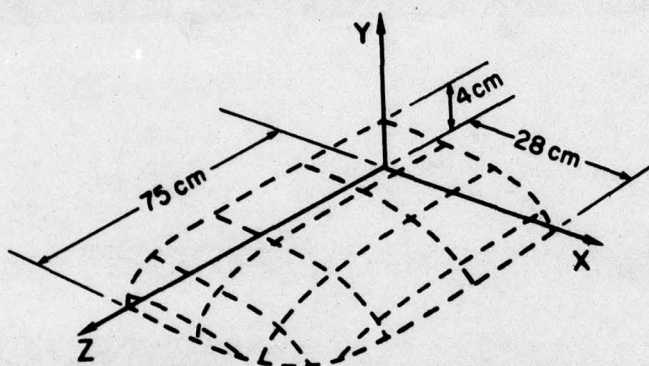


Fig. 5 — A plot of the Rowgowski surface used as electrodes in the laser heads.

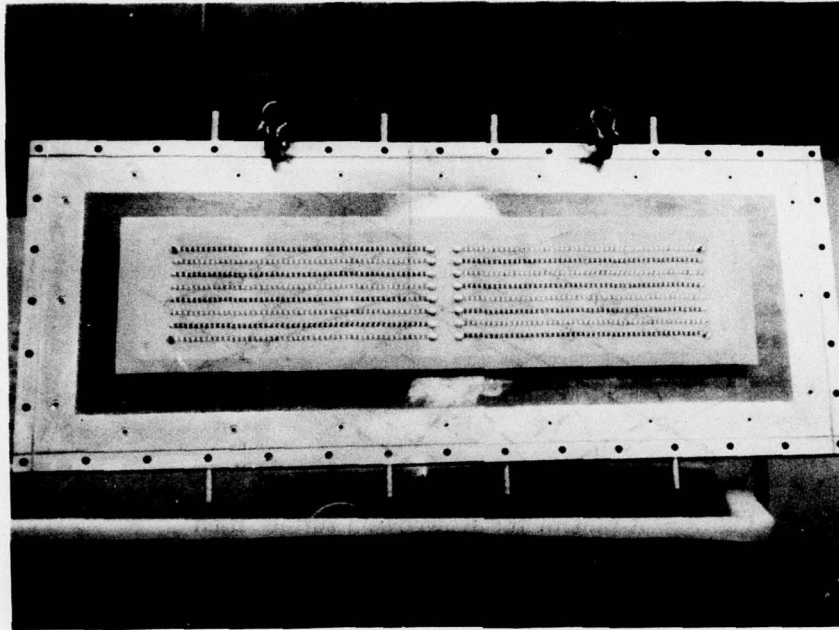


Fig. 6 — A photograph of the u-v preionizer spark board with arcs occurring between the washers.

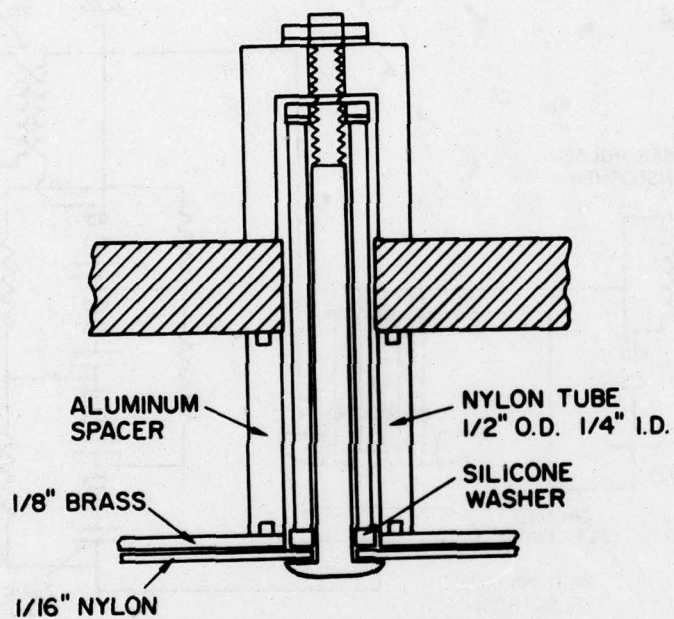


Fig. 7 — Detailed drawing of the high voltage feed-thru used in the u-v preionizer circuit.

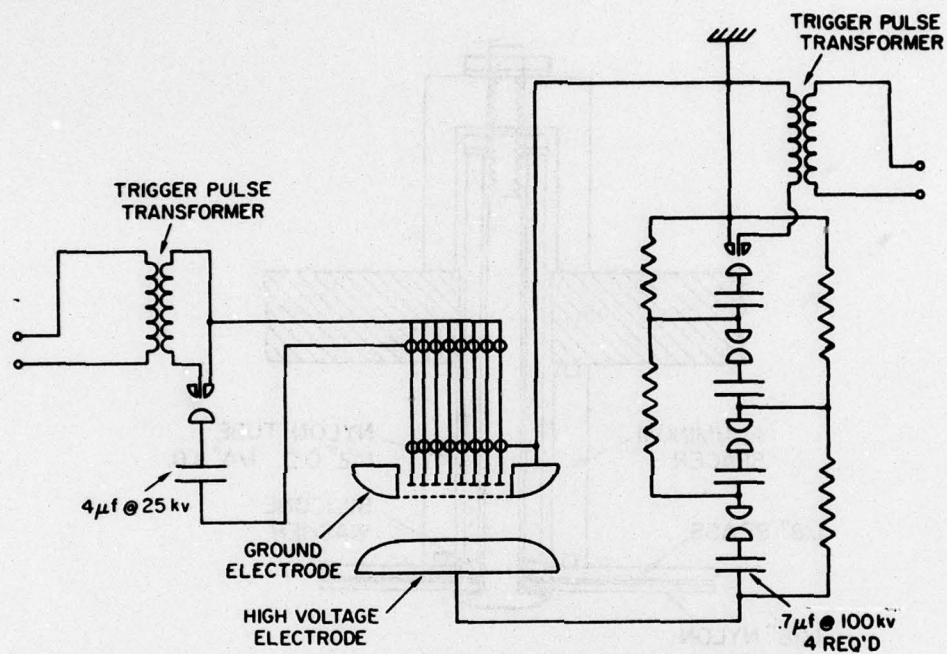


Fig. 8 — Electrical schematic diagram of the 35 liter atmosphere CO₂ laser head.

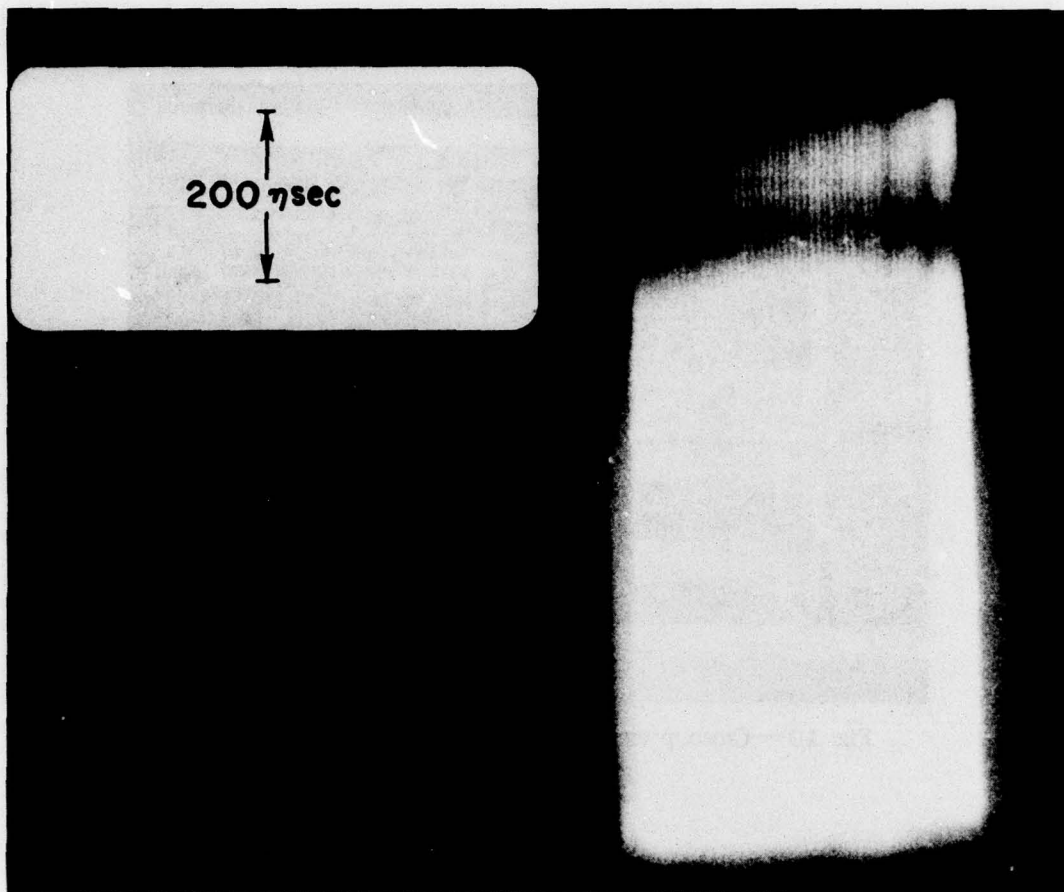


Fig. 9 — Streak camera photograph of the voltage breakdown of a row of washers in the u-v preionizing system. The row of 50 washers is horizontal and 48 cm long. Time sweeps downward at 200 nsec/cm.

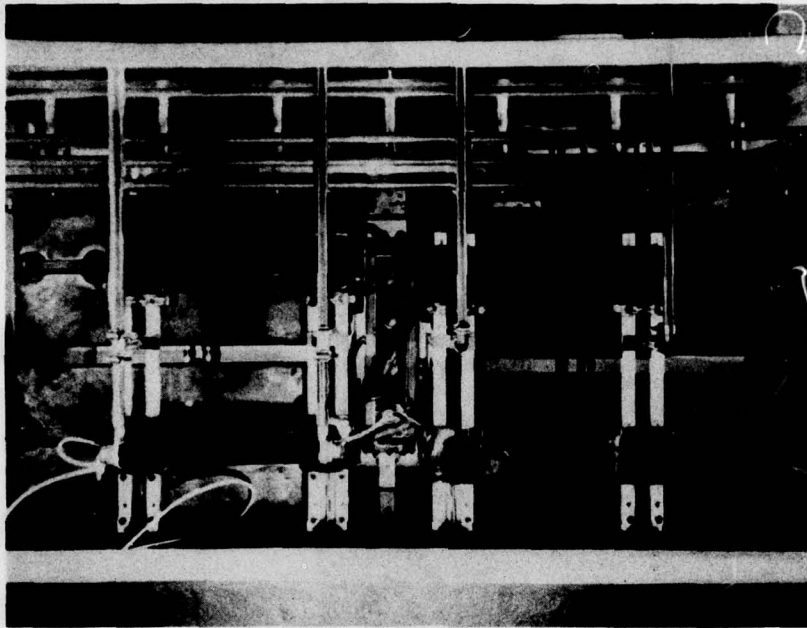


Fig. 10 — Closeup view of the laser head Marx generator.

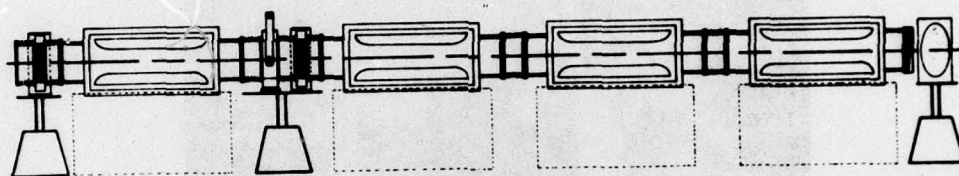


Fig. 11 — Schematic diagram of the laser system.

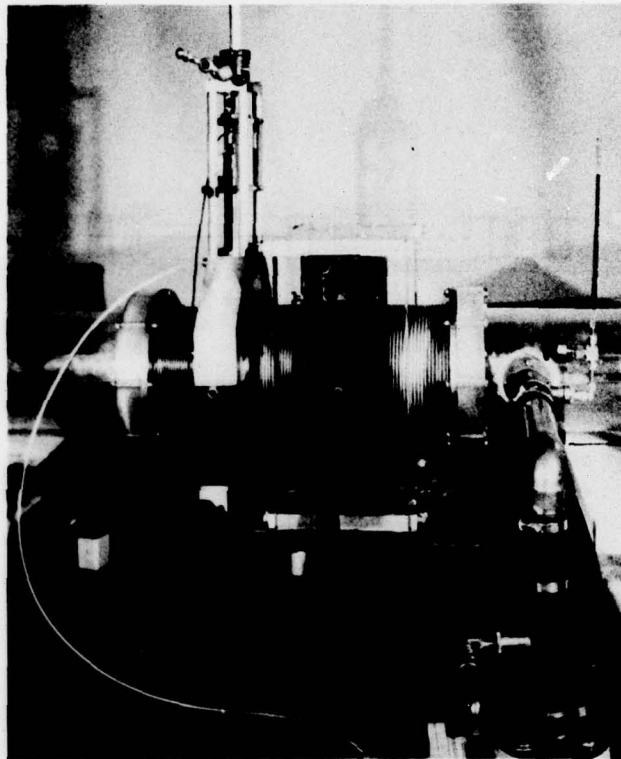


Fig. 12 — Photograph of the laser oscillator output mirror gimbal assembly and the autocollimator assembly.

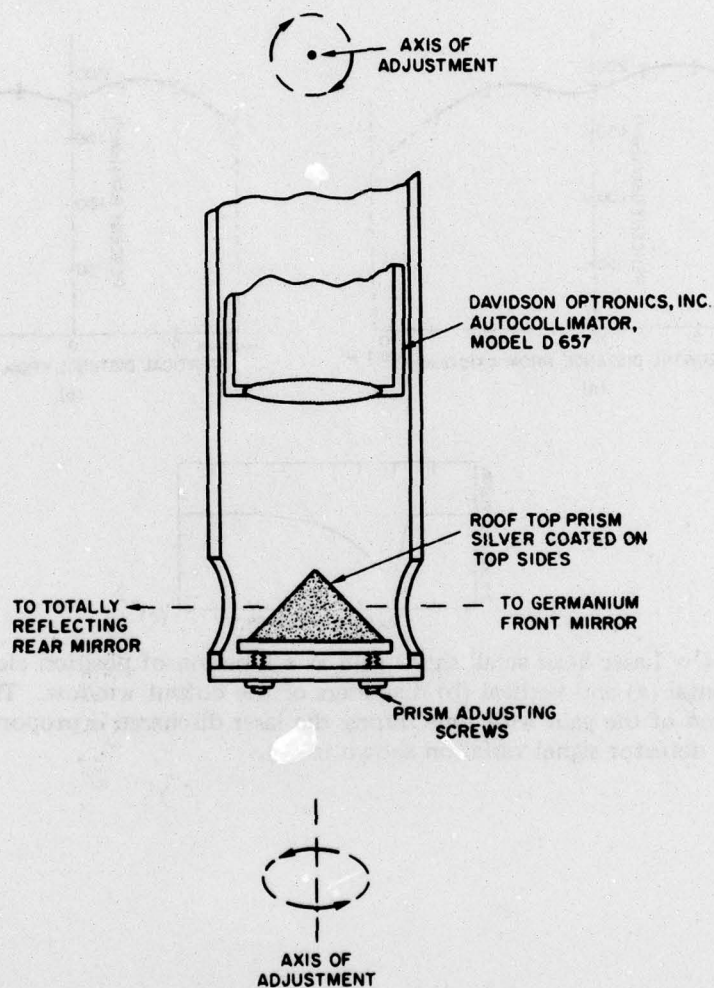


Fig. 13 — Schematic diagram of the autocollimator arrangement used to align the laser oscillator mirrors.

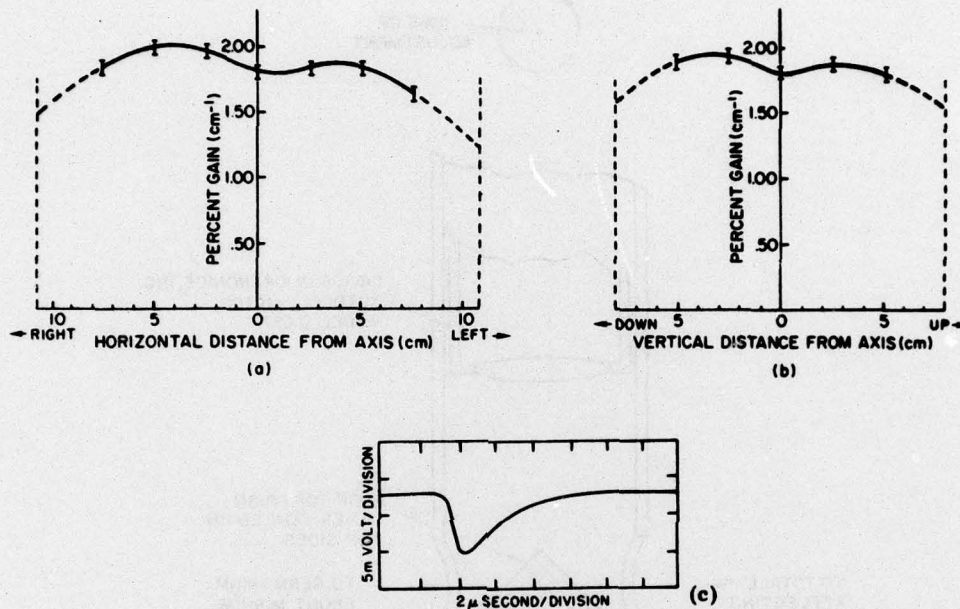


Fig. 14 — Laser head small signal gain as a function of position along horizontal (a) and vertical (b) diameters of the output window. The variation of the gain with time during the laser discharge is proportional to the detector signal variation shown in (c).