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NASA TM X-73485

(NASA-TM-X-73485) THE NASA HIGH POWER CARBON DIOXIDE LASER: A VERSATILE TOOL FOR LASER APPLICATIONS (NASA) 12 p HC $3.50 CSCL 20E
N76-30550
Unclas
G3/36 49572

NASA TM X-73485

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by R. B. Lancashire, D. L. Alger, E. J. Manista, J. G. Slaby, J. W. Dunning, and R. M. Stubbs
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at
Technical Symposium on Industrial Applications
of High Power Laser Technology sponsored by the
Society of Photo-Optical Instrumentation Engineers
San Diego, California, August 23-27, 1976

N O T I C E

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by R. B. Lancashire, D. L. Alger, E. J. Manista, J. G. Slaby,
J. W. Dunning, and R. M. Stubbs
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

E-5671

Abstract

The NASA Lewis Research Center has designed and fabricated a closed-cycle, continuous wave (CW), carbon dioxide (CO_2) high-power laser to support research for the indentification and evaluation of possible high-power laser applications. The device is designed to generate up to 70 kW of laser power in annular-shape beams from 1 to 9 cm in diameter. Electric discharge, either self-sustained or electron-beam-sustained, is used for excitation. This laser facility can be used in two ways. First, it provides a versatile tool on which research can be performed to advance the state-of-the-art technology of high-power CO_2 lasers in such areas as electric excitation, laser chemistry, and quality of output beams, all of which are important whether the laser application is government or industry oriented. Second, the facility provides a well-defined, continuous wave beam for various application experiments, such as propulsion, power conversion, and materials processing.

Introduction

The National Aeronautics and Space Administration (NASA) is engaged in a high-power laser research program. The general objective of this program is to define and evaluate the potential of high-power lasers for NASA applications. The Lewis Research Center of NASA is responsible for the systems definition portion of this program. In support of this broad technological responsibility, research and development activities (contractual and in-house) are conducted in key areas such as advanced lasing concepts, transmission of laser energy over long distances and its ultimate conversion into other forms, and the advancement of CO_2 laser technology in areas of interest to NASA. All of these areas have resulted from possible NASA mission scenarios which dictated the following basic laser system requirements:

(1) Multimegawatt laser devices
(2) CW operation for duration of several minutes to indefinite periods
(3) Completely closed-cycle operation (to eliminate storables in space)
(4) Large adaptive optics systems for transmission of high power over thousands of kilometers

The second and third requirements are not unique to NASA. Industrial users of multikilowatt lasers, faced with efficiency and economy considerations, will eventually require completely closed-cycle devices. Although NASA-Lewis has a significant interest in shorter wavelength lasers, carbon dioxide lasers offer an existing level of technological maturity which will serve as a reference for future high-power lasers operating at different wavelengths. It is for this reason that NASA-Lewis has designed and fabricated a CO_2, electric-discharge, closed-cycle, laser system which generates a beam with a wavelength of 10.6 μm. This system not only supplies a high-power beam for application experiments, but also provides the capability for investigation some basic parameters of CO_2 lasers which previously have been cursorily treated. This paper covers the general design of the high-power laser facility, some preliminary data, and operating characteristics.

Design Criteria

NASA's interest in CO_2 lasers is based on the fact that carbon dioxide - nitrogen - helium (CO_2-N_2-He) is the only high-power lasing medium which has been developed to the extent that it could satisfy the criteria just listed. Even then, there are characteristics of a closed-cycle, CW, CO_2 laser which are not clearly defined in such a way that the feasibility for use on future NASA missions may be determined. The following areas are of particular interest:

(1) Optimum electric excitation method for long-duration, high-power operation
(2) System efficiency
(3) Chemical poisoning effects on gas mixtures
(4) Optimum optical cavity configuration effects for best beam quality

The goal of the design of the NASA laser is to have a facility with the capability for investigating these areas and simultaneously conducting beam application experiments.

Excitation Method

Electric excitation has been considered the best method of exciting the CO_2 laser primarily because the efficiency of an electric discharge laser is apparently higher than that of a similar gas dynamic laser. However, the optimum method of electric excitation for long-duration continuous-high-output power remains to be determined. In any method, the major problem is one of controlling the level of electron generation. Electron-beam-sustained discharges have been promoted(1,2) as the best method of independent control of electron generation and electron energy in the discharge. This method requires large highly reliable electron transmission foils for long-duration operation together with very-high-voltage power supplies. Radiofrequency-stabilized, self-sustained discharges have been shown(3) to be reasonably successful, and also ultraviolet, preionized, self-sustained discharges have been suggested(4) as a possible solution to the electron avalanche control problem. An innovative solution to this problem has been suggested(5) in which a properly tailored string of 50-nanosecond electric pulses controls the electron avalanche process and maintains a steady-state plasma condition. This method, called impulse ionization, requires highly sophisticated pulse generating circuits. The most straightforward approach to electric excitation is a pure, self-sustained discharge. A question exists, however, of just how far this type of discharge can be scaled before the onset of instabilities.

The NASA high-power laser has been designed with a cavity which allows more than one type of discharge to be investigated in the same device. The pin-to-plane, self-sustained discharge(6) shown schematically in Figure 1(a), was chosen as the type to be evaluated first, and the electron-beam-sustained discharge (Fig. 1(b)) will be evaluated second. Output laser powers up to 70 kW are expected from the facility.

Gas Contamination

One of the major factors which has limited the operation of closed-cycle, CW, high-power lasers has been the effect of gas contamination due to plasma-induced chemical reactions in the lasing gases. To circumvent this problem, industrial type, multikilowatt CO_2 systems(1,3) supply makeup gases of up to 10 percent of the mixture of CO_2, N_2, and He to cleanse the gases. This makeup gas can substantially increase the cost of operating a system over an extended period, and furthermore require added gas storage space. Figure 2 shows some of the various reaction products that can occur in an electrically excited lasant mixture of CO_2, N_2 and He. It was shown in the work of reference 7 that the nitrogen-oxygen compounds were the worst contaminants. Results of that controlled experiment on a small, low-pressure (650 to 2000 N/m^2 (5 to 15 torr)) laser amplifier in which various contaminants were added are shown in Table 1. They indicate only 400 ppm of NO_2 can cause plasma instabilities, with complete loss of gain occurring with 1000 ppm. The NASA laser has been designed to assess and investigate contamination effects by using low-outgassing materials and high-vacuum technology. It is instrumented to monitor gas mixture compositional changes during operation. One of the goals is to determine the means of neutralizing the effects of contaminants.

Optical Configuration

Laser beam propagation is directly affected by the quality of the laser device output beam. The NASA laser has been designed to accommodate optics of various sizes in order to investigate the combined effects of beam size, optical paths, and electric discharge type on the output beam quality, both spatial and temporal. Optical configurations using single- and multiple-pass unstable oscillators or power amplifiers or both are possible in the device.

Description of Laser

A drawing of the NASA high-power laser is shown in Figure 3. The gas flow loop occupies a flow space of approximately 6 by 6 m (20 by 20 ft) and contains a flow volume of approximately 20 m^3 (700 ft^3). The major components are (1) the vacuum system and gas supply system (not shown in the figure), (2) the pressure blower, (3) the laser test cavity, (4) the diffuser, and (5) the heat exchanger. Each of these components is described in this section. The laser system operating specifications are listed in Table 2.

Vacuum and Gas Fill System

The vacuum system is used to evacuate the flow loop to below atmospheric pressure before the system is filled with the lasant gas mixture of CO_2, N_2, and He. A unique feature of this facility is the capability of obtaining a hard vacuum. The low background pressure, together with the use of stainless steel and other low-outgassing materials in the loop, removes from consideration the effect of residual gases causing contamination of the lasing gases. Three stages of vacuum pumping, two roughing systems, and a 50-cm (20-in) oil-diffusion pump allow the laser loop to be evacuated to a level of 1.3×10^{-4} N/m^2 (10^{-6} torr). The roughing systems alone can maintain the loop at less than 0.13 N/m^2 (1.0 μm Hg).

The gas fill system, located outside the building, consists of three large-capacity, high-pressure storage tanks for industrial grade CO_2, N_2, and He. The gases are introduced into the laser flow loop through the plenum tank.

Pressure Blower

The centrifugal blower has an impeller 1.83 m (6 ft) in diameter. Although designed and fabricated to NASA specifications, the general design is similar to common industrial exhaust blowers. An unusual characteristic, however, is the requirement that it operate over a pressure range from 1.3×10^4 to 1.1×10^5 N/m^2 (100 to 800 torr) and circulate gases at various densities and velocities around the laser loop. The velocity design point was 100 m/sec. The fractional amount of helium in the gas mixture, which varies from 50 to 80 percent, places the most restriction on the blower performance. The blower is driven through a variable-speed fluid coupling by a 250-hp motor.

The key to the successful operation of the laser, as a completely closed-cycle system without using makeup gases, is the seal between the shaft and the blower housing. The NASA choice was a seal consisting of multiple stages of ferrofluid barriers that are magnetically supported between the stationary annular magnets and the rotating shaft. This type of seal is described in reference 8.

Heat Exchanger and Diffuser

The NASA laser loop utilizes only one heat exchanger as opposed to the two that are found in most closed-cycle systems. The principle behind this design is that the gas is overcooled prior to entering the blower, which then does work on the gas to raise its temperature up to the control point, nominally room temperature. The NASA heat exchanger has two stages within one housing. The first stage uses water from a package cooling tower, and the second stage uses an ethylene glycol - water solution from a package chiller system. The heat exchanger coils are standard industrial air-conditioning coils consisting of swaged aluminum fins on copper tubes. They have a frontal area of approximately 5 m^2 (42 ft^2). Total heat removal capacity is 650 kW while a 20° C gas temperature is maintained in the plenum tank. The coils are capable of being outgassed by passing 82° C fluid through them.

Since the blower system must operate over a large range of pressures and densities, there are some conditions at which the pressure head developed is limited. therefore, a diffuser, installed downstream of the laser test cavity, was designed to recover as much as 80 percent of the pressure lost in the test cavity. The diffuser inlet has a cross section which is adjustable to match that of the test cavity.

Laser Test Cavity

The laser test cavity is shown in Figure 4. Flexibility is the key word in describing this cavity, in which the directions of the discharge, optics, and flow are mutually orthogonal. The cavity consists of four major components: the main frame and bellmouth section, the cathode section, the anode section, and the optics.

The main frame is a structure which connects the electrode sections, mirror mounts, and flow loop. It is approximately 1.4 m (4.5 ft) in the flow direction by 1.5 m (5.0 ft) in the optics direction. The open-side design allows different electrode configurations and spacings to be inserted in the top and bottom openings, as well as a variety of optical configurations. Spacing is controlled by inserting spacers resembling picture frames between the cathode and anode sections and the main frame. These spacers allow interelectrode spacings (and the optical cross section) to be adjusted from 1 to 9 cm in 2-cm increments. Inserted into the upstream opening of the main frame are two-dimensional bellmouth plates which can also be adjusted to the cathode-anode spacing. Their purpose is to aerodynamically tailor the gas stream entering the test cavity. The main frame is electrically isolated from the rest of the flow loop by fiberglass-epoxy spacers. The internal side walls are also lined with fiberglass and epoxy to minimize arc attachment to bare metal. There are five optics ports on each side of the main frame. These ports are 12 cm in diameter, and their centerlines are separated by 16.5 cm. Thus, single- or multiple-pass optical configurations are possible.

The cathode section consists of a stainless-steel frame 1 by 1.5 m, which is peculiar to the type of electric discharge being used. That is, the pin-to-plane self-sustained discharge assembly has its own cathode frame, as does the electron-beam-sustained discharge assembly. The pin-to-plane cathode frame is grid-shaped, which allows for five independent channels for electric excitation. The surfaces of this frame, exposed to the discharge, are coated with 0.5-mm (20 mils) of epoxy applied by using a fluidized-bed technique. Ten fiberglass-epoxy panels fit into these grid openings, two per channel. The electrodes (pins) are epoxied into the panels in rows and columns forming a hexagonal array with one pin per cm^2. The pins are 1.5 mm in diameter and are made of tungsten - 3 percent rhenium. The tips, which are pointed, protrude into the gas flow 1 cm for cooling purposes. This means the flow gap is 1 cm larger than the interelectrode spacing. In any one channel, there are 21 rows of pins with 74 pins per odd-number row and 72 pins per even-number row. Currently, each pin is ballasted with a 20-K Ω resistance, and each row of pins is ballasted from zero to 4500 Ω. The row ballast can be varied remotely to tailor the discharge current in the flow direction.

The cathode frame assembly for the electron-beam-sustained discharge allows for one channel of electric excitation. This assembly, shown in Figure 5, consists of a cathode plate and an electron gun. The cathode plate is a support structure for the screen cathode and the electron foil window. This window, which is typically 0.025-cm-(1.0-mil-) thick aluminum, serves as an electron-transparent divider between the laser gases and the high vacuum in the electron gun. The electron gun itself is in a large vacuum tank which houses the hot-filament electron sources, control grid, and screen anode. It is supported by the cathode plate. The filament and control grid assembly are electrically isolated from the vacuum tank and float at a high negative voltage. The electron gun will typically provide continuously 0.15 mA/cm^2 of 175-kV electrons through the 10- by 125-cm foil window. The electron-beam device is used to provide the electrons and ionization necessary to run a discharge between the laser-cavity anode and cathode by means of a separately applied electric field.

The anode frame section is essentially the same design for both methods of electric excitation. It consists of a fiberglass-epoxy plate, identical in size to the cathode frame, and has embedded in it an oil-cooled copper anode. The anode used for the pin-to-plane discharge is large enough to cover the three middle channels of the cathode frame and is 56 by 135 cm. The copper anode for the electron-beam-sustained discharge is 20 by 135 cm.

The basic optical configuration used in the laser cavity forms a single-pass unstable resonator. Possible variations of this basic configuration include folded unstable resonators and oscillator-amplifier combinations. Magnifications from 1.26 to 1.81 are currently available for use on single-pass configurations with a 2.1-m optical path length. Depending on the particular interelectrode spacing and scraper mirror hole size in use, these optics provide equivalent Fresnel numbers of 0.5 to 9.5 and output beam diameters from 2.4 to 8.3 cm. The mirrors, which are water-cooled copper, are fastened to mounts that are vibrationally isolated from the main frame by bellows. The mirrors can be remotely adjusted on two axes by using stepping motors. The beam exits vertically from the cavity through a zinc selenide window and is redirected to a horizontal position by an additional water-cooled flat copper mirror, which is also remotely adjustable.

Instrumentation and Control

The vacuum, gas fill, blower, and heat exchanger subsystems are controlled and sequenced during operations by a programmable controller. This device not only serves a labor-saving function, but also aids in trouble shooting and facilitates the changing of modes of operation. High-voltage controls and sequencing have been hard-wired for reasons of safety. Bulk laser power measurements are made by using a calorimeter cooled by ethylene glycol and water, which has controlled flow rate and precision thermistor bridges for temperature measurement. The calorimeter is calibrated through intercomparison tests with an NBS standard calorimeter. Beam profile observations are made by using an infrared camera sensitive to a 10.6-μm wavelength and are displayed on an oscilloscope. The quantitative analysis of the lasing gases is controlled by a microprocessor which permits continuous monitoring of the concentrations of the nitrogen-oxygen compounds as well as a periodic analysis by a gas chromatograph and mass spectrometer. All data, including pressures, temperatures, row currents, and voltages, are recorded and processed by using the NASA-Lewis central data processing computer facility.

Operational Characteristics

Initial operation of the laser has been achieved by using a single channel (channel 3) of the pin-to-plane type discharge at an interelectrode spacing of 5 cm. The first 16 rows, containing 1040 pins, have been energized. The discharge formed by rows 7 to 16 encompasses the nominal 5-cm-diameter unstable resonator, while the first several excited rows preionize the gas. Approximately 1.2 m of the 2.1-m optical path contain the excited medium. The initial optical resonator has a magnification of 1.26 or an output coupling of 36 percent. A typical row input power density distribution is shown in Figure 6. A uniform beam profile, as viewed by the infrared camera, has been used to set the individual row currents. This distribution indicates a nonsymmetrical deposition of electric energy into the volume of the optical resonator. The effect of this skewness for the condition shown in Figure 6 is not as deleterious to the beam profile as might be suspected. The major contributor to beam uniformity is the gain distribution across the optical cavity. Gain distribution is controlled by both mirror alinement and discharge conditions. Although input power density distribution determines the gross discharge effects, the distribution and level of electron density and the ratio of electric field to neutral density E/N affect the gain more directly. The variation of E/N in the optical region in Figure 6 is ± 15 percent around an average value of 1.8×10^{-16} V-cm^2 compared with a ± 40-percent variation in power density. The average electron density is computed to be 2.0×10^{10} cm^{-3} for the conditions of Figure 6. In a discharge with cross flow, much gain is blown downstream by the rapidly moving gas. This phenomenon was observed and measured at similar conditions on a small apparatus in the work of reference 6, where the peak gain occurred downstream of the last row of excited pins. Gain measurements in channel 4 are currently under way, and the results will determine, to a large degree, the necessary row power density distribution in channels 2, 3, and 4 to optimize both gain and optical configuration for either a single- or folded path oscillator-amplifier.

Laser output powers of up to 6.0 kW have been obtained at a variety of pressures, primarily in the 1.86×10^4- to 2.39×10^4-N/m^2 (140- to 180-torr) range, and at velocities from 70 to 125 m/sec. Mass flows for the 1:7:20 mixture of CO_2, N_2, and He have ranged from 0.6 to 1.6 kg/sec. Measured electrical efficiency as a function of specific laser power is plotted in Figure 7. Electrical efficiency is defined as laser power divided by power into the discharge. Power dissipated in the ballasts, which averages 20 to 25 percent of the total power, is not included in this efficiency. Specific laser power is the laser power divided by the mass flow and is used in the figure to coalesce the power data collected at different mass flows (velocities). These data were gathered by using different loads of gas with the discharge operating continuously from 2 to 31 min. When these data were taken, no results were available from the gas analysis monitoring system, and hence, any conclusions relative to gas contamination effects are premature. However, there is no experimental indication that any operational limitation has been reached from either gas contamination or discharge stability effects. The electrical efficiency, as indicated in Figure 7, is increasing as laser power increases.

The line drawn in Figure 7 is computed by using a model with inputs of electron density, discharge and optical volumes, and optical coupling. The model yields expected trends in laser performance. When normalized to the experimental data, it indicates a maximum electrical efficiency of greater than 9 percent can be expected at a pressure of 1.9×10^4 N/m^2 (145 torr) and a magnification of 1.26. Performance can be expected to improve at higher pressures if the input power density distribution is adjusted to maintain discharge stability and the optical configuration is altered to take advantage of the gain blown downstream. With these changes it is not unreasonable to assume an ultimate electrical efficiency of about 15 percent and a laser output from a single channel of approximately 20 kW. Efficiency and output powers obtained by using multichannel excitation (and folded path optics) will have to be determined experimentally since gas heating effects and interdependency of discharge effects between channels are not effectively handled by the existing analytical model.

The maximum expected output power of the laser using the electron-beam-sustained discharge will be two to three times higher than that for the self-sustained discharge. This value is dependent on the ability to optimize the input power, laser kinetics, and optical configuration. The maximum electrical efficiency, though, will not necessarily be higher. The higher output powers are possible because of the independent control of electron source and sustainer field, which allows higher input power densities to be deposited in the lasing gas while stability is maintained.

Concluding Remarks

A description of a versatile, continuous wave, completely closed-cycle CO_2 laser has been presented. The initial operation of the device has indicated that a self-sustained, pin-to-plane discharge can generate many kilowatts of laser power. After complete evaluation of this type of discharge plus the implementation of an electron-beam-sustained discharge, the laser should provide means of generating power in the 50- to 70-kW range. The simplistic nature of the pin-to-plane design offers, with sufficient development, advantages over the electron-beam system, particularly for output power in the 1- to 10-kW range. The major advantage is that the requirement for an extended life, maintenance free, electron gun system is eliminated. However, the pin-to-plane system does require considerable fabrication and installation labor.

The flexibility of the NASA high-power laser not only allows the capability of investigation various excitation techniques, gas contamination affects, and optical configurations, but also permits experiments in support of the NASA research programs in the areas of adaptive optics, laser propulsion, laser power conversion, and materials processing.

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Table 1. Nitrogen-Oxygen Contamination Effects(7)

Contaminant	Effect
NO	Gain and plasma impedance began to decrease at 0.1% (1000 ppm); complete loss of gain at 1.5% (15 000 ppm)
NO_2	0.04% (400 ppm) caused plasma instabilities; complete loss of gain at 0.1% (1000 ppm)
N_2O	0.08% (800 ppm) caused plasma instabilities; complete loss of gain at 0.2% (2000 ppm)

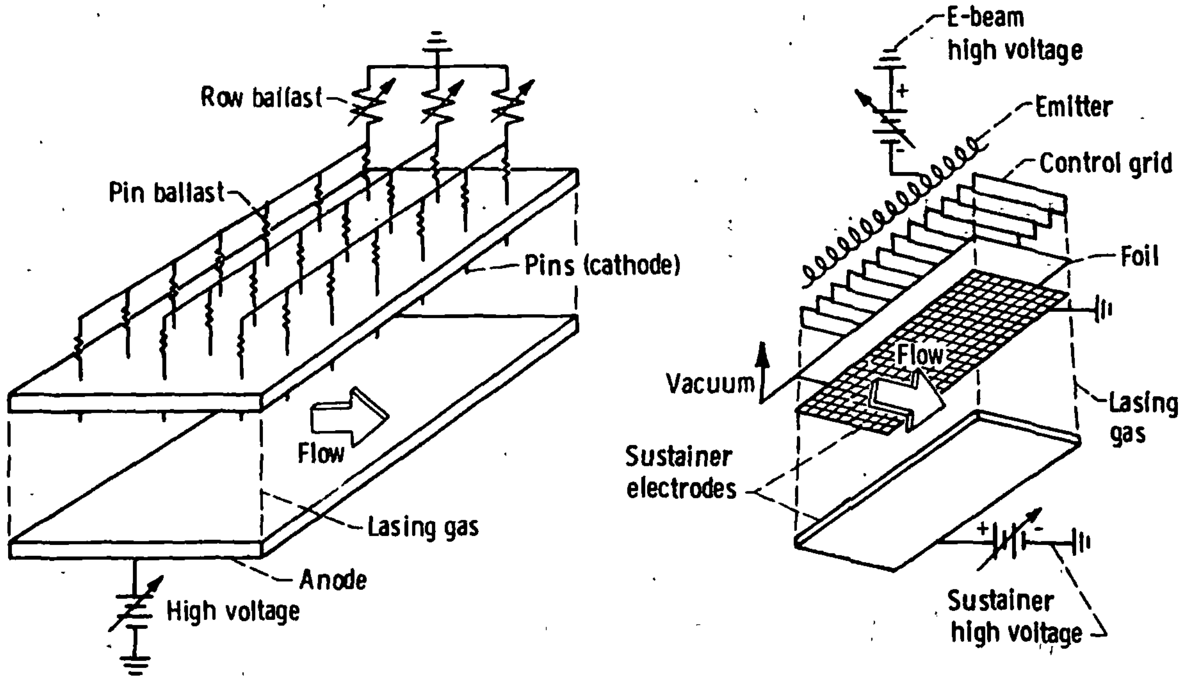
Table 2. NASA High-Power-Laser Specifications

(a) Flow loop

Pressurage range, N/m^2 (torr)	$1.33 \times 10^4 - 1.1 \times 10^5$ (100-800)
Vacuum capability, N/m^2 (torr)	1.2×10^{-4} (10^{-6})
Velocity range, m/sec	50-150
Mass flow range, kg/sec	1.0-12.5
Gas mixture, CO_2, N_2, He	50%<He<80%
Heat exchanger capacity (two stages), kW	650
Cavity flow area, cm	2 to 10 by 150

(b) Test cavity

Pin-to-plane discharge		Electron-beam discharge	
Channels for excitation and optics	5	Channels for excitation and optics	1
Channels currently in use	3	Channel size, cm	10 by 125
Cathode pin diameter, mm	1.5	Maximum electron current density, mA/cm^2	0.4
Pin material (sharpened)	tungsten - 3% rhenium	Maximum electron voltage, kV	225
Pin spacing		Typical thickness of aluminum foil, mm	0.025
Pins/cm^2	1	Electron source	hot cathode
Pins/row	72 or 74	Size of anode (oil-cooled copper plate), cm	20 by 135
Rows/channel	21	Interelectrode spacing, cm	2 to 10
Cathode ballast			
Pin resistors, kΩ	20		
Row resistors, Ω	0 to 4500		
Size of anode (oil-cooled copper plate), cm	56 by 135		
Interelectrode spacing, cm	1 by 9		
Maximum current, A	30		
Maximum applied voltage, kV	20		
Maximum excited area per channel, cm	12 by 125		



(a) Pin-to-plane self-sustained. (b) Electron beam sustained.

Figure 1. - Laser discharge schematics.

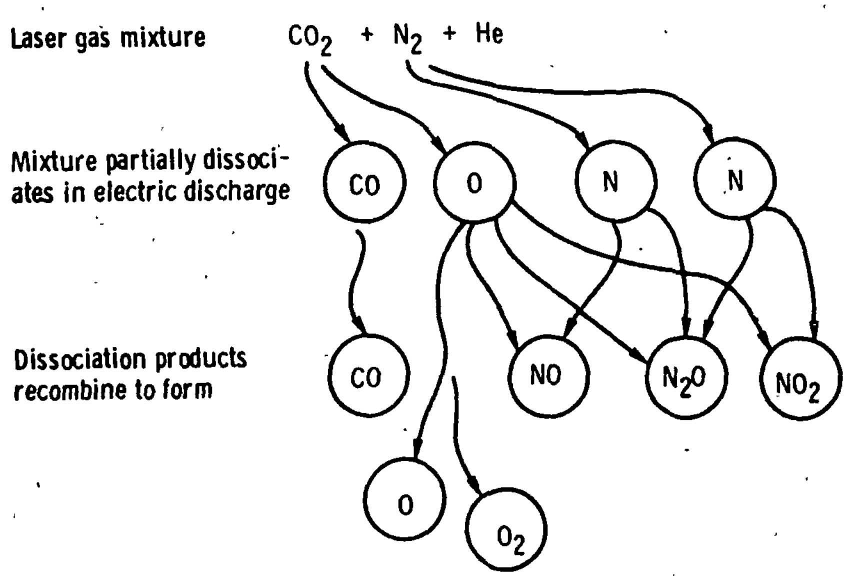


Figure 2. - Plasma-induced chemical reactions.

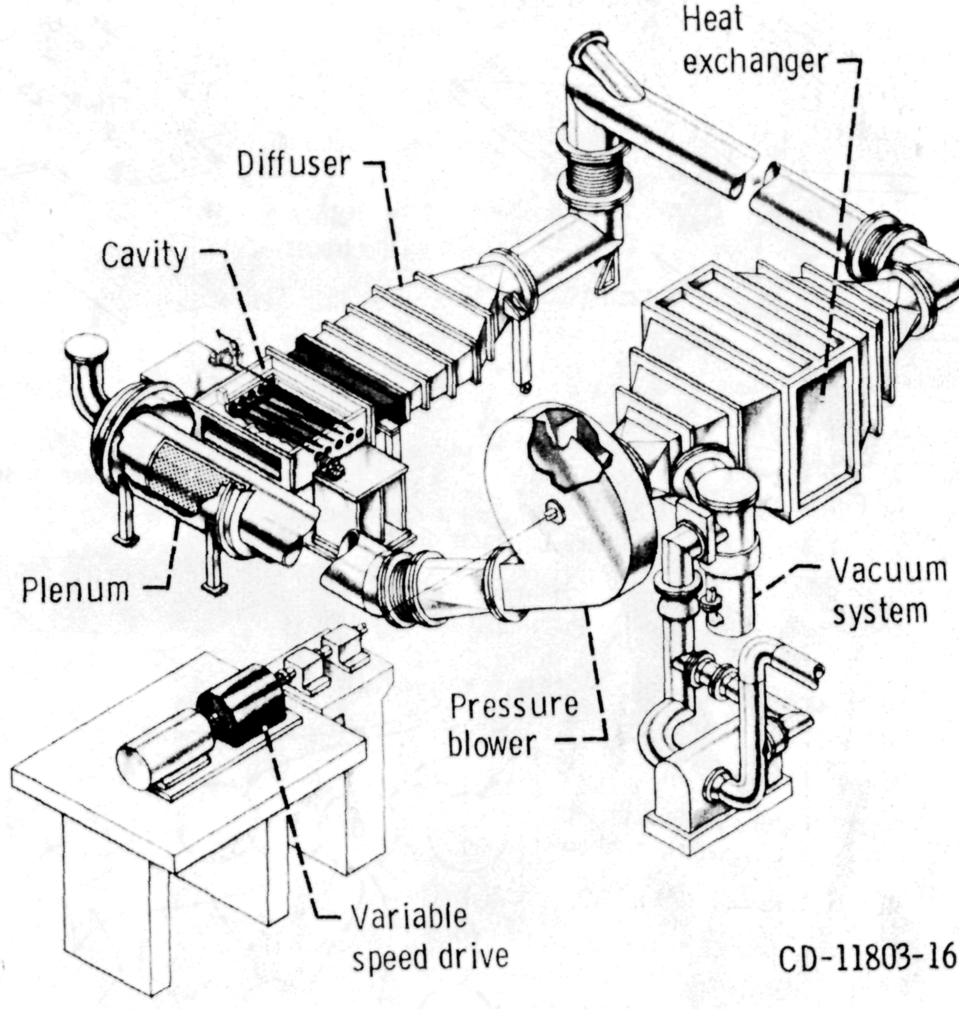


Figure 3. - NASA high-power laser.

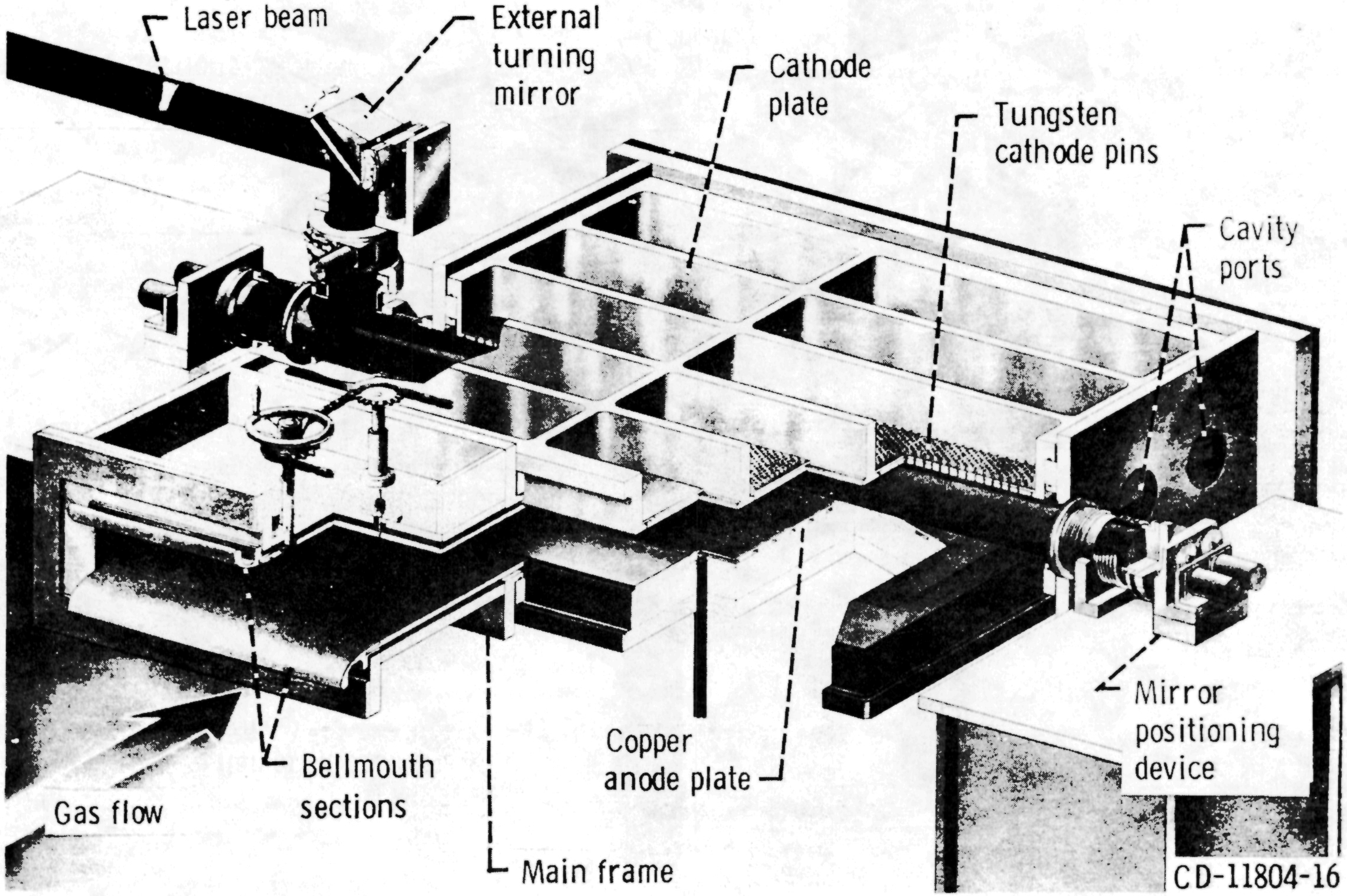


Figure 4. - Laser test cavity with pin-to-plane self-sustained discharge.

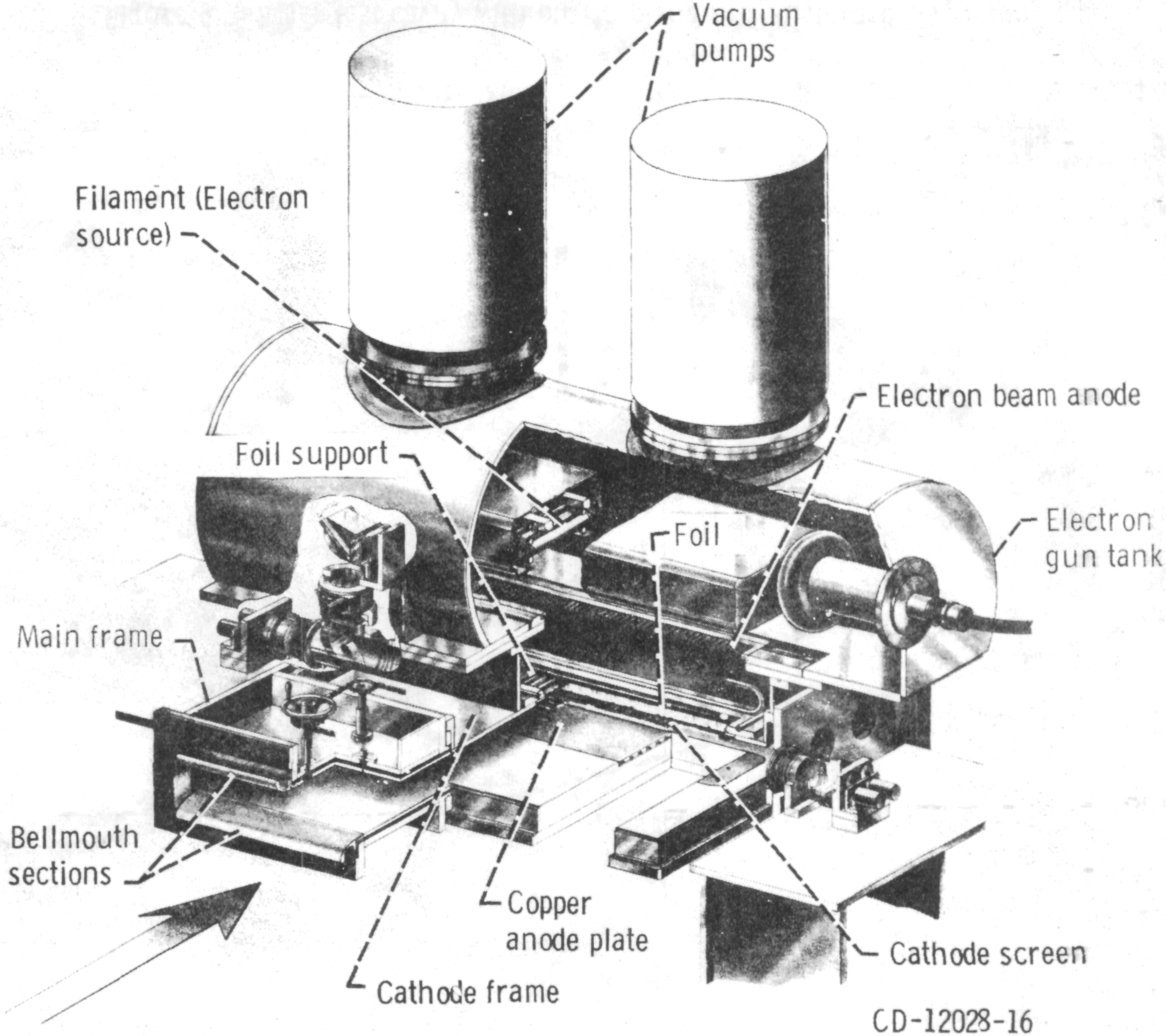


Figure 5. - Laser test cavity with electron-beam-sustained discharge.

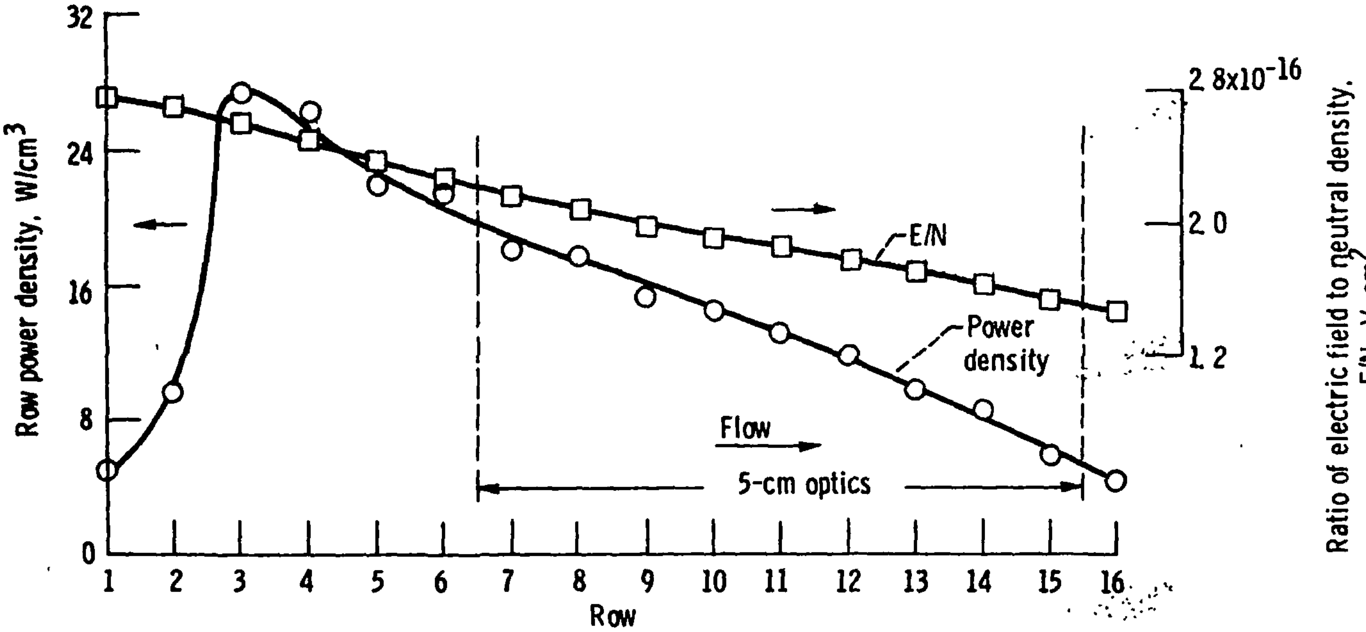


Figure 6. - Discharge power density and distribution of ratio of electric field to neutral density. Laser power, 5.1 kW; discharge power, 74.0 kW; ballast power, 24.3 kW; total current, approximately 14.78 A; gas velocity, 104.9 m/sec; pressure, 147.3 torr.

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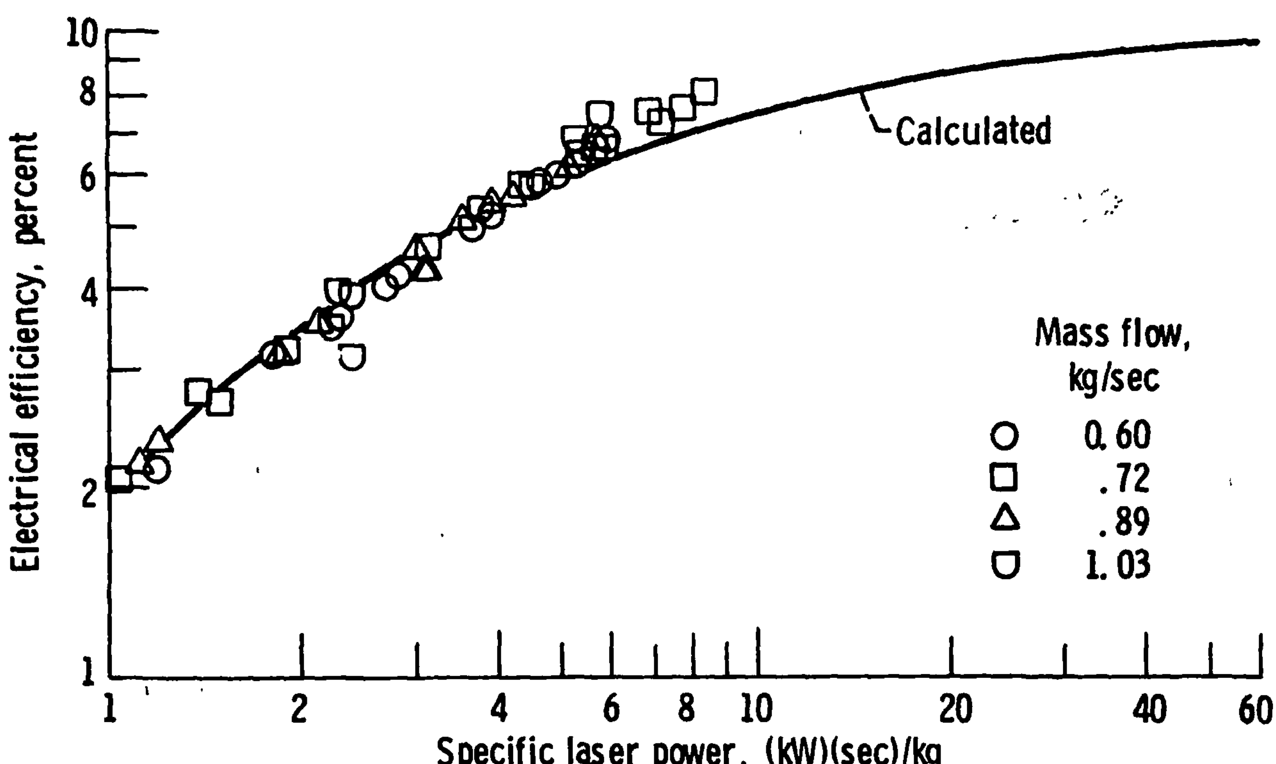

Figure 7. - Laser performance.