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A 30-KW CO2 MIXING LASER,(U)
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REPORT

MRL-R-751

A 30-kW CO_2 MIXING LASER

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and Peter J. Beckwith

Approved for Public Release

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This report describes an electric-discharge CO_2 mixing laser which has been constructed at MRL. This laser, which utilises plasma injection, delivers an output power of 30 kW at an overall efficiency of 9%.

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C O N T E N T S

* * *

A 30-kW CO_2 MIXING LASER

1. INTRODUCTION

Electric-discharge CO_2 laser systems are capable of high continuous output-power levels and have high efficiency, but tend to become complex and expensive at multi-kilowatt output-power levels. The difficulties which must be overcome include those of stabilising a high-power electric discharge against arcing, of cooling the discharge, and of maintaining the resonator region of the device at a pressure sufficiently low to allow efficient operation. Cooling can be accomplished by convection, although very high gas-flow rates are required and a large pumping facility becomes necessary. The tendency for the discharge to contract into an arc can be counteracted by pre-ionising the discharge gas by external means. Electron-beam guns are often used for this purpose, although they have some disadvantages such as the need for very high voltages and for windows which are both electron-transparent and durable.

An alternative, and simpler, method of stabilising high-pressure discharges has previously been developed at MRL (1,2,3). This method, which involves the pre-ionisation of the gas flow by passing it through an array of subsidiary arc discharges, allows stable discharges to be operated at pressures above 100 kPa (1 atm), and at electrical power densities above 70 MW/m^3. A continuous-wave mixing laser making use of this technique has been constructed at these laboratories, and has produced an output power of 30 kW at an efficiency of 9%. It is simple, robust and reliable, and can be manufactured in a workshop with standard machining facilities. A further benefit is that helium is used solely as a depopulating agent, and can be replaced if desired by a less expensive (though slightly less efficient) alternative such as H_2.

The purpose of this report is to provide constructional details of the laser, as well as a description of its ancillary equipment. The performance of the laser will be described, as will some of the factors which are at present limiting the maximum output power and run duration.

2. THE LASER

The laser is of the convectively-cooled, mixing type in which flowing N_2 at a pressure of 120 kPa is electrically excited before passing through a restriction into a region of low pressure (20 kPa), where it is mixed with CO_2. A small quantity of He is added to depopulate the lower laser level and the optical power is extracted by means of a resonator situated downstream of the mixing system. The laser is operated in a "blow-down" mode in which the gases are initially stored in pressure vessels and subsequently flow through the laser into a vacuum tank. A photograph of the laser is shown in Fig. 1 and a schematic diagram of the laser together with its ancillary systems is shown in Fig. 2.

The laser (Fig. 3) is essentially a flat rectangular box containing electric-discharge and resonator regions separated by a transitional region consisting of a flow restriction and a row of slotted tubes. Vibrational energy is deposited in the N_2 by the electric discharge and stored until transferred by molecular collisions to CO_2 injected (along with He) through the tubes. The advantage of this mixing system is that it allows the discharge and resonator regions to be separately optimised with respect to both pressure and gas composition. The optimum discharge gas is pure N_2 and maximum discharge power density is obtained at a pressure of around 120 kPa (3). The addition of CO_2 reduces the maximum discharge power density at any pressure by a factor of at least 2. The extraction of power however requires the presence of CO_2 in the resonator volume, and is most efficient at pressures below about 20 kPa. At these low pressures both the lifetime and velocity of the excited CO_2 molecules are increased, and there is less energy lost by collisional depopulation of the upper laser level.

2.1 Main-Discharge Region

The main-discharge volume has the dimensions 60 × 40 × 960 mm and is partitioned into 16 sub-volumes each 60 × 40 × 60 mm. Each sub-volume is supplied with ionised N_2 from 24 plasma jets arranged in a square (10 mm) array. The arrangement of electrodes and relevant dimensions are shown in Fig. 4.

In operation, a small arc discharge is struck between each copper pin and the perforated aluminium plate. Nitrogen passing through the 384 holes associated with the pin electrodes is ionised and enters the main-discharge volume. The individual pin currents and N_2 flow rates are 150 mA and 2.6 g/s respectively, so that the total pin current is 58 A and the total N_2 flow rate is 1 kg/s. The discharge characteristics obtained when voltage is applied to the main discharge between the stainless-steel mesh and the perforated plate are shown in Fig. 5. The voltage plotted is the average of the voltages on the 16 sub-volumes of the main discharge, and the current is the sum of the sub-currents. The discharge has a positive slope resistance and input powers of up to 170 kW can be achieved in the laser. This upper limit is determined by the onset of arcing in the discharge and so, when the laser is operated, it is usual to restrict the input power to 160 kW or less.

2.2 Resonator/Mixing Region

Excited N_2 flows into the mixing region through the contoured restrictors shown in Fig. 3. The restriction has a total length of 960 mm and the gap width is set to 3 mm, which results in a main-discharge pressure of about 120 kPa at a mass flow of 1 kg/s. The pressure in the resonator region depends on vacuum-tank pressure and exhaust-system impedance, and for low initial tank pressures (< 10 kPa) the present configuration results in a resonator pressure of about 20 kPa for the combined flow of CO_2, N_2 and He.

The mixing system consists of a row of 96 stainless-steel tubes each 30 mm high and 4 mm in outside diameter, spaced at 10 mm intervals. Each tube has 7 slots, 250 μm wide and 2 mm deep, facing downstream. The gas pressure in the manifold supplying the mixing tubes is approximately 100 kPa. The normal mixture is CO_2 and He in the ratio 1:2 and the mixture flow rate is 0.2 kg/s, so that the final gas composition is 7% CO_2, 79% N_2 and 14% He. Since it has been found that laser performance is only a slowly-varying function of mixture, the concentration quoted is only a typical value and is not critical for efficient operation of the laser. No attempt has been made to optimise the geometry of the mixing system since the present design provides a good extraction efficiency in the resonator and a reasonably uniform output beam from the laser.

The resonator is the normal stable type having a fully-reflecting concave copper mirror (radius of curvature 5 m) and a partially-transmitting flat output mirror. A KCl substrate with a quarter-wave layer of As_2S_3 on each face (reflectivity 50%), and a hole-coupled copper flat, have been used as output mirrors. The copper flat has three vertical reflecting strips 5 mm wide separated by slots also 5 mm wide. When the hole-coupled mirror is used, optical power can be extracted from the laser through a ZnSe window mounted parallel to the mirror or it can be focused through a small orifice as shown in Fig. 6. The nitrogen flow shown in this Figure is required to prevent contamination of the laser by atmospheric oxygen. Laser performance with the different resonator configurations is presented in Section 4.

3. ANCILLARY SYSTEMS

3.1 Gas Supply

The laser requires large mass-flow rates of a gas mixture containing N_2, CO_2 and He. It is necessary to ensure that contaminant gases, especially O_2 and water vapour, are excluded from the system as these have a deleterious effect on the main discharge. Commercial high-purity (99.99%) gases have been found suitable for the mixture. A schematic diagram of the gas system is shown in Fig. 7.

Pressure vessels are used to provide the gas flows into the laser, since the run time is already limited by the capacity of the vacuum tank. The N_2 tank has a volume of 2.8 m^3 and is usually filled to a pressure of 600 kPa, and the CO_2/He tank has a volume of 0.6 m^3 and is filled to a pressure of 350 kPa. Gas is supplied to the tanks from conventional high-pressure (15-MPa) cylinders manifolded in groups of four. Carbon dioxide and helium flow via conventional gas regulators, through separate flow-tubes, into the 0.6-m^3 pressure vessel. Control valves on the flow-tubes allow adjustment of the flow rates of the CO_2 and He to give any desired mixture. Nitrogen flows directly into the 2.8-m^3 pressure vessel from a dome-controlled regulator, which can supply greater flow rates than conventional regulators, thus minimising the filling time of the larger vessel.

The gases flow from the pressure vessels into the laser through fast-opening gate valves which are activated by a pneumatic cylinder. Constant flow rates are maintained by servo-controlled butterfly valves in the gas lines.

The nitrogen required for the operation of the output system shown in Fig. 6 is tapped from the plenum upstream of the copper pins (Fig. 3). The flow required for an orifice of 15 mm diameter is 50 g/s which is only 5% of the N_2 flow in the laser.

3.2 Electrical Power Supplies

Both the pre-ionising discharges and the main discharges are electrically excited by dc supplies utilising three-phase transformers with full-wave rectification. Each of the pre-ionising discharges is stabilised by means of an individual ballast resistor. Since the main discharges have a positive slope resistance (Fig. 5) no ballast resistors are required for stability, although a set of resistors is used to vary the discharge power. Schematic diagrams of the power supplies are shown in Fig. 8.

Power for the main discharges is obtained from eight oil-filled transformers, rated at 16.2 kV, 4.5 kVA (continuous), which were available prior to the design of the laser. This set of transformers is switched directly-on-line with series resistances, variable in the range 0-12.5 kΩ, between the transformers and each sub-volume of the main discharge. These resistances each comprise twelve 200-W, 25-kΩ resistors which may be simply connected to give 2, 4, 6 ..... 12 resistors in parallel. Total power into the main discharges may be varied by this means from about 60 kW to 160 kW. The overload on the transformers is permissible for the short run times involved.

Power for the pre-ionising discharges is derived in a similar manner from twelve 2.3-kV, 5.5-kVA oil-filled transformers. Each ballast resistor has a value of 10 kΩ and is rated at 50 W. These transformers are switched directly-on-line before the gas pressure in the laser has risen to its operating value, so facilitating the striking of the pre-ionising discharges and allowing the use of a transformer of relatively low voltage with a consequent saving in power. With this arrangement the power input to the pre-ionising discharges is 70 kW at a voltage of 1.2 kV and a current of 58 A.

3.3 Pumping Facility

Very large mechanical vacuum pumps are required for continuous pumping at mass-flow rates of 1.2 kg/s at a pressure of 20 kPa. However, for intermittent operation, these rates can be achieved by the use of a vacuum "dump" tank, and in the present facility a dump tank with a volume of 28 m^3

is used. This volume limits the maximum operating time to about 5 s, but this is adequate for the experiments envisaged. A 0.1-m^3/s rotary vacuum pump exhausts the dump tank between operations.

3.4 Control Panel and Monitoring

The control panel houses gas and electrical controls, a data-recording system, flow-tubes and pressure gauges. The pressure vessels are filled manually prior to laser operation. Gas and electrical supplies to the laser are actuated by a motor- riven sequential switch, and are turned off automatically at the end of a pre-set run time. The control panel is shown in Fig. 1, and a schematic diagram of the control sequence in Fig. 9.

The data-recording system consists of a 32-channel digital data logger with a 32 kilobit memory. Information stored in the memory during a laser run can be displayed on an oscilloscope or chart recorder. During each run of the laser, 17 voltages, 2 currents, 6 pressures and the main-discharge power are recorded.

An over-current sensor is incorporated in each of the 16 main-discharge circuits. If any of the main-discharge currents exceeds a pre-set value a light shows on the control panel and the laser run is automatically terminated. This fault condition can occur if excessive impurities are present in the N_2 supply.

4. LASER PERFORMANCE

The maximum output power achieved so far is 30 kW at an overall, or "wall-plug", efficiency of 9%. This performance was obtained with the coated KCl mirror (reflectivity 50%) for laser run times of up to 0.5 s. Run times longer than this cause damage to the mirror and the output power is drastically reduced. The conventional efficiency figure, which takes into account the power input to the main discharges (160 kW) and pre-ionising discharges (70 kW) but ignores the power dissipated in ballast resistors (90 kW), is 13%. The output beam is approximately uniform and has dimensions of 35 mm × 30 mm.

The hole-coupled mirror has a lower extraction efficiency than the KCl mirror but is more robust and is therefore used when longer run times are required. The output beam consists of four segments each 5 mm × 30 mm and has a maximum power level of 20 kW. When power is extracted through the ZnSe window the output waveform contains fluctuations of approximately ± 20% on a time scale of about 0.5 s (Fig. 10(a)). Thermal distortion caused by the high optical-power densities transmitted through the ZnSe is the most likely explanation for this effect, which has been overcome by using the optical system shown in Fig. 6 and eliminating the need for a transparent window. A typical output waveform obtained in this way is shown in Fig. 10(b). Over a 3-S run there is a small (15%) decrease in output power which is thought to be due to overheating of either the resonator mirrors or the pin electrodes. Further investigation of this problem is being carried out.

Operating parameters and performance of the laser are summarised in Table 1.

CONCLUSION

The principal features of the multi-kilowatt mixing laser constructed at MRL have been described. The laser is based on a simple technique in which large amounts of electrical power are deposited in a high-pressure discharge in N_2 and optical power is extracted efficiently at reduced pressure in a CO_2, N_2, He mixture. The best performance obtained so far is an output of 30 kW at an efficiency of 9%. Scaling of this device to higher powers is straightforward.

Investigations are being carried out with the aim of increasing the specific power of the discharge and the gas pressure in the mixing/resonator region, without compromising the laser efficiency. Some success has been achieved in both these areas and will allow the design of even more compact laser systems of this type.

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TABLE 1

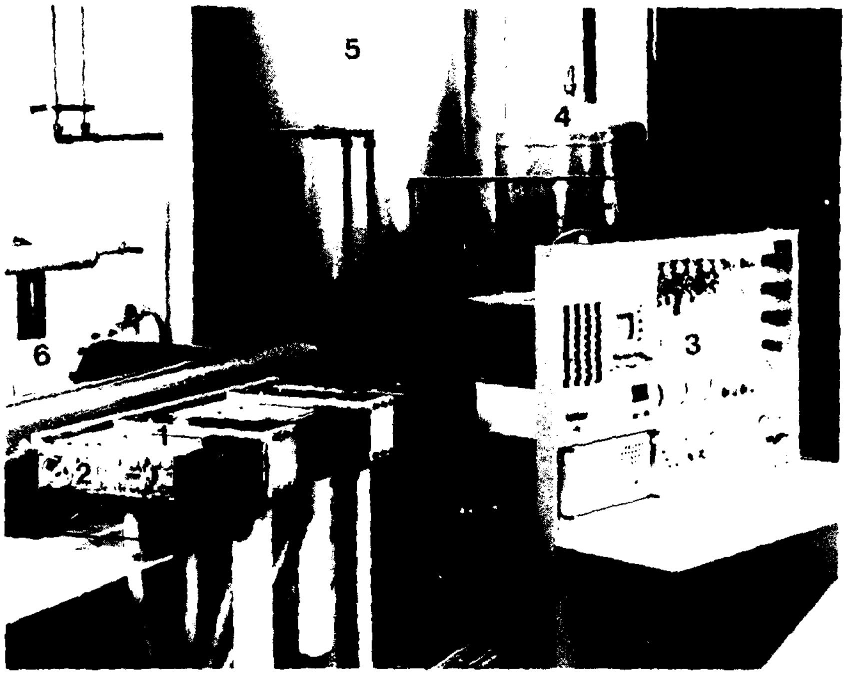
LASER PERFORMANCE AND OPERATING PARAMETERS

Discharge Dimensions	60 × 40 × 960 mm
Resonator Dimensions	35 × 30 × 1000 mm
Mixture $CO_2:N_2:He$	7:79:14
Mass Flow Rate	1.2 kg/s
Discharge Pressure	120 kPa
Resonator Pressure	20 kPa
Discharge Power Input (Total)	230 kW

Power Output

(1)	Partially-Transmitting Mirror (Reflectivity 50%)	30 kW*
(2)	Hole-Coupled Mirror	20 kW

* Run Time 0.5 s - Limited by Damage to Output Mirror



1 LASER BODY

2 OUTPUT WINDOW

3 CONTROL PANEL

4 CARBON-DIOXIDE AND HELIUM RESERVOIR

5 NITROGEN RESERVOIR

6 EXHAUST TO DUMP TANK

FIG. 1 - 30 kW LASER.

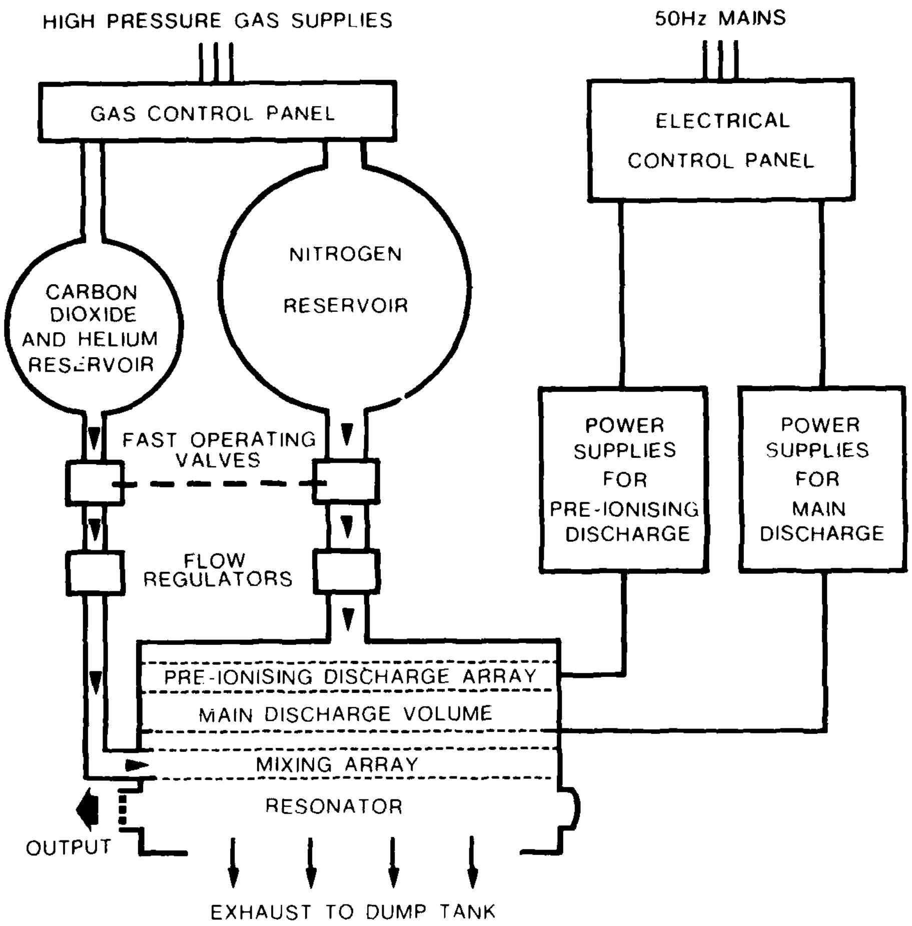


FIG. 2 - SCHEMATIC OF LASER AND ANCILLARY SYSTEMS.

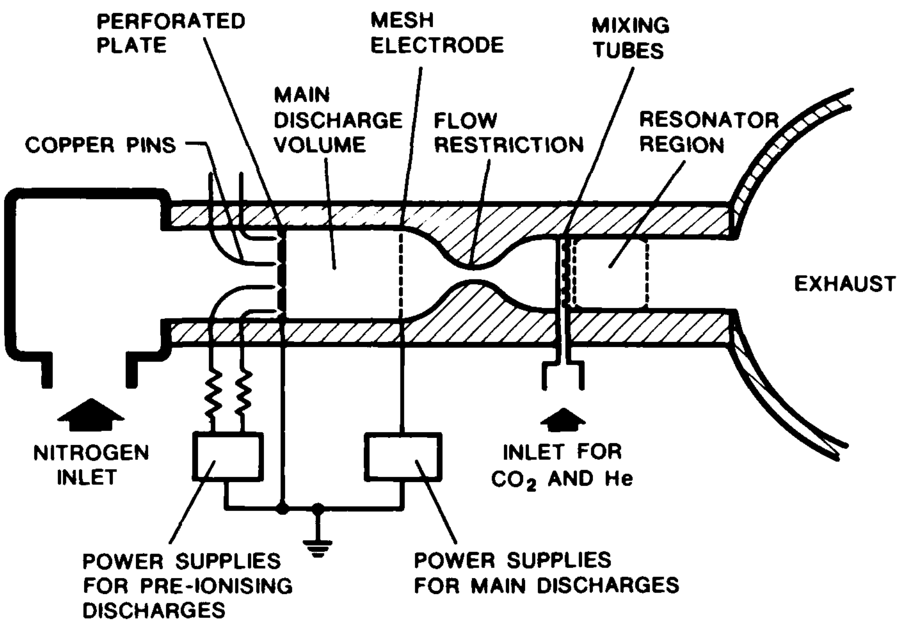


FIG. 3 - DIAGRAMMATIC REPRESENTATION OF LASER.

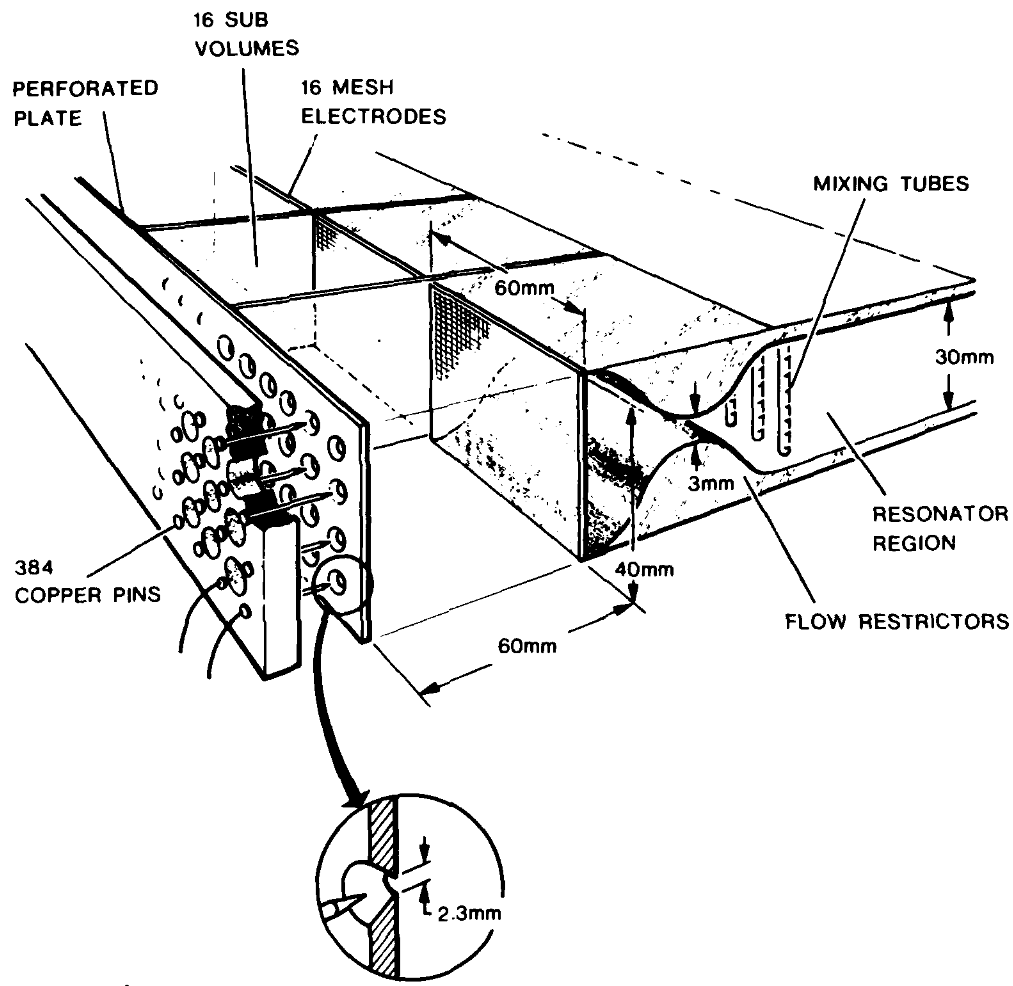


FIG. 4 - ARRANGEMENT OF ELECTRODES AND RELEVANT DIMENSIONS.

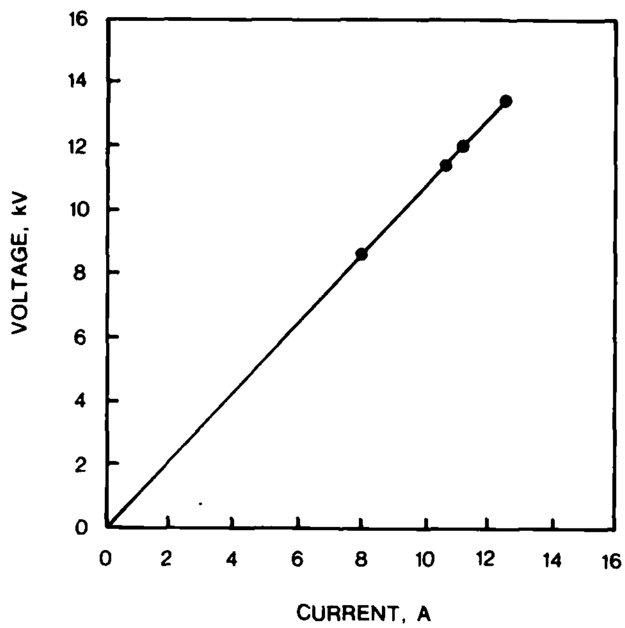


FIG. 5 - MAIN DISCHARGE CHARACTERISTICS.

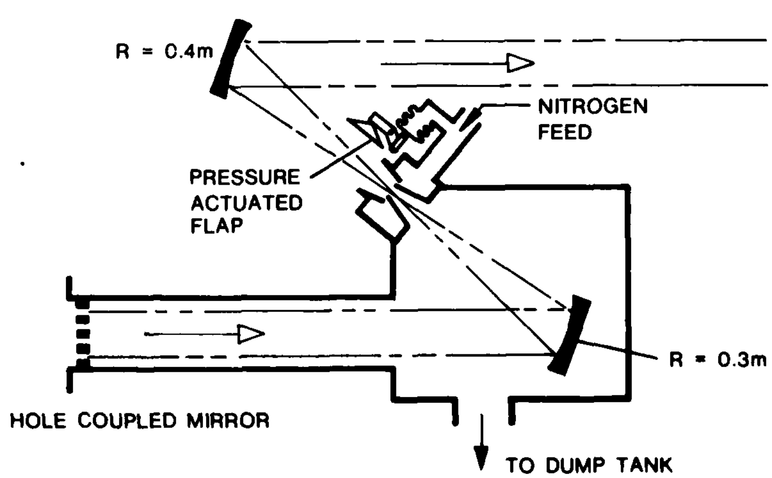


FIG. 6 - SYSTEM USED TO COUPLE POWER FROM THE LASER.

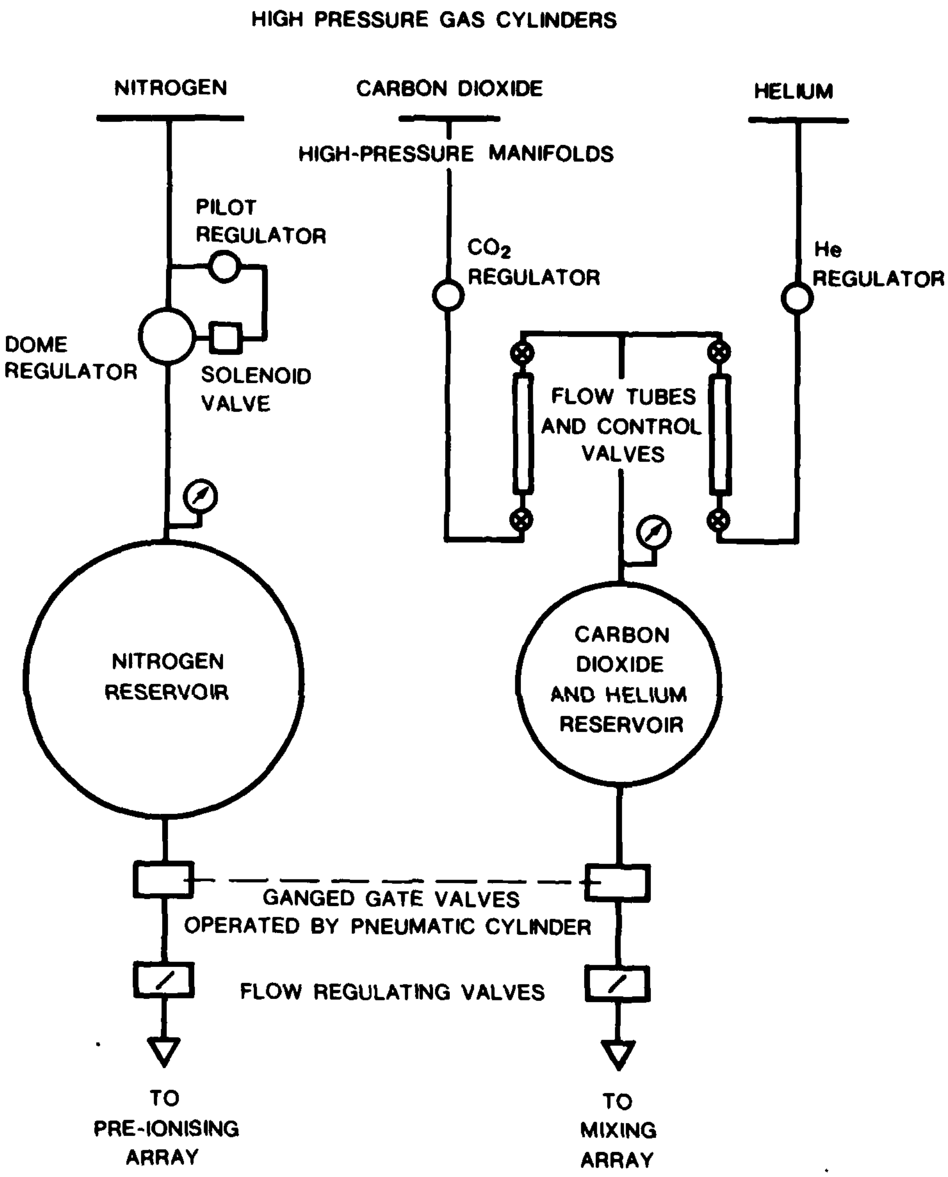
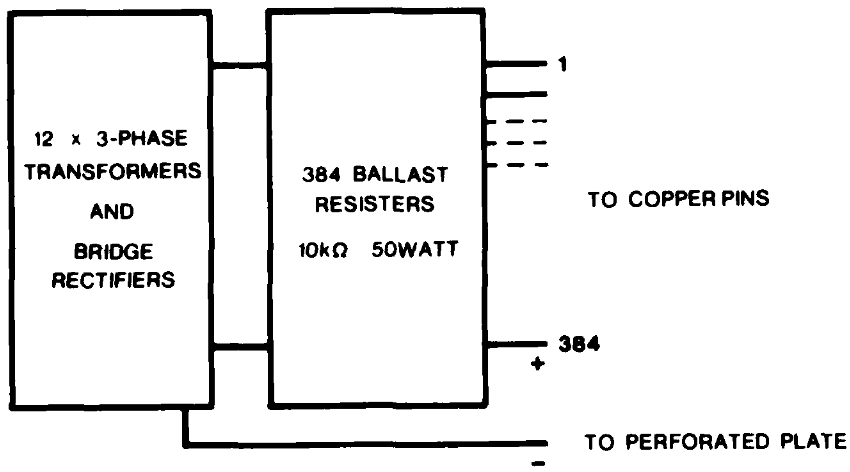
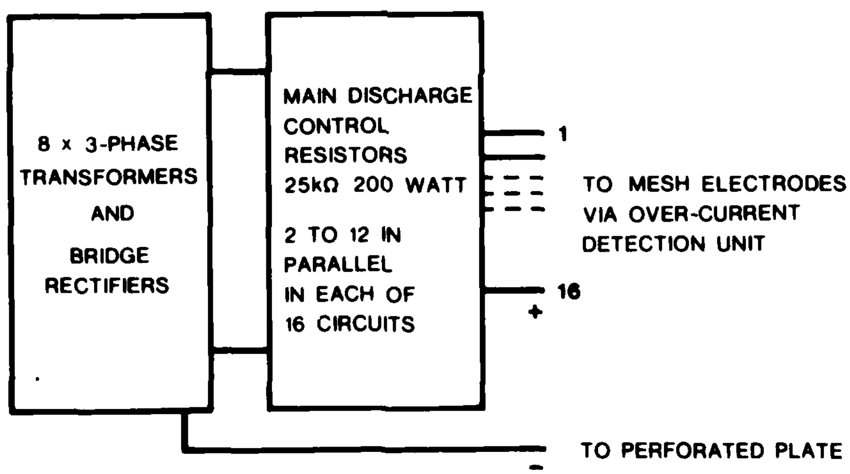


FIG. 7 - SCHEMATIC DIAGRAM OF GAS SYSTEM.



POWER SUPPLIES FOR PRE-IONISING DISCHARGES



POWER SUPPLIES FOR MAIN DISCHARGES

FIG. 8 - SCHEMATIC DIAGRAMS OF POWER SUPPLIES.

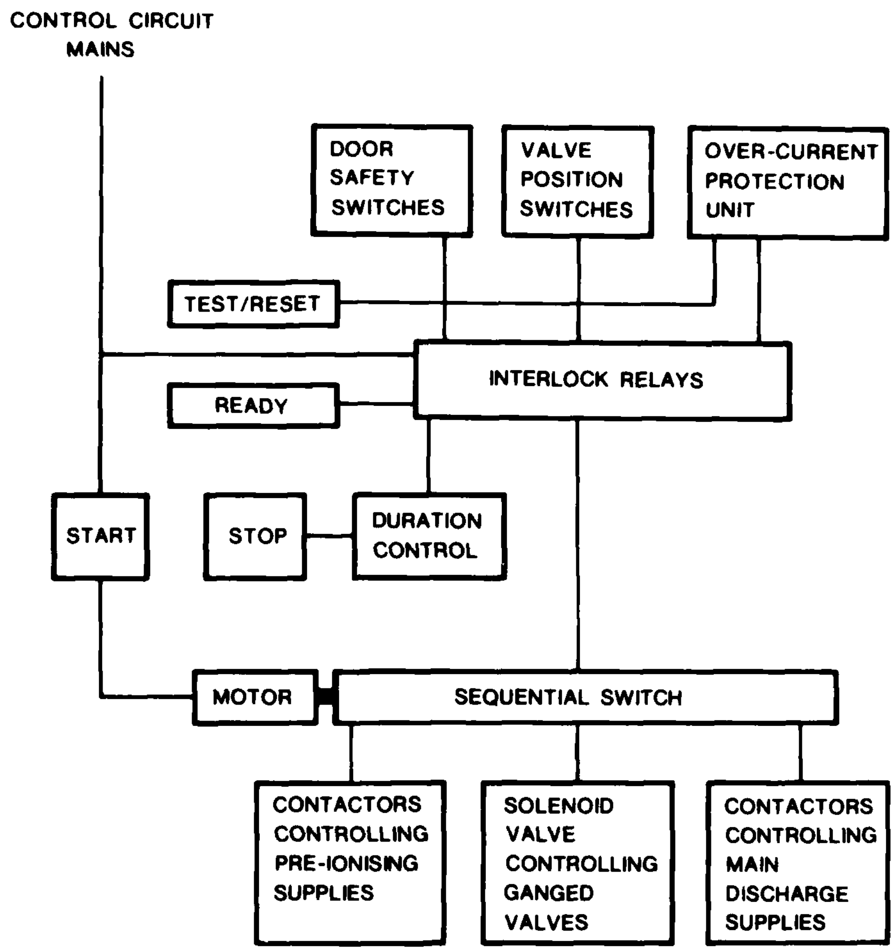


FIG. 9 - SCHEMATIC DIAGRAM OF CONTROL SEQUENCE.

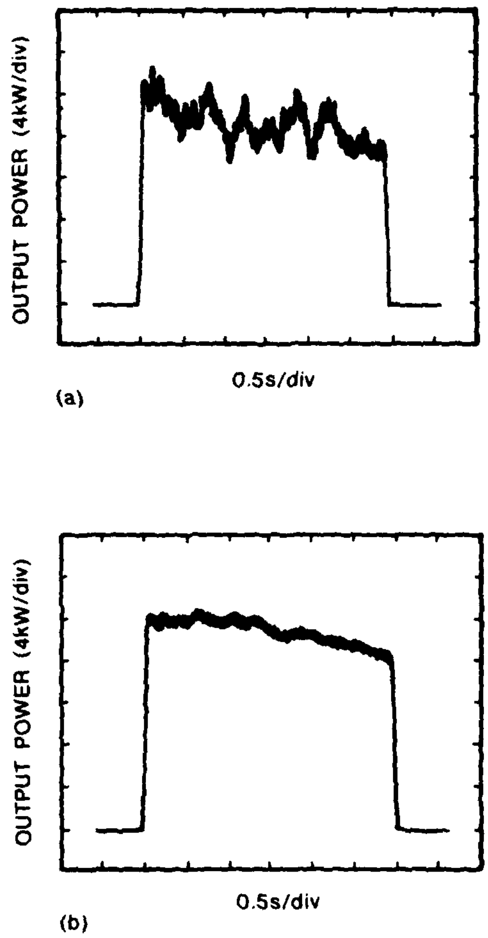


FIG. 10 - (a) OUTPUT WAVEFORM USING ZnSe WINDOW,
(b) OUTPUT WAVEFORM USING FOCUSING SYSTEM SHOWN IN FIG. 6.

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