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A Multiple Pulse CO<sub>2</sub> TEA Laser for Use in  
Thermal Blooming Studies

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## SUMMARY

The design, performance and operating characteristics of a multiple pulse CO<sub>2</sub> TEA laser constructed at AWRE for use in thermal blooming studies is described. Using unstable resonator optics, at the maximum pulse repetition frequency of ~ 10.4 Hz, this laser yielded a good quality output beam of mean power  $28 \pm 2$  W.

### 1. INTRODUCTION

This report describes a multiple pulse CO<sub>2</sub> laser designed and constructed at AWRE for conducting thermal blooming experiments. The basic specification of such a laser was that it should yield an average output power of a few tens of watts at a pulse repetition frequency ~ 10 Hz, have a good quality output beam and be positionally stable. To this end, a multiple pulse double discharge CO<sub>2</sub> TEA laser was constructed. This type of laser has the additional advantage that, because of its short pulse duration, single pulse thermal blooming effects can be kept to a minimum.

A number of single pulse and multiple pulse CO<sub>2</sub> TEA lasers have been described in the literature (1-3). Consequently, the basic operating principles of a CO<sub>2</sub> TEA laser will not be described in this report and the discussion will, in general, be limited to features of this multiple pulse laser which are not standard to single pulse devices.

### 2. LASER DESIGN

#### 2.1 Electrical circuit

The multiple pulse CO<sub>2</sub> laser described in this report employed a double discharge electrode structure (1), see figure 1. The cathode and anode were both constructed from aluminium alloy. In order to obtain the highest possible homogeneity of the lasing medium in the discharge volume, the glass insulated trigger rods, associated with this type of laser, were mounted in grooves milled in the cathode perpendicular to the optic axis, rather than parallel which is the normal method. This necessitated the use of ~ 150 trigger rods. The cathode-anode spacing was 3.9 cm, cathode width 6.5 cm and length 100 cm.

The electric discharge circuit of the laser is shown in figure 2. This design is similar to that of Hamilton et al. (3), except that it is of somewhat higher power rating. The mode of operation of the circuit was that the 0.32  $\mu$ F capacitor was resonantly charged, via the ~ 1500 H inductance L<sub>1</sub>, from a dc power supply variable from 0 to 30 kV. This meant that after the first laser shot C<sub>1</sub> was raised to a peak voltage approximately double that of the dc power supply. The normal oscillatory decay of the capacitor voltage to the level of the power supply following the attainment of this peak could not occur because of diode D<sub>2</sub>. The energy stored by this capacitor was deposited in the discharge volume by triggering the spark gap, Hartley Measurements Ltd Model SG501. Triggering the spark gap discharged C<sub>1</sub> into C<sub>3</sub>, to provide the corona discharge

from the sharp edges of the cathode, and into the pulse shaping network  $L_2C_2$  and then across the cathode-anode gap. Ideally, for this type of laser operating in the multiple pulse mode, the energy deposition in the lasing medium should be in the range 50 to 100 J/l and the cathode-anode voltage between 8 to 12 kV/cm (4). The optimum rise time for this voltage,  $\pi/2 \sqrt{L_2C_2}$ , across the electrodes is  $\sim 1 \mu\text{s}$  (1). Care was taken in coupling  $C_2$  to the electrodes to yield minimum inductance.

The maximum rate at which the discharge circuit could be fired and charged up again ready for operation was limited principally by the power rating of the transformer T, 5.5 kW, the current rating of the diodes  $D_1$  and  $D_2$  and the resonant charging time of the capacitor  $C_1$ ,  $\pi\sqrt{L_1C_1}$ . However, inductance  $L_1$  saturated during the resonant charging process and thus decreased the charging time from the 70 ms indicated by the component values in figure 2 to something less. The trigger circuit allowed a maximum frequency of firing of  $\sim 10.4$  Hz.

## 2.2 Gas flow

The lasing medium was an atmospheric pressure mixture of helium, nitrogen and carbon dioxide gases. Firing the discharge circuit and depositing energy in this gas mixture created gas products which were undesirable from the point of forming a stable glow discharge between the electrodes. Thus, it became necessary at the higher discharge frequencies to sweep these products out of the electrode volume and replace them with new gas before the next firing. The method adopted for doing this was to mount the electrodes in a box containing a large reservoir of gas and to continuously circulate this through the discharge volume (2,3).

The minimum gas flow required for arc-free laser operation can be calculated from the analysis of Dzakowic and Wutzke (5). For this laser the required flow rate was  $\sim 50$  l/s. This was achieved by mounting eight Imhof Bedco fans, type V113A 52, in a perspex panel dividing the laser gas reservoir box above the electrode structure, see figure 1. The total volume of the reservoir box was  $\sim 280$  l compared with a discharge volume of 2.5 l. In order to obtain the best possible homogeneity of the lasing medium the turbulence created by the flow of gas through the discharge region was kept to a minimum by mounting the cathode on the base of the laser box.

## 2.3 Optical design

In order to obtain the best possible beam quality, positive branch unstable optics were used in this laser. The radii of curvature of the concave and convex mirrors were  $\sim 7.6$  m and  $\sim 4.0$  m respectively, ie, the resonator had a magnification of 1.8. The cavity length was chosen to be  $\sim 1.8$  m. Both mirrors were made from beryllium-copper and were polished to better than  $\sim \lambda/10$  at  $10.6 \mu\text{m}$ . The convex mirror had a diameter of 1 cm and was mounted on a three-legged spider constructed from 1 mm steel.

Initially for high positional stability of the laser output the resonator mirrors were isolated from the discharge region, and its associated shock wave, by inserting Brewster angle KCl windows in the cavity. However, the inclusion of one let alone two such windows degraded the quality of the laser output to such an extent that it was unacceptable. The system finally adopted was to mount the

resonator mirrors in contact with the gas in the laser box, see figure 1, and to bring the laser beam out through a KCl window inclined at  $\sim 5^\circ$  angle of incidence to the output.

Alignment of the resonator mirrors was achieved by shining a 10 mW helium-neon laser through a 1 mm hole in the centre of the concave mirror along the optical axis of the cavity, and adjusting the laser output for maximum concentricity of the diffraction rings. In order to achieve the best beam quality it was found necessary to avoid the inhomogeneous discharge region near the cathode and to align the optical axis of the cavity  $\sim 4$  to 5 mm above the mid-point of the electrode gap towards the anode.

### 3. LASER PERFORMANCE

#### 3.1 Operating characteristics

The maximum single shot output energy obtainable from this laser was  $\sim 3.8$  J. This energy was obtained with a gas mixture comprising 74% helium, 13% nitrogen and 13% carbon dioxide with a cathode-anode voltage of  $\sim 9$  kV/cm. This performance represents an electrical energy deposition  $\sim 80$  J/l in the gas mixture and a lasing efficiency of  $\sim 15\%$ .

For reproducibility in multiple pulse operation it was desirable to operate the laser at a slightly reduced discharge voltage from the single pulse case. At the maximum repetition frequency of  $\sim 10.4$  Hz an electrode voltage of 33 kV was found to be satisfactory for consistent arc-free operation, although to achieve this, accurate adjustment of the cathode-anode gap had to be made. With the exception of the first two laser pulses in a train, which, due to the design of the charging circuit, yielded less and more energy than the mean of the following pulses respectively, the laser output energy per pulse at 10.4 Hz was  $2.7 \pm 0.2$  J with a shot-to-shot variation about the mean of less than  $\pm 4\%$ . The mean power of the laser output at this frequency was thus  $28 \pm 2$  W. A typical laser energy record for a train of 41 pulses taken using a pyroelectric Joulemeter with the laser operating at 10.4 Hz is shown in figure 3(a). One of these pulses, time resolved using a photon drag detector, is shown in figure 3(b). This profile is typical of a CO<sub>2</sub> TEA laser output comprising a leading gain switched spike, of rise time  $\sim 65$  ns and duration  $\sim 270$  ns in which  $\sim 35\%$  of the energy is contained, followed by a lower intensity tail of duration  $\sim 5$   $\mu$ s.

With a gas flow of  $\sim 32$  l/min into the laser box the laser could be operated without degradation of its output with an electrode voltage of 33 kV for periods in excess of 1 h at repetition frequencies up to  $\sim 1.9$  Hz. At higher frequencies the time that the laser could be satisfactorily operated decreased rapidly until at 10.4 Hz only 5.5 s of arc-free lasing could be obtained, see figure 4. At this frequency a duty cycle comprising 3 s operation followed by  $\sim 1$  min rest, required for the thermal blooming studies, was easily achievable.

#### 3.2 Beam quality

The laser output was, at least to a first approximation, lowest order transverse mode (6). Its near field intensity profile was an annulus modulated by the shadow of the spider on which the convex mirror was mounted, see figure 5(a). In the far field the intensity profile was a modified Airy pattern comprising a central maximum surrounded by a number of concentric rings, see figure 5(b).

The fraction of laser energy within a radius centred about the peak of the central maximum of the Airy profile was measured, as a function of radius, using a pyroelectric Joulemeter positioned at the focal plane of a 3.70 m focal length concave mirror which was located 8.7 m from the laser output. As the resonator cavity was not exactly confocal, this position was not the laser beam focus, although it was close to it. Data recorded with the laser operating at a frequency of 10.4 Hz are shown in figure 6. These are all normalised to the laser near field energy. Also shown in figure 6 is the integrated energy distribution calculated by solving the wave equation for the laser beam experimentally determined near field intensity profile assuming a spherical phase output and radial symmetry (7). The latter assumption, which is essentially that of ignoring the diffraction effects of the spider, is considered to have only a small effect on the central maximum and first diffraction ring of the far field intensity profile (8). The agreement between experiment and theory is good with approximately  $37 \pm 2\%$  of the laser energy being contained in the central maximum experimentally compared with a theoretical value of  $\sim 44\%$ . This good agreement indicates that the laser output phase was indeed close to being spherical and as such the laser beam was of high quality. The far field intensity profile, obtained by scanning a pinhole in front of a pyroelectric Joulemeter across a diameter, is shown in figure 7. The theoretical profile, calculated in the same manner as for the integrated energy distribution, is also shown in figure 7, and again the agreement between experiment and theory is good.

### 3.3 Stability

The positional stability of the laser output was measured by placing heat sensitive paper at the focus of 10 m focal length Cassegrain optics and recording the spatial co-ordinates of the centre of the burn mark made on this paper by firing the laser. The root mean square scatter about the mean of a large number of single shots fired in between 3 s bursts of laser operation at 10.4 Hz was  $\pm 18 \mu\text{rad}$ . This stability improved to  $\pm 7.6 \mu\text{rad}$  by inserting a Brewster angle KCl window in the cavity.

On most laser shots the oscillator resonated on the P(20) rotational line of the 001-100 vibrational transition and thus emitted radiation at  $10.59 \mu\text{m}$ . No other rotational lines were present in the output as observed on an Optical Engineering Spectrum Analyser, model 16A. Occasionally, however, the laser was seen to resonate on the P(18) line at  $10.57 \mu\text{m}$  instead of the P(20).

## 4. CONCLUSIONS

A multiple pulse CO<sub>2</sub> TEA laser has been designed and constructed for use in thermal blooming studies. By careful design of the resonator cavity, and optimisation of the discharge energy and voltage, lasing gas mixture and gas flow rate, a positionally stable, high quality, laser output beam has been obtained up to pulse repetition frequencies of  $\sim 10.4 \text{ Hz}$ . At the maximum repetition frequency the laser yielded a mean power output of 28 W. As such this laser met the requirements specified for its use in the thermal blooming experiments.

5. ACKNOWLEDGMENTS

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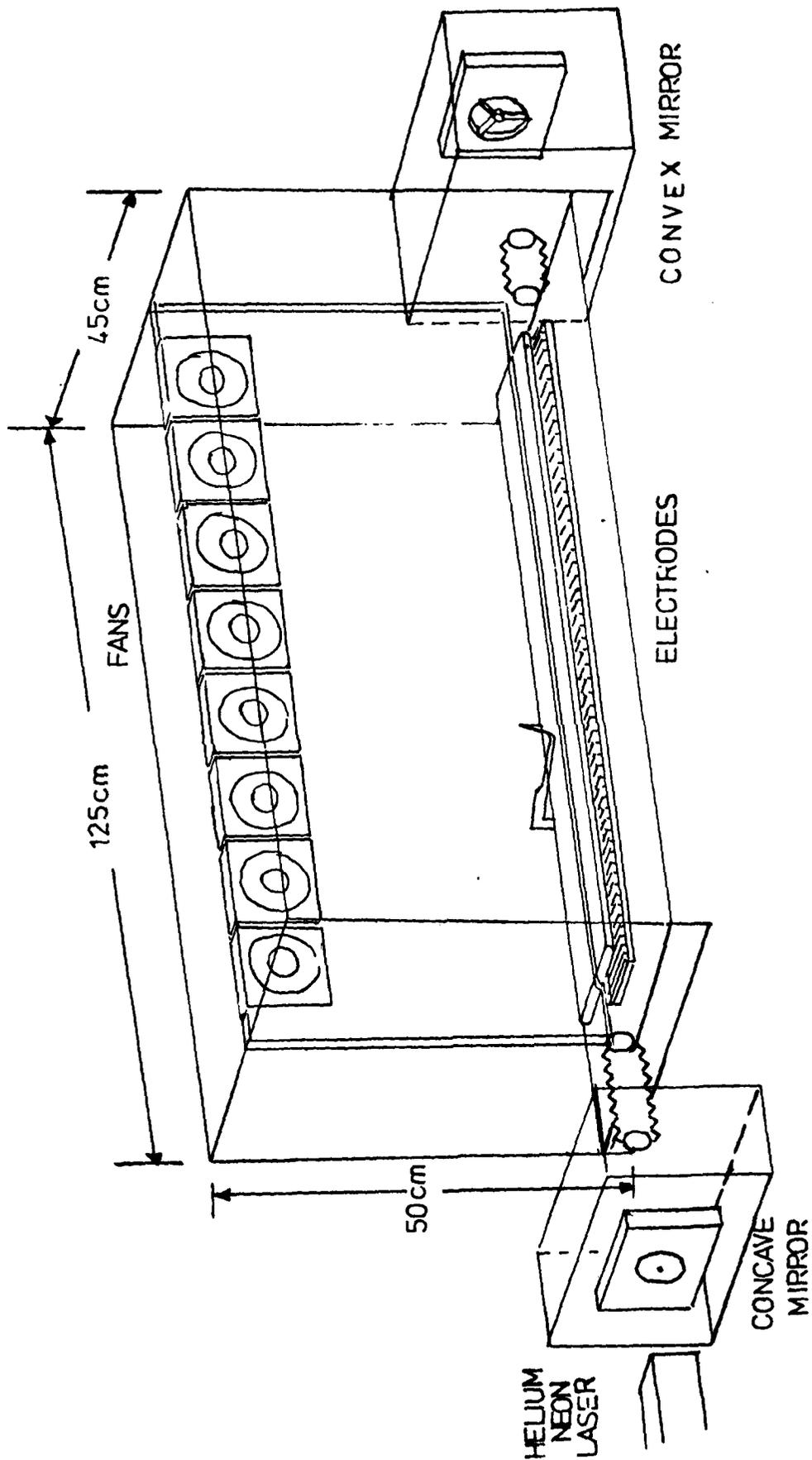


FIGURE 1. SCHEMATIC DIAGRAM OF MULTIPLE PULSE LASER SYSTEM

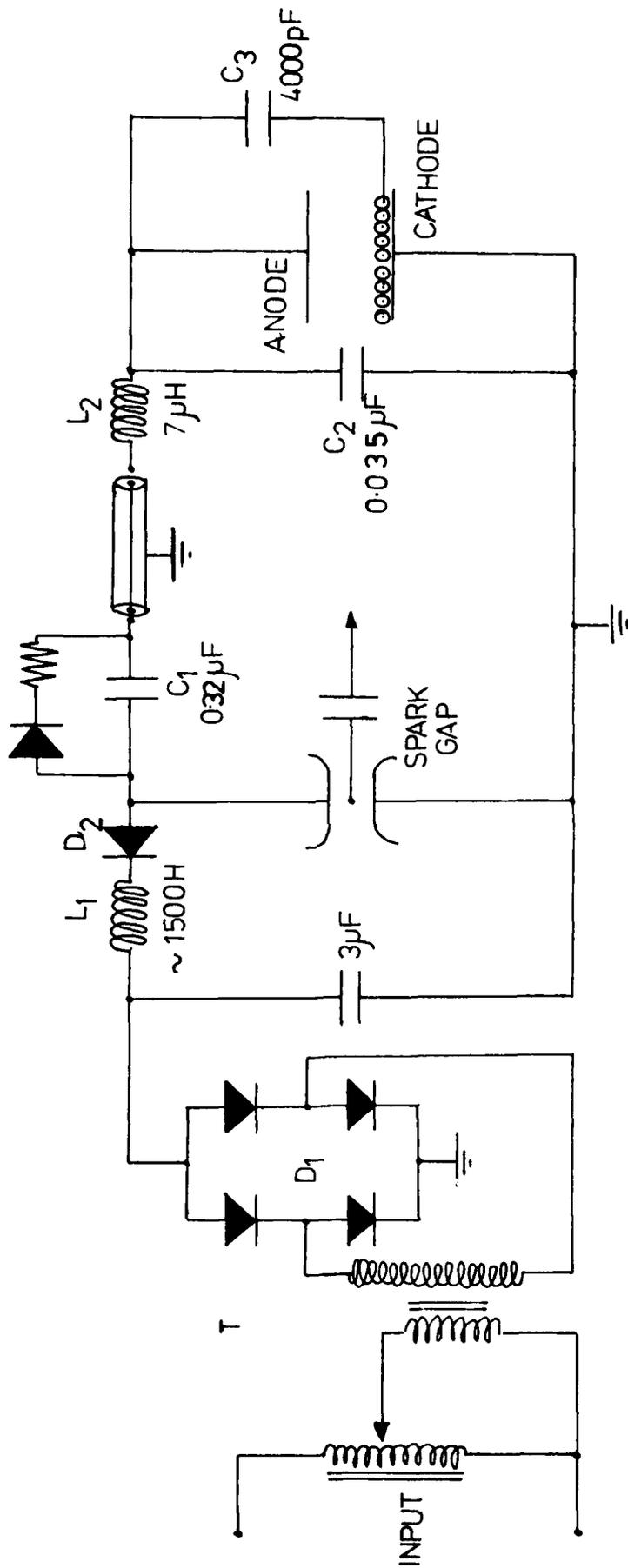


FIGURE 2. ELECTRICAL CIRCUIT OF MULTIPLE PULSE CO<sub>2</sub> TEA LASER

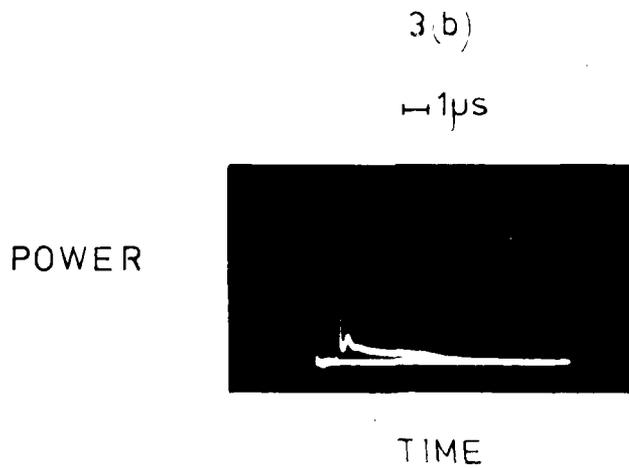
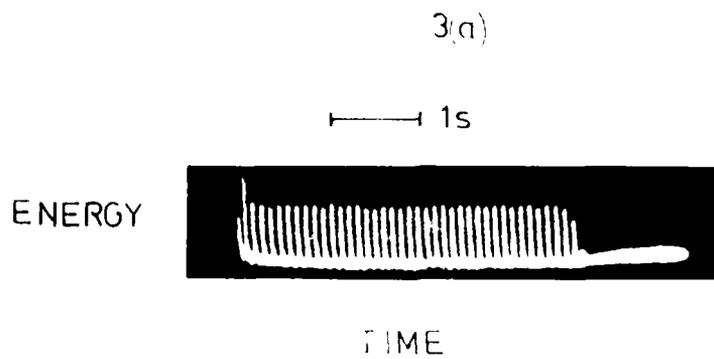


FIGURE 3. (a) LASER OUTPUT ENERGY FOR A TRAIN OF 41 PULSES AT A REPETITION OF 10.4 Hz AND (b) TEMPORAL PROFILE OF A SINGLE PULSE WITH THE LASER OPERATING AT 10.4 Hz

CATHODE - ANODE VOLTAGE = 33 KV

LASER GAS MIXTURE OF HELIUM, NITROGEN AND  
CARBON DIOXIDE IN THE RATIO 6:1:1.

GAS FLOW RATE = 32 l.min<sup>-1</sup>

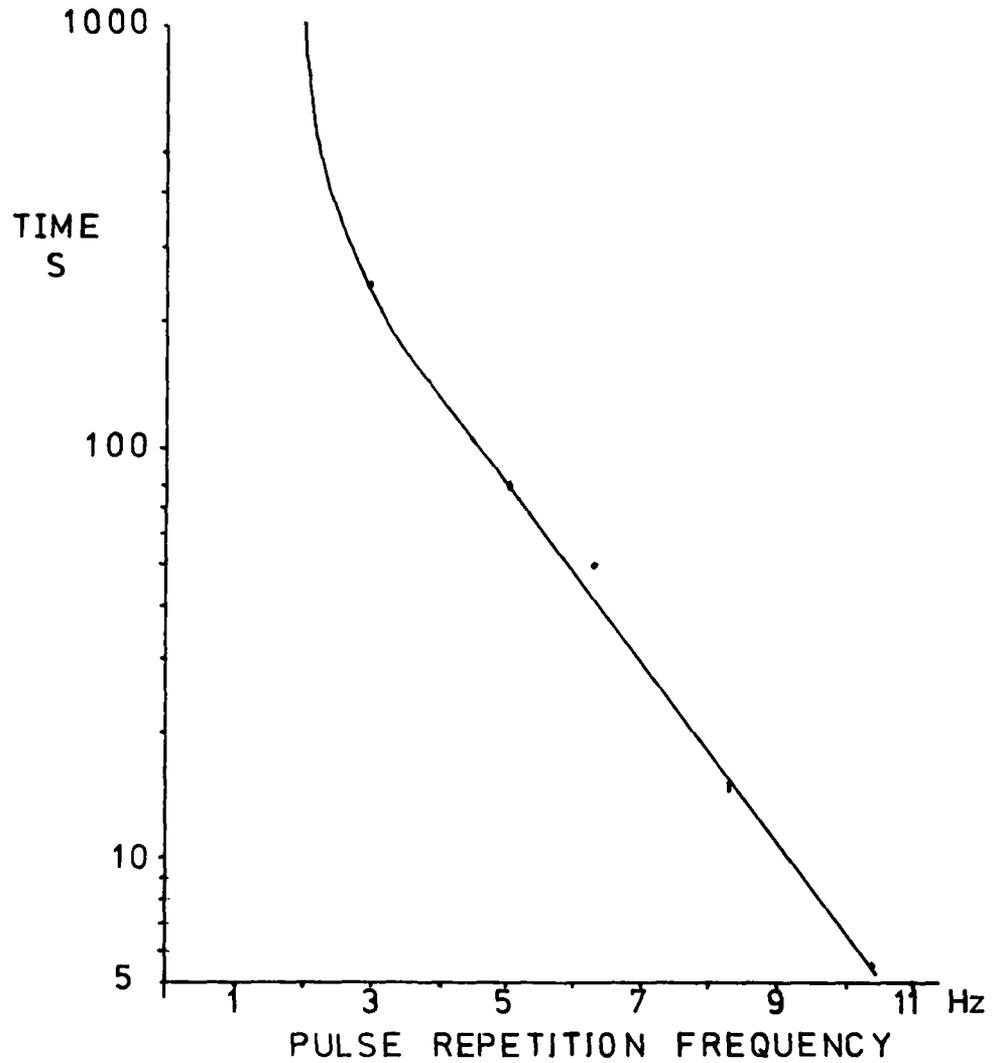


FIGURE 4. TIME OF OPERATION OF LASER WITHOUT ARCING VERSUS PULSE REPETITION FREQUENCY

5(a)



5(b)



FIGURE 5. (a) NEAR FIELD AND (b) FAR FIELD LASER BEAM SPATIAL INTENSITY PROFILES RECORDED BY IRRADIATING HEAT SENSITIVE PAPER

| EXPERIMENT  
— THEORY

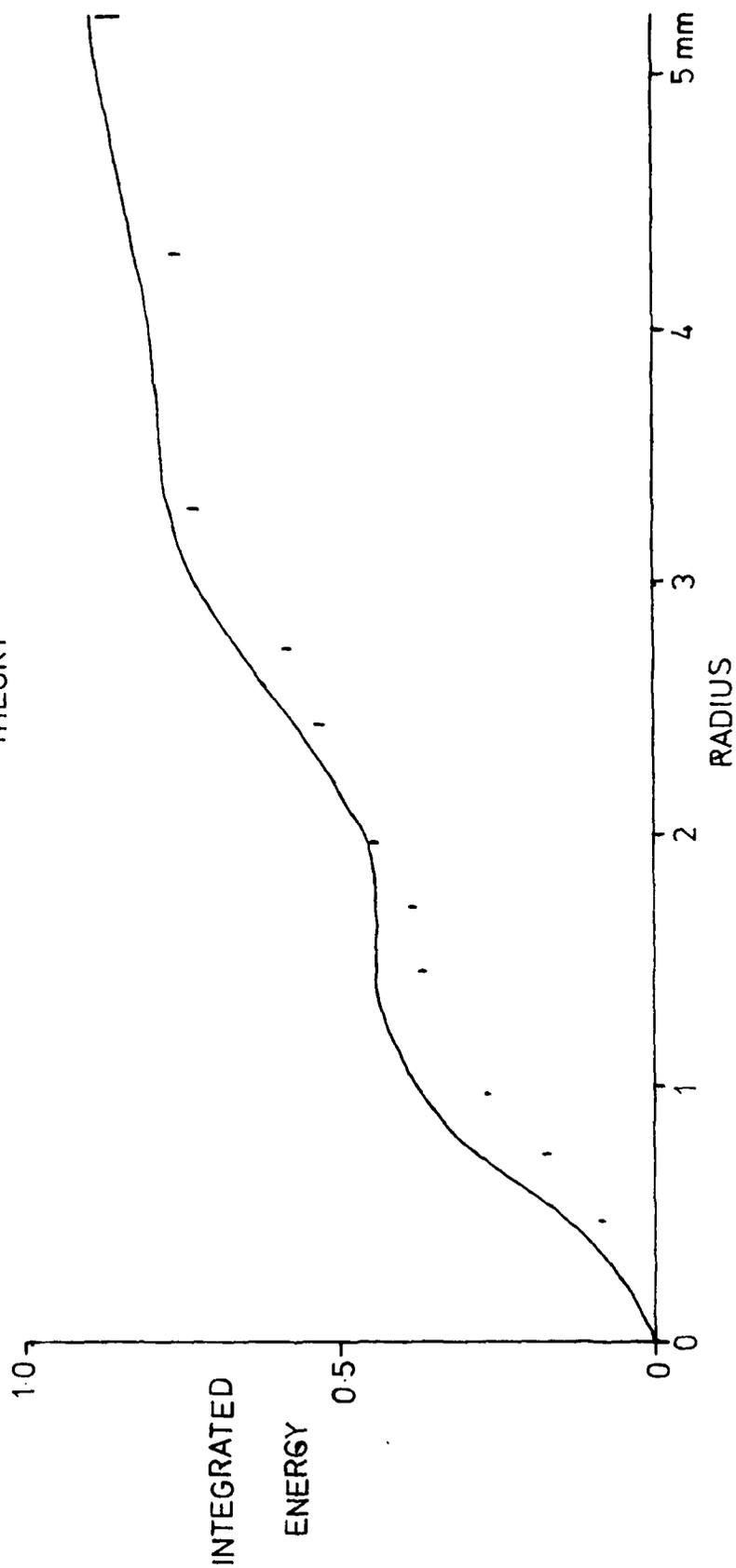


FIGURE 6. EXPERIMENTAL AND THEORETICAL INTEGRATED ENERGY PROFILES  
AT THE FOCAL PLANE OF A 3.70 m FOCAL LENGTH CONCAVE MIRROR

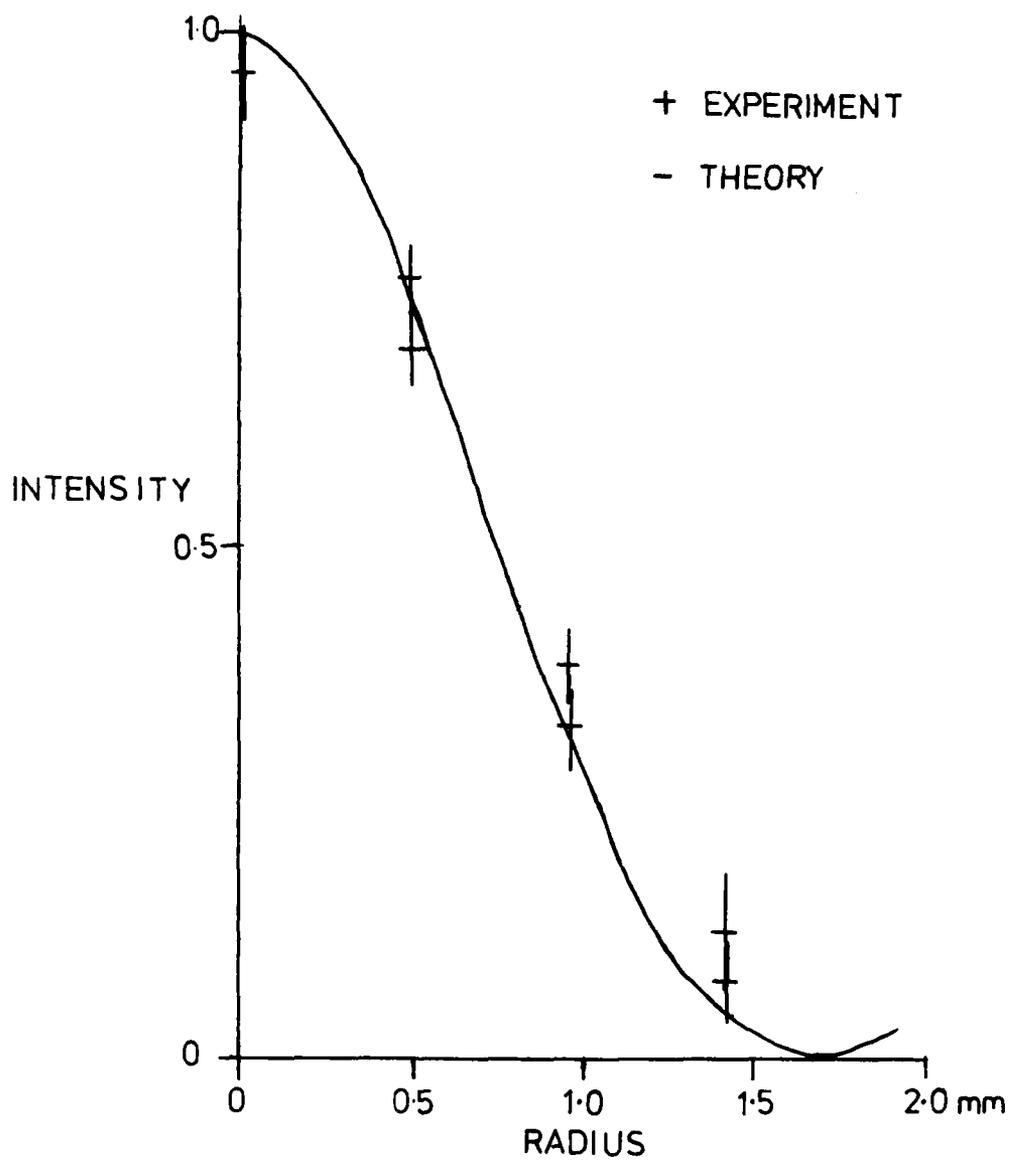


FIGURE 7. LASER BEAM EXPERIMENTAL AND THEORETICAL FAR FIELD SPATIAL PROFILES

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<p>Abstract</p> <p>The design, performance and operating characteristics of a multiple pulse CO<sub>2</sub> TEA laser constructed at AWRE for use in thermal blooming studies is described. Using unstable resonator optics, at the maximum pulse repetition frequency of ~ 10.4 Hz, this laser yielded a good quality output beam of mean power 28 <del>W</del> W. <i>approx</i></p> <p style="text-align: center;">+ or -      ↗      ↖      .....</p>			

Some Metric and SI Unit Conversion Factors

(Based on DEF STAN 00-11/2 "Metric Units for Use by the Ministry of Defence",  
DS Met 5501 "AWRE Metric Guide" and other British Standards)

Quantity	Unit	Symbol	Conversion
<u>Basic Units</u>			
Length	metre	m	1 m = 3.2808 ft 1 ft = 0.3048 m
Mass	kilogram	kg	1 kg = 2.2046 lb 1 lb = 0.45359237 kg 1 ton = 1016.05 kg
<u>Derived Units</u>			
Force	newton	$N = \text{kg m/s}^2$	1 N = 0.2248 lbf 1 lbf = 4.44822 N
Work, Energy, Quantity of Heat	joule	$J = \text{N m}$	1 J = 0.737562 ft lbf 1 J = 9.47817 $\times 10^{-6}$ Btu 1 J = 2.38846 $\times 10^{-4}$ kcal 1 ft lbf = 1.35582 J 1 Btu = 1055.06 J 1 kcal = 4186.8 J
Power	watt	$W = \text{J/s}$	1 W = 0.238846 cal/s 1 cal/s = 4.1868 W
Electric Charge	coulomb	$C = \text{A s}$	-
Electric Potential	volt	$V = \text{W/A} = \text{J/C}$	-
Electrical Capacitance	farad	$F = \text{A s/V} = \text{C/V}$	-
Electric Resistance	ohm	$\Omega = \text{V/A}$	-
Conductance	siemen	$S = 1 \Omega^{-1}$	-
Magnetic Flux	weber	$\text{Wb} = \text{V s}$	-
Magnetic Flux Density	tesla	$T = \text{Wb/m}^2$	-
Inductance	henry	$H = \text{V s/A} = \text{Wb/A}$	-
<u>Complex Derived Units</u>			
Angular Velocity	radian per second	rad/s	1 rad/s = 0.159155 rev/s 1 rev/s = 6.28319 rad/s
Acceleration	metre per square second	$\text{m/s}^2$	1 $\text{m/s}^2 = 3.28084 \text{ ft/s}^2$ 1 $\text{ft/s}^2 = 0.3048 \text{ m/s}^2$
Angular Acceleration	radian per square second	$\text{rad/s}^2$	-
Pressure	newton per square metre	$\text{N/m}^2 = \text{Pa}$	1 $\text{N/m}^2 = 145.038 \times 10^{-6} \text{ lbf/in}^2$ 1 $\text{lbf/in}^2 = 6.89476 \times 10^3 \text{ N/m}^2$
	bar	$\text{bar} = 10^5 \text{ N/m}^2$	-
Torque	newton metre	N m	1 in. Hg = 3386.39 $\text{N/m}^2$ 1 N m = 0.737562 lbf ft 1 lbf ft = 1.35582 N m
Surface Tension	newton per metre	N/m	1 N/m = 0.0685 lbf/ft 1 lbf/ft = 14.5939 N/m
Dynamic Viscosity	newton second per square metre	$\text{N s/m}^2$	1 $\text{N s/m}^2 = 0.0208854 \text{ lbf s/ft}^2$ 1 $\text{lbf s/ft}^2 = 47.8803 \text{ N s/m}^2$
Kinematic Viscosity	square metre per second	$\text{m}^2/\text{s}$	1 $\text{m}^2/\text{s} = 10.7639 \text{ ft}^2/\text{s}$ 1 $\text{ft}^2/\text{s} = 0.0929 \text{ m}^2/\text{s}$
Thermal Conductivity	watt per metre kelvin	$\text{W/m K}$	-
<u>Odd Units*</u>			
Radioactivity	becquerel	Bq	1 Bq = 2.7027 $\times 10^{-11}$ Ci 1 Ci = 3.700 $\times 10^{10}$ Bq
Absorbed Dose	gray	Gy	1 Gy = 100 rad 1 rad = 0.01 Gy
Dose Equivalent	sievert	Sv	1 Sv = 100 rem 1 rem = 0.01 Sv
Exposure	coulomb per kilogram	$\text{C/kg}$	1 $\text{C/kg} = 3876 \text{ R}$ 1 R = 2.58 $\times 10^{-4} \text{ C/kg}$
Rate of Leak (Vacuum Systems)	millibar litre per second	ml/s	1 mb = 0.750062 torr 1 torr = 1.33322 mb

\*These terms are recognised terms within the metric system.