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LUCAS HEIGHTS RESEARCH LABORATORIES

A THYRATRON-SWITCHED MODULAR CO_2 TEA LASER FOR INFRARED PHOTOCHEMICAL STUDIES

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ABSTRACT

A thyratron-switched, ultraviolet pre-ionised CO_2 TEA laser, consisting of four modules connected in series, has been designed and constructed at the AAEC Research Establishment. The laser can be operated in the TEM_{00} mode and is able to produce 2.5 J per pulse. The design and operation of the laser as a tool for infrared studies is discussed together with an evaluation of the effect of operating parameters on output characteristics.

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CARBON DIOXIDE LASERS; ELECTRONIC CIRCUITS; PERFORMANCE; SPECIFICATIONS; THYRATRONS

CONTENTS

1. INTRODUCTION

A number of continuous wave (CW) and pulsed CO_2 lasers, including the transversely excited atmospheric pressure (TEA) laser described here, have been built at the AAEC Research Establishment as part of a program to study their application to the isotopic separation of uranium [Eberhardt 1979; Hamilton et al. 1982]. Lasers of the TEA type are usually designed to produce high pulse energies (3 to 5 J) at high repetition rates (50 to 100 Hz) and, as a consequence, usually have high Fresnel numbers and operate in many transverse modes. The TEA laser described here differs in that it was required to operate as an amplifier in a single transverse mode (TEM_{00}) with a uniform gain profile, lower repetition rates (up to a few hertz) being acceptable. Although designed as a laser amplifier, it has also operated reliably as an oscillator; its performance in this role is also described.

2. DESIGN

The limitations experienced with a commercial laser necessitated a literature review of the design and operating characteristics of previously commissioned CO_2 TEA lasers (Appendix A). The conclusions of this review led to the design shown in Figure 1. To enhance operation in low order transverse modes, the structure is 2 m long and comprises four identical modules mounted in series. The main electrodes are fabricated from aluminium, machined to a 2/3 π Rogowski profile and spaced 15 mm apart. Alternate modules are rotated 90° to define a square active cross section of 2.25 cm^2, and to smooth out lateral gain variations, particularly at the electrode ends. Facing into the active volume is a pair of pre-ionisation sliding spark arrays, each having 30 diamond-shaped molybdenum electrodes. Two identical assemblies of a spark gap and its associated energy storage capacitors feed the pre-ionisation pulse to each of the four modules, and are mounted compactly and close to reduce inductance. Figure 2 shows the beam tube during assembly. The ends are sealed with window mounts holding NaCl windows at the Brewster angle. The etalon optics are external. Figure 3 shows the structure of the completed laser.

3. DISCHARGE CIRCUITS

Circuitry for both pre-ionisation (PI) and the main discharge is shown in Figure 4. The PI circuit uses two triggered spark gaps, each releasing 3.6 J into the sliding sparks of two modules. The main discharge energy of up to 22.5 J is stored in a single capacitor and switched by a hydrogen thyratron, a device which switches high voltages and currents (10 000 A) with a fast rise time (100 kA μs^{-1}) and low jitter. The PI and main discharge are controlled by solid state logic variable delay circuits giving delays in the range 0.5 to 10 μs to allow optimum selection of oscillator-PI-amplifier pulse timing.

4. GAS MIXTURE

Commercial grade He, N_2 and CO_2 are metered and processed with a specially designed gas handling rig which includes facilities for filtering and removing water vapour, oxygen (by MnO column) and other impurities, and allows the controlled addition of dopants. The gas mixture is fed into the beam tube through both window mounts and then extracted from the centre to purge gas decomposition products away from the NaCl windows, where they could otherwise deposit and lead to optical degradation. The gas mixture is typically $He/N_2/CO_2$ in the approximate ratio of 10:1:1 by volume with about 100 ppm (mg L^{-1}) of dopant, as described below.

5. MODIFICATIONS DURING DEVELOPMENT OF THE LASER

During the first test, lasing was unattainable, despite the correct functioning of the discharge circuitry and careful optical alignment using an He-Ne laser. We deduced that lateral lasing was bleeding away the energy deposited in the gain medium for longitudinal operation. This was caused by the method of assembly, which had been designed to assure accurate parallelism of anodes and cathodes, and by the highly polished state of the main electrodes (Figure 2). To overcome the problem, the structure was disassembled, and the electrodes were sand-blasted to a matt finish and re-installed to the same accuracy of alignment. Lasing then took place satisfactorily, but reflections could still be seen down the beam tube. These reflections were subsequently reduced by platinising the electrodes to give a matt black surface.

The next problem occurred when the main storage capacitor exploded, destroying the glass hydrogen thyratron. Fortunately, all high voltage components were enclosed in a metal box and no further damage occurred to personnel or equipment. The components were operating below their maximum ratings and neither the manufacturers nor the authors could determine the cause of the failure. Another failure occurred with one of the sealed spark gaps (EG&G Inc.) immediately it was put into service, an experience that has been observed by K. Gurs of the Bartelle Institut, Federal Republic of Germany (private communication). We instituted a similar modification, drilling a fine hole in the unit and introducing an external argon/hydrogen gas flow at 350 kPa (50 psi) across the gap. Subsequent operation has been satisfactory.

6. OPERATING CHARACTERISTICS

The laser was built as a tool for irradiation studies of uranyl chelates. Consequently, only those parametric studies of the operation necessary to achieve the design requirements were carried out.

In its final form, the laser routinely produced pulse energies up to 2.1 J on the 10P(20) line; up to 2.5 J could be obtained with careful optimisation of the many operating parameters. Introduction of a plane diffraction grating for line selection reduced the output pulse energy by only 10 per cent. In this form, the laser was operated routinely as an oscillator and required little maintenance at repetition rates of 0.3 to 2 Hz and pulse energies of 1 to 2 J (depending on frequency) in the TEM_{00} mode. Since the laser was designed as an amplifier, the long, narrow geometry and low Fresnel number limit the available output energy.

The full width at half maximum (FWHM) on the oscilloscope trace of the main discharge waveform (Figure 5) is 200 to 300 ns, which is the same as the laser pulse. In this trace it can be seen that the main spike is preceded by noise pickup from the pre-ionisation discharge.

Pulse-to-pulse reproducibility is shown in Figure 6. Under these conditions, the use of an additive such as benzene or tripropylamine (TPA) is essential to prevent arcing and loss of laser action. As the figure shows, TPA in low concentrations gave excellent results, and no traces of decomposition products could be detected after two days of continuous operation at 1 Hz pulse repetition rate.

The effect of the delay between the pre-ionisation and the main discharge is shown in Figure 7. Before the main electrodes were platinised, if the delay lasted more than 1 μs, it led to arcing and erratic operation, but with the coated electrodes, output energy decreased relatively smoothly for up to 5 μs. We attributed the latter result to the spiky microscopic structure of the platinum black, and the contribution of electrode surface ionisation effects to the prevention of arcing, rather than the volume ionisation produced by ultraviolet radiation.

The burn patterns reproduced in Figure 8 illustrate the beam profile. The reproducibility of minute detail, which is indicative of pulse-to-pulse uniformity of the laser plasma, could be maintained over the pressure range 80 to 100 kPa. The pattern of the unapertured beam indicates operation in a TEM_{23} mode. When using the laser in a single pass amplifier mode, a gain of about 6 was achieved with a 100 mJ oscillator pulse. Obviously, multipass operation will be necessary to extract the remaining energy from the amplifier. One advantage of a laser oscillator/amplifier combination is that the output energy can be continuously and very conveniently varied by simply delaying the probe pulse, provided that the statistical variation in the delay interval (jitter) is much less than the decay time of the upper laser level (approx. 5 ms). The jitter shown in Figure 9 is almost entirely due to the oscillator spark gap jitter; it could be reduced by a factor of 3 by replacing the present 'home made' trigger voltage transformer with a high performance unit that is commercially available. The entire delay circuitry was gratifyingly immune to the considerable radiofrequency interference generated when the laser fired.

For multi-photon dissociation photochemical studies, the laser fluence and beam diameter can be varied by incorporating into the system combinations of converging/diverging Ge lenses in special mounts. Fluences of up to 4 J cm^{-2} for hundreds of pulses can be accommodated safely, provided that the lenses are scrupulously clean. The laser flux can be conveniently varied by a factor of 10 using a ZnSe Brewster window polarisation attenuator in which the reflected energy is absorbed by a Teflon liner. An attenuator and a beam converging unit have been constructed and employed for this purpose.

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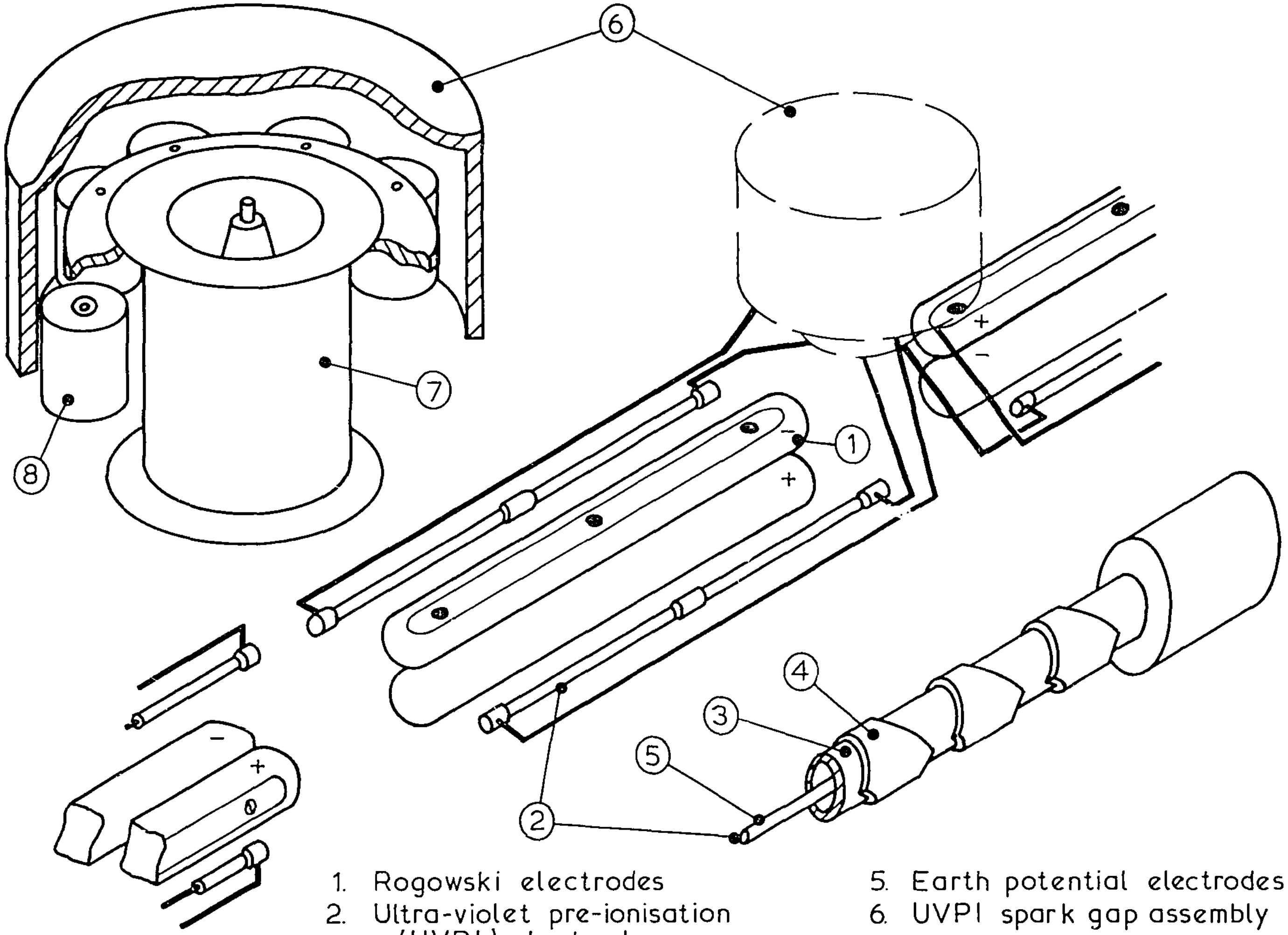


1. Rogowski electrodes
2. Ultra-violet pre-ionisation (UVPI) electrodes
3. Glass sleeve
4. Mo spark electrodes
5. Earth potential electrodes
6. UVPI spark gap assembly
7. Spark gap
8. Energy storage capacitors

FIGURE 1. LASER AMPLIFIER ARRANGEMENT

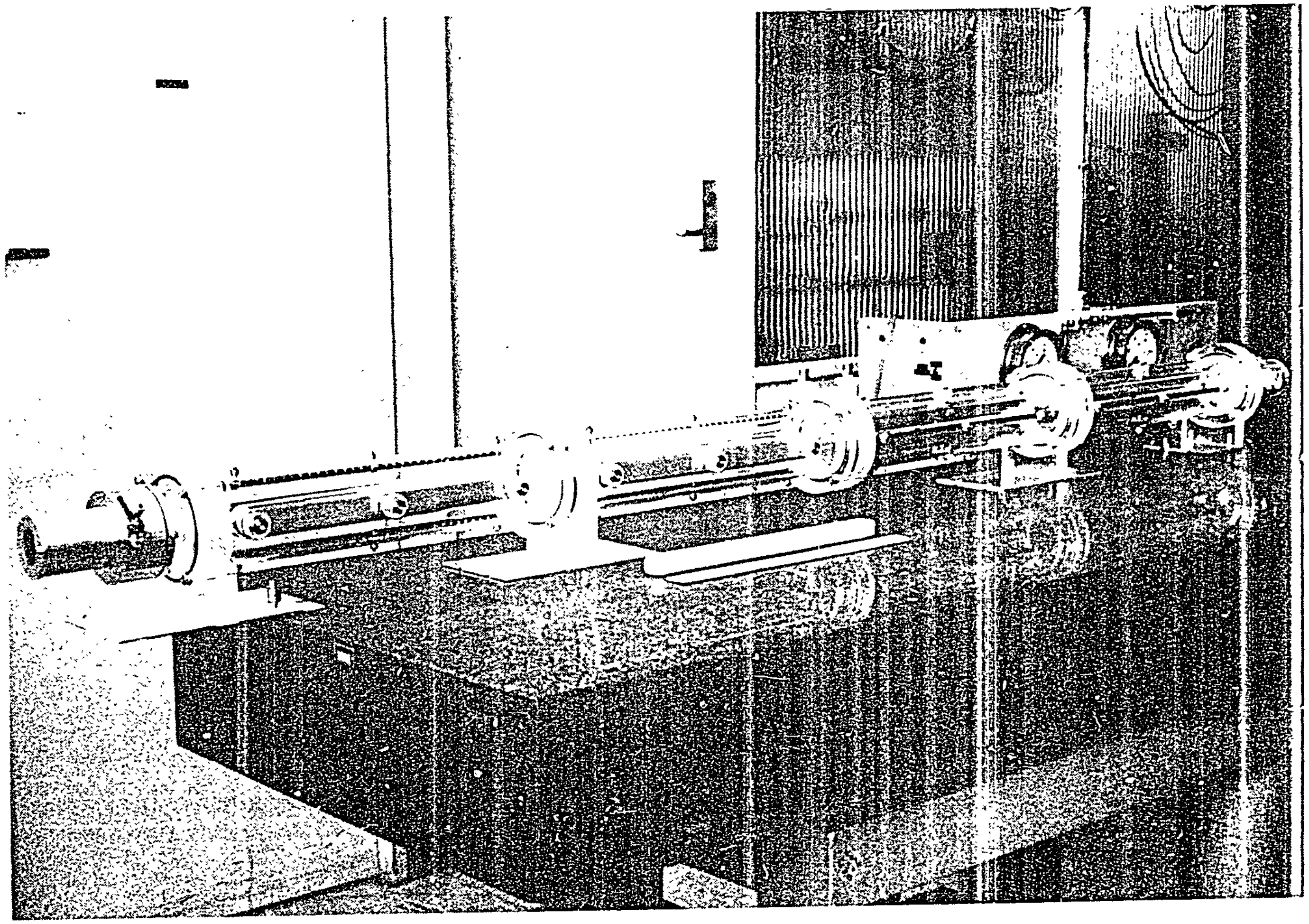


FIGURE 2(a) LASER AMPLIFIER MODULES

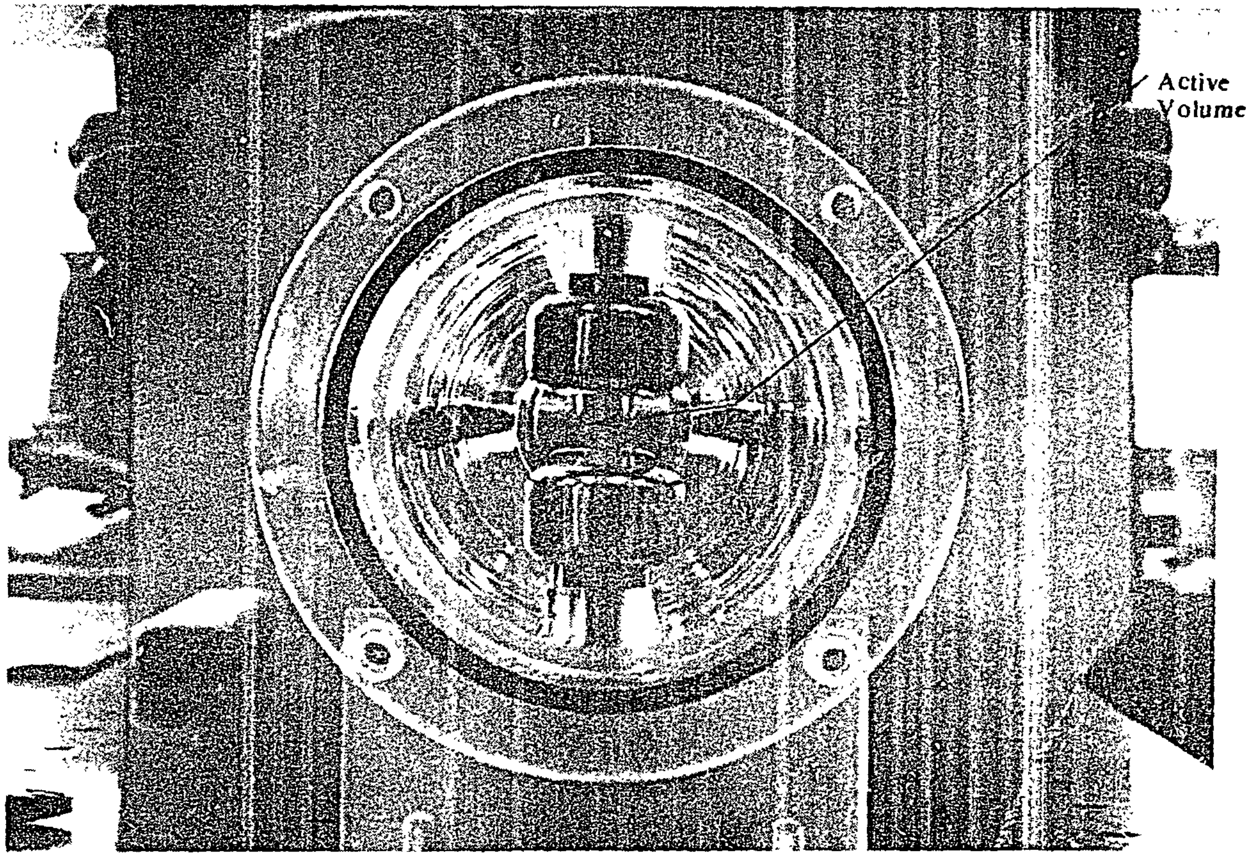


FIGURE 2(b) END VIEW OF LASER AMPLIFIER MODULE

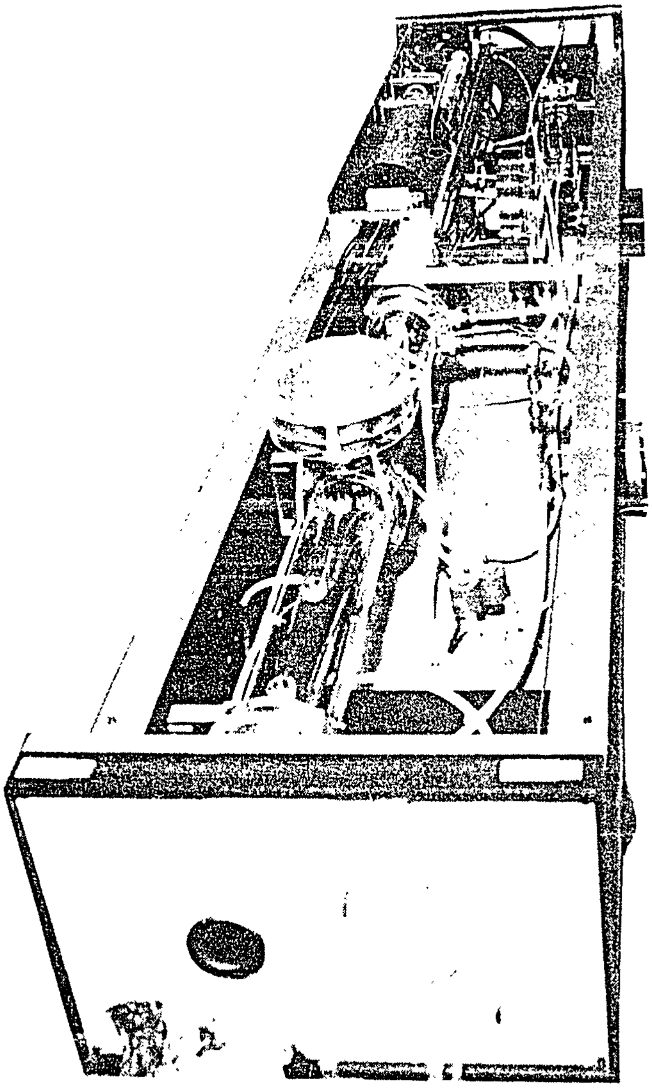


FIGURE 3. COMPLETED LASER

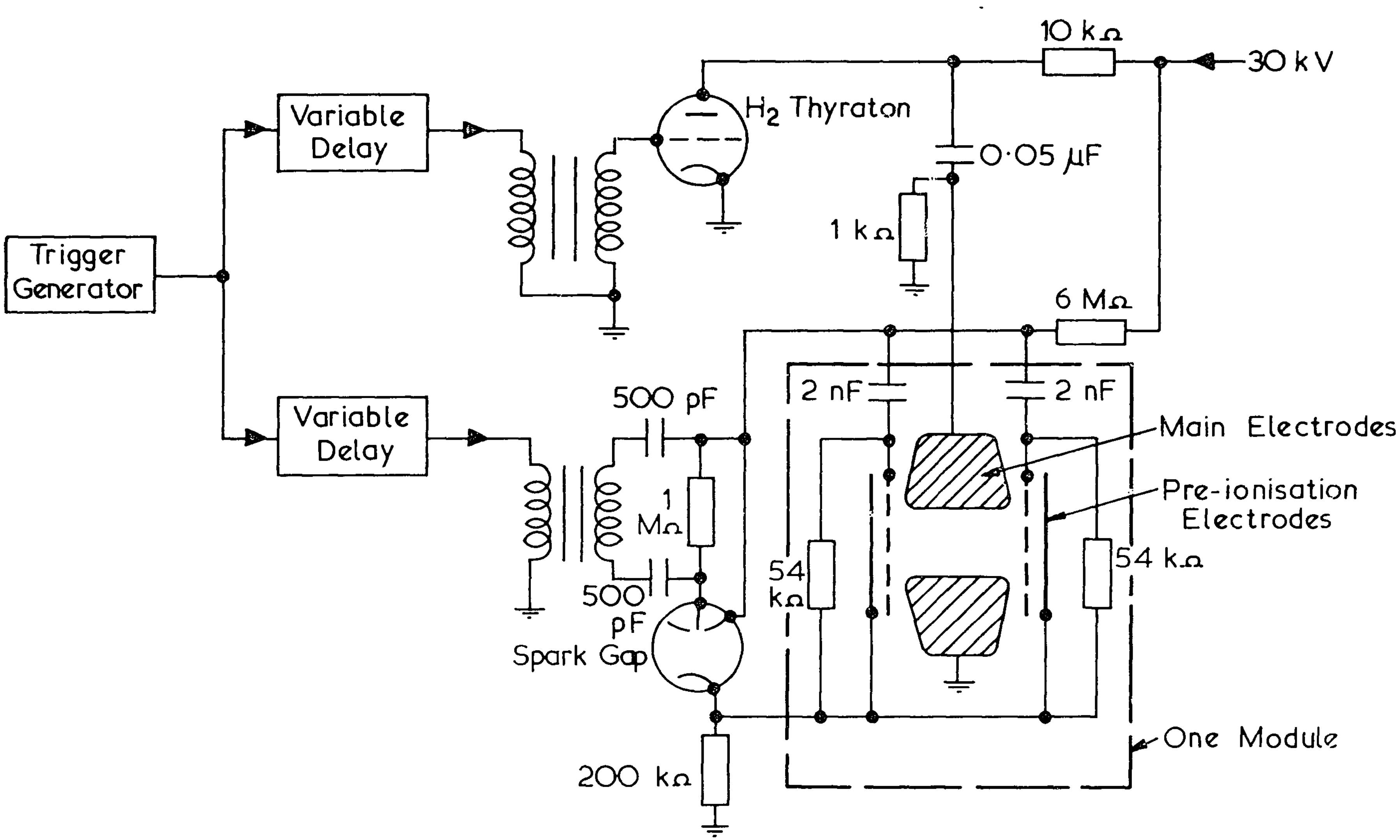


FIGURE 4. DISCHARGE CIRCUITRY

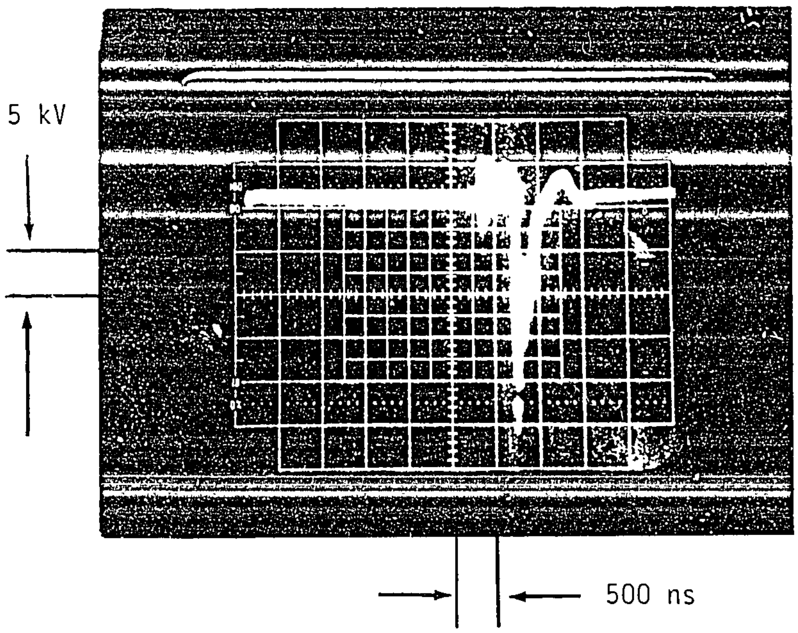
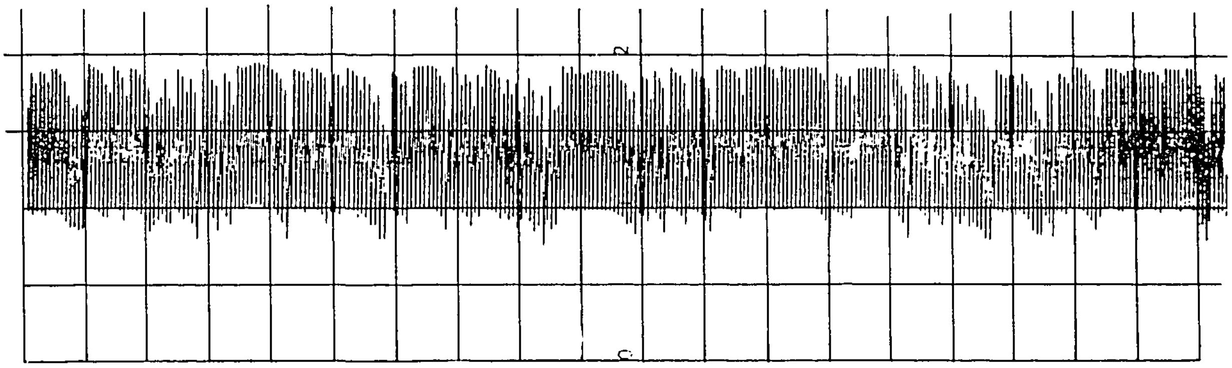
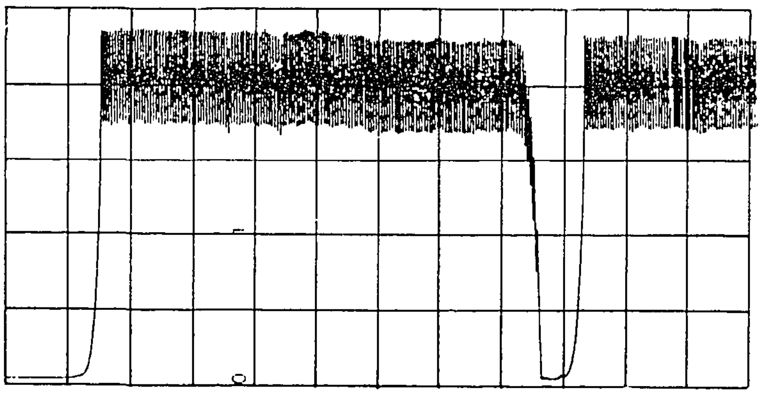


FIGURE 5. MAIN DISCHARGE WAVEFORM



LASER OPERATION AT A PRF OF 0.5 Hz. BENZENE ADDITIVE



PRF 1 Hz WITH ~100 PPM TRIPROPYLAMINE

FIGURE 6. PULSE REPRODUCIBILITY

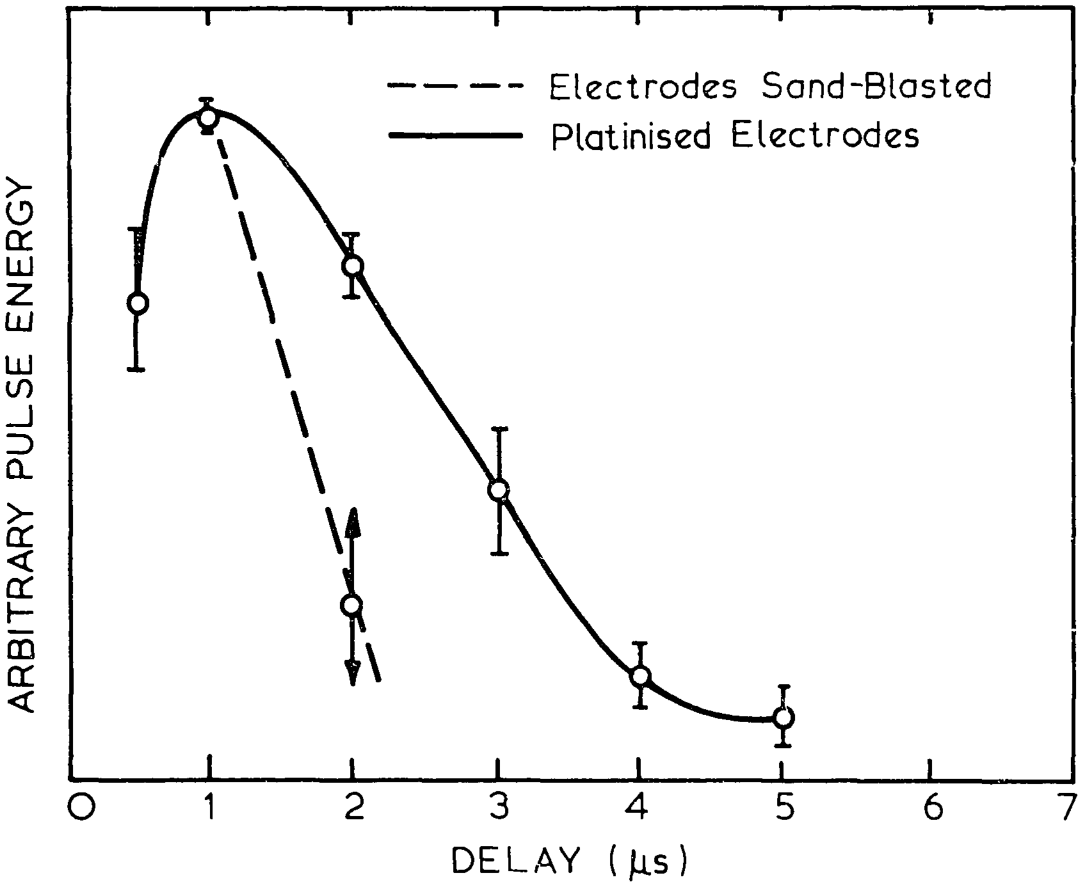


FIGURE 7. PRE-IONISATION TO MAIN DISCHARGE DELAY

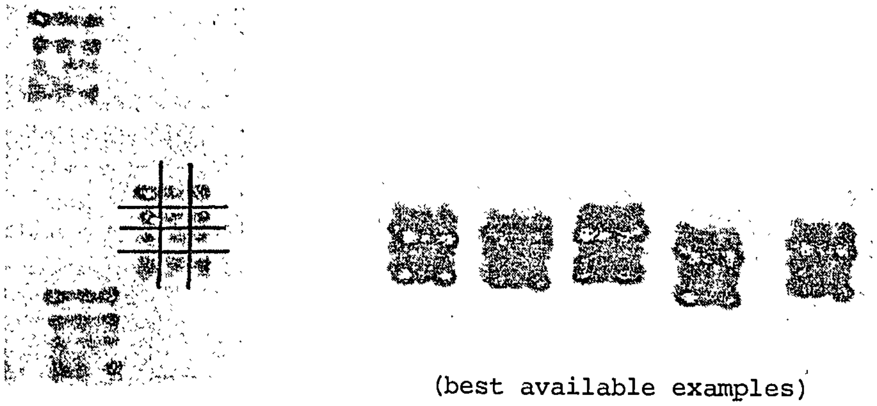

(best available examples)

FIGURE 8. LASER MODE PATTERNS: SINGLE PULSE, UNAPERTURED

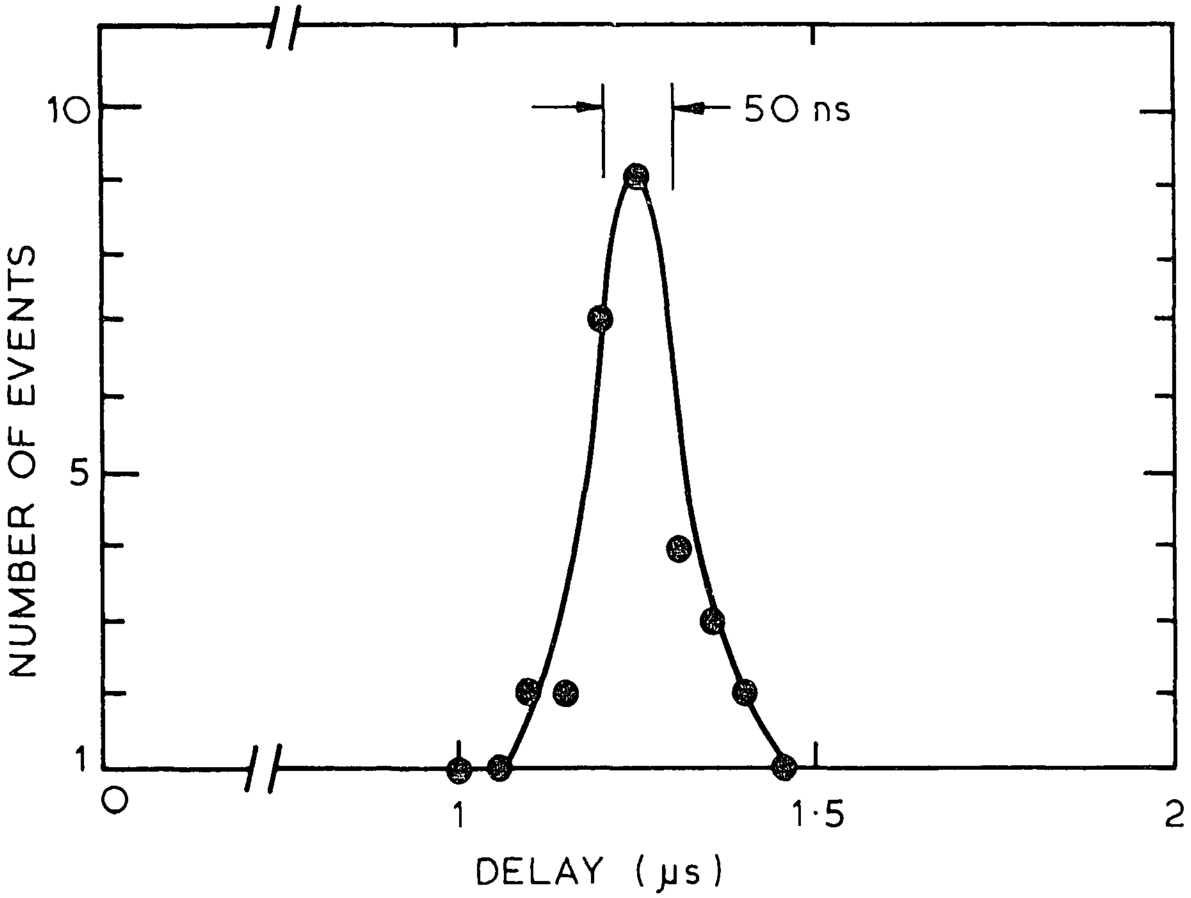


FIGURE 9. SYNCHRONISATION JITTER

APPENDIX A
DESIGN AND OPERATING PARAMETERS OF CO_2 TEA LASERS
A LITERATURE REVIEW TO 1977

by N. Hamilton

A1 INTRODUCTION

An examination of the specifications and operation of a commercial CO_2 laser in use at these laboratories revealed that planned and actual performances were far short of those generally reported for short pulse (a few hundred nanoseconds) small aperture (a few cm^2) CO_2 TEA lasers. Low efficiency, arcing and non-uniform gain have limited its value as a laser amplifier.

To assess improvements that could be made to performance by changes to the existing structure, the literature on the theory and operation of these lasers was reviewed. Broadly, the areas of significance were those pertaining to pre-ionisation techniques, electrode geometry and energy input circuitry.

A2 PRE-IONISATION

The objective of pre-ionisation (PI) is to ensure an arc-free, homogeneous glow discharge when the main energy pulse is injected into the gas mixture. Theoretical models indicate that electron densities in the range 10^4 cm^{-3} [Palmer 1974; Palmer and Wada 1974] to 10^8 cm^{-3} [Kline and Denes 1975] are a minimum requirement for such uniform discharges. Measured electron densities before uniform (assessed visually) discharges vary from 3 x 10^6 cm^{-3} [Denes and Kline 1977] to a more usual density of about 10^{10} cm^{-3} [Cohn and Ault 1973; Seguin et al. 1973, 1974; Richardson 1974]. Two effective techniques for achieving these electron densities are irradiation of the gas mixture either by ultraviolet photons or by an electron beam. Since the electron beam method is technically more complex and better suited to large aperture, sustained discharge devices, it is not discussed.

A2.1 Ultraviolet Pre-ionisation

As noted by Pan et al. [1972] the first deliberate use of ultraviolet pre-ionisation (UVPI) to initiate a uniform discharge was by Lamberton and Pearson following an idea by Hertz. Since an historical approach is not germane to this study, it will suffice to describe the current model for UVPI and its applications.

UVPI model

Ultraviolet photons produced from nitrogen excited in a spark discharge are transmitted through two 'windows' in the CO_2 absorption spectrum. One window (5 nm wide) is centred on 120 nm, the other (10 nm wide) is centred on 175 nm [McKen et al. 1976]. Photons at these energies are unable to ionise directly the major laser gas components to sufficient densities to account for observations [Liberman and Partlow 1974; McKen et al. 1976]. However, one-step ionisation of background impurities has been proposed as an explanation of this characteristic [Liberman and Partlow 1974; Babcock et al. 1976; McKen et al. 1976], e.g. with a 3 mJ spark, 1 $\mu g\ g^{-1}$ hydrocarbon impurity will provide electron densities of 4×10^5 cm^{-3} at 5 cm [McKen et al. 1976]. Seguin and his co-workers reported mean free paths for photo-ionisation of approx. 5 cm in the 120 nm window and 17 cm at 175 nm. Generally, geometric attenuation is observed [e.g. Babcock et al. 1976].

Additives

Although Deutsch [1972] found that the addition of hydrogen assists arc suppression, the first deliberate use of low ionisation potential additives to the gas mixture to increase PI electron density was reported by Schreiver [1972]. Additives studied in this and subsequent work include hydrogen [Smith et al. 1975], alcohols [Grigoriu and Brinkschulte 1973], benzene [Schreiver 1972; Grigoriu and Brinkschulte 1973; Seguin et al. 1974, 1977], xylene [Schreiver 1972; Grigoriu and Brinkschulte 1973; Morikawa 1977], acetone [Seguin et al. 1974], toluene [Schreiver 1972], nitric oxide [Smith et al. 1975; Bletzinger et al. 1975; Seguin et al. 1977], methyl ketone [Seguin et al. 1974], trimethylamine [McKen et al. 1976], trimethyl benzene [Deutsch 1972], benzylamine, dibutylamine [Morikawa 1977], tripropylamine [Seguin et al. 1973, 1974, 1976, 1977; McKen et al. 1976; Morikawa 1977], triethylamine [Seguin et al. 1973, 1974] and mixtures of the last two [Seguin et al. 1973, 1974]. Tripropylamine is added routinely to many lasers [Levine and Javan 1973; Clark and Lind 1974; Lind et al. 1974; Reits and Olbertz 1975; Olbertz and Reitz 1976; Kline et al. 1976], and Morikawa [1973] observed that it gives a greater electron density faster, and higher peak power, than xylene. However, Seguin et al. [1974] reported that benzene gave greater ionisation and their later results [Seguin et al. 1977] indicated that it may be more effective than tripropylamine in the 120 nm CO_2 window and hence better suited to small lasers. Additives that are detrimental to laser performance include water vapour [Denes and Lowke 1973], oxygen [Seguin et al. 1974; Bletzinger et al. 1975; Smith et al. 1975; McKen et al. 1976], carbon monoxide, nitrous oxide, nitrogen dioxide [Bletzinger et al. 1975; Smith et al. 1975] and carbon tetrachloride [Seguin et al. 1974]. Although Seguin et al. [1977] reported an increased ionisation with nitric oxide and Smith et al. [1975] observed increased power, Bletzinger et al. [1975] found that it decreases gain. The catastrophic effect of a trace of CCl_4, necessitating dismantling and cleaning of the system, was reported by Seguin et al. [1974].

Surface photo-electron contribution

The relative contributions to electron density of volume PI and photoelectric effect at electrode surfaces indicate that volume PI predominates [Cohn and Ault 1973; Judd and Wada 1974; Liberman and Partlow 1974]. Liberman and Partlow [1974] measured photon to electron yields for common electrode materials of 4×10^{-2} and related the relative importance of the two mechanisms to electrode spacing and impurity concentration with a crossover point of 10 $\mu g\ g^{-1}$ (ppm) at 3 cm spacing.

A3 ELECTRODE GEOMETRY

Main electrode shape

The diverse electrode configurations used are listed in Table A1, the designer's choice being dictated by the need to produce a uniform discharge in the active laser region, the assumption that a uniform field is a prerequisite for this, and the production of either a uniform discharge by empirically shaping the electrodes, a uniform field by basing the electrode design on profile models of Rogowski (see Cobine [1958], Bruce [1947] and Chang [1973]), or by using quasi-infinite plane electrodes [Schreiver 1972; Levine and Javan 1973]. The effect of electrode shape is discussed further in the subsection on gain profiles.

Pre-ioniser electrodes

As with main electrodes, many pre-ioniser electrode geometries have been used (Table A2). Generally, the distributed spark discharge, either in linear arrays [Richardson 1972; Browne and Webber 1976] or planar arrays [Richardson et al. 1973a, 1973b; Clark and Lind 1974; Kline et al. 1976; Denes and Kline 1977], is simple and effective. The planar arrays are arranged to irradiate the active volume parallel to the main field; the linear arrays irradiate transversely. Provided that the PI density is high, it appears that its distribution does not determine the gain distribution [Robinson 1976]. In vacuum, a 'sliding spark' along a dielectric surface between electrodes produces high currents at lower field intensities [Vodar and Astoin 1970]. Seguin and his co-workers, attributing the effectiveness of surface-gap automotive spark plugs for hard UV production to this and to their co-axial geometry, developed a 'plasma jet' source which operated satisfactorily on an input energy of 10 mJ [McKen et al. 1976]. Richardson [1974] described the function of the dielectric as producing capacitance 'between arcs' (i.e. between electrode sections) to reduce the requisite overall voltage. Browne and Webber [1976] earthed rods inside glass tubes to increase the capacitance to earth of each pin.

A4 ENERGY INPUT CIRCUITRY

The pre-ionisation circuit

Some aspects of the PI circuit can only be considered in conjunction with the main discharge circuit, and are discussed under that heading. Judd and Wada [1974] observed that qualitatively the product of the spark current and the delay between PI and the main discharge needed to exceed some critical value for satisfactory conditioning of the gas mixture. They deduced that input energy and not peak power was the important factor. Seguin and Tulip [1972] postulated that a low inductance circuit is necessary since increased hard UV emission was believed to result from high dI/dt. Later experimental results by Seguin et al. [1974] supported the need for low LC circuits. This was confirmed from spark emission spectrum measurements by McKen et al. [1976] which indicated that high current density and not rate of current rise was the controlling parameter.

The main discharge circuit

The discharge model of Egger et al. [1976] relates the optimum plasma homogeneity proportionally to the starting electron density; from this they deduced the necessity for a delay between the PI and main discharges. Other authors report optimum delay times, but satisfactory operation has been observed with delay times, determined accidentally by circuit parameters or deliberately imposed, of 70 ns [Robinson 1976], 100 ns [Burnett and Offenberger 1973], 100-160 ns [Pearson and Lamberton 1972], 300 ns [Kline and Denes 1975; Pavlovskii et al. 1976], $\geq$ 400 ns [Richardson et al. 1973], 500 ns [Morikawa 1977], approx. 1 μs 'not important' [Browne and Webber 1976], 1-3 μs [Dyer and James 1975], 2 μs [Pan et al. 1972], 2 μs ± 1 μs [Richardson et al. 1973], 2-5 μs [Judd 1973], and 'several μs' [Richardson 1974]. Table A3 lists relevant delay times against PI input energy parameters, where the data are available. No correlation is evident. Johns and Nation [1972] suggested that higher energies could be injected into the gas without arcing if the injection time were short compared with the time taken for the arc to bridge the gap, with calculated speeds between 5×10^6 and 3×10^7 cm s^{-1}. Kline et al. [1976] observed the onset of arcing at 4 μs in a 10 cm gap. With the addition of tripropylamine, no arcing occurred during the 12 μs discharge. Tulip et al. [1976] reported increased resistance to arcing with a 1 nF capacitor in parallel with the discharge. Bushnell et al. [1976] presented a model for this observation which attributed the improvement to higher electron density at the beginning of the current pulse. Seguin et al. [1972] reported that higher input energies were possible when the PI spark was in series with the main discharge, thus suggesting a sustaining effect.

A5 OPERATING CONDITIONS

The E/p relationship

In a $CO_2/N_2/He$ gas mixture in the ratio of 1:2:3, the transition to a self-sustained discharge occurs at an E/p of about 7 V cm^{-1} atm^{-1} [Judd and Wada 1974]. Richardson et al. [1973] gave the empirically-derived relationship

$$E = 27.8\ p^{2/3}\ \mathrm{kV\ cm^{-1}} \quad ,$$

where p is the maximum fractional partial pressure of CO_2 and N_2 for which reproducible uniform discharges are created, and is defined by

$$p = (p_{CO_2} + p_{N_2})/(p_{CO_2} + p_{N_2} + p_{He}) \quad .$$

There is evidence that roughened (e.g. sandblasted) main electrode surfaces assist in the production of uniform discharges [Schreiver 1972; Richardson et al. 1973; Reits and Olbertz 1975; Karasikov and Shamir 1976].

Pulse repetition rate (PRR)

Brown [1973] found that the major limitation on PRR was arcing due to the buildup of impurities, rather than gas heating. The flow rate required for his geometry was two complete gas changes per pulse.

A6 GAIN

High gain is a desirable attribute in all amplifiers. The need for uniformity of gain in a laser amplifier applies in the spatial sense as well as temporal (in this case, pulse-to-pulse). Gain measurements have been made on lasers employing both linear [Gibson et al. 1971; Robinson 1971] and helical [Robinson 1971] pin electrodes and solid electrodes of various geometries [Deutsch and Rudko 1972; Denes 1972; Richardson et al. 1973a, 1973b; Burnett and Offenberger 1973; Denes and Weaver 1973; Brown 1973; Judd and Wada 1974; Clark and Lind 1974; Robinson 1976; Denes and Kline 1977]. Gains generally vary between 1.2 to 5 per cent cm^{-1}, with uniformities over the active cross-section of a few per cent reported [Deutsch and Rudko 1972; Burnett and Offenberger 1973; Denes and Kline 1977]. The gain peaks a few μs after initiation of the discharge [Gibson et al. 1971; Robinson 1971, 1972; Deutsch and Rudko 1972; Burnett and Offenberger 1973; Denes and Weaver 1973; Judd and Wada 1974]. Robinson [1976] observed that the gain profile varies with electrode shape and separation, and with the applied voltage; with a particular electrode shape, the uniformity of the gain profile is dependent on field intensity. Denes and Weaver [1973] did not find this field intensity dependence; however, they found that the gain is determined primarily by the input energy and that the peak gain is proportional to CO_2 partial pressure. Burnett and Offenberger [1973] reported that the peak gain increased linearly with applied voltage over a range of gas mixtures.

A7 DESIGN MODIFICATIONS

The conclusions drawn from this study are as follows:

- Reliable laser operation with energies of a few joules per pulse and spatially uniform gains of a few per cent per centimetre can be achieved over a wide range of designs and operating conditions.

- Although some parameters for a particular laser design can be confidently stipulated in advance, others lack a sound basis for prediction and are best determined empirically.

The following planned design modifications to improve the existing laser are therefore proposed.

Laser tube

A new laser tube should be constructed from four 50 cm sections of 10 cm diameter acrylic tube. The increased diameter will allow the required active cross-section and PI electrode spacing. The modular construction will facilitate manufacture and assembly and permit rotation of each progressive main electrode pair through 90° to smooth out gain discontinuities at the electrode ends. Adaptors at the outer tube ends should accept the existing crystal holders.

Main electrodes

Convert to a 'double Rogowski' geometry with a 15 mm by 15 mm cross section and aluminium electrodes. Meticulous conformity to an ideal Rogowski profile is unnecessary.

Operating voltage

Choose a design centre of 25 kV to allow some tuning of the gain profile.

Pre-ionisation

Ultraviolet pre-ionisation should be provided by linear, distributed spark arrays on both sides of the active volume of each module. Spark discharges on a dielectric surface between stainless steel electrodes.

Arcing

Compare the performance of smooth and rough electrode surfaces.

Discharge circuitry

Use low inductance circuits of the simplest form initially, increasing their complexity only if it is necessary. The circuit shown in Figure A1 should be used as a starting point.

Gas mixture

The existing gas handling and purification rig will allow the removal of unknown impurities from the basic gas mixture and determination of the type and quantity of low ionisation potential additive best suited to laser operation. Note that this combined approach has not been reported elsewhere. The gas pressure and component proportions should be chosen for the best gain results.

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TABLE A1
ELECTRODE GEOMETRY

Configuration	Reference
Double Rogowski	Pearson and Lamberton 1972*; Deutsch and Rudko 1972*; Seguin et al. 1972; Grigoriu and Brinkschulte 1973; Richardson et al. 1973*; Burnett and Offenberger 1973; Richardson 1974*; Reits and Olbertz 1975; Karasikov and Shamir 1976; Olbertz and Reits 1976; Morikawa 1977; Eberhardt (AAEC private communication)
Rogowski/plane	Laflamme 1970; Pearson and Lamberton 1972*; Judd 1973; Judd and Wada 1974; Lind et al. 1974; Pavlovskii et al. 1976*
Double plane	Dumanchin et al. 1972; Pan et al. 1972; Schreiver 1972; Levine and Javan 1973; Cohn and Ault 1973; Brown 1973; Dyer and James 1975; Kline and Denes 1975
Double Bruce	Denes and Weaver 1973*; Browne and Webber 1976
Bruce/plane	Clark and Lind 1974
Double Chang	Robinson 1976
Empirically shaped	Kline et al. 1976; Denes and Kline 1977

*Approximate double Rogowski

TABLE A2
PRE-IONISATION ELECTRODE GEOMETRY

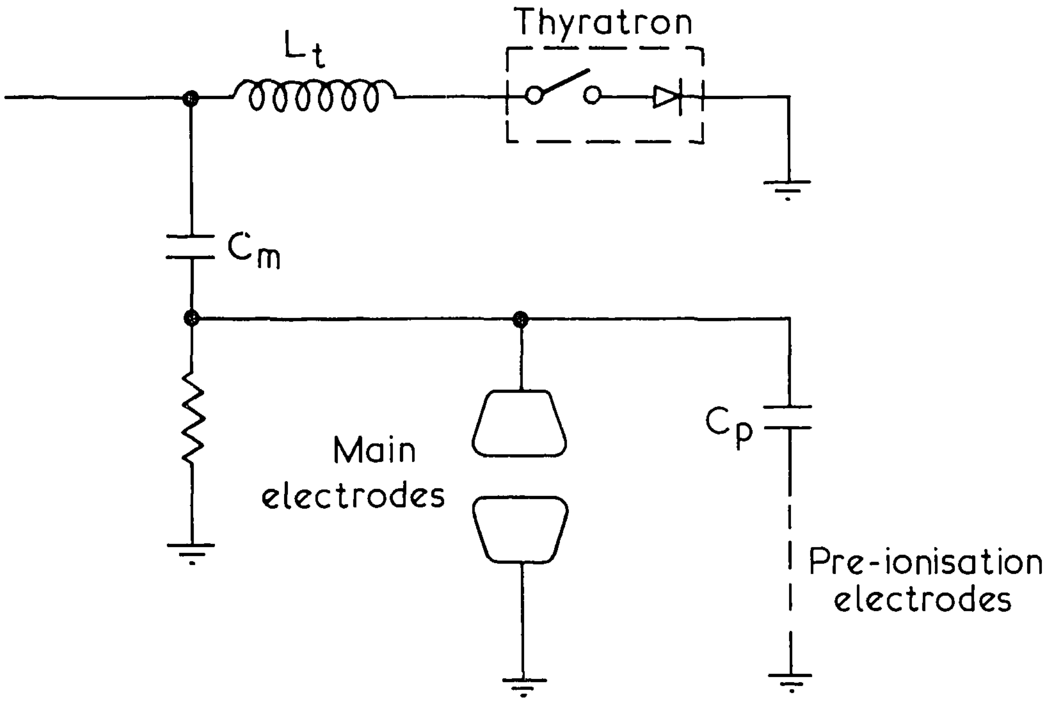
Configuration	Orientation to main discharge	Reference
Single wire	TS	Pearson and Lamberton 1972; Grigoriu and Brinkschulte 1973
Double wire	TD	Deutsch and Rudko 1972; Seguin et al. 1972; Reits and Olbertz 1975; Olbertz and Reits 1976
Multiple wires	P	Pavlovskii et al. 1976
Multiple wires in dielectric sheath	P	Pan et al. 1972; Brown 1973; Dyer and James 1975
Linear arrays of arc discharges between pins	P	Seguin and Tulip 1972; Cohn and Ault 1973; Morikawa 1977
	TS	Judd 1973; Tulip et al. 1976
	TD	Burnett and Offenberger 1973; Robinson 1976; Robinson and Hsieh 1977
Distributed arc on dielectric surface,		
linear	TS	Richardson 1974
	TD	Richardson 1974; Browne and Webber 1976; Eberhardt (AAEC private communication)
planar	P	Richardson et al. 1973a, 1973b; Clark and Lind 1974; Kline et al. 1976; Denes and Kline 1977
Stressed dielectric joints	TD	Denes and Weaver 1973
Others	TD	Levine and Javan 1973; Liberman and Partlow 1974; McKen et al. 1976

P = parallel
S = single
T = transverse
D = double

TABLE A3
PRE-IONISATION TO MAIN DISCHARGE DELAY

Reference	PI Input Energy ($J\ L^{-1}$)	Range, d (cm)	Normalised Input Energy ($J\ L^{-1}\ d^{-2}$)	Delay
Robinson 1976	34.6	9-12	0.35	70 ns
Burnett and Offenberger 1973	16.6	10	0.17	100 ns
Kline and Denes 1975	0.36	5	0.014	300 ns
Browne and Webber 1976	385	14	1.96	~1 μs 'not important'
Judd 1973	3	10	0.03	2-5 μs
Richardson 1974	222	5*	8.9*	'several μs'

*Not explicitly stated



L_t = Thyratron anode inductor, 12 μH

C_m = Main energy storage capacitor, 0·05 μF

C_p = Pre-ionisation capacitors total, 8 nF

FIGURE A1. TENTATIVE DISCHARGE CIRCUIT