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SOME ASPECTS OF LASER DESIGN

BY

S.S. WISEALL B.SC.

A MASTER OF PHILOSOPHY THESIS

SUPERVISOR: DR. D.C. EMMONY

Submitted in Partial Fulfilment of the Requirements for the Award of Master of Philosophy of the Loughborough University of Technology

APRIL 1982

Department of Physics

c by S.S. WISEALL 1982
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SUMMARY

This project was concerned with the design, construction and testing of a low powered carbon dioxide laser and a discharge pumped XeCl excimer laser. The thesis is presented in two separate parts; section A covers the carbon dioxide laser and section B covers the excimer laser. The reason for this separation is that the common overlap of design features and operation is very small.

A low power carbon dioxide laser was designed with possible industrial applications in mind. The final prototype produced a continuous wave output of 15 Watts at 10.6 μm in the T.E.M\textsubscript{00} mode. The power stability was about ±7% over an eight hour period. Further development of this laser by Rofin Ltd has led to a fully commercial 50 Watt, T.E.M\textsubscript{00} mode carbon dioxide laser.

An ultra-violet arc preionized excimer laser was designed for discharge operation with a hydrogen chloride (halogen donor), xenon and helium (buffer gas), gas mixture. Optimization of the geometry of the discharge head including the electrode profile and preionizing arcs led to XeCl (\(\lambda = 308\)nm) laser emission. The dependence of the output energy on the partial pressures of the HCl:Xe:He gas mixture and the capacitor charging voltage was investigated. A peak output of 9mJ was observed at a charging voltage of 28kV and helium pressure of 2.7bar.
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SECTION A

THE CARBON DIOXIDE LASER
INTRODUCTION

Since the first observation of laser action by Maiman in 1960\(^1\) much effort has been devoted to developing new types of lasers. One of the most important results of this work has been the carbon dioxide laser, discovered in 1964 by Patel\(^2\). In 1966 the first commercial industrial CO\(_2\) laser became available with an output power of 100 watts. Since that period the CO\(_2\) laser has developed rapidly to become perhaps the most widely used laser in the industrial environment. The prime reason for the importance of the CO\(_2\) laser is that it is the only laser capable of producing continuously and efficiently powers of up to several kilowatts. Two further contributing factors for its rapid development are the lasing wavelength of 10.6\(\mu\)m and the basic simplicity and availability of materials required to build a low-power device.

Industrial applications of the CO\(_2\) laser soon became apparent when it was considered as a precisely controllable, coherent thermal source that could be focused to produce very high power densities. Many non-metallic materials absorb heavily at 10.6\(\mu\)m and consequently material processing can be achieved at relatively lower output powers.

This section of the thesis on the CO\(_2\) laser considers some of the design principles of low power CO\(_2\) lasers and reviews some of their applications for industrial purposes. In particular, low power CO\(_2\) lasers are often used in the industrial environment for cutting, drilling or marking of non-metals. Maintaining quality control of the cut edge, hole profile or marking line is obviously very important. These factors are related to maintaining a stable, long-term output power in the fundamental T.E.M\(_{00}\) mode.
and this must be kept in mind when designing a CO$_2$ laser for such applications.

In association with a commercial company, a small low-power CO$_2$ laser has been built using a relatively new mouldable composite material (M.C.M.) to form the laser head. The device was characterized, with particular interest in the output power stability.
1. CO₂ EXCITATION AND DECAY MECHANISMS

The active medium of the carbon dioxide laser is an electric glow discharge in a mixture of carbon dioxide, nitrogen and helium. Laser emission at 10.6μm occurs from transitions between two low lying vibrational-rotational energy levels of the CO₂ molecule.

The lowest lying vibrational energy levels of the CO₂ and N₂ molecules in their ground electronic states are shown in figure 1. Since the CO₂ molecule is triatomic it has three distinct modes of vibration, shown in figure 1. The vibrational behaviour of the CO₂ molecule is described by three quantum numbers n₁, n₂ and n₃ which give the number of quanta in each vibrational mode. The corresponding level is therefore designated by these three quantum numbers written in the order n₁, n₂, n₃. For example, the 0₁°O level corresponds to an oscillation in which there is one vibrational quanta in mode 2, the bending mode. The superscript on the bending quantum number arises because the bending vibration of the CO₂ molecule can occur in two orthogonal planes, i.e., it is doubly degenerate.

The upper laser level, 00°1 is pumped by two very efficient processes. The first is direct electron impact with ground state CO₂ molecules. The collision process favours formation of the asymmetric stretching mode over the symmetric and bending modes and furthermore, the 10°0 and 0₂°0 levels de-populate relatively quickly to the 01₁°0 level. The second pumping process is resonant energy transfer from the N₂ molecule. Excitation of the N₂ molecule from the ground state to the V = 1 state by electron impact is a very efficient process, and the V = 1 level is metastable.
ENERGY LEVEL DIAGRAM FOR THE CARBON DIOXIDE LASER

GROUND STATE OF CO$_2$ (00$^0$0)

GROUND STATE OF N$_2$

FIGURE 1

ENERGY LEVEL DIAGRAM FOR THE CARBON DIOXIDE LASER
Collisions of the second kind occur between metastable \( \text{N}_2 \) molecules and ground state \( \text{CO}_2 \) molecules leaving the \( \text{CO}_2 \) molecule in the \( 00^01 \) upper lasing level. This collision and energy transfer process is very efficient because of the energy difference (\( \Delta E = 18\text{cm}^{-1} \)) between the \( 00^01 \) level of the \( \text{CO}_2 \) molecule and the \( V = 1 \) level of the nitrogen molecule.

The next point to consider is the decay rates of the various levels shown in figure 1. The lifetime of the various levels is limited by collisions, because the radiative lifetimes at these wavelengths are quite long. The lower level transitions \( 10^00 \rightarrow 02^00 \), \( 10^00 \rightarrow 01^10 \), and \( 02^00 \rightarrow 01^10 \) are very fast. It follows that these levels reach thermal equilibrium very quickly. This leaves the decay rate from the \( 01^10 \) level to the ground state level \( 00^00 \) to consider. If this decay were slow, it would lead to an accumulation of molecules in this state and consequently the \( 10^00 \) and \( 02^00 \) levels because they are in thermal equilibrium with each other. In this case the \( 01^10 \) level would be described as producing a bottleneck.

The lifetime of the \( 01^10 \) level is greatly influenced by the presence of helium and this is the main reason for its use. It does have the further advantage of possessing a high thermal conductivity. It helps to keep the \( \text{CO}_2 \) molecules cold by conducting heat away to the walls. A low \( \text{CO}_2 \) temperature is necessary to avoid population of the lower level by thermal excitation. Cooling of the discharge tube is normally employed to avoid thermal expansion of the laser cavity and to remove heat generated by the glow discharge; it has the added bonus of helping to maintain a low \( \text{CO}_2 \) temperature and consequently increase the output power.
PRINCIPLES OF OPERATION

2.1 The Electrical Discharge

The principle of operation of a continuous wave carbon dioxide laser is shown in figure 2. The discharge arrangement is usually termed a longitudinal discharge, the glow discharge being centred along the same axis as the laser cavity. With these CO₂ lasers there is a maximum power that can be extracted per unit discharge length, which is approximately 50Wm⁻¹ independent of the tube diameter. This figure assumes an optimised discharge current, gas pressure and gas mixture. The laser gas mixture is continuously passed through the discharge region to replace harmful dissociation products formed by the glow discharge, particularly carbon monoxide. In some industrial lasers the gas mixture is sealed off but continuously re-cycled having passed over a catalyst to re-form carbon dioxide from the carbon monoxide. A typical overall pressure of the gas mixture may be 20mbar in the approximate ratio 15:2:1 for helium, nitrogen and carbon dioxide respectively. When a sufficiently high voltage is applied to the anode the gas breaks down and a glow discharge is formed between the two electrodes. The voltage required for gas breakdown, usually termed the striking or breakdown voltage, depends upon the product of the inter-electrode separation and the gas pressure and mixture (Paschens Law). Its value for a typical 1m CO₂ laser will usually be in the range 20 - 30kV. Once the gas has broken down the voltage required to sustain the discharge reduces to the maintaining voltage. The current/voltage characteristic of the glow discharge in this region of operation has a negative slope, consequently some current control on the power supply must be included. This can be done simply be using a ballast resistor, the value of
FIGURE 2

SCHEMATIC DIAGRAM OF A CO₂ LASER
which is such that the overall resistance, glow discharge and ballast resistor is positive. High power dissipation ballast resistors are required since currents in the range $20 - 50\text{mA}$ and resistances of the order $10 - 80\text{k}\Omega$ may be required. If the ballast resistance is too high the maintaining voltage available at the anode and the overall efficiency of the laser are reduced.

2.ii CO$_2$ Laser Cavity Design

Before discussing the optical cavity of CO$_2$ lasers in particular it will be instructive to consider the important parameters of the general optical cavity. Consider figure 3, two mirrors with radii of curvatures $R_1$ and $R_2$ separated by a distance $L$. Geometrical ray analysis of a paraxial light ray bouncing between the two mirrors of figure 3 and staying near to the laser axis leads to the familiar stability diagram, figure 4. The stability criterion for confinement of the light ray can be expressed as

$$0 < g_1 g_2 < 1$$

where

$$g_2 = 1 - \frac{L}{R_2} \quad \text{and} \quad g_1 = 1 - \frac{L}{R_1}$$

Diffraction analysis of the general optical resonator was first carried out by Fox and Li$^6$. Using the Fresnel-Huygens diffraction approach they calculated the stable transverse field amplitude after many passes between the mirrors. Regions of high and low loss were found to exist as defined by the stability diagram, figure 4. The transverse field amplitudes resulting from the calculation are Hermite Gaussian (rectangular case) or Laguerre Gaussian (circular case). The lowest order solution is the spherical Gaussian. This distribution is usually termed the T.E.M$_{oo}$ mode (Transverse Electromagnetic mode).
Figure 3

General Optical Cavity

Mirror Separation - L
RADIUS OF CURVATURE OF MIRROR 1 - R₁
RADIUS OF CURVATURE OF MIRROR 2 - R₂

Figure 4

Stability Diagram

\[ g₁g₂ = -1 \]
\[ g₁ = 1 - \frac{L}{R₁} \]
\[ g₂ = 1 - \frac{L}{R₂} \]
The suffixes indicate the mode order. The field variation for this lowest order mode is given by

\[ U(x,y) = (2/\pi)^{1/2} \frac{1}{W} \exp \left[ -\frac{j\pi}{\lambda} \left( \frac{x^2 + y^2}{R} \right) \right] \exp \left[ -\frac{(x^2 + y^2)}{W^2} \right] \tag{2.3} \]

Normalising factor \hspace{1cm} Spherical wave phase factor \hspace{1cm} Gaussian amplitude distribution

Where \( x, y \) are the space co-ordinates orthogonal to the direction of propagation

\( R \) is the radius of curvature of the wavefront

\( \lambda \) is the wavelength

and \( W \) is the spot size

Equation 2.3 represents a transverse wave with a spherical phase factor variation and a Gaussian transverse amplitude variation. The field amplitude variation from equation 2.3 can be simply expressed as

\[ |U(x,y)| = (2/\pi)^{1/2} \frac{1}{W} \exp \left[ -\frac{(x^2 + y^2)}{W^2} \right] \tag{2.4} \]

The spot size \( W \) can be interpreted as expressing the half width of the amplitude distribution at any point. The peak field amplitude for this mode occurs on the optical axis. The minimum spot size along the axis is known as the beam waist \( W_o \), its position and the spot sizes at the mirrors can be related to the \( g \) parameters defined earlier.

\[ \text{Beam waist } W_o = \left| \frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2g_1 g_2)^2} \right| \left( \frac{\lambda^2 L^2}{\pi^2} \right)^{1/2} \tag{2.5} \]

\[ \text{Spot Size, Mirror 1 } W_1^2 = \frac{L \lambda}{\pi} \left| \frac{g_2}{g_1 (1 - g_1 g_2)} \right| \tag{2.6} \]
A schematic diagram of the variation in spot size for two given mirrors is shown in figure 5.

The frequency separation of the transverse and longitudinal modes can be calculated from the requirement that the round trip phase shift must be a multiple of $2\pi$. It can be shown that these frequencies are:

\[ f_{mnq} = \left| q + (n+m+1) \frac{\cos^{-1}(g_1 g_2)}{\pi} \right| \frac{c}{2L} \]

Where $c$ is the velocity light and $f_{mnq}$ is the frequency of oscillation of the $m$, $n$th transverse mode and the $q$th longitudinal mode. The frequency separation of the longitudinal modes are given by

\[ \Delta f_{\text{LONG}} = \frac{c}{2L} \]

The frequency separation of the transverse modes are

\[ \Delta f_{\text{TRANS}} = \left( \frac{\alpha}{\pi} \right) \Delta f_{\text{LONG}} \]

where $\alpha = \cos^{-1}(g_1 g_2)^{1/2}$

Thus, as the mirror curvature is increased at constant $L$, the frequency separation of the transverse modes for a given axial mode increases.

The frequency separation of the transverse and longitudinal modes of a CO$_2$ laser is generally not so important for industrial
FIGURE 5

PLANO-CONCAVE LASER CAVITY

BEAM WAIST $w_0$ OCCURS AT THE PLANE MIRROR END

$R_1 = 20m$ \hspace{1cm} $R_2 = 00$
$g_1 = 0.7$ \hspace{1cm} $g_2 = 1$
$w_1 = 6.5mm$ \hspace{1cm} $w_2 = 5.5mm$
applications. This is because the laser output is usually used as a controllable thermal source. However, longitudinal mode control is a well-established technique using piezo electric transducer (P.Z.T.) controlled mirror mounts and a feedback mechanism. Longitudinal mode control is often required in the scientific world where precise stable output frequencies are required.

These comments concerning the general optical cavity have important applications in laser design. The optical gain of each transverse mode determines whether it will appear in the laser output. The output from a CO$_2$ laser will normally be multi-mode and also vary in time. The advantage of a multi-mode output is that the discharge volume is a maximum and consequently the output power is also a maximum.

Grease, dust marks or inhomogeneities on the laser mirrors can affect the gain of a particular mode. Thermal expansion and/or mechanical vibrations of the laser cavity can also affect the mode output. The gain of a particular mode can therefore vary in time and produce the multi-mode output often observed. To produce an output in the T.E.M$_{00}$ mode a limiting aperture is placed inside the laser cavity. The intensity profile of the higher order modes is distributed relatively further from the laser axis than the T.E.M$_{00}$ mode. Consequently, the limiting aperture or mode stop allows only the T.E.M$_{00}$ mode to oscillate because this mode is confined most tightly to the laser axis. It has been found experimentally that the diameter of the mode stop should be approximately $(3.5 - 4.0)W$, where $W$ is the spot size at the position of the mode stop. Using the glass discharge tube as a mode stop is not recommended because internal reflections off the glass wall tend to produce a noisy output.
To maintain the T.E.M\textsubscript{oo} mode output in time the mirror mounts are usually rigidly held in place and the cavity constructed such that thermal expansion effects are minimal.

The main disadvantage of the T.E.M\textsubscript{oo} mode over a multi-mode output is the reduction in discharge volume and consequently power output. However, there are a number of advantages for the CO\textsubscript{2} laser to operate in the T.E.M\textsubscript{oo} mode. For a given output, the power density at the focus of a lens is a maximum for the T.E.M\textsubscript{oo} mode. Using a collimated beam of spot size $W$ and a lens of focal length $f$ the spot size at the focus is given by

$$w = \frac{f\lambda}{\pi W}$$

The focusing lens should have a diameter $d > 3W$ so that greater than 99% of the incident energy is transmitted. The very high attainable power levels at the focus mean that welding and cutting of many materials including metals is possible. A further advantage of the T.E.M\textsubscript{oo} mode is that the transverse intensity distribution at the lens focus is of the same form as that incident on the lens. There are no troublesome secondary diffraction peaks which may cause poor quality edge definition in marking and cutting applications. The final advantage of the T.E.M\textsubscript{oo} mode is its low divergence compared to higher order modes. Propagation over long distances without loss of energy density is important for certain applications, e.g., range finding, metrology, and in situations where the laser head is remote from the workpiece.

The final aspect to consider for laser cavity design is choice of mirrors, curvatures and materials used. To maintain the cavity in the low loss region of figure 4 a number of configurations are possible depending upon the relative values of $g_1$ and $g_2$. The type of cavity
often used in practice is shown in figure 5, a concave 100% reflector and a plane output coupler. The separation of the mirrors $L$ is usually chosen to be somewhat less than the radius of curvature of the 100% reflector. There are a number of reasons for this choice of cavity. One is that a plane mirror is easier to manufacture and is therefore cheaper. Another reason is that for $L < R_1$, a good compromise exists between maximising the modal volume and making the output least sensitive to mirror tilt. The 100% reflectivity of the rear reflector for CO$_2$ lasers is achieved by two methods: i) using thin metal films such as Gold, ii) using multi-coated dielectrics typical substrates may be Zinc Selenide, Galium Arsenide or Germanium. The optimum choice of reflectivity of the output coupler depends upon the ratio, laser length/diameter$^8$. The required reflectivity is achieved by again using multi-coated dielectrics, often Zns is used as a substrate. The output coupler may also have an anti-reflective coating on the output side to avoid reflections from this face. If a polarised output is required an element may be introduced into the laser cavity set at Brewsters angle $\theta$, see figure 2. Only oscillations polarized in a given direction will oscillate inside the cavity.
3. CO₂ Laser Applications

The CO₂ laser is probably the most widely used laser for industrial applications. Its output at 10.6μm acts as a very versatile, precisely controllable thermal source. The high wall-plug efficiency (10 - 30%), its scaleability with a continuous output from mW - 20KW, and the ability to electronically pulse the discharge make the CO₂ laser a particularly useful tool.

Industrial applications of the CO₂ laser are usually in one of the following areas: laser heat treatment, material processing... including cutting, drilling and marking, and finally welding.

3.1. Laser Heat Treatment

The most common requirement is to harden surfaces of components such as gears, rotating shafts, and bearing surfaces etc. The hardened alloy is produced from a phase transformation at the surface when it is suitably heated and quenched.

The laser beam is scanned across the surface to be treated at fairly high speed. Scanning takes place in the atmosphere at long working distances from the source. The beam can be manipulated and directed into bores and conventionally inaccessible regions. Dwell times of the order of a few hundred milliseconds are all that is required. The depth of heat conduction and the surface temperature increases with dwell time. The beam size, power, and dwell time are all adjustable to allow the user to produce well-defined hardened zones with well-defined depths. The heat is applied quickly so that virtually no distortion takes place. The rapid quenching is achieved simply by taking the laser beam off the component.
and allowing bulk conduction into the base of the material. Below their melting point metals are poor absorbers of the infra-red energy. An absorbing coating is therefore required for efficient energy coupling of the laser beam into the component to be treated. Fortunately, such coatings are easily applied. Some examples are:

a) Polycrystalline tungsten
b) Cupric oxide
c) Colloidal graphite
d) Manganese phosphate

or any normal chemical blackedizing treatment\(^9,10\). One advantage of the use of coatings is that with selective application selective hardening results. With a suitable coating absorbivities of about 90\% can be achieved.

An important aspect to consider about the use of a CO\(_2\) laser for surface treatment is one of economics. The output power requirements of the CO\(_2\) laser for these surface hardening applications is usually in the range 1 - 10KW. Such lasers are expensive pieces of capital equipment. It has been found that in many areas the cost of using laser systems compares favourably with other surface hardening methods such as nitriding and induction heating\(^11\).

In summary, the main advantages of the CO\(_2\) laser as an industrial tool for surface treatment are:

i) No part distortion is produced due to the heat treating process,
ii) Wear surfaces can be produced in localised regions,
iii) Treatment can be performed on the finished component after assembly,
iv) No clean-up after treatment is required,
v) Economically the process compares favourably with more established methods.
Surface hardening with a CO$_2$ laser is used in the automotive industry, especially on automated production lines. Ford, Fiat, and General Motors have used CO$_2$ lasers for surface hardening of valve seats, cams, crankshafts, cylinder walls and valve guides. An interesting industrial application employs a 1KW CO$_2$ laser for the production of wear stripes on a cast iron power steering gear housing manufactured by General Motors. Instead of heat treating the whole inner bore surface which is subject to sliding friction, five equi-distant tracks approximately 2mm wide are produced on the cylinder wall.

Surface cladding or coating is often employed when localised corrosion or wear resistance is required on a component having a composition not inherently capable of producing these properties. This technique does not involve a phase transformation followed by rapid quenching but the diffusion of additives into the surface.

A variation of the surface cladding technique occurs in the semiconductor industry. One of the essential operations in implantation doping of semiconductors is thermal annealing of the doped layer. This is essential for the restoration of the crystal structure disturbed by the ion bombardment of the original single crystal, and for the electrical activation of the implanted impurity. Conventional annealing is carried out in a furnace but it has been demonstrated that pulsed CO$_2$ lasers can be used to locally surface anneal just above the implanted layer$^{12}$. This technique offers great potential for the fabrication of integrated circuits.
3.ii Materials Processing

Laser machine tools provide advantages over their mechanical equivalents in a number of areas. They include:

i) No use of cutting lubricants, no tool wear, or tool slippage on curved surfaces,

ii) No distortion due to mechanical and thermal forces,

iii) The cutting action can involve very narrow kerf widths and consequently material wastage is minimal,

iv) The workpiece need not be rigidly clamped; and often with the aid of numerically controlled tables high potential accuracy is achieved.

The CO₂ laser is an ideal tool for automated processes requiring large numbers of small high quality and accurately positioned holes. The same argument applies to small radii external profiles, and slots, or closely spaced cuts.

The required output powers for a CO₂ laser in material processing depends upon the material to be processed and the cutting or drilling rate. Cutting thin metal sheets (<8mm) the output power requirement is in the range 1 - 5KW continuous. For many organic materials, plastics, paper, rubber, etc., the required output power is proportionately less because of their high absorption at 10.6μm, a maximum output power may be of the order ~0.5 - 1.0KW continuous. Cutting and drilling thin paper and plastics the output power required will usually be less than 200W continuous.

Mention has already been made of the advantage of a pulsed
output reducing thermal distortion. For drilling and cutting purposes there are other useful aspects of a pulsed output. The first is to operate the laser in what is termed the 'Enhanced Pulse Mode'. The output from a pulsed CO₂ laser consists of a leading edge spike up to ten times the average continuous wave power. Enhancement of the peak pulse amplitude by this factor depends upon optimising the pulse length, pulse rate, and maximum discharge current. This spike is used extensively for breaking down the surface reflectivity of metals very rapidly, and allowing the rest of the available energy to be efficiently coupled into the molten surface. In many plastic materials high-speed, high-density hole drilling with a single pulse per hole can be accomplished. When drilling holes at such high speeds it may be desirable to eliminate the tail of the pulse in order to prevent elongation of the hole on the entrance side after the pulse has finished penetrating the material. By optimising the gas mixture the tail of the pulse can be reduced without affecting the hole diameter where the pulse penetrates through completely.

A coaxially flowing gas jet surrounding the laser beam near to the work surface is often used in cutting applications. The gas jet has a number of useful purposes. The material is rapidly brought up to its melting point and the melt blown out of the cut zone. The gas removes vapourised products and prevents oxidation of the cut edge. The gas also prevents the reflection of vapourised material onto the back face of the focusing lens. If the vapourised products remain in the vicinity of the cutting zone an ionised plasma may form, the majority of the incident radiation would then be absorbed by the plasma preventing efficient energy coupling into the material. The gas jet helps to prevent plasma formation. An inert gas or air is used for cutting materials which are reactive with
oxygen (i.e., no exothermic reaction is produced) e.g., most non-metals, aluminium, stainless steel, nickel alloys, etc. For carbon steels and titanium alloys, oxygen is used to sustain an exothermic reaction between the gas and the rapidly heated metal. The gas assists in blowing the melt from the cut and has the advantages mentioned above, one further advantage is that the exothermic reaction can contribute up to 50% of the energy for the cutting process.

To appreciate the versatility of the CO₂ laser for material processing a few applications will now be considered.

3.ii.a Drilling

The CO₂ laser has been used to drill holes in many non-metallic materials such as polystyrene, acrylic, silicone, perspex and mylar. Holes produced from a single pulse have been applied to aerosol valves, spray nozzles and teats on babies' bottles. Perforating involving a high line density of small holes is an ideal example and has been applied to cigarette papers, and printed circuit boards. The CO₂ laser has also been used to drill ceramic materials.

3.ii.b Cutting

The CO₂ laser has been used in the suit manufacturing industry. The information about the suit to be made is entered into a computer which then steers the focused laser beam over the cloth and cuts out the suit. A major advantage with this technique is that the cloth edges are sealed, preventing fraying. This sealing action also occurs when other man-made materials, such
as nylon, are cut. The CO₂ laser has also been used as a laser scalpel in the medical field. The laser beam acts as a very fine scalpel and has the advantage of cauterising the wound as it cuts. It is often used to vapourise cancerous cells in places where access is difficult. The CO₂ laser has been used to cut glass and quartz tubes to precise lengths at high rates of production. The tube ends are left smooth and stress free. Many thin metals can be cut with complicated profiles, good quality parallel sided cuts mean that edge clean-up is minimal. Paper cutting at very high rates is another application. It eliminates the problem of debris associated with mechanical methods and produces a clean, smooth, narrow cut with no paper dust. The carton industry has used numerically controlled lasers to manufacture die boards that are used to stamp cartons and boxes.

3.ii.c Marking

A particularly interesting application of the CO₂ laser is flexographic laser engraving. The equipment is designed as a whole system. An optical scanner reads the artwork, detecting changes in the reflected light. The CO₂ laser is modulated by the signal from the scanner which selectively vapourises rubber away from the roller or plate, leaving a raised image that corresponds to the artwork image. One commercial system has a resolution of about 100 lines/inch. This is limited because the modulation of the CO₂ laser beam is achieved by pulsing the laser discharge on and off. The limiting frequency for this type of modulation is about 5kHz. A much higher resolution commercial system is available for reproducing high quality pictures for magazines etc. It involves modulation at frequencies up to 200kHz and at power levels up to 200W. Electro-
optic modulators capable of this performance are not commercially available. The required high power modulation is achieved by using an oscillator-amplifier combination with an electro-optic modulator inter-dispersed between the two.

For good quality printing rollers the CO\textsubscript{2} laser must have an extremely good output power and mode stability. A feedback signal and computer is usually involved in making the whole system very versatile and fast.

A similar but not so complicated laser engraving process is that of engraving pictures in wood for trophies, plaques and other novelty items. Marking with a CO\textsubscript{2} laser has also been done in the plate manufacturing industry. The master plate is engraved with the required pattern and the surface relief image is used as a 'stamp' for other plates. The main advantage is the time gained in producing the master plate.

3.ii.d Welding

The high absorption coefficient of many plastics means that sealing and welding these materials can be performed at very high speeds. Metal welding is accomplished at power densities in the range $10^6$ - $10^8$ W cm$^{-2}$. At these power densities metals can become molten and welded. At such power densities, the average power is usually in excess of 500W and more typically 1 - 2kW. The laser can be operated in a c.w. (continuous wave), or enhanced pulse mode. The enhanced pulse mode makes more use of the beam, but at a slower welding speed. Once the enhanced
pulse has broken the surface down, rapid power ramping downwards may be required to avoid vapourisation. At high average powers and with reactive materials a low pressure inert gas shroud is often employed.

The laser parameters can be optimised to suit a particular material. One of the most important material parameters for lasing welding is the thermal diffusivity. A low value of thermal diffusivity means that heat does not penetrate well into the material. A high thermal diffusivity can cause problems by allowing rapid removal of heat from the surface. Effective melting (and hence welding) with lasers depends on the propagation of a fusion front through the sample during the time of interaction, at the same time avoiding vapourisation on the surface. This process of welding is usually termed conduction welding. The pulsed mode has the advantage of a greater weld penetration for a given average power up to some threshold level of about 500W. Above this level only greater continuous power will suffice. The weld penetration depth can be increased by a longer dwell time with a continuous wave laser. This would however result in a slower weld speed and larger heat affected zones.

For deep penetration welds, multi-kilowatt c.w. CO₂ lasers are used. The maximum single pass penetration depth in steel is about 15 mm for the very high power lasers (~20KW). The high power beam is absorbed very rapidly, as in conduction welding, but is of sufficient power to vapourise material below the surface and near to the beam centre, without emitting it explosively. The high pressure vapour pushes the molten material to one side and an equilibrium condition arises where the vapour just prevents the
melt from collapsing. If a relative motion is now performed
between the laser and workpiece, at a suitable speed, then the
vapour keyhole advances whilst the melt behind the keyhole trail
solidifies to form the joint. This welding process is often
termed keyhole welding. Again, an inert gas shroud is often
employed to help increase the energy coupling into the metal.

Many of the advantages for laser welding are the same as
those for material processing and surface treatment. They can be
summarised as:

i) Flexibility,

ii) The non-contact nature of the process,

iii) The possibility of using it in a fully automatic system,

iv) The ability to produce welds near to heat sensitive
    components due to the small heat affected zone,

v) The faster weld speed compared to the electron beam
    method (which requires a vacuum),

vi) The ability to weld very small delicate items by using
    a small focused spot size,

vii) The ability to weld dissimilar metals.

The following table lists existing and potential applications
together with the salient characteristics being exploited.
WELDING APPLICATION

Dissimilar metals e.g. saw blade manufacture, fixing of valve seat inserts

Fabrication of stainless steel components, e.g. washing machine drums, food bowls and trays

Fabrication of electrical cabinets

Automotive components and body parts

Pressure vessel fabrication

Tube to tube joining

Tube to tubeplate joining

CHARACTERISTIC EXPLOITED

Minimal thermal disturbance

Fast, cosmetically acceptable

Hermetically sealed enclosures required

Fast, minimum distortion

Potentially high integrity and reproducible
3.iii Infra-red Holography

Holographic interest within the department stimulated the possibility of CO$_2$ laser holography. A non-contact optical interference method for comparing a 'master' component and a mass-produced item is difficult to perform in the visible region. This is because reproducing machined items to $\lambda/10$ tolerances is too difficult. However, the CO$_2$ laser wavelength of 10.6$\mu$m is much more amenable as a coherent source. At 10.6$\mu$m a greater difference tolerance could then be accepted between a holographic image and an almost identical real object. This technique would have possible applications for automatic quality control. The principle of decreasing the information content of an optical image has been successfully done in the visible range by the technique of speckle interferometry. This method can be used to look at the modal patterns of vibrating surfaces in real time.

A literature review of the current interest in CO$_2$ laser holography was therefore performed. The results of the survey can be classed into two main areas:

i) The formation and application of a phase reflective hologram for efficient material processing.

ii) The search for a suitable recording technique - this involves computer generated binary holograms, direct and indirect recording methods.

A reflective hologram is generally used because relatively few materials transmit at 10.6$\mu$m and for material processing the power involved are usually quite high. A transmission hologram
would therefore involve some absorption and possible damage to the hologram itself. The basic idea is to use a CO$_2$ laser beam as the reference beam onto a holographic plate. Reconstruction of the image recorded on the hologram occurs. The real image from the reflection hologram can be projected onto a work surface. Such a system holds promise as a means of performing complex material processing applications without the motion of the workpiece or laser. Often a large part of the capital cost of any laser processing system is the numerically controlled equipment needed to steer the beam or workpiece.

One clever technique was introduced by Sweeney et al.$^{15}$ and is illustrated in figure 6. The first diffracted order of the phase reflecting hologram is the output beam; the zero-order reflected beam is returned to the cavity to provide the necessary feedback. One disadvantage of using a holographic element of this type is that if the pattern on the workpiece is very complex or large, the resultant energy density in the projected pattern may be too low to perform the required material processing operation. An alternative method, again suggested by Sweeney et al.$^{16}$ is illustrated in figure 7. A holographic one-dimensional scanner will diffract a laser beam into a single spot that will scan over the desired pattern as the scanner is translated.

The most difficult problem is that of the recording technique used to form the hologram. There are a number of advantages in constructing a reflective holographic element as a computer-generated hologram. A digital computer is used to plot an appropriate fringe pattern which will cause the laser beam to be diffracted in the appropriate way. The main advantage of this technique is that a recording material sensitive to 10.6$\mu$m is not needed. The computer
Material processing with a holographic output coupler for a CO₂ laser

Pattern traced by focused beam

One dimensional holographic scanner
plot of the binary interference pattern is photographically reduced and a transparency formed. This is then used as a mask in a photo-resist technique\(^{15}\), resulting in a pattern with the required surface modulation. The surface is then coated with a reflective material such as aluminium to produce a phase reflective hologram.

Mention has already been made of the problem of recording an interference pattern at 10.6\(\mu\)m. Such a wavelength is too long to produce photoionization used in normal photographic recording materials. The direct recording technique usually involves absorbing thermal energy directly and to induce a spatially distributed temperature field on a material surface. This temperature field corresponds to the maxima and minima of the interference pattern. The temperature distribution is used to produce a physical or chemical change which produces a permanent recording.

One recording method involves using a c.w CO\(_2\) laser and the thermochromic recording material, Cu\(_2\)HgI\(_4\), cuprous mercuric iodide\(^{17,18}\). It changes colour abruptly at a well-defined phase transition temperature. There is also a hysteresis curve associated with this colour change which enables the recorded pattern to be preserved. Regions of constructive interference heat up the film to a higher temperature than regions of destructive interference. Each point on the film then cools down along its corresponding hysteresis curve. This results in a recording of surface reflectance proportional to the temperature variation. It is then photographed to produce a transparency and processed as described previously. This type of recording method has a number of problems - these can be considered as maintaining a uniform bias temperature, an awkward
second processing stage and the non-linearity of the recording process. The awkward second processing stage can be eliminated by using a high power CO$_2$ laser and a thin bismuth film as a recording material$^{19}$. Localised high temperature regions evaporate the bismuth film leaving a surface modulation corresponding to the interference pattern. Over-coating with a gold or aluminium layer produces the required phase reflective hologram. Similar evaporative techniques have involved using thin films of takiwax with xylene$^{20}$, and wax and gelatin films$^{21}$.

In view of the lack of a suitable, easy-to-use, holographic recording material at 10.6μm, the holographic-image real-object comparison idea mentioned at the beginning of this section becomes rather impractical.
Having discussed some of the CO₂ laser applications it is now possible to consider the main design principles required for the construction of a small c.w, low power CO₂ laser. Such a laser will have a length of about one metre, and a c.w power output of about 50W. Its probable use in industry would be for cutting and marking non-metallic materials such as plastics or wood. Longitudinal mode control with piezo-electric transducer (P.Z.T.) controlled mirrors is not required for such applications. This considerably simplifies the mirror mount design. A long term stable T.E.Mₐ₀ₐ mode output is required to achieve the maximum focused power density, and repeatable material processing. Associated with the stable T.E.Mₐ₀ₐ mode output, fluctuations of the output power should be less than 5%. This figure arises from considering many of the commercial systems already available. A long-term stable output power in the T.E.Mₐ₀ₐ mode can be achieved by controlling the parameters which affect the laser’s performance. For a discharge of a given length, these are:

i) Gas pressure, mixture, and gas flow,

ii) Discharge tube cooling,

iii) Discharge current,

iv) Mirror geometry and output coupler reflectivity,

v) Mode stop size,

vi) Cavity stability.

Items i), ii), and iii) are relatively easy to control, and furthermore, their control is achieved by elements external to the
laser head.

The choice of mirror geometry and output coupler reflectivity has been discussed earlier. The choice arises from a compromise between maximising the modal volume, making the output least sensitive to mirror tilt, and finally commercial availability and cost of the mirrors.

The diameter of the mode stop is usually determined experimentally but is normally within the range \((3.5 - 4.0)W\), where \(W\) is the spot size. Too small a mode stop diameter will certainly force the laser to oscillate in the T.E.M\(_{00}\) mode, but will truncate the Gaussian intensity distribution and consequently reduce the output power. A mode stop diameter which is slightly too large may allow low order modes to oscillate.

The remaining parameter is the cavity stability. Non-uniform thermal expansion or mechanical vibration of the laser cavity will cause a variation in the output power and mode. This is caused by the mirrors tilting relative to one another. Thermal cavity stabilisation of the commercially available c.w CO\(_2\) lasers, with power output less than 200W, usually involves one of two approaches. The first is to actively control the cavity temperature to about \(0.1^\circ\)C with a fluid continuously cycled around the cavity. A non-conducting oil is sometimes used so that high voltage insulation problems are overcome. The other approach is to construct the cavity from low thermal expansion materials such as invar rods. Isolation of the cavity from mechanical vibration of the surroundings is usually achieved by fixing the laser cavity on a heavy granite base and using heavy cast iron or granite mirror mounts. The actual laser discharge tube is usually de-coupled from the mirror mounts with the aid of some
In association with ROFIN LTD a relatively new mouldable composite material was used to construct the laser head of a CO$_2$ laser. The principle of operation was to achieve cavity stabilisation using a hybrid approach between the two previously mentioned ideas, i.e. active cavity temperature control and the use of low thermal expansion materials.
5. LASER DEVELOPMENT

Using the mouldable composite material (M.C.M.)\textsuperscript{22}, a number of laser head prototypes were made to determine the most suitable design.

5.1 First Prototype

The first prototype was concerned with the possibility of removing the normal requirement of a glass water jacket around the plasma tube and using the bare walls of the M.C.M. as the water containing vessel. To test the water absorbing properties of the material a 10cm x 10cm x 100cm block, with a 5cm hole centred along its axis was made. Several observations were made from this first test piece.

The thermal expansion of the M.C.M. was estimated by leaving the block in two different thermal environments and measuring the length of the block in both situations. A period of 3 - 4 hours was allowed in each environment before measurements were taken, this allowed an equilibrium to be established. The semi-quantitative figure of $10^{-5} \text{ K}^{-1}$ is in approximate agreement with the literature value for concrete.

The coolant water in contact with the bare M.C.M. caused a number of problems. Water absorption into the surface of the M.C.M. caused swelling and thus does not lead to a stable structure, furthermore, the associated high voltage insulation properties of the M.C.M. were drastically reduced. The resistivity of the dry M.C.M. was measured as $1\text{M} \Omega \text{cm}$ at 10 Kv. The reason for this relatively low value is the inherent water content of the material.
The second test piece is shown in cross-section in figure 8. It is identical to the first except that a P.V.C. tube insert was used to stop the discharge cooling water coming into direct contact with the composite. P.V.C. end caps were welded onto the P.V.C. tube to isolate the high voltage anode from the composite material and discharge cooling water. It was not possible to operate a glow discharge with this tube because discharge cooling water leaked through the P.V.C. end seal and onto the anode. Since this section was totally surrounded by the composite material, access was not possible.

5.ii Second Prototype

The problem of discharge coolant leakage onto the anode was overcome with the second prototype by using a glass water jacket surrounding the discharge tube. The major features of the discharge head are shown in figure 9. The laser tube was covered in grease to stop it sticking to the composite as it set. This also allowed the tube to expand somewhat when the discharge was operating. The anode was a stainless steel bush fixed concentrically onto the discharge tube with epoxy (Araldite). The air gap around the anode was filled with slow-setting silicone rubber to act as the high voltage insulator. The earth electrode was similar to the anode but was water-cooled via a series of copper tubing coils wrapped around the electrode. Conducting epoxy was used to improve the thermal contact between the stainless steel electrode and the copper cooling pipes. Glass T-pieces set into the discharge tube were used to allow the gas to enter at the anode and exit near the cathode. The borosilicate glass discharge tube was one metre long and had an internal diameter of 10mm. The dimensions of the laser head were...
FIGURE 8

CROSS-SECTION OF LASER HEAD

- LASER HEAD, COMPOSITE MATERIAL
- P.V.C. TUBE
- DISCHARGE TUBE
- COOLANT, WATER

10cm
FIGURE 9
LASER TUBE DESIGN

ARALDITE SEAL

1/4 CU PIPE

CONDUCTING EPOXY

WATER IN

WATER OUT

WATER OUT

ARALDITE SEAL

GLASS WATER JACKET

CRACK FORMED

H.V. ANODE

GAS IN

BRASS BUSH

ALUMINIUM MIRROR HOLDER

MIRROR ADJUSTING SCREWS

GLASS DISCHARGE TUBE

WATER IN

WATER OUT
1.1m x 0.1m x 0.1m. The mirror holders were adjusted by using threaded brass bushing set into the material. Gas and water pipes were led through the composite into a conduit pipe at one end.

The choice of resonator optics was limited by what was readily available at the time. A 10m concave multicoated germanium mirror was used as the 100% reflector, and a flat/flat ZnSe, 75% reflectivity output coupler.

A multimode output of approximately 10 watts was achieved at a moderate discharge current of 25mA and a non-optimised gas mixture, at a pressure of 15mbar. Final mirror tuning was achieved by adjusting the mirrors whilst the laser was operating. Great care was required at this stage because the metal mirror mount near the anode was electrostatically 'floating' at some fraction of anode voltage.

The laser operated continuously for about two hours before a serious fault occurred. A small crack in the glass water jacket developed near to the uncooled discharge tube housing the high voltage anode. Water managed to leak along the plasma tube and between the glass-silicone rubber interface near the anode. This occurred even though silicone rubber primer was coated onto the plasma tube to give a good attachment surface. The consequence of this was that gas breakdown could not be achieved because of the preferential breakdown via the water and laser head material. Since this region was buried in the composite material, access to the crack could only be achieved with the use of a hammer drill to remove the composite. The crack was repaired in situ and the free water removed.
Whilst the hammer drilling was in progress the laser mirrors were left in position. The interesting point here is that after the crack had been repaired and the laser switched on, the laser output rose to the same value as that prior to the drilling, but without mirror re-alignment. The mirrors had not become misaligned during the hammer drilling of the cavity head. This point demonstrates the idea that holding the laser tube and mirror holders in a solid matrix helps to isolate the laser from surrounding mechanical vibrations.

The actual cause of the crack was uncertain, but was probably due to the uncooled plasma tube near the anode stressing the cooled section as it expanded. The fact that the crack appeared in the glass water jacket very near to the uncooled plasma tube seems to justify this explanation.

5.iii Third Prototype

Experience gained from the previous two prototypes and in the building of a folded 6m laser cavity led to a re-appraisal of using a solid matrix surrounding the plasma tube. Practical aspects such as isolation of the anode from the laser head, access to internal faults and optics, such as Brewster windows, and finally tube replacement, were found difficult if not impossible to achieve using a solid matrix. Another important practical problem was concerned with optical alignment of the laser tube. The laser tube was mounted into a wooden mould and approximately aligned. The composite mixture was then added to the mould in a thin liquid form. To get a good quality finish, the composite mixture had to be vibrated in the mould to remove trapped air pockets. The laser tube
was then accurately aligned. Vibrating the laser tube in the mould, surrounded by the liquid composite mixture is obviously a poor building stage because of the possibility of tube damage. Furthermore, alignment of the tube after vibrations, and maintaining alignment as the composite sets, was found to be very impractical. Non-uniform setting of the composite tended to make the laser tube bend along its axis. Another problem was that a solid matrix around the laser tube made the laser head very heavy and difficult to handle.

Figure 10 is a schematic representation of the new laser head design. Instead of using a solid matrix around the laser tube, a rectangular trough was made from the mouldable composite material. Machined glass end plates were rigidly cast into the matrix to act as laser tube supports and as a base for the mirror holders.

This design suffers from none of the disadvantages of the previous designs. The laser tube is easily replaceable and accessible, a stand-off air gap around the anode was used to isolate it from the laser head. Optical alignment of the laser tube, and actually making the laser head, are now separate processes and do not interfere with each other. The weight problem is also substantially reduced. Although the end plates are rigidly fixed into the matrix, the laser tube is not. Consequently, a somewhat increased sensitivity to mechanical vibrations of the surroundings is to be expected. However, this was thought to be a satisfactory compromise because of the practical advantages mentioned above.
5.iii.a Laser Head Design

The laser head consists of a rectangular trough 1100mm long and 100 x 100mm in cross-section. The wall thickness is approximately 15mm. Water passes through several metres of pipe fixed internally in the laser head. Its purpose is to help maintain thermal cavity stability. The mirror mount arrangement is shown in figure 11. Machined glass end plates form the tube and mirror supports. Threaded brass bushes inserted into the glass end plates are used for holding the laser mirrors in place. Mirror adjustment is achieved by screwing the adjustment screws into the brass bushes thereby compressing the 'o' ring. Only one mirror mount arrangement is shown in figure 11, the other one is identical.

5.iii.b Control Unit

One of the design features of this CO₂ laser was that it should be easily transportable; this means a small power supply and control unit.

An active laser discharge length of one metre requires a breakdown voltage of 20 - 30KV. No such small power supply capable of supplying this voltage was available. The only available power supplies were two Hartley Measurements Ltd switched mode power supplies. Their relevant parameters were 9KV striking voltage (nominal), 4.5KV maintaining voltage (nominal), and a constant current output of 25mA (nominal). The striking voltage of 9KV meant that the laser tube was designed to operate as two independent 0.5m glow discharges (along the same axis), with a common earth electrode. Each power supply fed its own anode via a 50KΩ ballast
FIGURE 10
CROSS-SECTION OF NEW LASER HEAD

FIGURE 11
MIRROR MOUNTING ARRANGEMENT
resistor. A fan mounted to one side of the resistors helped dissipate the 30 watts of heat generated from each one.

The control unit is in two sections (two standard 19" Radio Spares cabinets). The upper one contains the two power supplies and their respective ballast resistors plus the fan. The lower one contains the gas and vacuum circuit, figure 12, an on/off solenoid valve for the discharge cooling water, and the simple mains electrical control circuit, figure 13.

5.iii.c Laser Tube Design

The first laser tube design is shown in figure 14. It consists of two cylindrical tungsten anodes mounted concentrically in the plasma tube. External connections were made via a glass-to-metal seal. The active discharge length was one metre, the internal diameter of the plasma tube being 10mm. The two water jackets were connected together by three symmetrically placed glass bridges. It was suggested that an uncooled central nickel earth electrode would be sufficient for a laser output power less than 50 watt c.w. This resulted in the rather complicated design shown in figure 15. A glass-to-glass seal was required on the plasma tube because of the way the laser tube was made, and to ensure a good glass-to-metal seal onto the nickel earth electrode. A dead space of about 10cm was allowed between the anode and the end of the plasma tube. This was to avoid preferential gas breakdown between the anode and the metal laser mirror holders rather than the central earth electrode.
FIGURE 12

GAS AND VACUUM CIRCUIT

FIGURE 13

ELECTRICAL CONTROL CIRCUIT
FIGURE 14

LASER TUBE DESIGN
CRACK OCCURRED HERE

CRACK OCCURRED HERE

PLASMA TUBE

GLASS/GLASS SEAL

SILICONE RUBBER TUBING

FIGURE 15

CENTRAL EARTH ELECTRODE
The laser operated for sometime before a crack appeared in one of the glass arms connecting the water jackets, near to the earth electrode. The first modification was to remove the central region of each of the glass arms and replace it with silicone water tubing. The most probable cause of the cracks was axial thermal expansion of the uncooled plasma tube near to the earth electrode. Since the glass arms suffered no proportionate expansion, they became stressed and eventually cracked. The silicone tubing was used to allow the uncooled plasma tube to expand without inducing stresses in the glass arms. When this modification was tried a crack appeared in the main body of the water jacket near the uncooled plasma tube. As a consequence of this, it was decided to re-design the earth electrode region using a water-cooled electrode. The design is shown in figure 16. The modified earth electrode is much simpler than the previous one, no glass arms are involved, nor glass-to-glass seals nor glass-to-metal seals. The laser tube was effectively cut in half to make two tubes, each 550mm long. Gas-tight seals between the plasma tube and the aluminium electrode were achieved with epoxy resin. Water flowed through a series of holes in the aluminium block and served to remove any heat generated at the electrode. The central region of the electrode within the discharge was extended to a suitable diameter to act as a mode stop.

After this modification to the central earth electrode the laser worked for many hours without any faults occurring. The next chapter is concerned with a characterization study of this particular laser.
FIGURE 16

RE-DESIGNED CONTROL EARTH ELECTRODE
6. LASER CHARACTERIZATION

6.i Discharge Characteristics

For a given length CO$_2$ laser, the tube diameter determines the optimum discharge current, total pressure and gas mixture for a maximum output$^3$. The optimum discharge current and total gas pressure for a 10mm internal diameter tube are in the ranges 35 - 40mA and 37 - 45mbar respectively$^8$. Neither of these were experimentally achievable. The first was not because the power supplies had no current control. The current through the ballast resistors was 25 ± 2mA for several gas pressures and mixtures. The optimum total gas pressure was not achievable because of the limited striking voltage of the power supplies. One power supply had a striking voltage of 11KV, the other 10.0KV, both having the same maintaining voltage of 4.5KV. No attempt was made to minimise the ballast resistance when the 50kΩ resistors were found to suffice. The voltage drop across the ballast resistors was 1.25KV, leaving the anodes of the discharge at a maintaining voltage of 3.25KV. The maximum usable gas pressure was 18mbar (15mbar He, 2mbar N$_2$, 1mbar CO$_2$) which gave an output of approximately 15 watts. This output was only achieved by increasing the gas pressure in the laser tube after the gas had broken down. Any further increase in pressure led to one arm of the double discharge arrangement not breaking down; usually the arm with the lower striking voltage. The optimum total gas pressure range for a maximum output, but with reliable gas breakdown, was found to be 13 - 16mbar. A few typical gas mixtures are summarized in Table 1 overleaf.
TABLE 1

CO₂ Laser Characterization - Summary

Maximum output power  
15 Watts
Output power stability  
7% (over eight hours)
Output power stability  
3% (over two hours)
Gas pressure  
13 - 16mbar

Gas Partial Pressures

<table>
<thead>
<tr>
<th>Total pressure mbar</th>
<th>He pressure mbar</th>
<th>N₂ pressure mbar</th>
<th>CO₂ pressure mbar</th>
<th>Approx output/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>10.5</td>
<td>1.5</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>14.3</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>16</td>
<td>13</td>
<td>2</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>18</td>
<td>15</td>
<td>2</td>
<td>1</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Mode  
Predominantly T.E.M₀₀

Divergence  
0.5mrad

Water flow-rate  
0.83 litres/min

Power Supplies

Ballast resistors (each)  
50Ω
Striking voltages  
11KV, 10KV
Maintaining voltage  
4.5KV
Voltage on anode  
3.25KV
Current from each supply  
25 ± 2mA
6.ii Optical Characteristics

A CO\textsubscript{2} laser of active length 1000mm and a tube internal diameter of 10mm has an optimum output coupler reflectivity of 70 - 80\%\textsuperscript{8}. The most suitable geometry for such a laser from the commercially available mirrors is a 2m or 5m concave 100\% reflector and a flat/flat output coupler.

The mirrors used in this laser were a germanium 10m concave (multi-coated dielectric) 100\% reflector, and a 75\% reflectivity, zinc selenide flat/flat output coupler. Calculations for the T.E.M\textsubscript{00} mode for this geometry give a spot size of approximately 0.3mm and a far field divergence of 0.4mrad.

The diameter of the mode stop at the centre of the discharge tube, figure 16, was 9mm. No attempt was made to optimise this value. The intensity distribution of the laser output in the near field was predominantly that of the T.E.M\textsubscript{00} mode. It was noticed that the output sometimes resided in the doughnut T.E.M\textsubscript{01} mode. Surrounding the near field output was a diffuse noise region produced from wall reflections. At a distance of 5m from the output coupler, the noise was diffracted out to leave a uniform noise-free intensity distribution with an approximate divergence of 0.5mrad.

6.iii Output Stability

Material processing applications with CO\textsubscript{2} lasers require a long-term stable output power to maintain quality control.

The laser output was monitored over an 8 - 9 hour day for a period of one week. Periodic water flow-rate and water input/output temperatures were also taken. Typically for no mechanical
vibration of the surroundings, an ambient air temperature of 18°C, water input temperature of 14.5 ± 0.5°C and a flow rate of 0.83 litres/min, an output power variation of 7% occurred over eight hours. When the laser was in equilibrium an output power stable to 3% was observed over 2 - 3 hours. The output power was not sensitive to mild physical vibration of the surroundings, or physical vibration of the laser head, or physical movement of the laser head.

The most interesting aspect from this study was the warm-up period of the laser. Shown in figure 17 is a graph of output power against time for a given gas mixture and pressure. The mirrors were initially adjusted to give a maximum output. The output power decays to a steady value, some 30 - 50% of the initial value, in a period of about 75 minutes. The mirrors were re-tuned to achieve the maximum output. This warm-up period is attributed to the time taken for the composite material in the laser head to come into equilibrium with the water passing through it and with the heat generated by the glow discharge. When the mirrors were tuned to give a maximum output at equilibrium, the output power of the laser steadily increased to this value when the laser was first switched on. This behaviour is indicated in figure 18.
FIGURE 17
LASER OUTPUT POWER AGAINST TIME

FIGURE 18
LASER OUTPUT POWER AGAINST TIME
7. DISCUSSION

The first two laser head designs involved surrounding the laser tube with the solid composite. The robustness of the laser head was clearly demonstrated by the hammer drilling of the composite, with the laser mirrors still attached. No mirror re-alignment was required after the laser was switched back on. However, many practical difficulties were found in using a solid composite around the laser tube, and they include: maintaining tube alignment whilst the liquid composite was vibrated, (to remove trapped air bubbles); maintaining tube alignment whilst the composite was setting over a period of approximately one week; and finally, isolating the anode from the composite. These matters, and others, are discussed more fully in chapter 5. The idea of the composite trough shaped design was to overcome these practical difficulties, but still maintain thermal and mechanical stability.

The thermal expansion of the composite material is approximately the same as that of aluminium. A passive temperature-controlled system was used whereby water passed through several metres of silicone tubing, set into the laser head. Thereafter the water passed through the water jackets surrounding the plasma tube. The principal of the water-cooled cavity was that day-to-day variations in the tap water temperature are quite small, and by maintaining a constant water flow, some degree of thermal stability of the cavity would be achieved.

The major constraining factor in the tube design was the requirement to use two small power supplies. This was unfortunate because it would have been somewhat easier, and cheaper, to design a one metre tube with a single anode. Small, commercial power
supplies are available which would be suitable for such a one metre active length discharge. The initial tube design involving three electrodes, concentrically placed inside the plasma tube, was too complex. There were two reasons for using concentric electrodes. The first was to improve discharge uniformity, and the second to simplify the high voltage insulation of the anode from the composite. The glass-blowers who made the laser tube had great difficulty in forming the metal-glass, and glass-glass seals, whilst keeping the metal electrodes concentrically placed inside the plasma tube. The 'one-off' nature of the laser tube meant that it was expensive to make. The hollow glass arms connecting the two water jackets on either side of the uncooled central earth electrode were perhaps superfluous. Their purpose was simply to allow water to flow from one jacket to another. In hindsight, a better solution would have been to connect the water jackets together via a short length of plastic hose. Even though the uncooled earth electrode was always hot when the discharge was operating, the faults always occurred on one or more of the water carrying glass arms. The cracks which appeared in the laser tube near the earth electrode meant that the whole earth electrode region had to be re-styled by the glass blower. As a consequence of this, it was decided to water cool the earth electrode and so completely remove any possible thermally-induced stresses.

The maximum output power of the laser in the T.E.M_{oo} mode was 15 Watts. The major reason why an output of 50 Watts was not achieved was due almost entirely to the power supplies. The potential at each anode was measured as 3.25KV, the discharge current
was 25mA. Eighty watts of electrical energy were therefore dissipated in each half metre section, giving a total power dissipation of 160 Watts. An output power of 15 Watts represents an efficiency, in terms of power dissipated in the discharge tube, of 9.5%. Considering it was not possible to operate the laser at its optimum gas pressure this figure is quite reasonable.

It was noticed that the output was not always in the T.E.M$_{00}$ mode. It sometimes resided in the doughnut T.E.M$_{01}$ mode. Possible explanations are:

i) The use of a 9mm diameter mode stop - this dimension was not optimised in any way,

ii) A 10m concave 100% reflector in a one metre laser meant that mirror adjustments become extremely sensitive for mode control,

iii) The small diameter mirror holders and the small diameter adjusting screws with their coarse threads made fine mirror adjustments very difficult.

The laser head had an output power variation of 7% over an eight hour period. This figure is somewhat higher than the 5% often quoted in the trade literature for commercial lasers. The warm-up period of the laser was about 75 minutes and is too long if the laser is to be used as an industrial tool. There are several areas where improved design would have reduced the output power fluctuation and the warm-up period of the laser. The water temperature entering the head was found to fluctuate by about 0.3°C over an eight hour period and vary by 0.5°C from day to day. For a period of one week
(16 - 20 June 1980) the average water temperature entering the composite was 14.3 ± 0.5°C. After passing through the laser head the water passed through the laser tube and central earth electrode. The water temperature leaving the laser tube tended to decrease by about 0.3 - 0.5°C over an eight hour period. Fluctuations in the flow rate were expected due to the local demand varying the mains water pressure. However, no significant fluctuations were measured. The water flow rate of 0.83 ± 0.01 litres/min was limited by the flow resistance caused by the several metres of the narrow, 2mm diameter silicone water pipe set into the laser head. With a fluctuating output power and water input temperature a steadily decreasing water output temperature would not be expected. One possible explanation is that the room temperature steadily decreased during the day. This seems unlikely though, because the measurements were taken in the Summer period.

The total power absorbed by the water in passing through the laser head was approximately 235 Watts, (temperature rise 4°C, flow rate 0.83 litres/min). The contribution to this figure from the electrical discharge was 145 Watts (I.V - output power). The remaining 90 Watts can be accounted for by the difference between the water temperature entering the laser head and the initial temperature of the head itself (room temperature). This figure of 90 Watts corresponds to a temperature rise of 1.5°C for the water having passed through the laser head. The long warm-up period of the laser is now readily explained. An equilibrium must be established between the water passing through the laser head and the composite itself. This corresponds to a slow reduction in the temperature of the composite. If the mirrors are aligned with the composite at room temperature, the observed reduction in output
power is explained by the thermal contraction of the composite changing the mirror alignment. Perhaps the best way to substantially reduce the warm-up period of the laser would be to reduce the difference between the water input temperature and the initial temperature of the laser head. This could be achieved in several ways. One way would be to continuously cycle water through the laser head, even with the discharge turned off. The equilibrium would then be permanently established. This technique is rather wasteful, a better method would be to use a closed loop cycle - preferably with an active temperature control on the cooling water. The water input temperature and the temperature of the composite could then be equalised. Another approach in combination with these methods would be to use a lower thermal expansion composite. Recent work has produced a composite with a thermal expansion almost comparable to that of Invar\(^{22}\). The thermal conductivity of the materials between the cooling water and the composite also limits the rate at which an equilibrium can be established. Silicone rubber tubing was used in this case, and was a poor choice from a thermal conductivity point of view. A better choice would have been to use copper tubing. Finally, the warm-up period of the laser could have been reduced by reducing the mass of the composite used. Only one composite trough was made, and no attempt to optimise the wall or base thickness was tried. This procedure would obviously be a compromise between maintaining mechanical stability and reduction in the warm-up period. Reducing the thickness of the base of the trough might well achieve this.
8. CONCLUSIONS

A continuous wave output power of 15 Watts in the T.E.M$_{00}$ mode was achieved. This rather low figure for a one metre discharge length was limited by the power supplies available. Their striking voltages were 10KV and 11KV, each supplying a constant 25mA at a maintaining voltage of 4.5KV. Two independent 0.5m glow discharges were produced from two anodes with a common earth electrode. Output power variation of 7% occurred over an eight hour day. A period of approximately 75 minutes was required for the output power to stabilise from the moment the laser was switched on. This was caused by the time required for the water entering the composite head to come into equilibrium with the laser head itself, which was initially at room temperature. Several possibilities for improving the output power stability and reducing the warm-up period exist, these include: optimising the composite material wall thickness, using a lower thermal expansion composite, and an actively temperature-controlled water cycling loop for water passing through the composite.

Further development of the laser head and control unit has led to the production of a 50 Watt, T.E.M$_{00}$, fully commercial system. A much improved composite is used which has a thermal expansion comparable to that of Invar, and consequently improves the thermal stability of the laser.
SECTION B

THE EXCIMER LASER
INTRODUCTION

Within the last few years a new type of pulsed high pressure gas laser called the 'Excimer Laser' has received increasing interest. It is characterized by a pulsed output in the ultra-violet with a number of lasing wavelengths available in the range 125 - 350nm. Excimer lasers rely on the production of bound, excited, ionic molecules which radiate strongly to a ground repulsive state. The two main excimer laser pumping techniques are electron beam pumping and electric discharge pumping. The term 'Excimer' refers to the excited state of the lasing molecule. Laser emission therefore occurs by transitions between electronic states of the excimer molecule. Strictly speaking, an excimer molecule refers to an EXCIted homonuclear diMER molecule, hence the term excimer. The first excimer laser was discovered by Basov in 1970\(^\text{39}\), it was the liquid xenon excimer \(\text{Xe}_2^*\), lasing at 173nm. Also available for lasing action are exciplex molecules. These are 'EXCIted comPLEX' heteronuclear molecules. The best known of these are the rare gas halide molecules such as \(\text{KrF} (\lambda = 248\text{nm})\) discovered in 1975\(^\text{24}\). The term 'excimer laser' is generally taken to cover lasers produced from excimer molecules or exciplex molecules. The rare gas halide molecules such as \(\text{KrF} (\lambda = 248\text{nm})\) or \(\text{XeCl} (\lambda = 308\text{nm})\) form the most efficient excimer lasers. They also have lower threshold pump power density requirements than the shorter wavelength lasing rare gas excimers such as \(\text{Xe}_2^*\). The first discharge pumped rare gas halide excimer laser was the \(\text{XeF} \) excimer, \((\lambda = 351\text{nm})\), discovered in 1976 by Burnham\(^\text{43}\).

Rapid development of the discharge pumped excimer laser has occurred since then due to its lower cost and more manageable
size on the laboratory scale compared to electron beam pumped devices.

There are a large number of potential applications for excimer lasers. One application is as a pump source for molecular dye lasers. The excimer laser offers a higher efficiency and therefore a higher output energy than the normally used nitrogen laser. The excimer laser can also offer a very long static fill lifetime, thus making a significant reduction in the cost of consumable gas. This point is particularly relevant for the XeCl excimer where very long gas lifetimes have been observed. Another application of the excimer laser is photochemistry. The ultra-violet photon energy of several electron volts can be used to selectively excite electron energy levels of the substance in question. A tuning element would normally be introduced inside the laser cavity so giving a very selective control over the excitation process. A major potential application in this area is isotope separation. As an industrial tool the excimer laser is receiving increasing interest from the semiconductor industry. Large area surface annealing of semiconductor slices is one possible application. In terms of laser annealing the short wavelength gives the advantage of efficient coupling of the laser energy into the materials surface and also shallow annealing depths. The final and perhaps major potential application of the excimer laser is for the inertial confinement fusion program. Recent work has shown an increased compression efficiency at ultra-violet wavelengths. The KrF laser is also relatively efficient, (~1%), which becomes important as the laser is scaled to large sizes.
This section of the thesis on the excimer laser reviews the principles on which they operate, (mainly related to rare gas halide lasers), and the design, construction and testing of a simple discharge pumped XeCl excimer laser. The review section covers the major excimer laser pumping methods employed at present and considers in some detail electrical discharge pumping. The experimental part of the work mainly involved altering the discharge conditions to achieve a suitable pump source and thereafter optimising the laser gas mixture.
9. RARE GAS HALIDE LASER SPECTROSCOPY

The general structure of a rare gas halide molecule is shown schematically in a molecular potential energy diagram, figure 19. In this case, M represents a rare gas and X the halogen. Laser emission occurs by electronic transitions between the exciplex/excimer state \((MX)^*\) and the ground state.

The deeply bound upper laser level \((MX)^*\) is ionic in nature and can be represented by \(M^+X^-\). The excited state is basically a positively charged inert gas ion \(M^+\) and a negative halogen ion, \(X^-\), held together by coulombic forces. A p orbital electron is transferred from the fully occupied p shell of the inert gas atom to the halogen, leaving a partially occupied \(p^5\) shell for the rare gas ion and a fully occupied \(p^6\) shell for the halogen ion. The ionic species forming the upper laser level \(M^+\) and \(X^-\) are therefore in the \(2p\) and \(1s\) states respectively.

In the region of the equilibrium internuclear separation of \(M-X, R_o\), the upper laser level splits into a \(2\Sigma\) and a \(2\pi\) state. This is due to the two possible orientations of the partially occupied p orbital of the rare gas ion relative to the halogen ion. Of these, the \(2\Sigma\) state is the lower and is called the B state. The \(2\pi\) state is referred to as the C state. From Figure 19 it is apparent that the upper laser level \((MX)^*\) is bound with respect to dissociation into an inert gas atom \(M\) and a excited halogen atom, \(X^*\). It is also bound with respect to dissociation into \(M^* + X\). Predictions of various properties of excimer states \((MX)^*\) are based on the similarity of these excited states to the ionic ground states of the alkali halides. This similarity derives
ENERGY

\[ M^+ + X^- \]

\[ M^* + X \]

\[ M + X^* \]

**FIGURE 19**

STRUCTURE OF RARE GAS MONOHALIDES
from the fact that a rare gas halide ionic excited state differs by only one electron from an alkali halide. Thus, the properties of (KrF)* are similar to those of the ionically bound RbF. The similarity extends further in that the rare gas excited states such as Kr* have low ionization potentials resulting in similar chemical properties to rubidium.

The lower laser level is the covalent ground state that occurs from collisions between $^1S$ rare gas atoms and $^2P$ halogen atoms. It is generally dissociative or weakly bound and will decay within one vibrational period $\sim 10^{-12}s$. This makes an ideal lower laser level, effectively removing the problem of bottlenecking.\textsuperscript{24} Again, in the region of the equilibrium internuclear separation, $R_0$, the ground state splits into a $^2\pi$ state and a $^2\Sigma$ state. The ground state splits for the same reason as the upper state does except that this time it is the halogen atom that has the partially occupied p orbital. The $^2\Sigma$ state has the lowest energy and because it forms the ground state for the dominant laser transition it is referred to as the $X$ state. This state is generally flat or weakly bound (255cm$^{-1}$ for XeCl$^\text{25}$). The $^2\pi$ state is always repulsive and is referred to as the $A$ state.

For the case shown in Figure 19 laser emission is centred near the two wavelengths $\lambda_1$ and $\lambda_2$. Emission terminating on the $A$ state, near wavelength $\lambda_2$, is characterized by a relatively broad continuum. The bandwidth for radiative transitions to the $X$ state is relatively narrow due to the fairly flat potential energy curve in the region of $R_0$. Consequently, the gain ($\alpha \frac{\lambda_2}{\Delta \omega}$) is larger for the $B(2\Sigma) + X(2\Sigma)$ transition and gives rise to the major laser
transitions observed to date. The excitation energy of the excimer in the B state may be approximated by

$$E^* \approx IP \text{ (rare gas)} - EA \text{ (halogen atom)}$$

where IP stands for ionization potential and EA stands for electron affinity. The smaller the halogen ion the smaller will be the equilibrium separation $R_o$ and so the greater the ionic dissociation energy. Consequently, the fluoride rare gas excimer states will have the lowest energy B states. The $B - X$ emission wavelengths of the halides of a given noble gas decrease monotonically with increasing atomic number of the halogen. The ionization potentials of the noble gases increase with decreasing atomic number and therefore the $B - X$ emission wavelengths of a given halide with different noble gases decrease monotonically with decreasing atomic number. These comments are confirmed in Table 2 where the various rare gas halide excimers and their lasing wavelengths are shown.
<table>
<thead>
<tr>
<th>Excimer Molecule</th>
<th>Lasing Wavelength/nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>KrF</td>
<td>248</td>
</tr>
<tr>
<td>KrCl</td>
<td>222</td>
</tr>
<tr>
<td>XeF</td>
<td>352</td>
</tr>
<tr>
<td>XeCl</td>
<td>308</td>
</tr>
<tr>
<td>XeBr</td>
<td>283</td>
</tr>
<tr>
<td>ArF</td>
<td>193</td>
</tr>
<tr>
<td>ArCl</td>
<td>175</td>
</tr>
</tbody>
</table>

**TABLE 2**

**Lasing Wavelengths of the Rare Gas Halide Excimers**
10. RARE GAS HALIDE KINETICS

The lasing medium for rare gas halide lasers consists of a three component gas mixture at a pressure of a few atmospheres. The major component, greater than 90%, is the buffer gas, usually chosen from helium, neon or argon. The second component is the rare gas which will form one half of the excimer molecule, e.g., krypton or xenon. Finally, there is the halogen donor such as F₂, NF₃, Cl₂ or HCl.

Population inversion is achieved through selective excitation reactions of the gas mixture in a plasma state. Creation of the plasma has been accomplished both by electrical excitation and electron beam excitation. Both of these techniques are discussed later. The main purpose of both pumping mechanisms is to create excited rare gas atoms and ions.

Excitation to the rare gas halide upper laser level occurs primarily through two types of process. The first is the so called 'harpooning' reaction involving an excited rare gas atom M* and the halogen donor XY.

\[ M^* + XY \rightarrow (MX)^* + Y \]

where Y is the radical attached to the halogen. In the case where XY is the Y₂ halogen molecule, the reaction rate is largest and the selectivity of the process approaches unity. The term 'harpooning mechanism' derives from a consideration of the electron that transfers from M* over to XY to create (XY)⁻. The latter is unstable with respect to dissociation into X⁻ + Y in the presence of the large electric field of the M⁺ ion. As a
result, the temporary $M^+(XY)^-$ triatomic species falls apart to become the ion pair $M^+X^-$, leaving behind a $Y$ atom.

The second major excitation process is three body ion-ion recombination, i.e.,

$$M^+ + X^- + A \rightarrow (MX)^* + A$$

where $A$ is some third body, often a buffer gas atom. The dominant reaction for a given situation depends on the pumping process, the partial pressures of the constituents of the gas mixture, the constituents themselves and the overall pressure. Typically, the harpooning reactions are considered dominant in electric discharge pumped lasers and ion-ion recombination considered dominant in electron beam pumped lasers\(^\text{30}\). The ion-ion recombination reaction is probably dominant with monofluorides due to the very rapid production of $F^-$ ions by dissociative attachment. For example, the reaction time for the process

$$F_2 + e^- \rightarrow F^- + F$$

is only 10ns\(^\text{26,27}\). More detailed kinetic pathways and reaction processes for rare gas halide excimer formation are considered by Hutchinson\(^\text{30}\), for example.

Much of the published literature is concerned with the formation of the KrF excimer, particularly for electron beam pumped devices. As an example, consider the formation of the KrF excimer molecule with argon as the buffer gas and fluorine as the halogen donor.
10.1 Ion Channel Processes

Energetic electrons can interact with the buffer gas

\[ e(\text{fast}) + \text{Ar} \rightarrow \text{Ar}^+ \]

Cold secondary electrons can form negative ions from the fluorine donor

\[ 2e(\text{slow}) + \text{F}_2 \rightarrow 2\text{F}^- \]

Recombination can occur through ionic states

\[ \text{Ar}^+ + \text{F}^- \rightarrow (\text{ArF})^* \]

or through molecular states

\[ \text{Ar}^+ + 2\text{Ar} \rightarrow \text{Ar}_2^+ + \text{Ar} \]

argon
excimer

\[ \text{Ar}_2^+ + \text{F}^- \rightarrow (\text{ArF})^* \]

The excited (ArF)* molecule can then react to form (KrF)* in a displacement reaction

\[ \text{ArF}^* + \text{Kr} \rightarrow \text{KrF}^* + \text{Ar} \]

Other kinetic pathways can also occur

\[ \text{Ar}_2^+ + \text{Kr} \rightarrow \text{Kr}^+ + \text{products} \]

\[ \text{Kr}^+ + \text{F}^- \rightarrow \text{KrF}^* \]

\[ \text{Kr}_2^+ + \text{F}^- \rightarrow \text{KrF}^* + \text{products} \]
10.ii Harpoon Reactions

Direct electron impact with the rare gas atoms can form excited metastable states

\[ e + Ar \rightarrow Ar^* + e \]
\[ e + Kr \rightarrow Kr^* + e \]

The harpoon reaction for argon is

\[ Ar^* + F_2 \rightarrow ArF^* + F \]

and the ArF* excimer can again react with Kr in a displacement reaction to form KrF*

\[ ArF^* + Kr \rightarrow KrF^* + Ar \]

The Kr excited state also undergoes harpoon reactions.

\[ Kr^* + F_2 \rightarrow KrF^* + F \]

10.iii Quenching Processes

Efficient formation of the upper state excimer level (MX)* does not necessarily imply a high laser energy output. Quenching of the upper state may compare favourably with stimulated emission and so terminate laser oscillation. The most important loss processes from the upper laser level are collisional quenching and photoabsorption. A major problem is quenching by collisions with \( F_2 \).

\[ KrF^* + F_2 \rightarrow \text{products} \]
The radiative decay and F₂ quenching lifetime of the upper laser level are equal at a fluorine pressure of 6 torr. This reaction therefore limits the optimum fluorine concentration to low levels, usually less than 0.5%. Another significant collisional quenching process involves interaction with the rare gas atom. Quenching by the buffer gas may occur.

\[ \text{KrF}^* + \text{Ar} \rightarrow \text{products} \]

At higher pressures three body trimer formation can also efficiently quench the upper laser level.

\[ \text{KrF}^* + \text{Kr} + \text{M} \rightarrow \text{Kr}_2\text{F}^* + \text{M} \]

where M may be the seed rare gas or the buffer gas.

Photoabsorption by the halogens is most important in XeCl (308nm) and KrF (248nm) lasers. Reactions such as

\[ \text{F}^- + \text{hv} \rightarrow \text{F} + \text{e}^- \]

and

\[ \text{Cl}^- + \text{hv} \rightarrow \text{Cl} + \text{e}^- \]

tend to occur. The latter can be avoided by using HCl in place of Cl₂ as the halogen donor. In KrF lasers NF₃, SF₆ and N₂F₄ have been used in place of F₂, however, some trade-off generally occurs between reduced photoabsorption and unfavourable formation kinetics.
11. EXCIMER LASER PUMPING TECHNIQUES

The required pump power, $p$, to achieve laser threshold oscillation varies as

$$p \propto \frac{\Delta \lambda}{\lambda^5}$$

where $\Delta \lambda$ is the spontaneous emission linewidth and $\lambda$ the laser transition wavelength. The excimer laser transition is characterized by a relatively wide spontaneous emission bandwidth ($\Delta \lambda$) and for emission in the ultra-violet very high pumping powers are required, typically $1 - 10\text{MWcm}^{-3}$ for rare gas halide (RGH) lasers. Such high power densities can only be achieved transiently and therefore excimer lasers have a pulsed output.

There are two basic pumping mechanisms; pure electron beam pumping and avalanche electric discharge pumping. Both of these pumping techniques have been investigated extensively for carbon dioxide lasers. However, the requirements for the excimer laser are much more severe than for the CO$_2$ laser. Generally, higher pump powers are required and components in contact with the halogen-containing gas mixture must be resistant to chemical attack. Furthermore, the highly electronegative nature of the halogen has a tendency to produce arcs in the excited plasma. The latter problem is particularly relevant to electric discharge pumped devices.
11.1 Electron Beam Pumped Excimer Lasers

The principle of this technique is to use an intense source of electrons to volumetrically ionize the high-pressure laser gas mixture. Electron beams have been used to excite the short wavelength excimer species Ar$^*_2$ (126nm), Kr$^*_2$ (147nm) and Xe$^*_2$ (173nm). In fact, electron beam excitation of liquid xenon was used by Basov$^{39}$ in 1970 to observe the first laser action by an excimer molecule, Xe$^*_2$. Shortly after, Koehler$^{40}$ demonstrated laser action in high pressure gaseous xenon also pumped with an electron beam.

A schematic representation of an electron beam pumped excimer is shown in Figure 20. Most systems contain a Marx generator$^{41}$ to attain the high voltage needed to accelerate the electrons. A Marx generator essentially consists of a set of capacitors which are charged in parallel by a D.C. high voltage supply delivering a voltage which is just manageable in the laboratory, (<100KV). The capacitors are discharged in series through the load by means of spark gaps and produce a high voltage output, typically in the range 0.1 - 2.0MV. In order to achieve high voltage risetimes at the electron emitter (the cathode), the Marx generator is usually connected to a pulse forming line, normally consisting of a co-axial oil or water capacitor. The Marx generator charges the pulse forming network relatively slowly and when the voltage has risen to a high enough value a low inductance spark gap closes, transmitting the charge to the load via a transmission line. The high voltage pulse is applied to the cathode of a vacuum diode. The diode compartment must be evacuated to pressures of about $10^{-4}$ torr. The electron emitter is usually a
Figure 20

Schematic Diagram of an Electron Beam Pumped Excimer Laser
knife-edge shaped piece of graphite. The anode can be a grid or separate metal foil but in most cases it is the high tensile strength metal foil separating the laser gas from the diode vacuum. Often, titanium foil is used. If the pressure difference across the foil is high, an extra foil support structure is used, consisting typically of an array of holes or slots with a transparency of 70 - 80%.

Several geometries for the cathode relative to the laser gas cell have been tried. The choice generally involves some form of trade-off between cost, simplicity, power density and pumping homogeneity. The most simple and commonly used configuration is the one-sided transverse geometry. This arrangement and several others are shown in figures 21a – e. The main disadvantage of the transverse geometry is the inhomogeneous power deposition. This can be improved by a guide magnetic field or by injecting the electron beam from two or more sides as shown in figure 21b. Beam deposition uniformity is excellent in co-axial geometries, as shown in figure 21c. With these devices, a metal tube containing the laser gas mixture acts as the anode and holds off the high pressure differential. Two other techniques that have been applied to electron beam pumped CO₂ lasers are axial pumping, figure 21d and the use of multi-bladed cathodes, figure 21e. Both techniques produce very homogeneous pumping. The main disadvantage with the axial technique is the very high current density emitted from the rather small circular graphite cathode. This leads to rapid deterioration of the titanium foil. In order to reduce this, two foils can be used, one as the anode and the other to act as a laser mirror for the optical cavity.
FIGURE 21
DIFFERENT PUMPING GEOMETRIES FOR ELECTRON BEAM PUMPED EXCIMER LASERS

H.V. - HIGH VOLTAGE
L.C. - LASER CELL
V.D. - VACUUM FOR DIODE
FIGURE 21.d

AXIAL PUMPING

FIGURE 21.e

MULTI-CATHODE PUMPING
11.ii Electric Discharge Pumped Excimer Lasers

The second major pumping technique is the avalanche electric discharge. This technique uses a fast electrical discharge to excite a large volume of the laser gas at a pressure of up to about three atmospheres. The molecular excimer lasers \( \text{Ar}_2^* (126\text{nm}), \text{Kr}_2^* (147\text{nm}) \) and \( \text{Xe}_2^* (173\text{nm}) \) have not been discharge pumped because of the higher threshold power density required at the shorter wavelengths. However, all of the electron beam pumped rare gas halide lasers can be discharge pumped. The first such discharge pumped rare gas halide excimer was \( \text{XeF} \) lasing at 351nm\(^4\). 

There are two main problems in exciting a large volume of gas using a self-sustained avalanche electric discharge. The first problem is that the voltage required to obtain a discharge increases with distance. The problem is further increased because the avalanche nature of the discharge means that the peak applied voltage is greater than the static breakdown voltage of the laser gas. The second problem is preventing the discharge becoming a localised arc which would result in non-uniform pumping of the discharge volume. This problem is increased because of the high pressure operation and the presence of an electronegative halogen component in the gas mixture. To initiate the main discharge as a glow discharge and suppress arc formation, an initial uniform volumetric distribution of electrons produced between the main discharge electrodes is required. The preionizing electrons are usually produced from distributed ultra-violet sources situated near the main discharge. Short wavelength ultra-violet light
(λ<150nm) is used to volumetrically photo-preionize the main gap. The source of the electrons produced by the ultra-violet light is not certain but has been attributed to organic impurities present in the discharge vessel. The addition to the discharge region of a XeCl excimer of small concentrations of benzene additives to improve preionization has been studied by Taylor et al.\(^4\)

The solution to the first problem is readily achieved by making the discharge path transverse to the laser axis, thus making it a 'Transverse Excited Atmospheric' or T.E.A. laser. Decreasing the discharge length so that breakdown voltages are readily attainable necessitates an increase in the area over which the discharge is distributed to achieve the same discharge volume. A transient glow discharge is therefore required over the electrodes' surface. This makes the solution to the second problem — preventing arc formation — that much more difficult.

The two main kinetic formation channels for rare gas monohalide excimers are the two-step harpooning reaction and the ion-ion recombination reaction. The former mechanism requires the formation of excited metastable rare gas atoms. The latter process requires ionization of the rare gas atoms. Since both the excited state and ionic state of the rare gas atoms are created from electron collisions, electron energies in excess of several electron volts are required. As high an electric field/gas density, \(E/N\), as possible is therefore required. To achieve a high \(E/N\) value a short voltage risetime across the discharge electrodes must be used in order to over-volt the discharge gap. When the gap breaks down, the voltage across it decreases as the electrons avalanche (moderated by dissociative electron attachment to the halogen donor) and the current increases. The dynamic impedance of the discharge
rapidly approaches zero, resulting in the formation of the streamer arcs that eventually destroy the glow discharge after approximately 30 - 50ns. Thus, for a maximum excitation, the optimum transverse discharge lasts for about 30 - 50ns. During this stable glow discharge period all of the useful energy must be deposited into the gas at as high an E/N and consequently discharge impedance as possible.
11.ii.a Arc Formation in Discharge Pumped Excimer Lasers

The prevention of arc formation is a major difficulty when designing discharge pumped rare gas halide lasers. Arc formation severely reduces the output energy of the laser due to the much reduced excitation volume. The narrow gas column of the arc becomes heated, causing a localised refractive index change which can act as a scattering source for the laser light. Finally, the very high current densities produced by the arc can cause electrode damage by sputtering. Arc formation is generally found to occur in localised regions of high input power. The localised enhancement of $E/N$ is generally caused by spatial non-uniformities in:

1) The electric field between the main discharge electrodes,
2) The initial preionization electron density,
3) The gas density or temperature.

A non-uniform electric field between the main discharge electrodes can be caused by the finite dimensions of the electrodes or by surface roughness. Field enhancement due to roughness can be overcome by polishing. Uniform field electrode profiles are generally designed so that the electric field on the curved portion of the electrode is always less than that in the central flat region and furthermore, field variations in the central flat region of the electrodes are minimised. The most well-known of these are the Rogowski profile, the Bruce profile and the Chang profile. A comparison of the Rogowski and Bruce profiles by Harrison shows that the Rogowski profile produces a more uniform electric field distribution but requires a much larger electrode width/electrode separation ratio, (aspect ratio) for
the same gap.

The problem of the initiation of a glow discharge in favour of arc formation in a preionized T.E.A. laser is considered by Palmer. The basis of the physical model is that the preionization electron density be large enough to cause appreciable spatial overlap of the primary electron avalanches and consequent smoothing of the space-charge field gradients at the stage when streamer formation would otherwise occur. Inherent in the model is an assumption of a uniform preionization electron density. The importance of a spatially uniform preionization electron density is now apparent. In regions of poor preionization the primary electron avalanche density is not sufficient to eliminate the tendency of secondary avalanches to converge towards a single primary avalanche and thus cause streamer-arcs.

The technique of ultra-violet photo-preionization is generally done with an auxiliary electrical discharge such as a flashband circuit, triggered just prior to the main discharge. The maximum laser energy output has been found to occur when the main discharge is initiated at the peak of the ultra-violet preionization flash. A great deal of the development work on discharge pumped rare gas halide lasers has gone into the type of ultra-violet preionization source and the way it is geometrically situated relative to the main discharge electrodes.

The combination of the effect of the electric field uniformity and preionization uniformity on high pressure glow discharges has been considered by Hasson and Bergman. They
considered a localised discharge formation time for each elemental area of the electrode's surface. Uniform glow discharges are produced when the local discharge formation times are equal over the electrode's area. The local formation time is controlled by a combination of the local electric field and local electron preionization density. The practical implication of this work is that by controlling the geometry of the preionizing source, non-critical electrode profiles can be used. This approach is useful because the uniform field electrode profiles such as the Chang profile have the complication that they need to be produced on a numerically controlled machine.

The effect of the local gas density or temperature fluctuations on arc formation is represented in Figure 22.

\[
\frac{E}{N} \leftarrow \alpha \rightarrow I \rightarrow T \rightarrow N
\]

**FIGURE 22**  
ARC FORMATION FEEDBACK MECHANISM
A positive feedback mechanism can operate whereby a local increase in current, $I$, causes the temperature, $T$, to rise, the local density, $N$, to fall and therefore $E/N$ to rise. The increased excitation rate further increases the ionization rate, $\alpha$, and therefore current and so completes the feedback loop.
11.ii.b Electrical Discharge Circuits

For a maximum laser output the capacitatively stored energy in the discharge circuit must be delivered into the discharge during the stable glow discharge time. The amount of energy that can be delivered during the stable operating time of the discharge is governed by:

i) The voltage at breakdown which is governed by the voltage rise time,

ii) The rate of energy deposition which is directly related to the current rise time,

iii) The impedance matching of the energy source to the discharge volume.

The principle of operation of a number of electrical circuits is shown in figures 23 - 25. All employ a fast electrical switch, a spark gap or thyatron to dump the energy in the storage capacitors into the discharge region as fast as possible.

A Blumlein type circuit is shown in figure 23. The inductance and capacitance pair \( L_1, C_1 \) and \( L_2, C_2 \) are made from a parallel plate transmission line. A discharge is initiated by charging the entire transmission line and closing a low inductance switch at one end. The low inductance values of \( L_1 \) and \( L_2 \) mean that very fast discharges of the order of 10ns can be achieved\(^{27}\). True Blumlein operation does not normally occur because of the inductance of the spark gap switch, \( L_{sg} \). A better model is the one described by Burnham et al\(^{54}\). The device operates as a lumped component \( LC \) generator. When the spark-gap switch, \( SG \) in figure 23, closes the current in the left-hand loop undergoes the first part
FIGURE 23
BLUMLEIN CIRCUIT

FIGURE 24
CAPACITOR DUMPING CIRCUIT

FIGURE 25
L.C. INVERSION CIRCUIT

R.S.G. - RESISTANCE SPARK GAP
L.S.G. - INDUCTANCE SPARK GAP
S.G. - SPARK GAP
D.R. - DISCHARGE REGION
of a damped oscillation, the frequency of which is determined by the capacitance $C_1$ and the inductance of the switch $L_{sg}$. At some point in the rising part of the first cycle the main discharge fires as the voltage across the main electrodes increases. Blumlein-type circuits can produce efficient operation for rare gas halide lasers because of their low voltage and current rise times and good impedance match between the discharge plasma and the Blumlein circuit. Several devices have been operated with such circuits$^{54,55,56}$. Their main disadvantage from a practical view point is that they have limited scaleability and are usually used for small discharge volumes.

A capacitor dumping circuit is shown in figure 24. The capacitor $C_1$ is charged up from a high voltage supply and acts as the energy storage element. When the spark gap switch, $SG$, is closed, the charge from $C_1$ is transferred to the capacitor $C_2$ which acts as a peaking capacitor. The circuit should be arranged so that the main discharge fires when the voltage across $C_2$ is near its peak value. The inductance $L_1$ controls the voltage rise time across the main electrodes while the inductance $L_2$ controls the current rise time. To minimise the inductance $L_2$ the peaking capacitors, which are usually discrete doorknob capacitors, should be mounted as close as possible to the main discharge region. An auxiliary storage capacitor is also charged to act as the energy storage element for the preionization circuit. Such an arrangement has been investigated by Webb et al.$^{33}$. A similar pulse-charged circuit arrangement has been investigated by Sze and Scott$^{57}$. However, they used charged coaxial cables for $C_2$. For high repetition rates, thyatrons are used instead of spark gap switches, the main problem being that fairly large inductances, $L_1$, are
required to keep the peak thyratron currents within allowable limits.

The last circuit to be considered is the LC inversion circuit shown in figure 25. The operating conditions of LC inversion circuits for rare gas halide excimer lasers have been investigated by Burnham and Djeu and Sze. Capacitors $C_1$ and $C_2$ are charged to some common voltage at point A. When the spark gap switch $SG$ closes, the ringing arm combination of $L_1$, $C_1$ and the equivalent spark gap resistance undergoes a damped oscillation. On the first voltage oscillation the lower discharge electrode swings to an opposite polarity to that of the opposite discharge electrode and gas breakdown proceeds as before. As with the capacitor dumping circuit, $L_1$ controls the voltage rise time and $L_2$ the current rise time.
ll.i.i.c Principles of Spark Gap Operation

The requirements for a fast electrical switch for capacitor discharge circuits can be summarized as follows:

i) The switch should be non-conducting during the capacitor charging period,

ii) The switch should be capable of closing very rapidly at pre-determined times,

iii) The switch resistance should be as small as possible during the discharge of the capacitor,

iv) The switch should regain its non-conducting state rapidly after the end of the pulse.

The requirements of low resistance and rapid closing of the switch suggest that either spark gaps or thyratrons be used. Hydrogen thyratrons offer the highest pulse repetition rates and lowest jitter times for application with T.E.A. lasers. However, their expense precludes their discussion in this section. Thyratron operation is considered by Frungel for example. An extensive amount of literature is available concerning spark gap switches. Past experience with triggered spark gaps has shown their cost, robustness and relative simplicity make them useful for operation with T.E.A. lasers.

The triggered spark gap consists of three electrodes in a pressurized envelope. A triggered spark gap is shown schematically in figure 26. The two main electrodes carry the load current after conduction is initiated by a trigger electrode. When the minimum trigger voltage required to initiate a complete breakdown is plotted
FIGURE 26

SCHEMATIC DIAGRAM OF A TRIGATRON SPARK GAP

FIGURE 27

OPERATING CHARACTERISTIC OF A TRIGGERED SPARK GAP
against the main electrode to electrode (E to E) voltage, a curve typical of all triggered spark gaps results, as shown in figure 27.

The curve is divided into three regions; a cut-off region where firing does not normally occur, a normal operating plateau region and a region above the point marked static breakdown voltage (SBV), where the gap self-fires simply from over-voltage on the two main electrodes. The self-breakdown voltage is determined by the gas used, the gas pressure, the electrode spacing and the electric field uniformity.

Triggered spark gaps should always be operated well above the minimum trigger voltage and well above the cut-off voltage portions of the operating curve to avoid the possibility of random misfire. Likewise, they should always be operated well below the static breakdown voltage to avoid the chance of prefire. The normal operating range is the region between E-E(min) and E-E(max). The minimum operating voltage represents about \( \frac{1}{3} \) of the maximum operating voltage. The maximum operating voltage is typically 80% of the self-breakdown voltage.

The delay time of a spark gap is measured between the trigger voltage breakdown and the main gap conduction. It depends upon the E-E voltage and trigger mode. The delay is minimised at the upper end of the E-E range. The spark gap trigger mode refers to the relative polarities of the opposite, adjacent and trigger electrodes as shown in figure 26. Generally, it has been found that a positive trigger pulse and negative D.C. opposite electrode voltage gives the widest operating range and minimum delay time.
The total spark gap jitter is the shot to shot variation in the delay time plus the shot to shot variation in the trigger breakdown time. Spark gap jitter may be minimised by using a fast rising trigger pulse which over-volts the trigger-electrode adjacent-electrode gap. Time jitter of the main discharge can be further reduced by operating the spark gap near to self-breakdown and using a large electrode aspect ratio which is defined as electrode diameter/electrode-electrode separation.
11.ii.d Ultra-violet Preionization Techniques

Many of the ultra-violet preionization techniques used for rare gas halide lasers originated from earlier work done on the development of T.E.A. CO\textsubscript{2} lasers\textsuperscript{36}. However, the preionization electron density must be higher and more uniform for rare gas halide lasers than for T.E.A. CO\textsubscript{2} lasers\textsuperscript{28,44,50,64}. Tallman\textsuperscript{52} has considered the main ultra-violet preionization techniques for excimer lasers and these are illustrated in figure 28. The single-sided and double-sided arc array shown in figure 28 consists of a series of arc sources placed on one or both sides of the electrodes and distributed along their length. The double-sided technique produces a more uniform illumination than the single-sided technique and consequently a more uniform preionization electron density. Assuming no ultra-violet absorption, the preionization electron density in a thin spherical shell at a distance r from the arc source varies as $1/r^2$\textsuperscript{64}. This implies that the arc sources should be placed as close as possible to the main discharge electrodes. This factor becomes even more important when ultra-violet absorbing species are present in the discharge. The line density of arc sources distributed along the electrodes' length should be maximised to achieve a uniform longitudinal ultra-violet illumination. The third ultra-violet preionization technique shown in figure 28 is an adaptation of the double discharge arrangement originated by Laflamme\textsuperscript{38}. This technique has been used to produce a very uniform ultra-violet preionization source for rare gas halide lasers\textsuperscript{52}. An initial preionizing discharge occurs between the upper electrode and the mesh electrode. Ultra-violet photons are then transmitted through the mesh and volumetrically ionize the main discharge.
ULTRA-VIOLET PREIONIZATION TECHNIQUES

FIGURE 23

SINGLE SIDED ARC ARRAY

DOUBLE SIDED ARC ARRAY

THREE ELECTRODE MESH SYSTEM
region between the mesh and the lower electrode.

Other preionization techniques include: the Lamberton and Pearson\textsuperscript{37} corona discharge from a wire adjacent to the main discharge electrodes, X-ray preionization\textsuperscript{28} and laser-induced preionization using another excimer as the ultra-violet source\textsuperscript{44}.

All of the ultra-violet preionizing discharges must be synchronized to the initiation of the main discharge. The optimum time delay between the preionizing and main discharge has been found to be in the range $50 - 200\,\text{ns}\textsuperscript{51}$. A commonly used circuit configuration, a capacitance dumping circuit is shown in figure 29. It uses two storage capacitors and two high voltage switches (spark gaps or thyratrons) - one pair for the main discharge and the other for the flashboard circuit. With spark gap switches the main operational disadvantage is the inevitable timing jitter introduced between the firing of the flashboard and initiation of the main discharge. This problem can be reduced by triggering the main discharge circuit and the preionizing circuit from a common spark gap switch.
FIGURE 29

TYPICAL CIRCUIT CONFIGURATION FOR A RARE GAS HALIDE EXCIMER LASER
A third pumping technique is electron beam sustained discharge pumping. This approach is a hybrid of the previous two and uses both an electron beam and electric discharge. The electron beam is used to sustain the discharge by supplying electrons to make up for the difference between the ionization rate and electron attachment rate. A major advantage of this technique over pure electron-beam pumping is an increase in the proportion of metastable rare gas atoms present in the discharge. This leads to the excimer upper state formation via the efficient two-step harpoon mechanism. Electron-beam sustained discharges also have an advantage over pure electrical discharge pumping. When the discharge is operating, the electron beam maintains a low plasma impedance which is resistant to arc formation. The stable glow discharge time is increased and therefore more efficient operation is possible. Because of the limitations of electron-beam pumping (e.g., foil damage) it is desirable to put most of the energy into the laser by means of the electrical discharge rather than the electron beam. The ratio of the discharge power to the electron beam power is called the enhancement ratio and is usually of the order of three for actual systems.
12. DESIGN AND OPERATION OF A DISCHARGE PUMPED EXCIMER LASER

12.i Circuit Operation

The circuit configuration is shown in figure 30. It is a capacitative dumping circuit with a storage capacitor, \( C_1 \), charged to a voltage, \(-V_0\). The most important feature is that the internal peaking capacitors, \( C_2 \), are directly connected to only one of the plates supporting the main discharge electrodes. Instead of a direct connection a small gap is left between the stud forming the terminal of each ceramic capacitor and a pin connected to the top support plate. When the spark gap in the external circuit is fired, a rapidly rising voltage appears between these pins and the capacitor studs. These small gaps breakdown before the main discharge gap and are bridged by arcs which allow charging current to flow to the internal capacitors from the external storage capacitors. When the internal capacitors have been charged to the voltage required for breakdown in the main gap, the direction of current flow in the bridging arcs reverses. The internal capacitors then discharge via this route as a parallel array in series with the main discharge.

The inductance associated with the storage capacitor, \( C_1 \), the trigatron spark gap and connections to the laser head controls the voltage risetime and therefore peak voltage across the discharge. The inductance associated with the peaking capacitors, the physical area of the current loop and main discharge controls the current risetime and therefore peak current.

Throughout the charging cycle of the peaking capacitors
FIGURE 30

ELECTRICAL CIRCUIT FOR THE XeCl EXCIMER LASER
the arcs irradiate the main discharge volume and form the ultra-violet preionizing sources. The peaking capacitors are ceramic doorknob capacitors which are distributed along the electrodes' length to provide a uniform illumination.

Of the three ultra-violet preionization schemes shown in figure 28, Tallman considers the double discharge arrangement to provide the most uniform preionization. However, work here and at Oxford has shown that the light transmission of the mesh and its surface roughness severely affects the tendency towards arc formation in the main discharge. A sufficient longitudinal arc density adjacent to the main electrodes ensures a uniform illumination with the double-sided arc arrangement shown in figure 28.

This automatic preionization scheme was first used by Webb et al. and offers a number of advantages. One is that the use of a single spark gap eliminates the time jitter between the preionization discharge and the main discharge. The major advantage is probably that the design is flexible and interchanging components such as discharge electrodes or peaking capacitors is relatively easy.
12.ii Spark Gap Triggering Circuit

Spark gap delay time and jitter is minimised by using a fast rising trigger voltage. The basic circuit of the trigger unit is shown schematically in figure 31. Energy stored in the storage capacitor is switched into the primary of a transformer via an electrical switch. The output from the secondary of the transformer is applied to the trigger electrode of the spark gap. Two types of switching device were used; a thyristor and a thyratron. The thyratron that was used is the relatively inexpensive inert gas filled (xenon) 2D21. The switching time for the 2D21 thyratron, or ionization time, is about 0.5μs. For a corresponding thyristor the switching time is approximately ten times longer. This was borne out by experimental observations of the unloaded outputs of the trigger units.

The interaction of the low voltage thyratron and thyristor circuits with three types of pulse transformer was investigated. Figures 32a-g show the open circuit waveforms across the secondary of the three types of pulse transformer using the thyratron and thyristor trigger units. The three types of pulse transformer investigated were:

i) a car ignition coil
ii) a laboratory wound transformer
and
iii) a Hartley Measurements Ltd (HML 513-0030) commercial pulse transformer.

The high inductance of the car ignition coil gave very little difference between the thyratron and thyristor units, with voltage risetimes of about 30μs. Several laboratory wound
CURRENT LIMITING RESISTOR

SWITCHING DEVICE

ENERGY STORAGE CAPACITOR

PRIMARY OF PULSE TRANSFORMER

FIGURE 31

SCHEMATIC DIAGRAM OF THE TRIGGER UNIT CIRCUIT
THYRATRON TRIGGER UNIT

THYRISTOR TRIGGER UNIT

FIGURE 32a

CAR IGNITION COIL, HORIZONTAL 10μs/div, VERTICAL 5KV/div

FIGURE 32b

FIGURE 32c

2:100 FERRITE CORE TRANSFORMER
HORIZONTAL 0.2μs/div, VERTICAL 5KV/div

FIGURE 32d
1:100 FERRITE CORE TRANSFORMER
HORIZONTAL 0.2μs/div VERTICAL 5KV/div

HARTLEY MEASUREMENTS TRANSFORMER
HORIZONTAL 0.5μs/div, VERTICAL 5KV/div

THYRISTOR TRIGGER UNIT
transformers were investigated by Godfrey. The effect of loading the thyatron and thyristor units with a 2:100 turns ratio and a 1:100 turns ratio transformer is shown in figures 32c-f. The thyristor trigger unit produced the fastest risetime in both cases. The Hartley Measurements pulse transformer gave a longer voltage risetime but a higher peak voltage than the 2:100 turns ratio transformer. The Hartley Measurements device was designed for a 35kV output with a 300V input, a higher turns ratio therefore explains the higher peak voltage achieved with this device. The lower risetime and peak voltage achieved by the thyatron trigger unit is probably due to a limiting 30A cathode current through the 2D-21 thyatron. The current limit due to the thyatron therefore limits the voltage which appears across the primary of the pulse transformer.

Trigger breakdown voltage measurements were taken on the pressurized spark gap discussed in section 12.iii. A typical example is shown in figure 33. The peak trigger voltages varied linearly from 4-6KV with jitter times of 50-100ns and voltage risetimes of 0.5-0.8µs over the nitrogen pressure range 1.3-2.0 atmospheres (absolute). The trigger-electrode adjacent-electrode distance is about 1mm. Figure 34 shows the voltage waveform across a uniform field 4mm air gap using the thyatron unit and the car ignition coil. The peak voltage is 12.5kV with a risetime of 27µs and a jitter time of about 15µs. Figures 33 and 34 correspond to the D.C. self-breakdown voltage of 3KV/mm/Atm for the spark gap. This implies very little over-voltage on the trigger electrode even though there is a factor of thirty difference in the voltage risetime between
FIGURE 33
TRIGGER VOLTAGE WAVEFORM
HORIZONTAL 0.2\mu s/div, VERTICAL 2KV/div

FIGURE 34
UNIFORM FIELD 4mm AIR GAP, BREAKDOWN WAVEFORM
HORIZONTAL 5us/div, VERTICAL 2.5KV/div

N_2 \text{ PRESSURE } 2\text{Atm}
JITTER \sim 75\text{ns}
the car ignition coil and the Hartley Measurements or laboratory wound transformer. The delay time and total jitter of another nitrogen pressurized spark gap were measured by Godfrey. At low D.C. voltages on the opposite electrode, spark gap delay time of 30µs were found; at about 85-90% of the self-breakdown voltage of the main gap the delay was reduced to 0.1µs with a jitter of 50ns.
12.iii Trigatron Spark Gap Design

The trigatron spark gap is shown in the cross-section in figure 35. A picture of the dis-assembled spark gap is shown in figure 36. The pressurized cavity consists of two aluminium plates screwed onto an insulating nylon body. Between the two is an 'o' ring to form the pressure seal. The main electrodes (with non-critical profiles) screw onto the aluminium plates. One electrode has a threaded hole in its centre to receive a modified car ignition spark plug (Champion G-61) to form the trigger electrode.

The spark gap was designed to operate over the voltage range 15 - 30KV and between 60 - 80% of its self-breakdown voltage, using dry nitrogen in the pressure range 1.2 - 2.0 atmospheres. The design parameter on the main gap was 30KV/cm/Atm. Nitrogen was flowed through the discharge region to remove discharge reaction products. An electrode aspect ratio (electrode diameter/main gap) of about 4:1 was recommended to produce a uniform field and low jitter. It is therefore better to operate the spark gap at high pressures with a small main gap. A recommended electrode material was stainless steel, however, 40mm stainless steel rod was not readily available and so brass was used instead. An important practical point was the ease in dismantling the spark gap for cleaning purposes and removing deposits due to sputtering. This was especially relevant for the trigger discharge and this is why a replacable car ignition spark plug was used as the trigger electrode.

The assembled spark gap mounted on the high voltage storage capacitor is shown in figure 37. The pulse transformer
ALUMINIUM PLATE

SPARK PLUG

NYLON BODY

GAS IN

GAS OUT

ALUMINIUM PLATE

MAIN ELECTRODE

FIGURE 35

TRIGATRON SPARK GAP DESIGN
FIGURE 36
Dismantled Spark Gap
FIGURE 37

ASSEMBLED SPARK GAP
and trigger unit are included to indicate relative sizes. When the spark gap was operated, several observations were made.

i) In order to stop the high voltage tracking over the outer surface of the spark gap, the edges of the aluminium plates were rounded to improve field uniformity. More importantly though, the metal pipe fittings where the gas enters and leaves the spark gap were replaced by nylon ones.

ii) The initial main gap was 8mm and found to be too large for reliable triggering when operated in the voltage range 15 - 30KV. A smaller gap of 6mm was found to be much more suitable. Table 3 shows the minimum electrode-electrode voltage and the self-breakdown voltage over the pressure range 1 - 2 atmospheres.

Table 3

D.C. Spark Gap Breakdown Measurements

<table>
<thead>
<tr>
<th>Pressure of N₂ /bar</th>
<th>Minimum E-E voltage /KV</th>
<th>Self-breakdown voltage/KV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>1.2</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>1.4</td>
<td>10</td>
<td>29</td>
</tr>
<tr>
<td>1.6</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>1.8</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The self-breakdown voltage varies linearly over the pressure range involved and gives a breakdown figure of approximately 30KV/cm/Atm. This is in agreement with the design parameter mentioned earlier.

iii) Brass was found to be a suitable electrode material which did not sputter away significantly around the trigger electrode hole. However, when an insufficient nitrogen flow rate was used a black 'sooty' type residue coated both electrodes in the discharge region. The residue did not seem to impair the spark gap's performance and could be removed by simply wiping away with a cloth.

A similar spark gap using aluminium electrodes was operated by Nablan. No black residue was observed and therefore the spark gap needs cleaning less frequently. The main problem with aluminium electrodes was the high sputtering rate of the material around the trigger hole. This led to unreliable triggering.

iv) Reliable triggering was only found to occur when the trigger discharge between the trigger-electrode and adjacent-electrode was physically inside the main discharge. If the trigger hole around the spark plug was not suitable a discharge will occur inside the hole and the ultra-violet light from this discharge will not illuminate the main gap sufficiently. These points are illustrated in
figure 38 where the correct and incorrect operation is shown. Correct operation was ensured by using a small nylon insert placed around the trigger pin of the spark plug. The trigger discharge then occurred as a surface discharge between the trigger pin edge and the adjacent-electrode.
TRIGGER DISCHARGE GEOMETRY
A general view of the assembled laser is shown in figure 29. The 50nF (Maxwell) external storage capacitor is connected to the laser head by thin brass sheets via the spark gap. The laser head design can be considered in two parts: the pressure cell and the discharge head. The pressure cell contains the laser gas mixture - its construction is indicated in the cross-sectional drawing shown in figure 40. P.V.C. was used as a constructional material because of its relative inertness to attack by the halogen donor, HCL. Six bolts served to clamp the square P.V.C. end plates to the standard pipe end flange. An 'o' ring set into the pipe end flange formed the vacuum/pressure seal between the flange and end plates. The cell was evacuated and pressurized via a single tube through the P.V.C. end plate. Mirror adjustment was achieved by compressing the 'o' ring on the mirror in the appropriate direction using the adjusting screws. The three adjusting screws for the output coupler are shown in figure 39. The diameter of the laser optics was 25mm; the rear mirror an aluminium reflecting surface, over-coated with silicon dioxide, the output coupler being a standard spectrosil B fused silica flat. An aluminium interface plate was used between the mirror holder and P.V.C. end plate so that the mirror adjusting screws turned in aluminium rather than the easy-wearing P.V.C.

The main problem in constructing the pressure cell was attaching the P.V.C. end flange squarely to the pipe end. The P.V.C. cement that was used to seal the joint between the pipe and end flange dries in a few seconds when the two parts come into contact with each other. The method used for making a pressure/vacuum tight
FIGURE 39

GENERAL VIEW OF THE EXCIMER LASER
FIGURE 40
CONSTRUCTION OF LASER HEAD
electrical connection through the P.V.C. pipe is shown in figure 41. The 'o' ring sits directly on top of the P.V.C. tube and is compressed by the internally chamfered washers to achieve a proper seal. A series of such connections distributed along the tube's length, as shown in figure 39, served to produce stripline connections from the discharge head to the spark gap and storage capacitor.

The pressure pipe contains the discharge head which sits centrally inside the P.V.C. pipe. This is illustrated in figure 42 where a cross-sectional drawing of the laser is shown. The laser head assembled and sitting inside the P.V.C. pipe is shown in figure 43. The construction of the head is indicated in figures 44 and 45, where the head is shown in an assembled and dismantled state. It consists of two rectangular aluminium plates held apart at the four corners by P.V.C. pillars. The aluminium electrodes of a non-critical profile are screwed onto the aluminium plates. The main discharge gap is 20mm and can be adjusted by varying the P.V.C. pillar height. The internal peaking capacitors consist of a parallel array of eight 1.25nF steatite and porcelain, barium titanate (BaTiO₃) doorknob capacitors mounted on either side of one electrode. The total internal capacitance is therefore 20nF. A small gap of about 3mm was left between each screw-point and the top of the capacitor which forms the gap for the preionizing arc. Slots were cut in the aluminium plates to receive the capacitors and screws. This enabled the horizontal distance of the preionizing arc to the main discharge to be varied. Asymmetric electrodes were used so that the preionizing arcs could be situated adjacent to the central portion of the main discharge. The peaking capacitors were purchased without metallic studs mounted on
P.V.C. TUBE

BOLT

CHAMFERED WASHER

BRASS SHEET

BRASS SHEET

FIGURE 41

PRESSURE/VACUUM TIGHT ELECTRICAL CONNECTION THROUGH P.V.C. TUBE
INTERNAL PEAKING CAPACITORS

P.V.C. PILLARS

ALUMINIUM PLATES

P.V.C. TUBE

MAIN DISCHARGE ELECTRODE

PULSE TRANSFORMER

TRIGATRON SPARK GAP

PREIONIZING PINS

BRASS SHEET ELECTRICAL CONNECTIONS

50nF STORAGE CAPACITOR

FIGURE 42

LASER ASSEMBLY
FIGURE 43

DISCHARGE HEAD SITUATED INSIDE THE P.V.C. TUBE
FIGURE 45

DISMANTLED DISCHARGE HEAD
either end, they simply had an evaporated silver coating over the ceramic. Brass studs, one for attaching to the aluminium plate and the other to receive the preionizing arc were attached to the silver contacts using Wood's metal solder. Care had to be taken when soldering so as not to over-heat the solder and not to oxidise the joint by using insufficient flux. The geometric position of the preionizing arcs relative to the main discharge was altered by tilting the capacitors as is shown in figures 44 and 45. The capacitors were leaned towards the main discharge so that the preionizing arcs illuminated a maximum discharge volume. The preionizing pins shown in figure 42 were replaced by a continuous sheet of brass attached to the upper aluminium plate and bent so as to achieve the correct preionizing arc position. This is indicated most clearly in figure 45.
12.v Gas Handling System

The gas handling system is shown in figure 46 and is relatively self-explanatory. The principle of operation is to evacuate the system to 1 mbar with the rotary vacuum pump and then to isolate the pump from the rest of the system. The low pressure gauge controls the addition of HCl and xenon. Helium is then added as the buffer gas. The halogen filter mounted on the rotary vacuum pump removes HCl when the system is to be re-evacuated.

All three gases were of greater than 99.99% purity. The helium and xenon bottles were both regulated by single-stage regulators to give a maximum output of 2.7 bar and 2.0 bar respectively. A technique was used whereby no HCl regulator was required. HCl regulators are relatively expensive and have been known to fail. Prolonged exposure of the stainless steel diaphragm to the very corrosive HCl gas has sometimes led to it cracking. The method used was to pressurize a small section of stainless steel pipe (AC in figure 46) to some fraction of the full HCl bottle pressure of 600 lb. HCl at a reduced pressure was then released into the pressure cell of the laser via another control valve.

Those components in contact with the high pressure HCl were made of stainless steel. PTFE pipe and brass components were used in the rest of the system. Three makes of gas fittings were used: Swagelok, Gyrolok and Enots. The first two, Swagelok and Gyrolok were found to be more suitable under vacuum than Enots. A permissible vacuum leak rate of 1–2 mbar/hour was used. The system was also pressure tested at 2.7 bar using soap solution around all joints. An important practical point is that the compression fittings should not be over-tightened. It
FIGURE 46
GAS HANDLING AND VACUUM SYSTEM

ON/OFF VALVE

NEEDLE VALVE
is also useful to inspect the compression olives for scratches before assembly as this is a possible leak source.

The low pressure indicator is a 0 - 1000 mbar, Leybold-Heraeus gauge designed for use with corrosive gases. To reduce the affect of HCl on the gauge it was isolated after the helium pressure had been increased to 1.0 bar. The halogen filter mounted on top of the vacuum pump was simply a cell containing sodium hydroxide crystals. The gases from the vacuum pump were vented to the outside atmosphere.

Passivation of the pressure lines and pressure cell is an important aspect to consider before the discharge is operated with a laser gas mixture. Contaminants such as water vapour can not only stop the laser operating but also react with the HCl gas to form hydrochloric acid vapour. This extremely corrosive compound can then attack the components within the system. The procedure adopted for passivation was to initially flush the system several times with helium after pumping down to ~0.1 mbar each time. Discharge operation seemed to improve in the laser gas mixture if the discharge was operated before this in helium and a helium plus the HCl mixture (<5% HCl). Two possible explanations for this behaviour are:

i) Electrode conditioning,

ii) Discharge reaction products originating from the HCl, coating the internal components and so improving passivation for when the laser gas mixture is added.

The passivation procedure was to initially operate the discharge in helium at 2.7 bar for about five minutes, then to evacuate and
use a helium plus HCl mixture, usually 0.2 - 0.3% HCl. The
discharge was then operated for about 15 minutes at about 1HZ
repetition rate. A new helium plus HCl mixture was then added
and the procedure repeated except the gas was kept in the cell
and the discharge operated intermittently over a 3 - 4 hour
period. This seemed to give time for the HCl to react chemically
and produce a passivated layer over the internal components.

The procedure for adding gas to the pressure cell was
relatively straight-forward. With all valves closed on the
xenon and helium lines, HCl was added to the required pressure
as indicated on the low pressure gauge. The HCl valves were
then closed and the xenon added finally followed by the helium.
An extra on/off valve was used after the needle valve on the
xenon and helium lines to help prevent HCl attacking the needle
valves. The xenon and helium lines were kept pressurized with
their respective gases to stop HCl contaminating these sections.

When the laser was not being operated the pressure cell
was left at about 2.5bar so that any leaks would be outwards.
When the pressure cell was allowed up to atmosphere for
dismantling, it was noticed that the internal components often
appeared wet. This wetness was presumably HCl and its reaction
products reacting with water vapour in the atmosphere.
12.vi Laser Operation

12.vi.a Discharges in Helium

The laser was initially operated in pure helium to gain some understanding of the important parameters which control the discharge quality. The maximum operating voltage was about 32KV and was limited by the power supply, safety aspects and corona discharges in the air. The maximum operating pressure was 2.7bar (absolute) and was limited by the pressure regulator on the helium bottle. Operation in helium soon showed that the distance between the main discharge electrodes and preionization pins, (distance AB in figure 47) had to be optimised to prevent preferential arcing between the two. The first pair of discharge electrodes were made from 10mm wide aluminium, (337mm long) and rounded so that a central 4mm wide flat region existed on the top of both electrodes. The main gap was 17mm. When the distance AB was too small an arc discharge occurred between the stud on the peaking capacitor and the main discharge electrodes in preference to a glow discharge between the main electrodes. In order to marginally increase the distance AB without moving the capacitors further from the main electrodes epoxy (araldite) was covered over the metal capacitor stud except for its very tip. Slots were cut in both aluminium plates so that the distance AB shown in figure 47 was variable. The minimum distance AB to prevent side arcs but to produce a uniform, characteristically 'pinkish' helium glow discharge was 30mm.

The effect on the glow discharge in helium of varying the preionizing gap BB in figure 47 was investigated. The effect on the glow discharge of applying the voltage transient to either
FIGURE 47

Schematic diagram of the position of the preionization pins relative to the discharge electrodes.
aluminium plate was also investigated. The peak voltage and pressure at which a uniform glow discharge could be achieved was used as a comparison figure. Three preionization gaps were tried, 2/3mm, 4/5mm and 10mm. For each gap, both polarities on one aluminium plate were tried, i.e., the plate holding the preionization pins as anode (relative to the other plate) and the plate holding the peaking capacitors as anode.

With a 2/3mm preionization gap and the capacitor plate acting as anode the extreme range for a glow discharge was 20KV at a pressure of 1.8bar. With the plate holding the preionizing pins as anode a glow discharge was achieved up to a maximum charging voltage of 32KV at a maximum operating pressure of 2.7bar. At lower pressures, the limiting charging voltage to produce a glow discharge instead of an arc discharge were similar when either aluminium plate acted as anode. With the 4/5mm preionizing gap and the 10mm preionizing gap the difference in performance between the differing plate polarities was less noticeable. The best operational parameters therefore should be - a preionizing gap of 2/3mm with the plate holding the preionizing pins acting as anode.
12.vi.b Nitrogen Laser Operation

When the discharge was operated using one particular bottle of helium, ultra-violet laser emission was observed and shown to be nitrogen laser emission at 337nm. The helium bottle which produced the UV emission was discovered to have a purity of only 98%. The remaining impurity was considered to be air. Lasing was observed to occur over the pressure range 1 - 2bar with an estimated nitrogen content of 15 - 30mbar.

12.vi.c Operation in Xe:HCl:He mixtures

An estimate of the required gas mixture for XeCl excimer operation using HCl as the halogen donor and helium as the buffer gas was found from the literature. The maximum HCl concentration at any pressure was 0.5% but more typically about 0.2%. The Xe:HCl ratio varied from 5:1 to 25:1. The pressure range was generally from 1 - 3bar. Xenon gas is very expensive and only a limited supply was available, operation at a lower Xe:HCl ratio was therefore preferred. The following Xe:HCl ratios were tried with helium as a buffer gas at a pressure varying up to 2.7bar and a charging voltage varying up to 30KV.

\[
\begin{align*}
\text{Xe:HCl} & \quad = \quad 7:1 \\
\text{Xe:HCl} & \quad = \quad 10:1 \\
\text{Xe:HCl} & \quad = \quad 12:1 \\
\text{Xe:HCl} & \quad = \quad 15:1 \\
\end{align*}
\]

All mixtures gave a blue fluorescent output, the intensity of which increased with charging voltage. Varying the helium pressure had no affect on the fluorescent output. The output was
also not sensitive to adjustments on the rear laser mirror. Visual observation of the glow discharge showed streamer arcs between both edges of the main electrodes. To check that the fluorescent output was not caused by contaminants, as was present in the helium previously, the following gas mixtures were tried:

<table>
<thead>
<tr>
<th>Gas Mixture</th>
<th>Fluorescent Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure helium, 0.7 - 2.5 bar</td>
<td>No fluorescent output</td>
</tr>
<tr>
<td>15 mbar Xe 1 - 2 Atm He</td>
<td>Fluorescent output</td>
</tr>
<tr>
<td>10 mbar Xe 1 - 2 Atm He</td>
<td>Fluorescent output present</td>
</tr>
<tr>
<td>1.75 mbar HCl</td>
<td>+ He - No fluorescent output</td>
</tr>
<tr>
<td>3.5 mbar HCl</td>
<td></td>
</tr>
<tr>
<td>6.0 mbar HCl</td>
<td></td>
</tr>
</tbody>
</table>

These results indicate that it was the xenon causing the fluorescence, contaminants in the xenon bottle were disregarded because research grade xenon was used, (>99.99% purity). A range of laser gas mixtures, charging voltages and gas pressures were tried without any laser emission being observed. It was felt that incorrect mirror alignment or the presence of streamer arcs in the main discharge were the probably explanations for the lack of lasing emission.

The laser mirrors were accurately aligned using a helium neon laser. A small laser output was observed and measured using an absorbing cone calorimeter, (calibration 18mJ/div). With an HCl content of 2 mbar and a Xe:HCl ratio of 15:1, an output varying between .75 - 1.5 mJ was obtained at 2.7 bar over the range 20 - 32 KV.
The variation of laser output energy against helium pressure is shown in figure 48 for two gas mixtures. The output energy appears to be scaling linearly with pressure up to 2.7bar.

To improve on the electric field uniformity it was decided to try wider electrodes, (20mm). This enabled the curvature of the electrodes' edge to be increased. Again the electrode-edge preionizing gap distance, AB in figure 47, had to be optimised. The following operational parameters were used:

main discharge gap 19.5mm
preionizing gap ~3mm
distance AB = 32mm

The glow discharge in helium at high pressure was observed to be rather non-uniform and streamer-like. Helium-HCl gas mixtures in the range 1 - 5mbar of HCl were tried. A non-uniform discharge was observed even with 1mbar of HCl. Finally, a 10:1, Xe:HCl laser gas mixture was tried. No lasing was observed, only the familiar fluorescent output from xenon.

With wider electrodes the distance from the preionizing arc to the centre of the main discharge is increased. The preionization electron density in this region must therefore be decreased. An estimate of the reduction in the preionization electron density is going from 10mm wide electrodes to 20mm wide electrodes can be made by assuming a $1/r^2$ dependance, (see Chapter 11). Assuming the arc-source electrode-edge distance is constant in both cases (~30mm) the reduction is given by the factor $35^2/40^2 = .76$. It was felt that this reduction might be
FIGURE 48

LASER OUTPUT PLOTTED AGAINST HELIUM PRESSURE
counter-acted somewhat if the illumination of the main discharge by the preionizing arcs could be improved. The peaking capacitors were therefore mounted on the aluminium plates at a tilt as shown in figure 45. In this way the capacitor edge and epoxy covering does not obscure the preionizing arc as much. With a preionizing gap of 3mm and capacitor-stud electrode-edge distance of 32mm a uniform glow discharge was achieved over the pressure range 0.9 - 2.5bar. Three He:HCl mixtures were tried with 1, 2 and 5mbar of HCl. The main discharge consisted purely of arcs when the 5mbar of HCl was used. This indicated an approximate figure for the maximum HCl content in a Xe:HCl:He gas mixture. Laser emission was observed for several gas mixtures with the capacitors tilted relative to the main electrodes as described.

The laser energy measurements shown in figures 49 to 52 were taken with a pyroelectric, GentecED-500 joulemeter with a calibration figure of 2.5mJ/mV. Figure 49 is a graph of the output energy plotted against helium pressure. This was for a 3.5mbar HCl, 15mbar Xe gas mixture at a charging voltage of 26KV. The output energy reaches a peak of 5.5mJ at a pressure of 2.2bar. The variation of laser output energy with helium pressure shown in figure 50 was for a 3.25mbar HCl, 20mbar Xe gas mixture measured at a charging voltage of 28KV. The graph only begins to become concave towards the pressure axis at about 2.2bar, although the output is still increasing with pressure. A maximum output of 8.5mJ was measured at 2.7bar. The main differences in circumstance between figures 49 and 50 is the increase in charging voltage, 28KV instead of 26KV and an increase in the Xe:HCl ratio of about 6:1 instead of 4:1. A relative comparison of the efficiencies can be made at a given pressure if the results
FIGURE 49

LASER OUTPUT ENERGY PLOTTED AGAINST HELIUM PRESSURE
Figure 50

Laser output energy plotted against helium pressure

3.25 mbar HCl
20 mbar Xe
28 KV

Output from laser - 17 hours later
from figure 49 are multiplied by the factor \((28/26)^2\). This takes account of the difference in charging voltage and therefore stored energy in the main capacitor. The results are shown in Table 4 up to a pressure of 2.2bar. The difference in output energy can be accounted for by the difference in charging voltage up to a pressure of 2.2bar. These results show that the two gas mixtures have about the same operating efficiencies up to the optimum operating pressure of 2.2bar for the 3.5mbar HCl, 15mbar Xe gas mixture. Thereafter, the efficiencies differ greatly.

Included in figure 50 is the output energy of the laser after it had been left to stand over-night, (17 hours). The output has decreased to 30 - 35% of its initial value over the 17 hour period. This gives a linear reduction in the output energy of about 4%/hour.

Figure 51 shows the output energy plotted against helium pressure for a slightly lower HCl content, 2.5mbar, but the same Xe:HCl ratio as that in figure 50, 6:1. These measurements were taken at a charging voltage of 24KV. The gradient of the graph in figure 51 appears to be decreasing as the pressure is increased. This suggests the peak output is at a lower pressure than that for figure 50. A peak output of 6mJ was measured at 2.7bar. A comparison between the results in figure 50 and figure 51 is shown in Table 5. It indicates that the efficiency of the laser with the 2.5mbar HCl content is about 90% of that of the results taken with the 3.25mbar HCl content.

Figure 52 shows a graph the laser output energy plotted against charging voltage at three different helium pressures, 1.7bar, 2.3bar and 2.7bar. The gas mixture is the same as that in figure 51. The format of the variation is similar for all
Table 4

Comparison of Laser Efficiency Data from Figures 49 and 50

<table>
<thead>
<tr>
<th>Pressure</th>
<th>A/mJ</th>
<th>B/mJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>3.2</td>
<td>2.78</td>
</tr>
<tr>
<td>1.6</td>
<td>3.65</td>
<td>3.47</td>
</tr>
<tr>
<td>1.7</td>
<td>4.2</td>
<td>4.29</td>
</tr>
<tr>
<td>1.8</td>
<td>4.8</td>
<td>4.9</td>
</tr>
<tr>
<td>1.9</td>
<td>5.45</td>
<td>5.45</td>
</tr>
<tr>
<td>2.0</td>
<td>6.0</td>
<td>5.9</td>
</tr>
<tr>
<td>2.1</td>
<td>6.2</td>
<td>6.26</td>
</tr>
<tr>
<td>2.2</td>
<td>7.2</td>
<td>6.4</td>
</tr>
</tbody>
</table>

A = Output from figure 50

3.25mbar HCl; 20mbar Xe; 28KV

B = Output from figure 49 \((28/26)^2\)

3.5mbar HCl; 15mbar Xe; 26KV
FIGURE 51

LASER OUTPUT ENERGY PLOTTED AGAINST HELIUM PRESSURE
### Table 5

Comparison of Laser Efficiency Data taken from Figures 50 and 51

<table>
<thead>
<tr>
<th>Pressure /bar</th>
<th>A/mJ</th>
<th>B/mJ</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>3.65</td>
<td>3.13</td>
<td>.86</td>
</tr>
<tr>
<td>1.7</td>
<td>4.2</td>
<td>3.81</td>
<td>.91</td>
</tr>
<tr>
<td>1.8</td>
<td>4.8</td>
<td>4.49</td>
<td>.93</td>
</tr>
<tr>
<td>1.9</td>
<td>5.45</td>
<td>5.03</td>
<td>.92</td>
</tr>
<tr>
<td>2.0</td>
<td>6.0</td>
<td>5.5</td>
<td>.91</td>
</tr>
<tr>
<td>2.1</td>
<td>6.2</td>
<td>5.9</td>
<td>.95</td>
</tr>
<tr>
<td>2.2</td>
<td>7.2</td>
<td>6.39</td>
<td>.89</td>
</tr>
<tr>
<td>2.3</td>
<td>7.65</td>
<td>6.8</td>
<td>.89</td>
</tr>
<tr>
<td>2.4</td>
<td>8.1</td>
<td>7.07</td>
<td>.88</td>
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<td>2.5</td>
<td>8.4</td>
<td>7.41</td>
<td>.88</td>
</tr>
<tr>
<td>2.6</td>
<td>8.65</td>
<td>7.69</td>
<td>.89</td>
</tr>
<tr>
<td>2.7</td>
<td>8.85</td>
<td>7.96</td>
<td>.90</td>
</tr>
</tbody>
</table>

A = Output from figure 50  
3.25mbar HCl, 20mbar Xe, 28KV

B = Output from figure 51 x(28/24)^2  
2.5mbar HCl, 15mbar Xe, 24KV
FIGURE 52

LASER OUTPUT ENERGY PLOTTED AGAINST CHARGING VOLTAGE
three pressures, as expected. As the pressure is increased the peak output occurs at a higher charging voltage as indicated by the dotted line. This is readily explained in terms of the discharge parameter $E/p$. For a constant discharge gap, as the pressure is increased the voltage required to maintain the optimum $E/p$ must also increase.
13. DISCUSSION AND CONCLUSIONS

The main design constraint for the pressure cell was the use of P.V.C. as a constructional material. This limited the halogen donor to HCl and therefore the laser to a XeCl excimer. P.V.C. is chemically inert to HCl but this is not the case with fluorine. Suitable fluorine resistant plastics are polytetrafluoroethylene, P.T.F.E., manufactured by I.C.I. Ltd under the trade name of Fluon, and chlorotrifluoroethylene, manufactured by 3M's Ltd under the trade name of Kel-F 81. These latter two materials were not used because of their expense. Perspex was also considered as a possible constructional material but was found to be chemically attacked by HCl and fluorine.

Improvements in the laser head design became apparent with hindsight. Two in particular are worth noting. The discharge uniformity was difficult to observe because it was enclosed in an opaque P.V.C. tube. Transparent P.V.C. tube is believed to be available and this would certainly improve visual observations. Laser emission was found to depend critically on the correct alignment of the laser mirrors. Precise control of the alignment of the laser mirrors by compression of an 'o' ring was found to be very difficult. This was because the 'o' ring was always tightly compressed to prevent the laser gas mixture leaking to the atmosphere. A technique to overcome this problem would be to use UV transmitting windows such as fused silica and external micrometer controlled mounts to hold the laser mirrors. Laser oscillation between the fused silica windows could be prevented by tilting them at a few degrees relative to the normal to the laser axis.
Initially several laser gas mixtures were tried but no lasing emission was observed. This was probably caused by arcing in the main discharge preventing lasing. Improvement in the volumetric preionization and electric field uniformity led to the observed laser output. The preionization was improved by optimising the distance between the internal capacitor stud and main electrode and also tilting the capacitors so that the illumination of the main discharge by the preionizing arc was improved. The electric field uniformity was improved by using wider electrodes and therefore increasing the radius of curvature of the electrode's edge.

The XeCl laser energy output using helium as a buffer gas was generally observed to increase as the helium pressure was increased. In the pressure region of 2.7bar the variation in laser output energy for most gas mixtures tended to become concave towards the pressure axis indicating the optimum pressure for the particular gas mixture was being approached. This behaviour was also observed by Sze, the peak output is associated with the optimum E/p value for laser operation. Extrapolating the results in figures 50 and 51 gives a maximum laser output in the pressure region of 3.0bar. This is in approximate agreement with Sze using helium buffer gas. This behaviour of an optimum E/p value for a maximum laser output is shown in figure 52. The optimum charging voltage increases with pressure to maintain the optimum E/p.

The maximum observed output energy was about 10mJ, measured at a charging voltage of 30Kv and helium pressure of 2.7bar. This corresponds to a stored energy of 22.5J in the 50nF storage capacitor. These figures give a wall-plug efficiency of about
0.045%. This figure is rather low compared to the generally accepted figure of 0.5 - 2%\textsuperscript{28,45}. However, a comparable figure of 0.09% was obtained by Kearsley et al\textsuperscript{51} with a similar laser design. The large discrepancy between the two efficiencies is partly due to a difference in definition. The wall-plug efficiency for the XeCl excimer described here includes the preionization circuit. The figure of 0.5 - 2% only involves the total energy dissipated in the main discharge, it does not include the energy dissipated in the preionization circuit.

The limitation of using a small quantity of xenon meant that a full optimization procedure could not be investigated. Further work could involve the optimization of the many parameters that are readily changeable. An optimised gas mixture could be found, preferably with a low Xe:HCl ratio. The main electrode profiles and discharge gap could be varied to improve field uniformity. The effect on the laser output of varying the external and internal capacitance, and also their ratio $C_1/C_2$ could also be investigated. This would necessarily produce a change in the inductance of the relevant portion of the circuit which controls the voltage and current risetimes. An improvement in the preionization uniformity should occur if the longitudinal arc density is increased. This could be achieved by using smaller diameter internal capacitors and therefore increasing the number per unit length.
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