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L E SHARP
A T WETHERELL

Culham Laboratory
Abingdon Berkshire

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by

L.E. Sharp and A.T. Wetherell

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ABSTRACT

By optimizing the discharge parameters of a pulsed HCN laser, peak powers up to 1 kW have been obtained with the output radiation predominantly in the lowest transverse mode.

The production of discharge impurities at high input power limits the long term repetitive operation to 450 W output. Details of the variation of power with discharge voltage, repetitive rate, gas composition and flow rate are given and suggestions for further increasing the power are made.

U K A E A Research Group,
Culham Laboratory,
Abingdon,
Berks

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CONTENTS

I. INTRODUCTION

The 337 μ wavelength of the H C N laser is very convenient for laboratory scattering experiments on turbulent plasmas where the correlation length of density fluctuations can typically be of the order 10^{-2} to 10^{-1} cm. As the scattered signals can be many orders of magnitude smaller than the incident beam, radiation sources suitable for this measurement require high power and small beam divergence. Unfortunately the gain of the H C N laser (compared with the CO_2, ruby and glass lasers) is very low[1,2] and the peak power previously reported in the literature[3-6] is of order 10 watts. This is in general too low to obtain time resolved spectra of the turbulence since the presently available detectors with sufficient sensitivity have too narrow a bandwidth[7].

In order to increase the output power of the H C N laser we have optimized the resonator and discharge parameters and so produced a repetitive peak pulsed power of 450 watts predominantly in the lowest transverse mode. This is a factor 10 greater than most reports and a factor 4 greater than that reported by Stafsudd et al[6]. We have found that in the self Q-spoiled mode of operation[8], the power increases roughly in proportion to the volume, so that the largest useful output for this type of laser will be set by the maximum acceptable physical size.

II. EXPERIMENTAL PROCEDURE

A schematic diagram of the gas laser system is shown in Fig.1. The discharge tube is constructed from Pyrex with an internal bore of 15 cm and length 367 cm. The Fabry-Perot resonator is formed from two circular aluminized plate glass mirrors, 14 cm diameter and mounted approximately 360 cm apart on flexible bellows, which allow independent axial and tilt adjustment. The radiation is coupled out from the cavity by a small central hole in the fixed mirror via a 100 μm thick Mylar vacuum window. Excited HCN molecules are produced by an axial electrical discharge through a continuous flowing methane nitrogen gas mixture at a total pressure of 0.7 torr. The excitation current was produced by a 10 Ohm 10 μs pulse line charged to a maximum voltage of 20 kV and discharged through an ignitron switch to two copper electrodes in the side arms, shown in Fig.1. The gas current was typically 560 amps and the pulse repetition rate was 3 s^{-1}. The radiation was monitored either by a Golay cell or, where time resolution was required, with an InSb photoconductive detector cooled to 1.5 °K in a magnetic field of 7.1 kG.

III. OPTIMIZATION OF OUTPUT POWER

A. Gas Parameters

The peak output power was found to be very sensitive to the composition (nominally 1:1) of the gas mixture which was therefore optimized experimentally each time. It was less dependent on the total gas pressure and flow rate, as shown in Fig.2. For subsequent measurements the operating conditions were standardized at a total pressure of 0.7 torr, and a flow rate of 1.4 ℓtorr/min which is in the region of a broad maximum.

Fig.3(a) shows that the laser output power plotted as a function of discharge voltage is relatively insensitive to the repetition rate over the range $1 - 8\ s^{-1}$. At higher rates we have observed a marked increase of a factor of 2 in the output power for discharge voltages (measured between the electrodes) greater than 16 kV, but this condition lasted for only about 100 consecutive discharges, presumably due to an increased concentration of other discharge compounds which quench the laser action at these small flow rates. As we have not studied this region in detail, for the purpose of the present investigation we have standardized the repetition rate to $3\ s^{-1}$; Fig.3(b) shows the output power as a function of discharge voltage at this rate. The output power is maximum at a discharge voltage of 16 kV, corresponding to a total input energy of 90 J. The decrease in power for higher input energies is probably due partly to the laser saturation effect reported by a number of authors[1,2] and seen by us for smaller diameter resonators (III. B), and partly to the instability of the discharge column when the current channel starts to pinch. This latter effect could be minimized by producing a number of transverse discharges along the resonator which would allow the current in each discharge to be less than the limit set by the Bennet relation[9].

B. Resonator Geometry

As well as the geometry already described we have also examined two other cavities of identical length but with diameters of 5 and 7.5 cm. Although comparison between them is complicated by the different currents needed for different size tubes (the current density must be approximately constant) the maximum power increased at least in proportion to the volume. Because mode purity and ease of alignment were important we did not further increase the volume by increasing the length. For the smaller diameter tubes the guiding effect of the walls[10] produced by total internal reflection from the glass, was found to strongly influence the output power and mode structure but was not as important for the 15 cm diameter tube where the Fresnel number = 4.

IV. OUTPUT COUPLING AND MODE STRUCTURE

We tried four different coupling holes, and found maximum peak power output for $d = 2.7$ cm. This corresponds to 4% of the total mirror area compared with 8% found by Kotthaus[11].

To obtain an estimate for the effective spot size, we follow the suggestion of Smith and Sorokin[12] in taking the plane parallel configuration equivalent to mirrors of large radii of curvature. The value of the radius of curvature is deduced from Fox and Li's[13] numerical result that the phase at the flat mirror's edge lags the centre by 30°. With this approximation the expression for the effective spot size (radius) W of the equivalent curved mirrors of diameter d is:[12]

$$W^4 = \frac{d^2 L \lambda o}{4.13} \quad (L = 360 \text{ cm}, \quad d = 14 \text{ cm}, \quad \lambda = 337\,\mu),$$

giving $W = 2.6$ cm. If we assume that the spot has a Gaussian profile then the output coupling from the lowest transverse mode is approximately 50%.

Fig.4 shows the transverse variation of the radiation intensity across the emergent beam measured in the focal plane of a PTFE hyperbolic lens ($f = 20$ cm) placed at the laser output aperture. It shows a single main lobe with a full width of 0.9 cm at the −10 dB level. This is nearly twice the 0.5 cm width calculated for a uniformly illuminated aperture and approximately the same as the value 0.8 cm for a strongly tapered illumination function of the form[13] :

$$\left(1 - \frac{2\rho}{d}\right)^2$$

In comparing these results the following three factors must be taken into account. First, the 2 mm iris at the entrance window of the Golay radiation detector will introduce an instrumental broadening of 3 - 4 mm. Secondly the spatial distribution of the TEM_{00} mode itself varies across the aperture[14] so that we would expect a spot diameter between the two calculated values, and finally there will be a contribution from the TEM_{01} mode. A study of the laser interferogram for the cavity (Fig.5) suggests that the contribution from the TEM_{01} mode should be less than 20% so that the above results would be consistent with the output radiation being predominantly determined by the lowest transverse mode TEM_{00}.

Schwaller et al[15] have pointed out that the maximum gain line width for the 337 μm transition, $\Delta\nu_{gain} \sim$ 5-8 MHz,[16] is usually less than the minimum beat frequency between the modes:

$$\Delta\nu_{gain} < \Delta\nu_{modes} ,$$

and as a consequence the laser should oscillate in a single mode. The above criterion certainly holds in our case for the longitudinal modes where the minimum separation $\Delta\nu \approx C/2L$ is 40 MHz. The situation is different, however, for the lower transverse modes for which $\Delta\nu = \nu_{q00} - \nu_{q10} = 1$ MHz, and $\Delta\nu = \nu_{q00} - \nu_{q01} = 5$ MHz. Here the frequencies have been calculated from the well-known expressions[17]:

$$L_{qmn} = \frac{\lambda}{2}\left[q + \frac{1}{N}\left(\frac{P_{mn}}{2\pi}\right)^2\right] \qquad \ldots (1)$$

and

$$\nu_{qmn} = \frac{c}{2L_{qmn}} ,$$

where

$$N = \frac{a^2}{L} \approx 4 .$$

L_{qmn} is the resonance length of the $TEM_{q+1,m,n-1}$ mode, q is the longitudinal mode number, d the diameter of the mirrors, and P_{mn} is the n^{th} zero of the Bessel function of order m. Since on the laser axis the intensity of the TEM_{q01} mode is a minimum while the TEM_{q00} is maximum, the former should not contribute significantly to the output radiation for small coupling holes. The TEM_{q10} also appears to have little influence, as seen in the oscillogram shown in Fig.6, where there is no indication of the beats expected if this mode was present.

By measuring the intensity of the laser output as a function of resonator length[10] we can identify the various modes which may be excited within the cavity by comparing the position of the peaks of the resulting interferogram with the values of L_{qmn} given by equation (1). Such a resonator interferogram is plotted in Fig.5 where the dominant laser frequencies have been identified with a Czerny-Turner grating spectrometer, and the dominant modes from the relative position of the peaks.

V. TIME RESPONSE OF OUTPUT PULSE

Fig.6 shows the time variation of the output pulse; its duration is considerably shorter than the 100 μs observed by Steffen and Kneubühl[10], and calculated by them on the basis of Q-spoiling. The shorter time has been attributed by Steffen and Kneubühl[10], and McCaul[8], to the change in the optical path length caused by the change in the refractive index of the plasma during its decay. This sweeps the TEM_{qoo} cavity mode through the 337 μm gain-line and thus effectively shortens the pulse.

VI. ABSOLUTE POWER MEASUREMENT

Three methods were used to determine the peak power of the laser:

(1) The total energy of the laser pulse was measured with a factory calibrated Golay cell. The beam was suitably attenuated with calibrated absorbers and then focused onto the Golay entrance window with a TPX lens. The peak power was then estimated from the pulse shape obtained from the oscillogram, Fig.5.

(2) The InSb detector signal from the laser pulse was compared with that from a mercury lamp whose radiation was modulated with a high speed chopper. The mercury lamp and cavity[18] had been previously calibrated against a lead glass plate of known emissivity, heated to 250 °C. Calibrated

absorbers were inserted in the laser beam until the two signals being compared were of equal amplitude. A Czerny-Turner grating spectrometer, tuned to 337 μ, was used as a wavelength filter of 17 μ width and the higher orders rejected by grooved transmission filters[17].

(3) The power of a CW HCN (42 mW) laser was calibrated against a heated lead glass plate using a Golay cell: the output beam of the pulsed laser was attenuated with calibrated absorbers until the resultant signal from an InSb detector was the same as that obtained from the high speed (mechanical chopper) modulated beam of the CW laser.

VII. CONCLUSION

Our experiments suggest that the output power of the HCN laser might be further increased by as much as an order of magnitude using presently available techniques. First, if multiple transverse glow discharges are used, the column instability caused by high axial current should be eliminated while allowing adequate HCN production and excitation. Secondly, by increasing the repetition rate above $10\,s^{-1}$ while suitably adjusting the gas flow rate, we might expect an increase in output power of the type observed, without the consequent quenching presently experienced. Finally, by further increasing the tube diameter, the dependence on volume can be exploited. With suitable mirror geometry, it should be possible to obtain an output power of several kilowatts with the laser still operating predominantly in the lowest transverse mode.

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REFERENCES

[1] O.M. Stafsudd and Y.C. Yeh, I E E E J. Quantum Electron. QE-5, 377 (1969).

[2] R.G. Jones, C.C. Bradley, J. Chamberlain, H.A. Gebbie, N.W.B. Stone and H. Sixsmith, Appl. Opt., 8, 701 (1969).

[3] R. Turner and T.O. Poehler, J. Appl. Phys., 39, 5726 (1968).

[4] F. Arams, C. Allen, M. Wang, K. Button and L. Rubin, Proc. I E E E, 55, 420 (1967).

[5] L.E.S. Mathias, A. Crocker and M.S. Wills, I E E E J. Quantum Electron., QE-4, 205 (1968).

[6] O.M. Stafsudd, F.A. Haak and K. Radisavljevic, I E E E J. Quantum Electron, QE-3, 618 (1967).

7 R.K. Willardson and A.C. Beer, Eds., Semiconductors and Semi-metal, vol.5, Infrared Detectors, (Academic Press, New York, 1970.)

8 B.W. McCaul, Appl. Opt., 9, 653 (1970).

9 See D.J. Rose and M. Clark, Jr., Plasma and Controlled Fusion (M I T Press, Cambridge, Mass., 1961).

10 H. Steffen and F.K. Kneubühl, I E E E J. Quantum Electron, QE-4, 992 (1968).

11 J.P. Kotthaus, Appl. Opt., 7, 2422 (1968).

12 W.V. Smith and P.P. Sorokin, The Laser (McGraw-Hill, New York, 1966).

13 A.G. Fox and T. Li, Bell Syst. Tech. J., 40, 453 (1961)

14 S. Silver, Microwave Antenna Theory and Design, (Dover, New York, 1965).

15 P. Schwaller, H. Steffen, J.F. Moser and F.K. Kneubühl, Appl. Opt., 6, 827 (1967).

16 C.C. Bradley, N P L, (private communication)

17 F.K. Kneubühl and H. Steffen, Phys. Letts., 25A, 639 (1967).

18 M.F. Kimmitt and W. Bardsley, R R E Memo. no. 2124, (June 1965).

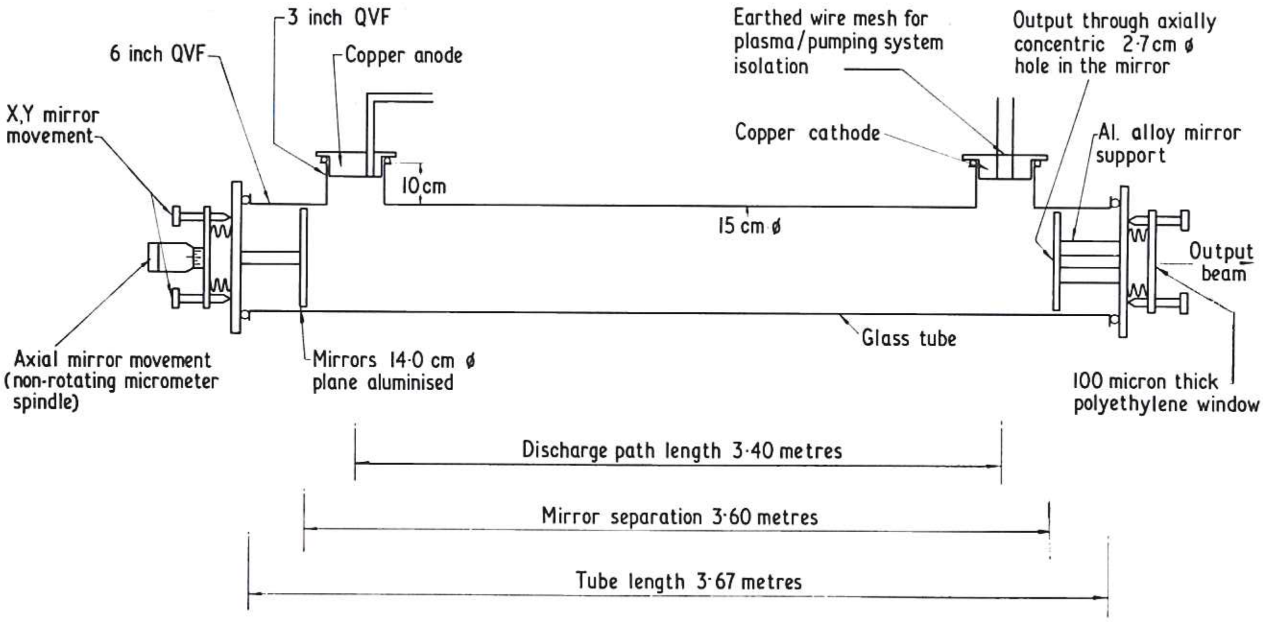

Fig.1 Schematic diagram of the laser cavity and discharge tube.

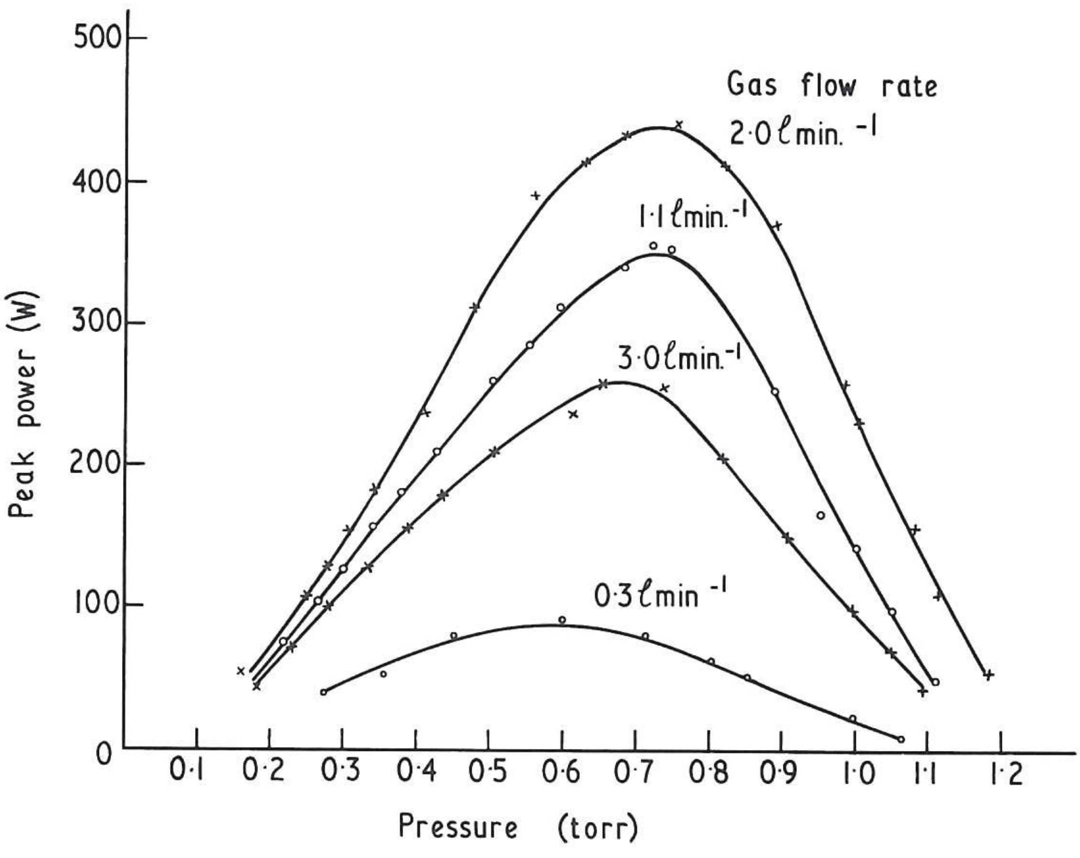

Fig.2 The laser output power vs pressure for different gas flow rates. Gas mixture of N_2 and CH_4 at the nominal ratio 1:1, V = 16 kV, I = 560 A, repetition rate 3 s^{-1}.

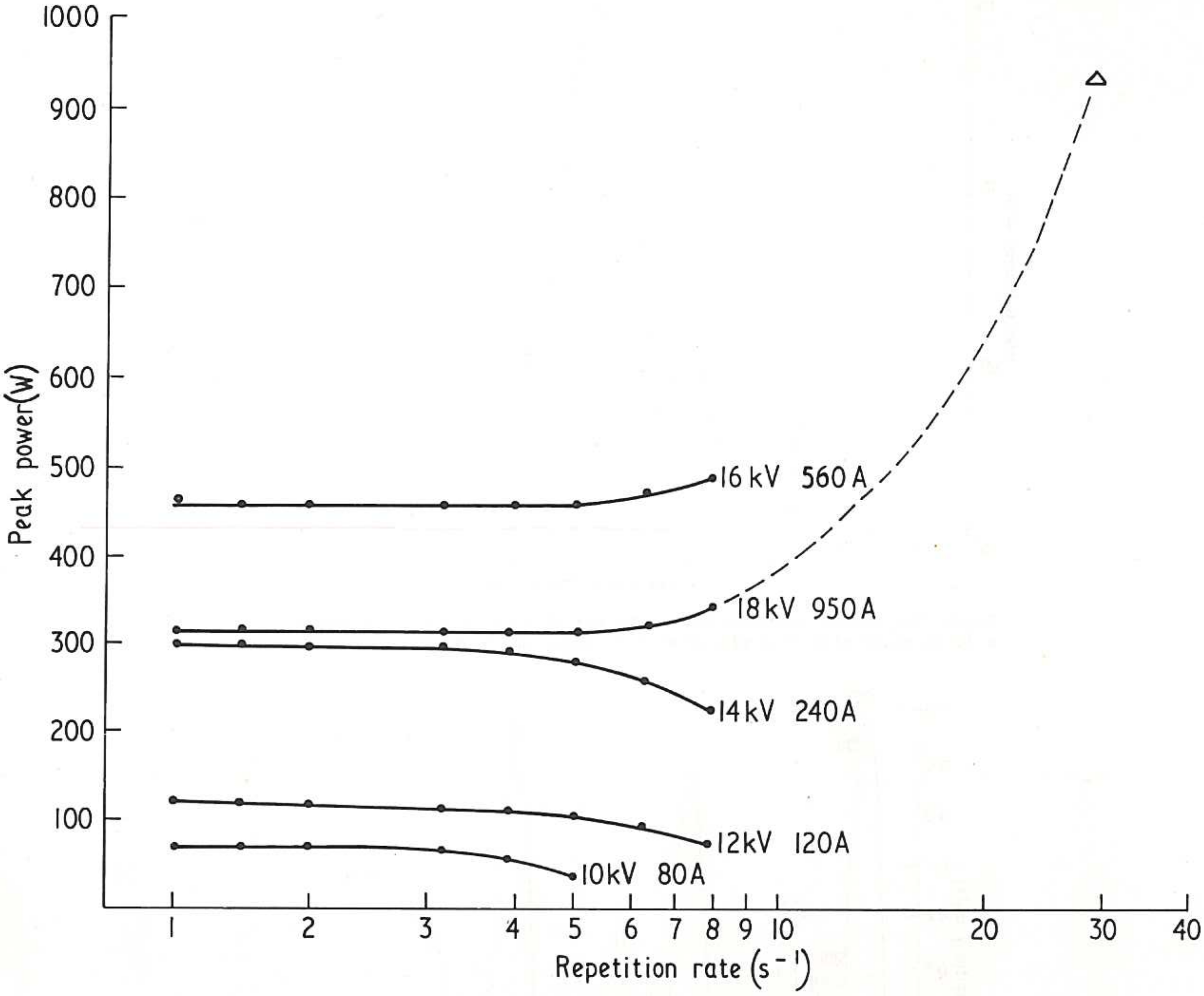

Fig.3a The laser output power for different discharge voltages plotted as a function of repetition rate. The point △ indicates power measured at V = 18 kV, but this value decreased after 100 discharges to less than 100 watts; pressure = 0.7 torr; flow-rate 2.0 ℓ min^{-1}.

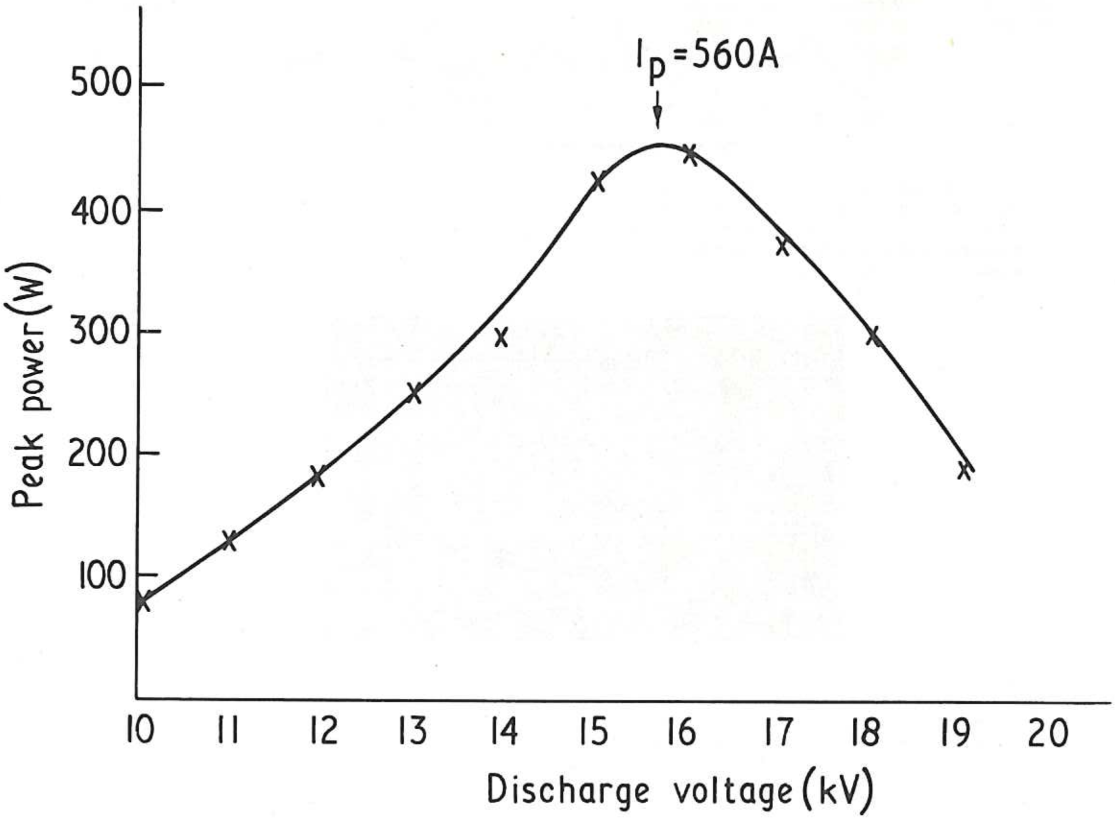

Fig.3b The laser output power vs discharge voltage for a repetition rate of 3 s^{-1}; pressure 0.7 torr; flow-rate 2.0 ℓ min^{-1}.

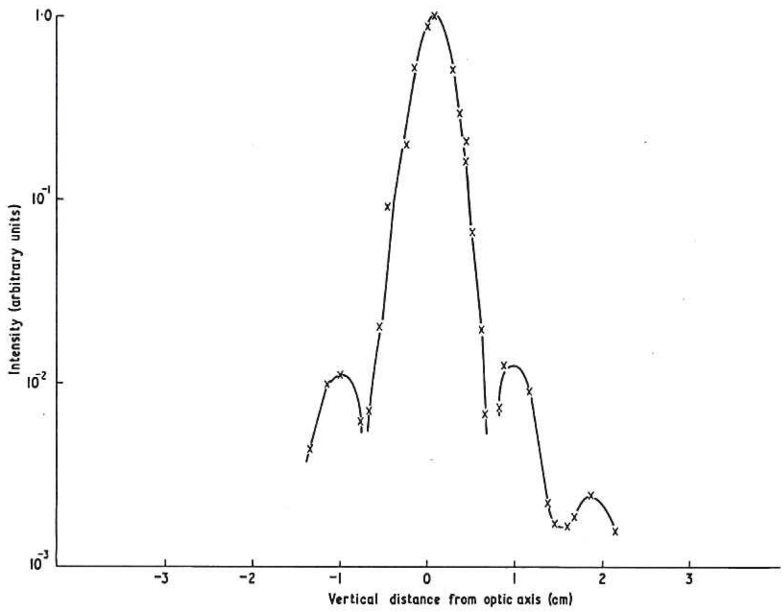

Fig.4 The radial distribution of the output beam at the focal plane of a 20 cm hyperbolic lens placed at the output aperture.

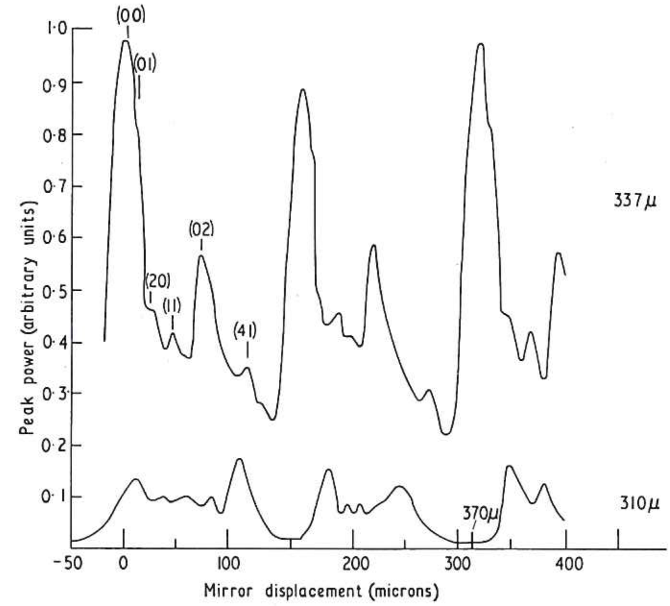

Fig.5 Laser resonator interferogram for the two dominant transitions of 337 μ and 310 μ using a Czerny-Turner spectrometer to define the wavelengths. Detector - InSb at 1.5 K, 7.1 kG. A bar has been placed on the graph to show the maximum power measured for the 370 μ transition. The figures in brackets are the transverse mode numbers, for the 337 μ line.

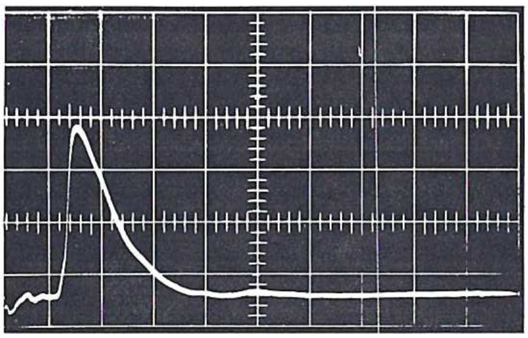

Fig.6 The oscillogram of the laser output pulse when the cavity has been tuned for single mode operation; detector InSb at 1.5 K, 7.1 kG. A delay of 30 μs occurs between the laser and current pulses; time scale 20 μs/cm; V = 16 kV; I = 560 A, 10 μs duration; repetition rate $3 s^{-1}$; pressure 0.7 torr; flow-rate 2.0 ℓ min^{-1}.