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A hollow-cathode discharge CW multicolour He–Cd$^+$ laser module

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Abstract. We report on the design and performance of a hollow-cathode discharge continuous wave He–Cd$^+$ laser module, which is capable of simultaneously delivering stable, milliwatt power output at the three primary spectral lines blue, green and red. A mixture of these lines can result in a wide band of colours, including white light. The laser can be formed from one or more laser modules. A module consists of two anodes with a hollow cathode located between them. Two long, narrow cylinders (50 mm long, 4 mm in diameter) separated by a wider cylinder (10 mm long, 10 mm in diameter) are made in the hollow cathode . The narrow cylinders serve as hollow cathodes, while the wider cylinder efficiently stabilizes the discharges in the narrow cathode cylinders, making them spatially similar. Owing to this particular cathode design the laser module, with a 10 cm active length, stably and effectively lased at seven wavelengths in blue (λ = 441.6 nm, 3 mW), green (λ = 533.7 nm, 0.3 mW; λ = 537.8 nm, 0.4 mW), red (λ = 635.5 and 636.0 nm, total 0.2 mW), and infrared (λ = 723.8 and 728.4 nm, total 0.1 mW). The optimum He pressure, Cd vapour pressure and cathode current were 8 mbar, 0.01 mbar (corresponding to a cathode temperature of 533 K), and 260 mA, respectively. The short- and long-term laser output power variations were less than 1% (peak-to-peak). The laser has exhibited stable operation for 300 h without discharge deterioration. The above allows us to claim that the presented hollow-cathode discharge continuous wave He–Cd$^+$ laser module should be useful as a simple, short, long-lived, multicolour laser source, operating at milliwatt output power levels. However, for higher output power level demands (tens of milliwatts) three or four laser modules must be used.

1. Introduction

Today, in the fourth decade of intense development of laser technology, there is still a permanent demand for simple, reliable and inexpensive laser systems that simultaneously generate the three primary spectral lines blue, green and red, a mixture of which can result in a wide band of colours. This demand is mainly due to the fast introduction of lasers for information processing, including full-colour printing, film-to-video conversion and vice versa, film recording and reproduction, image simulation, displays, holographic recording and storage and optical date storage. Among other possible applications are surface inspection (such as medical endoscopy and laser colour microscopy), inspection of photosensitive materials and multicolour measurements.

Since its first introduction (Karabut *et al* 1969, Sugawara and Tokiwa 1970, Sugawara *et al* 1970, Schuebel 1970a, b) the hollow-cathode discharge (HCD) He–Cd$^+$ laser has been one of the most promising candidates for such a multicolour laser system. The HCD He–Cd$^+$ laser oscillation wavelengths in red (636.0 and 635.5 nm), green (537.8 and 533.7 nm), and blue (441.6 nm) are close to those of the ideal three primary spectral lines 610, 540 and 450 nm (Thornton 1971), thus offering a chance for a very wide range of colour reproduction. This was demonstrated when Fujii *et al* (1975) obtained simultaneous, well-colour-balanced oscillations in red, green and blue with their flute-type HCD He–Cd$^+$ laser. The beam emitted by this laser appeared white, therefore, following the inventors, a HCD He–Cd$^+$ laser emitting such a beam is commonly called a white-light laser. The high ability of the HCD white-light He–Cd$^+$ laser to reproduce full-colour pictures has been shown practically by Takashima *et al* (1986, 1991). Moreover, the demonstration

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of multicolour lasing of a HCD He–Cd^+ laser at an output power close to 200 mW and a noise-to-signal ratio lower than 1% (Fuke *et al* 1987) improves the commercial attractiveness of HCD white-light He–Cd^+ lasers. Unfortunately, severe technological problems associated with control of pressure and distribution of metal vapour in the discharge region, discharge uniformity and stability, gas component separation due to cataphoresis, erosion of the cathode surface due to discharge sputtering, build-up of gaseous impurities, loss of He buffer gas, and so on, which shorten the lifetime of the HCD white-light He–Cd^+ lasers to hundreds of hours, have so far made these lasers impractical for commercial applications.

In many studies of HCD He–Cd^+ lasers, for practical reasons, pulsed or half-rectified discharge currents were used for laser excitation. However, development of a practical continuous wave (CW) HCD He–Cd^+ laser, excitation of which is inevitably associated with direct current (DC) excitation, has been attempted only by a few researchers. The DC excitation of the HCD He–Cd^+ laser causes new technological problems, mainly associated with heat dissipation, temperature distribution in the discharge tube and electrical arcing, which are not met under pulsed or half-rectified discharge current excitation. Since this paper mainly deals with problems associated with implementation of the HCD white-light He–Cd^+ laser as a commercial device, here we will only refer to previous publications, which deal with the problems arising from the DC excitation.

A survey of the works on DC-excited HCD white-light He–Cd^+ lasers shows that there have been two directions in the development of a practical HCD white-light He–Cd^+ laser system. The first direction aims at developing a laser, which consists of one or more short-cylinder hollow-cathode modules having a physically robust structure. In such a design, regulation of operating parameters, including distribution of cadmium vapour and the discharge current along the hollow cathode, is relatively simple. Mainly due to this simplicity, 1000 h operating lifetimes have been achieved in some of the short-cylinder HCD white-light He–Cd^+ laser devices. This development direction is represented by the laser designs proposed by Fukuda and Miya (1974), Hernquist (1978), Kawase (1979), Wang (1983), Mizeraczyk *et al* (1988a, b), Bergmann and Schubert (1989), Sasaki *et al* (1989) and Tsuda and Piper (1989). The second direction, represented by the designs of Fujii *et al* (1980a, b) and Fuke *et al* (1986a, b, 1987), aims at development of a long-cylinder hollow-cathode white-light He–Cd^+ laser. With that laser design there are more operational problems with discharge stability and uniform distributions of cadmium vapour and the discharge current in the hollow cathode. To overcome these problems, if it is possible at all, rather sophisticated electronic control of temperature along the laser tube is necessary, as was shown by Fuke *et al* (1986a, b, 1987).

Because of the mentioned technical problems, there is presently no HCD white-light He–Cd^+ laser device available on the laser market, although a laser device with a structure resembling the design of Fuke *et al* (1986a, b, 1987) was introduced on the market by Nihon Dempa Kogyo Co, Ltd, Japan a few years ago. It was shortly thereafter withdrawn, at least from Europe, however. The models of the HCD white-light He–Cd^+ laser device based on the designs of Kawase (1979), Wang (1983) and Fuke *et al* (1986a, b, 1987) were presented at several laser exhibitions (Laser and Applications 1982 and 1983, Laser Focus/Electro-optics 1986 and Laser Focus World 1989).

In this paper we present results of our effort to develop a simple HCD multicolour He–Cd^+ laser device exhibiting long-life stable operation at milliwatt output power levels with the aim of meeting the following requirements.

(i) The laser head should consist of a simple, short-cylinder hollow-cathode module. Such a design allows stable laser operation and long operating lifetime (1000 h). Relatively low output powers, in particular in the green and red, inherently associated with the short-module laser, can be increased in a laser configuration consisting of more than one module.

(ii) The discharge current and cadmium vapour density in the hollow cathode should be independently controlled.

(iii) The temperatures of the hollow cathode and Cd reservoir must be accurately controlled. To achieve uniform cadmium vapour distribution along the hollow cathode the temperature gradient along the cathode should be minimized.

(iv) For minimizing the temperature gradient along the hollow cathode and optimizing excitation efficiency the discharge current must be properly distributed along the hollow cathode.

(v) Precautions against sputtering of the cathode should be implemented.

(vi) Cadmium and helium loss should be minimized.

(vii) Build-up of gaseous impurities must be alleviated.

The details of the laser tube design and conditioning presented in this paper show that much care has been taken to fulfill the above requirements. The laser operating parameters presented prove that most of these requirements have been met.

2. Design and conditioning of the HCD He–Cd^+ laser tube

For practical realization of a simple HCD multicolour He–Cd^+ laser we chose a laser module concept of Mizeraczyk *et al* (1988a, b), which seems to meet most of the operating conditions listed above. Following this concept we designed a HCD He–Cd^+ laser module, the geometry of which is shown in figure 1. The laser can consist of one or more modules, depending on the laser output power desired. The laser module presented consisted of two anodes, located on opposite sides of the hollow cathode and separated from it

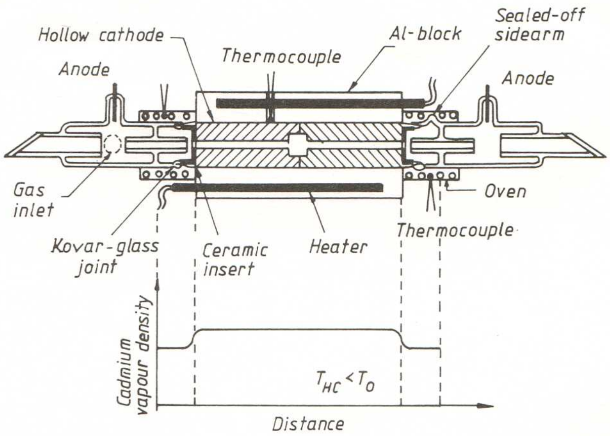

Figure 1. Scheme of the hollow–cathode discharge He–Cd^+ laser module and expected distribution of Cd vapour in the module.

by fused silica capillary tubes (3 mm inner diameter, 5 cm long). The anodes were made of tungsten rod having a diameter of 1 mm. The positive columns created in the fused silica capillary tubes, as parts of the glow discharges established between the anodes and the cathode, served to confine the cadmium vapour within the cathode region by cataphoretic action. The laser tube part including the fused silica capillary tube and the neighbouring region is called the cataphoretic confinement section, after Hernquist (1970, 1978). The efficiency of the cadmium vapour confinement within the cathode region by the cataphoretic confinement section seems to be very high, if not perfect, since, similarly to Hernquist (1972) and Mizeraczyk *et al* (1992), we were not able to see any traces of cadmium having diffused out of the cathode region after hundreds of hours of laser operation. Using alumina oxide ceramic capillary tubes with machinable ceramic inserts as a tightening between them and the outer glass tube, instead of fused silica capillary tubes in the confinement sections, failed because they deteriorated the cadmium confinement, presumably due to a relatively high thermal conductivity of the machinable ceramic used (Corning 'Macor'). A relatively long glass sidearm with a narrow inner diameter of 5 mm, the far end of which served as a temporary reservoir of distilled Cd pellets, was connected to one of the cadmium confinement sections.

The He–Cd positive columns, built up in the cataphoretic confinement sections on the axis of the HCD He–Cd^+ laser, may contribute to absorption of the generated laser lines and thus decrease the output power of the laser, in particular if multimodule laser configuration is considered. However, in a separate experiment (Mizeraczyk *et al* 1993) we found that the absorption of the 441.6 nm He–Cd^+ laser line by the He–Cd positive column used for cadmium confinement is relatively low (about 0.1% for a He–Cd positive column a few centimetres long). Estimates show that such a low absorption should not decrease the 441.6 nm output power of a HCD He–Cd^+ laser by more than a few percent. The amount of absorption of the red and green lines of the HCD He–Cd^+ laser is not known.

The hollow-cathode section of the laser tube consisted of a massive kovar tubing with an outer diameter of 25 mm. The cathode was bored to give a bore diameter of 4 mm and a length of 2 × 50 mm with a wider cylindrical section (length 10 mm, diameter 10 mm) in the cathode middle. The wider cylindrical section of the cathode plays an important role in discharge operation. It separates both discharges, established in the narrow-bore parts of the cathode, and makes them stable and symmetrically distributed along both narrow cathode bores. Manufacturing feasibility required that the cathode was made out of two identical parts, which were arc-welded together (laser welding was also tried with good results), see figure 1. After welding and positioning of the ceramic inserts, which prevent the discharge running to other parts of the cathode than the bore (and also decrease cathode sputtering), the hollow-cathode segment was cleaned by simultaneous pumping and baking up to about 1200 K for several days. Then the glass parts of the laser tube, namely the cadmium confinement sections, the anode and the Brewster window regions, were sealed with kovar–borosilicate glass tubular joints to the cathode segment. The fused silica Brewster windows were sealed by soldering them to the fused silica extension stubs. Thus, the whole laser tube except the long glass outlet, serving as the temporary Cd reservoir, could be baked under vacuum up to about 750 K.

The procedure of laser tube conditioning was as follows. First the tube with distilled Cd pellets in the far end of the long glass side-arm of the temporary Cd reservoir was connected to a conditioning system that allowed high-vacuum pumping, gas handling and tube baking. The whole tube, except the temporary Cd reservoir, was simultaneously pumped and baked up to 750 K for 24 h. The tube was next conditioned with a discharge in pure hydrogen (10 mbar, 200 mA in total through both anodes) under flowing gas conditions for several hours. This should cause desorption of oxygen from the cathode surface. Next, the tube was once more simultaneously pumped and baked up to 750 K for 24 h. After cooling the tube to room temperature the Cd pellets were redistilled from the temporary Cd reservoir into the cadmium confinement section, and, keeping the vacuum, the tube was flame sealed directly at the temporary Cd reservoir side-arm connection to the cadmium confinement section. Now, the evacuated tube was separated from the conditioning system by sealing it at one of the vacuum-tight gas inlet side-arms. After mounting a heavy wall aluminium cylinder (with electrical heaters in it) as a hollow-cathode envelope as well as two ovens outside the cataphoretic confinement sections (see figure 1), the laser tube was connected through one of the remaining gas inlet side-arms to a high-vacuum (10^{-8} mbar) and gas handling system with facilities for delivering ^3He and ^4He from flasks (helium purity 0.999 996) directly or through permeation glass filters (Roth 1976). Then, after breaking through the vacuum-tight gas inlet the tube underwent the final conditioning procedure with discharge and helium exchange for several hours under external heating of the hollow-cathode region, using the electrical heaters in the cylindrical Al block. During this process the cataphoretic confinement section containing redistilled cadmium was kept at a temperature below 400 K, at which temperature cadmium practically does not vaporize. Next, by running the discharge (always from the two anodes) and adequately heating the cataphoretic confinement sections, but without external heating of the hollow cathode, the cadmium from one of the confinement sections was introduced into the hollow cathode by cataphoresis and diffusion, so that it formed a thin layer on the inner walls of the hollow cathode. This completed the conditioning procedure.

The requirements of accurate temperature control of the hollow cathode and Cd reservoir, and minimized temperature gradient along the hollow cathode are critical for efficient operation of the HCD He–Cd^+ white-light laser. We found that even the massive kovar tubing of diameter 25 mm, used as a hollow cathode in this work, could not alone assure a uniform temperature distribution along the hollow cathode (figure 2). This is due to a strongly inhomogeneous distribution of discharge current along the cathode caused by the anodes being positioned outside the hollow cathode (the so-called longitudinal hollow-cathode discharge, Mizeraczyk (1983)). However, since the cathode is directly accessible from the outside in this design, the above-mentioned heavy wall Al cylinder having high thermal conductivity was mounted in intimate thermal contact with the hollow cathode. This Al cylinder, with the electrical heaters placed in it, served, first, to minimize the temperature difference along the hollow cathode, and, second, to control the hollow-cathode temperature. The outside diameter of the Al cylinder was fixed at 60 mm. With this choice the heat dissipation was high enough to keep the cathode temperature below 450 K (figure 3) when it was heated only by the discharge but without the heaters. At this temperature the Cd vapour pressure is well below the optimum needed for laser operation. Controlled by a thermostat (on- and off-duty), use of the external heaters only provided optimum hollow-cathode temperature for lasing.

The cadmium vapour density in the hollow cathode was regulated as follows. Having cadmium distributed as a thin layer inside the hollow cathode, we started the discharge and simultaneous heating of the hollow cathode and cadmium confinement sections with the electric heaters and both side-end ovens, respectively. After reaching a temperature of 450 K both confinement sections were always maintained about 20 K above the hollow-cathode temperature. At given temperatures of the hollow cathode (T_{HC}) and cataphoretic sections (T_O) the density of cadmium vapour in the hollow cathode corresponds to the saturated pressure of Cd vapour produced above the Cd thin layer deposits at temperature T_{HC}, whereas the Cd vapour density in the cataphoretic confinement sections is unsaturated and originates from vapour diffused into them from the hollow-cathode region. Since Cd vapour in the confinement sections cannot diffuse towards the anodes due to cataphoresis, the unsaturated Cd vapour density in the confinement sections is defined by the saturated pressure of the Cd vapour in the hollow-cathode region and temperature T_O. As a result a Cd vapour density distribution along the laser tube as illustrated in figure 1 should be expected. By raising both temperatures T_{HC} and T_O, the Cd vapour density corresponding to maximum output laser power can be achieved. During operation the temperatures of the hollow cathode and side-end ovens were stabilized within ±0.5 K by a thermostat with thermocouple sensors placed in the Al block and both side-end ovens. For stabilization of laser output power we chose not to use the thermocouple signals for thermostat control, however. Instead we used the voltage drop between the anode and cathode, since we found its correlation with the laser output power to be higher than that between the laser output power and the

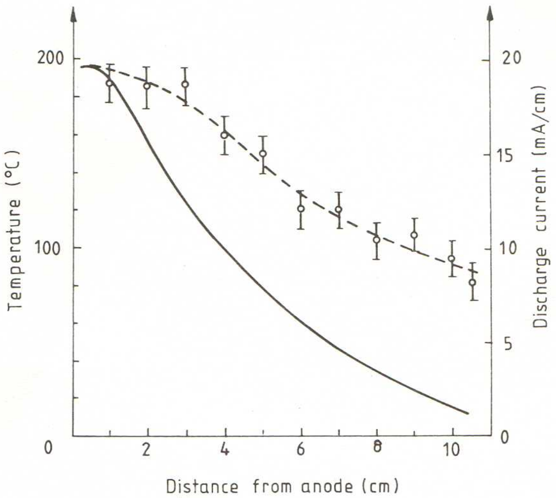

Figure 2. Distribution of temperature along a hollow-cathode module made of kovar (length 10.5 cm, inside and outside diameters 4 mm and 19 mm, respectively), He pressure 6.7 mbar, discharge current 140 mA. The hollow cathode was supplied from only one anode. The full line illustrates the axial distribution of the discharge current (Mizeraczyk 1983).

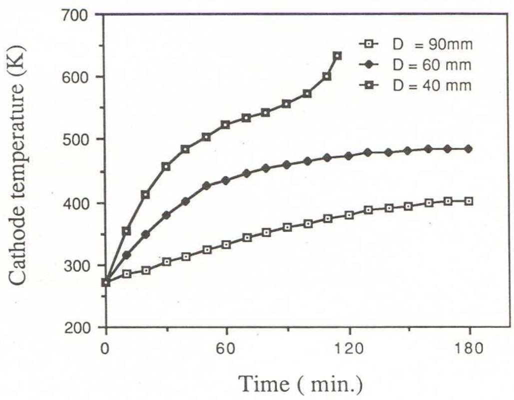

Figure 3. Temperature of the hollow-cathode module as a function of heating time for cylindrical heat radiators (Al blocks) of different diameters *D*: 40, 60 and 90 mm.

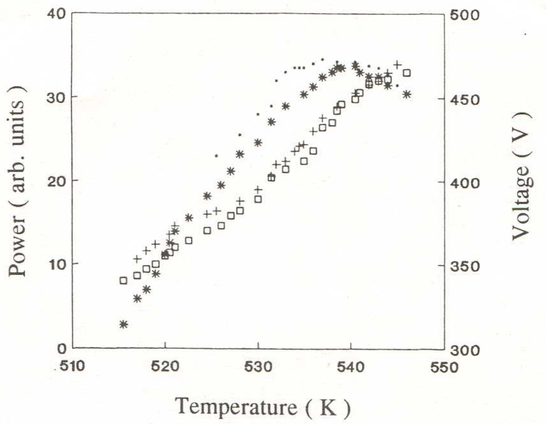

Figure 4. He–Cd$^+$ laser output power (•, ∗) at $\lambda = 533.7$ and 537.8 nm, and operating voltage (+, □) as a function of hollow-cathode temperature for two different rates of increase of the hollow-cathode temperature. Points (•) and (+) correspond to faster increasing temperature.

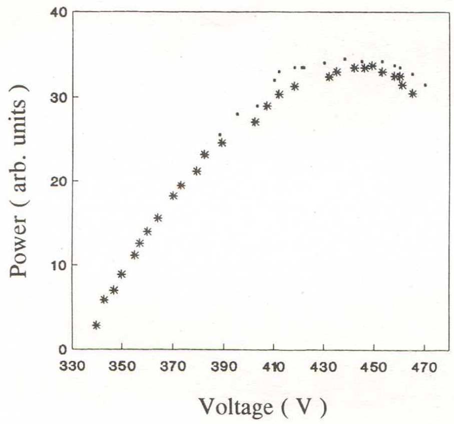

Figure 5. He–Cd$^+$ laser output power ($\lambda = 533.7$ and 537.8 nm) as a function of operating voltage for faster (•) and slower (∗) increase of the hollow-cathode temperature. He pressure 12 mbar, total discharge current 260 mA.

oven temperatures (figures 4 and 5).

The discharge was maintained by an unstabilized DC power supply that delivered current through two 2.5 kΩ resistors, which ballasted each anode. The typical discharge current flowing to each anode was 130 mA. Owing to the particular cathode design and the precautions taken against non-uniform distribution of Cd vapour along the hollow cathode both anode discharge currents were stable and equal within ±5 mA.

For multi-line operation, including white-light emission, high-reflectivity ($R > 99.9\%$) broad-band mirror pairs, about 70 cm apart, were used. Their radii of curvature were by no means optimized for maximum laser power extraction from the optically active volume of the laser. For laser line selection and single-line operation a birefringent filter (Mentel *et al* 1992) inserted in the laser resonator was used. Small-signal gains on the laser transitions were measured with a computerized intra-resonator assembly having two counter-rotating Fresnel plates, which we use routinely for measuring internal losses of the laser resonator (Reich *et al* 1991). Maximum laser output power was extracted from the laser resonator with a Fresnel plate, set at its optimum out-coupling angle.

3. Laser performance

Owing to the particular cathode design the discharge currents to both anodes were stable and symmetrically distributed along the narrow-cylinder parts of the hollow cathode. This resulted in stable and effective CW multicolour laser operation at seven wavelengths in blue ($\lambda = 441.6$ nm, 3 mW), green ($\lambda = 533.7$ nm, 0.3 mW; $\lambda = 537.8$ nm, 0.4 mW), red ($\lambda = 635.5$ and 636.0 nm, total 0.2 mW) and infrared ($\lambda = 723.8$ and 728.4 nm, total 0.1 mW). The corresponding small- signal gains were 12, 11, 15, 4.5 and 3.7% m^{-1}. All these values were obtained for higher order transverse mode (multimode) operation of the laser. For comparison, in some other short-cylinder HCD He–Cd$^+$ laser devices the output powers were as follows: the laser (19 cm active length, 4 mm bore diameter) of Sasaki *et al* (1989) delivered 1 mW of multimode white-light laser beam; the output power of the laser (5.5 cm active length, 1.2 mm bore diameter) designed by Hernquist (1978) was 2.5 mW (multimode) at the blue line (441.6 nm); the laser of Tsuda and Piper (1989), having an active length of 6 cm and a bore diameter of 2 mm, yielded approximately 2 mW combined multimode output power in the blue and green (533.7 and 537.8 nm) lines; the longer multimodule laser of about 25 cm active length and 3 mm bore diameter developed by Wang (1983) simultaneously generated 18 mW in blue, 8 mW in green and 5 mW in red (635.5 and 636.0 nm) under multimode operation.

In our laser the optimum He pressure, Cd vapour pressure and total discharge current were 8 mbar, 0.01 mbar (corresponding to a temperature of 533 K) and 260 mA. The optimum operating voltage between the anodes and the cathode was 430 V. No influence on laser performance was observed using ^{3}He as a buffer gas instead of ^{4}He, both delivered from the flasks either directly or through the permeation glass filter. Without external means for stabilizing the output power, except for temperature control, the short-term laser output power variations were lower than 1% peak-to-peak (figure 6). The drift of laser output power per hour was also lower than 1%. Until the end of the experiment the laser exhibited stable operation for 300 h without discharge deterioration. This allows us to claim that the presented HCD CW He–Cd$^+$ laser module should be useful as a simple, short, long-lived, multicolour laser source operating at milliwatt output power levels.

Despite an almost tenfold increase in laser output power compared with that reported earlier for a similar 10 cm long laser module (Mizeraczyk *et al* 1988a, b), the laser output power offered by our 10 cm long module is still insufficient for many practical applications. Therefore, for higher output power level demands three or four laser modules must be used. Such a multimodule laser would operate at output power levels of tens of milliwatts (Mizeraczyk *et al* 1988a, b).

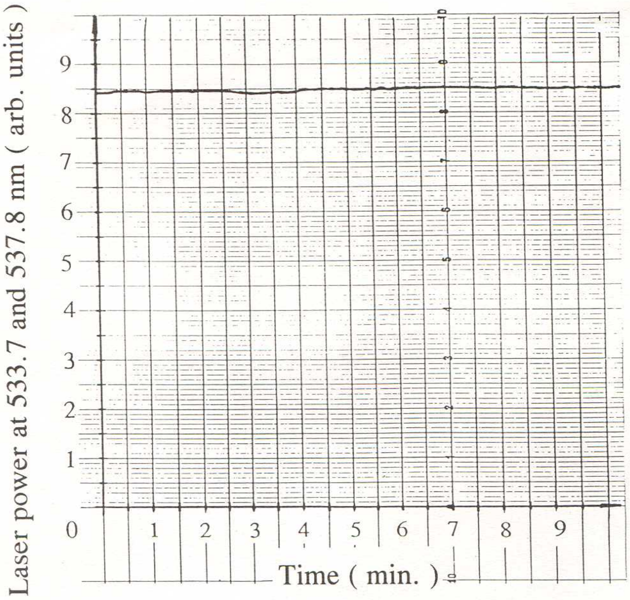

Figure 6. He–Cd$^+$ laser output power (λ = 533.7 and 537.8 nm) as a function of time. He pressure 8.5 mbar, total discharge current 260 mA.

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