Comparison of Cu-II 781 nm Lasers Using High-Voltage Hollow-Cathode and Hollow-Anode-Cathode Discharges

K. A. Peard, Z. Donkó, K. Rózsa, L. Szalai, and R. C. Tobin

Abstract—Voltage—current characteristics and the Cu-II 780.8 nm laser performances are described for a novel segmented hollow cathode and for three- and four-slot hollow-anode cathode (HAC) tubes. Each of these operate at a higher voltage and with higher slope resistance than a conventional hollow cathode and produce improved laser performance. The best laser performance is obtained with the segmented tube. The application of a longitudinal magnetic field raises the discharge voltage and enhances the laser performance for the segmented tube and raises the voltage for the four-slot HAC tube. The magnetic field lowers the voltage and reduces the laser performance with the three-slot HAC tube. The voltage effects are attributed to the deflection of the fast electrons by the magnetic field and represent experimental evidence for the oscillation of electrons in a hollow-cathode discharge.

I. INTRODUCTION

HOLLOW-CATHODE discharges have been extensively used as the basis of lasers employing ionic transitions [1], [2]. The advantage of the hollow-cathode discharge is that it generates a high density of fast electrons, which are necessary in the excitation process of ionic lasers. Laser oscillation has been obtained in noble gas discharges (e.g., He–Ar, He–Kr) as well as in noble gas–metal vapor mixtures employing a metal vapor partial pressure of $10^{-3} - 10^{-4}$ mbar. The metal vapor is produced either by heating (e.g., in He–Cd, He–Zn) or by sputtering (e.g., in Ne–Cu, He–Au) resulting from ion bombardment at the cathode surface. In the cathode-sputtered metal ion lasers that are the subject of this paper, the buffer gas ions participate in a charge-transfer reaction whereby metal vapor atoms are ionized and selectively excited into upper laser levels of the metal ions, thus producing the population inversion, which is required for laser action. The metal ions so produced also participate in the sputtering process [3].

The most common geometries are slotted and cylindrical hollow cathodes [4], [5], which typically operate at a discharge voltage of 300–400 V. There are advantages to be gained by increasing the operating voltage of the hollow-cathode discharge [6]. The increased voltage raises both the energy and the density of the fast electrons and it enhances the sputtering yield for the ions bombarding the cathode. Schemes that have been employed to increase the operating voltage include: 1) the use of internal anodes such as an array of rods or a perforated cylindrical metal tube located coaxially inside the cathode (the HAC tube) [6], [7]; 2) the application of a longitudinal magnetic field to a slotted HAC [16]; 3) the introduction of insulating blocks on the surface of a cylindrical cathode, which break the surface of the cathode up into segments [8]; and 4) the use of a helical cathode [9].

The slotted HAC geometry has also been used by Rocca et al. [10] in a charge-transfer-pumped Hg-II laser excited by a transverse e-beam. Their device employed a two-slot anode and consequently, the discharge geometry is closely related to that of the segmented hollow-cathode tube described in the present work. However, they used thermal generation of the metal vapor and a composite cathode material for the electron guns.

This paper reports a comparison of the discharge characteristics and the laser performances of four hollow-cathode discharge arrangements that support high-voltage discharges with steeper positive $V-I$ characteristics than a conventional hollow-cathode discharge. The high-gain 780.8 nm Cu–II transition was studied since it allows the use of a short gain length. To our knowledge, this is the first demonstration that the achievement of a high-voltage discharge is a desirable but insufficient requirement for efficient laser action. We have shown that laser action is enhanced by raising the discharge voltage if the fast electrons that are focused toward the center of the discharge tube can either oscillate in the potential well between opposed cathode surfaces or can dissipate most of their energy in a single transit of the discharge. Measurements showing the effect of a longitudinal magnetic field on the discharge characteristics and the laser performance for each tube are also presented. These are inter-
The discharge tubes, each having an active length of approximately 5 cm, were constructed as described below.

Two of the tubes were of the HAC type (HAC3 and HAC4), similar to that previously described by Zhang et al., who have already used this geometry to demonstrate successful laser operation on the Cu-II 780.8 nm transition [7]. The tubes comprise a cylindrical, slotted, stainless-steel anode tube with an outside diameter of 4 mm and a wall thickness of 0.25 mm placed coaxially inside a cylindrical copper cathode with an internal diameter of 4.6 mm. The anode for HAC3 had two sets of three slots and that for HAC4 had two sets of four slots, each set 24 mm in length cut parallel to the tube axis and located symmetrically around the circumference of the tube. It was expected that while the four-slot arrangement would allow oscillation of the electrons and an increase in voltage with the application of a longitudinal magnetic field, the three-slot tube would exhibit the opposite behavior. The slot widths were 2.4 and 1.6 mm in the HAC3 and HAC4 tubes, respectively [see Fig. 1 (a) and (b)]. These HAC designs maximize the cross section of negative glow available for laser action.

The second pair of tubes (HC1 and HC2) were of a new segmented hollow-cathode design [see Fig. 1 (c) and (d)]. It was earlier shown that a high-voltage hollow-cathode discharge can be built by dividing the cathode surface with anode rings on the same cylindrical surface [2]. However, the present paper is the first report of a high-voltage hollow-cathode laser employing anodes and cathodes on the same cylindrical surface, and in this work, the anodes and cathodes were arranged around the common cylindrical surface. The segmented tube, in contrast with the HAC tubes, allows the entire discharge cross section to be used for laser action. Each electrode was formed by machining a concave quadrant with a 2 mm radius along one long edge of a copper bar with a 12.7 mm square cross section 50 mm in length. Four such rods were stacked so that the machined corners enclosed a discharge volume of the circular cross section. Brass plates (25.7 mm square) at each end of the array prevented discharges from forming on the end surfaces of the electrodes. In each tube, all electrodes, including the end plates, were provided with separate electrical connections so that the discharge characteristics and laser performance of a number of electrode configurations could be studied. Alumina spacers were employed to maintain a 0.3 mm separation between adjacent electrodes and between the ends of the electrodes and the end plates. The 0.3 mm dimension was chosen since it is sufficiently small to exclude the discharge from the gaps between the electrodes over the range of pressures and applied voltages of interest. The edges of the spacers were located at least 5 mm from the discharge to minimize the risk of a short circuit developing due to deposition of metal on the edges of the spacers.

The spacers extended to the external surfaces of the discharge tubes, where low-vapor-pressure epoxy resin was applied along all joints to provide a vacuum seal. In one of the tubes (HC2), cavities of 1.5 mm in width and 2.0 mm in depth were machined symmetrically along the full length of the active surfaces of two of the electrodes and these two electrodes were mounted diametrically opposite to each other. Their purpose, connected as anodes, was to provide a small additional volume in which the discharge may operate, thus allowing investigation of any consequent effect on the discharge characteristics and laser performance.

The four discharge tubes described above were mounted in tandem between Brewster windows that were located approximately 12 cm from the nearest discharge. The experiments were conducted with either a static or a slow-flow (5 cm³ min⁻¹) buffer-gas fill of helium with a 4 percent addition of argon to enhance the sputtering of copper atoms from the cathodes. A pulsed power supply was employed that could deliver a maximum current pulse of 1.6 A and a maximum discharge voltage of 1200 V. The pulse duration of 0.5 ms was sufficiently long for the laser output to approximate continuous-wave conditions towards the end of the pulse. The laser cavity was formed by a pair of mirrors with a nominal reflectance of 99.9 percent at the 780.8 nm Cu-II transition wavelength. The active cathode area in each tube was “conditioned” by operating the discharge for a certain period to clean the active surfaces by ion bombardment. The stability of the operating voltage under fixed conditions was used as the test for the achievement of a reproducible cathode condition. In all tests, the transmission of the output coupler was approximately 0.1 percent and the laser output power was measured using a Spectra Physics power meter (Model 404) with a 1 kΩ load resistor.
III. RESULTS AND DISCUSSION

A. Voltage–Current Characteristics

The voltage–current characteristics for various configurations of the HC1 tube and for the HAC tubes at a constant pressure of 15 mbar are represented in Fig. 3. With all quadrant segments of the HC1 tube connected as cathodes and the end plates connected as anodes [Fig. 2 (a)], the classical, hollow-cathode, flat $V-I$ characteristic was observed. (See curve (a) of Fig. 3.)

With the progressive connection of one or more of the segmented electrodes in the HC1 tube as anodes, the remaining electrodes being connected as cathodes as shown in Fig. 2 (b), (c), and (e), the voltage–current characteristics acquire a positive slope and there is a corresponding increase in the discharge voltage for a given current and pressure as the number of anodes increases. For electrode configurations having less than four cathodes, part of the negative glow is adjacent to anode surfaces that act as sinks for electrons. At a given current density and pressure, the increase in operating voltage as the number of cathodes decreases from four to one [see Figure 3, curves (a), (b), (c), and (e)] is attributed to the progressive loss of charges from the discharge. To maintain the ion current at the cathode that is necessary for the discharge to be self-sustaining, an increased operating voltage is required.

A comparison is made in Fig. 3 between the $V-I$ characteristics of the segmented discharge tube with two diametrically opposed cathodes (the "- + - +" configuration) and the characteristics of the same tube configured with two adjacent cathodes and two adjacent anodes (the "- - + +" configuration) [see curves (c) and (d)]. The latter configuration has a much higher operating voltage for the same current density value. The most important difference between the two cases is that in the - + - + configuration, the fast electrons are able to oscillate. The comparison indicates the importance of oscillation of the fast electrons in ion and photon production in these tubes [11].

The segmented-cathode tube (in high-voltage configurations) and the HAC tubes all have voltage–current characteristics with similar general features, including the dependence on the buffer-gas pressure. Typical characteristics for a range of buffer-gas pressures are shown in Fig. 4, the corresponding discharge tube being HC1 with two opposing cathodes and two opposing anodes [the - + - + configuration, Figure 2 (c)]. The $V-I$ characteristics of the HC2 tube in the - + - + configuration (with the electrodes having machined cavities connected as anodes) bore no significant difference to those shown in Fig. 4. For each high-voltage hollow-cathode tube and current density value, the reduction in the operating voltage with an increase in the buffer-gas pressure is attributed to a reduced diffusion loss of charges from the negative glow. In an additional experiment [12], the authors have observed a higher operating voltage with a 2.5 cm tube than with a 5 cm tube since the loss of the charges from the ends of the discharge results in a greater loss per unit volume of discharge in the shorter tube.

The relationships between voltage and current density for the three- and four-slot HAC tubes (HAC3 and HAC4) at various pressures are compared in Fig. 5. The characteristics have the same general shape as those for the high-voltage configurations (number of cathodes ≤ 3) of the segmented hollow-cathode tube with the difference that, for both HAC3 and HAC4, for each value of pressure and current density, the operating voltage is higher than the corresponding value for the segmented hollow-cathode tube in the - + - + configuration. The higher operating voltage for the HAC4 tube than for the segmented hollow-cathode tube (- + - + configuration) can be explained as follows. The negative glow is divided into four sections in the HAC4 tube compared with two larger sections in the - + - + configuration of the segmented hollow-cathode tube. Thus, the surface area through which charges can be lost per unit volume of the negative glow is larger in the HAC4 tube and a greater fractional diffusion loss of electrons and ions from the negative glow results. A comparison of the characteristics of the HAC3 and HAC4 tubes shows that at each pressure, there is a current density value ($J^*$) for which the two tubes have equal operating voltage ($V^*$). For $J < J^*$, HAC4 has the higher operating voltage, the converse applying for $J > J^*$. Apart from the difference in the active surface areas of the cathodes, (incorporated in the calculations of current density), HAC3 and HAC4 differ in two respects that would affect the operating voltage at a particular current density and pressure. First, the negative glow is divided into 60° sections in HAC3 compared with 90° sections in HAC4. In the absence of other factors, the associated smaller diffusion loss of ions and electrons from negative glow regions in HAC3 compared with HAC4 would result...
in a lower operating voltage for HAC3. Second, each active segment of cathode in HAC4 is diametrically opposite another cathode segment making possible the oscillation of fast electrons, provided that the average range that a fast electron is capable of traveling before dissipating its energy (the "reaching distance" [13]) exceeds the cathode diameter. With HAC3, each active segment of cathode is diametrically opposite an anode so that electrons emitted from the central regions of the cathode segments cannot oscillate and may be lost at the anode after one transit of the negative glow. (Since the width of the segments of exposed cathode exceeds the width of the anode strips, electrons emitted from the edges of the cathode segments may oscillate.) Thus, at a particular pressure, whether HAC3 has a greater or lesser operating voltage than HAC4 will depend respectively on whether the reaching distance of the fast electrons is greater or less than the diameter of the discharge. Calculations of the reaching distance (following Persson [13]) for corresponding values of buffer-gas pressure and $V^*$ yield values for the reaching distance that approximately equal the discharge diameter.

**B. Laser Performance**

Graphs representing the dependence of the laser threshold current on buffer-gas pressure for various configurations of the segmented tube (HC1) and for the HAC tubes are shown in Fig. 6 and graphs representing the dependence of the laser output power on discharge current at a buffer-gas pressure of 15 mbar for the same tubes are shown in Fig. 7. This pressure was the highest value employed, and over the range of currents tested, gave the highest output power for each configuration of the HC1 tube at each value of discharge current. In the case of the HAC tubes, although the optimum pressure for each value of discharge current is approximately 10 mbar, high values of discharge current (e.g., 1.4 A) were not accessible at such a pressure because of the voltage limitation of the power supply, and in this work, the maximum laser output power with the HAC tubes was obtained at 15 mbar.

The highest output power (2.2 mW) and lowest threshold current (0.21 A) observed in this work were obtained with the HC1 tube using the $-+--+$ configuration. With the same tube, a progressive increase in the number of
cathodes from two to three and four produced a corresponding increase in the threshold current at each buffer-gas pressure (see Fig. 6). In particular, for a pressure of 15 mbar, the threshold current and power for the conventional hollow-cathode, HC1 (4 K), are approximately 3 and 2 times greater, respectively, than the corresponding values for CH1 (−−−+). At each pressure, an increase in the number of cathodes for the HC1 tube results in a decrease in the laser output power for a given current (see Fig. 7 for the results at 15 mbar). These trends may be attributed to the corresponding decrease in the tube operating voltage, high values of which favor efficient ionization and laser excitation. It was only appropriate to test the HC2 tube with the electrodes having machined cavities connected as anodes and HC1 and HC2 gave almost identical laser performances in the −−−+ configuration.

The −−−+ configuration of the HC1 tube results in a much higher operating voltage than the −−−+ configuration and, in the absence of other factors, would be expected to give improved laser performance. However, for a pressure of 15 mbar, the threshold current (−−−+) was 0.39 A compared with 0.29 A for the −−−+ configuration, and for the same pressure, using the maximum attainable current (0.5 A) in the −−−+ configuration, the laser output power was 0.03 mW compared with 0.6 mW for the −−−+ configuration under the same conditions. The −−−+ configuration could only be tested at high pressures and for low values of discharge current because of the limitations of the power supply. The reduced laser performance of the tube in the −−−+ configuration is attributed to the correspondingly less-efficient excitation of the discharge volume. This, in turn, arises from the asymmetrical nature of the excitation and its concentration, particularly at the high pressures (~15 mbar) that favor laser oscillation in the −−−+ configuration, in a region adjacent the cathode. Visual inspection of the fluorescence emission reveals that the excitation is weaker near the center of the discharge under these conditions. For the same reason, the laser performance of the HC1 tube with only one electrode connected as a cathode is expected to be even worse. Power-supply voltage limitations precluded the testing of this configuration at currents exceeding 0.1 A.
toward the axis of the discharge tubes, and (for some of the geometries), the ability of the fast electrons to oscillate, thereby maximizing the number of ion pairs that each fast electron can create in the negative glow. The highest output powers allowing a comparison of HC1 and the HAC tubes under identical conditions (1.4 A, 15 mbar) were 2.3 and 1.9 mW for the HC1 (−+−+ configuration) and HAC tubes, respectively. The corresponding operating voltages were 790 and 1050 V, respectively, the lower operating voltage of HC1 being technologically advantageous. The 60 percent greater efficiency of HC1 compared to HAC tubes is achieved despite its lower operating voltage. This may be due to the internal anode surfaces (which act as sinks for diffusion of copper vapor) being further from the center of the discharge than is the case with the HAC tubes. A much greater improvement in efficiency (by a factor of 3) is apparent when comparing HC1 (−+−+) to the conventional hollow-cathode, HC1 (4 K).

C. The Effect of a Longitudinal Magnetic Field

In general, the application of a longitudinal magnetic field to a hollow-cathode discharge results in a decrease in the operating voltage and a deterioration in the laser performance [14, 15]. Zhang et al. have shown that the application of a longitudinal magnitude field of appropriate magnitude to a four-slot HAC discharge results in an increase in the operating voltage and a consequent increase in the laser output power [16]. In this section, the effects of the application of uniform longitudinal magnetic fields to discharges in the segmented hollow-cathode tube and the three- and four-slot HAC tubes are described.

Fig. 8 shows the relationship between discharge voltage and magnetic field strength for HC1 (−+−+ configuration) and the HAC tubes, the buffer gas pressure being 15 mbar. Fig. 9 represents the corresponding effect of the magnetic field on the laser output power for HC1 and HAC.

With the HC1 and HAC tubes, the action of the magnetic field is to bend the fast electrons toward the anodes where they are captured. Hence, they cannot oscillate and a compensating increase in the discharge voltage is required in order to maintain the discharge. With the HC1 tube, for the values of current and magnetic field strength employed, the above effect resulted in a monotonic increase in the operating voltage with increasing field strength. This is attributed to a corresponding increase in the fraction of the fast electrons that are lost in this way before their energy has fallen below the ionization threshold. The increase in the discharge voltage is accompanied by a reduction in the laser threshold current and an increase in the laser output power (see Fig. 9).

The application of the magnetic field to the HC1 tube with all four electrodes connected as cathodes (i.e., forming a conventional hollow cathode) resulted in a reduction in the discharge voltage and the laser output power,

Fig. 7. Laser output power versus discharge current for the HAC tubes and various configurations of HC1 at a buffer gas pressure of 15 mbar.

Fig. 6 shows that at each pressure, HAC3 has a lower threshold current than HAC4. It was also found that for corresponding values of pressure and current, HAC3 has the higher output power (see Fig. 7 for the comparison at 15 mbar). The superior laser performance of HAC3 compared with HAC4 at a lower pressure, such as 7.5 mbar, could be attributed to a higher operating voltage over the range of currents of interest. However, for a given discharge current at a pressure of 15 mbar, the operating voltage of HAC3 is lower than that of HAC4 by approximately 50 V [see Figs. 3 (f) and 3 (g)] and it is proposed that the superior performance of HAC3 is due to a more homogeneous pumping of the discharge volume. This results from the injection of fast electrons from three slots separated by 120° and the consequent excitation of the volumes adjacent each anode. In HAC4, with slots separated by 90°, the volumes adjacent each anode are not directly excited by the fast electrons.

The characteristics that favor efficient laser operation of the discharge geometries reported in this paper are the enhanced excitation and sputtering resulting from the higher operating voltage than that of a conventional hollow-cathode discharge, the focusing of the fast electrons toward the axis of the discharge tubes, and (for some of the geometries), the ability of the fast electrons to oscillate, thereby maximizing the number of ion pairs that each fast electron can create in the negative glow.
consistent with the observations of Cristescu et al. and Rocca et al. [14], [15]. This demonstrates again the link between an increased operating voltage and increased laser excitation.

Fig. 8 also shows the increase in discharge voltage with the HAC4 tube for moderate values of a uniform magnetic field and the existence of a peak in the discharge voltage as the magnetic field is increased at a given current and pressure. This confirms the observations of Zhang et al. [16], who attributed this effect to the onset of “sideways” trapping of the fast electrons. Zhang et al. have also demonstrated the correlation between an increased discharge voltage and an increased laser output power upon application of a moderate nonuniform magnetic field to a four-slot HAC tube.

With the HAC3 tube, the application of a longitudinal magnetic field of moderate value results in a reduction of the operating voltage and a corresponding reduction in the laser output power (see Figs. 8 and 9). For this tube, the fast electrons emitted from the central regions of the exposed areas of cathode are unable to oscillate with zero magnetic field. The application of the moderate field bends these fast electrons toward a cathode resulting in the observed reduction in discharge voltage and an associated reduction in the laser output power. A further increase in the magnetic field strength bends the fast electrons toward an anode adjacent the cathode that initially emitted them thus causing an increase in the voltage and the appearance of a minimum in the graph of voltage versus magnetic field strength (see the curve for 600 mA in Fig. 8). The value of the magnetic-field strength required to produce the minimum-discharge voltage increases with increasing voltage (and current) as expected from a consideration of the dependence of the curvature of the path of the fast electrons on the discharge voltage and magnetic-field strength (compare the HAC3 curves for 600 and 1400 mA in Fig. 8).

The small initial positive slope observed in the 1400 mA curve for the HAC3 tube in Fig. 8 is attributed to the fact that in this tube, each anode subtends at the tube axis a smaller angle than the diametrically opposite cathode. Hence, with zero field, fast electrons emitted from the edges of the cathodes can oscillate. The oscillation of these emitted from one edge of the cathode is prevented.
by the application of a magnetic field. This effect by itself would raise the tube voltage and at low field values, may override the initial decrease in voltage, which would be expected as the fast electrons emitted from other parts of the cathode are deflected toward a cathode.

IV. CONCLUSIONS

A comparative study of the voltage–current characteristics and laser performances for several geometries of an infrared copper ion laser (780.8 nm CuII transition) has been described. The devices include a novel segmented hollow-cathode tube together with three- and four-slot hollow-anode cathode tubes, all of which operate at a higher voltage and with higher slope resistance than a conventional hollow cathode. In these tubes, part of the negative glow is bounded by anodes and charges can be lost at these boundaries. A higher operating voltage is required to increase the volumetric rate of ionization, thereby compensating for the ion loss by diffusion from the negative glow. The effect of a uniform longitudinal magnetic field on the discharge voltage and laser output power has also been reported.

The advantages that these tubes offer for laser operation are as follows.

1) A higher operating voltage compared to a conventional hollow cathode. This results in increased ionization and excitation and in a higher sputtering yield for ion bombardment at the cathode.
2) A better stability against arcing compared to conventional hollow-cathode discharges, resulting from the higher slope resistance.
3) The focusing of the fast electrons toward the tube axis, which increases the laser excitation in this region.

The lowest threshold current and power and the highest laser output power and efficiency were achieved using the segmented hollow-cathode tube configured with a pair of diametrically opposed cathodes. This tube operates at a significantly lower voltage than the HAC tubes, thus offering technological advantages in power-supply design. Accordingly, a more complete parametric study of a segmented hollow-cathode laser has been completed and will be reported elsewhere. The design has also been selected for the development of a compact ultraviolet metal ion laser. The authors have already achieved strong laser action with a low threshold current on the 283 nm Au-II transition using a short (5 cm) segmented hollow-cathode tube and are currently studying the scaling of this type of laser and its extension to other metals. This work will also be reported elsewhere.

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REFERENCES


Ken Peard was born in Melbourne, Australia in 1940. He obtained the B.Sc. in Physics in 1960 and the B.Sc. (Hon) and M.Sc. in Physical Metallurgy in 1969 and 1972 respectively, all from the University of Melbourne. He received the Ph.D. degree from Monash University in 1994. Since 1962 he has lectured in the Department of Applied Physics at Victoria University of Technology, Melbourne (previously called Footscray Institute of Technology). His main research interest is sputtering-based metal vapour lasers.

Zoltán Donkó was born in Özd, Hungary, in 1965. He graduated in 1989 from the Faculty of Electrical Engineering of the Technical University of Budapest. In the same year he was awarded a Ph.D. scholarship at the Central Research Institute for Physics. He has received his Ph.D. degree in Engineering Physics from the Technical University of Budapest in 1992. His work is mainly concerned with experimental investigations and modelling of gas discharges and research of hollow cathode lasers.
K. Rózsa, photograph and biography not available at the time of publication.

László Szalai was born in 1969 in Békéscsaba, Hungary. Since 1989 he has been a student of József Attila University, Szeged, Hungary. From 1992 he participates in the research of cathode sputtered metal ion lasers at the Research Institute for Solid State Physics.

R. C. Tobin was born in Melbourne, Australia, in September 1933. He received the B.Sc. (Hons.) degree from the University of Melbourne in 1960, and the Ph.D. degree from Monash University in 1980.

After working as a Scientific Officer at the Aeronautical Research Laboratories, Melbourne from 1960 to 1964, he was appointed as a Lecturer in the Department of Physics, Monash University, in 1964, where he is currently a Senior Lecturer.

His main research interests are in the field of gas discharge lasers and particularly in sputtering-based metal vapour lasers.

Dr. Tobin is a Fellow of the Australia Institute of Physics.