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Innovative Lasers for Uranium Isotope Separation

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Abstract

Copper vapor lasers have important applications to uranium atomic vapor laser isotope separation (AVLIS). We have spent the first year of our project investigating two innovative methods of exciting/pumping copper vapor lasers which have the potential to improve the efficiency and scaling of large laser systems used in uranium isotope separation. Experimental research has focused on the laser discharge kinetics of 1) microwave and 2) electron beam excitation/pumping of large-volume copper vapor lasers. During the first year, the experiments have been designed and constructed and initial data has been taken. Highlights of some of the first year results as well as plans for the future include the following:

Microwave resonant cavity produced copper vapor plasmas at 2.45 GHz, both pulsed (5 kW, 5kHz,) and CW (0 -500 Watts) have been investigated using heated copper chloride as the copper source. The visible emitted light has been observed and intense lines at 510.6 nm and 578.2 nm have been observed. Initial measurements of the electric field strengths have been taken with probes, the plasma volume has been measured with optical techniques, and the power has been measured with power meters. A self-consistent electromagnetic model of the cavity/plasma system which uses the above data as input shows that the copper plasma has skin depths around 100 cm, densities around 10^{12} #/cc, collisional frequencies around 10^{11}/sec, , conductivities around 0.15 (Ohm-meter)$^{-1}$. A simple model of the heat transfer predicts temperatures of ~900 K. All of these parameters indicate that microwave discharges may be well suited as a pump source for copper lasers. These preliminary studies will be continued during the second year with additional diagnostics added to the system to verify the model results. Chemical kinetics of the system will also be added to the model. Mirrors will be added to the system and attempts to measure amplification will be made.

An electron beam pumped copper vapor system (voltage 350 kV, current - 1.0 kA, pulselength 300 ns) has been designed, fabricated and tested. Heated copper chloride has initially been used as the copper vapor source. Time resolved light emission was observed and followed the current of the beam. Due to inefficiencies of using CW heating of the copper vapor in a pulsed experiment and transporting it in the vapor state to the beam deposition site, during the next year we plan to investigate novel, pulsed, copper vapor sources. We plan to evaluate two alternative techniques for pulsed generation of copper vapor: 1) Exploding wires and 2) Flashboard sources. The flashboard source has a number of potential advantages, including larger copper vapor volumes and repetitively pulsed operation. Experiments will be performed on electron beam pumped amplification of Cu laser lines using a recently purchased copper vapor laser. Oscillator experiments will be designed on the basis of the amplifier data. Modeling of the chemical kinetics of e-beam pumped copper vapor will be initiated.

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I. Introduction and Background

Atomic Vapor Laser Isotope Separation (AVLIS) is an important new method of producing enriched uranium. It is based upon the principle that ^{235}U and ^{238}U absorb different wavelengths of visible light. A copper vapor laser (CVL) is used to excite/pump dye lasers which generate the specific wavelengths needed to photoionize ^{235}U atoms in a vapor stream of uranium. These ^{235}U photo-ions are then deflected by electromagnetic fields onto a collector, whereas ^{238}U atoms pass straight through the system, unaffected. The high selectivity of the AVLIS method provides large efficiencies (greater than 10,000), unlike gaseous diffusion and gas centrifuge techniques which rely on isotopic mass differences and result in low enrichment efficiencies (0.01). The combination of high enrichment efficiency, low capital, low energy and low operating costs, make AVLIS an attractive, economic alternative to traditional separation techniques. The Department of Energy has funded a Laser Demonstration Facility which is currently developing the AVLIS technique at Lawrence Livermore National Laboratory (LLNL).

The Department of Energy has chosen copper vapor lasers (CVLs) as their "baseline technology"[1] for AVLIS because CVLs have the optimal properties for this method. Advantages of copper vapor lasers are: 1) copper vapor lasers can be driven at high repetition rates (4 kHz) which are needed to maintain large efficiencies, 2) CVLs have short pulse lengths (200 ns) needed to provide photoionization before relaxation can occur, 3) CVLs produce large average powers necessary to separate large amounts of materials, and 4) laser isotope separation CVLs produce narrow band light at the needed wavelengths. Copper vapor lasers currently used in the DOE AVLIS facility at LLNL are driven by repetitively pulsed electrical discharges between electrodes located near the ends of the insulating laser tube. However, electrical discharge type of excitation schemes have a number of technical problems which need to be solved.

There are several important shortcomings of the pulsed discharge copper vapor lasers currently used in the AVLIS program at LLNL. In order to achieve economies of scale in laser isotope separation, it is required that copper vapor lasers are scalable to large volumes and powers. However, there has been some concern[1,2] over the physical limitations of the size of the electrical discharge chambers because large-diameter copper vapor lasers exhibit a "plasma skin effect" which can delay the penetration of the applied electric field. Plasma skin effects can cause hollow laser beam intensity profiles. Furthermore the length of electrical discharge[1] cannot be extended indefinitely because of the limitations in high-voltage pulsed power technology.

During the past year (9/1/89 - 5/31/90) we have initiated an investigation of two, new, innovative methods of excitation/pumping copper vapor lasers which will enhance their applicability to isotope separation and may overcome the shortcomings of the conventional electrical discharge excitation/pumping method:

1) Microwave excitation/pumping, and

2) Electron beam excitation/pumping.

The first innovative laser excitation system we are in the process of investigating uses microwaves to heat and excite lasing transitions in copper vapor plasmas. We have been investigating microwave excitation/pumping systems which utilize an Asmussen microwave resonant cavity. During this first year, we have shown that this system allows energy deposition through distances many times the ordinary skin depth (~100 cm) as well as achievement of electron densities which are orders of magnitude larger than the critical density (10^{11} - 10^{12} #/cm^{-3}).

There are other advantages to using microwaves for laser excitation/pumping: 1) Microwave energy can be very efficiently coupled to the gas. We have achieved efficiencies of greater than 95% in helium-copper chloride discharges. 2) high power, repetitively pulsed microwave technology is well established from radar work and is relatively inexpensive, particularly at 2.45 GHz, 3) microwave systems are scalable to high powers (several MW commercially available magnetrons), 4) the pulse rate needed for the application to isotope separation (several kHz) are well within the range of commercially available microwave systems, and 5) waveguide transmission of microwaves from the source to the load is reliable, inexpensive, and does not add inductance as would a high voltage cable. An additional feature of microwave discharges is the absence of electrodes, so electrode contamination of the laser medium and degradation of the electrodes and laser windows are eliminated. The most significant advantage of microwave excitation/pumping is that large volumes of plasmas can be generated and sustained. For example, plasma volumes greater than 1000 cm^3 at 2.45 GHz and 2.5 kW have been produced by Bosisio et al.[3] We have determined the the skin depth to be on the order of 100 cm, indicating the scalability to large radii.

The only previous studies of microwave pumped lasers have centered around rare-gas halogen excimer lasers[4-8] and ArXe excimers[9] where the microwaves were typically coupled to the gas in a waveguide. Lasing in HeNe[10] and argon[11] have been demonstrated in France on a small resonant cavity called a surfatron. In general, overall efficiencies of microwave-to-light conversion varied from 0.1% to 1%, comparable to efficiencies achieved with conventional discharges. Some of the advantages to microwave discharge pumped lasers were high microwave deposition efficiency as well as the potential for very high repetition rates and improved control over the laser pulse shape.[7]

The second method we are investigating is electron beam excited/pumped copper vapor lasers. Electron beam excitation/pumping of gas lasers has been demonstrated to be extremely efficient in a number of large-volume gas laser systems[12-13], (e.g. CO_2 and KrF). To the best of our knowledge there are no open publications of the investigations of electron beam excited copper discharges with the exception of a recent Russian paper[14] presenting a theoretical model which calculates various characteristics of an electron beam pumped copper vapor laser.

Electron beam excitation would have a number of advantages in pumping large copper vapor lasers for atomic vapor laser isotope separation: 1) Extremely large laser gas volumes can be excited, since the electron range can be very large, 2) electron beam excitation <u>does not</u> exhibit a plasma skin effect as does electrical discharge pumping, 3) electron beam excitation produces very uniform laser output power profiles for large area beams, 4) electron beams can deposit a larger amount of energy to the system (by two or three orders of magnitude) compared to the few joules deposited by the electrical discharges,[14] 5) electron beam excitation does not require the use of electrodes which can degrade and cause contamination, and 6) electron beam excitation is very efficient in converting electron beam energy to laser output energy. Borovich et al.[14] estimate that 3% of the electron beam energy could result in laser energy from an electron beam pumped copper vapor laser.

II. Objectives of Research

The overall objects of our three year project are to investigate two innovative excitation/pumping techniques for copper vapor lasers used in uranium isotope separation: 1) Microwaves, and 2) Electron beams. The goals of the research are:

1) To demonstrate the feasibility and the advantages of microwave and electron beam excitation/pumping of copper vapor lasers for atomic vapor laser isotope separation:

   a) Excitation of large copper vapor laser volumes,

   b) Efficient transfer of microwave and electron beam energy to optical energy of copper vapor lasers,

   c) Uniform optical laser beam profiles, and

2) To develop the scaling laws for application of microwave and electron beam pumped copper vapor lasers to large scale uranium atomic vapor laser isotope separation.

During the first year we have made progress on achieving part 1a and 1b of the objectives. These results are described in the next section

III. Progress during 9/1/89 - 5/31/90

III. A Introduction

During the first several months of the first year of our project, the microwave experimental apparatus and the electron beam experimental apparatus have been designed, assembled and tested. More recently, preliminary data has been taken using these systems. The details of these microwave pumped copper vapor plasmas are given in Section III B and the details of the results of the electron beam pumped copper plasmas are given in Section III C.

As proposed for this project, we have also purchased a commercial copper vapor laser for amplification studies. This laser was recently installed in our lab and tested. During the next year it will be used to measure the amplification properties of both the microwave produced and electron beam produced copper vapor plasmas.

Copper chloride vapor was initially produced by heating copper chloride in a quartz tube surrounded by glass wool. The temperature of this oven was controlled by heat tapes powered by a variac. This method turned out to have disadvantages for both pumping systems. In the microwave discharge system it was difficult to control the vapor temperature and density as the copper chloride vapor traveled down the discharge tube. Glass wool was used to surround the quartz tube in an effort to reduce the temperature gradients but the remaining temperature gradients were large enough to cause difficulties in sustaining the discharge. The application of steady state microwaves at about 100 Watts was capable of producing relatively stable and uniform copper vapor discharges, without the aid of the heater tape. In the future we plan to use the CW microwaves to heat the copper chloride and the pulsed microwaves to produce the population inversion.

The heat tape system was not optimal for the electron beam pumped discharge system either. Again there were large temperature gradients, making it difficult to transport the copper chloride vapor to the electron beam deposition area. The heat tape could not be used directly in this region and the copper chloride tended to cool down and plate out. Plus, it was difficult to make very dense vapor needed to slow down the electrons and efficiently use their energy via electron - copper collisions. And, using a steady state source to produce the copper chloride vapor for a pulsed experiment was not very energy efficient. In addition, discharge experiments have shown that it is necessary to dissociate the copper chloride and then wait ~300 μsec for relaxation of the dissociated copper atoms, before efficient pumping of a population inversion can occur. During the next year we will concentrate on two innovative methods for copper vapor production: 1) exploding copper wires and 2) flashboards. Design of this portion of the experiment is given in Section III C.

III B. Progress in the Microwave Pumped Copper Vapor

The experimental system was assembled and tested and preliminary data was gathered. The experiment consists of a microwave circuit for transmitting and measuring 2.45 GHz microwave power (see Figure 1), a right angle cylindrical resonant cavity for transferring the microwave power to the laser gas discharge and a quartz tube for containing the gas mixtures. (See Ref. 15 - 18 for cavity details). A quartz tube, 2.54 cm in diameter, was placed along the center axis of the microwave cavity and contained the discharge. The quartz tube (melting temperature ~2000 K) was surrounded by glass wool in an attempt to keep the wall temperature close to the discharge temperature and to reduce the temperature gradients.

The Asmussen cavity consisted of a 17.8 cm diameter right cylindrical cavity made of brass, with a sliding short which allowed for adjustable cavity lengths from 6 to 16 cm.[18] The sliding short and the excitation probe were adjusted for each operating point so that the incident power was maximized and the reflected power was minimized. This cavity is designed to excite various electromagnetic modes at 2.45 GHz depending upon the position of the sliding short and probe position. Because of the simplifying electromagnetics and the ease of operation, the cavity was always used in the TM_{012} mode.

Steady state (0 - 300 Watts) or pulsed (5 kHz, 1 microsecond pulse length, 5 kWatts) microwaves entered the laser cavity through a directional coupler so that incident and reflected power could be monitored simultaneously with calibrated microwave diodes and/or power meters. The attenuation of the microwave circuit between the power meters and the coupling probe was calibrated using a network analyzer so that the power delivered to the cavity could be determined. Power meters and or microwave diodes were connected to the two arms of the directional coupler so that the forward (P_f) and reflected (P_r) power could be measured. The power delivered to the cavity was taken as $P_t = P_f - P_r$.

The reactor flow system consists of a mechanical pump, gas bottles of high purity buffer gases (helium), a back pressure regulator, a back pressure monitor and an upstream pressure

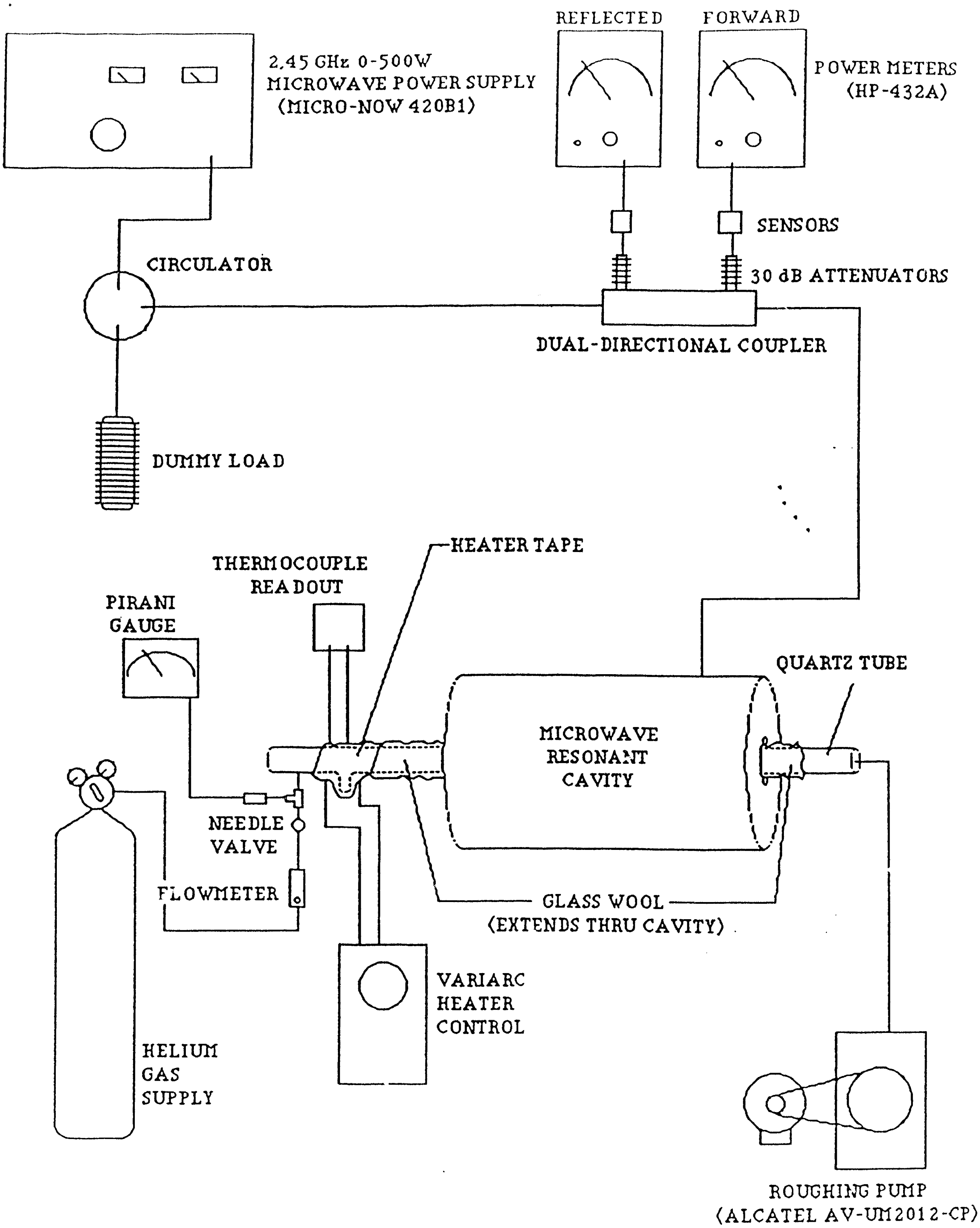


Figure 1. Schematic of microwave pumped chopper-chloride experiment.

monitor. As mentioned earlier, heat tape wound around the portion of the glass tube right outside of the cavity was initially used to produce copper vapor from heated copper chloride. It turned out that the application of CW microwave power at power levels above 100 Watts did a much better job of producing uniform, easy to control and sustain discharges. We tried to produce copper vapor with the pulsed microwave system alone but the power densities were not high enough and were not sustained long enough to produce much copper vapor. Once a small amount of copper vapor was produced with the pulsed system, the discharge became very unstable and difficult to control. During the next year, we plan to use two circulators coupled to the pulsed and the CW microwave supply simultaneously so that CW microwave power can be applied at the same time as the pulsed microwave power. It is our goal that the the CW microwaves will heat and vaporize the copper chloride and the microwave pulses will produce the population inversion. See Figure 2 for photos of CW microwave heated copper chloride vapor.

The radial electric field at the wall of the cavity was measured with a 2 mm microcoaxial probe attached to a power meter. The power measured by the probe[19] was proportional to $|E_{rw}|^2$. The cavity Q, Q_o, was also measured in the empty cavity by measuring the full width of the resonant frequency using a frequency sweep generator and oscilloscope and dividing by the resonant frequency. The square of the radial electric field for the TM_{012} mode can be found by solving Maxwell's equations and the appropriate boundary conditions[2]:

$$E_r^2(r,z) = [\frac{A\beta}{k_c}]^2 J_1^2(k_c r)\sin^2(\beta z) \qquad (1)$$

where $k_c = X_{01}/d$ and X_{01} is the first zero of the zeroth Bessel function ($X_{01} = 2.405$), d $= 2\pi/L$ where L is the length of the cavity (14.4 cm) and A is the amplitude coefficient. Figure 3 shows the probe data along with a theoretical fit to the square of Eqn. (1).

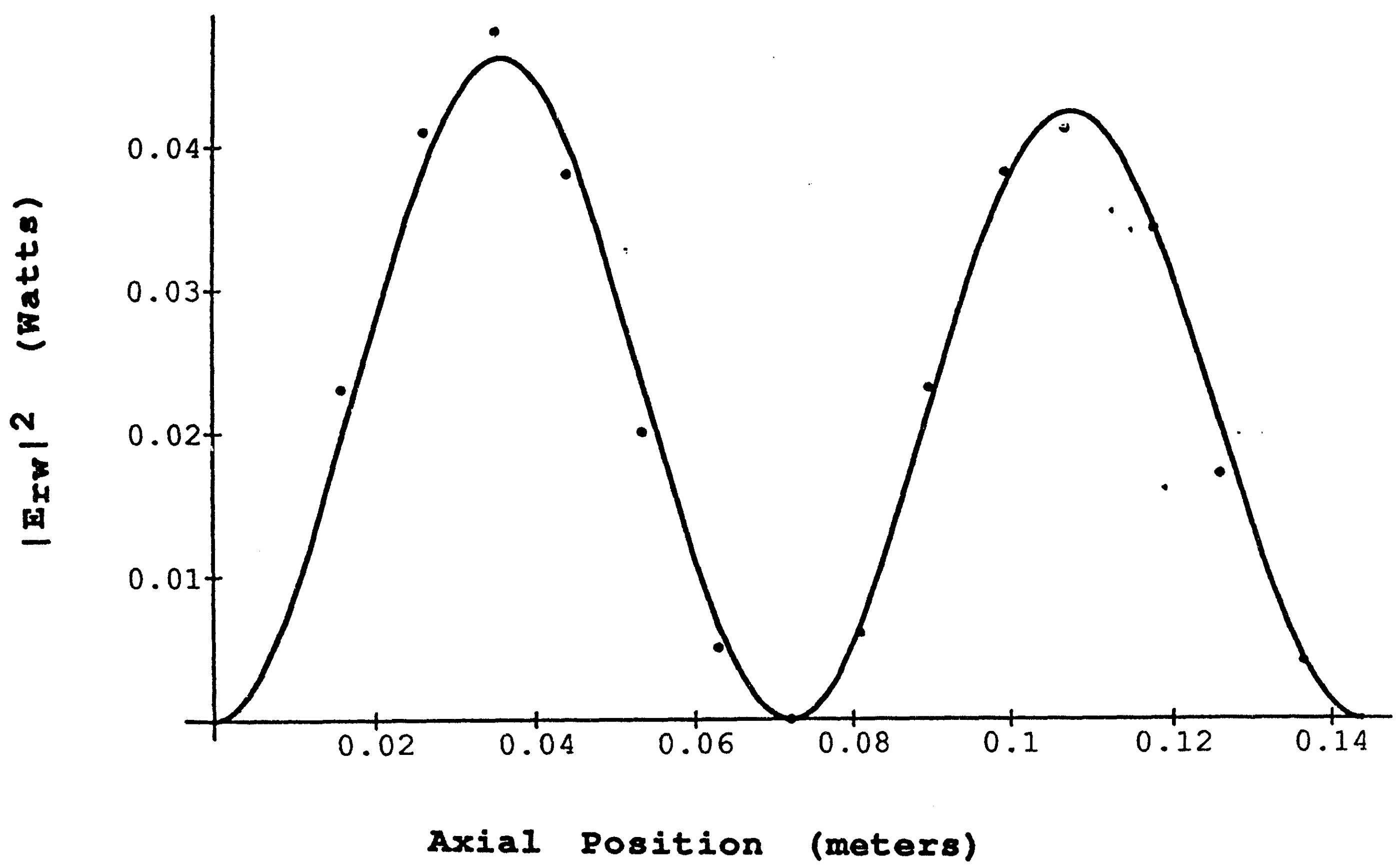


Figure 3. $|E_{rw}|^2$ as measured by the coaxial probe as a function of position along with the theoretical fit to the data.

The power absorbed by the plasma, P_p is equal to the power delivered to the cavity, P_t minus the power lost to the coupling structure, P_c, i.e. $P_p = P_t - P_c$. P_c can be determined by comparing probe measurements taken in the presence of the plasma to probe measurements taken in the empty cavity with no plasma present. Note that P_c was at most a couple of watts. The efficiency of the cavity was determined as equal to the ratio of $P_p / P_t \times 100\%$. The efficiency was always greater than 85% for the measurements reported here and often were as high as 95%.

Optical emission spectroscopy was taken with a 1 meter spectrograph and an image intensified, 1024 element, detector head coupled to an optical multichannel analyzer (OMA). Light produced by the plasma was collected through a screened port at the side of the cavity and imaged onto the entrance slit of the spectrograph.

For both CW microwave heating and for heat tape heated copper chloride, intense lines at 510 and 578 nm were observed depending upon the plasma conditions. (See Fig.4 for example of spectra. Note that the intensity of the copper lines is very large relative to the copper chloride lines. E.g. 510 nm line is the largest line observed with an intensity of about 16,000 counts. The 578 nm line has an intensity of 6,000, the second largest line observed.) The plasma was visually observed to be bright blue at the point that the copper lines were most intense. This occurred at helium pressures of about 2 -3 Torr and then disappeared for pressures slightly above 3 Torr and then reappeared at pressures above 10 Torr. Pulsed microwave discharges tended to produce typical helium emission lines only. Occasionally blue emission from copper during pulsed operation was observed but was extremely unstable.

Preliminary time resolved studies of the light emission were made. The CW power supplied is filtered such that there is very little power ripple. Thus, the light emission was basically in a steady state situation once the copper was heated to a vapor state. Using the pulsed microwave source and the gating capabilities of the optical multichannel analyzer, we observed that the vast majority of the optical emission occurs in 100 ns, about 0.3 to 0.5 microseconds into the

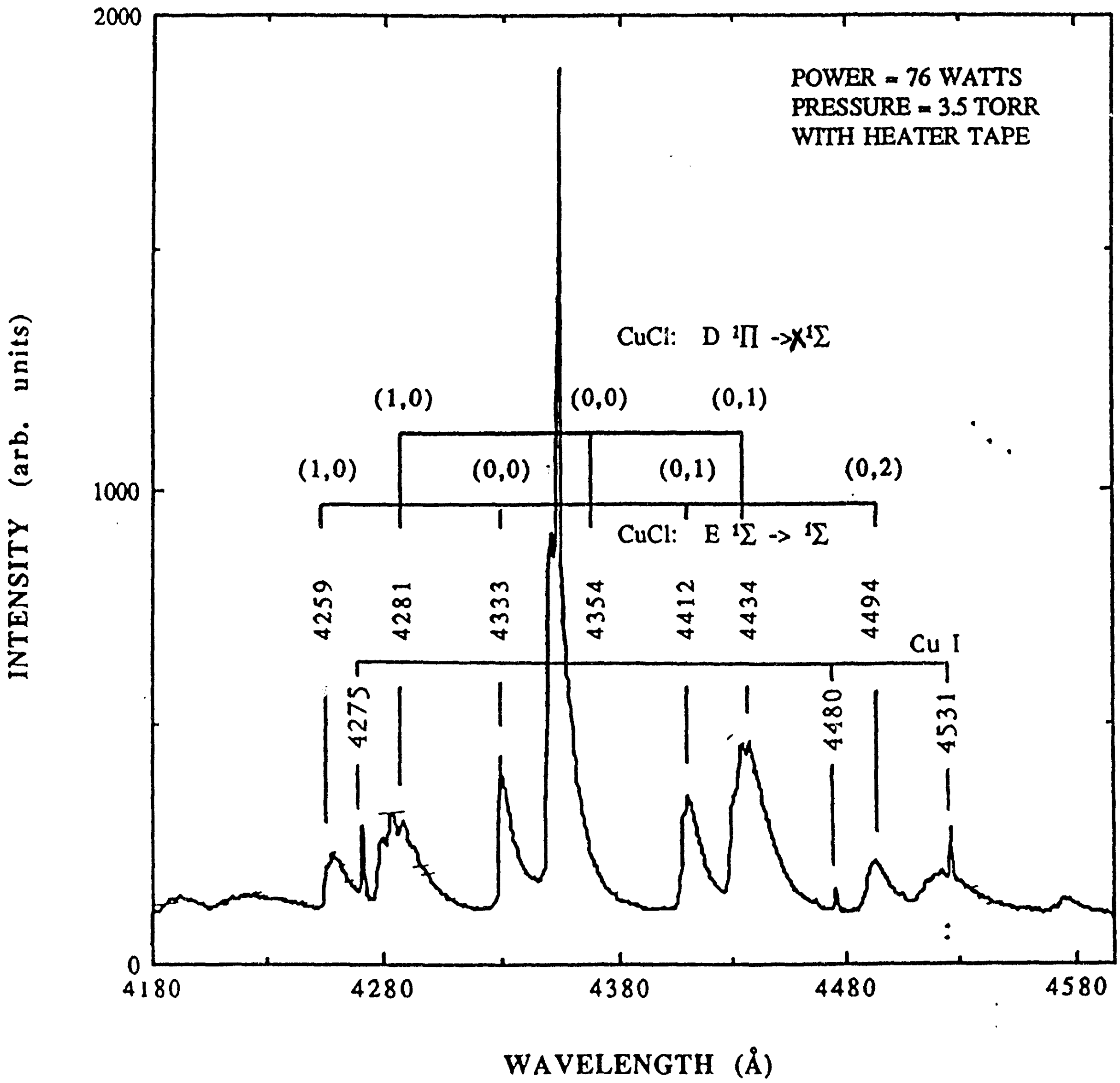


Figure 4a. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

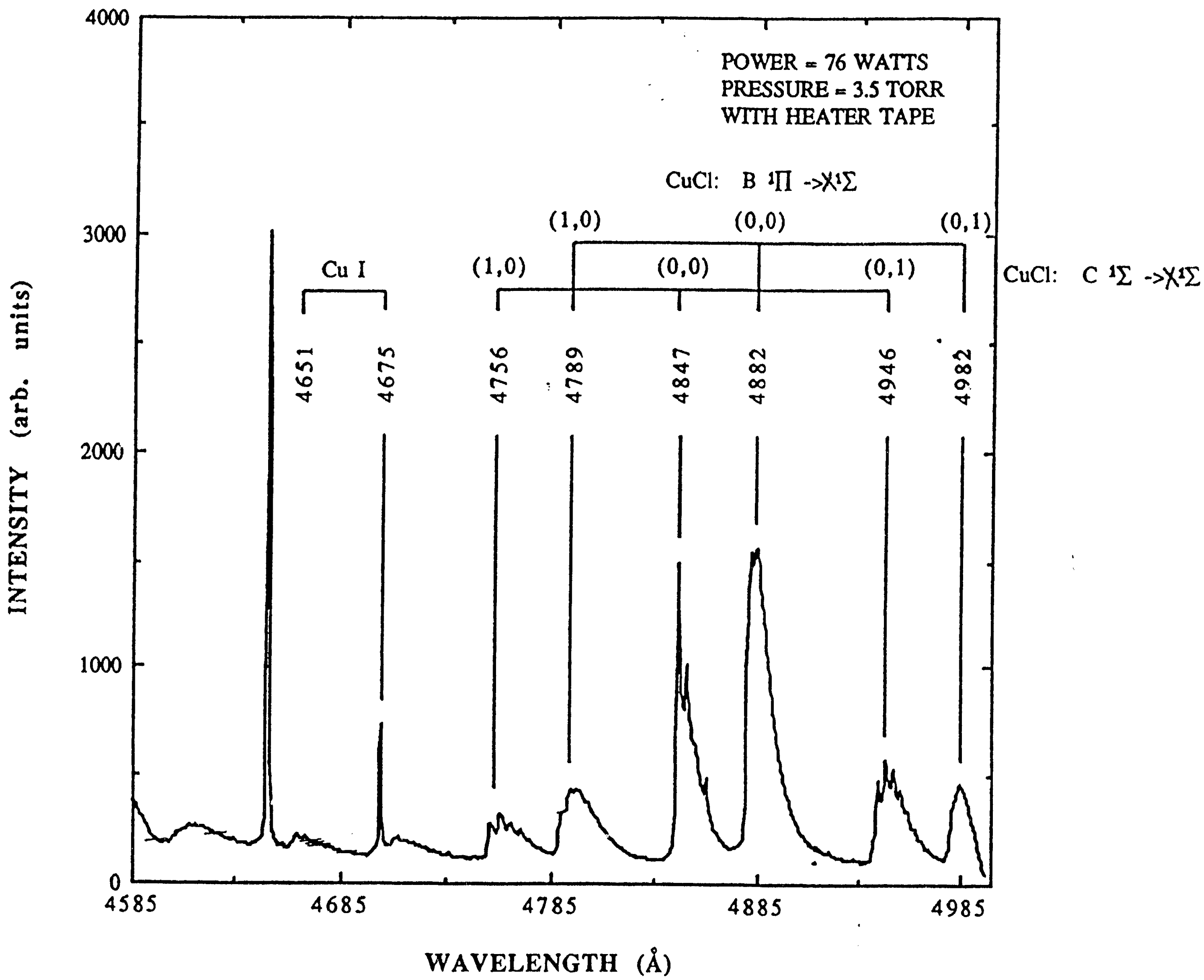


Figure 4b. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

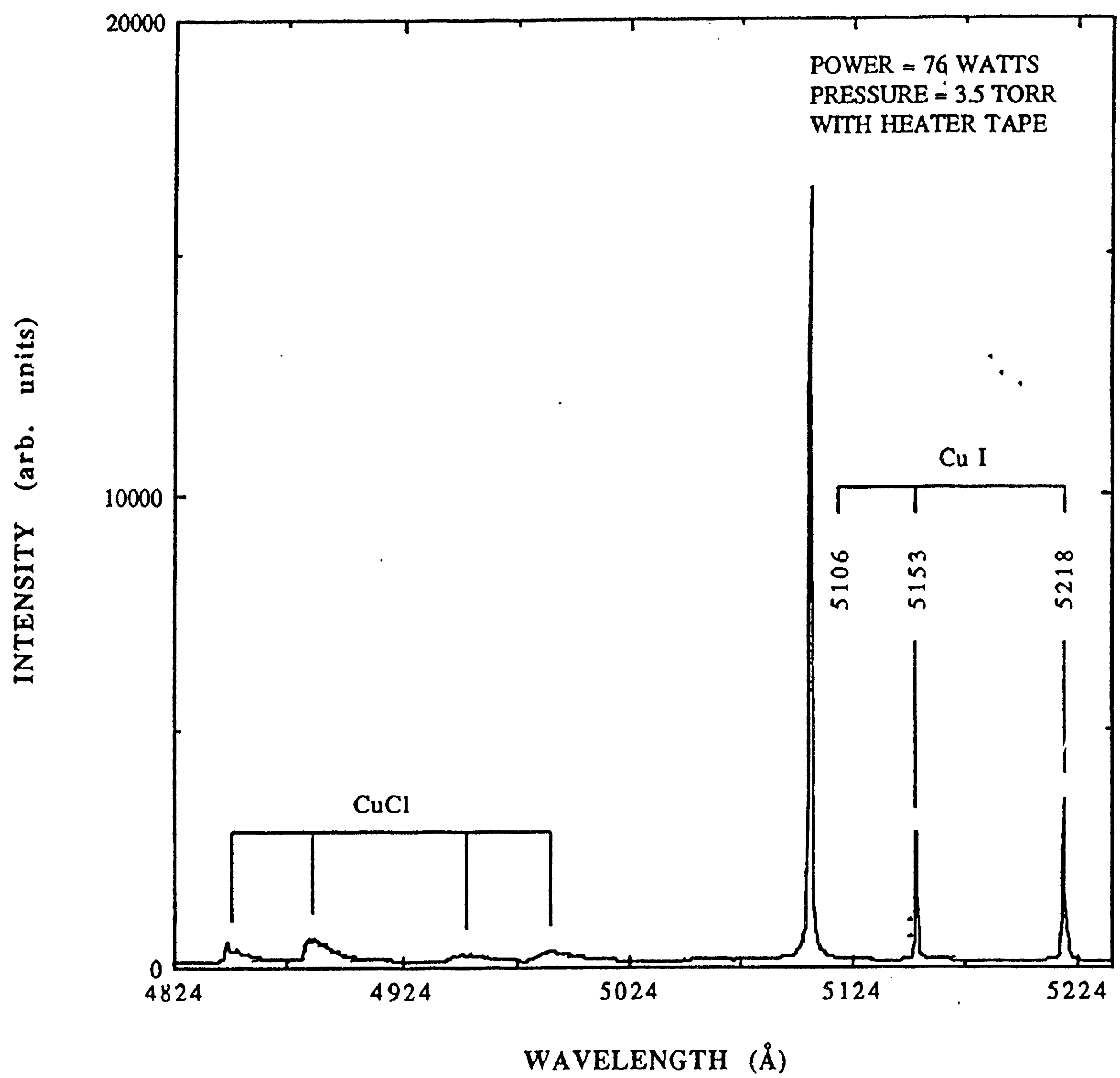


Figure 4c. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

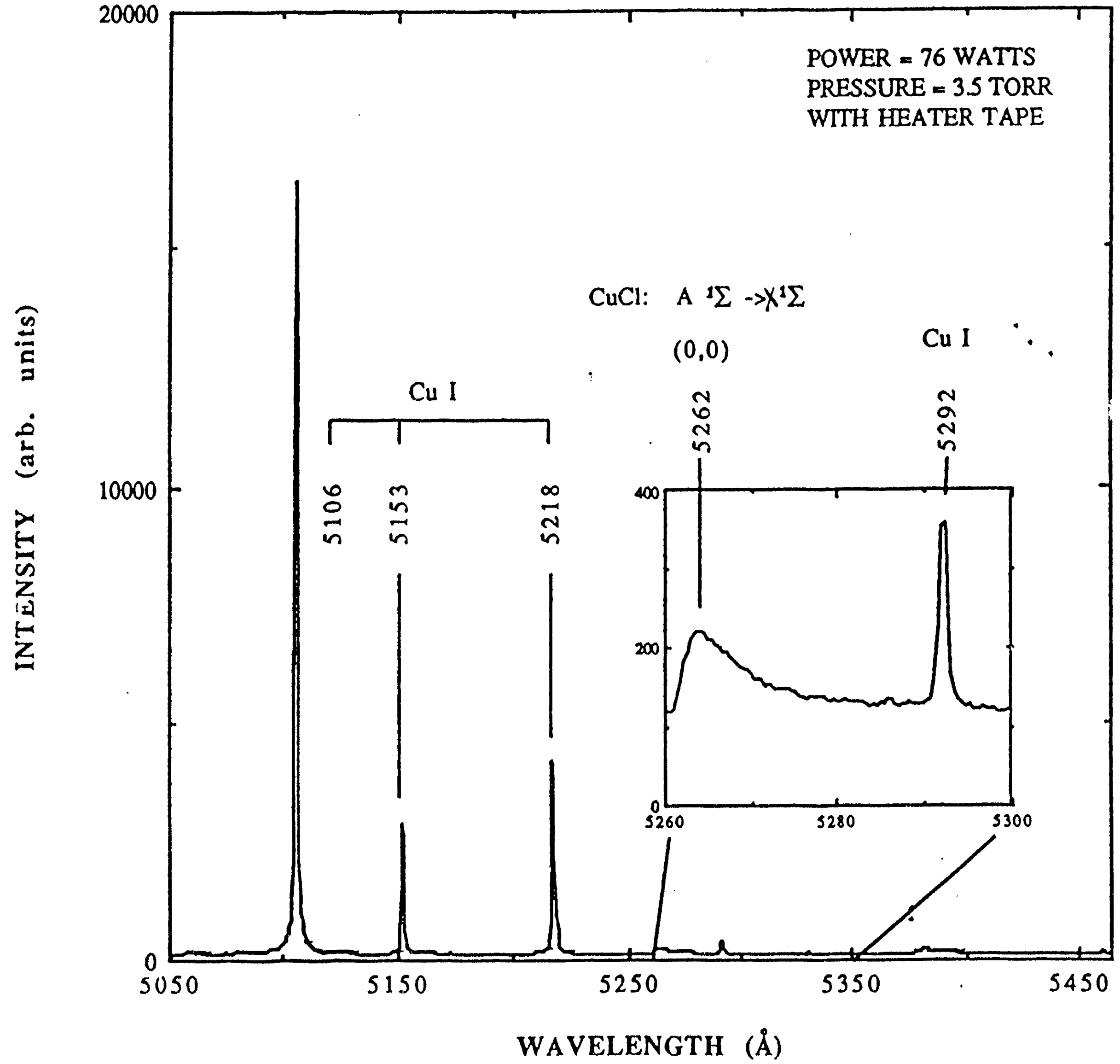


Figure 4d. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

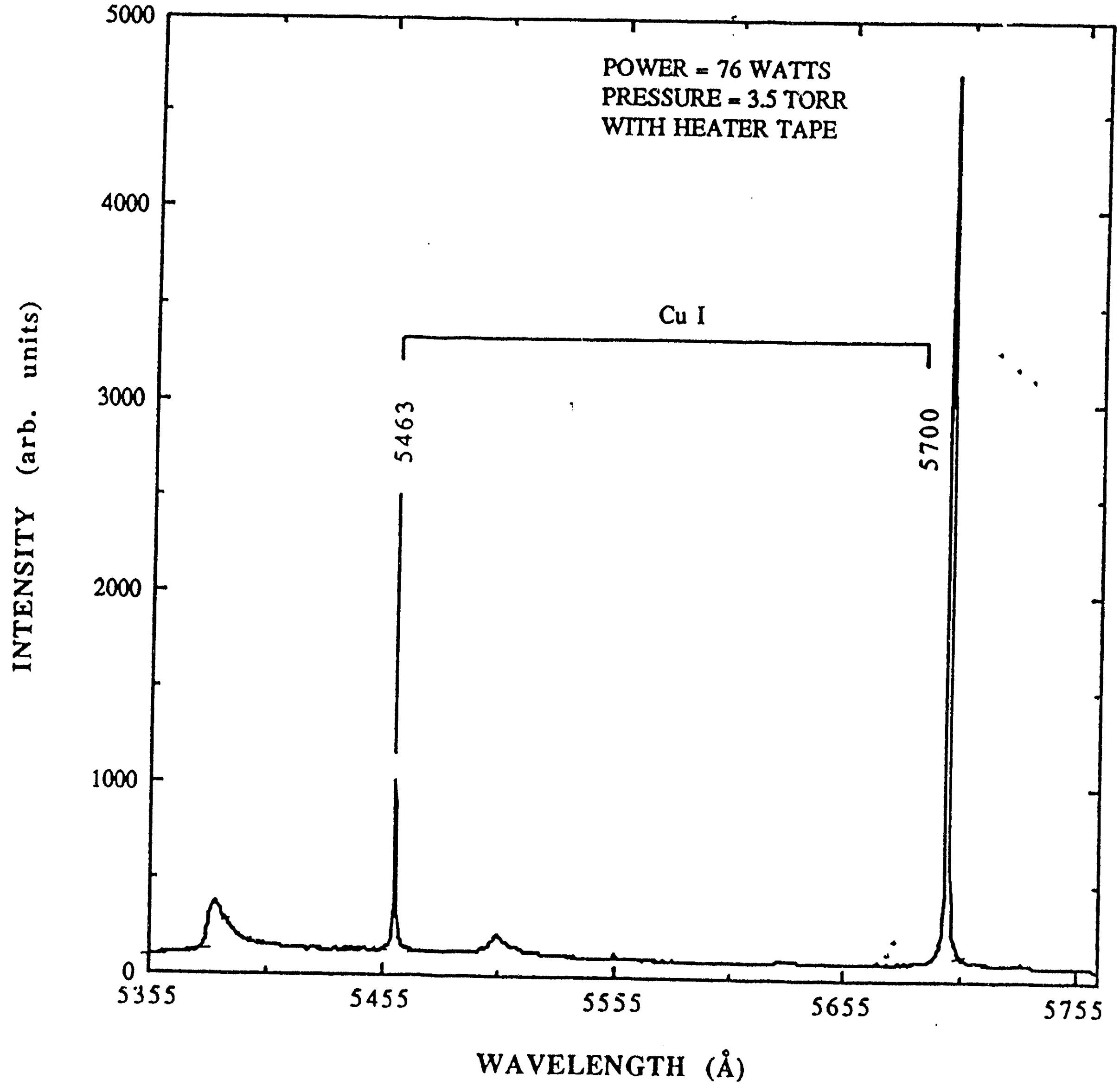


Figure 4e. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

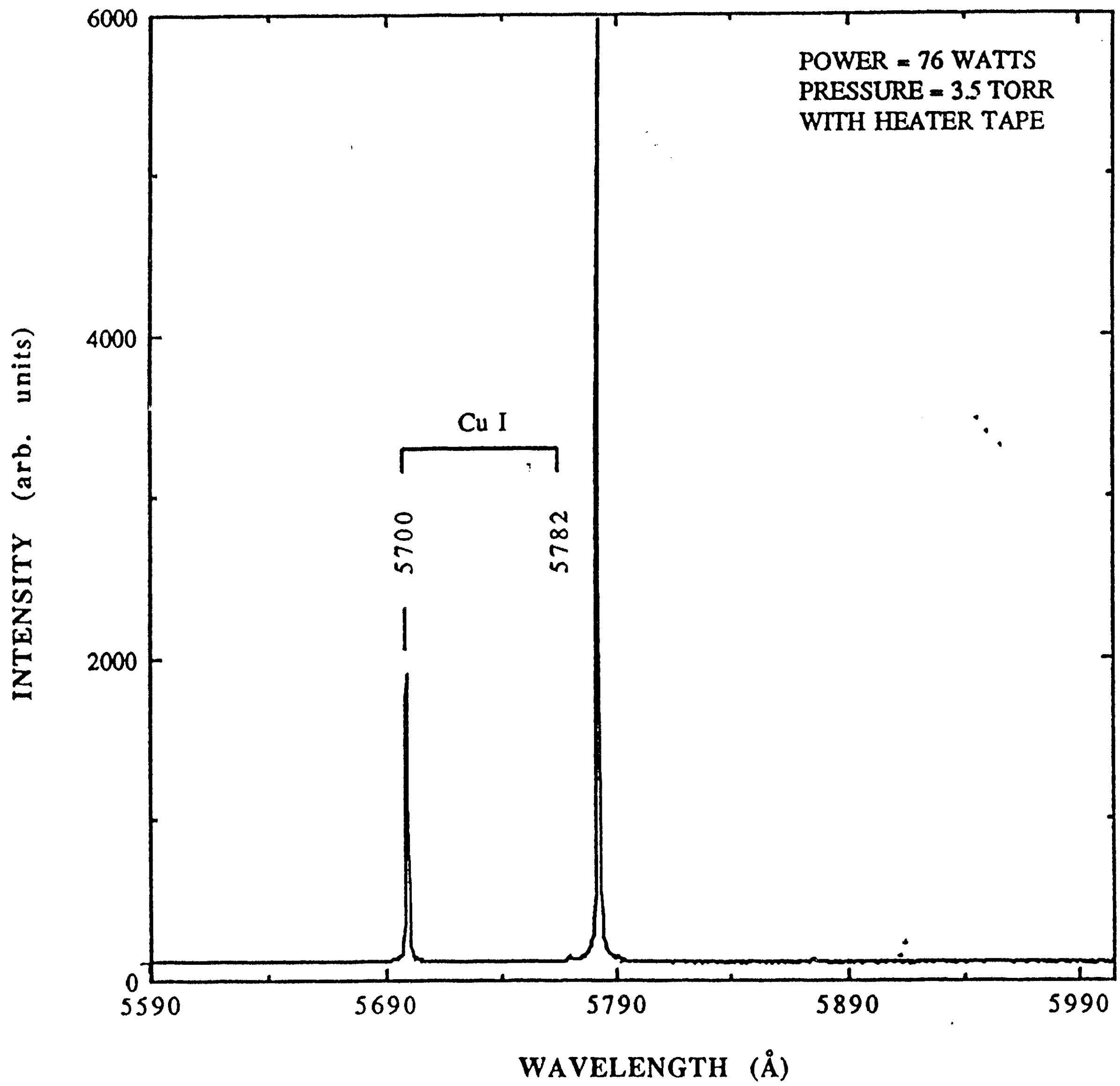


Figure 4f. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

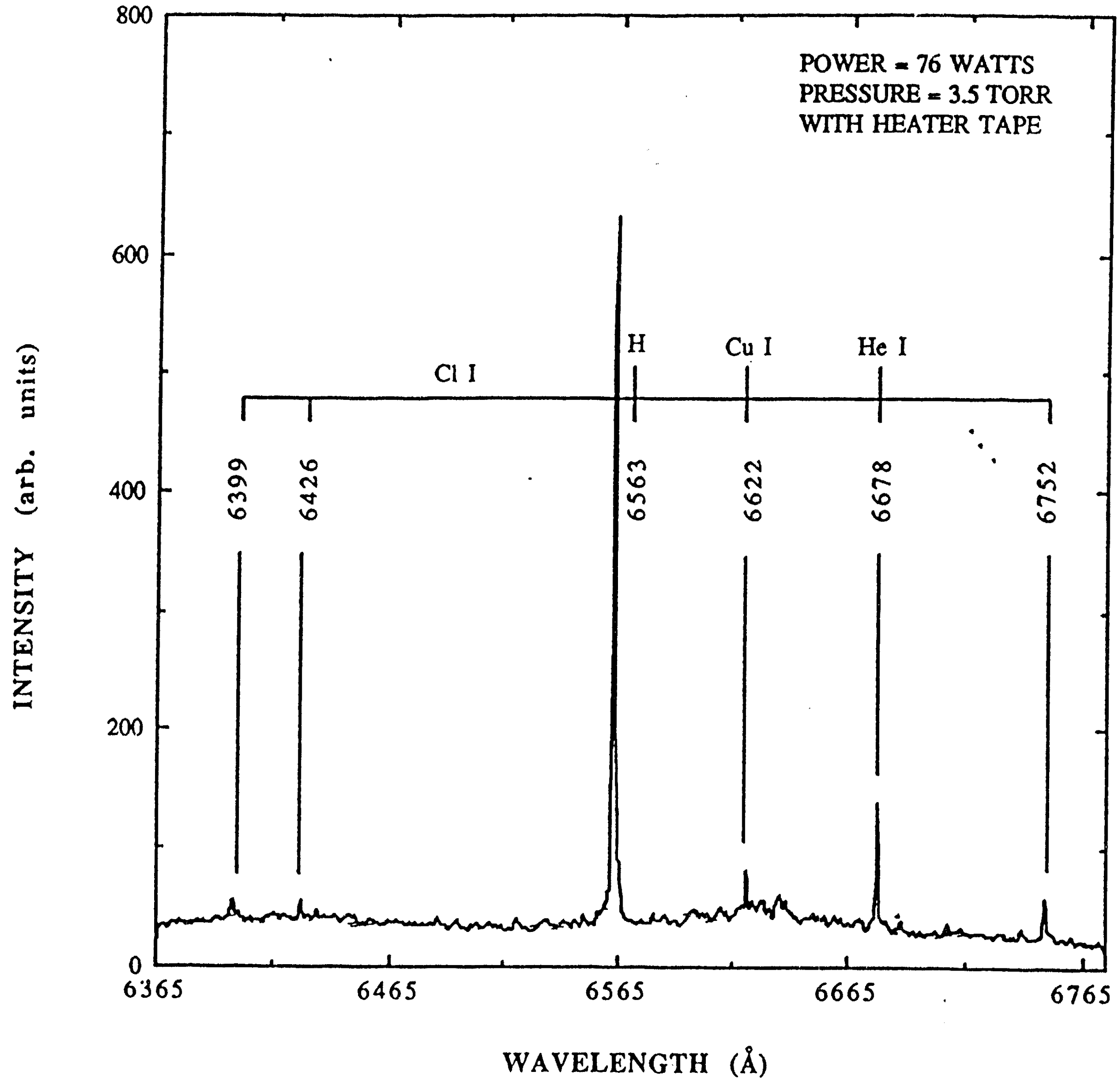


Figure 4g. Optical emission spectra of a helium plasma at 3.5 Torr which contained heated copper chloride (using the external heat tapes). The absorbed power was 76 watts, CW.

microwave pulse. From examining the microwave diode traces, this appears to be the time when the most microwave power is absorbed by the plasma and the cavity resonant condition is met. Currently the smallest gates available on the OMA are about 100 ns. Note that repetition rates of 5 kHz were necessary to sustain the discharge. We may be able to use slower rep rates when the pulsed system is used in conjunction with the heating capabilities of the CW system. We plan to investigate timing effects further during the next year.

The volume of the plasma was determined by measuring the length and cross sectional area separately. The length was measured with a fiber optic cable inserted into the same cavity holes as those used for the electric field measurements. Since the holes were spaced about 0.9 cm apart, the accuracy of this measurement was limited to about this value. The length of the plasma decreased with increasing overall gas pressure. The axial dependence of the light emission was inversely proportional to the electric field, see Fig.5.

In experiments examining air we have measured the cross sectional area using the spectrograph and OMA where in this case the detector array was rotated by 90° at the exit plane of the spectrograph. Light was gathered from the axis of the plasma and carefully imaged onto the entrance slit of the spectrograph. Thus the detector measured light at one wavelength as a function of position. Generally, light emission is fairly uniform as a function of radius. We have not yet tried this technique on CuCl plasmas because we have been using the spectrograph to examine the optical emission signatures. However, we expect similar results to those found with air. Visually we have observed the plasma filling the quartz tube.

A laser deflection method was attempted in order to determine the gas temperature of the discharge. A He-Ne laser was passed through the plasma and imaged onto a very sensitive position detector. If the temperature gradients are sufficiently large, then the laser beam will be very slightly bent through the temperature gradient and will be measured as a shift in position on

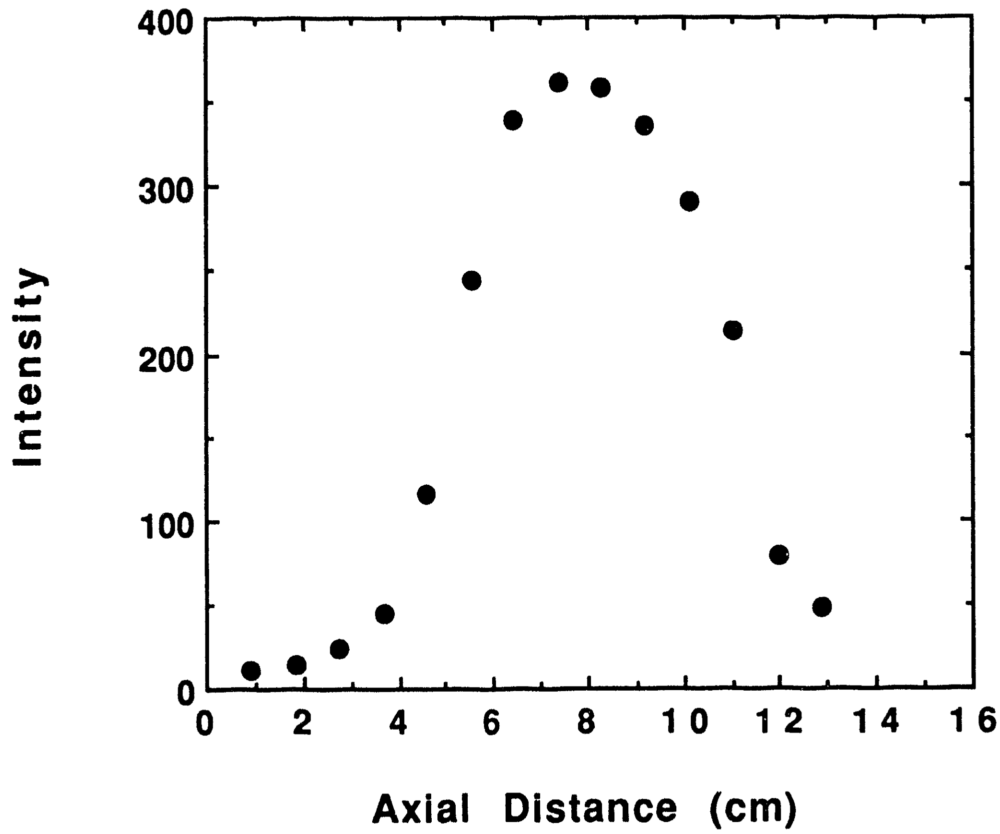


Figure 5. The light emission as measured by the fiber optic cable as a function of axial

the face of the detector. Unfortunately the discharges did not seem to have a large enough gradient to be measured by this method.

The gas temperature was calculated from the absorbed power and the plasma lengtł .sing the following simple model based upon Eden and Cherrington.[20] If all of the energy deposition to the position.electron gas through Joule heating is lost by collisions with the neutral gas, and assuming a steady state temperature distribution, then for the neutral gas the energy balance can be written as:

$$\vec{\nabla} \bullet (\kappa \vec{\nabla} T) + \vec{J} \bullet \vec{E} = 0 \qquad (2)$$

Integrating over the plasma volume (since over 96% of the energy is absorbed by the plasma), and using Gauss' theorem and the fact that the integration of the Joule heating term is the absorbed power, P(r), we get:

$$\kappa \frac{dT}{dr} = -\frac{1}{2\pi r L} P(r) \qquad (3)$$

The length of the plasma is denoted by L. The thermal conductivity, κ, depends upon temperature. Data of the thermal conductivity[20-21] as a function of temperature was well described by $\kappa = \kappa_0 T^{1/2}$ where k is equal to 8.9×10^{-3} Watts/m-$^oK^{3/2}$. The radial dependence of the power was assumed to be of the form[19] $P(r) = r^2/a^2 \, P_p$, where P_p is defined earlier. Thus equation (10) can be integrated to give:

$$T(r) = [T_w^{3/2} + \frac{3}{8\pi k_o} \frac{P_p}{L} (1 - \frac{r^2}{a^2})]^{2/3} \qquad (4)$$

We assumed that the wall was at least 695 K since this is the melting point of copper chloride and we knew from observation that the blue copper plasma extended to the wall. The temperature at the center of the plasma, based upon this model, is approximately 870 K. Taking an average temperature of 783 K, the vapor pressure of the CuCl can be determined, if the CuCl is in equilibrium with the helium gas. (This is probably the case for the CW microwave excitation case.) The vapor pressure is approximately 0.75 Torr.[22]

An electromagnetic analysis of the cavity and plasma system was formulated. The plasma is assumed to be a lossy dielectric where the dielectric constant and the conductivity are assumed to be complex. The absorbed power, plasma volume and electrical probe data is input into the model and the model then calculates the wave vector in the plasma region, and ultimately the complex conductivity and dielectric constant. In addition to determining the electric and magnetic fields from this model, the electron density and electron collisional frequency can also be calculated. Even though this model was written for the copper vapor discharge research, the model was initially tested using previous data from air discharges. (We have been studying air for several years and have accumulated a good deal of experimental data.) These results have been written up into a paper and are being submitted for publication. Thus, the details of this model are given in the paper, which appears at the end of this report. Note that the effects of the glass wool upon the dielectric constant of the microwave cavity were not taken into account in this model. The glass wool is probably a source of error since the diameter of the glass wool around the quartz tube was substantial (around 1 cm). The glass wool will be added to the model in the upcoming year.

This model was used to examine the preliminary copper vapor plasma data Conductivities of around 0.15 - 0.23 (Ohm - meter)$^{-1}$ were calculated. Electron densities of 9 x10^{11} - 3 x10^{12} and electron collision frequencies of 2 - 4x10^{11} were typical. Skin depths of 100 - 160 cm were also calculated. Typical radial and axial electric fields are shown in Figure 6 and agree in shape which those found for air discharges. The electron densities are similar to those found in air discharges. Note that the collisional frequencies are considerable higher than those predicted for pure helium, where collisional frequency for pure helium discharges should be around 1 - 2x10^{10} (see Ref. 23), where the pressure is corrected for the increased temperature.

These results indicate that microwave pumped copper vapor is, based upon these prelimary results, an attractive laser source. The skin depths are very large, indicating that large radii and large volume of copper vapor plasmas can be excited. Uniform copper discharges can be produced using microwaves. Copious amounts of 510 nm and 578 nm radiation can be produced with microwave excitation. The next year's project will focus on optimizing this radiation as a function of the various input and plasma parameters.

III C. Progress in the Electron Beam Pumped Copper Vapor

Research during the first year has concentrated on the generation of copper vapor in an electron beam interaction chamber. The fabricated system is depicted in Figure 7. The electron beam is generated by a long-pulse Febetron generator with the following parameters:

Peak voltage = 350 kV,

Peak diode current = 1 kA and

Pulselength = 300 ns.

Voltage is measured by a capacitive strap monitor while diode current is detect by a B-dot loop. The electron beam diode region is evacuated by a diffusion pump. The electron beam cathode is a field emission type fabricated by carbon string woven into a brush pattern through holes in an aluminum plate. This assembly is mounted into the aluminum cathode stalk. The foil-covered-hibachi anode is designed to withstand a gas pressure of 1 atmosphere on the copper vapor side and $< 10^{-4}$ Torr vacuum on the cathode side. A titanium foil of thickness 0.025 mm is used with a perforated stainless steel (hibachi) support structure of 40% transparency. This diode design results in an injected electron beam current of about 200 Amps in the electron beam copper vapor interaction chamber.

Copper vapor is produced by heating CuCl in a quartz tube surrounded by glass wool and a brass chamber. Temperature is controlled by heat tapes powered by a variac. The quartz tube is coupled to the electron beam chamber through a brass feedthrough flange with a viton O-ring seal.

The electron beam interaction chamber is a cylindrical aluminum design with inside dimensions of 8.3 cm diameter, 22 cm length, and total volume of 1.19 liters. Viewing windows

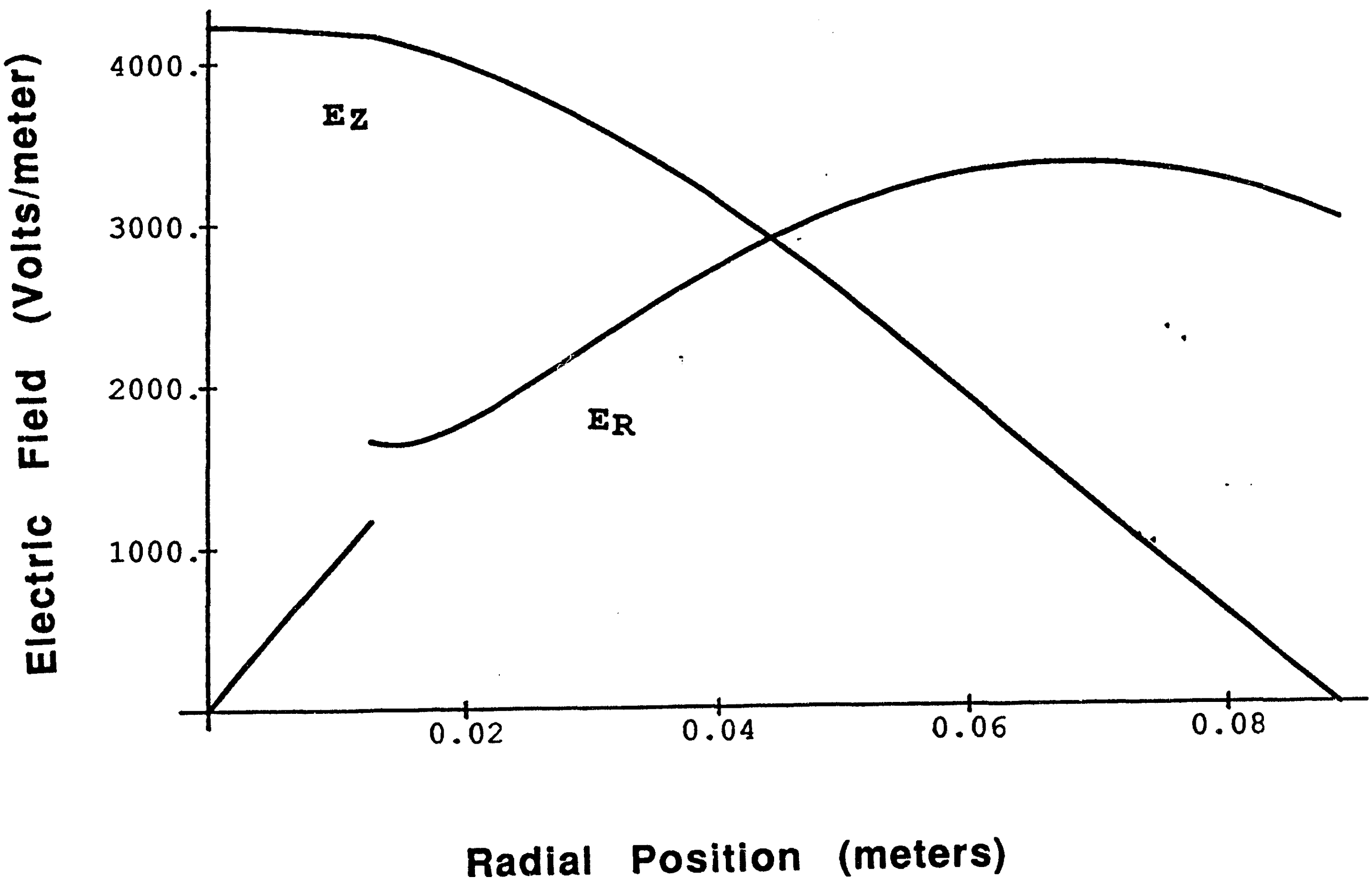
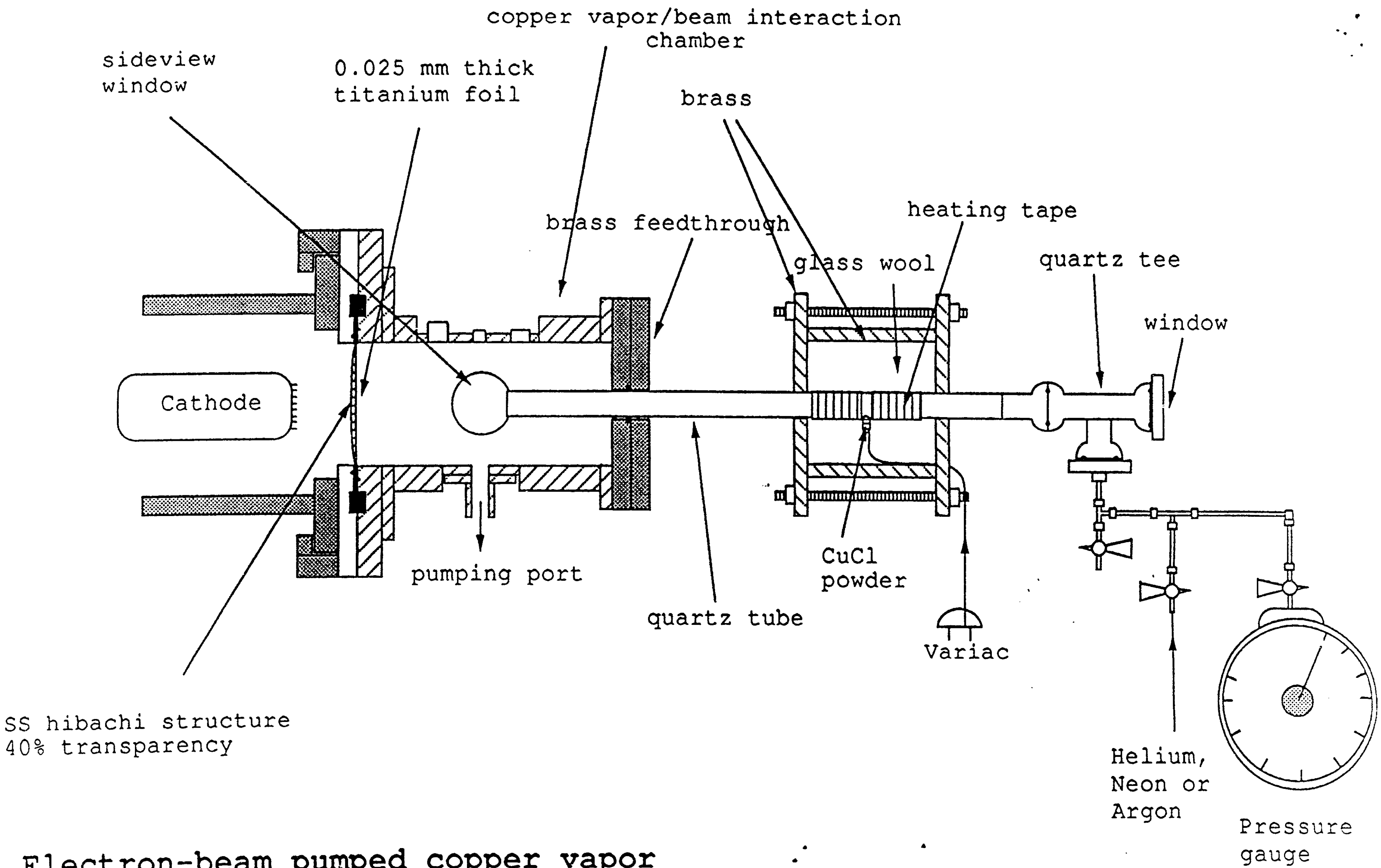


Figure 6. Radial and electric field for a helium/copper-chloride plasma at a pressure of 3.5 Torr and 78 Watts of power as predicted by the electromagnetic model.



<u>Electron-beam pumped copper vapor experimental setup</u>

Figure 7. Schematic of the electron beam pumped copper vapor experiment.

are located on both sides and on the top of the chamber. The lower chamber port is used for pumping out the chamber by means of a rotary pump.

Initial experiments have been performed on the electron beam pumped copper vapor system. In these experiments, the copper vapor source chamber was heated under vacuum conditions. After reaching equilibrium (~40 minutes) a static fill of 20 Torr helium was leaked into the chamber. The electron beam was injected into this mixture. Initial diagnostics included: e-beam voltage, diode current, fiber-optic coupled to a photomultiplier tube in a Faraday cage, and color open shutter photography. Initial results shown in Figure. 8 show that the envelope of the visible light emission roughly follows the electron beam power.

Color photographs (Figure 9) of the electron beam pumped optical emission show a blue glow in both the He and He/CuCl case. The emission intensity decreased when air was leaked into the system. We are planning to utilize two fiberoptic links with filters at the copper laser lines in order to monitor the temporal evolution of copper laser emission. Full spectroscopic studies can be performed by means of a spectrograph in the Faraday cage.

One limitation of the present experiments has been that the steady-state CuCl oven produced a low concentration of copper vapor in the helium buffer. Thus, a pulsed source of copper vapor would greatly improve the efficiency of electron beam pumped copper vapor lasers as we propose for the next year.

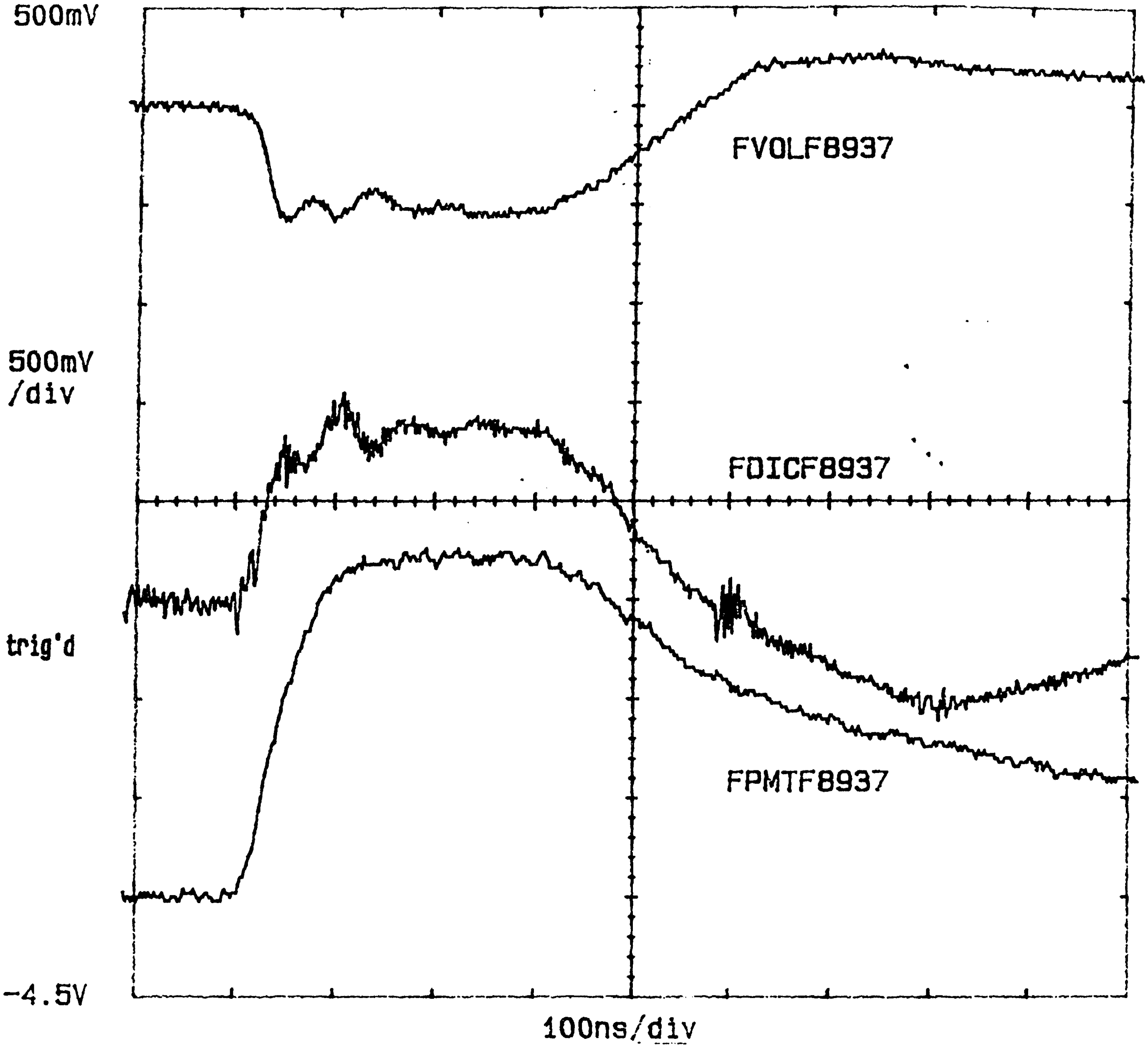


Figure 8. Diode voltage (top trace), electron beam current (middle trace) and light emission (bottom trace) as a function of time.

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IV. Students supported

The following students were supported in full or part for the period covered by this progress report.:

Will McColl	M.S. Student
Hong Ching	M.S. Student
Peter Ventzek	Ph.D Student

V. Publications:

Attached is a copy of a paper which was recently submitted to the IEEE Transactions on Plasma Science. It is entitled, "Microwave Resonant Cavity Produced Air Discharges", by M. Passow, M. Brake, P. Lopez, W. McColl and T. Repetti. The model contained in the paper was developed for this project, but it was tested out on some previously taken data.

We also plan to submit a paper to the American Physics Society Plasma Physics Conference to be held this November, in Cincinatti, Ohio. This paper will detail the results which are presented in this progress report. We will forward a copy of the abstract shortly.

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