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USING A BLACK BODY SOURCE TO ENHANCE LINE EMISSION IN A LASER PRODUCED PLASMA

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We report on the studies of coupling of black body radiation with metal vapors in a crossed heatpipe. The electron density of the laser produced plasma was estimated using a Mach-Zehnder Interferometer. The formation of clusters in a over heated heatpipe is also reported.

INTRODUCTION

Well defined homogeneous metal vapors with precise information on the density and temperature needed for spectroscopic applications are usually generated with a heatpipe oven.[1] Metal vapor–inert gas mixtures have been used extensively in non-linear optics for generation of tunable narrow band coherent light sources[2] in the UV and VUV regions[3] where non-linear crystals can not be used.[4] Recently, heatpipe ovens have been used in a soft X-ray source[5,6] which subsequently pumps surrounding metal vapors for production of short wave length lasers. Early experiments on population inversion in UV and X-ray regions used X-ray filters to eliminate unwanted spectral components from the pumping source. In order to attain efficient pumping, Harris et al[7] suggested the use of a black body source resulting from a laser produced plasma (LPP) to excite the vapor or gas. Using a similar configuration Silfvast et al[8] were the first to demonstrate a photo-ionization laser. The pumping rate depends on the density of the photons from an LPP source interacting with metal vapors. Since the emission from the LPP source is absorbed as it propagates through the vapor medium, it is essential to look for the coupling of the black body emission with the surrounding metal vapors. In the present paper we report results of studies of cadmium plasma in a crossed heatpipe. The studies were done with and without a background LPP. We also discuss the conditions for optimum working of a heatpipe. We report the formation of Cd clusters in the over heated heatpipe. The present paper is organized as follows: In Section 1, we discuss the details of the experimental setup used. Section 2 describes the optimum working conditions for the crossed heatpipe and the formation of Cd clusters. In Section 3 studies on cadmium metal vapors in the presence of a black body are presented.

1. EXPERIMENTAL DETAILS

The crossed heatpipe used was a 1″ diameter stainless steel pipe, with a stainless steel rolled wire mesh in all the four arms. The central zone was heated using a heating tape wrapped around the pipe and a fire brick structure covered the heated zone to reduce convection losses. To avoid deposition of vapors on the windows, a water jacket was provided for cooling at the end of each of the four arms. To study the effect on efficiency of getting metal vapor plasma in the presence of background plasma, a high Z metal target, tungsten, was inserted in one of the arms, opposite to the direction of the incident laser beam. The plasma was produced by focusing radiation from an Nd : YAG laser with a 18 cm focal length quartz lens onto a tungsten target for tungsten plasma and at the center of the heatpipe for metal vapors. We have used a Nd : YAG laser (DCR-4G Spectra Physics) with Gaussian limited mode structure and its harmonics $2\omega_o$, $3\omega_o$, $4\omega_o$ delivering up to 900 mJ in 2.5 ns (FWHM) at the fundamental with a repetition rate of 10 pps. In order to expose a fresh surface of the target to the laser pulses the target was continuously rotated using a small electric motor. The other two arms of the heatpipe were used for viewing and recording of emission from plasma. The plasma was imaged on to the slit of a monochromator (HRS-2, Jobin Yvon) and detected using a photo multiplier tube (PMT) (IP-28, Hamamatsu). The PMT has a reasonable flat response in the visible region. The signal from the PMT was fed into a strip chart recorder.

The density of the laser produced plasma was estimated using a Mach-Zehnder Interferometer.[9] The experimental layout is shown in Figure 1. A $2\omega_o$ (0.532 μm) radiation was used as a probe beam. The collimated probe beam was split into two beams of equal intensity at the beam splitter BS_1 and were recombined at the beam splitter BS_2. The heatpipe was placed in one arm and a compensating glass plate was placed in the other arm of the interferometer. The total phase difference between the beam passing through the heatpipe and the reference beam is $\left[\frac{2\pi}{\lambda}\int_o^{r_o} 1-\mu)\,dx\right]$ where μ is the refractive index of the dispersive medium, r_o the radius of the plasma and λ is the probe wavelength. The interferogram was recorded on a pan chromatic film using a lens less camera. The interferogram were enlarged, digitized, and analyzed for fringe shift and density evaluation. With the assumption of cylindrical symmetry around the central axis of the expanding plasma, the electron density could be calculated at various distances from the target surface by using a cubic polynomial Abel's inversion. The density n_e of the tungsten plasma could be estimated by measuring the shift in the fringes arising from changes in the refractive index and using,[10,11]

$$n_e = \frac{4\pi^2 m_o \varepsilon_o c^2}{e^2 \lambda\, \Delta}\, \varepsilon_j$$

where Δ is the fringe spacing and

$$\varepsilon_j = \frac{1}{r_o} \mathop{\varepsilon}\limits_{k=o}^{n-1} a_{jk}\, N_k$$

where a_{jk} are the Abel coefficients.[12] N_k is the value of the fringe shift N(x), with x $= \frac{kr_o}{n}$. n is the number of channels.[12]

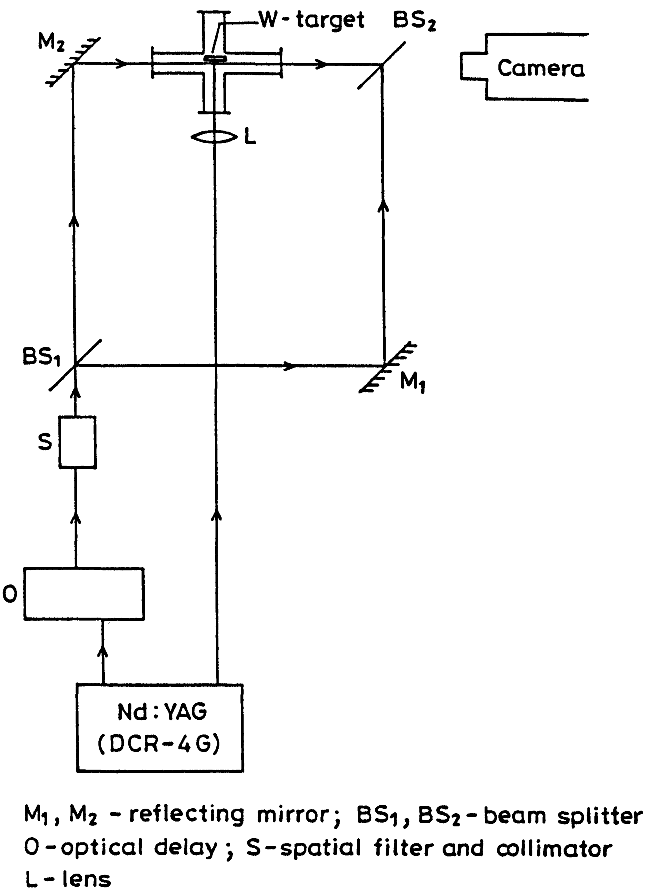

Figure 1 Mach-Zehnder Interferometer set up for density measurement.

2. WORKING OF THE HEAT PIPE AND CLUSTER FORMATION

To start with, the system was baked by heating it to temperatures exceeding 300°C for several hours with helium pressure in excess of 100 Torr. The system was evacuated to a pressure of $\leq 10^{-4}$ Torr and then filled with helium at required pressure. The laser beam was focused at the center of the heatpipe using a quartz lens to generate cadmium plasma. The temperature was slowly raised to 450°C with He gas pressure of 7–8 Torr, but no cadmium plasma was observed visually. However, when the buffer gas pressure was increased to 52 Torr and the temperature kept at 400°C a week cadmium plasma was observed. Increasing temperature further at the same buffer gas pressure, increased the intensity of the plasma. When the heatpipe was operated at 500°C, the corresponding Cd density being $2.73 \times 10^{17}/cm^3$, an intense green ball of cadmium plasma could be seen on viewing through one of the side arms. Figure 2 shows a Cd spectrum at oven temperature of 500°C. The He pressure was 52 Torr and laser energy 900 mJ. An estimate of the temperature of the metal vapor plasma was made by taking ratio of the intensity of the spectral lines.[13] The observed temperature is 0.5 eV. The intensity of the emitted cadmium lines decreased with increase in the He gas pressure. This is because at higher pressures the atomic velocity is so low

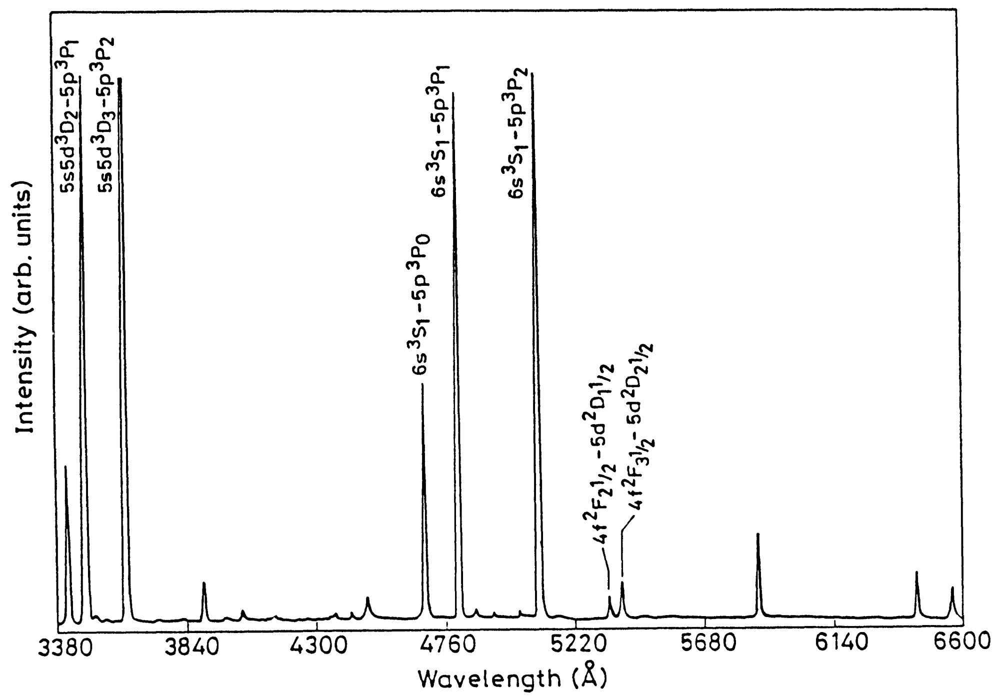

Figure 2 Visible spectrum of Cd metal vapor plasma; T = 500°C, He: 52 Torr.

that the plasma plume significantly reduces in volume and hence has less atomic density. It was also observed that increasing the wall temperature beyond 500°C decreased the intensity of the green blob. This could be due to particulate formation,[14,15] the so called 'fogging' in the heatpipe. To confirm and visually observe the formation of clusters, a weak He-Ne laser beam was sent close to the center of the heatpipe. The pattern in transmitted laser beam was observed on a wall, about 4 m away from the heatpipe. The convective movement of the dust-like particles was clearly visible in the beam. We feel that this particulate formation is due to cadmium clusters formed by condensation of the metal vapors in the cold zone at the boundary with the buffer gas. The latter acts as a third body to stabilize collision complexes between atomic and small molecular species to foster growth of the cluster species. It is similar to the effect used for production and characterization of small metal clusters[16] where an ablated plasma expands into sufficient pressure of the background gas. A slight variation of the technique has been used for the deposition of C_{60} on various substrates.[17] Though at times a useful phenomenon, the poor conditions of operation for the heatpipe result in cluster formation of the metal. The presence of clusters might severely affect the plasma emission resulting in a decrease in plasma intensity. Similar effect was also observed when the central part of the heatpipe is suddenly over heated. Generation of a high Cd vapor density required for efficient plasma production appears to be the most difficult technical problem in experiments such as ours. Our experience shows that the temperature of the heatpipe should be increased very slowly and should not exceed the value at which the vapor pressure of the metal vapor and the buffer gas pressure are equal.

3. COUPLING OF BLACK BODY EMISSION WITH METAL VAPORS

One of the aims of the present work is to report the use of laser produced soft X-rays from high Z laser produced plasma for pumping metal vapors. It is known that by focusing the laser radiation to a small area on to solid target it is possible to create a high temperature high density recombining plasma. Near the surface of the target, the plasma emission is primarily due to free-bound and to line radiation. However, for high Z target continuum radiation dominates over the line radiation. The broad band emission can be approximated to a black body with the same characteristic temperature as that of the plasma.[18,19] The broad band soft X-ray emission from a laser produced plasma has been used to directly populate the upper laser level from the ground level,[5,6] the pumping rate is essentially determined by the photon density of the pumping source. The fact that at short wavelength, inner shell photo-ionization has a higher probability than ionization of a outer electron, the most probable process with the radiation peaked in the range 200–300 Å for high Z target is photo-ionization. Based on this excitation scheme population inversion has been observed[5] in the wavelength range 109–748 nm. We have also reported[20] cadmium photo-ionization laser between the $4d^9\ 5s^2\ {}^2D_{5/2}$ and the $4d^{10}\ 5p^2P_{3/2}$ levels at 441.6 nm.

In order to study coupling between background plasma and Cd plasma, a tungsten target fixed to a rod was inserted into one of the arms of the heatpipe. The laser radiation was focused to a spot of 100 μm on to the tungsten target with helium gas at a pressure of 7–8 Torr. No heating of the heatpipe was done. A bluish white plasma of tungsten could be seen visually at the target surface. In order to photo-ionize the cadmium metal vapor, the heatpipe temperature was raised to 420°C and the laser radiation was focused on to the tungsten target. A bluish white plasma very close to the target surface and a green plasma due to cadmium vapor extending up to 7–8 mm away from tungsten surface were observed. It is worth reiterating that no Cd plasma was observed when the heatpipe was not heated. The Cd plasma was imaged on to the slit of the monochromator and the resulting spectrum recorded at 4–5 mm away from tungsten surface is show in Figure 3. The He pressure was about 7 Torr and laser energy 900 mJ. On comparing the two spectra (Figure 2 and figure 3) it becomes clear that the intensity of all lines increases drastically (sensitivity in figure 2 is five times more than that of Figure 3) and Cd II transitions which were absent in Figure 2 become observable in Figure 3. Thus it is seen that LPP can be a very effective pumping source for higher ionic states of Cd. Since we are interested in Cd II transitions it is worthwhile to consider the possible routes for a Cd II transition at 441.6 nm in particular. Though the process of inner shell photo-ionization is dominant, one should also look at the effect of photo-electrons

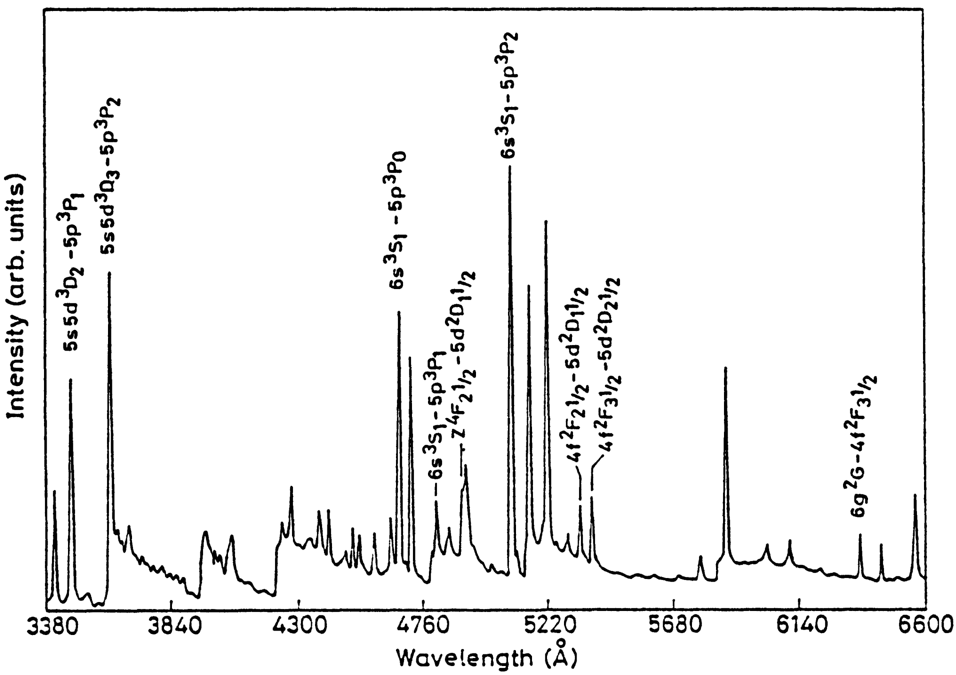

Figure 3 Visible spectrum of Cd metal vapor plasma in presence of tungsten plasma; T = 420°C, He: 7 Torr.

which are immediately present after photo-ionization. The energy distribution of the photo-electrons has a maximum around 40 eV and is determined by the photon energy distribution and wavelength dependence of the photo-ionization cross section. If we compare the ionization cross sections[21,22] for various levels of Cd we find that the cross section for $5s^2$ level is larger than 5p states in the region above 50 eV. Thus using a black body emission peaked in the range 200–300 Å one would expect that $5s^2\ ^2D$ states are formed almost exclusively by removal of inner shell electron while the ordinary 5p, 5d, 6p states are formed by ionization of one electron and excitation of another electron. The emission from the LPP source is absorbed as it propagates through the vapor medium and hence in our case affects the density and temperature of the medium. Thus the coupling between the background plasma and the Cd plasma affects the pumping rate for a photo-ionization process. Figure 4 shows the radial density distribution of tungsten plasma at 2 mm away and parallel to the tungsten target surface. The delay between the 1.06 μm beam and the probe beam is 19 ns. Using the configuration in Figure 1 the density of the cadmium plasma in the presence of the background target was also estimated. Figure 5 shows a radial profile of cadmium plasma density at 5 mm away and parallel to the tungsten surface. The density decreases as we move out radially at various axial positions of the laser produced plasma. Comparison of Figure 4 and 5 reveals that even at 5 mm away and parallel to the black body source the density of cadmium plasma is larger than at 2 mm for tungsten plasma alone. Thus the black body emission does help in pumping the cadmium vapor. We estimate the temperature of the Cd plasma at 4–5 mm away from the surface of the target to be 0.3 eV. At this distance the influence of plasma electrons is negligible.[20]

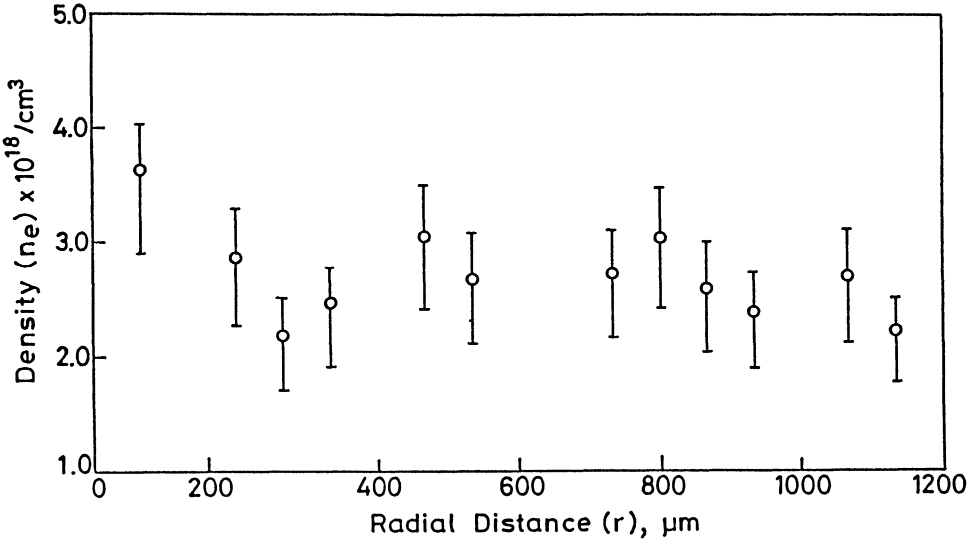

Figure 4 Radial density profile of tungsten plasma at 2 mm away and parallel to the target when no heating of the heatpipe was done; He: 7 Torr.

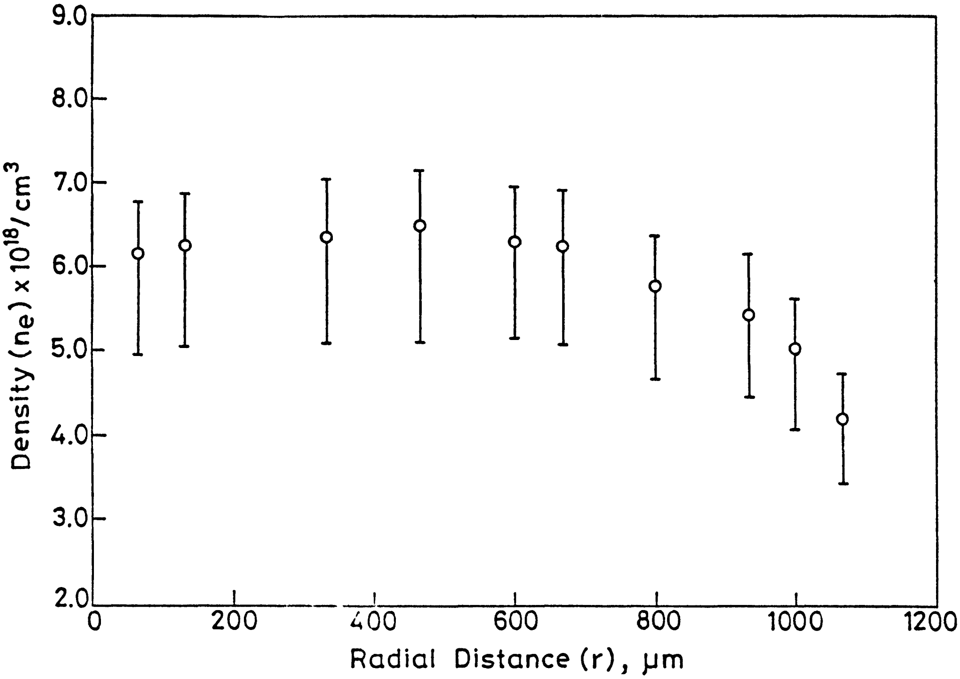

Figure 5 Radial profile of cadmium plasma density at 5 mm away and parallel to the target; T = 420°C, He: 52 Torr.

In conclusion, we have studied the Cd metal vapor plasma in a heat pipe. Cluster formation was observed when the heatpipe was over heated. To study the effect of black body pumping, Cd metal plasma was studied in the presence of tungsten target. Increase in intensity of the emitted lines from the higher ionic states of metal plasma in the presence of the black body source suggests that laser produced plasma can be very effective as a pumping source.

Acknowledgement

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