Novel Target Configurations for Selective Ionization State Studies in Molybdenum

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ABSTRACT

Details of experiments aimed at achieving low ionization state selectivity in molybdenum are presented. Targets are excited with a 10 J CO₂ laser and the resultant VUV spectrum (300 - 700 Å) has been studied. Combinations of focal spot size, target depth, and target geometries are compared. Simple attenuation of energy is shown not to vary ionization stage composition significantly. Experiments conducted with grazing incidence targets result only in a hot plasma. Modular targets with cooling cylinders of various radii demonstrated good selectivity of the ionization states, but with low absolute signals. Finally, results from combinations of focal spot adjustment and radiative cooling illustrate increased control over desired plasma temperature and density for spectroscopic studies of molybdenum.

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Introduction

Plasma Spectroscopy is both an important diagnostic tool, being used to measure impurity concentrations and ion temperature, and as an aid in understanding basic atomic processes. Laser research has relied heavily on the proper identification of potential lasing transitions. This work describes experimental techniques used to generate molybdenum plasmas suitable for studying transitions for Mo V- Mo XIV. Also, recent discrepancies^{1,2} in line identification for Mo VII ions prompted an independent verification of the VUV transitions for the 300-700 Å region using a laser produced plasma. The results of this study agree with the new identification given by Reader and Feldman.¹ A proposed scheme for an x-ray laser³ using multiphoton processes to achieve doubly excited transitions in Kr I like Mo VII requires control over the density and temperature of a molybdenum plasma. This data will be used as a basis for describing the heating and cooling of partially stripped high Z plasmas

Experimental Arrangement

Figure 1 shows the setup used for these experiments. The laser was a commercial 10 Joule 150 ns FWHM CO₂ laser operated in an unstable resonator configuration. The laser output was focused with a single 50 cm spherical lens. Line focus experiments were performed with the insertion of a hand ground negative curvature optic. The targets were made up of components of pure Mo (99.9 %). Crater damage after hundreds of shots showed less than 0.5 mm penetration. The target position was changed after every ten shots to ensure surface consistency from shot to shot. At every new position several cleaning shots were taken to remove oxide layers before taking spectra. The spectra were recorded with a McPherson 1.5 m grazing incidence spectrometer modified to take a multi channel plate (MCP) and a 1024 pixel detector giving a time integrated measurement. The 600 lines/mm holographic grating is very efficient in second order and thus extended the

lower limit of the range from 300 Å to 150 Å. Our data acquisition system is Macintosh based and has been described in detail elsewhere.⁴

Experimental Results:

I. Energy Attenuation

Varying the input energy was expected to allow selectivity of ionization stages of molybdenum. The input energy was changed by inserting various thicknesses of teflon in the beam path. An absorption coefficient for teflon at 10.6 μm was measured to be 5.9/mm using a calibrated beam splitter and calorimeter arrangement. Figure 2 shows a typical spectrum centered around 650 Å for a full beam shot (10 J) and a shot with 0.254 mm of teflon inserted (2.2 J). Although there is a slight increase in the relative intensity of the lower stages of ionization, the primary effect of reducing the input energy is a decrease in absolute intensity of the entire spectrum. This prevents this approach from being a means of generating the cooler plasmas we wanted to study. Furthermore, overlap between 2nd order Mo X, and Mo XI lines made the verification of the Mo VII lines impossible. At energies below 1 J (teflon thickness greater than 0.38 mm) no spectra were observed.

II. Grazing Incidence Targets

In these experiments, the effects of line focus were to be mimicked by having the target struck at angles of 30° and 10° giving a 2.5 and 8 times reduction in the power density while maintaining total energy deposited. Figure 3 shows the geometry used in these experiments. Care was taken to avoid reflections or interactions of the expanding plasma with surrounding surfaces. These target configurations did not provide any cooling of the plasma. The spectra resulting from these angled targets were identical to those produced with a normal incidence arrangement. Our explanation, for this effect, is that although the initial power density on the solid target is reduced, the plasma expands into the direct focus of the laser. At these plasma

temperatures, classical inverse bremsstrahlung absorption is expected to be greater than 80 %.^{5,6} This would drive a heating wave which would penetrate the entire plasma length.

III. Modular Target Experiments

The purpose of these targets was to effect the cooling of the plasma through interaction with the walls of a cylinder composed of target material. This simultaneously prevents the sharp decreases in density characteristic of free expansion. A modular design was used which permitted quick changes in target geometry while preserving alignment. Figure 4 shows a typical target makeup. The laser is normally incident on a stack of molybdenum plates (1-2.5 mm thick). Each plate has either a hole, of various radii , drilled through it, or a rectangular hole with a knife edge in the middle. In all targets, the bottom three pieces in the base formed a spacer which defines the alignment of the target with the spectrometer. In addition, the bottom piece was used to reflect stray plasma and laser light away from the field of view of the spectrometer. These three pieces were used in all target configurations. Later references to a target configuration will describe only the pieces that are stacked on top of the bottom three.

Combinations which had cylinders of various radii and length stacked together did not result in any significant cooling of the plasma. Length of a cylinder is defined by the thickness of the plate the hole was drilled through. However, the combination of a cooling cylinder and a knife edge piece did reduce the plasma temperature. Figure 5 shows the results for a 1 mm wide knife edge stacked below a 2.5 mm long 1.5 mm radius cooling cylinder. Figures 5a and 5b show that the spectra obtained when the knife edge is stacked above the alignment pieces alone (5a) and when a 2.5 mm long cooling cylinder is placed between the alignment pieces and the knife edge (5b) were similar. These spectra are similar to that for a slab target. These figures show that the small difference in position of the knife edge above the alignment pieces (and hence the focal spot size at the knife edge) does not dramatically affect the resultant plasma. In addition, in this configuration the

1.5 mm radius cooling cylinder does not have any effect on the plasma. Figure 5c shows the result when the previously mentioned cooling cylinder is placed above the knife edge. This target was checked for any direct interaction between the incident beam and the sides of the cylinder. There is no clipping of the beam by the cylinder. Thus the observed decrease in plasma temperature was not due to any aperturing of the beam. The lower temperature plasma that is seen (i.e., the observed spectrum included lines of Mo V and Mo VI only) is due to a plasma shutter. The higher density maintained in the volume of the cooling cylinder is suspected of producing a plasma shutter that reduces the resultant temperature of the observed plasma.

IV. Expansion Cooling

Figure 6 details the arrangement used to study the effect of free expansion on the plasma temperature and density. The laser was point focused normally incident on a planar target. A 1 mm slot in a mask could be positioned at any height above and parallel to the target. The spectrograph slit is behind and parallel to the slot. The plasma was studied for mask positions 0 - 4 mm above the target surface in 1 mm increments. Above 4 mm signal levels are sufficiently small as to place a limit of 5 mm on the spatial extent of the plasma. This differs from previously reported results⁶ for Carbon where reasonable signals were obtained up to 10 mm above the target surface. Figures 7-9 show representative spectra for molybdenum targets near 320, 410, and 650 Å, respectively. In each figure, the dominant lines are identified, blends are indicated by a dual assignment. Spectra are shown for all wavelength regions for the mask a) at the target surface, b) 2 mm above the target surface, and c) 4 mm above the surface. The conclusions from these spectra are best summarized with figs. 10 a,b. Figure 10a is a plot of the average intensity for several ionization states. This is calculated by averaging the intensities of lines from a specific charge state that were free of blends at any mask position, and of comparable intensity. There was only one clean line for both Mo VIII and MoXIV so these intensities are plotted directly. The key point from this figure is that there is a frozen temperature profile associated

with this type of cooling. Although the absolute intensities of all the lines decreased due to the density decrease, the relative intensities remained constant. The drop in density can be inferred from fig. 10b which is a plot of the background intensity (continuum radiation) with distance above the target for the point focus. As the bremsstrahlung emissivity scales as $(n_e)^2 T_e^{-1/2}$ this motivates the strong density dependence of our intensities.

V. Expansion Cooling With Beam Defocussing

As shown in the preceding section, simple expansion cooling could not effectively generate cold molybdenum plasmas because of the fast decrease in electron temperature and Mo densities. By placing a salt flat, with hand ground negative curvature in one axial direction, we were able to expand our 200 μm focal spot size to a line measuring 2.5 by 13 mm. The resulting power density at normal incidence on a planar target ($1.5 \cdot 10^8 \text{ W/cm}^2$) gives a controllable, predominately cold, plasma at a distance greater than 1mm above the target surface. Figures 11-13 for the line focus correspond to those in figs. 7-9 for the point focus. In these figures, the key point is that the charge state balance does change significantly with the distance above the target. The extent of the plasma is the same as for the point focus case, approximately 5 mm. Figures 11a-13a show the dominance in intensity of Mo X-XIV. Figures 11b-13b show that 2 mm above the target surface, the intensities of the hot molybdenum transitions (Mo XI - Mo XIV) are much smaller than those of the colder ions. The final group of figures at 4 mm show that the hot transitions are nonexistent. Figure 14a is the plot of the average line intensities versus distance for the line focus. Here it is clearly seen that over the same 5 mm spatial extent as covered in the point focus experiments, the dominant charge states range from the hot Mo XI-XIV to a mixture of Mo V-VIII. Figure 14b again is the curve of background intensity for the line focus. It shows a slightly slower drop off in density. This can be attributed to the expected cylindrically symmetric expansion resulting from the line geometry of these plasmas as compared to the spherical expansion for a plasma created by the point source. These spectra, when examined specifically for line identification of Mo VII, show agreement with the recent results of Reader & Feldman.¹ Further examination of the target surface indicated the existence

of hot spots. These likely contributed significantly to the intensity of the observed high ionization states. Intentionally blocking the portion of the beam that was suspected of producing the hot spots reduced the intensities of the hot molybdenum ions to almost zero. Better spatial control over the beam should reduce the creation of the hot ions thus reducing the observed intensities of these ions even further.

Conclusions

Through a proper selection of laser power density, and position above the target surface, we have achieved control over the temperature and density of a molybdenum plasma. We have generated both cold plasmas, where the dominant ionization stages are Mo V- Mo VIII, and hot plasmas, where Mo X is the lowest ionization state seen. Ranges between these two have also been observed but have not been presented here. Spectroscopic analysis of the cold plasma, concentrating on Mo VII, has confirmed the new line identification of Reader and Feldman.¹ The spatial extent of these plasmas (~ 5 mm) is significantly smaller than that of lower Z elements.

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Figure Captions

Figure 1. Experimental Arrangement.

Figure 2. Molybdenum spectra near 650Å. a) Spectrum for full beam (10 J), b) Spectrum with 0.010" teflon insered (2.2J).

Figure 3. Target Arrangement for the grazing incidence experiments.

Figure 4. Composition of the modular targets a) cross sectional view, b) perspective as seen with the laser impinging on the top plate.

Figure 5. Spectra near 650 Å for the modular molybdenum target.

Figure 6. Arrangement for Expansion Cooling Experiments.

Figure 7. Spectrum for a 200 μ point focus on a planar target near 320 Å.

Figure 8. Spectrum for a 200 μ point focus on a planar target near 410 Å.

Figure 9. Spectrum for a 200 μ point focus on a planar target near 650 Å.

Figure 10. a) Line intensities vs distance for the 200 μ point focus, b) background intensity vs distance for the point focus.

Figure 11. Spectrum for a line focus on a planar target near 320 Å.

Figure 12. Spectrum for a line focus on a planar target near 410 Å.

Figure 13. Spectrum for a line focus on a planar target near 650 Å.

Figure 14. a) Line intensities vs distance for the line focus, b) Background intensity vs distance for the line focus.

Experimental Setup

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

a) At target surface

b) 2mm above target surface

c) 4 mm above target surface

Fig. 7

a) At target surface

b) 2mm above target surface

c) 4 mm above target surface

Fig. 8

a) At target surface

b) 2mm above target surface

c) 4 mm above target surface

Fig. 9

a)

Background Intensity vs Distance for the Point Focus

b)

Fig. 10

a) At target surface

b) 2mm above target surface

c) 4 mm above target surface

Fig. 11

Fig. 12

a) At target surface

b) 2mm above target surface

c) 4 mm above target surface

Fig. 13

Fig. 14

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