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Near field imaging of a saturated table top X-ray laser

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ABSTRACT

High resolution 2D imaging experiment on the saturated 18.9 nm Ni-like soft X-ray laser is presented. The imaging experiment allows measurement of the absolute output energy and intensity of the X-ray laser, while gives detailed information on the spatial characteristics of the X-ray laser for understanding the physics and further improving the performance of the X-ray laser.

Keywords: X-ray lasers, X-ray imaging

1. INTRODUCTION

Recent development of high power, short pulse, compact laser systems using the chirped pulse amplification (CPA) technique [1] and the implementation of the transient collisional excitation (TCE) scheme [2] have made a big leap in X-ray laser development. The transient collisional excitation scheme [2-4] uses a low intensity, long laser pulse ($\sim 10^{12}$ - 10^{13} W cm⁻², ~ 1 ns) to generate plasmas from solid targets, which is heated ~ 1 nanosecond later by a high intensity, short laser pulse ($\sim 10^{15}$ W cm⁻², ~ 1 ps) to generate the population inversion in the Ne- or Ni-like ions. Hydrodynamically, this is analogous to those prepulse and multiple pulse pumping schemes [5, 6] with the first pulse preparing a large scale length plasma with proper ionization, which allows better propagation of the X-ray laser beam and more efficient absorption of the short heating pulse. Kinetically, the ultrafast heating by the short, intense laser pulse makes it possible to generate unprecedented high gain [2-4] and enable the X-ray laser to saturate over a small target length. The scheme takes the advantage of the compactness of the CPA systems which makes it possible for table-top X-ray laser development using laser pumps.

Using the TCE scheme, laser has been demonstrated in both Ne- and Ni-like ions with wavelengths ranging from 12 nm to 33 nm [3, 4, 7-9], and saturated operation has been achieved at a number of wavelengths [7, 8, 10]. However, the characteristics of the X-ray laser, such as the near and far field beam pattern, the pulse duration, and the spatial coherence, remain unknown.

In this report, we present systematic imaging experiment on the 18.9 nm Ni-like Mo table top X-ray laser, which reveal detailed information about the general performance of the laser, as well as its beam properties.

2. EXPERIMENTS

The experiment was performed on the compact multipulse terawatt (COMET) laser system at the Lawrence Livermore National Laboratory. The laser occupies two standard optical tables of dimension 1.2 m $\times$ 3.6 m with total area less than 10 m². This system is a hybrid CPA laser consisting of a Ti: sapphire oscillator and a regenerative amplifier tuned to 1053 nm and a 4-stage Nd: phosphate glass amplifier. The two final 50-mm diameter amplifiers generate two beams with pulse duration of 600 ps FWHM (full width at half maximum). One of the beams is compressed in a vacuum compressor to generate a short pulse of ~ 1 ps FWHM duration. The second is sent through a delay line to adjust the delay between the

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arrivals of the two beams on the target. The two beams were co-aligned and propagated under vacuum to the target chamber where they are focused using a cylindrical lens and a paraboloid combination. The short pulse is focused on to the target to form a $\sim 80 \mu\text{m} \times 12.5 \text{ mm}$ line focus, while the long pulse is deliberately defocused by a factor of 2 to ensure the overlap with the short pulse. With the typical energies, the irradiance on the target surface are lower than 10^{12} and $10^{15} \text{ W cm}^{-2}$ for the long and the short pulses, respectively. The laser can be fired once every 4 minutes and parameters including energy, pulse shape, pulse separation, near field image and spectrum were monitored. In addition, an X-ray slit camera with a $25\text{-}\mu\text{m}$ spatial resolution with a charge-couple device (CCD) monitored the uniformity of the line focus.

A traveling wave excitation setup is implemented using a 5-segment stepped mirror, which generates a phase velocity of $\sim c$ along the line focus, verified by high-resolution optical streak camera measurement. For some of the experiment, we also replaced the stepped mirror with a flat one to compare the performance of the X-ray laser with and without the traveling wave excitation.

We used both near field imaging and spectroscopy methods in the experiment (Fig. 1). Normally, the x-ray laser output is sent to an on-axis flat field grating spectrometer coupled to a back-thinned, CCD camera with a wavelength coverage of 14 - 35 nm and gives time-integrated spectra with angular resolution in the horizontal plane.

To obtain the near field image of the X-ray laser, we used a multilayer mirror imaging system. The diagnostic consists of three $\text{Mo}_2\text{C/Si}$ multilayer mirrors. One of them is spherical and images the output aperture of the X-ray laser onto a back-thinned X-ray CCD camera. The mirror can be translated sideward to let the beam go into the flat field spectrometer. Two flat mirrors, one with normal incidence and the other with 45° incidence, are used to fold the beam to obtain a magnification of about 14.1. With the $24\text{-}\mu\text{m}$ pixels of the CCD, this gives a maximum spatial resolution of $1.7 \mu\text{m}$. The normal incidence multilayer mirrors have 31 $\text{Mo}_2\text{C/Si}$ layer pairs with a spacing of 10 nm which gives a peak reflectivity of 47% and a bandwidth of 1.5 nm FWHM at 18.9 nm. The 45° mirror has 16 layer pairs with 14.85 nm spacing and peak reflectivity of 27% and a bandwidth of 2.5 nm FWHM at 18.9 nm. The total reflectivity peaks at 5.9% with a bandwidth of 1 nm. To block the visible light and to avoid saturation of the CCD, aluminum filters of a variety of attenuation are used. The narrow transmission band of the system is verified with null shots on Nb ($Z=41$) and Ti ($Z=22$) targets.

3. RESULTS AND DISCUSSION

2.1 Far field beam divergence measurement

We use Mo ($Z=42$) slab in the experiment, which lases on the Ni-like $3d^9 4d \ ^1S_0 \rightarrow 3d^9 4p \ ^1P_1$ transition at 18.9 nm and $3d^9 4f \ ^1P_1 \rightarrow 3d^9 4d \ ^1P_1$ transition at 22.6 nm (Fig. 2). Here *LS* notation is used. Measuring the intensity of the 18.9 nm line as a function of target length, we obtained a total gain length of 16.6 for 10-mm targets, verifying its saturated operation [10].

Figure 1. Top view of the schematic setup for the X-ray laser experiment. For the high resolution near field imaging experiment, the three multilayer X-ray mirrors M1, M2, and M3 are used to relay the output aperture of the X-ray laser onto the CCD camera. Here M1 is spherical and is used at normal incidence; M2 and M3 are flat mirrors. The X-ray laser can be sent to the flat field spectrometer with M1 translated out of its way.

As the target length increases, the beam divergence becomes smaller, as given in Fig. 3. This is consistent with the expected gain-narrowing effect due to the lasing behavior. At target length of 10 mm, the divergence in the target normal direction is 3-5 mrad, and the deflection angle is about 10 mrad from the target surface.

2.2 Near field beam pattern

Figure 4 gives a set of the near field beam pattern under different pump conditions. In the images, laser is incident from the top and the target surface is at $z=0$, determined by locating the drastic change of the background emission. As can be seen in the figure, the lasing apertures normally have a high intensity, crescent-shaped core, with a low intensity outer skirt. Though one can see small-scale inhomogeneity, which may be caused by the different gain lengths experienced by the individual rays, the large-scale inhomogeneity observed in previous imaging experiment with long drive laser pulses is not observed [11, 12].

In the experiment, the shape, size, and intensity of the near field patterns change with conditions. For example, with the short pulse energy E_s held constant at about 5 J, increasing the long pulse energy E_L increases the size of the lasing aperture [Fig. 5 (a)]. This is expected due to the larger plasma generated by the larger long pulse, and the larger plasma hold a larger gain region. As a longer delay between the long and the short pulse also results in a larger plasma, increasing the delay between the two pulses while keeping the energy constant in both pulses gives a similar effect, which is shown in Fig. 5 (b).

Figure 4. Near field images of the Ni-like Mo 18.9 nm X-ray laser under different conditions. (a) $\Delta t=0.1$ ns, $E_L=0.98$ J; (b) $\Delta t=0.4$ ns, $E_L=2.54$ J; (c) $\Delta t=0.7$ ns, $E_L=4.84$ J. The target length is 10 mm and the short pulse energy is $E_s=5$ J. The scales are from 0 to 20000, 30000, and 30000 for (a), (b), and (c) in CCD counts, respectively.

Figure 5. Distances of the lasing aperture from the target surface as a function of the (a) long pulse energy E_L at a fixed delay of $\Delta t=0.7$ ns and (b) as a function of the delay between the long and the short pulse at a long pulse energy of about $E_L=1.2$ J. The target lengths are 10 mm for all shots. The short pulse energy E_S is kept constant at 5 J. Displayed are the distances of the inner and outer edges of the lasing aperture measured at half the peak intensity.

Note that the laser aperture for the $\Delta t=0.1$ ns case is farther away from the target surface in comparison with the $\Delta t=0.4$ case. We believe this is because of the refraction of the X-ray laser beam due to the steep density gradient as the result of the small delay, which does not allow the plasma to expand and relax its density profile.

Though the width of the lasing region in the z direction changes dramatically with the pump condition, the width in the transverse direction (y direction) is constantly ~ 90 μm , roughly the width of the line focus of the short pulse.

2.3 Measurement of the absolute X-ray laser output energy

To measure the absolute output of the X-ray laser, we first subtract the background plasma emission, then integrate the image and convert the total CCD counts into the energy using the CCD efficiency ($\sim 40\%$), the multilayer mirror reflectivity, and the filter transmission. Taking into account of the uncertainties in the filter thickness, the mirror reflectivity and the CCD quantum efficiency, the measurement is believed to be accurate within a factor 2.

As expected, the output energy is a strong function of the pump condition (Fig. 6). In Fig. 6 (a), the output laser energy is plotted as a function of the long pulse energy E_L for four different delays. It is obvious that for each delay, there is an optimum long pulse energy that maximizes the X-ray laser output. This behavior is a convolution of the ionization

Figure 6. (a) X-ray laser output as a function of the long pulse energy E_L with $E_S=5$ J; (b) X-ray laser output as a function of short pulse energy E_S at a constant long pulse energy of $E_L=2.8$ J. For both cases the delay is $\Delta t=0.7$ ns and the target length is 10 mm.

Figure 7. Output energy and area of the aperture for a set of non-consecutive 9 shots with $E_s=4.9$ J and $E_L=1-1.47$ J, which demonstrates the reproducibility and stability of the X-ray laser system. The target length is 10 mm, and the delay Δt is 0.7 ns.

balance, the X-ray propagation and plasma heating processes. At any delay, too small a long pulse may have two negative effects. The first is that it may not generate a plasma that has a large enough density scale length expected for reducing the refraction loss of the X-ray laser. The second is that it may not be able to generate the expected lasing ions in the plasma therefore directly reduces the gain. On the other hand, too large a long pulse, may generate a plasma that is too large for the short pulse to heat to the right temperature. The plasma may also be over-ionized. Both effects reduce the gain.

In Fig. 6 (b), the output energy of the X-ray laser is displayed as the function of the short pulse energy at a constant long pulse energy $E_L=2.8$ J. As expected, the output increases monotonically with the short pulse energy, because a large short pulse heats the plasma harder hence generating a higher plasma temperature. This in turn enhances the monopole excitation rate and increases the gain.

By dividing the X-ray laser output by the area of the output aperture and an estimated pulse duration of ~ 7 ps, we obtained the intensity of the X-ray laser at its output aperture. We found the X-ray laser normally has intensities in the range of GW cm^{-2} , and in many cases exceeds the theoretical saturation intensity of 1.7 GW cm^{-2} . Together with the beam divergence of $5 \times 10 \text{ mrad}^2$ estimated from Fig. 3, its brightness is found in the order of $10^{22} \text{ photons s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2}$ in a 0.01% BW, 4-5 orders of magnitude higher than the brightest synchrotron sources at the same wavelength [10].

2.4 Stability, reproducibility and target durability

A practical table-top X-ray laser would be working at a high repetition rate, therefore the stability, reproducibility and the target durability become important. To this end, the imaging experiment provides us with very valuable information both about the X-ray laser output and the near field beam pattern for assessing its performance.

For shots on fresh target surfaces under similar conditions, both near the field pattern and the output of the X-ray laser seem to be very stable. Figure 7 gives the output and the aperture size for a set of non-consecutive shots with the short pulse energy $E_s=4.9$ J and long pulse energy $E_L=1-1.4$ J. For these shots, the deviation of the output energy and the area of the output aperture are less than 15%, resulting a intensity deviation of the same level. This demonstrates the stability and reproducibility of the X-ray laser system.

To look at the reusability of the target, we purposely accumulated 11 shots on one location of the target and monitored its near field pattern and thereby the output energy. Figs. 8 (a) and (b) compares the near field beam pattern of the X-ray laser, where (a) is for the first shot and (b) is for the 11th shot. Obviously, the beam pattern changes considerably and becomes very inhomogeneous after 11 shots. The laser crater is clearly visible and has a V shape. The gain region becomes broader in the target normal direction. Clearly, the crater generated by the laser has a significant impact on the hydrodynamics. This modifies the density profile of the plasma, which in turn modifies the gain distribution and the

Figure 8. Comparison of the near field beam pattern for the first and the eleventh shots for a set of consecutive shots accumulated on the same target location of a 10 mm long target. $E_L=0.96$, $E_S=4.85$, $\Delta t=0.7$ ns.

propagation of the X-ray laser. This suggests possible control of the spatial mode of the X-ray laser by changing the target geometry, which is important for a practical X-ray laser.

Surprisingly, though the spatial mode of the X-ray laser changes from shot to shot in the above mentioned sequence, the total output, which is shown in Fig. 9, seems reasonably stable. This makes it a reliable source for certain applications where the output energy is the key issue.

3. CONCLUSION

In conclusion, detailed imaging experiment has enabled us to fully assess the performance of the 18.9 nm Mo X-ray laser. We examined the near field beam pattern, the beam divergence, as well as its stability and reproducibility. Comprehensive understanding of the data presented needs detailed modeling of the system.

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Figure 9. X-ray laser output of a set of consecutive shots accumulated on the same target. The condition is similar to that of Fig. 8.

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