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Development of short pulse soft x-ray lasers

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ABSTRACT

X-ray lasers with pulse duration shorter than 20 ps allow the possibility of imaging laser produced plasmas with μm resolution. In addition, the high peak brightness of these new sources will allow us to study nonlinear optics in the xuv region. In this paper we will describe our efforts to produce collisionally pumped short pulse x-ray lasers. Initial results, which have produced ~ 45 ps (FWHM) x-ray lasers, using a double pulse irradiation technique are presented along with a discussion of the prospects for reducing the pulse width.

1. INTRODUCTION

Soft x-ray lasers have now been demonstrated by researchers worldwide¹. These systems utilize single pulse optical lasers to produce a hot and uniform plasma suitable for laser amplification and propagation. To date soft x-ray lasers operating in the range 35 - 300 Å (40 to 350 eV) have been reported². Although both collisional and recombination schemes have been utilized the highest gain length products and consequently output power has been observed for neon-like collisionally pumped schemes. Recently saturated output has been reported in selenium², germanium³ and Yttrium⁴. The high brightness of these lasers make them well suited for x-ray imaging and interferometry. In fact, most optical diagnostic techniques currently used to study low density plasmas can easily be extrapolated to the soft x-ray region. The setup we are currently employing to perform moiré deflectometry experiments of laser produced plasmas is shown in figure 1. The x-ray laser beam is collected with a spherical multilayer mirror which collimates the beam and backlights a secondary plasma irradiated by another optical laser beam. The second plasma is imaged with a spherical mirror onto a detector. The advantages of operating in the x-ray region are that the adverse effects of refraction and absorption are greatly reduced. For two dimensional plasma imaging the spatial resolution is limited by the pulse length of the x-ray laser or alternatively the gate time of the detector. Gated detectors with large active areas have temporal resolutions at best in the range of 100 to 200 ps. For characteristic expansion velocities of 10^7 cm/s this corresponds to a spatial resolution of 10 - 20 μm which is well below that possible with available imaging optics. Therefore, there exists a real need to produce x-ray lasers with pulse duration shorter than the 200 ps (FWHM) routinely produced with exploding foil targets.

Figure 1. Experimental setup to use x-ray laser to measure electron density in high density plasmas.

2. GENERATION OF SHORT PULSE X-RAY LASERS

Demonstrated x-ray lasers are either collisionally pumped systems in which inversions are produced in steady state conditions or recombination x-ray lasers which rely on transient inversion to achieve gain. The gain duration in conventional (also called quasi-static) recombination x-ray lasers⁵ is determined by cooling and recombination rates and typically results in pulse widths >200 ps. This allows very little control over the output pulse length without significantly reducing the total gain. Alternatively, very short pulse widths are predicted for optical field ionized recombination x-ray lasers⁶ but these systems are yet to be demonstrated and require ultrashort pump lasers which will severely limit the total output energy. Similar limitations exist for inner shell pumped x-ray lasers⁷ which offer the possibility of very short pulses and short wavelength x-ray lasers. In contrast, collisionally pumped x-ray lasers have achieved large gain length products and have been shown to operate over a wide range of pump conditions and a variety of targets. In addition, the wide wavelength range over which collisionally pumped systems operate will allow to take advantage (or alternatively avoid) line absorption in plasma probing experiments.

In order to produce saturated x-ray lasers with pulse duration shorter than 20 ps (imaging resolutions of ~ 2 μm) we have begun experiments which irradiate an exploding foil with multiple pulses. The concept is illustrated in figure 2. The first pulse heats and explodes a thin foil target to produce a plasma with low density gradients. The second

pulse then ionizes the preformed plasma to produce conditions for high gain. The energy of the first pulse can be significantly lower than the second pulse since high electron temperature are not necessary. This improves the efficiency of this approach by reducing radiation and thermal losses during the hydrodynamic expansion⁸.

Figure 2. Schematic drawing illustrating the double pulse irradiation technique for producing short pulse x-ray lasers.

In order to test this technique and illustrate the importance of density gradients in x-ray laser performance we have performed experiments on the NOVA laser with yttrium x-ray laser targets. A 3 cm long foil consisting of 2000 Å of yttrium on 1000 Å of lexan was irradiated from both sides with two 100 ps pulses of 0.53 μm laser light separated by 300 ps. The total intensity on target was 2.4×10^{14} W/cm² and 1.6×10^{14} W/cm² for the first and second pulse respectively. In figure 3 we show the time resolved emission spectra in both hard x-ray and xuv range. The hard x-ray emission (fig 3A) shows characteristic neon-like and fluorine-like 3-2 and 4-2 transitions which indicate that appropriate ionization conditions for gain are produced during both pulses. In contrast, the xuv spectra (fig 3B) shows strong J=2-1 x-ray laser emission at 155 Å during the second pulse only. The most likely reason for this is that during the first pulse the high density gradients refract the x-ray laser emission out of the gain region. In figure 4 we show the temporal evolution of both the x-ray laser and hard x-ray emission. The x-ray laser emission has a time duration of 45 ps (FWHM) making this the shortest x-ray laser pulse width demonstrated.

Although in this experiment we used comparable intensity for both pulses it would be clearly more efficient to reduce the intensity of the first pulse and increase the pulse separation to allow for expansion. Alternatively, a better pulse shape may consist of a low intensity pedestal which irradiates the foil until the high intensity short pulse irradiation. Using this approach we should be able achieve saturation x-ray laser output intensities⁴ of 4×10^{11} W/cm² with factors of ~ 4 less energy. Extending this technique to shorter output pulses will require shorter optical laser irradiation or a reduction in irradiation intensity to shorten the duration of neon-like ions. In addition, a traveling wave pump geometry⁹ in

which the optical irradiation travels along the foil at the speed of the x-ray laser emission will be necessary. We are currently developing both capabilities on the NOVA laser facility and plan to perform experiments to demonstrate ~ 20 ps x-ray laser output within several months.

Figure 3. Time history of hard x-ray (A) and xuv (B) spectrum in neon-like yttrium. The strong $J=2-1$ transition at 155 Å is clearly observed in first and 2nd order.

Figure 4 Time history of hard x-ray (4-2 transitions) and $J=2-1$ x-ray laser transition in neon-like yttrium.

3. CONCLUSIONS

Motivated by the prospects of using x-ray lasers to probe high density plasmas and study nonlinear optics we have begun the development of short pulse x-ray lasers. The wide wavelength coverage and robust performance of collisionally pumped neon-like x-ray lasers makes these systems an ideal test bed. Using a double pulse irradiation technique we have been able to demonstrate pulse widths significantly shorter than conventional exploding foil x-ray lasers. Although our initial results have only achieved ~45 ps output pulses with appropriate pump lasers the double pulse technique should easily achieve the sub 20 ps pulse width desired for high spatial resolution plasma imaging.

4. ACKNOWLEDGMENTS

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