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Generation of X-Ray Pulses with Rapid Rise Times to Pump Inner-Shell Photo-Ionized X-Ray Lasing in Carbon at 45 Å

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ABSTRACT

An investigation of the rapid rise time of x-ray emission from targets heated by an ultrashort-pulse high-intensity optical laser was conducted for use as a pump for inner-shell photo-ionized x-ray lasing. Results of x-ray rise times from instantaneously heated Au rod targets show little benefit for using optical pulse widths less than 30 fs. Gain calculations for inner-shell photo-ionized lasing show that large gains can be obtained for pulse widths between 30 and 100 fs. Calculated spectra, using the hydrodynamic/atomic kinetics code LASNEX, from a 1 J, 65 fs FWHM pulse optical laser incident on a structured Au target gave a gain of 11.5 cm^{-1} in C at 45 Å.

Keywords: x-ray laser, inner-shell, photo-ionization, Carbon, ultra-short pulse

1. INTRODUCTION

Inner-shell photo-ionization (ISPI) x-ray lasing is a very attractive approach to short wavelength lasing ($\lambda < 50$Å). The scheme was proposed by Duguay and Rentzepis[1] but problems of collisional ionization associated with the relatively long pulse optical lasers available at that time caused x-ray lasing to never be realized. However, with the advent of chirp-pulsed amplification significant energy can be put into ultra-short pulse (USP) laser systems with $\Delta t < 100$ fs. Prior work done by Kapteyn[2] and Strobel, *et. al.*[3] concentrated on very short wavelengths, $\lambda \leq 15$ Å where x-ray lasing has not been achieved. However, the energy required for USP driving lasers is at least 10 J for lasing at 15 Å. We present results for C at 45 Å as a representative low-Z element where lasing can be tested experimentally using current high energy USP lasers. Carbon has a smaller Auger rate compared with Ne and a longer lasing wavelength thus requiring a less energetic pump source.

Although current x-ray lasers using Ni-like ions operate at above and below the wavelength considered in this paper, 45 Å, they require high energy ($E > 1$ kJ) driving lasers[4]. As a result of using a lower energy driving laser ($E \approx 1$ J), an inner-shell x-ray laser would operate at a higher repetition rate, albeit with less energy in each x-ray pulse. Despite a very short lasing duration ($\Delta t < 100$ fs) and small cross sectional area ($A \approx 10^{-6}$ cm^2), the large saturation intensity, I_{sat}, associated with the relatively large Auger rate out of the upper lasing state[5] results in significant energy per pulse yielding a high average energy.

The required large flux of ionizing x rays is obtained from a high-Z target by an USP high-intensity optical laser. To achieve a high absorption of the driving laser's energy a structured target, parallel grooves on a solid material, or a composite of clusters, *e.g.*, gold-black, can be used[6]. The cluster targets are relatively inexpensive to produce but difficult to model due to their fractal properties. Work done by Marjoribanks, *et. al.*[7] show high x-ray conversion efficiencies in structured targets composed of a two-dimensional lattice of cylindrical absorbers[8]. Modeling of the x-ray emission from these targets, heated by an USP high-intensity optical laser, is performed for Au.

In this paper we provide target design, review the inner-shell scheme for x-ray lasing in C, and discuss the requirements for the ionizing x-ray source in rise time and flux. The properties of the x-ray source are determined from modeling of a high-Z target heated by an USP driving laser. Gain calculations for C at 45 Å are presented and the driving laser requirements to obtain a gain length of order 10, which is needed to show clear evidence of lasing, are determined.

2. INNER-SHELL PHOTO-IONIZATION

An USP ($\Delta t \leq 100$ fs) optical laser with energy ≥ 1 J is used to produce a hot plasma at line focus. The plasma generates a broad-band x-ray spectrum with a rapid rise time. A low-Z filter is sandwiched between the target and lasant to stop a majority of the low energy x rays that can ionize outer-shell electrons and thus populate the lower-laser state. The remaining high energy x rays primarily photo-ionizes the inner-shell electrons of the lasant atoms. This produces a population inversion, and resulting positive gain for an allowed 2p-1s radiative transition in the singly charged ion for a sufficiently intense x-ray source.

Inner-shell photo-ionized x-ray lasing places constraints on the x-ray source but has a high quantum efficiency. A large K-shell pump rate is needed to compete with the fast Auger decay rate and a fast x-ray rise time is needed to outpace the L-shell collisional ionization. Electron induced ionization from energetic electrons emitted from both photoionization and Auger decay to the lower-laser state limits the magnitude and duration of positive gain. A line source with the difference in energy with the lasant's K edge being within the L-shell energy would provide maximum coupling of x-ray energy to the lasant atoms, because the cross-section is peaked at threshold. In addition, such a line source would effectively reduce electron ionization of the L shell from photo-ionized electrons. The energy spectrum of the photo-ionized electrons is dependent on the x-ray source. As stated above an optimized source can mitigate this problem. However, the negative effect of Auger electrons will not be affected. If the rise time of the x rays is rapid enough, lasing can be achieved before significant electron ionization can occur. Ultra-short pulse x-ray lasing is inherent in this scheme which is important for many applications *involving* fast dynamical processes.

To achieve lasing a filter is needed in order to reduce the low energy x rays. A low-Z filter can be chosen to optimize the ratio of the x rays at K-shell energies to x rays at the L-shell energies in the lasant. Filtering is primarily through K-shell ionization of the low-Z filter element. For C, we find that 2 microns of Li with E_K = 59.9 eV yield maximum gain. This thickness does result in a reduction of x rays at the K edge of C by 60%. However this is required to sufficiently reduce the amount of lower energy x rays. There are windows of high transmission below the filter's K-edge energy and a trade-off is made between filtering at the lasant's K edge to reduce the low energy photons enough for lasing to occur. Geometrical effects associated with the plasma being a line source of finite transverse extent and with the separation between the plasma and the lasant given by the filter thickness are included in our calculations.

3. X-RAY EMISSION

Structured targets, as compared to flat targets, have been shown to have larger absorption and greater conversion efficiency[9]. Research is currently being conducted into the issues of coupling properties of grooved targets by J. J. Gauthier, *et. al.*[10]. We have previously modeled the emission from such targets assuming absorption in an optical skin depth[11]. Grooved targets, in general, are expensive but easy to model. cluster targets, e.g., gold-black, are inexpensive but hard to model and have a tendency to build up on the vacuum vessel walls. An inexpensive structured target consisting of vertical rods looks promising and LASNEX modeling results of an isolated rod are presented here. Here also, the energy is assumed deposited in an optical skin depth and the atomic kinetics are calculated with an average-atom atomic model that includes spin-orbit coupling.

We first investigate the rise-time limitations of these targets by uniformly and instantaneously heating the rod target (d = 500 Å) to 600 eV. The temperature was determined from calculations of the electron temperature of a 1 J, 65 fs pulse at peak intensity. Since the expansion is small within the time span of interest we did not include hydrodynamic expansion. One can

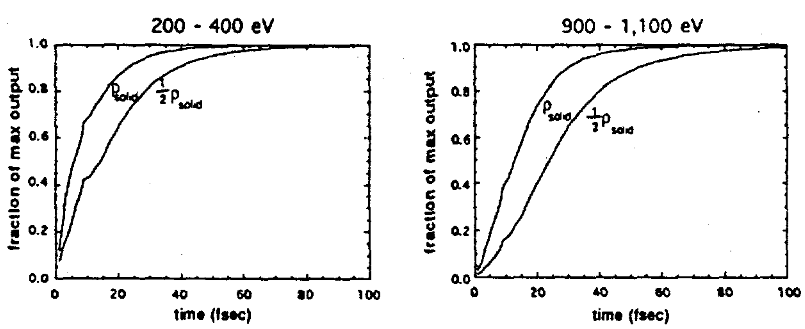

FIGURE 1. X-ray rise time and output from Au targets instantaneously heated to 600 eV show little benefit for pulse widths less than ≈ 30 fs.

$\int_{E_{min}}^{E_{max}} I(E)dE\ (^{TW}/_{cm^2})$	ρ_{solid}	$\frac{1}{2}\rho_{solid}$
$200-400eV$	38.4	17.2
$900-1{,}100eV$	97.2	39.3

TABLE 1. Maximum intensity in the ranges 200-400 eV and 0.9-1.1 keV for solid and half solid density Au from instantaneously heated (electron temperature = 600 eV) 500 Å diameter rods.

see in figure 1. that for solid density Au emission reaches 80% of its maximum value in 16 fs for 300 eV photons and 23 fs for 1 keV photons and for half solid density Au emission reaches 80% of its maximum value in 29 fs for 300 eV photons and 40 fs for 1 keV photons. Thus in going to shorter and shorter pulse widths one must be aware that a limit in the rise time of the incoherent x-ray source exists. There seems to be little benefit for the inner-shell scheme in pulse widths less than 30 fs. Convergent values for the intensity integrated over a 200 eV range is given in table 1 for both solid and half-solid density Au for the ranges centered on 300 eV and 1 keV. If we consider equal mass then the Intensity of the 1/2 density Au will be up by a factor of two; however, the rise time will still be slower for the less dense material.

4. RESULTS

Previous work[2,3] has shown that for gains of order 10 cm^{-1} in Ne, a maximum blackbody temperature of order 500 eV with rise time of 50 fs is required. Similar gains were achieved[12] in C with a maximum temperature of 150 eV and the same time requirements. LASNEX modeling of an isolated Au rod of diameter 250 Å with energy deposited within an optical skin depth show that a driving laser requirement of 1 J with the same rise time of 50 fs gives a comparable source. We have divided the LASNEX results by a factor of three to account for geometric effects and absorption in the target base.

Optimizing for C we show that a 1 J, 65 fs source incident on a structured target composed of vertical Au rods of diameter 500 Å a gain of order 10 cm^{-1} for C at a density of 4×10^{19} cm^{-3} in CH_4 (not treating molecular effects) with a 61 fs FWHM x-ray laser pulse at 45 Å. The source intensity is shown in figure 2 along with the gain. In figure 3, the populations of the upper- and lower-laser states are plotted. From this plot we can see that the upper-laser state population follows the intensity which is expected given the fast Auger exit channel out of the upper state. This will be the case unless the intensity changes on a time scale faster than the inverse of the Auger rate which for C is 10.7 fs. The lower-laser state population grows exponentially due to electron-ionization. Since the degeneracy between the lower- and upper-laser states is 3 to 1, the gain goes to zero when the lower-state population reaches three times the upper-state population.

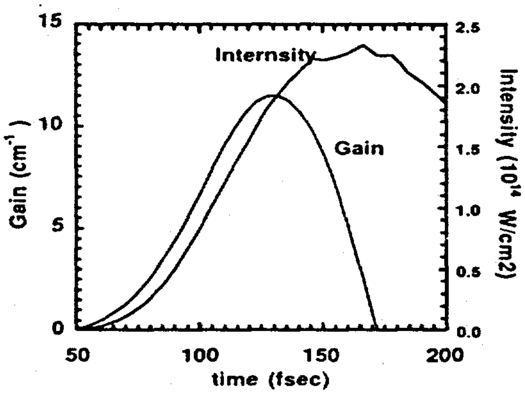

FIGURE 2. A peak gain coefficient of 11.5 cm^{-1} with FWHM = 61 fs is shown for C along with the intensity of the source.

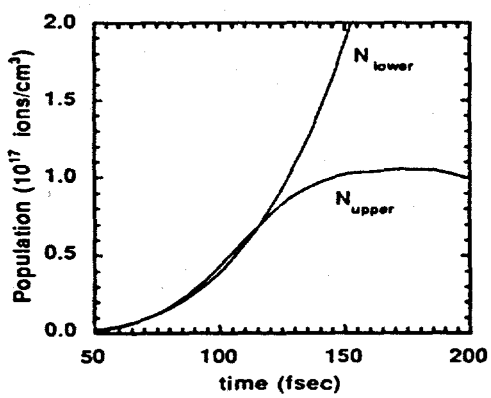

FIGURE 3. Time dependent plots of the upper- and lower-laser state populations are shown corresponding to gain in Fig.2.

5. CONCLUSIONS

Modeling using LASNEX of a driving laser with energy of 1 J, 65 fs FWHM, incident on a structured target composed of vertical rods (d = 500 Å) is sufficient to produce a large gain-length product. Gains of over 10 cm^{-1} were found for C of a density of 4.0×10^{19} cm^{-3} using a 2 μ Li filter. Collisional ionization to the lower lasing levels limits the duration of lasing giving a pulse of order 60 fs FWHM. Modeling of instantaneous heated targets indicate that rise time limits are on the order of 30 fs.

6. ACKNOWLEDGMENTS

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