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Inner-Shell Photo-Ionized X-Ray Laser Schemes for Low-Z Elements

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Abstract. Gain calculations for inner-shell photo-ionized lasing in C at 45 Å are performed. An incident x-ray source represented by a 150 eV blackbody with a rise time of 50 fsec gives a gain of order 10 cm^{-1}. The x-ray source and thus the driving optical laser requirements are significantly reduced as compared to what is needed for Ne at 15 Å. We expect that existing ultra-short pulse lasers can produce the required x-ray source and thus produce a table-top x-ray laser at 45 Å.

I. INTRODUCTION

Previous theoretical work in inner-shell photo-ionized (ISPI) laboratory x-ray laser schemes have mainly focused on the 5 to 15 Å wavelength regime, where laboratory x-ray lasing using any approach has not yet been obtained. This was investigated for Ne at 15 Å by Kapteyn[1] and extended by Strobel *et al.*[2] also treating Mg at 10 Å. The experimental validation at these short wavelengths is dependent on the development of an ultra-short pulse (100 fsec FWHM) optical laser with energy of order 10 J or greater. Current "table-top" size ultra-short pulse (USP) lasers with energy of order 1 J exist. We present results for C at 45 Å as a representative low-Z element where lasing can be tested experimentally using current high energy ultra-short pulse lasers. Carbon has a smaller Auger rate compared with Ne and a longer lasing wavelength thus requiring a less energetic pump source. An x-ray laser at 45 Å, just outside the water window, is optimal for many biological applications[3].

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 ≈ 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 ($\Delta t < 100$ fsec) 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.

In the ISPI scheme, lasing takes place between the L shell and the K shell. Neutral Ne having a closed L shell makes it a good candidate for ISPI lasing, yet current lasers can not provide the needed energy to produce a significant gain-length product[1]. Because of the open L shell structure in C, it is relatively easier to both collisionally- and photo-ionize the L shell thus destructive filling of the lower-lasing state is more severe for C than Ne. Due to the lower energy requirements for K-shell ionization of C and the smaller Auger rate the requirement on the intensity of the pump is reduced as compared to Ne; however, the rise time requirements are not changed. A blackbody source is chosen to represent the x-ray source yet by optimizing the target material it may be possible to use a line or band source which would give more efficient pumping.

In section II we discuss general details of the ISPI scheme first proposed 25 years ago by Duguay and Rentzepis[6]. In section III we report our results for C at 45 Å and in section IV discuss conclusions.

II. INNER-SHELL PHOTO-IONIZATION

An USP (100 fsec FWHM) 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. Rapid Auger decay of the 1s hole state competes with the lasing transition and produces a large number of energetic electrons into the lasant material. Electron induced ionization to the lower-laser state limits the magnitude and duration of positive gain. Ultra-short pulse x-ray lasing is inherent in this scheme.

A high intensity source of x rays is required to compete with the Auger rate and cause a significant upper-laser state population. 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[7]. The cluster targets are relatively inexpensive to produce but difficult to model due to their fractal properties. A new inexpensive structured target consisting of vertical rods[8] has been shown to also have high absorption properties[9]. We are currently modeling this type of target, but in this paper we concentrate on gain calculations for an assumed x-ray source.

A time dependent single temperature blackbody is used to approximate the x-ray emission from the plasma. For work done using a Au target composed of parallel grooves this is shown to be a conservative assumption[10]. An ideal source would be a line source with the difference in energy with the lasant's K edge being within the L-shell energy. This provides 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 ionizations of the L shell from photo-ionized electrons. In the lasing medium, electrons come from both photon ionization and from Auger decay. 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.

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 Ne it was found that 3.5 microns of Be with $E_K = 118.4$ eV yield maximum gain. In C, we find that 2 microns of Li with $E_K = 59.9$ eV is optimal. 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.

III. RESULTS

Previous work[1, 2] 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 fsec is required. We find that for C a much reduced blackbody temperature ($T_{bb} \approx 150$ eV), with the same 50 fsec rise time, gives comparable gains. Shown in fig. 1 are blackbody spectrums appropriate for Ne and C. The filtered spectrum is also shown with the K edges marked for reference. As can be seen for both Ne and C the peak of the filtered spectrum is to the right of the K edge allowing for the broad band nature of the filtered spectrum to be taken advantage of. However, the cross section decays rapidly from its maximum value at the K edge, for example, in C at the peak of the filtered spectrum the cross section is 1/4 of its K-edge value, where as the filtered spectrum only increases by a factor of 2 of its K-edge value. This results in the convolution of the intensity and the absorption cross-section having a peak very near the K edge and decreasing monotonically for higher energies. The replacement of the broad-band source with a line source near the K edge or a

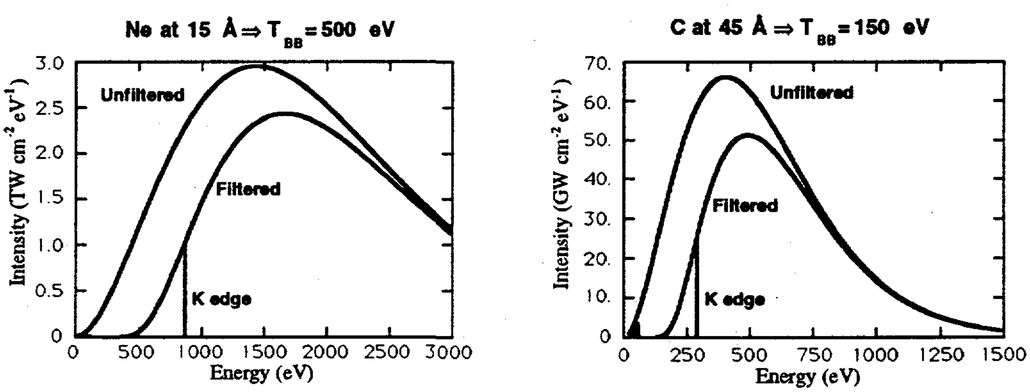

FIGURE 1. X-Ray source requirements for both Ne at 15 Å and C at 45 Å. The filtered source for Ne uses a 3.5 μm Be filter and for C a 2 μm Li filter is used.

band of emission above the K edge would reduce the requirements on the source. For a line source at the K edge the flux required for the x-ray source is approximately 1/6 that of the 150 eV broad-band source.

For the time dependence of the x-ray source we use a simple expression appropriate for a sech^2 driving pulse[1]. Expressed in terms of a blackbody temperature it is given by the equation,

$$T_{bb} = T_{Max}\left[0.02\int_{-\infty}^{t} \text{sech}^2(1.76t'/\tau)dt'\right]^{4/9}$$

where τ is the FWHM of the driving laser and T_{max} is the maximum temperature (model assumes no cooling). This is shown in fig. 2 for T_{max} = 150 eV and τ = 50 fsec which are appropriate parameters for C. The corresponding gain curve in fig. 2 is for a neutral C density of 4.0 x 10^{19} cm^{-3} mixed with 4 H atoms for every C atom. Molecular effects of CH_4 were not treated. The x-ray source is taken to have a traverse extent of 10 μm used in conjunction with a 2 μm Li filter. Results for C using a driving laser with τ = 100 fsec show a reduction in gain by a factor of 3. As shown in fig. 2, the gain has a FWHM of ≈ 60 fsec, showing the ultra-short pulse nature of this scheme. In fig. 3, the populations of the upper- and lower-laser states are plotted with the filtered intensity of the x-ray source. 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 fsec. The lower-laser state population grows exponentially due to electron-ionizations. 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.

Given the calculated gain coefficient, a line source of x rays with a length of order 1 cm is required in order to have a gain-length product of order 10. (Gain-length products between 5 and 10 provide clear evidence of lasing.) Assuming a conversion efficiency to incoherent x rays of 20%, the energy required for the

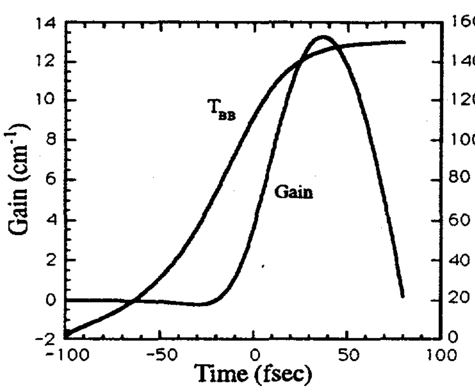

FIGURE 2. A gain coefficient of 13 cm^{-1} with FWHM = 58 fsec is shown for C with T_{max} = 150 eV time dependent blackbody source.

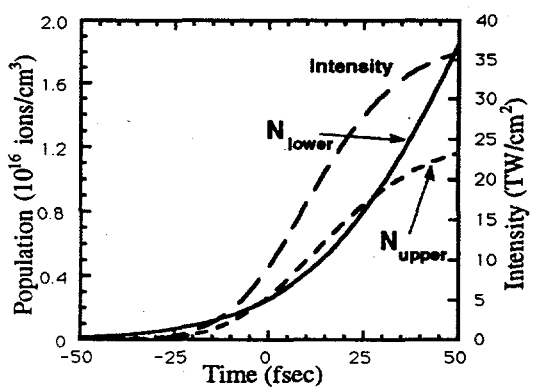

FIGURE 3. Time dependent plots of the upper- and lower-laser state populations leading up to max. gain are shown along with the filtered intensity of the source.

driving laser is 1.0 J. Lasers with this energy are currently available. The major issue is whether the rise time of the x rays is sufficiently rapid ($\tau \approx 50$ fsec) since this can not be currently measured.

IV. CONCLUSIONS

Theoretical work on inner-shell photo-ionized x-ray lasers in the 5 to 15 Å wavelength regime shows that the equivalent blackbody temperature of the x-ray source must be of the order 500 eV, requires a driving laser with energy of order 10 J or greater. Our preliminary results for C at 45 Å indicated a driving laser with energy of order 1 J 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 x 10^{19} cm^{-3} using a 2 μ Li filter and a maximum black-body temperature of 150 eV pumped with 50 fsec rise time. Collisional ionization to the lower lasing levels limits the duration of lasing giving a pulse on the order of 60 fsec FWHM. Such short coherent x-ray emission is important for many applications involving fast dynamical processes.

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