X-ray absorption by highly charged ions in plasmas: toward photo-pumping x-ray laser

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Abstract. We have investigated new photo-pumping scheme, in which intense Kα line is used as "emitter" and highly charged ions in plasma are used as "absorber". We focus the precise wavelength matching between the aluminum Kα line (0.833816 nm) and the resonance line 2p$^5$-2p$^5$4d (2p$^{1/2}$, 4d$^{3/2}$), of the neon-like zinc ions (0.83400 nm) and calculate the excited level populations of the neonlike zinc ions by use of a Monte-Carlo simulation code. The calculated result shows that substantial amplification gain in the transition of 2p$^5$3p - 2p$^5$4d line at a wavelength of 3.5 nm can be expected in this scheme. We also propose the experimental setup for this scheme, which implies this scheme is feasible under the present technology of ultra-short pulse laser and optics.

1. Introduction

In the photo-pumping x-ray laser scheme, spectral line emission from particular ions is absorbed by different element ions to create the population inversion in the latter. The success of this scheme as an x-ray laser depends upon exact spectral matching between the emission line and the absorption line. The widths of the spectral lines of ions in plasma, that are due mainly to the Doppler broadening and the Stark broadening, are typically $\Delta \lambda / \lambda < 0.01\%$. Therefore high resolution spectroscopic studies are required to find an appropriate pair of the "emitter" and "absorber" ions. Indeed, in the early 1990s, the atomic physics group at the Lawrence Livermore National Laboratory (LLNL) has determined the accurate wavelengths of many spectral lines of highly charged ions by use of the electron beam ion trap (EBIT) [1, 2]. The data obtained by the EBIT group, in collaboration with the x-ray laser specialists at LLNL, was used to find the candidate pairs of ions for photo-pumping x-ray lasers.

However, the scheme using "emitter" ions and "absorber" ions has a technical difficulty: the emitter and the absorber ions should be located as close as possible so that the pumping emission reaches to the absorber ions efficiently. At the same time, the electron temperature should be high for the emitter to increase the emissivity of the ions, whereas the lower temperature is preferred for the absorber ions to avoid the "thermal" population in the lower lasing level, which reduces the amplification gain. This implies that the use of "emitter" ions and "absorber" ions is not practical under usual laser irradiation...
geometry [3]. In this presentation, we propose the use of Kα line from solid target as the emitter coupled with the laser-produced plasma as the absorber. We take aluminum Kα line (0.83816 nm) and resonance line $2p^6-2p^34d (2p_{1/2}, 4d_{5/2})_2$ of the neon-like zinc ions (0.83400 nm) as an example and calculate the excited level populations of the neonlike ions by use of a Monte-Carlo simulation code.

2. Monte-Carlo simulation and calculated result

Figure 1 shows the simplified energy level diagram of the neon-like zinc ions. In our model, the ground state $2p^6$, the $(2p_{1/2}, 3p_{1/2})_0$ level, $(2p^33p)$, the $(2p_{1/2}, 4d_{5/2})_1$ level, $(2p^44d)$, and the neighbouring levels of the $2p^44d$ level are included, and collisional-radiative processes among these levels are taken into account. The Kα line is absorbed by the transition of $2p^6-2p^44d$ resonance line, and the following collisional-radiative processes transfer the populations into other levels. The size of the zinc plasma is defined as 20 $\mu$m $\times$ 20 $\mu$m $\times$ 5 mm in the $x$-, $y$- and $z$-directions, respectively. We consider a sliced area in the plasma with the size of 20 $\mu$m $\times$ 20 $\mu$m in the $x$-$y$ plane and the thickness of 100 nm. This sliced area is divided into $(x, y)$ mesh with the size of 100 nm $\times$ 100 nm. The plasma parameters, i.e., the electron density, $n_e$, the electron temperature, $T_e$, the neon-like ion density, $n_{\alpha}$, and the ion temperature, $T_i$, are assumed to be 100 eV, $2 \times 10^{21}$ cm$^{-3}$, 50 eV, $10^{20}$ cm$^{-3}$, respectively. The Kα photons come into the plasma from the $y$-direction. The linewidth ($\Delta \lambda/\lambda$) of the Kα line is assumed to be $\sim 10^3$, and that of the $2p^6-2p^44d$ resonance line is determined by the Doppler broadening.

![Figure 1. Energy level diagram of the Ne-like Zn ions. The aluminum Kα line can be absorbed by the transition of the $2p^6-2p^44d (2p_{1/2}, 4d_{5/2})_2$.](image)

The calculation procedure is as follows: Firstly the frequency of the Kα photon and the $x$-position are determined, randomly. Secondly the absorption length of the Kα photon in the plasma is calculated to determine the $y$-position where the Kα photon is absorbed. This routine is repeated $N$ times, where $N$ is the number of Kα photons coming into the calculation area in the time step. Thirdly, for each $(x, y)$ position, we determine the absorbed photon is lost by collisional-radiative processes to other excited levels or not. If the collisional-radiative processes take place, we count the increase of the other level populations. If not, it is determined that the resonance emission event occurs or not. In the case of the resonance emission process, the frequency of the resonance emission is determined randomly within the spectral linewidth, and the direction of the emission and the absorption length are calculated. From these information, we judge the photon is absorbed in new $(x, y)$-position or escapes from the plasma. The procedure 1–3 is iterated with 1 fs time step, and the temporal evolution of the excited level populations are calculated.
in the early time region $t$ is much longer than $s$.

The temporal evolution of the 2$^p 3p$ level population divided by their statistical weights. The amplification gain coefficient of the 2$^p 3p$-2$^p 4d$ line at a wavelength of 3.5 nm is also attached (right-hand side ordinate), where the line shape of the lasing line is assumed to be Gaussian due to Doppler broadening.

Figure 3 shows the temporal evolution of the 2$^p 3p$ and 2$^p 4d$ level population divided by their statistical weights (left-hand side ordinate) under the K$\alpha$ pump with the duration of 500 fs (FWHM). The amplification gain of the 2$^p 3p$-2$^p 4d$ line is presented. From the number of the 2$^p 3p$ excited ions in the early time region ($t \sim 0$ fs), it is found that around 20% of the K$\alpha$ photons can be absorbed in the plasma. Under the assumption of the absence of the radiation trapping effect, the lifetime of the 2$^p 4d$ level is $\sim 70$ fs, which is in accordance with the spontaneous transition probability of this level, whereas with the radiation trapping effect, the effective lifetime extends up to 250 fs. It should be noted that under the present plasma parameters, the absorption length of the resonance line is around 500 nm. This implies that once the K$\alpha$ photons are absorbed in the plasma, due to the small absorption length of the 2$^p3d$-2$^p 4d$ resonance line, the photons cannot escape from the plasma unless other collisional-radiative processes or the x-ray lasing process take place. This is one of the advantages of this scheme as the x-ray laser gain medium.

The $n(4d)/g(4d)$ increases as time proceeds and decreases for $t > 600$ fs. This is due to the decrease in the pumping rate together with the collisional depopulation to the neighbouring levels whose time constant is $\sim 300$ fs. Substantial amplification gain is obtained in the time region of $t = 300 - 800$ fs. This gain duration is much longer than that of other schemes for the shorter wavelength x-ray lasers using inner-shell ionized atoms [4, 5], in which the generation of the gain competes with Auger decay process, therefore the expected gain duration is less than 10 fs. This quite short duration induces the practical difficulties in the pumping method of shorter wavelength x-ray lasers so far. The long duration of the gain ($\sim 500$ fs) in the present result indicates that the present scheme is feasible without any complicated pumping technique.

The $n(3p)/g(3p)$ increases gradually and at around $t = 1000$ fs, the $n(3p)/g(3p)$ becomes larger than $n(4d)/g(4d)$. This result may be slightly overestimation. Because in the present calculation the collisional de-population process from the 2$^p 3p$ to the neighbouring levels, e.g., 2$^p 3s$, 2$^p 3d$ are not
taken into account. Including this effect, the \( n(3p)/g(3p) \) may become smaller, which leads to the enhancement of the amplification gain.

3. Target design and pumping geometry

In Fig. 4, we propose the experimental set-up for this photo-pumping scheme. Target is an aluminum foil with the thickness of 4 µm, and 0.2 µm-thick zinc is deposited on it. The zinc side is irradiated by double pulses of pumping laser with both the intensities of \( 10^{15} \) W/cm\(^2\), separated by 100 ps to create neon-like zinc ions in plasma. After a certain time delay, the opposite side (the aluminum side) is irradiated by an ultrashort pulse with 300fs duration and \( 10^{15}-10^{16} \) W/cm\(^2\) intensity to generate intense aluminum K\( \alpha \) line. The energy conversion efficiency from the pump laser to K\( \alpha \) line is at least around \( 10^{-5}/\text{sr} \) [6]. Since the distance from the K\( \alpha \) source to the absorber is around 10 µm, the effective solid angle of the K\( \alpha \) source to neon-like zinc plasma is 5 sr, therefore we can deliver 250 µJ of K\( \alpha \) photons into the zinc plasma, which is much larger than the assumption in the calculation in section 2. The transmittance of the 4 µm-thick aluminum foil for the K\( \alpha \) photons is more than 70%.

It is noted that under the intensity of \( 10^{15}-10^{16} \) W/cm\(^2\), suprathermal electrons with the energy of several KeV are generated on the surface of the aluminum side, however virtually all the energy of the suprathermal electrons is transferred into bremsstrahlung due to 4 µm-thick aluminum foil. Since the aluminum foil works as a spectral window for the continuum emission, the heating effect of the plasma due to the continuum radiation becomes small.

4. Summary

We have investigated new photo-pumping scheme by use of the aluminum K\( \alpha \) line and the \( 2p^6-2p^5d \) resonance line of the neon-like zinc ions. The population kinetics code shows that substantial amplification gain in the transition of \( 2p^53p-2p^54d \) line at a wavelength of 3.5 nm can be expected in this scheme. This scheme is one of the feasible "water-window" x-ray lasers using a laboratory size pumping source.

5. References

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Figure 4. Experimental set-up for the photo-pumping scheme. Target is 4 µm-thick aluminum foil, and 0.2 µm-thick zinc is deposited on it. Zinc side is irradiated with 100 ps-duration double pulses and the aluminum side is irradiated by 300 fs-duration single pulse.