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ABSTRACT

Nearly four decades ago H-like and He-like resonantly photo-pumped laser schemes were proposed for producing X-ray lasers. However, demonstrating these schemes in the laboratory has proved to be elusive. One challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. Given a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the advent of the X-FEL at LCLS we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes. In this paper we model the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV with the X-FEL at LCLS. We predict gain on the 4f – 3d transition at 231 Å. We also examine the feasibility of photo-pumping He-like V and lasing on the 4f – 3d transition at 38.7 Å, which would be within the water-window. In addition we look at the possibility of photo-pumping Ne-like Fe and creating gain on the 4d – 3p transition at 53 Å and the 3p – 3s transition at 255 Å.

Keywords: X-ray laser, X-FEL; Photo-pumping

1. INTRODUCTION

From the earliest days of lasers, resonantly photo-pumped laser schemes using H-like and He-like ions were proposed for producing X-ray lasers [1]. However, demonstrating these schemes in the laboratory has proved to be elusive. One challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. Given a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the advent of the X-FEL at LCLS [2] we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes. In this paper we model the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV with the X-FEL at LCLS. We predict gain on the 4f – 3d transition at 231 Å that is an order of magnitude larger than the gains predicted [3] two decades ago using the Saturn pulsed power machine at Sandia National Laboratory to create the Na pump line.

We also examine the feasibility of photo-pumping He-like V and lasing on the 4f – 3d transition at 38.7 Å, which would be within the water-window. This and other potential H and He-like schemes are shown in Table 1 and discussed in Ref. 1.

Table 1. Resonantly photo-pumped laser schemes with 4f – 3d lasing in H and He-like ions							
Pump Line		λ_P (Å)	Absorbing Line		λ_A (Å)	$\Delta\lambda_P/\lambda_P$ (%)	λ_L (Å)
Na	He-α_S	11.003	Ne	He-γ_S	11.000	0.022	231
K	Ly-α_2	3.3521	Cl	Ly-γ_2	3.3511	0.029	64.8
Cr	He-α_T	2.1925	Sc	Ly-γ_2	2.1917	0.036	42.5
Mn	Ly-α_1	1.9247	V	He-γ_S	1.9255	0.040	38.7
Cu	Ly-α_1	1.4253	Fe	Ly-γ_2	1.4253	0.006	27.7
Sr	Ly-α_2	0.82708	Se	Ly-γ_1	0.82765	0.069	16.2
Nb	He-α_S	0.72175	Rb	He-γ_T	0.72143	0.044	14.4

In addition we look at the possibility of photo-pumping Ne-like Fe and creating gain on the 4d – 3p transition at 53 Å and the 3p – 3s transition at 255 Å. Photo-pumping Ne-like Fe was proposed years ago but it was very difficult to find a good resonance, even though the Ly-α line of H-like Ne was a potential match [4].

2. CHARACTERISTICS OF THE LCLS X-FEL

With the advent of the X-FEL at the LCLS facility we looked at the characteristics [5] of this laser to see if it would be relevant for exploring photo-pumping X-ray laser schemes. The basic features of the X-FEL is that it can produce a tunable X-ray source that extend from 800 to 8500 eV. It operates at a 120 Hz repetition rate with approximate output of 10^{12} photons per pulse. The beam has a spectral bandwidth is 0.1% of the fundamental, a pulse duration of 200 fs, and an unfocused spot size of 400 μm square. The beam can be rapidly tuned over 3% of the fundamental energy by adjusting the electron beam energy. Using these numbers gives a spectral intensity $I_\varepsilon = 5 \times 10^{11}$ W / (eV cm^2). We can calculate the line strength of the X-FEL beam in photons per mode $n_\varepsilon = 1.579 \times 10^{-5}\ I_\varepsilon / \varepsilon^3$ where ε is the photon energy in eV. Looking at some typical photon energies $n_\varepsilon = 5.5 \times 10^{-3}$ at 1127 eV and drops to 2.95×10^{-5} at 6442 eV for the unfocused beam. For a photo-pumped laser scheme the beam strength in photons per mode is approximately the same as the maximum fractional population divided by the statistical weight of the level being pumped.

3. HE-LIKE NE X-RAY LASER SCHEME

One of the early resonantly photo-pumped schemes that were tried experimentally was the Na-pumped Ne scheme that used the He-α line of Na to photo-pump the He-γ line of Ne and create gain on several n = 4 to n = 3 transitions in He-like Ne. Figure 1 shows the three principal laser lines that were predicted to have gain, the 4f – 3d line at 231.1 Å, the 4d – 3p line at 231.6 Å, and the 4p – 3s line at 222.7 Å. It is important to note that while the 4p – 3s line lases directly from the 4p level that is being photo-pumped, the other two lines depend on collisional excitation to transfer population from the 4p to 4d to 4f states. Since these states are very close in energy they tend to equilibrate very quickly if there is sufficient density in the plasma.

To model this system we started with the conditions used on the Saturn pulsed power experiments done many years ago [3]. The starting condition was an ion density of 10^{18} cm^{-3} for the Ne plasma and a temperature of 25 eV. The CRETIN code [6] was used to model the kinetics in one dimension (1D) to scope out the potential gain that could be achieved. At this density, for the unfocused X-FEL beam at LCLS tuned to 1127 eV (11.000 Å), the photo-ionization rate for Ne plasma in the Be-like sequence is only 1.2×10^6 sec^{-1}, so we quickly realized that the X-FEL can not be used to ionize Ne from neutral down to He-like. For the calculations we assume that a separate laser or discharge is used to prepare the plasma in the He-like Ne ground state so that the X-FEL can be used to just do the photo-excitation of the laser plasma. Figure 2 shows the time-dependent strength of the X-FEL in photons per mode that illuminates the He-like Ne plasma. The calculation is done so that the X-FEL pulse peaks at 300 fsec on the time axis. Figure 3 shows the predicted gain for the three strongest laser lines in He-like Ne. The dominant line is the 4f – 3d transition that has a peak gain of 4.07 cm^{-1} at 984 fs. In contrast the 4d – 3p line has a peak gain of 2.16 cm^{-1} at 530 fs and the 4p – 3s line has a peak gain of 1.16 cm^{-1} at 385 fs. The 4f – 3d gain peaks almost 700 fs after the peak of the X-FEL drive pulse because of the time needed for electron collisions to transfer population from the 4p level via the 4d level.

Another scheme from Table 1 that we modeled was the Mn-pumped V scheme that lases near 38 Å. Again the X-FEL replaces the Ly-α line of H-like Mn. We initially modeled this scheme using an ion density of 10^{18} cm^{-3} for the V plasma but quickly realized that the 4p-4d collision rate was too slow to equilibrate population among the n = 4 levels so we increased the ion density to 10^{19} cm^{-3}, used an electron and ion temperature of 100 eV, and put all the initial population in the He-like V ground state. This gives a 4p – 4d collision rate of 9.6 ps^{-1}. Given the low pump strength at 6439 eV we assumed we could focus the X-FEL to reduce the beam size a factor of 10 and increase the beam intensity a factor of 100. Figure 4 shows the time-dependent strength of the X-FEL in photons per mode that illuminates the He-like V plasma. The calculation is done so that the X-FEL pulse peaks at 300 fsec on the time axis. Figure 5 shows the predicted gain for the three strongest laser lines in He-like V. The dominant line is the 4f – 3d transition at 38.7 Å that has a peak gain of 16.2 cm^{-1} at 445 fs. In contrast the 4d – 3p line at 38.6 Å has a peak gain of 7.0 cm^{-1} at 375 fs and the 4p – 3s line at 37.8 Å has a peak gain of 8.5 cm^{-1} at 315 fs.

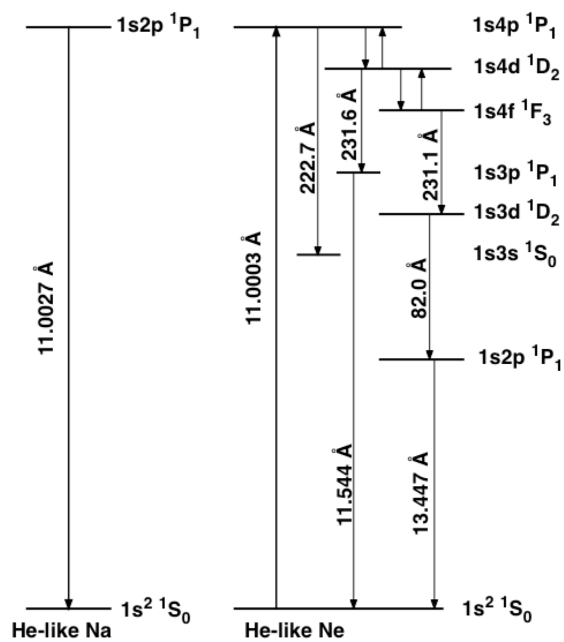

Fig. 1 Energy level diagram for He-like Na photo-pumping He-like Ne.

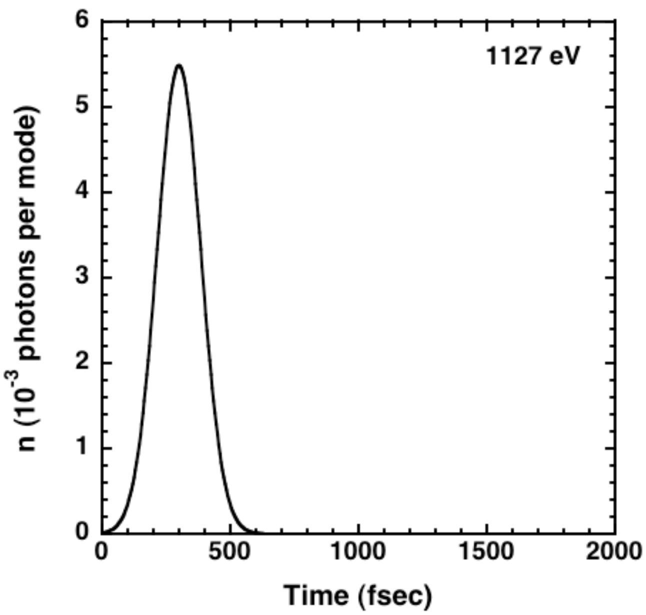

Fig. 2. Intensity of the X-FEL pulse at 1127 eV versus time for an unfocused beam.

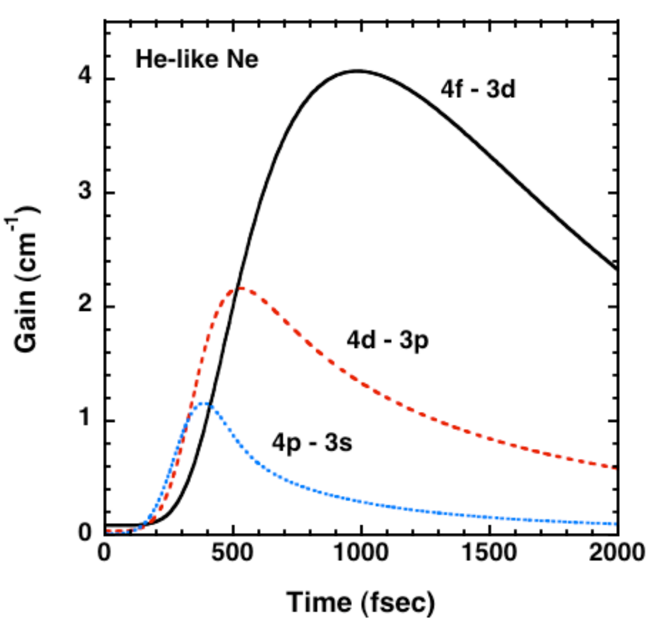

Fig. 3. Gain versus time for three laser transitions of He-like Ne driven by the X-FEL at 1127 eV.

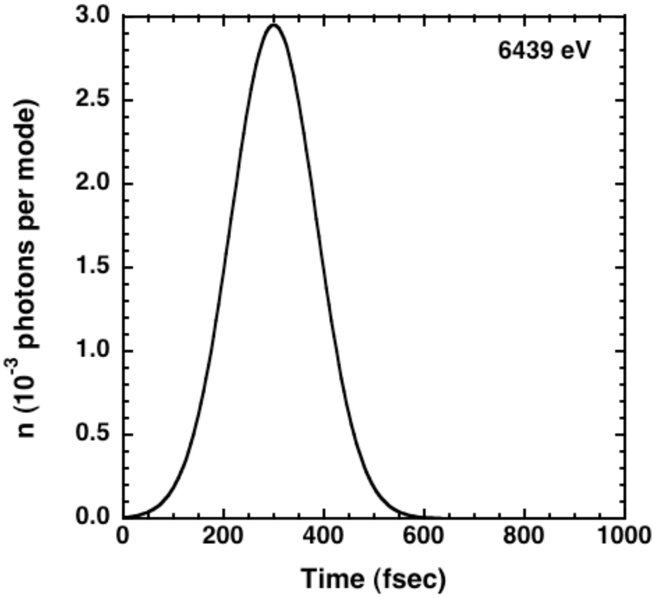

Fig. 4. Intensity of the X-FEL pulse at 6439 eV versus time for a focused beam.

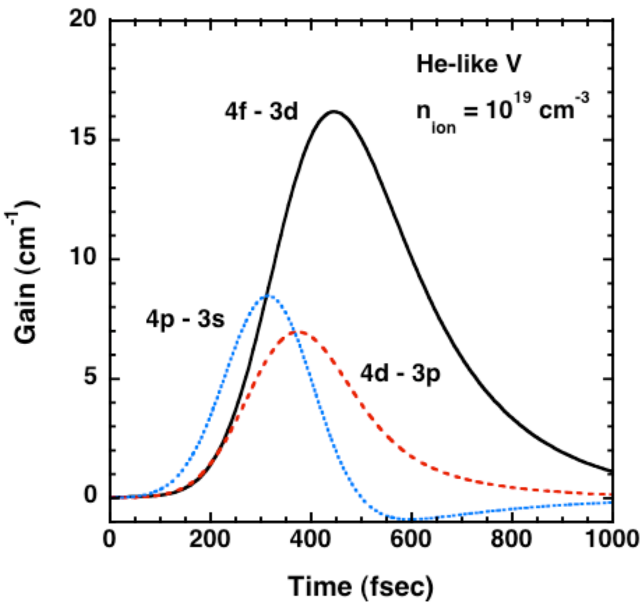

Fig. 5. Gain versus time for three laser transitions of He-like V driven by the X-FEL at 6439 eV.

4. NE-LIKE IRON X-RAY LASER SCHEME

Another type of resonantly photo-pumped X-ray laser scheme that has been proposed in the past is using the Ly-α line of H-like Ne to resonantly photo-pump the ground state of Ne-like Fe via the 2p – 4d transition, as shown in Fig. 6. In this scheme one can expect gain on the 3p – 3s line at 255 Å because the 3p upper laser level with J = 0 is meta-stable for decay to the ground state. To model this scheme with CRETIN we created an atomic model for Ne-like Fe and then assumed we had an ion density of of 10^{18} cm^{-3}, electron and ion temperatures of 100 eV, and the initial population in the Ne-like Fe ground state. The X-FEL replaces the Ly-α line of Ne at 1022 eV. The temporal history of the X-FEL is similar to Fig. 2 except the peak line strength is 7.4 x 10^{-3} photons per mode.

Figure 7 shows the calculated gain versus time for two laser lines of Ne-like Fe. The 4d – 3p line at 52.8 Å has a peak gain of 3.7 cm^{-1} at 365 fs while the 3p – 3s line at 255 Å has a peak gain of 1.8 cm^{-1} at 760 fs. In previous modeling of Ne-like systems we expect lasing on the 3p – 3s line as part of a classic 4-level system. The long life of the 3p – 3s line is not surprising since the upper laser state is meta-stable with a spontaneous decay rate of 0.015 ps^{-1}. In contrast the 4d – 2p transition decays at 6.4 ps^{-1} and the 4d - 3p transition decays at 0.22 ps^{-1} so the 4d – 3p gain is terminated as the population builds up in the 3p meta-stable state.

5. CONCLUSIONS

Since the early days of laser research H-like and He-like resonantly photo-pumped laser schemes have been proposed for producing X-ray lasers. However, demonstrating these schemes in the laboratory has proved to be elusive. One challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. Given a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the advent of the X-FEL at LCLS we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes. In this paper we model the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV with the X-FEL at LCLS. We predict gain on the 4f – 3d transition at 231 Å. We also show the feasibility of photo-pumping He-like V and creating gain on the 4f – 3d transition at 38.7 Å, which would be within the water-window. Finally we show the possibility of photo-pumping Ne-like Fe and creating gain on the 4d – 3p transition at 53 Å and the 3p – 3s transition at 255 Å. Given the tunable nature of the X-FEL we are no longer restricted to studying photo-pumping in just the materials that have accidental resonances with strong pump lines but we can now study any ion of interest that falls within the spectral range of the X-FEL. In addition to looking for gain and lasing the X-FEL can also be used to study the kinetics of these laser systems by observing the dynamic evolution of the fluorescent lines.

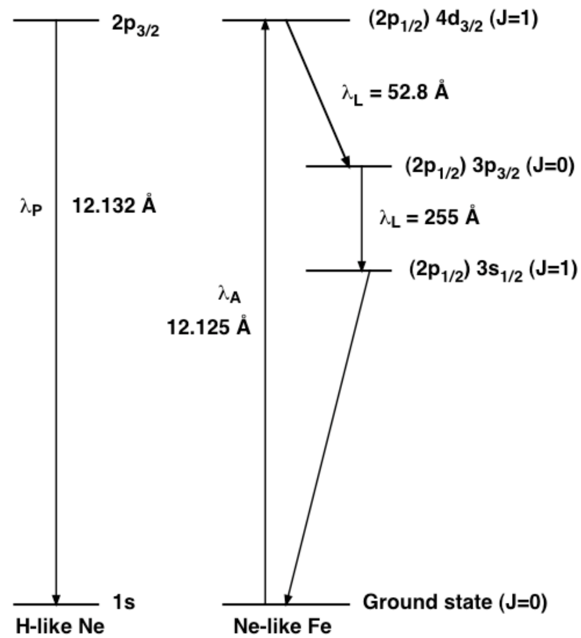

Fig. 6 Energy level diagram for H-like Ne photo-pumping Ne-like Fe.

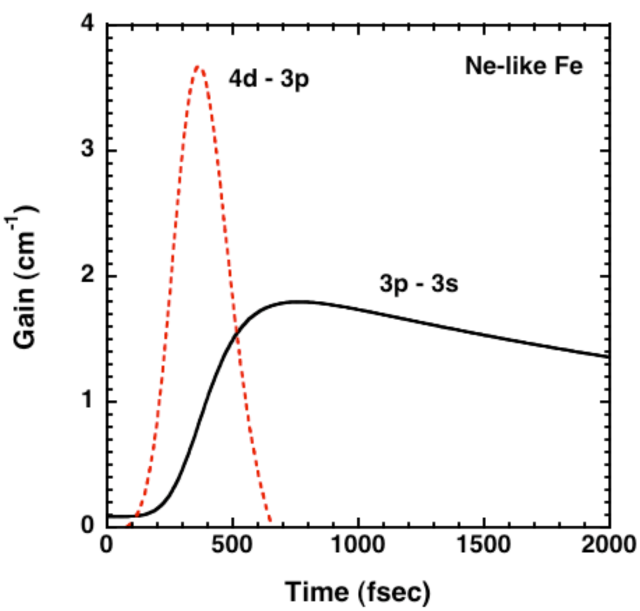

Fig. 7. Gain versus time for two laser transitions of Ne-like Fe driven by the X-FEL at 1022 eV.

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