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Shattering the Myth of the Resonantly Photo-Pumped Neon-like Titanium Laser

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ABSTRACT

Several years ago neon-like titanium(Z=22) was made to lase at 326 Å on the 3p → 3s(J = 0 → 1) transition.[1] At the time it was suggested that the lasing may be due to resonantly photo-pumping the neon-like titanium 2p → 4d lines using 3s → 2p and 3d → 2p lines in carbon-like and nitrogen-like titanium which results in lasing on the 3p → 3s transition in neon-like titanium. The strongest argument for this explanation was that adjacent elements (scandium and vanadium) did not lase while titanium was unique in having the above mentioned resonance. In addition a prepulse was required to make the titanium lase, suggestive of the formation of a low density plasma, and the plasma was very overstripped, so the above mentioned pump lines should be quite strong for photo-pumping. We have reinvestigated this laser system and will present results which show lasing on the 3p → 3s(J = 0 → 1) transition in neon-like chromium(Z=24), iron(Z=26), and nickel(Z=28) at 285, 255, and 231 Å respectively. This destroys the myth of titanium being unique and makes highly unlikely that the previously mentioned photo-pumping mechanism is playing a significant role in the titanium laser. The chromium, iron, and nickel experiments all require a prepulse in order to lase and our calculations suggest that the prepulse is an exciting new way to create a uniform low density plasma when illuminating a thick slab target. This allows the proper conditions for gain and laser propagation for low Z neon-like ions and may also be applicable to other systems such as low Z nickel-like ions. We also will present experiments done on other low-Z materials and offer an explanation as to how the hyperfine effect is destroying the gain of neon-like ions with odd Z.

1. EXPERIMENTAL SETUP

Experiments were conducted at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda = 0.53$ μm. In a typical experiment the Nova laser illuminates a 125 μm thick, 4.5 cm long slab target of iron or one of the other materials used. The above length of the target was reduced by a 16% gap in the center which results in an actual length of 3.8 cm. The pump laser beam was a 600 ps FWHM gaussian pulse with 1100 J of energy in a 120 μm wide (FWHM) by 5.4 cm long line focus, resulting in a peak intensity of 3.4×10^{13} W/cm^2. A 6 J prepulse (also 600 ps FWHM) preceded the main pulse by 7 ns.

The principal instruments were a time-gated, microchannel plate intensified grazing-incidence grating spectrograph(MCPIGS) and a streaked flat field spectrograph(SFFS); both of these instruments observed the axial output of the X-ray laser. The MCPIGS provided angular resolution over 10 mrad near the X-ray laser axis, while the SFFS integrated over an angular acceptance of 10 mrad. The angular resolution of both instruments was perpendicular to the target surface. The MCPIGS used a 600 line/mm grating and had spectral coverage of approximately 150 to 680 Å. A second MCPIGS spectrometer with a 1200 line/mm grating and spectral coverage of 75 to 340 Å was located 45° off-axis to observe the strong 2p → 2s emission lines from the plasma and provide information about the ionization balance. When measuring the laser lineshape the SFFS was replaced with a high-resolution, grazing incidence grating spectrometer which recorded time-integrated but spatially resolved data using a Princeton Instruments camera with a backside illuminated EEV CCD. This spectrometer was centered on the laser axis with an angular acceptance of 12 mrad and had a measured spectral resolution of 20000 at 146 Å.

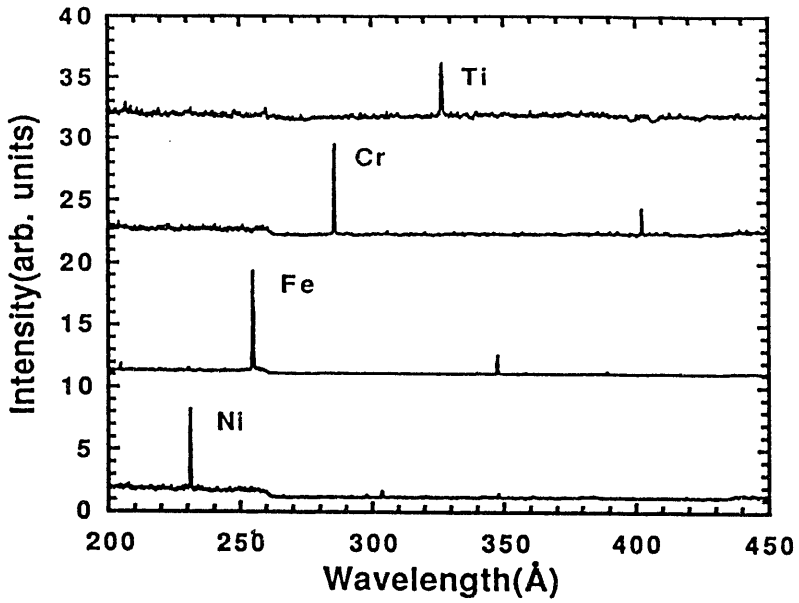

Fig. 1. MCPIGS spectra of 3.8 cm long targets of Ti, Cr, Fe, and Ni.

2. EXPERIMENTAL RESULTS

Experiments have now been done on all elements from calcium(Z=20) to copper(Z=29) using a prepulse before the main pulse. Different illumination conditions were used depending on the element. Lasing was determined by observing the high spectral brightness of the lasing lines relative to the strong emission lines on-axis, the absence of the lasing lines off-axis, the short time duration of the lasing relative to the optical drive pulse, and the exponential growth of the laser output as the length was increased.

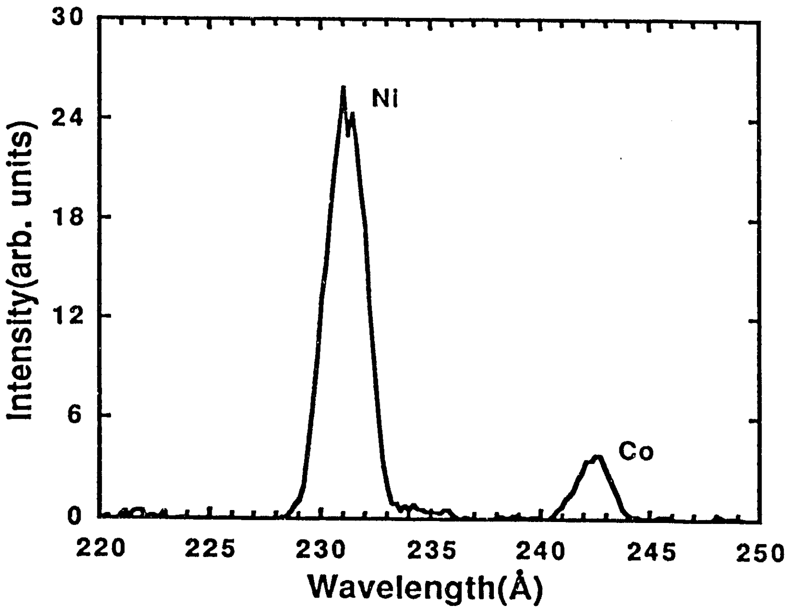

Fig. 2. Time integrated spectra of Ni and Co taken by SFFS.

In the previous work on titanium[1], titanium(Z=22) had lased only when a prepulse was used while scandium(Z=21) and vanadium(Z=23) had not lased even with the prepulse. Since then we have seen lasing in chromium and iron[2] while scandium and vanadium still do not lase. In the most recent experiments we see strong lasing on the $\overline{2p}_{1/2} 3p_{1/2} (J = 0) \rightarrow \overline{2p}_{1/2} 3s_{1/2} (J = 1)$ lines at 326, 285, 255, and 231 Å in titanium, chromium, iron, and nickel, respectively. The MCPIGS spectra are shown in Fig. 1. Also seen are some weak $J = 2 \rightarrow 1$ lines in chromium, iron, and nickel. The titanium $J = 2 \rightarrow 1$ line at 472 Å is seen in one experiment where a 200 Å thick layer of titanium was deposited on a nickel substrate and illuminated with the prepulse conditions described previously.[1]

In the experiments on calcium(Z=20), which was tried twice, we did not observe lasing. However the calcium was very reactive with air and a black layer was quickly observed to form on the surface of the calcium when exposed to air. In spite of our efforts to keep the calcium under vacuum some exposure to air did occur when aligning the targets and may have caused the calcium not to lase. We also did experiments with manganese(Z=25), cobalt(Z=27), copper(Z=29). For manganese there was no obvious sign of lasing while cobalt and copper both lased weakly on the $J = 0 \rightarrow 1$ line as well as the $J = 2 \rightarrow 1$ lines. Figure 2 shows a time integrated SFFS spectra of cobalt and nickel from one experiment where a cobalt and nickel foil where glued together and each side illuminated separately by one beam of NOVA under identical conditions. As seen in the figure, the neon-like nickel $J = 0 \rightarrow 1$ line at 231 Å is much brighter than the neon-like cobalt $J = 0 \rightarrow 1$ line at 242 Å . Table 1 summarizes the laser lines observed and includes our current calculations of the line positions.[2]

Figure 3 shows a typical time history of the $J = 0 \rightarrow 1$ laser line at 285 Å for neon-like chromium recorded by the SFFS. Lasing occurs near the peak of the optical drive pulse and lasts for several hundred picoseconds.

The angular distribution of the 285 Å chromium line on the MCPIGS shows the intensity peaking on the laser axis and falling to one half peak intensity 4 mrad off axis. This is evidence that lasing occurs in a region far off the target surface where the plasma has small gradients in the electron density. By comparison, the 236 Å laser output for a typical slab target of germanium peaks 13 mrad off-axis with a FWHM divergence of 10 mrad.[3]

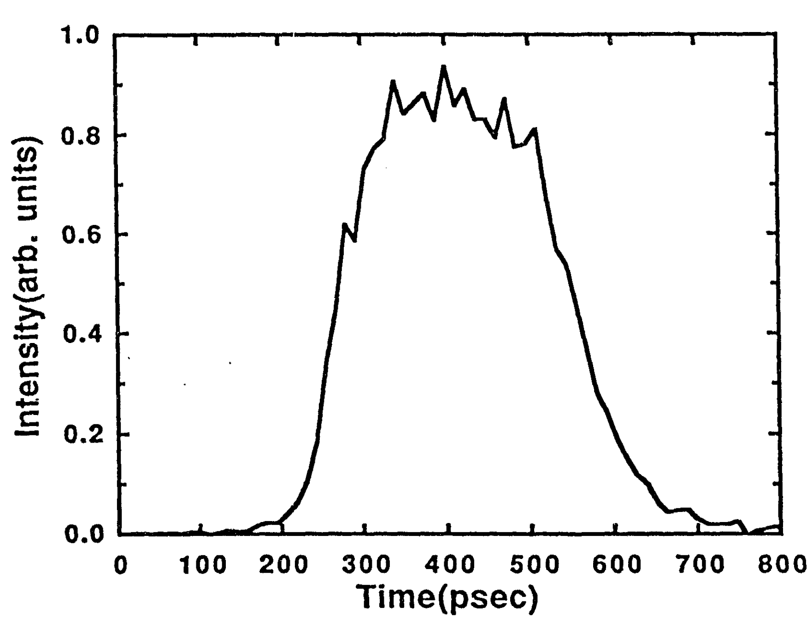

Fig. 3. Intensity of 285 Å Ne-like Cr laser line vs time.

3. ANALYSIS

When neon-like titanium was first observed to lase[1] at 326 Å its behavior was considered anomalous as compared with known neon-like lasers. The absence of lasing in neighboring elements of scandium and vanadium and the existence of resonances between titanium lines suggested that the lasing w⁻ enhanced by resonant photo-pumping of the neon-like titanium by strong emission lines from carbon-like and nitrogen-. titanium. These resonances are unique to titanium and this mechanism explained the requirement for overionizing the titanium so as to produce the pump lines. In those experiments, titanium produced evidence for lasing in only 60% of the experiments. Titanium is now lasing reliably on every shot as the prepulse energy is now more reproducible. The uniqueness of the titanium was the strongest argument for the resonant photo-pumping hypothesis and it is now clear that titanium is not unique and that this hypothesis is quite unlikely. Calculations suggest that direct collisional excitation of the upper laser state by monopole collisions is the main mechanism driving the $J = 0 \rightarrow 1$ line with other mechanisms such as recombination playing an important role in the other laser lines. Radiative transport processes are also important for all the lines and mechanisms such as self pumping need to be studied more to understand their importance.[4,5]

Based on our calculations, we believe the prepulse is playing a key role in creating a larger, more uniform density plasma, at the low densities required for lasing at these wavelengths. Previous calculations showed that single pulse illumination of slab targets produce density gradients which are very steep and are therefore limited in their effective lasing length by refraction.[3] To understand the effect of the prepulse we did LASNEX 1D computer simulations of the titanium laser with and without the prepulse. The calculations with the prepulse use a 550 J main pulse with a 3 J prepulse 7 ns early while the calculations without the prepulse use an 160 J main pulse. Both calculations assume a 4.5 cm long slab target driven by a 600 ps FWHM gaussian pulse of 0.53 μm light. The prepulse calculations correspond to experimental conditions in which lasing was observed, as shown in Fig. 1, while the calculations without the prepulse use an intensity chosen by scaling from successful experiments in neon-like germanium.

Table 1. Wavelengths of observed laser lines for Ne-like Ti, Cr, Fe, Co, and Ni.

Ion	Lines observed	λ_{obs}(Å)	λ_{calc}(Å)
Ti XIII	$J = 0 \rightarrow 1$	326.3 ± 0.5	326.24
	$J = 2 \rightarrow 1$	472.2 ± 0.5	472.04
	$J = 2 \rightarrow 1$	507.6 ± 0.5	507.64
Cr XV	$J = 0 \rightarrow 1$	240.2 ± 0.5	240.17
	$J = 0 \rightarrow 1$	285.5 ± 0.5	285.46
	$J = 2 \rightarrow 1$	402.2 ± 0.5	402.32
	$J = 2 \rightarrow 1$	440.7 ± 0.5	440.78
Fe XVII	$J = 0 \rightarrow 1$	204.2 ± 0.5	204.80
	$J = 0 \rightarrow 1$	254.9 ± 0.5	254.92
	$J = 2 \rightarrow 1$	347.6 ± 0.5	347.84
	$J = 2 \rightarrow 1$	388.9 ± 0.5	389.15
Co XVIII	$J = 0 \rightarrow 1$	242.4 ± 0.5	242.35
	$J = 2 \rightarrow 1$	318.0 ± 0.5	318.11
	$J = 2 \rightarrow 1$	324.5 ± 0.5	324.74
	$J = 2 \rightarrow 1$	367.3 ± 0.5	367.50
Ni XIX	$J = 0 \rightarrow 1$	231.1 ± 0.2	231.16
	$J = 2 \rightarrow 1$	297.7 ± 0.3	297.84
	$J = 2 \rightarrow 1$	303.6 ± 0.3	303.80
	$J = 2 \rightarrow 1$	347.5 ± 0.5	348.04

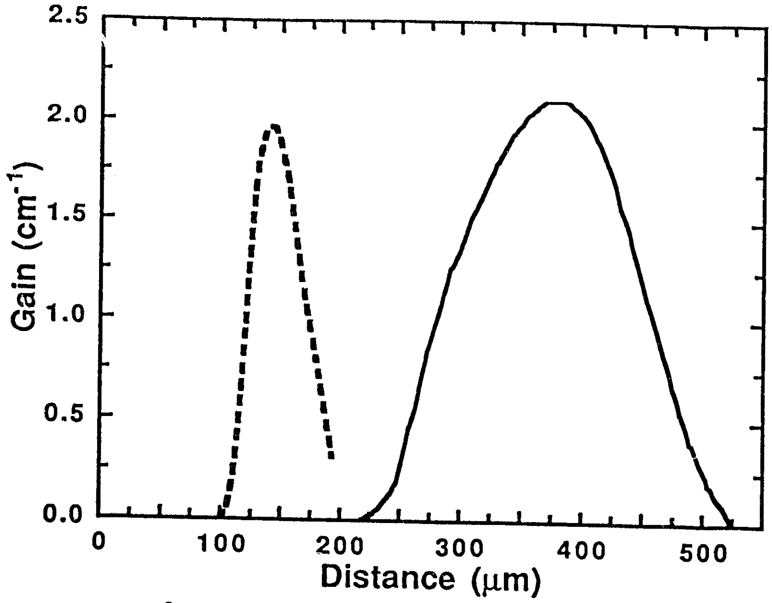

Fig. 4. Gain of the 326 Å Ne-like Ti line vs distance from the surface of the slab in the direction of the hydrodynamic expansion. Two cases are shown: with(solid) and without(dashed) the prepulse.

At the time of peak illumination by the optical drive pulse, Fig. 4 shows the gain of the 326 Å neon-like titanium laser line versus distance from the surface of the foil in the direction of the hydrodynamic expansion for the two cases. While the peak gain is similar in both cases, the spatial FWHM of the gain is 180 μ with the prepulse as compared to 50 μ without the prepulse. At the region of peak gain, the electron temperature varies between 210 and 240 eV, the ion temperature between 44 and 47 eV, the neon-like fraction between 26 and 38%, and the electron density between 2 and 1 x 10^{19} cm^{-3} for the cases with and without the prepulse, respectively. The difference between the two cases is the gradient in electron density and the size scale; otherwise the plasma conditions are very similar.

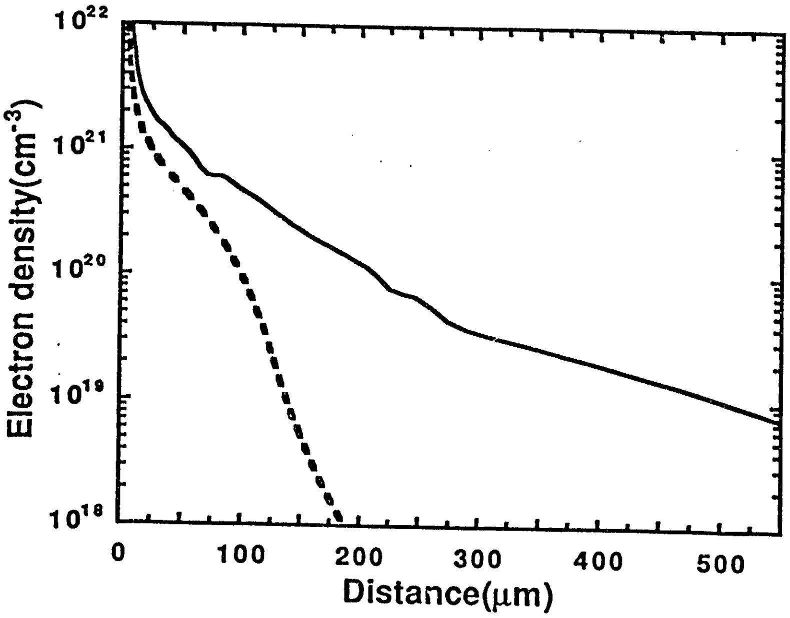

Fig. 5. Electron density of the Ti plasma vs distance from the surface of the slab in the direction of the hydrodynamic expansion. Two cases are shown: with(solid) and without(dashed) the prepulse.

Figure 5 shows the electron density versus distance from the surface for the two cases at the time of peak illumination by the optical drive pulse. For the case without the prepulse the larger density gradient is quite apparent. At the peak of the lasing, the prepulse case has an electron density gradient of 1.3×10^{21} cm^{-4} while the gradient is 5.2×10^{21} cm^{-4} for the case without the prepulse. Assuming a constant gradient, a lasing photon propagating down the lasing axis would travel 1.4 cm before it was refracted from the middle to the edge of the gain region for the case without the prepulse. For the case with the prepulse, the same photon would travel 5.4 cm before reaching the edge of the gain region, defined as the position where the gain is one half its peak value. Therefore, the prepulse is creating a larger gain region with a lower density gradient which allows most of the photons to be amplified by the entire length of the laser. The combination of the small gain region with the inability to propagate the length of the laser is no doubt the reason these lasers have not worked without the prepulse.

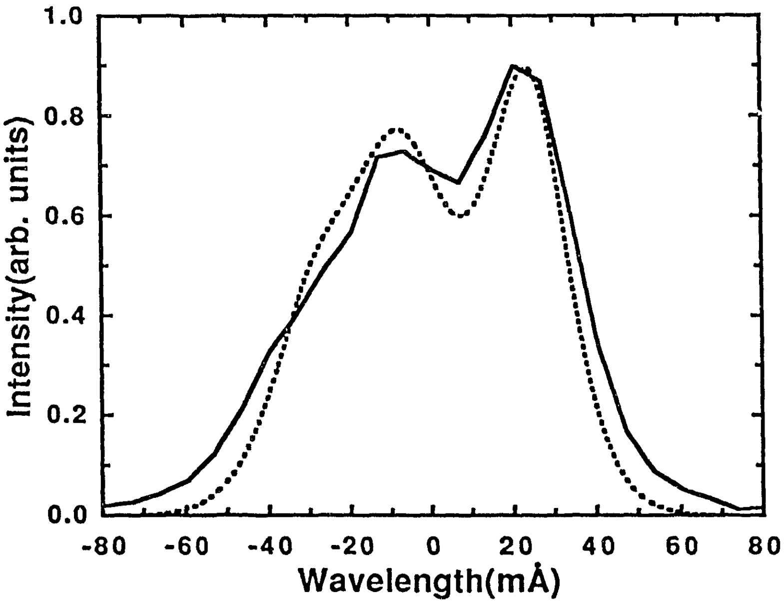

Fig. 6. Comparison of the theoretical predictions(dotted line) with the observation(solid line) for the intensity vs wavelength around line center for the J = 0 → 1 laser line in Ne-like Nb at 145.9 Å . The curves are normalized to the same intensity and a peak gain-length product of 2 is assumed for the theoretical curve.

Since elements with odd Z have a nuclear spin and a nuclear moment and those with even Z tend to have no nuclear spin, one possible explanation for the nonlasing, or poor lasing, in the neon-like ions with odd Z is that hyperfine splitting is playing an important role in the gain of the neon-like laser lines. Hyperfine splitting can affect the gain of the laser line by effectively increasing the linewidth. Since the gain is inversely proportional to linewidth the gain will decrease. If the splitting is large enough, a single line may be split into several weaker lines. In studying the impact of hyperfine on neon-like laser lines it turns out that the hyperfine effect is largest for the J = 0 → 1 line which dominates the spectra of the low-Z neon-like ions. Motivated by this anomalous behavior we did a series of experiments, described in a previous paper,[6] to measure the lineshape of the J = 0 → 1 laser line in neon-like niobium. Niobium was chosen because it has a very large nuclear spin, I = 9/2, and a large nuclear moment, $\mu = 6.167$, its wavelength is in the range of the high resolution spectrometer which we had available, and it had been observed to lase.[7] Figure 6 shows the measured intensity versus wavelength for the niobium line. Two components are clearly visible with a separation of 28 mÅ , which is very close to the 32 mÅ prediction given the 7 mÅ resolution of the spectrometer. This is the shortest wavelength transition and most highly ionized plasma in which the hyperfine effect has been directly observed. If we consider vanadium, assuming an ion temperature of 50 eV based on calculations, the hyperfine splitting reduces the gain coefficient of the J = 0 → 1 laser line at 304 Å by 40%. Given a nominal gain coefficient of 2.6 cm^{-1} for titanium, this reduces the gain coefficient to 1.6 cm^{-1} for vanadium. For the 3.8 cm long targets tried with vanadium, this would make the vanadium fifty times weaker than the titanium. While this is still within the detectable range of the diagnostics, the hyperfine effect appears to play a major role in the non lasing of vanadium and scandium and the poor lasing of the other odd Z ions.

4. CONCLUSIONS

We show that titanium is not a unique neon-like ion which lases at low-Z but that by application of a new technique using a low intensity prepulse before the main optical drive pulse many low-Z, neon-like ions can be made to lase. It is therefore very unlikely that resonant photo-pumping is playing a major role in the gain of the neon-like titanium laser. The hyperfine effect is shown to play a dominant role in explaining why the neon-like ions with even Z lase much better than the odd Z ions. Finally, neon-like X-ray lasers are now available over a previously inaccessible range of wavelengths.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. T. Boehly, M. Russotto, R. S. Craxton, R. Epstein, B. Yaakobi, L. B. Da Silva, J. Nilsen, E. A. Chandler, D. J. Fields, B. J. MacGowan, D. L. Matthews, J. H. Scofield, and G. Shimkaveg, "Demonstration of a narrow divergence X-ray laser in neon-like titanium," Phys. Rev. A **42**, 6962-6965 (1990).
2. J. Nilsen, B. J. MacGowan, L. B. Da Silva, and J. C. Moreno, "Prepulse technique for producing low-Z Ne-like XUV lasers," University of California report UCRL-JC-112704, Livermore, CA 94550 (1993).
3. T. Boehly, R. S. Craxton, R. Epstein, M. Russotto, and B. Yaakobi, "X-ray lasing in thick foil irradiation geometry," Opt. Comm. **79**, 57-63 (1990).
4. B. N. Chichkov and E. E. Fill, "A neon-like X-ray laser photoresonant pumping scheme," Opt. Comm. **74**, 202-206 (1989).
5. J. Zhang and E. E. Fill, "Resonantly photo-pumped Fe^{16+} soft X-ray laser," Optical and Quantum Electronics **24**, 1343-1350 (1992).
6. J. Nilsen, J. A. Koch, J. H. Scofield, B. J. MacGowan, J. C. Moreno, and L. B. Da Silva, "Observation of hyperfine splitting on an X-ray laser transition," University of California report UCRL-JC-113267, Livermore, CA 94550 (1993), also Phys. Rev. Lett.(in press).
7. J. Nilsen, J. L. Porter, B. J. MacGowan, L. B. Da Silva, and J. C. Moreno, "Neon-like X-ray lasers of zirconium, niobium, and bromine," J. Phys. **B 26**, L243-247 (1993).

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