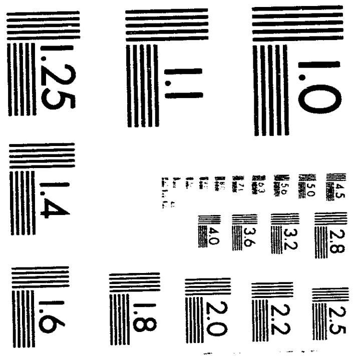
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

UCRL-JC116080
PREPRINT

Progress in understanding and improving X-ray Lasers

Joseph Nilsen, Juan C. Moreno, Jeffrey A. Koch, James H. Scofield,
Brian J. MacGowan, and Luiz B. DaSilva

This paper was prepared for submittal to the
Proceedings of the International Conference on Lasers '93
Lake Tahoe, Nevada, December 6-10, 1993

January 11, 1994

Lawrence Livermore National Laboratory

Progress in understanding and improving X-ray Lasers

Joseph Nilsen, Juan C. Moreno, Jeffrey A. Koch, James H. Scofield, Brian J. MacGowan, and Luiz B. Da Silva

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, California 94550

Abstract

We discuss the use of a prepulse technique to achieve lasing in low-Z neon-like ions on the 3p → 3s(J = 0 → 1) transition. In neon-like titanium(Z=22), chromium(Z=24), iron(Z=26), nickel(Z=28), zinc(Z=30), and germanium(Z=32) this transition lases at 326, 285, 255, 231, 212 and 196 Å respectively. We present results using this technique on selenium(Z=34) and show how the J = 0 → 1 transition at 182 Å suddenly becomes a strong line. The observation that the low-Z ions with odd Z have not lased lead us to investigate the potential impact of hyperfine splitting on the laser gain. In our experiments we measure the lineshape of the 3p → 3s(J = 0 → 1) transition in neon-like niobium and zirconium and observe a 28 mÅ splitting between the two largest hyperfine components in the niobium(Z=41) line at 145.9 Å, in good agreement with theory. In zirconium(Z=40), no splitting is observed since the hyperfine effect is proportional to the nuclear moment, and the principal isotopes of zirconium have zero nuclear moment, as is typical for even-Z elements. Finally we discuss the use of low density foams for the laser target and present results which show lasing in zirconium aerogel with an initial density of 90 mg/cm^3.

Experimental Setup

Experiments were conducted at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda = 0.53$ µm. In a typical experiment on the low-Z materials the Nova laser illuminates a 125 µm thick, 4.5 cm long slab target of nickel 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 34 TW/cm^2. A 6 J prepulse (also 600 ps FWHM) preceded the main pulse by 7 ns. For the selenium experiments, a 1 µ thick coating of selenium on a nickel substrate was used as the target and the main pulse was increased to 2200 J. The prepulse intensity and delay was kept the same as above. For the niobium and zirconium experiments 3.0 cm long slab targets were illuminated by a 500 ps square pulse with 2.4 kJ of energy in a 120 µm wide (FWHM) by 3.6 cm long line focus, resulting in a peak intensity of 130 TW/cm^2. For the zirconium aerogel experiment a 2.0 cm long target was illuminated by a 500 ps square pulse with 2.4 kJ of energy in a 120 µm wide (FWHM) by 2.4 cm long line focus, resulting in a peak intensity of 200 TW/cm^2.

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 MCPIGS used a 600 line/mm grating and had spectral coverage of approximately 150 to 680 Å. For the zirconium and niobium experiments a 1200 line/mm grating was used with spectral coverage of approximately 75 to 340 Å. 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 and spectral coverage of 2 Å . The angular resolution of all three instruments was perpendicular to the target surface.

Experimental Results and Analysis

Experiments have now been done on all elements from scandium(Z=21) to germanium(Z=32) except for gallium(Z=31) using a prepulse before the main pulse.[1-4] Different illumination conditions were used depending on the element but most were tried with the nominal conditions described above. 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

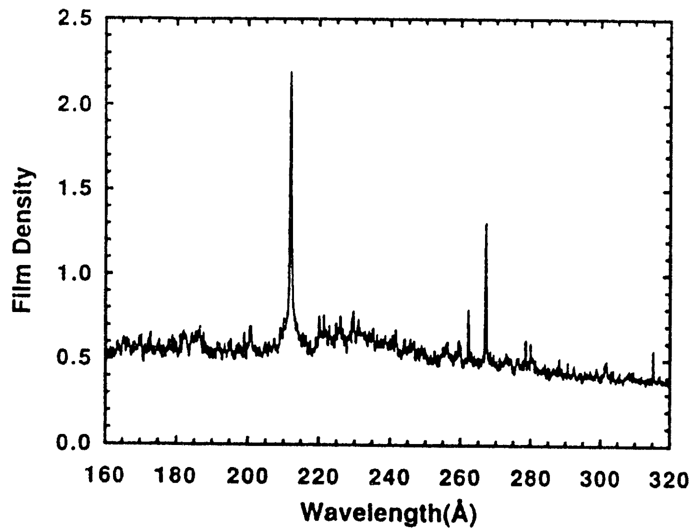

Fig. 1. MCPIGS spectrum of a 3.8 cm long target of zinc using the prepulse technique.

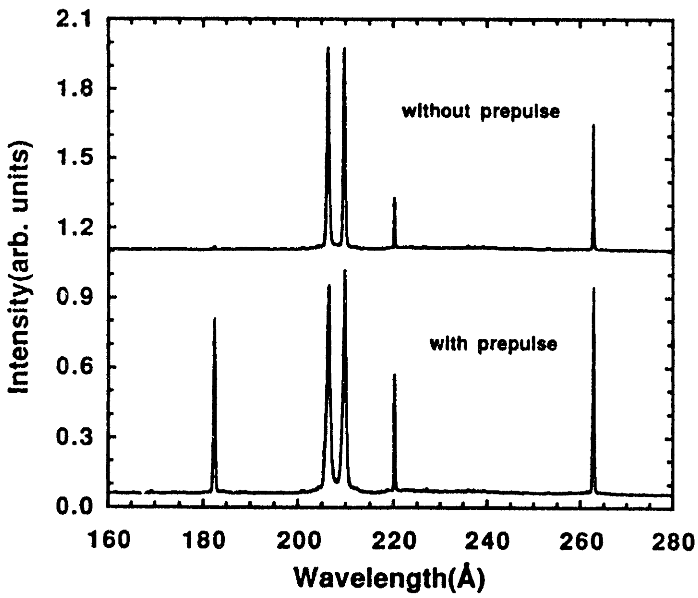

Fig. 2. MCPIGS spectra of 3.8 cm long targets of selenium with and without prepulse.

exponential growth of the laser output as the length was increased. In the experiments[1-4] we saw strong lasing on the $\overline{2p}_{1/2}\,3p_{1/2}$ (J = 0) → $\overline{2p}_{1/2}\,3s_{1/2}$ (J = 1) lines at 326, 285, 255, 231, 212, and 196 Å in titanium, chromium, iron, nickel, zinc, and germanium, respectively while scandium(Z=21), vanadium(Z=23), and manganese(Z=25) do not lase. Weak lasing was observed in cobalt(Z=27) and copper(Z=29). For the even Z ions we also observed some weak J = 2 → 1 laser lines. Figure 1 shows the spectrum from the MCPIGS spectrograph for a zinc target. Film density is used so as to show the weak J = 2 → 1 laser lines at 262 and 267 Å . The strong J = 0 → 1 laser line at 212 Å completely dominates the spectrum and is fifteen times more intense than the next strongest line. Recent experiments on selenium with and without the prepulse observed a dramatic change in the spectra, as shown in Fig. 2. When the prepulse is used, the J = 0 → 1 line at 182 Å suddenly jumps up and becomes a strong line as was originally predicted but never observed in standard X-ray laser experiments.[5]

Based on our calculations, we believe the prepulse is playing a key role in creating a larger, more uniform density plasma, at the 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.[6] 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 the low-Z neon-like lasers have not worked without the prepulse.

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

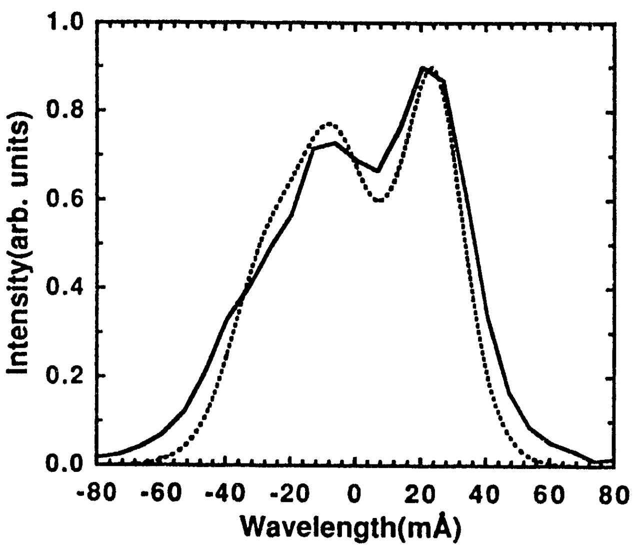

Fig. 3. Comparison of the theoretical predictions(dotted line) with the observation(solid line) for the intensity vs wavelength around line center for the J = 0 → 1 laser line in neon-like niobium at 145.9 Å . The curves are normalized to the same intensity and a peak gain-length product of 2 is assumed for the theoretical curve.

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,[7] 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.[8] Figure 3 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 on a laser transition.[7] 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.[9]

To eliminate the violent hydrodynamics which takes place when a solid target is heated by an optical laser such as Nova we are pursuing the use of foam targets which could potentially be fabricated at the final density needed for lasing and be volume heated by the Nova laser, thereby eliminating the large density gradients in the plasma. These density gradients cause significant refraction of the X-ray laser as it propagates down the laser axis and limits the effective length of the plasma as well as the laser coherence. We have tried several experiments on different foams with modest success. To achieve very low density we have tried molybdenum-doped agar foam (a hydrocarbon foam) at 3 mg/cm^3 and selenium-doped agar foam at 8 mg/cm^3. Both foams were nominally 50% metal by weight and neither lased. The agar has the difficulty that the cell size is micron scale and the foam must be doped with the element of interest, either as small particles or a compound. A more promising route is using aerogels such as zirconium aerogel which has a small cell size the order of 500 Å and is pure zirconium oxide, so the doping issue is avoided. The lowest density zirconium aerogel we have tried is at 90 mg/cm^3 and it lased quite well as shown in Fig. 4 which presents the intensity versus wavelength as measured with the MCPIGS

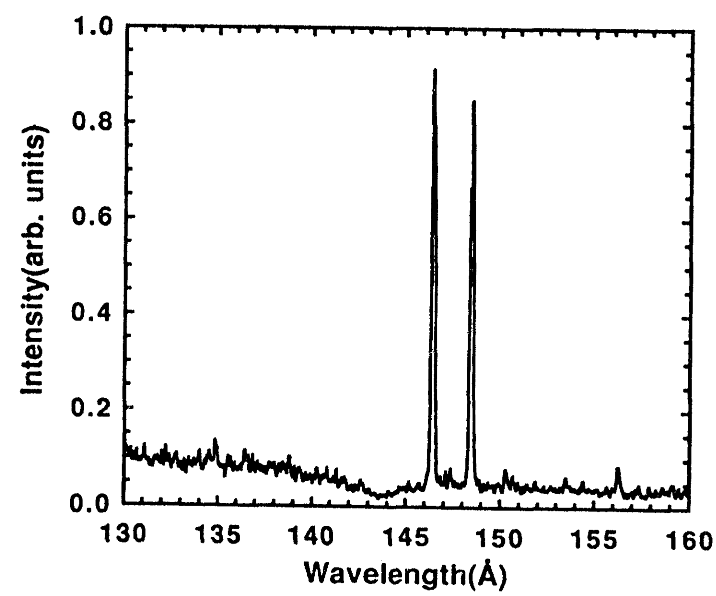

Fig. 4. MCPIGS spectrum of a 1.7 cm long target of zirconium aerogel.

spectrograph. The pair of J = 2 → 1 lines at 146 and 148 Å lase quite well. Presently we are trying to produce lower density aerogel. Silicon aerogel is the most mature technology and can be produced down to 1 mg/cm^3 so we are optimistic that the zirconium aerogel density can be lowered to the 1 - 3 mg/cm^3 range appropriate for lasing.

Conclusions

We show that using the prepulse technique we can achieve lasing on many low-Z neon-like ions from titanium to germanium. Using this technique on selenium caused the "missing" J = 0 → 1 line at 182 Å to lase quite strongly. The hyperfine effect is shown to be the dominant line broadening mechanism for the 3p → 3s(J = 0 → 1) neon-like niobium laser line at 145.9 Å. We measured the lineshape of this transition and observed a 28 mÅ splitting between the two largest hyperfine components, in good agreement with theory. This is the largest hyperfine splittings ever measured on a laser transition. Finally lasing is observed for the first time using a foam target of zirconium aerogel.

Acknowledgements

The authors would like to thank Larry Hrubesh for providing the zirconium aerogel and Sharon Alvarez, Hedley Louis, Tony Demiris, Judy Ticehurst, and the Nova facilities crew for providing support for the experiments. The support of S. B. Libby, D. A. Nowak and D. L. Matthews is greatly appreciated. Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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 X-ray lasers," Phys. Rev. **A 48**, 4682 - 4885 (1993).
3. J. Nilsen, J. C. Moreno, B. J. MacGowan, and J. A. Koch, "First observation of lasing at 231 Å in neon-like nickel using the prepulse technique," Applied Physics **B 57**, 309 - 311 (1993).
4. J. Nilsen and J. C. Moreno, "Observation of the missing 18.2 nm laser line in neon-like selenium," University of California report UCRL-JC-115290, Livermore, CA 94550 (1993).
5. R. C. Elton, *X-ray Lasers* (Academic Press, Inc., San Diego, 1990), pp. 99 - 126.
6. 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).
7. 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," Phys. Rev. Lett. **70**, 3713-3715 (1993).
8. 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).
9. J. H. Scofield and J. Nilsen, "Hyperfine splittings of neonlike lasing lines," Phys. Rev. **A** (in press 1994).

DATE
FILMED
4/7/94

END