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Juan C. Moreno, Robert C. Cauble, Peter Celliers, Luiz B. Da Silva,
Joseph Nilsen, and Alan S. Wan

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

ABSTRACT

We are developing techniques to shorten the time duration of neon-like x-ray lasers while maintaining their high brightness in order to optimize their usefulness as a plasma diagnostic. Adjusting the duration of the pump laser pulse is shown to directly influence the duration of neon-like x-ray laser transitions. Using slab targets, multiple 100 ps pulses and traveling wave geometry we have shortened the duration of lasing transitions down to 45 ps for both the neon-like germanium and yttrium x-ray lasers. However for the neon-like yttrium laser the intensity of short duration pulses are down two orders of magnitude from the long duration pulses because of limitations of the driving laser. We are presently looking at curved targets and pulse shaping in order to more efficiently pump the Ne-like x-ray laser system and increase the output intensity of the lasing lines. The relative merits of using the germanium x-ray laser at 196 Å compared to the yttrium x-ray laser at 155 Å are discussed.

Keywords: x-ray laser, plasma diagnostic, laser-plasma interaction, xuv spectroscopy

1. INTRODUCTION

Neon-like collisionally excited x-ray lasers are now being successfully used to probe highly ionized, fast evolving plasmas using radiography, Moire deflectometry, and interferometry[1-3]. While recombination x-ray lasers hold the possibility of being more efficient, their operation at large gain-lengths has not been demonstrated and their gain duration is determined mainly by recombination and cooling rates. Neon-like x-ray lasers on the other hand have easily demonstrated operation near saturation[4,5] and their gain duration, which is determined mainly by the duration of the optical laser pulse, can be shortened down to the ps regime. For a neon-like system a drive pulse of 600 ps duration typically results in an x-ray laser pulse of ~ 250 ps duration. Because of its very high brightness and nearly monochromatic output at 155 Å, the neon-like yttrium x-ray laser produced with a 600 ps drive laser has been the laser of choice for plasma diagnostic applications.

However to use an x-ray laser as a probe of high density laser-produced plasmas it would be preferable to have a pulse duration of less than 100 ps. This would provide a truer "snapshot" of the plasma and reduce blurring than can result from the hydrodynamic motion of the plasma. One can shorten the drive pulse to produce a shorter x-ray laser pulse but this generally also requires a higher intensity drive in order to achieve the correct ionization balance and gain conditions. One method used to help overcome this problem is to use multiple pulses of short duration, typically 100 ps, and spaced 300 ps or more apart.[6-8] These multiple pulses create a larger more uniform density plasma. The first pulse ionizes the material but the resulting plasma is not hot enough for significant gain and in addition the density gradients are too steep to allow the x-ray laser to propagate. The second and third pulses then heat the expanding plasma and larger, stable regions with high gain are produced which allow the x-ray laser to propagate better.[9]

When the gain duration becomes comparable to or less than the propagation time of the x-ray laser photons along the gain medium, then there will be a reduction in the effective gain since plasma conditions will change as the x-rays propagate along the plasma length. Tilting the wave front of the driving laser to match the propagation velocity of the x-ray laser allows one to extract the maximum energy out of the x-ray laser since the gain conditions are now maximized along the entire length of the gain medium.[7] This technique for exciting the plasma, usually called traveling wave excitation, has produced x-ray laser pulse durations as short as 45 ps.[6,7]

Using long slab targets there is the additional problem that refraction of the x-ray laser beam will lower the effective gain. A method which has been shown to compensate for refraction is to use curved targets which match the propagation path of the x-ray laser photons and also reduce the divergence.[10]

We are interested here in producing a short duration, high intensity x-ray laser for applications such as probing a material or high density, laser-produced plasma. In section 2 we discuss experiments in which the duration of the optical drive pulse was varied. In section 3 we discuss the possibility of using a shaped optical drive pulse to more efficiently drive the x-ray laser and we present some initial measurements. A comparison between the neon-like Y and Ge x-ray lasers is then presented in section 4. Finally our conclusions and future work are discussed in section 5.

2. Y SLAB X-RAY LASER

Experiments were performed to study the duration of the Y x-ray laser using a laser drive that varied in duration from 100 ps to 1 ns. The optical drive laser used for these experiments was the Nova laser at Lawrence Livermore National Laboratory. Targets were made from 100 μm thick yttrium slabs. The intensity on target was typically 10^{14} W/cm^2 with a 3 cm long line focus and 120 μm width. Because of a 16% gap in the laser beam, the effective length of the target was 2.52 cm. For time-gated spectra of the neon-like x-ray laser lines we used a 1-meter grazing incidence spectrograph (McPigs) with a microchannel plate detector viewing one end of the x-ray laser axis. A flat field spectrograph (SFFS) using a varied line space grating and a streak camera detector, viewed the opposite end of the x-ray laser and was used to obtain time-resolved spectra at somewhat lower resolution.

Figure 1 shows measured time histories of the neon-like Y x-ray laser line at 155 Å for the 100 ps and 600 ps duration optical drive laser pulses. The intensity on target was ~ 10^{14} W/cm^2. Note that the measured power is only an estimate based on comparisons to earlier measurements of power for the Y 155 Å line at saturation.[11] For the 100 ps drive we used 3 pulses separated by 400 ps and observed lasing on the second and third pulse. For the 150 ps and 300 ps drive we used two pulses, separated by 500 ps and 800 ps respectively, and observed much brighter x-ray lasing on the second pulse. The longer duration pulses were square-Gaussian pulses typically used on Nova.

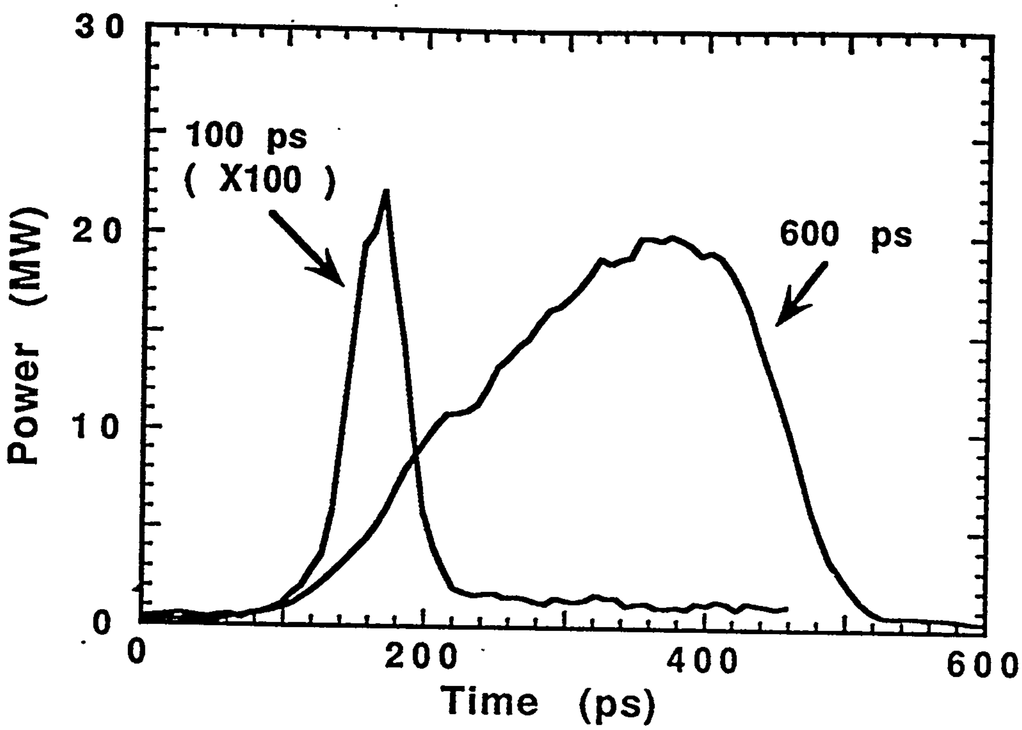

Figure 1. Measured time histories of Y 155 Å laser intensity for 100ps and 600 ps drive pulses. The intensity for the 100 ps drive case is multiplied by 100.

Our measured values for x-ray laser duration and energy for six different duration optical drive lasers is summarized in Table 1. While the relative x-ray laser energies are accurate, the absolute energies in the table are only approximate based on earlier measurements. We observe that the duration of the Y laser line at 155 Å is consistently somewhat less than half the duration of the drive laser. The intensity of the Y laser line at 155 Å is down two orders of magnitude when the multiple 100 ps drive is used compared to the 600 ps drive. We conclude that in order to shorten the 155 Å laser pulse we must sacrifice on the output brightness. One option to overcome this problem is to increase the intensity of the driver laser pulse. Indeed for foil targets irradiated by two beams of Nova, the output intensity of the Y 155 Å laser at saturation has been demonstrated to be quite high.[11] However for most applications it is not practical to use more than one laser to create the x-ray laser. We will discuss in the following sections several options available to shorten the pulse width while maintaining a high brightness laser line.

Our results were modeled using a lagrangian hydrodynamics code (Lasnex)[12] to simulate the density and temperature profiles. These results were then input into a postprocessor code (GLF)[13] that computed the gain profiles as a function of time. A difficulty in modeling the Ne-like Y laser line at 155 Å is that this line is actually an overlap of two lines, the J=0-1 transition and the J=2-1 transition. This overlap most likely explains the high brightness of this line. While the J=0-1 transition is calculated to have larger gain, it is generally not observed to be the brightest line except in cases when a prepulse or multiple pulse drive is used.[7-9,14] Calculations and measurements indicate that the J=0-1 line, which is populated mainly by collisional excitation, does not propagate well because it originates in a higher density region of the plasma where density gradients are much larger. The J=2-1 lines on the other hand are strongly populated by recombination and originate in a lower density region of the plasma. Prepulse and multiple pulse driven plasmas have reduced density gradients which allow the J=0-1 line to propagate better and become brighter relative to the J=2-1 lines. The relative contributions of the J=0-1 and J=2-1 transitions to the Y 155 Å line will be discussed more in section 4.

Drive laser pulse width (ps)	Drive laser energy (J)/pulse	Number of pulses	X-ray laser pulse width (ps)	X-ray laser energy (mJ)
100	400	3	45	0.01
150	550	2	70	0.03
300	1200	2	140	0.5
450	1800	1	180	2.6
600	2400	1	240	3.0
1000	3270	1	350	5.0

Table 1. Summary of our measurements of the pulse width and energy of the Y 155 Å laser line for a set of laser drive pulses varying in duration from 100 ps to 1 ns.

3. PULSE SHAPING

We have investigated modifying the pulse shape of the drive laser in order to optimize the coupling of the drive laser to the plasma and produce a more efficient x-ray laser. Our method here is similar to using a prepulse or multiple pulses.[9,14] In this case we have a lower intensity foot in the drive pulse which heats the plasma to conditions nearly sufficient to produce gain in neon-like Y. Then at the tail end of the pulse we have a short duration gaussian pulse which further ionizes the plasma and produces large gain and amplification. Figure 2 shows the time history of a shaped drive pulse and resulting Y x-ray laser line at 155 Å. The FWHM of the Y laser line is 170 ps, while the energy is ~2 mJ.

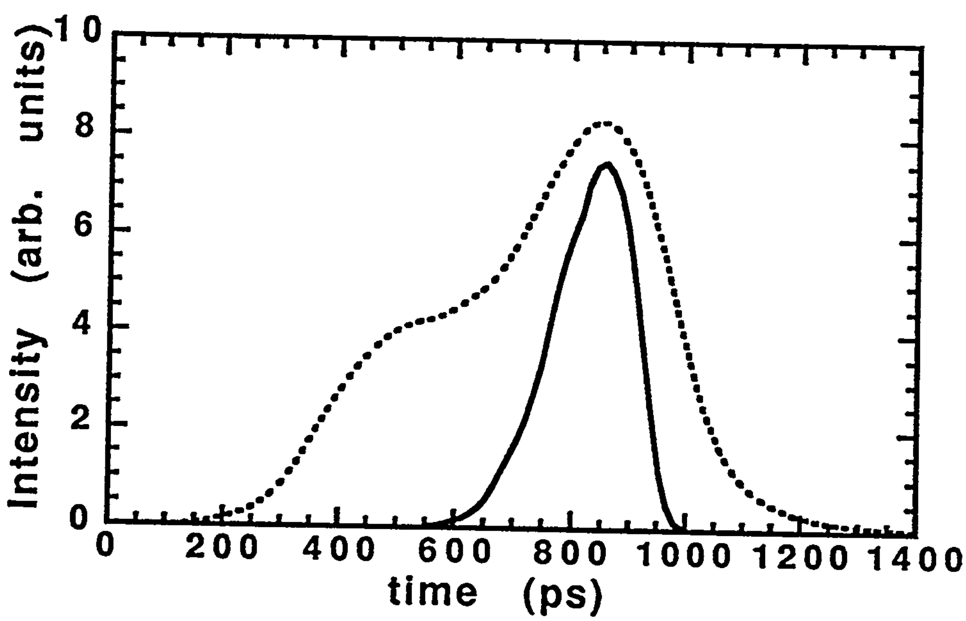

Figure 2. Time histories of the Y 155 Å laser line (solid line) and the optical drive pulse.

This is not yet an optimum pulse shape since the x-ray laser pulse width is still higher than 100 ps and the energy is down somewhat. Our goal is to optimize the shape and intensity of the foot of the drive pulse in order to ionize the plasma just to the neon-like ionization stage but with still small population inversion during this time. There may be a limit as to how short we can make the Y laser and still maintain its high brightness. As we discuss in the next section, when the driver pulse is shortened the contribution of the J=2-1 component to the 155 Å line may decrease significantly, making it more difficult to achieve high amplification for a given driver laser intensity. We are presently modeling these results and planning future experiments with a more optimized pulse shape.

4. COMPARISON OF Y AND GE X-RAY LASERS

While the Y laser at 155 Å has very high gain and high brightness, it is difficult to produce both a short duration x-ray laser pulse and high brightness given the limitations of the drive laser. One option is to use the neon-like Ge x-ray laser which requires less intensity in the drive laser to produce high amplification. For this neon-like laser the J=2-1 lines are dominant when using a long duration (≥ 500 ps) driver pulse. However, when using short duration (100 ps) multiple pulses in the driver laser it is observed that the J=0-1 line at 196 Å becomes the dominant laser line. Figure 3 shows a comparison of the Ne-like Ge and Y spectra for an optical laser drive of 600 ps duration. The Y spectrum is nearly monochromatic, although one can observe the J=2-1 line at 157 Å at roughly 1/100 the integrated intensity of the 155 Å line.

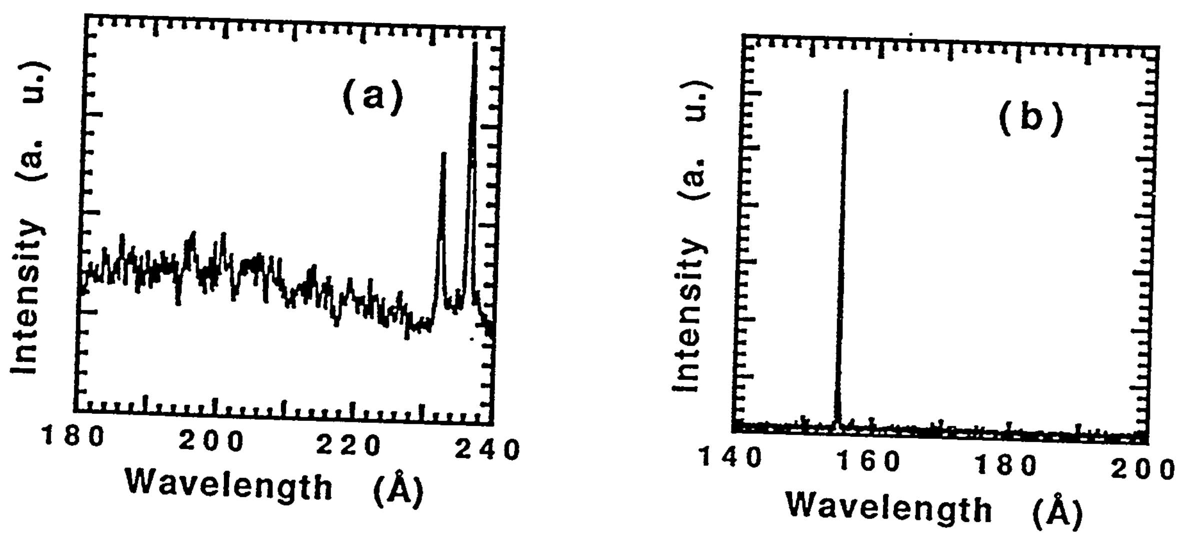

Figure 3. Comparison of the Ne-like Ge and Y spectra with a 600 ps drive laser and 2.52 cm length target. (a) Ne-like Ge spectrum. (b) Ne-like Y spectrum.

The neon-like germanium laser is a robust and strong x-ray laser and also nearly monochromatic when using multiple pulses. Comparative spectra for the 100 ps drive case are shown in Fig. 4. The output intensity of Y and Ge lasers are comparable for 2.52 cm long targets using multiple 100 ps pulses. Both of these lasers are however over two orders of magnitude down in intensity compared to the Y laser using a 600 ps laser drive. In the Y spectrum in Fig. 4 we again observe a strong peak at 155 Å but there is no evidence of a line at 157 Å. This indicates that the J=0-1 transition is now much stronger than the J=2-1 transition at 155 Å, which is consistent with the general observation that the J=0-1 line becomes brighter when using a prepulse or multiple pulses. If the J=2-1 transition is the dominant contribution to the 155 Å line for long duration driver pulses then this would also explain why the intensity of 155 Å line is so much less when using 100 ps pulses.

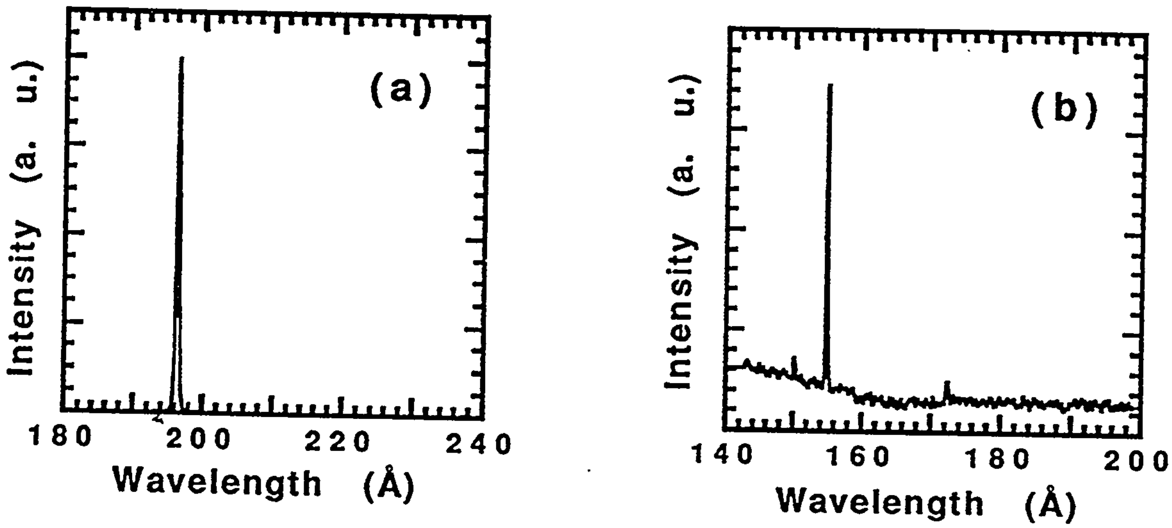

Figure 4. Comparison of the Ne-like Ge and Y spectra with a 100 ps drive laser and 2.52 cm length target. (a) Ne-like Ge spectrum. (b) Ne-like Y spectrum.

Recently we have performed experiments using 3.78 cm long Ge targets irradiated by multiple 100 ps pulses and using traveling wave excitation. Our method of tilting the wave front is to insert a grating in the pre-amplifier section of the drive laser and use the first order diffraction from the grating.[7] To produce the 45 degree tilt of the wave front in the driving laser for these longer length targets we employed a new 1500 g/mm grating.

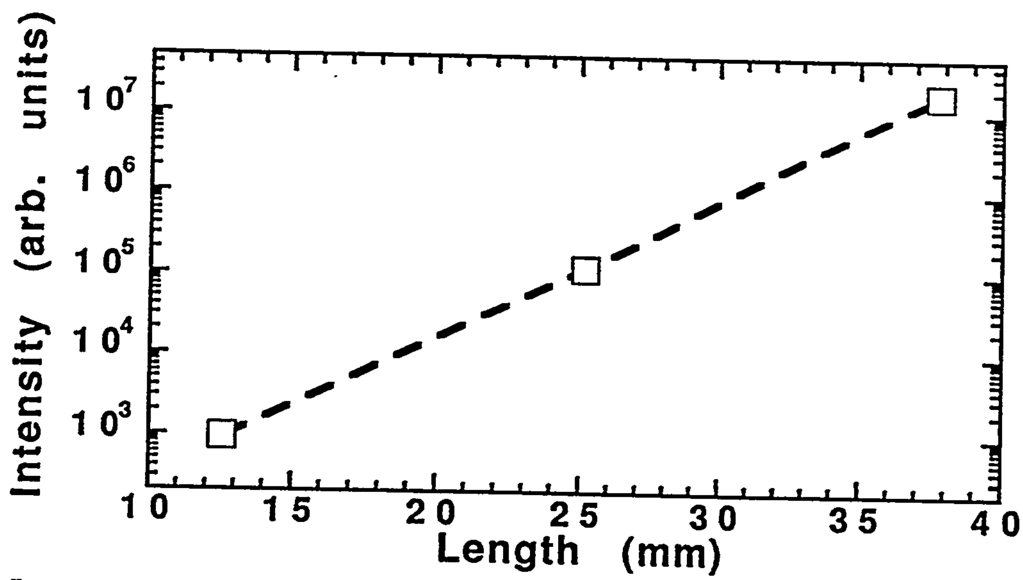

Figure 5. Integrated intensity of the Ne-like Ge laser line at 196 Å for three different targets lengths. The gain is ~ 4 cm^{-1}.

In Fig. 5 we show a plot of the integrated intensity of the 196 Å line of Ge for a range of different target lengths using earlier as well as present measurements. From the scaling with length we can calculate a gain of G=4 cm^{-1} and a gain-length product of ~ 15. This is near the saturated regime for these lasers. From a relative calibration of the measured intensity we estimate that the Ne-like Ge 196 Å laser intensity is within a factor of 5 of the Ne-like Y 155 Å laser intensity with a 600 ps drive. The much shorter pulse duration of the Ge laser makes it an attractive candidate for plasma diagnostic experiments.

5. CONCLUSION

The Y x-ray laser is a good choice as a plasma diagnostic because of its high brightness and nearly monochromatic emission at 155 Å. However reducing the pulse width is difficult due to the stringent requirements on driver intensity. In addition, the relative contribution of J=0-1 and J=2-1 components of the 155 Å line may change depending on the drive laser pulse width. Pulse shaping is being investigated to more efficiently pump the Y laser and also shorten the pulse duration. Another option being pursued to produce a short, bright x-ray laser is to use the Ge x-ray laser at 196 Å. With 3.78 cm long targets we have achieved brightnesses for the Ge 196 Å laser line approaching the Y 155 Å laser while at the same time keeping the pulse duration short (~ 50 ps). Another good feature for the Ge 196 Å line is that it is on the long wavelength side of the Al L edge which allows one to use readily available Al filters which have high transmission at this wavelength.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. R. Cauble, L. B. Da Silva, T. W. Barbee, Jr., P. Celliers, J. C. Moreno, and A. S. Wan, "Micron-resolution radiography of laser-accelerated and x-ray heated foils with an x-ray laser," *Phys. Rev. Lett.* 74, 3816-3819 (1995).
2. D. Ress et al., "Measurement of laser-plasma electron density with a soft x-ray laser deflectometer," *Science* 265, 514-517 (1994).
3. L. B. Da Silva, T. W. Barbee, Jr., R. Cauble, P. Celliers, D. Ciarlo, S. Libby, R. A. London, D. Matthews, S. Mrowka, J. C. Moreno, D. Ress, J. E. Trebes, A. S. Wan, and F. Weber, "Electron density measurements of high density plasmas using soft x-ray laser interferometry," *Phys. Rev. Lett.* 74, 3991-3394 (1995).
4. D. Matthews, M. Rosen, S. Brown, N. Ceglio, D. Eder, A. Hawryluk, C. Keane, R. London, B. MacGowan, S. Maxon, D. Nilseon, J. Scofield, and J. Trebes, *J. Opt. Soc. Am.* 4, 575 (1987).
5. A. Carillon, et al., "Saturated and near-diffraction-limited operation of an xuv laser at 23.6 nm," *Phys. Rev. Lett.* 68, 2917 (1992).
6. L. Da Silva, R. A. London, B. J. MacGowan, S. Mrowka, and D. L. Matthews, "Generation of a 45-ps-duration 15.5-nm x-ray laser," *Opt. Lett.* 19, 1532-1534 (1994).

7. J. C. Moreno, J. Nilsen, and L. B. Da Silva, "Traveling wave excitation and amplification of neon-like germanium 3p-3s transitions," *Opt. Commun.* **110**, 585-589 (1994).
8. H. Daido, R. Kodama, K. Murai, G. Yuan, M. Takagi, Y. Kato, I. W. Choi, and C. H. Nam, "Significant improvement in the efficiency and brightness of the J = 0-1 19.6-nm line of the germanium laser by use of double-pulse pumping," *Opt. Lett.* **20**, 61-63 (1995).
9. J. Nilsen and J. C. Moreno, "Nearly monochromatic lasing at 182 angstroms in neonlike selenium," *Phys. Rev. Lett.* **74**, 3376-3379 (1995).
10. R. Kodama, D. Neely, Y. Kato, H. Daido, K. Murai, G. Yuan, A. MacPhee, and C. L. S. Lewis, "Generation of small-divergence soft x-ray laser by plasma waveguiding with a curved target," *Phys. Rev. Lett.* **73**, 3215-3218 (1994).
11. L. B. Da Silva, B. J. MacGowan, S. Mrowka, J. A. Koch, R. A. London, D. L. Matthews, and J. H. Underwood, "Power measurements of a saturated yttrium x-ray laser," *Opt. Lett.* **18**, 1174-1176 (1993).
12. G. B. Zimmerman and W. L. Kruer, *Com. Plasma Phys. and Cont. Fusion* **2**, 51 (1975).
13. H. A. Scott and R. W. Mayle, "GLF - A simulation code for x-ray lasers," *Appl. Phys. B* **58**, 35-43 (1994).
14. 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**, 4682-4685 (1993).