CONF-9509339--1

UCRL-JC-121199
PREPRINT

Review of Neon-like and Nickel-like Ions Lasing on the J = 0 → 1 Line Using the Prepulse and Multiple Pulse Techniques

J. Nilsen, J. C. Moreno, L. B Da Silva, T. W. Barbee, Jr., Y. Li, P. Lu, E. E. Fill, H. Fiedorowicz, A. Bartnik

This paper was prepared for submittal to the
International Workshop on X-ray Lasers and Optics
Mianyang, China
September 10-14, 1995

November 1995

Review of neon-like and nickel-like ions lasing on the $J = 0 \rightarrow 1$ line using the prepulse and multiple pulse techniques

Joseph Nilsen, Juan C. Moreno, Luiz B. Da Silva, and Troy W. Barbee, Jr.
Lawrence Livermore National Laboratory, Livermore, California 94550

Yuelin Li, Peixiang Lu*, and Ernst E. Fill*
Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

Henryk Fiedorowicz and Andrzej Bartnik
Institute of Optoelectronics, Military University of Technology,
2, Kaliskiego Str., 01-489 Warsaw, Poland

ABSTRACT

We discuss the use of a prepulse technique to achieve lasing in low-Z neon-like ions on the $3p \rightarrow 3s(J = 0 \rightarrow 1)$ transition. Lasing has now been observed on this transitions for neon-like ions from chlorine(Z=17) to selenium(Z=34) with wavelengths ranging from 528 Å to 182 Å. For the germanium targets we present two dimensional space resolved images of the laser output with magnification of ten. Using a gas puff target as an alternative to the prepulse technique, we observe lasing at 469 Å in neon-like argon(Z=18).

Using a series of 100 ps pulses 400 ps apart to illuminate germanium and selenium plasmas we present results which now show the $3p \rightarrow 3s(J = 0 \rightarrow 1)$ transition to dominate the other laser lines even for selenium. Using these short pulses together with a traveling wave geometry we are able to produce bright short X-ray pulses which can be used in imaging experiments. For germanium targets we present the first space and time resolved images of the laser output with magnification of twenty.

Applying the multiple pulse technique to nickel-like ions we observed lasing at 79 Å on the $4d \rightarrow 4p(J = 0 \rightarrow 1)$ transition in nickel-like neodymium(Z=60) when a series of 100 - 150 ps pulses which are 400 - 500 ps apart are used to illuminate slab targets of neodymium. To maximize the laser output for neodymium we combine the advantages of coupling two slab targets, using the traveling wave geometry, and curving the target surface.

PREPULSE EXPERIMENTS

Several years ago we demonstrated a new prepulse technique which enabled many new low-Z neon-like ions to lase for the first time.[1] In those experiments, which were conducted at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda = 0.53\ \mu m$, the $J = 0 \rightarrow 1$ laser line dominated the spectra as was originally predicted but never previously observed. In a typical Nova experiment, a 4.5 cm long slab target was illuminated by 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. To view the laser output the principal instruments were a time-gated, microchannel-plate-intensified, grazing-incidence, grating spectrograph(MCPIGS) and a streaked, flat-field spectrograph(SFFS). The MCPIGS used a 600 line per mm grating and had spectral coverage of approximately 150 to 680 Å. Figure 1 shows MCPIGS spectra of Ti, Cr, Fe, and Ni slab targets which all lased on the $J = 0 \rightarrow 1$ laser line at 326, 285, 255, and 231 Å, respectively. Weak lasing on the usual pair of $J = 2 \rightarrow 1$ lines is also observed. These experiments opened up a whole new regime of low-Z neon-like X-ray lasers which were now accessible to smaller laser facilities. Before the prepulse technique, germanium was the lowest-Z neon-like x-ray laser which worked well. Most laser facilities were too small to move to higher Z and the lower Z materials just did not work.

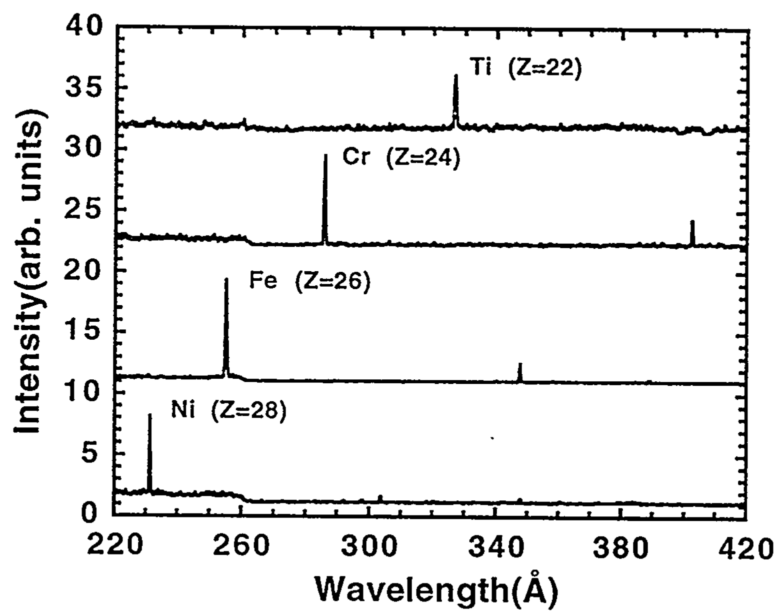

Fig. 1. MCPIGS spectra of 3.8 cm long targets of Ti, Cr, Fe, and Ni.

Since the prepulse technique was demonstrated at LLNL, many groups around the world have begun to use this technique. At the Max-Planck-Institut für Quantenoptik(MPQ) experiments have been conducted using the Asterix IV laser facility to study elements from Cl(Z=17) to Ge(Z=32).[2] The Asterix IV laser is an iodine laser with a single beam which produces up to 600 J at 1.315 µm in a 450 ps pulse. To make the prepulse, a pair of mirrors is inserted into the beam path before and after the final steering mirror. The prepulse is set to 5.23 ns before the main pulse and can be varied up to 15% of the main beam energy. Neutral density filters are used to reduce the prepulse level without changing the main beam. The Asterix output is focused to a 3 cm long by 150 µm wide line focus using a 30 cm diameter cylinder lens array. Typically slab targets are used with lengths up to 3 cm. The main diagnostic used in the experiments was a transmission grating spectrometer coupled to a thinned backside illuminated CCD which recorded time-integrated but space or angularly resolved spectral data. In extending the prepulse technique to lower-Z ions, recent experiments have observed lasing in scandium(Z=21), calcium(Z=20), potassium(Z=19), and chlorine(Z=17) with wavelengths of 352, 383, 421, and 529 Å , respectively. Figure 2 shows spectra of these four ions lasing. The targets used were Sc, CaF_2, and KCl. These are the lowest-Z neon-like ions to lase so far.

Numerical modeling of the plasmas driven using the prepulse technique suggest that the prepulse is helping to create a larger, more uniform plasma with smaller density gradients which enables the $J = 0 \rightarrow 1$ laser line to

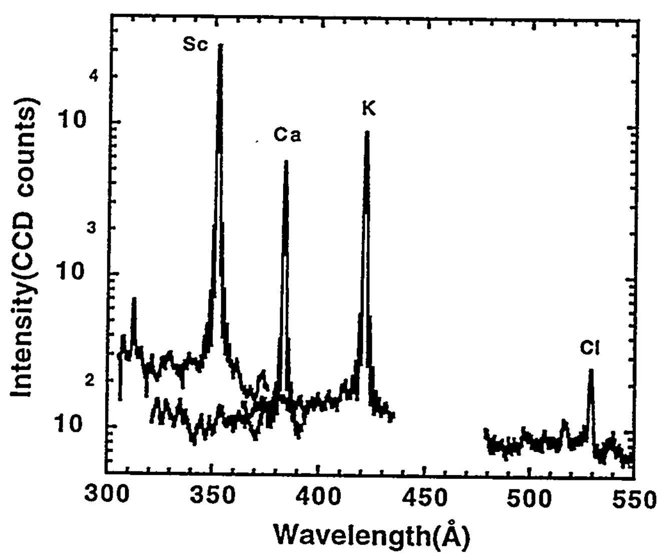

Fig. 2. Spectra of Sc, CaF_2, and KCl targets from Asterix experiments.

propagate better. An alternative to using the prepulse technique is to use a low density target. An electromagnetic valve to produce an elongated gas puff target has been developed at the Institute of Optoelectronics in Warsaw and was recently tried on the Asterix laser facility.[3] In this case no prepulse was used as the gas puff created a gas target of approximately 0.1 atm which was directly heated by the main Asterix pulse. Figure 3 shows spectra for a 2.7 cm long Ar plasma from the space-resolved spectrometer for experiments done using Asterix with 400 J of energy. The neon-like argon $J = 0 \rightarrow 1$ line at 469 Å dominates the spectra. A second laser line at 451 Å is also observed and believed to be a neon-like $3d \rightarrow 3p$ transition which is photo-pumped by the strong $3d \rightarrow 2p$ resonance line at 41 Å .

Figure 4 shows the lasing mechanism for the $3d\ ^1P_1 \rightarrow 3p\ ^1P_1$ laser line at 450.9 Å in Ne-like Ar. The $3d\ ^1P_1 \rightarrow 2p\ ^1S_0$ line at 41.47 Å in Ne-like Ar resonantly photo-pumps an electron in the ground state of the Ne-like Ar ion to the $3d\ ^1P_1$ upper laser state.[4] The $3p\ ^1P_1$ lower laser state is primarily destroyed by collisional mixing with the other nearby 3s and 3d states. Unlike other resonantly photo-pumped X-ray laser schemes which require a strong pump line from a separate plasma which is resonant with a line in the laser medium, this scheme is self pumped using a single plasma and therefore has a perfect resonance. The pump line is made very bright by having the plasma be optically thick on this line, which is the strongest line in the plasma and has an oscillator strength of 2.2.

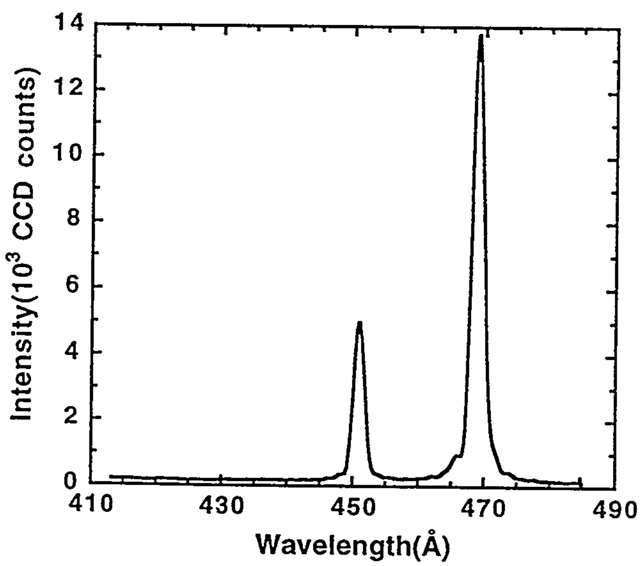

Fig. 3. Spectra of Ar gas puff target from Asterix experiments.

IMAGING OF PREPULSE EXPERIMENTS

To better understand the effect of the prepulse we did a series of experiments to image the output of the Ne-like Ge X-ray laser in two dimensions(2D) using a curved multilayer mirror. We chose Ge because it lases with and without the prepulse on the J = 0 → 1 line at 196 Å and the J = 2 → 1 lines at 232 and 236 Å. We fabricated multilayer mirrors with peak reflectivity at 196 and 234 Å and bandwidths of 15 Å so that we could study the J = 0 → 1 line separately from the pair of J = 2 → 1 lines. The J = 0 → 1 line was always predicted to be the dominant laser line but was observed weakly, if at all, in the early X-ray laser experiments which used single pulse illumination of foil or slab targets.[5] In these experiments the curved mirror has a radius of curvature of 50 cm which gives it a focal length of 25 cm. The mirror is placed 27.5 cm from the end of the X-ray laser. The laser output is imaged onto a CCD which is 275 cm from the mirror, giving a magnification of 10 in 2D. A wire fiducial was placed 312 μm above the surface of the Ge slab target. The targets used in the experiments were made by coating 1 μm of germanium on a copper substrate whose surface was machined with a diamond turning machine to be flat to better than 0.5 μm.

In the experiments we varied the prepulse from 0 to 1.65 to 15% of the main pulse. The energy of the main pulse was typically 320 J from the Asterix laser resulting in an intensity on target of 16 TW/cm^2. For the no prepulse case the signals were too weak to be seen. The best lasing was

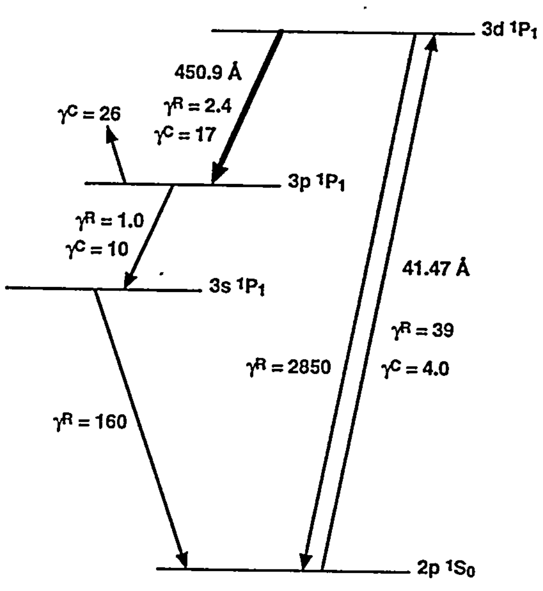

Fig. 4. Energy level diagram showing self photo-pumped Ne-like Ar laser

observed for the 15% prepulse case. Figure 5 shows a 2D near field image of the 196 Å laser line. Lasing peaks about 100 μm from the target surface and the emission region is quite small. The signal has significant variations in the line focus direction which are probably due to the cylinder lens which actually consists of six segments which create six partially overlapping line foci. For the pair of 232 and 236 Å lines, Fig. 6 shows the 2D near field image. Lasing now occurs over a much larger region further from the surface.

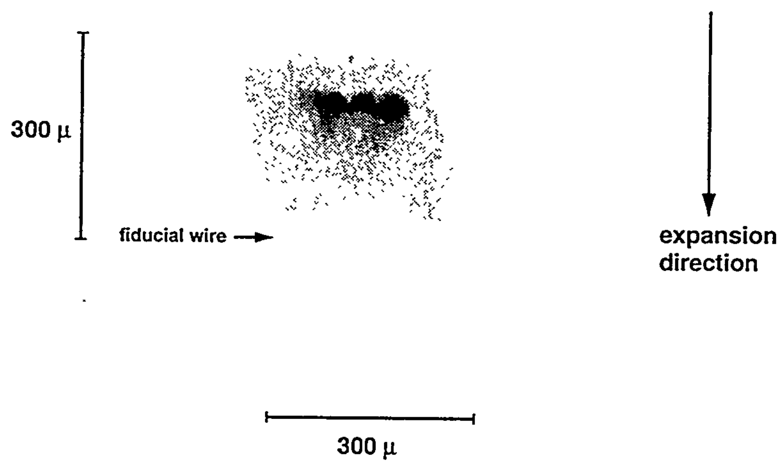

Fig. 5. 2D image of Ge 196 Å laser output for 15% prepulse case.

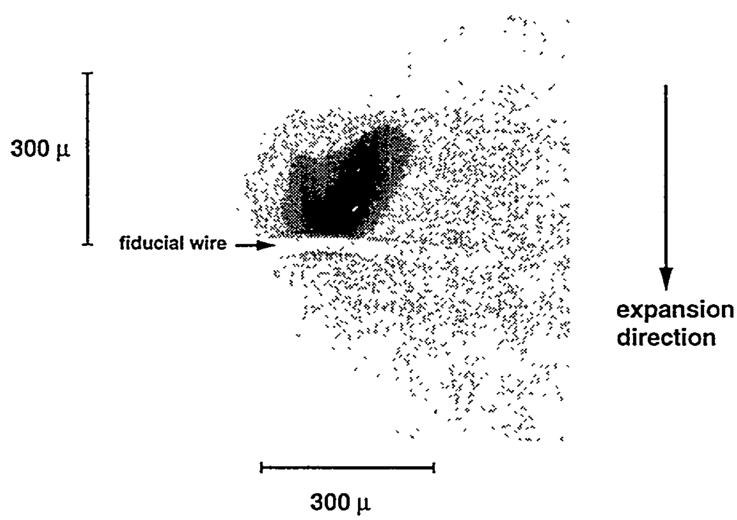

Fig. 6. 2D image of Ge 232 & 236 Å laser output for 15% prepulse case.

The lasing intensity is weaker than the 196 Å line however.

MULTIPLE PULSE EXPERIMENTS

As an alternative to the prepulse technique we have developed the multiple pulse technique which uses a series of short pulses(100-150 ps) which are 400 - 500 ps apart to illuminate slab targets of Ge, Se, and Nd. The prepulse technique currently works best for the low-Z Ne-like ions. For mid-Z ions such as Ge and Se we have found that the multiple pulse technique works better and makes the $J = 0 \rightarrow 1$ line completely dominate the output. In typical experiments on the Nova laser we use a series of 100 ps pulses with 270 J of energy which are 400 ps apart to illuminate a 3 cm long Ge slab target. To eliminate the transit time effects we use a traveling wave geometry.[6] Fig 7. shows the spectrum from the MCPIGS spectrograph. The 196 Å line is two orders of magnitude brighter than the 232 and 236 Å lines. When we do the same experiment with Se targets using 400 J, we observe the $J = 0 \rightarrow 1$ line at 182 Å to completely dominate the output for the first time.[7]

To attempt to understand the plasmas driven by the multiple pulses we used curved multilayer mirrors to image the output of the Ge laser onto a streak camera. This gives us spatial resolution in 1D and time resolution. Fig. 8. shows a time resolved 1D image of the 196 Å laser line for a Ge target which was illuminated from both sides by two beams of Nova. The target is 125 μm thick and has a wire fiducial 187 μm above one surface of the target. Lasing occurs during the second and third pulse. This is seen clearly for

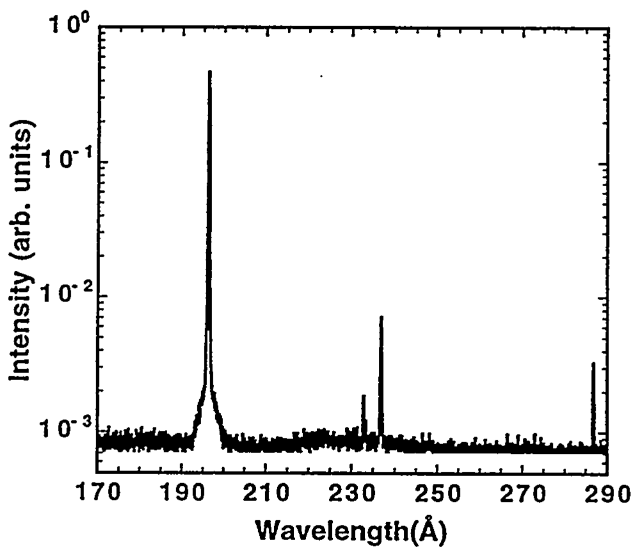

Fig. 7. MCPIGS spectra of Ge target illuminated by multiple pulse technique.

the plasma on the right.

Since the multiple pulse technique worked so well for the mid-Z Ne-like ions we decided to try this with the Ni-like slab targets. After some initial failures doing 3 cm long slab targets of Dy, Gd, and Sm, we tried Nd targets and observed a weak indication of lasing. To have the best chance of observing the lasing in Ni-like Nd we combined several different ideas to maximize the output. We used curved targets to try to reduce the refraction effects.

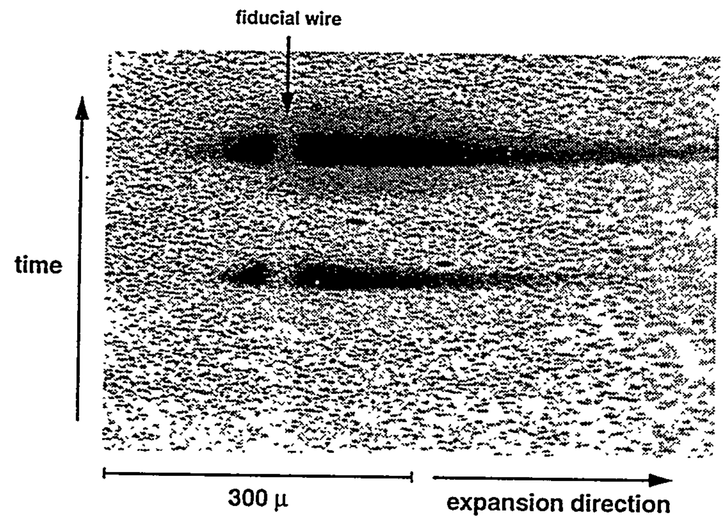

Fig. 8. 1D image of Ge 196 Å laser output for multiple pulse illumination.

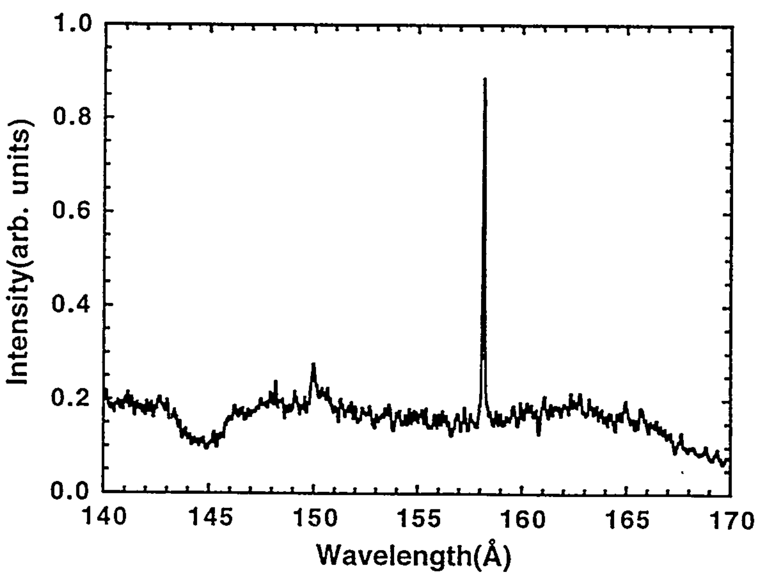

Fig. 9. MCPIGS spectra of Nd target illuminated by multiple pulse technique.

We used the traveling wave geometry to eliminate the transit time effects. We coupled two slabs lengthwise to increase the length of the target. We increased the pulse width to 150 ps to reduce the timing tolerances needed for coupling the double slab target. The experiments used a series of three 150 ps pulses 500 ps apart with 600 J of energy in each pulse for an intensity of 110 TW/cm^2 for the 3 cm long slabs. Two beams of Nova were used to illuminate the two slabs, with Nova beam 7 delayed by 117 ps to account for the transit time from the left end of the first slab target to the left end of the second target, which were 3.5 cm apart.[8] Fig. 9 shows a spectrum from the MCPIGS spectrograph. A single strong Ni-like Nd 4d → 4p (J = 0 → 1) laser line at 79 Å , seen in second order at 158 Å , dominates the emission spectrum. In the streak camera data, this line has a FWHM duration of 38 ps and occurs during the rising edge of the second pulse 140 ps before the peak of the continuum emission. For this experiment the Nova energy fell by 30% on the third pulse so no lasing was observed on the third pulse. Normally lasing is observed on the second and third pulse.

CONCLUSIONS

Using the prepulse technique, we show that the 3p → 3s (J = 0 → 1) line lases and dominates the output of the neon-like lasers with Z = 17 - 32. Using a gas puff target as an alternative to the prepulse we observe lasing at 469 Å in Ne-like Ar and also observe a line at 451 Å which we suggest is lasing on a 3d → 3p transition due to a self photopumped process. Using a series of 100 ps pulses 400 ps apart we observe the J = 0 → 1 line at 182 Å in Ne-like Se to dominate the spectra for the first time. This multiple pulse technique seem to be better optimized than the prepulse technique for the mid-Z Ne-like ions. We apply the multiple pulse technique to Ni-like Nd and observe lasing on the 4d → 4p (J = 0 → 1) at 79 Å . We also present 1D time-resolved and 2D time-integrated near-field images of Ne-like Ge lasers using both the prepulse and multiple pulse technique to help explain how both these methods help create larger scale length plasmas with lower electron density gradients which enable the lasers to work better.

ACKNOWLEDGEMENTS

The authors would like to thank the Asterix and Nova facilities crew for providing support for the experiments. The work of the LLNL authors was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48. Yuelin Li and Peixiang Lu are supported by the Alexander von Humboldt

Foundation. This work was supported in part by the Commission of the European Communities in the framework of the Association Euratom/Max-Planck-Institut für Plasmaphysik and the State Committee for Scientific Research of Poland under grant No. 2 P302 059 07.

*Permanent address: Shanghai Institute of Optics and Fine Mechanics, Academia Sinica, Shanghai, China.

REFERENCES

1. J. Nilsen, B. J. MacGowan, L. B. Da Silva, and J. C. Moreno, Phys. Rev. A **48**, 4682 (1993).
2. E. E. Fill, Y. L. Li, G. Pretzler, D. Schlögl, J. Steingruber, and J. Nilsen, SPIE Proceedings 2520, 134 (1995).
3. H. Fiedorowicz, A. Bartnik, M. Szczurek, E. E. Fill, Y. L. Li, P. X. Lu, and G. Pretzler, SPIE Proceedings 2520, 55 (1995).
4. J. Nilsen, H. Fiedorowicz, A. Bartnik, Y. L. Li, P. X. Lu, and E. E. Fill "*A self photo-pumped neon-like X-ray laser,*" University of California report UCRL-JC-121829, Livermore, CA (1995).
5. R. C. Elton, *X-ray Lasers* (Academic Press, Inc., San Diego, 1990), pp. 99 - 198.
6. J. C. Moreno, J. Nilsen, and L. B. da Silva, Opt. Comm. **110**, 585 (1994).
7. J. Nilsen and J. C. Moreno, Phys. Rev. Lett. **74**, 3376 (1995).
8. J. Nilsen and J. C. Moreno, Opt. Lett. **20**, 1386 (1995).

Technical Information Department · Lawrence Livermore National Laboratory
University of California · Livermore, California 94551