Intense $J=0-1$ soft-x-ray lasing at 28.5 nm in neonlike chromium

A. R. Präg, F. Loewenthal, and J. E. Balmer
Institute of Applied Physics, University of Berne, Sidlerstrasse 5, CH-3012 Berne, Switzerland
(Received 14 March 1996; revised manuscript received 19 July 1996)

Intense $3p$-$3s$, $J=0$–1 soft-x-ray lasing at 28.5 nm in neonlike chromium has been observed experimentally using a compact Nd:glass laser as the driver. 2.4-cm-long polished chromium slab targets were irradiated with up to 100-J/500-ps pulses at the fundamental wavelength of 1.054 μm. The prepulse technique was applied using a defined prepulse 5 ns before the main pulse and with a prepulse-to-main pulse energy ratio of 0.7%. It is demonstrated that a pump energy of ~80 J, corresponding to a pump irradiance of approximately 9 TW/cm^2 is sufficient to observe soft-x-ray lasing at 28.5 nm. At a drive laser energy of ~90 J a gain coefficient of (2.2±0.5) cm^{-1} was measured. The one-dimensional space-resolved measurements show that the 28.5-nm laser line is emitted from a 60-μm-wide (full width at half maximum) plasma region.
[S1050-2947(96)08111-5]

PACS number(s): 42.60.By, 32.30.Rj, 52.50.Jm

Since the first demonstration of soft-x-ray lasing in collisionally pumped neonlike selenium at wavelengths near 21 nm [1,2] the possibility of scaling to shorter wavelengths as well as the development of tabletop x-ray lasers driven at pump energies well below the kilojoule level has been extensively discussed. It is obvious that for practical applications the size and costs should be reduced in comparison to the high-power laser facilities currently needed. Important progress in this direction was made through the introduction of the prepulse technique in which a low-energy prepulse irradiates the target a few nanoseconds before the main driving pulse [3–17]. X-ray laser research now seems to be possible also for laboratories that are equipped with drive lasers well in the sub-kJ energy range. Nilsen *et al.* [4] recently reported on $3p$-$3s$, $J=0$–1 lasing in neonlike chromium ($Z=24$) at the wavelength of 28.5 nm, applying the prepulse technique and using a delay of 7 ns between the prepulse and the main pulse, a prepulse-to-main pulse energy ratio of 0.5%, and a drive laser energy of 1100 J in a pulse of 600 ps duration. The authors worked with a 5.4-cm-long line focus irradiated at 34 TW/cm^2 by two beams of the NOVA laser-fusion facility.

Recently it was reported that in neonlike plasmas $J=0$–1 lasing in the extreme ultraviolet (XUV) region was observed with drive laser energies considerably below 200 J. Li, Pretzler, and Fill [9] demonstrated lasing on the 38.3-nm line in neonlike calcium at a pump irradiance of 5 TW/cm^2 and Präg *et al.* [14] and Zhang *et al.* [15] achieved lasing on the 32.6-nm line in neonlike titanium at an irradiance as low as 2.5 TW/cm^2. Furthermore, the possibility of establishing compact x-ray lasers also at shorter wavelengths was discussed.

A tabletop laser-driven nickellike soft-x-ray laser was reported by Basu *et al.* [18] and Hagelstein *et al.* [19] using a multiple-pulse technique with 3–5 pulses of 80 ps duration, separated in time by 7.5 ns, and approximately 1 J of energy. The authors observed a line at the wavelength of 20.4 nm that was identified with the predicted wavelength of the $4d$-$4p$, $J=0$–1 lasing line in nickellike niobium ($Z=41$). The maximum irradiance on the target was estimated to be 10 TW/cm^2. The authors mentioned that the brightest signals are observed about 500 ps after the second pump pulse. This is in contrast to measurements in the case of nickellike neodymium ($Z=60$), where lasing is observed on the rising edge, i.e., before the peak, of the main driver pulse, as reported recently by Nilsen and Moreno [20].

Alternative successful approaches to the development of tabletop XUV lasers were reported by Rocca *et al.* [21] on neonlike argon at the wavelength of 46.9 nm using a high-power capillary discharge and by Lemoff *et al.* [22] on palladiumlike xenon at 41.8 nm driven by a 10-Hz Ti:sapphire chirped pulse amplification system with a pulse duration of approximately 40 fs.

Using a pump-laser energy of only 8 J high-gain lasing in neonlike titanium at the wavelength of 32.6 nm was reported recently by Nickels *et al.* [23]. A 1-ps short main pulse of 3-J energy was preceded by an 1-ns-long prepulse of 5-J energy. At the pump irradiance of ~1 PW/cm^2 a gain coefficient of 19 cm^{-1} was measured. Using a line focus of 5 mm length a total gain-length product of 9.5 was evaluated.

In this work we report on an experimental demonstration of $3p$-$3s$, $J=0$–1 soft-x-ray lasing at 28.5 nm in neonlike chromium using a compact Nd:glass-drive laser. Applying the prepulse technique at a fixed prepulse-to-main pulse energy ratio of 0.7% we demonstrate lasing on the 28.5-nm line at a pump energy of 82 J corresponding to an irradiance of 9 TW/cm^2. This represents, to our knowledge, the lowest pump irradiance for which soft-x-ray lasing at a wavelength shorter than 30 nm in a neonlike ion has been reported to date.

The experiments were performed using the tabletop Nd:glass laser of the Institut für Angewandte Physik at the University of Berne, which is capable of delivering up to 120 J at 1.054 μm with a pulse duration of 500 ps [full width at half maximum (FWHM)]. An actively mode-locked and Q-switched Nd:glass master oscillator is followed by a chain of five rod amplifiers with clear apertures increasing stepwise up to 90 mm. The host material is phosphate glass and the Nd doping is chosen between 3% and 0.7% with the lower

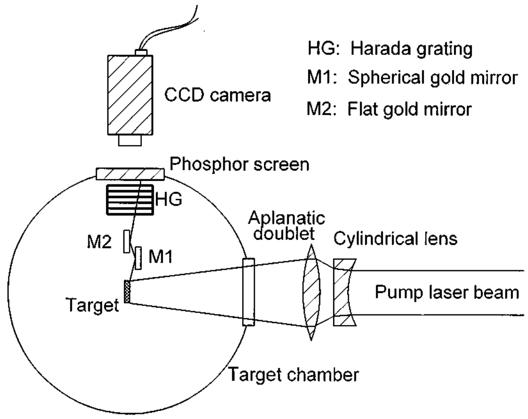

FIG. 1. Setup of the target chamber, the focusing optics, and the x-ray diagnostics used for the measurements.

values for the rods of higher diameter. The beam is expanded stepwise by a telescope and three spatial filters applying the image relay technique [24]. In front of the second amplifier an apodizing aperture is used in order to obtain a nearly rectangular intensity profile and a high-energy extraction efficiency at the end of the amplifier chain.

A line focus 2.5 cm long and approximately 80 μm wide is produced by using an aplanatic doublet with a focal length of 500 mm combined with a cylindrical lens with a focal length of -1700 mm. All the surfaces of the focusing optics are antireflection-coated and have a clear aperture diameter of 100 mm. The beam diameter is 85 mm. A defined prepulse of 0.7% at a constant delay of 5 ns is produced with the aid of an antireflection-coated beamsplitter in the beam path of the double-passed 90-mm amplifier. The spatial coincidence of the prepulse and the main pulse was adjusted to better than 10 μm, given by the resolution of the charge-coupled device (CCD) camera used for the adjustment. The energy of the main pulse was varied between 60 and 100 J by varying the gain in the amplifier rods. The laser irradiated 2.4-cm-long polished chromium slab targets with the line focus slightly overfilling the target on both sides for maximum uniformity [25].

The principal diagnostic used was a time-integrating, space-resolving spectrometer. The spectrometer consists of a 1200 grooves per mm, concave (radius of curvature: 5649 mm), Harada-type aberration-corrected reflection grating

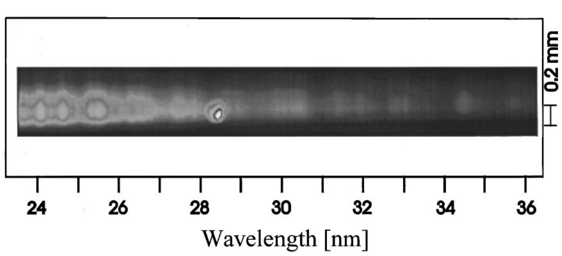

FIG. 2. One-dimensional space-resolved spectrum for a 2.4-cm-long chromium target. For this shot a 0.7% prepulse was used and the energy of the main pulse was 82 J. The $J=0\text{–}1$ lasing line at 28.5 nm is observed to dominate the spectrum. The wavelength axis is in the horizontal direction and covers the spectral region between 23 and 35 nm.

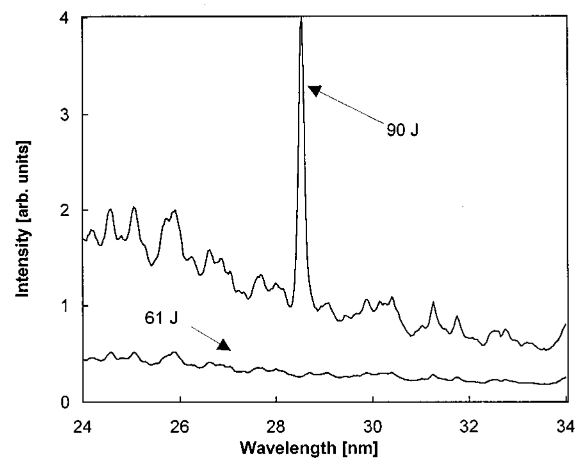

FIG. 3. Spectral scans along the wavelength axis for two different main pulse energies and a 0.7% prepulse.

[26], working at the grazing-incidence angle of 3°, and a 40-mm-diameter $P20$ phosphor screen coupled to a cooled CCD camera having a pixel size of 25×25 μm^2. The spectrometer looked axially onto one end of the plasma column with the spatial resolution in the direction perpendicular to the target surface. The one-dimensional spatial resolution, which was measured to be better than 25 μm, was realized by using a spherical gold mirror with a radius of curvature of 2 m, which was adjusted at a grazing-incidence angle of 5.5°. The mirror forms an image of the plasma column on the phosphor screen with a magnification of 3×. The diameter of the gold mirror is 30 mm and the acceptance angle of the spectrometer is 22 mrad. The grating disperses the incident radiation perpendicularly to the direction of the spatial resolution. The wavelength coverage was 12 nm with a spectral resolution of 0.2 nm. The experimental setup of the target chamber, the focusing optics, and the spectrometer are shown schematically in Fig. 1.

The measurements were performed with a fixed prepulse-to-main pulse energy ratio of 0.7% and without a prepulse. Without an intentional prepulse, lasing on the $3p\text{-}3s$,

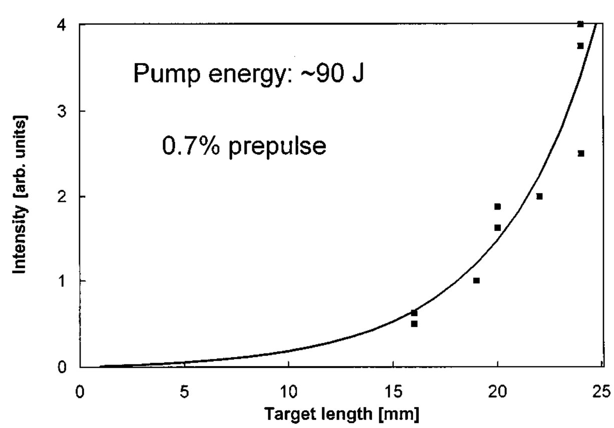

FIG. 4. Lasing intensities for the $J=0\text{–}1$ lasing line at 28.5 nm as a function of the target length for a drive laser energy of 90 ± 5 J and a 0.7% prepulse. A least-squares fit to the Linford-formula [27] yields a gain coefficient of 2.2 ± 0.5 cm^{-1} and is shown as a solid line.

$J=0$–1 line at 28.5 nm in neonlike chromium was not observed. Figure 2 shows a typical CCD image of a one-dimensional space-resolved spectrum for a 2.4-cm-long chromium target irradiated at a main pulse energy of 82 J. The wavelength axis is in the horizontal direction and the spatial resolution is given in the vertical direction. The $3p$-$3s$, $J=0$–1 lasing line at 28.5 nm is clearly seen in the spectrum that covers the wavelength range of 23–35 nm. The lasing line is emitted in an approximately 60-μm-wide plasma region (FWHM). The spatial resolution of the spectrum shows a considerable difference between the lasing line and other nonlasing lines.

In Fig. 3 intensity traces along the spectral coordinate are plotted for two different main pulse energies but the same prepulse-to-main pulse energy ratio of 0.7%. The scans are taken at the position of peak intensity of the x-ray lasing line. The 28.5-nm line is seen to dominate the spectrum at a pump energy of 90 J, corresponding to an irradiance of 10 TW/cm^2, whereas it is not observed at the lower-pump energy of 61 J. For a drive laser energy of 90 ± 5 J and a 0.7% prepulse, the intensity of the lasing line at 28.5 nm was measured for the different target lengths L between 1.6 and 2.4 cm. The experimental result is shown in Fig. 4. A least-squares fit to the Linford formula [27] gives a gain coefficient of $g=2.2\pm0.5$ cm^{-1} and is represented as a solid line in the figure. The total gain-length product is $gL=5.3\pm0.8$ and dividing by the pump laser power P a ‘‘gain-producing efficiency’’ of $gL/P=30$ TW^{-1} can be evaluated.

In summary, we have experimentally demonstrated $J=0$–1 soft-x-ray lasing at 28.5 nm in neonlike chromium. The prepulse technique was applied with a constant delay time of 5 ns between the 0.7% prepulse and the main pulse. Lasing with a gain coefficient of 2.2 ± 0.5 cm^{-1} was observed for a drive laser energy of $\sim$90 J, corresponding to a pump irradiance of 9 TW/cm^2. To our knowledge, this is the lowest pump laser energy reported to date for a neonlike soft-x-ray laser at a wavelength shorter than 30 nm. Further reduction of the drive laser energy may be possible, for example, by variation of the delay time between the prepulse and the main pulse and/or by using a series of pump laser pulses of shorter duration (multiple-pulse technique). The chromium laser is pumped with a very compact tabletop drive laser, which is capable of delivering a maximum of 120 J in 500 ps, and which can be operated by a single person. The total laser system and the target chamber including the diagnostics can be accomodated in a laboratory area of about 9×4 m^2.

The authors would like to thank Professor H. P. Weber for stimulating discussions and B. Locher for the chromium target preparation. This work was supported in part by the Swiss National Science Foundation.

[1] D. L. Matthews, P. L. Hagelstein, M. D. Rosen, M. J. Eckart, N. M. Ceglio, A. U. Hazi, H. Medecki, B. J. MacGowan, J. E. Trebes, B. L. Whitten, E. M. Campbell, C. W. Hatcher, A. M. Hawryluk, R. L. Kauffman, L. D. Pleasance, G. Rambach, J. H. Scofield, G. Stone, and T. A. Weaver, Phys. Rev. Lett. **54**, 110 (1985).

[2] T. N. Lee, E. A. McLean, and R. C. Elton, Phys. Rev. Lett. **59**, 1185 (1987).

[3] 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, Phys. Rev. A **42**, 6962 (1990).

[4] J. Nilsen, B. J. MacGowan, L. B. Da Silva, and J. C. Moreno, Phys. Rev. A **48**, 4682 (1993).

[5] J. Nilsen, B. J. MacGowan, L. B. Da Silva, J. C. Moreno, J. A. Koch, and J. H. Scofield, Opt. Eng. (Bellingham) **33**, 2687 (1994).

[6] J. Nilsen, J. C. Moreno, B. J. MacGowan, and J. A. Koch, Appl. Phys. B **57**, 309 (1993).

[7] J. Nilsen and J. C. Moreno, Opt. Lett. **19**, 1137 (1994).

[8] J. Nilsen and J. C. Moreno, Phys. Rev. Lett. **74**, 3376 (1995).

[9] Y. Li, G. Pretzler, and E. E. Fill, Phys. Rev. A **52**, R3433 (1995).

[10] Y. Li, G. Pretzler, and E. E. Fill, Phys. Rev. A **51**, R4341 (1995).

[11] Y. Li, G. Pretzler, and E. E. Fill, Opt. Lett. **20**, 1026 (1995).

[12] E. E. Fill, Y. Li, D. Schlögl, J. Steingruber, and J. Nilsen, Opt. Lett. **20**, 374 (1995).

[13] E. E. Fill, Y. Li, G. Pretzler, D. Schlögl, J. Steingruber, and J. Nilsen, Phys. Scr. **52**, 158 (1995).

[14] A. R. Präg, A. Glinz, J. E. Balmer, Y. Li, and E. E. Fill, Appl. Phys. B **63**, 113 (1996).

[15] J. Zhang, S. T. Chunyu, Y. L. You, Q. R. Zhang, S. J. Yang, W. Z. Huang, D. Y. Wu, X. Q. Zhuang, S. P. Liu, Y. Q. Cai, F. Y. Du, X. D. Yuan, X. F. Wei, Y. K. Zhao, H. S. Peng, and J. Nilsen, Phys. Rev. A **53**, 3640 (1996).

[16] M. Nantel, A. Klisnick, G. Jamelot, P. B. Holden, P. Jaegle, Ph. Zeitoun, G. Tallents, A. G. MacPhee, and C. L. S. Lewis, Opt. Lett. **20**, 2333 (1995).

[17] J. Warwick, C. L. S. Lewis, A. MacPhee, M. Holden, J. Krishnan, G. Tallents, P. Jaegle, G. Jamelot, A. Klisnick, M. Nantel, B. Rus, and Ph. Zeitoun, RAL Annual Report No. TR-95-025 1994–1995 (unpublished), p. 12.

[18] S. Basu, P. L. Hagelstein, M. H. Muendel, and S. Kaushik, Appl. Phys. B **57**, 303 (1993).

[19] P. L. Hagelstein, J. Goodberlet, M. Muendel, T. Savas, M. Fleury, S. Basu, and S. Kaushik, *4th International Colloquium on X-Ray Lasers, Williamsburg, 1994*, AIP Conf. Proc. No. 332 (AIP, New York, 1994), p. 41.

[20] J. Nilsen and J. C. Moreno, Opt. Lett. **20**, 1386 (1995).

[21] J. J. Rocca, V. Shlyaptsev, F. G. Tomasel, O. D. Cortazar, D. Hartshorn, and J. L. A. Chilla, Phys. Rev. Lett. **73**, 2192 (1994); J. J. Rocca, F. G. Tomasel, M. C. Marconi, V. N. Shlyaptsev, J. L. A. Chilla, B. T. Szapiro, and G. Giudice, Phys. Plasmas **2**, 2547 (1995).

[22] B. E. Lemoff, G. Y. Lin, C. L. Gordon III, C. P. J. Barty, and S. E. Harris, Phys. Rev. Lett. **74**, 1574 (1995).

[23] P. V. Nickles, M. Schnürer, M. P. Kalashnikov, I. Will, and W. Sandner, Proc. SPIE **2520**, 373 (1995).

[24] J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, Appl. Opt. **17**, 2052 (1978).

[25] A. Glinz and J. E. Balmer, Opt. Commun. **111**, 285 (1994).

[26] T. Kita, T. Harada, N. Nakano, and H. Kuroda, Appl. Opt. **22**, 512 (1983).

[27] G. J. Linford, E. R. Peressini, W. R. Sooy, and M. L. Spaeth, Appl. Opt. **13**, 379 (1974).