High-gain x-ray lasing at 11.1 nm in sodiumlike copper driven by a 20-J, 2-ps Nd:glass laser

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Evidence of high gain pumped by recombination has been observed in the $5g-4f$ transition at 11.1 nm in sodiumlike copper ions with use of a 20-J 2-ps Nd:glass laser system. The time- and space-integrated gain coefficient was $8.8 \pm 1.4\ \mathrm{cm}^{-1}$, indicating a single-transit amplification of ~60 times. This experiment has shown that 2 ps is the optimum pulse duration to drive the sodiumlike copper recombination x-ray lasing at 11.1 nm.

A major objective in the development of x-ray lasers is to reduce the drive energy to make these soft-x-ray sources widely available for use in applications. Recombination schemes operating with adiabatic cooling are, in this respect, in principle more favorable than collisionally pumped schemes in extending x-ray lasers to shorter-wavelength ranges because recombination schemes have a favorable scaling with wavelength and an intrinsically high quantum efficiency.[1–4] This is so because recombination schemes operate on transitions involving a change in principal quantum number. Systematic studies suggest that the interaction of picosecond laser pulses and fiber targets produces a rapid heating close to solid density, thus enhancing the adiabatic cooling during the following expansion phase. The rapid cooling[5,6] in turn leads to high gain in recombination lasers. There are reasons therefore to believe that it is possible to achieve high-gain operation of x-ray lasers with a considerably reduced drive energy by use of picosecond high-brightness laser pulses. Toward this goal, a series of experiments was conducted at the Rutherford Appleton Laboratory. A gain of $12.5 \pm 1.5\ \mathrm{cm}^{-1}$ was recently demonstrated on the hydrogenlike carbon 3–2 transition at 18.2 nm by use of 20-J 2-ps laser pulses focused on 7-μm-diameter carbon fibers.[7]

Lithiumlike and sodiumlike ions are analogous to hydrogenlike ions, having one electron in the outer atomic shell but one or two inner atomic shells, respectively. They have higher quantum efficiency than hydrogenlike ions. Amplification was observed for many transitions in both lithiumlike and sodiumlike ions when nanosecond driver pulses were used.[8,9]

With a view to a possible extension of the high-gain operation of recombination x-ray lasers to shorter wavelengths, we chose sodiumlike copper for the present investigation. We report here an observation of high gain at 11.1 nm in a sodiumlike copper recombination x-ray laser driven by 20-J, 2-ps high-brightness pulses from the chirped pulse amplification beam at the Vulcan laser facility.

The experiment was conducted with the Vulcan high-power Nd:glass laser. The Vulcan laser can be operated either in the normal mode, in which mode-locked pulses of 1-ns duration are amplified, or in the chirped pulse amplification mode, in which picosecond pulses from a separate oscillator are stretched and recompressed after amplification. In both cases the pulse-to-background intensity contrast ratio is better than 10^6.[10]

The laser pulses, with a maximum energy of 45 J, were focused with an $f/3$ off-axis parabola in conjunction with an $f/3$ off-axis spherical mirror to a line 7 mm long and 20 μm wide. Thus, for the 1-ns and 2-ps pulses, after a 50% reflection loss by the compression gratings and the focusing system, intensities

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of 1×10^{13} W/cm^2 and 5×10^{15} W/cm^2, respectively, were reached on the line focus.

The targets used in the experiment were copper-coated (thickness typically >300 nm) carbon fibers of 1-cm length and 7-μm diameter supported at one end. They were positioned to better than ± 2 μm spatial accuracy and ± 1 mrad angular accuracy by a split-field microscope system.[3,7] We placed the free end of the target well within the line focus to avoid creating a cold output end in the plasma and varied the irradiated length by moving the line focus axially along the fiber, which was always at the same location. The coating process frequently resulted in bending of the fiber targets, so only fibers with a deviation from straightness of <20 μm were used in the experiment.

Two soft-x-ray spectrometers viewed the line plasma in the axial direction along the line from both sides as primary diagnostics. One of the spectrometers was a flat-field grazing-incidence soft-x-ray spectrometer with a 1200-line/mm aperiodically ruled grating. It recorded the spectral range from 5.0 to 30.0 nm on an x-ray-sensitive phosphor screen coupled to a charge-coupled device. Spatial resolution in the spectra was provided by two cylindrical mirrors, which imaged the fiber end onto the detector plane of the spectrometer, giving $\sim$40-μm resolution along the direction of the incident laser beam at 2$\times$ magnification.[11] The other spectrometer was a 5000-line/mm transmission grating, which covered the spectral range from 3.0 to 50.0 nm. These spectra were recorded on Kodak 101-05 plates. The evaluation of the spectra was carried out with a digital densitometer. The densitometer yields time-integrated spectra with a spatial resolution of $\sim$0.05 nm.

The length and the spatial homogeneity along the length of the irradiated fibers were monitored by means of an x-ray pinhole camera, which was filtered to see $h\nu \sim 500$ eV and viewed the line focus at 45 deg from above. A falling of x-ray output along the line focus was observed toward the output end of the plasma because of the geometry and the beam intensity profile with an intensity ratio of $\sim 1:0.7$. A KAP crystal spectrometer was also used at 45 deg to the fiber axis to measure the ionization balance of the plasma.

A series of spectra from the on-axis flat-field spectrometer is shown in Fig. 1. The spectra correspond to three irradiated lengths of copper fiber. The lower spectrum is from a 2.3-mm irradiated length of copper fiber. In the middle is a spectrum from a 3.3-mm-long copper-fiber plasma. The upper one is from a 4.6-mm irradiated length of copper fiber. In these spectra, only the dominating $5g-4f$ line emission at 11.1 nm was observed. This is in contrast to steady-state ablation from either fiber or slab targets with long-pulse (nanoseconds) drive lasers where many other sodiumlike lines [e.g., $5g-4f$, $5f-4d$, $6g-4f$, and $6f-4d$ in Fig. 2(a)] are present. The irradiated intensity on fibers for the data in Fig. 1 was $\sim 5 \times 10^{15}$ W/cm^2. There are mainly neonlike resonance lines and only comparatively weak fluorine-like and oxygenlike lines in the resonance line spectra recorded with a crystal spectrometer. This plasma ionization is close to the optimum condition for the sodiumlike copper recombination lasing according to our simulations.

Extensive simulation was carried out with a one-dimensional Lagrangian hydrodynamic code, MEDUSA, coupled to an atomic physics code for study of the behavior of the fiber targets under irradiation. The code was used in cylindrical geometry to describe the recombination laser gain for fiber targets, and it was tested in predicting the performance of experimental targets in several previous investigations.[3,7,12] The modeling predicted an electron temperature of 12.1 eV and an electron density of 2.0×10^{18} cm^{-3} at 70 ps after the drive laser pulse when the gain on the $5g-4f$ transition reached its maximum value of 12 cm^{-1} at 80 μm from the target surface in the expanding plasma.

There is a clear difference between the spectra produced by 2-ps pulses [Figs. 1 and 2(b)] and the spectrum produced by 1-ns pulses [Fig. 2(a)], with a significantly higher ratio of continuum to line emission in the 2-ps spectra. Short picosecond laser pulses can heat targets significantly before any expansion occurs, generating plasmas at densities close to solid density, in contrast to the interaction of nanosecond-long pulses with targets for which the main heating occurs at densities close to the critical density.

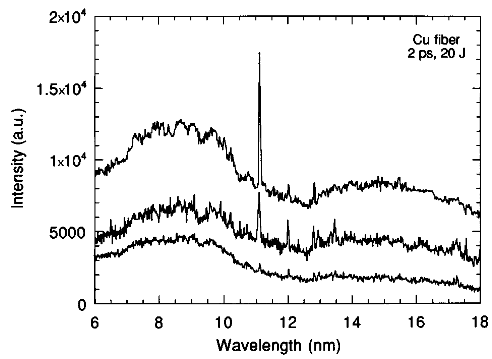

Fig. 1. On-axis spectra of the copper-fiber target with 2.3-mm (lower spectrum), 3.3-mm (middle one), and 4.6-mm (upper spectrum) lengths irradiated by 20-J 2-ps laser pulses at 5×10^{15} W/cm^2.

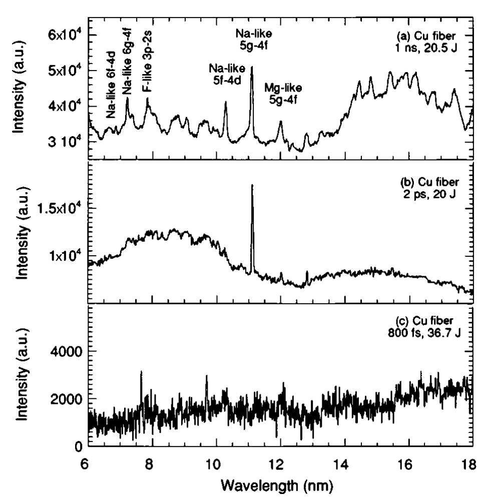

Fig. 2. (c) Axial copper-plasma spectrum generated by 20-J drive energy in 800-fs pulses in comparison with those generated by (b) 2-ps and (a) 1-ns pulses.

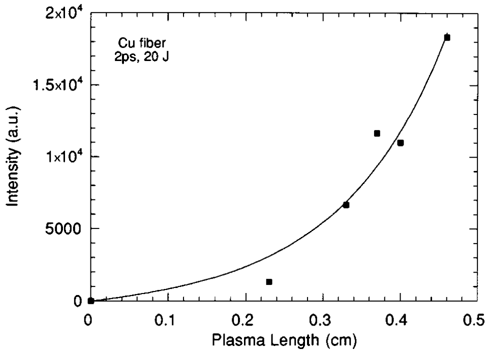

Fig. 3. Fitted gain to the experimental data for the $5g-4f$ transition in sodiumlike copper ions by the Linford formula.

At short lengths the $5g-4f$ line transition is weak compared with the continuum background emission. The intensity of this line emission increases nonlinearly with the plasma length and becomes dominant in the spectra for longer targets, giving a strong indication of stimulated emission on the $5g-4f$ transition. The results of these measurements of the $5g-4f$ lasing emission are plotted in Fig. 3. The gain coefficient was estimated by least-squares fitting of the Linford formula[13] to the data, giving 8.8 ± 1.4 cm^{-1}, corresponding to a maximum single-transit gain of 60 times on the $5g-4f$ transition at 11.1 nm for a 4.6-mm-long plasma. The reasons that the $5f-4d$ line emission at 10.3 nm was not amplified are still under investigation.

We fabricated the fiber targets by thermal coating 7-μm-diameter carbon fibers with a layer (thickness > 300 nm) of copper. The maximum single-transit gain was limited mainly by the constraints imposed by the available length of straight copper-coated fibers. The coating process frequently resulted in bending of the fiber targets, and, as a result, the longest straight copper-coated fibers were limited to 5 mm. However, after the experiment we found that longer straight copper-coated fibers could be manufactured by sputtering cold-copper ions into the surface of carbon fibers. A further experiment using longer fiber targets is being planned.

Recombination lasers operating with adiabatic cooling require an expansion rate as rapid as possible but with sufficient time for ionization to take place. These requirements in principle define an optimum pulse duration for high-gain operation of recombination lasers.[5–7] To investigate this issue further we made a comparison experiment with different pulse durations. Figure 2(c) shows a spectrum of copper plasma generated by 800-fs laser pulses compared with those driven by 2-ps [Fig. 2(b)] and 1-ns [Fig. 2(a)] pulses, respectively, with similar energies. The nanosecond and picosecond spectra show that essentially the same ionization stages are reached, with sodiumlike recombination lines giving the strongest emission. However, the plasma generated by 800-fs pulses shows only weak lines from lower ionization stages. Similar phenomena were observed for hydrogenlike carbon plasmas, for which 2-ps pulses have been demonstrated to be the optimum duration for high-gain operation of the recombination x-ray lasing at 18.2 nm,[7] whereas the carbon plasma generated by 800-fs laser pulses did not produce any strong line emission. It is not clear at present whether reduced coupling to the target or insufficient time for ionization or difference in cooling rate of the plasma is responsible for the absence of lasing with 800-fs pulses. The experimental facts are, however, definite.

In conclusion, we have observed evidence of high-gain operation on the $5g-4f$ transition at 11.1 nm in sodiumlike ions driven by 20-J 2-ps laser pulses. It has been shown that a 2-ps pulse duration is nearly optimum to drive sodiumlike recombination x-ray lasing at 11.1 nm.

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