Demonstration of Soft X-Ray Lasing with Neonlike Argon and Nickel-like Xenon Ions Using a Laser-Irradiated Gas Puff Target

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We report the first demonstration of soft x-ray amplification in an elongated plasma column produced by laser irradiation of a gas puff target. The gas puff target is formed by the pulsed injection of gas from a high-pressure solenoid valve through a nozzle in the form of a narrow slit. The plasma column to be used as an x-ray laser active medium is produced by irradiating the gas puff target with a high-power laser beam focused to a line. Lasing in neonlike argon at 46.9 nm and strong indications of lasing in nickel-like xenon at 10.0 nm were observed.

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Currently x-ray lasers operate with highly stripped ions in hot and dense plasmas produced by high-power laser pulses. The x-ray laser active medium has the form of an elongated plasma column with the cross section of about 100 μm and the length typically limited to a few centimeters by available laser power densities [1]. To allow propagation along a gain direction without substantial refraction of the x-ray laser beam associated with transverse gradients in the electron density, the electron density distribution must be kept as uniform as possible in the active medium. The plasmas produced by laser heating of solid targets have typically large gradients which result in severe refraction effects. Therefore, a number of methods for producing low-density gradients or for compensating the refraction have been applied in x-ray laser experiments. These include laser exploding foils [2], magnetically confined laser plasma [3], double target geometry [4], prepulse technique [5,6], and curved slab target [7]. The last two methods have caused a significant improvement in the performance of a soft x-ray laser in terms of the peak intensity and the beam divergence [8]. However, the further improvements in the pumping efficiency are still needed for the realization of x-ray lasers pumped with table-top, repetitive-operating laser systems [9–14].

In this Letter we present a new class of soft x-ray lasers in which an active medium in the form of an elongated plasma column is produced by laser irradiation of a gas puff target, instead of a solid. The gas puff target is obtained by pulsed injection of gas from a high-pressure reservoir through a nozzle into a vacuum chamber. The nozzle in the form of a long slit allows us to create an elongated gas puff suitable for production of an x-ray laser medium by its perpendicular irradiation with the use of a high-power laser beam focused to a line.

In previous experiments [15–17] using a circular nozzle, we have generated laser-produced plasmas with an electron temperature of 300 eV and electron densities of up to 10^{20} cm^{-3}. In these investigations it was shown that the plasma produced from a gas puff target differs substantially from the plasma produced after irradiation of a solid target. The strong density gradients, typical for plasmas from a solid, do not exist in the plasmas from a gas puff, resulting in a flat electron density profile. Another advantage of the gas puff target is the possibility of working at a high repetition rate and the absence of debris emitted from the laser-irradiated target.

For work related to x-ray lasers a high-pressure solenoid valve was developed, which has a nozzle in the form of a narrow slit [18]. By irradiation with line-focused high-power laser pulses homogeneous plasma columns up to 4 cm in length were generated with various gases [19,20]. X-ray laser experiments using Ar and Xe as target gases were carried out at Max-Planck-Institut für Quantenoptik using the Asterix IV iodine laser facility. The Asterix IV laser generates up to 600 J of light at 1.315 μm in a 450-ps pulse [21]. The laser output was focused to a 3-cm-long by 150-μm-wide line focus by a 30-cm-diameter cylinder lens array [22]. The laser beam irradiated gas puff targets created using a solenoid valve. The description of the valve and the results of the characterization of the created gas puff targets by means of optical interferometry and x-ray backlighting methods are given elsewhere [19]. The valve was charged with gas at a pressure up to 8 atm. Gas flowed from the valve through a 3-cm-long and 400-μm-wide sonic nozzle.

A simplified scheme of the experimental arrangement is shown in Fig. 1. The laser beam illuminated the target in the transverse direction with respect to the flow of gas. The laser focus position was placed about 200 μm above the nozzle output. The maximum gas pressure in the interaction region, roughly estimated from the optical interferometry measurements [19], was about 0.1 atm. The line focus was overfilling the target and,

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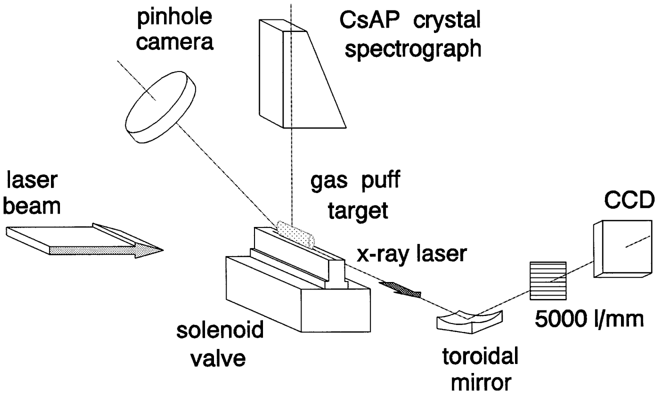

FIG. 1. Schematic of the experimental arrangement.

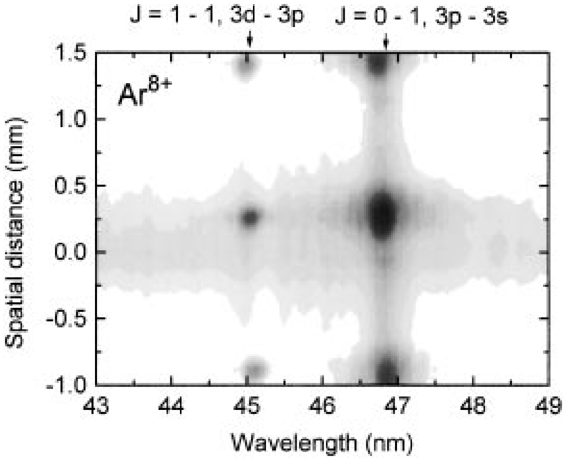

FIG. 2. A spatially resolved axial spectrum for the 2.7-cm-long plasma column produced as a result of irradiation of the gas puff argon target with 470 J laser pump energy.

thus, residual absorption in the cold gas did not occur. The principal diagnostic was a time-integrated, spatially resolved transmission grating spectrometer to measure soft x-ray emission in the axial direction from the plasma column. It was coupled to a thinned, backside-illuminated charge coupled device [23]. The spatial resolution in the direction perpendicular to the flow of gas was provided by a toroidal mirror. A 5000 lines per mm freestanding transmission grating with a 50-μm-wide slit dispersed the incident radiation perpendicularly to the spatially resolved direction. Using the instrument we could measure soft x-ray spectra in a wavelength up to 60 nm with a coverage of 7.2 nm, and a spectral resolution of about 0.15 nm. The grating has a supporting structure perpendicular to the grating bars with a period of 4 μm that disperses the incident emission along the spatial direction and generates a spurious spectrum which is represented by the two spots above and below the main spot in the vertical direction. To measure the exact length of the plasma column a pinhole camera with a pinhole of 50 μm in diameter was used. X-ray spectra in about the 1-keV energy range were measured by means of a CsAP flat crystal spectrograph with a 10-μm Be filter.

An example of the spatially resolved axial spectrum for the 2.7-cm-long plasma column produced after irradiation of the gas puff region target, with backing pressure in the valve of 5 atm, is shown in Fig. 2. A bright laser emission at 46.9 nm in neonlike argon on the $J = 0\text{-}1$, $3p\text{-}3s$ transition [24] is clearly seen. The argon laser spot is accompanied by the diffraction spots due to the grating support and the slit on top of the grating. The pumping energy in this shot was 470 J: however, the 46.9-nm line was seen even for about 100 J of pumping energy.

To estimate the gain coefficient, the length of the plasma column was varied by screening part of the incident pump laser beam. Figure 3 presents typical spectra for plasma columns 0.9, 1.8, and 2.7 cm long. A trace along the spectral direction was taken across the maximum of the laser line in Fig. 2. Figure 4 shows the intensities integrated over the linewidths of the $J = 0\text{-}1$ line of neonlike argon laser lines for three plasma column lengths. A fitting of the data of the Linford formula [25] gives a gain coefficient of 1.65 cm^{-1}, corresponding to

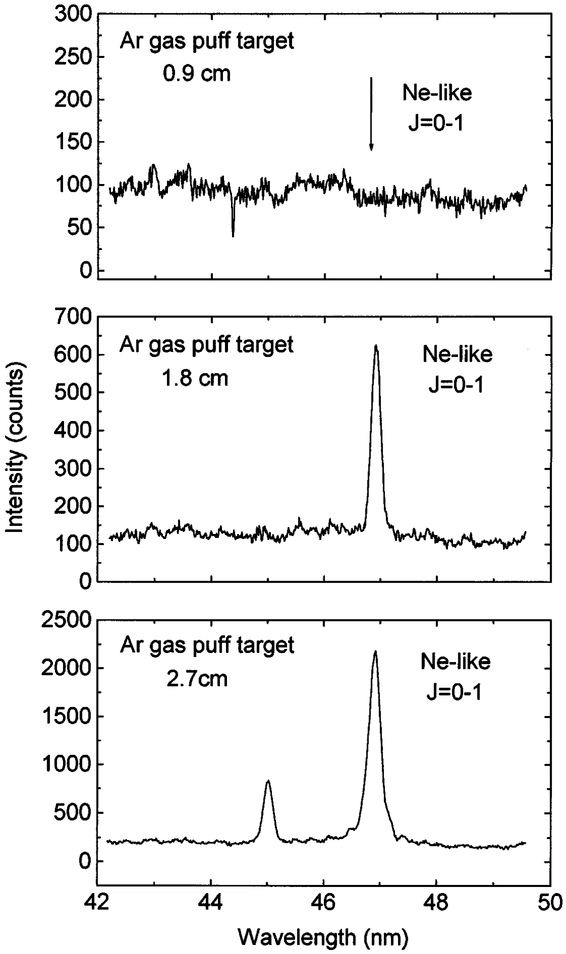

FIG. 3. Spectra for the laser-irradiated gas puff argon target under various plasma column lengths with the lasing line on the $J = 0\text{-}1$, $3p\text{-}3s$ transition in neonlike argon at 46.9 nm.

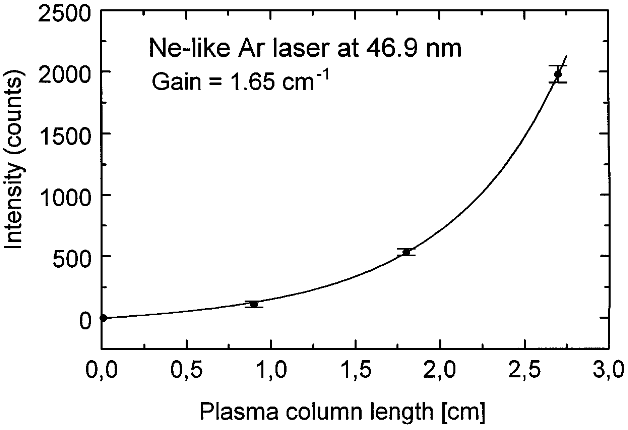

FIG. 4. Integrated line intensity of the $J = 0$-1 of neonlike argon as a function of the plasma column length. A fitting to the Linford formula [25] gives a gain coefficient of 1.65 cm^{-1}, corresponding to a gain-length product of 4.45.

a gain-length product of 4.45 for the 2.7-cm-long plasma column.

In the spectra obtained for the 2.7-cm-long plasma column, besides the main spectral feature, that is the $J = 0$-1 laser line at 46.9 nm, a strong line at 45.0 nm is clearly seen (see Fig. 3). This line was not observed for the shorter plasma columns. It was also weaker in the lower-irradiance shots and disappeared for the pump laser energy of about 200 J. Recently this line has been identified as the $3d$-$3p$ transition in neonlike Ar which would be expected to lase by a self-photopumping mechanism [26].

The observed lasing line in neonlike argon is the first demonstration of soft x-ray amplification in a plasma column produced from a laser-irradiated gas puff target. The lasing in neonlike argon at 46.9 nm has been recently observed in a capillary discharge-created plasma [27].

Turning now to the results with xenon, we show in Fig. 5 the spatially resolved axial spectrum for a 2.7-cm-long plasma column produced after irradiation of the gas puff xenon target. The pumping energy in this shot was 528 J, and the gas backing pressure in the valve was 8 atm. A strong line at 10.0 nm is clearly seen. A trace along the spectral direction across the maximum of this line is presented in Fig. 6. The x-ray spectral measurements in the 1-keV range have shown a strong M-shell emission of Ni-, Co-, Fe-, and Mn-like xenon ions from the plasma column, and one could expect lasing at 10.0 nm in nickel-like xenon on the $J = 0$-1, $4d$-$4p$ transition [28]. The x-ray lasing region for xenon is much narrower when compared to the argon laser. It is also slightly displaced from the center of the gas puff target, which is exhibited by the maximum of the background emission. Probably this is connected with the appropriate value of the plasma density along its spatial profile. This phenomenon has been observed recently in the case of neonlike lasers created using a laser-irradiated solid target [29]. Unfortunately, the reproducibility of the emitted intensity was rather poor and therefore a gain measurement could not be made. However, the small spatial extent of the emitting region gives strong evidence for lasing.

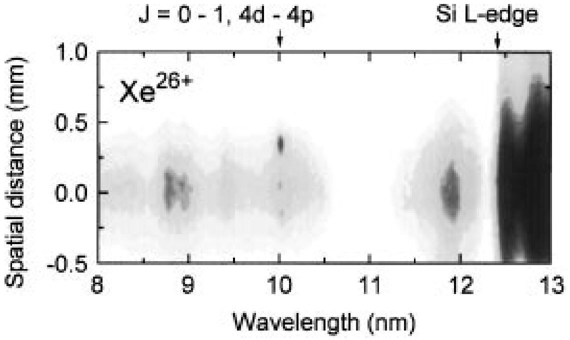

FIG. 5. A spatially resolved axial spectrum for the 2.7-cm-long plasma column produced as a result of irradiation of the gas puff xenon target with 528 J laser pump energy.

In conclusion, we have realized the first demonstration of soft x-ray amplification in an elongated plasma column produced by laser irradiation of a gas puff target. We observed lasing in neonlike argon at 46.9 nm with the $J = 0$-1, $3p$-$3s$ transition and strong indications of gain in nickel-like xenon at 10.0 nm with the $J = 0$-1, $4d$-$4p$ transition. We point out that these $J = 0$-1 lasers work without a prepulse, which proves that indeed the electron density gradient is the parameter controlling $J = 0$-1 lasing [28]. The laser-irradiated gas puff target is a novel method for producing an x-ray laser active medium, which provides a low electron density gradient, debris-free operation and the option of a high repetition rate.

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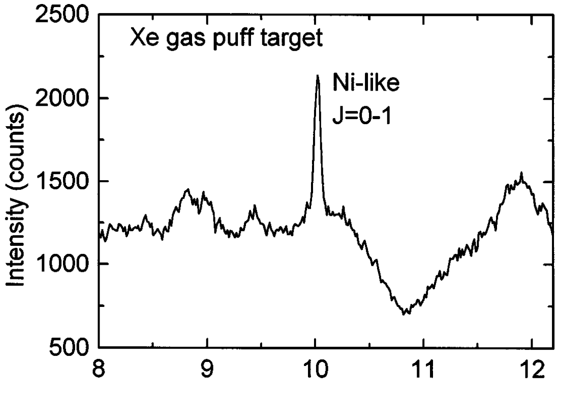

FIG. 6. Spectrum for the gas puff xenon target with lasing on the $J = 0$-1, $4d$-$4p$ transition in nickel-like xenon at 10.0 nm.

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