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# X-ray laser emission from a laser-irradiated gas puff target

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**Abstract.** The paper describes the research on soft X-ray lasers with an active medium created using a gas puff target irradiated with high-intensity laser pulses. The gas puff target in a form of an elongated gas sheet is produced by pulsed injection of gas through a slit nozzle using a high-pressure electromagnetic valve. The method of generation of soft X-ray lasers using a laser-irradiated gas puff target has been developed at the Institute of Optoelectronics. The collaborative experiments were performed at various laser laboratories using high-intensity laser systems to irradiate the gas puff target and pump the X-ray laser active medium. Results of these experiments are presented and discussed. Works aimed at increasing the efficiency of X-ray lasers using a longitudinally irradiated gas puff target are also reviewed.

**Key words:** X-ray lasers, laser-produced plasmas, X-ray optics, gas puff target.

## 1. Introduction

Soft X-ray lasers generating the quasi-monochromatic, partially coherent photon beams in the wavelength range shorter than a few tens of nanometer are being studied in many laboratories around the world. Since the first demonstration of X-ray lasing in 1985 [1,2], significant progress has been made in this field. Laser action has been observed at wavelength as short as 3.5 nm. Because of the extremely high single pulse spectral brightness soft X-ray lasers offer unique research possibilities and many applications [3].

The X-ray laser action is realized in a highly ionized plasmas. Soft X-ray lasers operate as simple amplifiers of spontaneous emission in a hot elongated plasma column with the length from a few millimetres to a few centimetres and about 100 μm in diameter. The plasma column is usually obtained by irradiation of an appropriate target with a high-intensity laser beam focused to a line, however, a high-current plasma discharge can be used as well [4]. X-ray laser physical background and basic techniques are discussed in a book by Elton [5] and more recently – in a review paper by Tallents [6]. Detailed information on research on X-ray lasers during last years can be found in the proceedings of the biennial International Conference on X-ray Lasers [7–14].

Two principal schemes of excitation of an X-ray laser are used. In the collisional excitation scheme either neon-like or nickel-like ions are excited from the ground state ($2p$ for neon-like or $3d$ for nickel-like ions) to the laser upper levels ($3p$ or $4d$, respectively). As the laser lower levels ($3s$ or $4p$) are radiatively coupled to the ground state, they are depopulated by resonance emission and population inversion between $3p$–$3s$ or $4d$–$4p$ is created.

X-ray laser action in the recombination scheme requires a hot plasma, that contains highly ionized bare nuclei or helium-like ions. Rapid cooling during the hydrodynamic expansion of the plasma causes fast recombination, that leads to the population of excited states of hydrogen-like or lithium-like ions. The first excited state is depopulated by resonance emission giving population inversion between the first and higher excited states. Typical temperatures of plasmas to obtain population inversion of highly charged ions are several hundred eV for the collision excitation scheme and several tens of eV for the recombination one. To heat plasmas to such temperatures power density of laser radiation at the target should exceed $10^{13}$ Wcm$^{-2}$ in the case of the collision scheme, and $10^{12}$ Wcm$^{-2}$ in the case of the recombination scheme.

In the early X-ray laser experiments single nanosecond laser pulses were used to form the elongated plasma column and pump the active medium. It caused that large laser facilities, to be able to produce subnanosecond laser pulses of energy in the range of several hundred J up to several kJ, were required to pump X-ray lasers [3], making strong limitation of the studies. Significant progress towards the realization of a laser-driven table-top X-ray laser has been achieved during the last few years using different variants of the prepulse technique [15–19]. In this technique a solid target is irradiated with several laser pulses. The first pulse is used to create a large-scale length plasma, which has the appropriate density range for gain and sufficiently small density gradients for laser propagation. The subsequent pulses can be absorbed more efficiently and heat the preformed plasma to lasing conditions. Efficient, high-brightness soft X-ray lasers with neon-like and nickel-like ions have been demonstrated at wavelengths between 87 nm and 5.9 nm [20–23]. Saturated amplification in nickel-like palladium at pump

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energies below 30 J was obtained [24]. In the above technique the pulse duration is held constant and ranges from 75 ps to 1 ns.

Further reduction of the pump energy can be achieved using a transient gain scheme proposed theoretically some time ago [25,26]. In this scheme the first pulse is usually a long, nanosecond laser pulse that produces a preformed plasma, whereas the second pulse is a short, picosecond's pulse that heats the preformed plasma to produce a large transient population inversion. The separation time between these two pulses is about 1 ns. The advantage of this scheme is that less than 10 J of laser energy from a tabletop laser generating picosecond's high-power laser pulses with a chirped-pulse amplification (CPA) is sufficient for lasing. The first transient gain X-ray laser was demonstrated at 32.6 nm in neon-like titanium at the Max-Born-Institute [27]. Lasing with nickel-like palladium ions at 14.7 nm has been observed at Lawrence Livermore National Laboratory [28]. Saturated operation of transient gain X-ray lasers was demonstrated for both neon-like [29] and nickel-like ions [30] with low pump energy. X-ray lasing with nickel-like silver ions has been demonstrated for pumping with a single picosecond's pulse of less than 1 J of energy [31].

Quite recently, a new scheme of grazing incidence pumping (GRIP) was proposed. In this scheme a preformed plasma column, produced by a longer (nanosecond) pulse at normal incidence onto a target, is pumped by focusing the short (picosecond's) pulse at a determined grazing incidence angle to the target. It makes that the pump laser path is longer and an increase in the laser absorption in the gain region can be obtained. Additionally, there is an inherent travelling wave, close to c, that increases the pumping efficiency. Using the GRIP scheme a 10 Hz X-ray laser operating at 18.9 nm pumped with a sub-J pulse from a Ti:Saphire laser has been demonstrated [32,33]. Strong lasing at 18.9 nm was also observed using the longitudinal pumping of the active medium at 10 Hz repetition rate [34]. These approaches open the way for a practical table-top soft X-ray laser suitable for various applications.

In this paper we present investigations on soft X-ray lasers generated by laser irradiation of a gas puff target, instead of a solid one. The gas puff target in a form of an elongated sheet of gas is created by pulsed injection of gas from a high-pressure solenoid valve through a narrow slit nozzle. The method of X-ray laser active medium formation has been developed at the Institute of Optoelectronics [35]. A fundamental difference when using the gas puff compared to solid targets is that the gas puff target is providing the gain medium at a density closer to the lasing conditions. The laser-plasma coupling is also much different as compared to a solid since the plasma is starting below its critical density. The gas puff provides better control over the density and minimizes gradients in the plasma. Additionally, the use of a gas puff instead of a solid target offers the advantage of developing a high repetition rate X-ray laser with no target debris production.

This paper reviews the works on soft X-ray lasers based on a laser-irradiated gas puff target, concentrating on the recent experiments with the picosecond-laser-irradiated gas puff target. The X-ray laser experiments were performed at various laser laboratories abroad using laser systems generating high-intensity pulses to irradiate the gas puff target and pump the X-ray lasers. In the experiments high-pressure electromagnetic valves to produce gas puff targets, developed and characterized at the Institute of Optoelectronics, were used. Section 2 will present the collaborative experiments on the collisionally excited nanosecond-pulse-laser pumped X-ray lasers performed at the Max-Planck-Institute of Quantum Optics in Garching, Germany, and at the Ecole Polytechnique in Palaiseau, France. Section 3 will describe the experiments on the transient gain X-ray lasers with a picosecond-laser-irradiated gas puff target performed at the Lawrence Livermore National Laboratory in Livermore, USA and the Advanced Photon Research Center JAERI in Kyoto, Japan. Finally Section 4 describes future plans to increase the efficiency of X-ray lasers based on a laser-irradiated gas puff target by using the longitudinal and the GRIP pumping schemes.

## 2. Electron collisional excitation soft X-ray lasers with a nanosecond-laser-irradiated gas puff target

X-ray laser experiments with the use of the gas puff target were performed at the Max-Planck-Institut für Quantenoptik in Garching, Germany and at the Ecole Polytechnique in Palaiseau, France. Scheme of the experimental arrangement used at Garching is shown in Fig. 1.

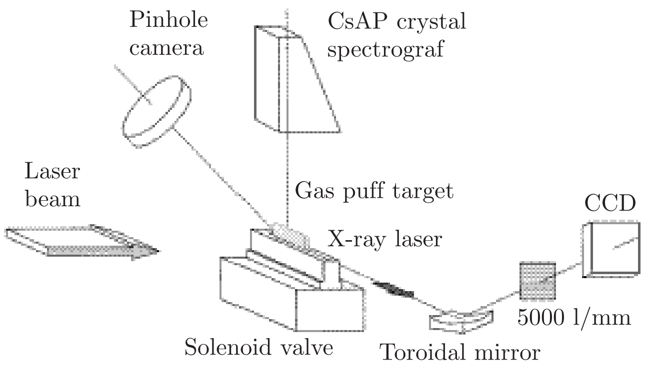
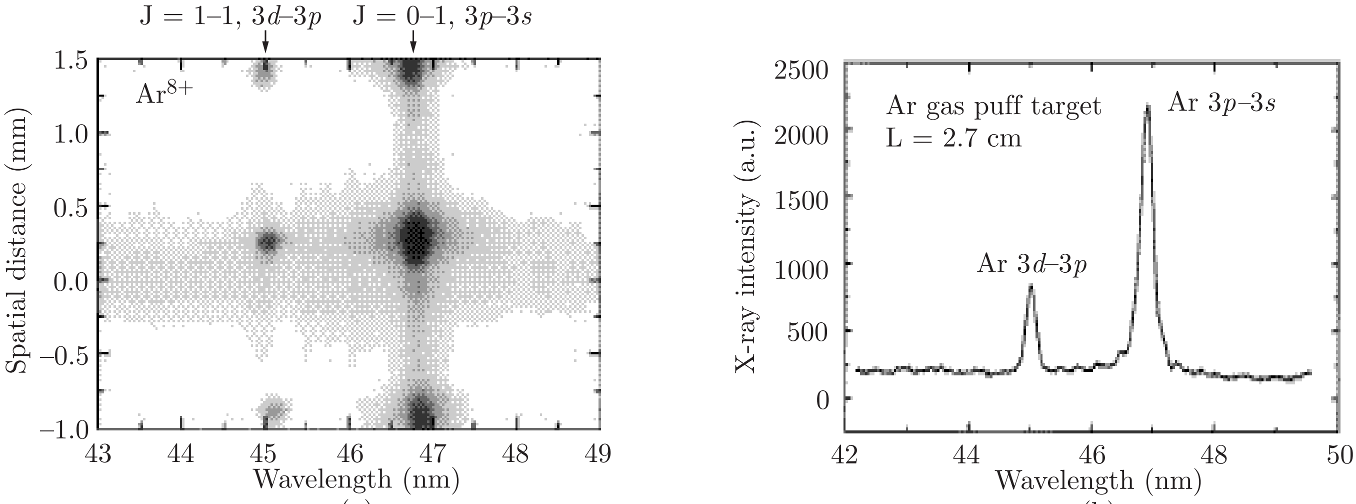


Fig. 1. Schematic of the experimental arrangement at the MPQI, Garching to study soft X-ray lasers produced with a laser-irradiated gas puff target

The gas puff targets, produced by means of a solenoid valve, were characterized with optical and X-ray backlighting methods. To irradiate a gas puff target a high-power iodine laser system Asterix IV was used [36]. The formation of plasma columns up to 3-cm long has been



(a) (b)

Fig. 2. Spatially resolved axial spectral image (a) and the corresponding spectral distribution (b) for the 2.7-cm-long plasma column produced as a result of irradiation of the argon gas puff target with 470 J laser pump energy

investigated using X-ray pinhole imaging and X-ray crystal spectroscopy. Soft X-ray emission from the column in axial direction was measured with two transmission grating spectrometers coupled to the CCD camera and to the X-ray streak camera. The detailed description of the experimental arrangement is given elsewhere [37].

Typical example of the spatially resolved axial spectral image for the 2.7-cm-long plasma column produced after irradiation of the argon gas puff target, with backing pressure in the valve of 5 bar, is shown in Fig. 2a. The corresponding spectral distribution of emission is presented in Fig. 2b. A bright laser emission at 46.9 nm in neon-like argon on the $3p^1S_0 \rightarrow 3s^1P_1$ transition is clearly seen. The laser pumping energy in this shot was 470 J, however, the 46.9 nm line was seen even for about 100 J of pumping energy. The gain coefficient for this laser line, measured by varying the length of the plasma column was 1.65 cm$^{-1}$, corresponding to a gain-length product of 4.45 for the 2.7-cm-long plasma column [38]. In the spectra obtained for the argon plasma, besides the main spectral feature at 46.9 nm, a strong line at 45.0 nm was observed. This line has been identified as the $3d^1P_1 \rightarrow 3p^1P_1$ transition in neon-like argon which lasing by a self-photopumping mechanism [39].

In the case of the xenon gas puff targets strong indication of lasing on $4d$–$4p$ transition for nickel-like ions at 10.0 nm was observed [38]. Unfortunately, the reproducibility of the laser line intensity was rather poor and therefore a gain measurements could not be made. Soft X-ray lasing with nickel-like xenon ions has been studied in the experiments performed at the Ecole Polytechnique in Palaiseau using the high-power Nd:glass LULI laser to irradiate the gas puff target. The energy of the laser pulse was about 400 J. The parameters of the plasma column created from a gas puff target irradiated with the LULI laser were determined using the X-ray spectroscopy methods. Soft X-ray lasing with nickel-like xenon ions at two lines near 10 nm was observed and their wavelengths were, for the first time, precisely measured [40].

## 3. Transient gain soft X-ray lasers using a picosecond-laser-irradiated gas puff target

**3.1. Soft X-ray lasers with neon-like argon ions.** The experiment has been performed at the Lawrence Livermore National Laboratory in Livermore, USA using the Compact Multipulse Terawatt (COMET) laser system [41,42]. The gas puff target was formed using a solenoid valve developed and characterized at the Institute of Optoelectronics. The used valve, presented in Fig. 3a, is similar to that described in [43–45]. It was equipped with a 0.9 cm long nozzle with a 500 μm wide slit. Argon gas was used to form the gas puff targets. The valve is able to form gas puff targets with 1 Hz repetition rate, however, a new design of the valve can operate up to 100 Hz. In the experiment single shot measurements were performed because the COMET laser fires once every 4 minutes.

Two laser pulses of time duration 0.6 ns and 6 ps with a total energy of 10 J, were focused onto an elongated, sheet-like gas puff target of the maximum length of 0.9 cm. The laser beams illuminated the target in the transverse direction with respect to the flow of gas. The line focus with length of 1.6 cm was achieved by using a cylindrical lens in combination with an on-axis paraboloid. The target was irradiated using the travelling wave geometry. The line foci overfilled the target to avoid absorption of X-rays in the cold gas. The length of the plasma column was changed by blocking part of gas puff from being irradiated. The distance between the foci and the nozzle output and the best-focus position in respect to the nozzle axis were adjusted to optimize the X-ray laser output.

We also changed the tilt angle between the nozzle and the line foci by rotation of the valve. The gas puff target were characterized using X-ray backlighting technique [43,45]. The typical gas density profiles are shown in Fig. 3b. The maximum gas density in the interaction region was about 4 mg/cc for a gas backing pressure in the valve of 10 bar and a valve time delay of 300 µs between the opening of the valve and the laser pulse. The gas density in the interaction region could be controlled by changing the valve time delay. The soft X-ray spectrometer equipped with a variable-spaced flat-field grating and a CCD camera was used to measure X-ray laser spectra along the axis of the line focus. Additionally, the plasma column was imaged using a X-ray camera with two crossed slits. The details of the experimental setup are given elsewhere [46–49].

Soft X-ray lasing with neon-like argon ions, and strong amplification both on the $3p$–$3s$ transition at 46.9 nm and the $3d$–$3p$ transition at 45.1 nm was demonstrated with gain coefficients of 10.6 $\mathrm{cm}^{-1}$ for both lines on a target length of 0.9 cm [46]. A typical on-axis spectrum of the argon soft X-ray laser is presented in Fig. 4a. The laser energy in this shot was 3.84 J for the long pulse and 6.26 J for the short pulse. The separation time between laser pulses was 1 ns, and the line foci were placed at 150 µm above the nozzle output. The output of both lines was stable and reproducible as a result of optimizing the experimental conditions. Under the optimum conditions a gain measurements have been performed by blocking part of the laser beams on the target to shorten the length of the plasma column.

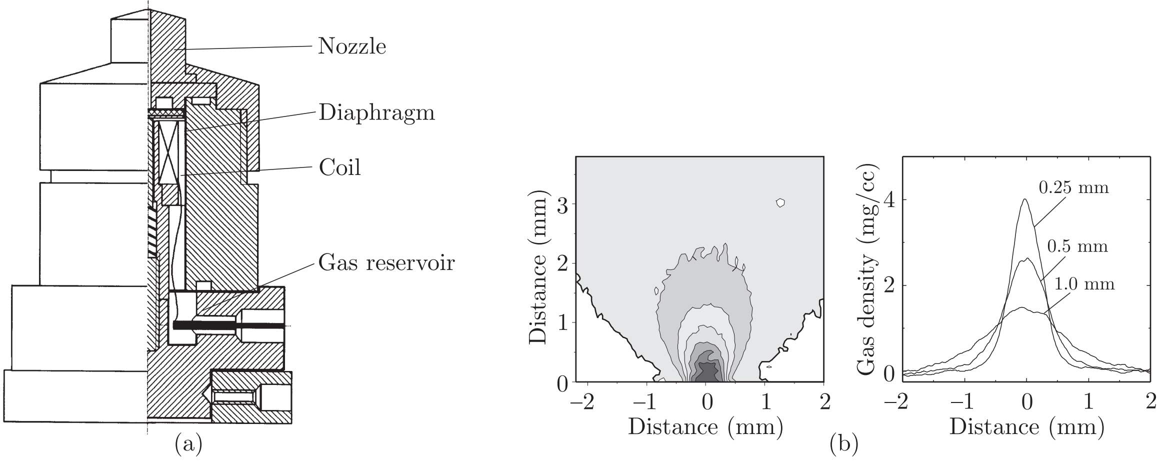


Fig. 3. Schematic of the solenoid valve developed at the Institute of Optoelectronics to form elongated gas puff targets for laser-driven soft X-ray lasers (a), and typical gas density profiles for the krypton gas puff target measured using X-ray backligthing technique (b)

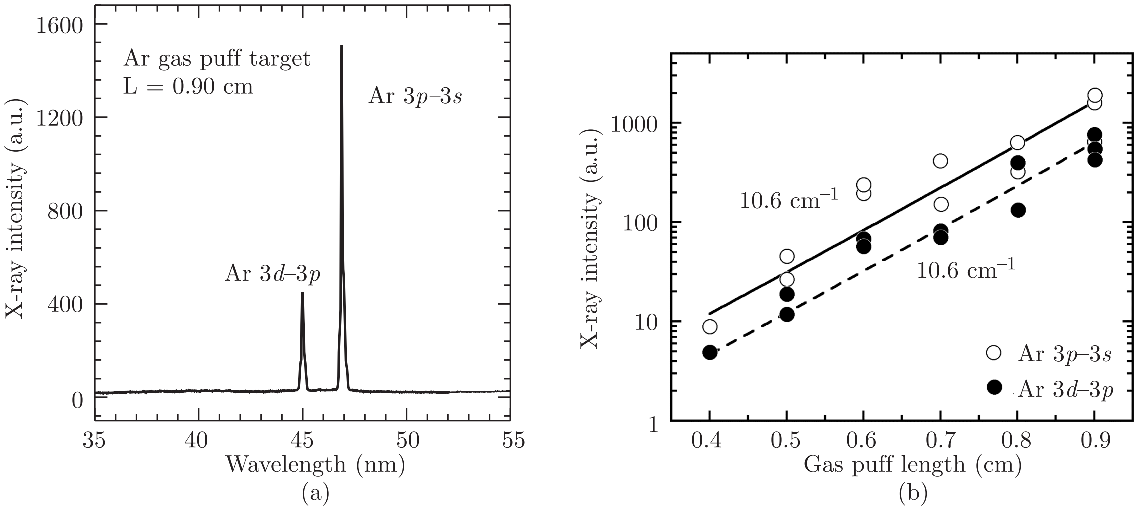


Fig. 4. Results of X-ray argon laser measurements: on-axis spectrum of a 0.9-cm-long argon gas puff target irradiated with a 3.84 J, 600-ps FWHM pulse followed by a 6.26 J, 6-ps pulse showing two lasing lines: the collisionally excited $3p^1S_0 \rightarrow 3s^1P_1$ laser line at 46.9 nm and the self-photopumped $3d^1P_1 \rightarrow 3p^1P_1$ laser line at 45.1 nm (a), Neon-like argon $3p^1S_0 \rightarrow 3s^1P_1$ (open circles) and $3d^1P_1 \rightarrow 3p^1P_1$ (closed circles) X-ray laser line intensity versus length of the plasma column (b). Fits to the Linford formula are shown by the solid and dashed lines. The fitted gain coefficients are 10.6 $\mathrm{cm}^{-1}$ for both lines

The intensity of the X-ray laser lines versus the plasma column length is shown in Fig. 4b. Using the Linford formula [50], a gain coefficient of 10.6 $cm^{-1}$ for both laser lines was determined.

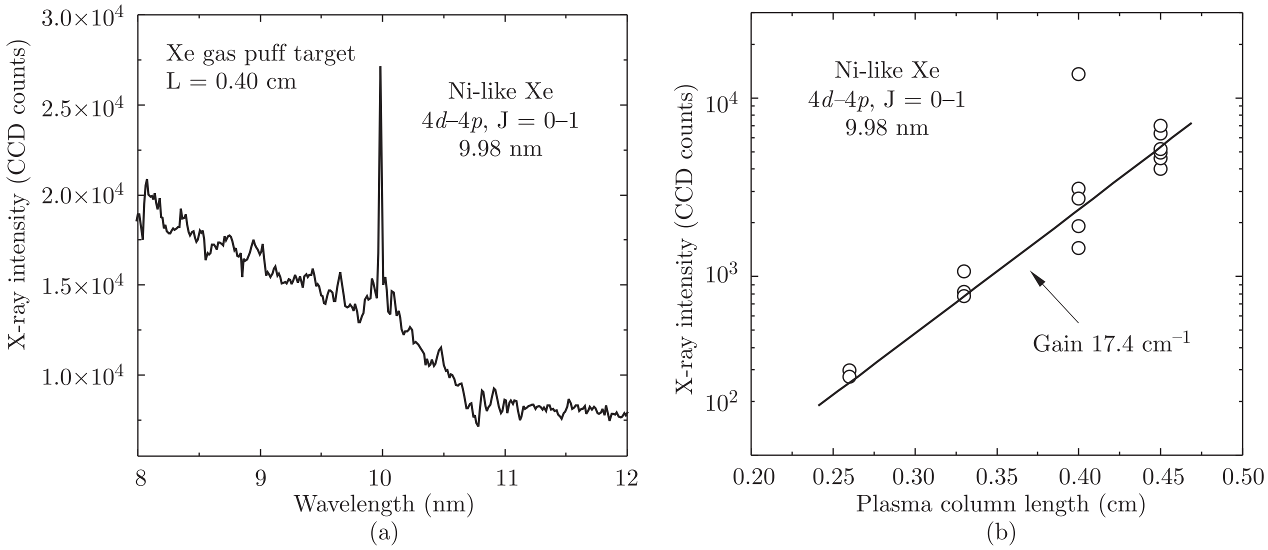
Spectral and spatial characteristics of the X-ray laser beams have been measured for various parameters of the gas puff targets and the pumping laser pulses [47,49]. The beam divergence was measured to be 9–12 mrad (FWHM), containing narrow 1.2–3.0 mrad (FWHM) features [49]. Experiments with a gas puff target up to 2-cm-long are planned in the near future and demonstration of a saturated soft X-ray laser with neon-like argon ions is expected. The intensity of the self-photopumped $3d$–$3p$ laser line at 45.1 nm was generally 0.35–0.6 the intensity of the collisionally excited $3p$–$3s$ line at 46.9 nm. However, for some conditions we observed the $3d$–$3p$ laser line to be more intense than the $3p$–$3s$ line. This suggests that the neon-like $3d^1P_1 \rightarrow 3p^1P_1$ laser line could become the dominant line under suitable plasma conditions [51,52].

A soft X-ray laser with neon-like argon has been also demonstrated at the Advanced Photon Research Center JAERI in Kyoto, Japan using the same type of gas puff target irradiated with two picosecond laser pulses of a total energy of 9 J [53]. A higher gain coefficient of 18.7 $cm^{-1}$ and a narrower beam divergence of less than 3.7 mrad was measured for the $3p$–$3s$ transition at 46.9 nm with gas puff targets up to 0.45 cm long. Additionally, the $3d$–$3p$ line at 45.1 nm was not observed. A possible explanation of the differences between these two experiments can be connected to the larger than expected deflection angle of $\sim$ 26 mrad for the X-ray laser beams presumably due to refraction of the X-rays in a higher density plasma column. Indeed, when the X-ray output measurements for the 0.9 cm long plasma column are neglected, the estimated gain coefficient for the shorter column will be similar for both experiments. This subject has been discussed in a previous paper [54], however, more precise measurements of the gas density and the plasma density profiles as well as detailed studies of laser gas puff coupling are required to give better insight into the amplification process.

### 3.2. Soft X-ray lasers with nickel-like xenon ions.

The nickel-like xenon ion X-ray laser using a picosecond-laser-irradiated gas puff target was demonstrated for the first time in the experiments performed in Kyoto [55]. The experimental setup is the same as in the previous experiments on neon-like argon lasers. In the experiment two 3 ps laser pulses with a total energy of 18 J were used to create soft X-ray lasing in xenon gas puff targets. The energy ratio of the prepulse to the main pulse was approximately 1:8. The line focus was with a length of 0.55 cm and width of 20 μm. The results of the experiments are shown in Fig. 5.

Typical axial spectrum for the laser-irradiated xenon gas puff target with a plasma column length of 0.40 cm are presented in Fig. 5a. Strong X-ray lasing line on the transient collisionally excited $(3d_{3/2}, 4d_{3/2})_0 - (3d_{5/2}, 4p_{3/2})_1$ transition at 9.98 nm is clearly seen for nickel-like xenon ions. Figure 5b shows the line intensity versus plasma column lengths for both lasing lines. The data points were obtained under the conditions of total driving laser energy of 18.0 ±2.0 J. Using the Linford formula [50], gain of 17.4 ±2.7 $cm^{-1}$ for the strong nickel-like xenon lasing line at 9.98 nm was measured for target lengths up to 0.45 cm.



(a) (b)

Fig. 5. Results of X-ray xenon laser measurements: on-axis soft X-ray emission spectrum for a 0.40-cm-long xenon gas puff target irradiated with a 2 J, 3 ps prepulse followed by a 16 J, 3 ps main pulse showing the strong collisionally excited nickel-like xenon $4d$–$4p$, J = 0–1 lasing line at 9.98 nm (a), X-ray laser intensity versus length of the plasma column for nickel-like xenon X-ray laser line (b). Fits to the Linford formula is shown by the solid line. The fitted gain coefficient is 17.4 ±2.7 $cm^{-1}$

## 4. High-density double-stream gas puff target for X-ray laser experiments

To improve the soft X-ray lasers a new gas puff target for experiments on laser-driven X-ray lasers was developed. The target is based on a double-stream gas puff target approach [56] and is formed by pulsed injection of active gas through the central nozzle in a form of a slit, which is surrounded with an additional outer nozzle. The outer nozzle is supplied with light gas. The stream of active gas injected through the central nozzle is confined by the outer stream of light gas, thus the central stream poses high density of gas at relatively large distance from the nozzle output. It allows efficient absorption of laser radiation in the plasma. Moreover, the central stream has a steep density gradient, which is advantageous for X-ray laser experiments.

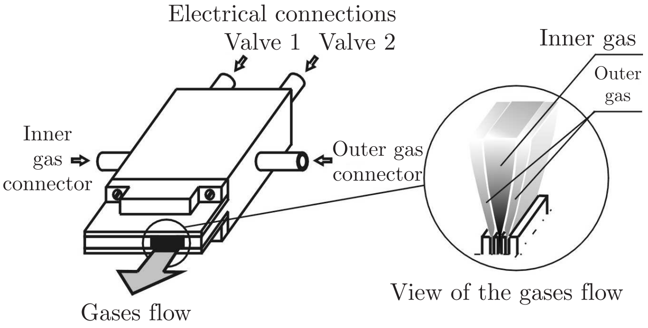


Fig. 6. Schematic of the valve system to form a high-density elongated double-stream gas puff targets for X-ray laser experiments

Schematic of the valve system to form the elongated double-stream gas puff target is shown in Fig. 6. The valve system contains two separate electromagnetic valves combined in a common body. The system is equipped with the nozzle setup that is composed of the central slit nozzle and the surrounding-one. The central nozzle is 0.25 mm wide and up to 9 mm long. The width of the outer nozzle is 0.25 mm. Each nozzle is supplied with different gas separately from the valves. The valves are driven by the electric pulses synchronously with the X-ray laser-driving pulse. The gas density spatial profiles of the target can be controlled by changing the gas backing pressure and the time delays between the laser pulse and the opening of the valve.

The gas puff targets have been characterized with the use of X-ray backlighting technique. A laser-plasma X-ray source based on a krypton gas puff target irradiated with a Nd:YAG laser generating 4 ns and 0.8 J laser pulses was used as a backlighter. X-ray radiation at the wavelength of about 0.7 nm was selected by 20 µm Si filter combined with 10 µm Be filter. The X-ray shadowgrams of the gas puff targets were registered with the use of a CCD camera (Reflex s.r.o.). The typical X-ray shadowgram of the elongated xenon-helium double-stream gas puff target is shown in Fig. 7b. For comparison the shadowgram of the ordinary xenon gas puff target (without injection of helium) is presented in Fig. 7a. The confinement of active gas (xenon) injected from the central nozzle by the outer gas (helium) is clearly seen. The corresponding target characteristics (gas density spatial profiles) for the xenon and the xenon/helium targets are presented in Fig. 8.

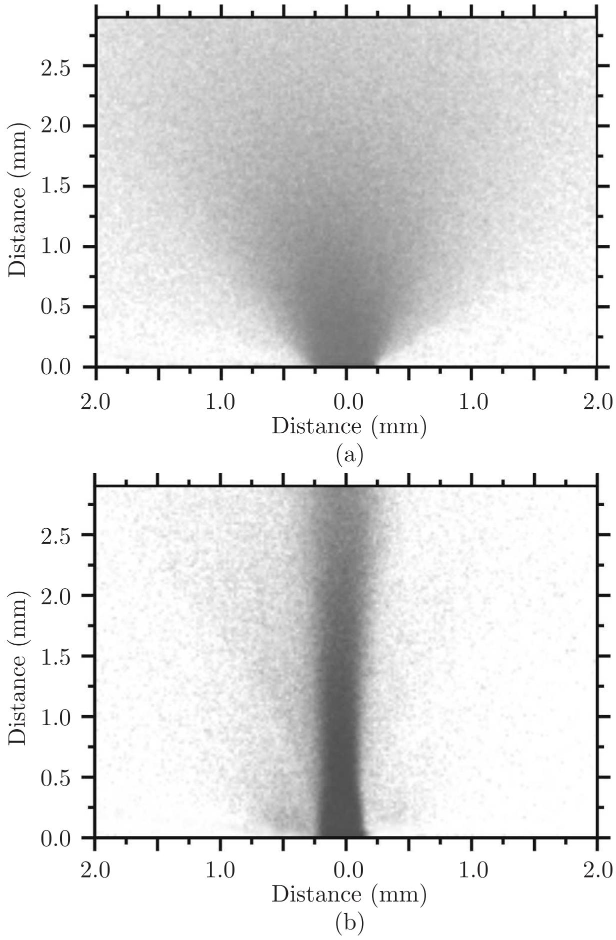
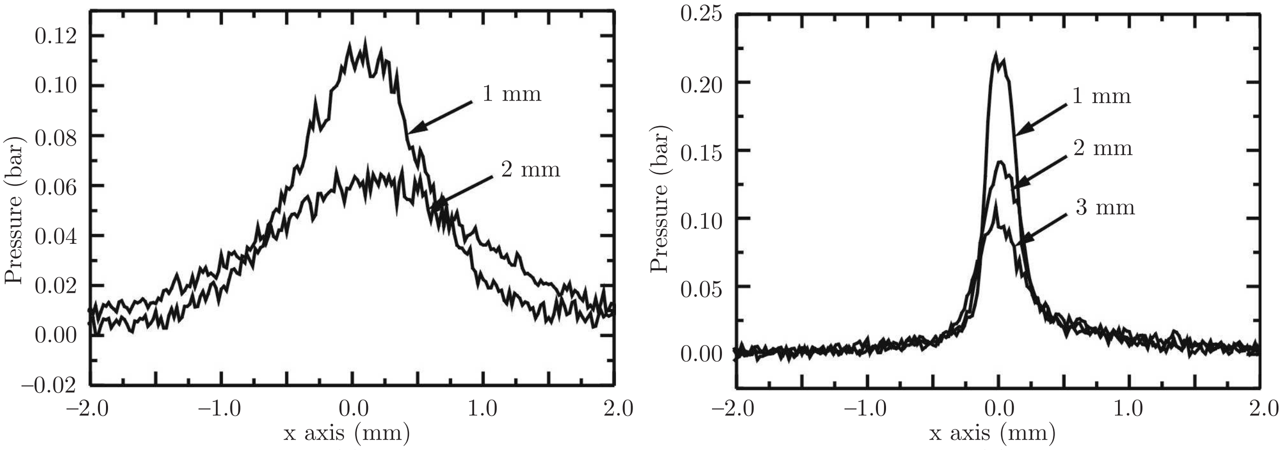


Fig. 7. Typical X-ray shadowgram of the ordinary xenon gas puff target: (a) and the elongated xenon/helium double-stream gas puff target (b) for comparison

The new target will be used in the experiments on laser-driven X-ray lasers planned in the near future. It will be used in the experiments on the longitudinally-pumped X-ray lasers with an active medium in a form a plasma channel produced by irradiation of a gas puff target with a laser beam focused with an axicon [57]. Preliminary collaborative experiment has been performed at the Max-Born-Institute for Nonlinear Optics in Berlin, Germany and will be continued [58]. The collaborative experiments on soft X-ray lasers pumped using the GRIP scheme will be performed at the X-ray laser laboratory of the Colorado State University in Fort Collins, USA [59]. The new target will be also used in the collaborative experiment on photo-pumped soft X-ray laser, where high-density helium gas puff target is irradiated with the VUV FEL laser facility at DESSY in Hamburg, Germany [60]



(a) (b)

Fig. 8. The target characteristics (gas density spatial profiles) for the ordinary xenon gas puff target (a) and the double-stream xenon/helium gas puff target (b)

and in the experiments on higher harmonics generation [61,62]. The collaborative experiments on the transient gain soft X-ray laser with a high-density gas puff target is planned also at the Advanced Photon Research Center JAERI in Kyoto, Japan [63].

## 5. Conclusions

Research on a new class of soft X-ray lasers proposed at the Institute of Optoelectronics, with an active medium created using a gas puff target irradiated with high-intensity laser pulses, have been reviewed. The gas puff target in a form of an elongated gas sheet is formed by pulsed injection of gas through a slit nozzle using a specially designed high-pressure electromagnetic valve. The X-ray laser collaborative experiments were performed at various laser laboratories abroad using laser systems generating high-intensity pulses required for pumping the X-ray lasers.

The first soft X-ray laser with neon-like argon ions based on a laser-irradiated gas puff target was demonstrated using a high-energy iodine laser system ASTERIX IV at Max-Planck-Institut fur Quantenoptik in Garching, Germany. Efficient transient gain soft X-ray lasers with neon-like argon and nickel-like xenon ions were demonstrated in collaborative experiments at the Lawrence Livermore National Laboratory in Livermore, USA and the Advanced Photon Research Center JAERI in Kyoto, Japan. In these experiments the electromagnetic valves developed and characterized at the Institute of Optoelectronics were used. A new high-density gas puff target approach for experiments aimed at increasing the efficiency of X-ray lasers using a longitudinally-pumping and the GRIP scheme has been also described. The use of a gas puff target instead of a solid-one offers the advantage of developing a high repetition X-ray laser with no target debris production.

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