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XUV Amplification in a Recombining *z*-Pinch Plasma

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Amplification of extreme ultraviolet (XUV) radiation at wavelengths about 50 nm in a recombining *z*-pinch plasma is reported. Discharge currents of 40 kA were used to produce highly uniform plasma columns with a diameter of less than 500 μm and a length of up to 9 cm. During the expansion of the pinch plasma, amplification at the 4*f*-3*d* and 4*d*-3*p* transitions of lithiumlike oxygen OVI was observed. The gain-length products were determined to be 2.5 (4*f*-3*d*) and 2.2 (4*d*-3*p*), corresponding to gain coefficients of 0.28 and 0.24 cm^{-1}, respectively. [S0031-9007(96)00009-9]

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Soft-x-ray lasing was achieved for the first time by means of high power lasers more than ten years ago [1,2]. During the past decade laser-produced plasmas turned out to be the most successful technique for soft-x-ray amplification. Substantial progress has been made in reducing the wavelength and increasing the power of the laser transitions. Because of the improvements, new applications of these soft-x-ray lasers became possible, as, for example, the diagnosis of dense plasmas [3]. However, the large pump lasers for this kind of soft-x-ray laser experiments are only available at a few large laser facilities in the world. Therefore the development of compact soft-x-ray lasers with higher efficiency and repetition rates ("table-top devices") is an important task of x-ray laser research today.

One approach is capillary discharges, which are reported to yield amplification of the Balmer-α transition of hydrogenic carbon in some cases [4,5]. The reproducibility of these discharges, however, was rather poor; gain was only achieved at the very first shots using freshly prepared capillaries [5]. For that reason these experiments are essentially limited to single shot, and the capillaries have to be replaced frequently.

Recently, experiments were performed in a gas-liner pinch [6] with recombining lithiumlike ions. The comparison of radial and axial line intensities revealed amplification for the $4f$-$3d$ transitions in oxygen and fluorine.

However, the most convincing demonstration of soft-x-ray gain in a fast, small diameter pinch discharge was achieved in 1994 [7]. The underlying physical principle had been suggested, although for a different excitation scheme, in 1991 [8]. The corresponding pinch dynamics of the experiment of Ref. [7] have been reported in [9,10]. In the experiment, argon gas fillings were used to generate a homogeneous plasma column on axis. Amplification in the neonlike argon at 46.9 nm was demonstrated by means of variation of the discharge tube length, resulting in a maximum gain-length product of $GL = 7.2$. The supposed pump mechanism for this kind of soft-x-ray lasers using neonlike ions is electron collisional excitation.

The work reported in this contribution, however, has concentrated at the second prominent pump mechanism based on collisional recombination, which is important, especially for hydrogenic and lithiumlike ions. The amplification of the $4f$-$3d$ and $4d$-$3p$ transitions of lithiumlike oxygen at 52.0 and 49.8 nm is reported in this Letter. The intensity enhancement with increasing plasma length was measured, and the corresponding gain coefficient was determined for the $4f$-$3d$ and $4d$-$3p$ transitions to be 0.28 and 0.24 cm^{-1}, respectively. The discharge tube length was increased up to 9 cm leading to a gain-length product of $GL \approx 2.5$ ($4f$-$3d$) and $GL \approx 2.2$ ($4d$-$3p$).

For an enhanced reproducibility, increased repetition rate, and lifetime compared to the methods mentioned above, we proposed the use of a cylindrical plasma generated in the core of an ultrafast, small diameter z-pinch discharge [8]. The plasma column of this type of pinch discharge has comparable dimensions of less than 500 μm in diameter and some centimeters in length, as typical capillary plasmas.

The main difference between a capillary discharge and a fast z-pinch plasma results from the initial gas filling used in z-pinch experiments. In the case of a classical capillary discharge the material in the plasma is ablated from the insulator walls, and the plasma parameters could only be varied by the amplitude of the discharge current. In a fast z pinch the plasma dynamics can be controlled additionally by variation of the initial gas pressure. The ion species results from the used gas fill instead of the wall material. Erosion and damage of the insulator can be made very small due to the large distance between the dense plasma column and the insulator walls. Therefore such a device is, in principle, suitable for repetition rates in the order of several hertz.

For the production of the investigated plasma columns a high-voltage pulse generator is used, consisting of a three-stage Marx generator (3×50 nF, charging voltage 60–100 kV), and a coaxial pulse forming line with deionized water as dielectric. This pulse generator delivers current pulses of 30–50 kA in amplitude at a typical current

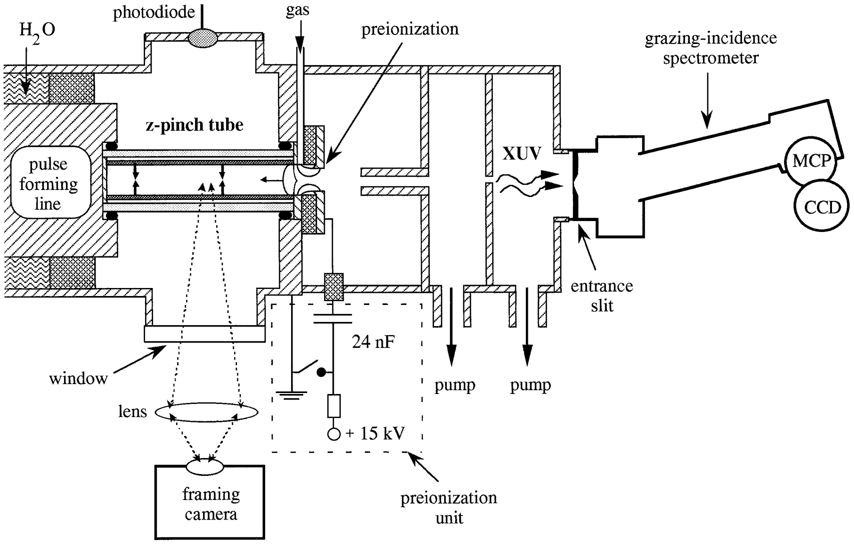

FIG. 1. Schematic drawing of the experimental setup with the used diagnostic tools. The z-pinch tube terminates the coaxial pulse forming line. The axially emitted XUV radiation is observed by means of a grazing incidence spectrometer and a MCP coupled with a CCD camera.

rise rate of 1.5×10^{12} A/s. Before the main pulse is applied to the discharge volume, a predischarge is ignited to preionize the gas filling [8]. This preionization is necessary for a homogeneous and highly uniform formation of the z pinch. The experimental setup and the diagnostic tools are shown in Fig. 1. The axially emitted XUV radiation was observed by means of a 1.5 m grazing-incidence spectrometer with a 600 lines/mm grating at an angle of 86° and an entrance slit of 30 μm. The XUV radiation was detected by a gated microchannel plate (MCP) coupled to a slow scan charge coupled device (CCD) camera. The spectral resolution of the detection system is 0.3 Å in the range of 50 nm, and the time resolution is about 5 ns, due to the gating of the MCP.

The axially radiated XUV emission is detected during the different phases of the pinch evolution for discharge tube lengths of 30, 44, 60, and 90 mm. Simultaneously, the discharge current is monitored on a digital oscilloscope, as well as the light output in the visible region using a fast Si photodiode (side-on). The peak intensity observed by this photodiode is temporally correlated to the moment of maximum compression, due to the strong increase in continuum radiation at the time of stagnation of the converging shock front on axis. Because of this measurement, it is guaranteed that all discharges were performed with the identical pinch dynamics, i.e., identical (±2 ns) pinch times. The current amplitude was set to 40 kA, and only shots with a relative deviation in the current of less than ±3% were accepted. The optimum initial pressure for the aforementioned discharge conditions was about 20 Pa oxygen. A differential pumping system is used to flow the working gas through the discharge tube.

The high rate of current rise leads to a fast compression of the plasma, away from the insulator walls towards the axis. Because of the high compression velocity, a shock front is formed which propagates in the radial direction towards the symmetry axis. The maximum implosion velocity of this shock front was measured with a fast framing camera to $v_{\max} = 1.4 \times 10^7$ cm/s. While the shock front collapses on axis, a highly ionized plasma column is generated. In Fig. 2 a picture of the shock front

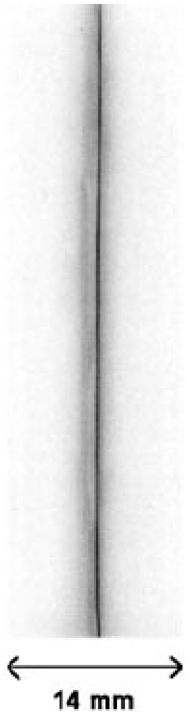

FIG. 2. Shock generated plasma column on axis (inner diam ≤ 500 μm, length $= 90$ mm) for a discharge current of 40 kA, at an exposure time of 5 ns.

stagnating on axis is presented, showing the production of a long, small diameter, highly uniform plasma. The diameter (FWHM) of the plasma column as determined from these measurements is less than 500 μm, whereas the inner diameter of the discharge tube amounts to 14 mm.

In Fig. 3 three typical spectra are shown as observed during the different stages of a pinch discharge of 90 mm length. The first spectrum at 100 ns after the start of current was obtained during the compression phase of the plasma, showing mainly OIII and OIV lines corresponding to a relatively low electron temperature. In the second spectrum at 153 ns the shock front collapses on axis, and a high degree of ionization is achieved. Doppler and Stark effect broadened oxygen lines of lithiumlike OVI dominate the spectrum. At that moment, electron temperature and density reach their maxima [$T_e \approx 50$ eV, $N_e \approx (4 \pm 1) \times 10^{19}$ cm^{-3}] and are comparable to the plasma parameters in capillary plasmas [11,12]. Finally, the third spectrum at 198 ns was made during the expansion phase, when the electron temperature rapidly decreases due to adiabatic expansion, heat conduction, and radiation, while the electron density has dropped considerably below 3×10^{18} cm^{-3}. The OVI lines of the $4f$-$3d$ and $4d$-$3p$ transitions at that time become extremely narrow while the peak intensities are still high.

A comparison of this behavior for different discharge tube lengths yields no significant changes of the spectra during the compression and pinch phases. In the expansion phase of the plasma, however, a strong enhancement of the OVI-line intensities at $\lambda = 52.0$ and 49.8 nm was observed with increasing plasma length. Figure 4 presents three spectra for discharge tube lengths of 30, 44, and 90 mm. The spectra were all taken around $t = 198 \pm 2$ ns, corresponding to about 45 ns after maximum compression, with an exposure time of 5 ns. It is obvious that the intensity of the two OVI lines increases considerably with increasing plasma length, while the intensities of the neighboring OIII and OIV lines remain constant. These two OVI lines clearly dominate the spectrum in the case of the 90-mm-long plasma column. A plot of the measured intensities versus the discharge tube length is shown in Fig. 5. The exponential rise with increasing plasma length is obvious. The best fit of the measured data to the Linford formula [13] gives gain coefficients of 0.28 cm^{-1} for the $4f$-$3d$ and 0.24 cm^{-1} for the $4d$-$3p$ transition, respectively.

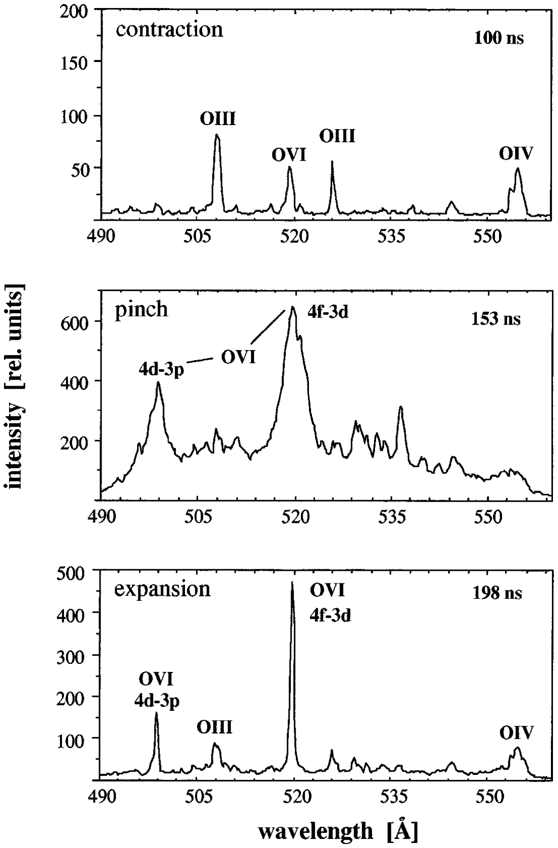

FIG. 3. Time-resolved spectra of the axial XUV emission of the plasma in the range from 490 to 560 Å during the different phases of the pinch evolution. The initial pressure was 20 Pa of oxygen in a 90-mm-long tube, at a discharge current of 40 kA.

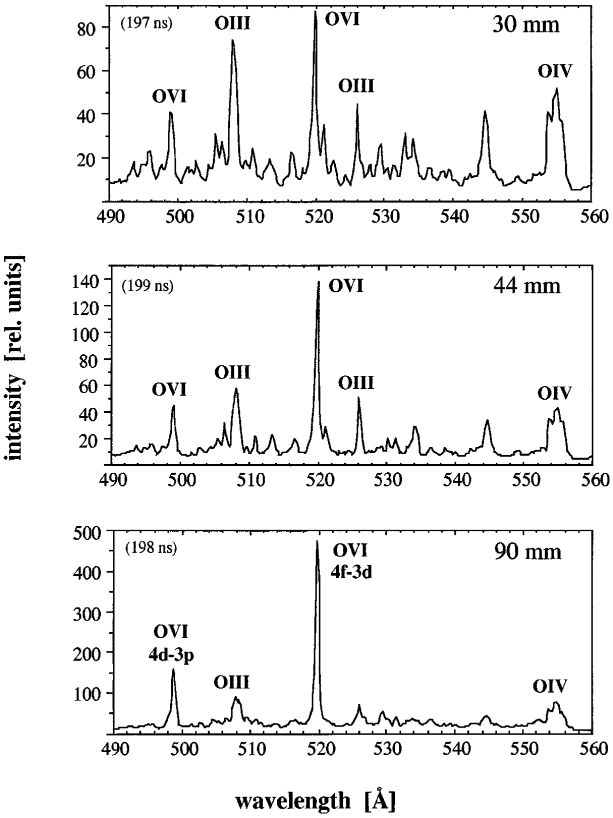

FIG. 4. Time-resolved spectra of the axial emission around 52 nm for different discharge tube lengths. The discharges were performed with a 40 kA current pulse in a pressure of 20 Pa oxygen.

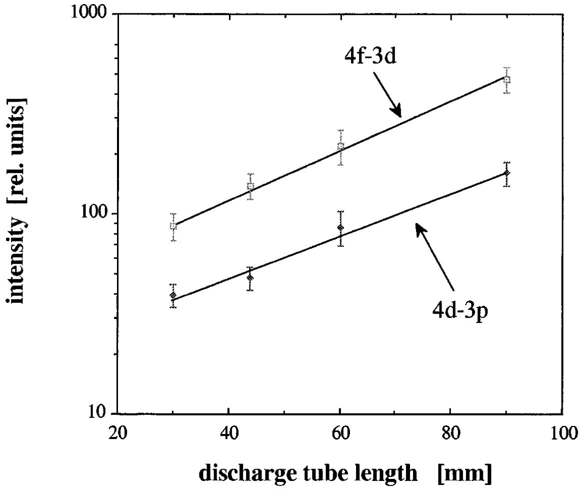

FIG. 5. Intensities of the $4f$-$3d$ and $4d$-$3p$ lines of lithiumlike oxygen OVI as a function of the discharge tube length.

At a plasma length of 9 cm this leads to a gain-length product of 2.5 for the $4f$-$3d$ and 2.2 for the $4d$-$3p$ transition.

In conclusion, we have demonstrated XUV amplification in a shock-wave generated plasma column, driven by a fast, compact z-pinch discharge. The observed amplification occurred about 45 ns after maximum compression, during the expansion of the plasma. The plasma cools rapidly in this phase due to adiabatic expansion and electronic heat conduction. Three-body recombination is supposed to be the main pump mechanism, leading to inversion of the $4f$-$3d$ and $4d$-$3p$ transitions in lithiumlike oxygen. The intensity of the respective lines was time-resolved measured for different plasma lengths, and a maximum gain-length product of 2.5 was obtained for a plasma length of 90 mm.

This type of compact, fast z-pinch discharge is a very promising excitation scheme for table-top soft-x-ray lasers. It is also suitable for soft-x-ray laser transitions in other ions as well as for other pump mechanisms, such as, for example, electron collisional excitation. For this excitation scheme, almost saturation, exp(14), has been achieved in a pinching electrical discharge plasma [14]. The corresponding laser efficiency is typically of the order of 10^{-6} [10]. The main advantage of the fast z-pinch discharge, as compared to competing principles, is its excellent reproducibility, its low cost due to the high conversion efficiency of direct electrical to plasma internal energy, and the high degree of freedom in choosing the appropriate plasma parameters and ion species.

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