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LES DÉVELOPPEMENTS RÉCENTS DES LASERS À RAYONS X
RECENT PROGRESS IN X-RAY LASERS

Collisionally pumped hybrid soft X-ray laser in Ne-like sulphur

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Abstract. We describe an experiment demonstrating XUV amplification following collisional excitation in a capillary discharge plasma irradiated by a picosecond IR laser pulse. Guiding and temporally resolved transmission of the pump laser beam are also demonstrated and analysed. The short pump laser pulse heated rapidly the electrons producing amplification in the $3p^1S_0$–$3s^1P_1$ transition of Ne-like sulphur at 60.84 nm. The estimated gain–length product was equal to 6.8, while the beam divergence reached 2.5 mrad for 30 mm capillary. This new, hybridly pumped collisional soft X-ray laser with the transient gain offers a new way towards efficient table-top XUV sources. © 2000 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

plasma / X-ray laser / collisionnal excitation / hybrid pumping / plasma waveguide / X–UV spectroscopy / capillary discharge

Laser X–UV collisionnel à pompage hybride dans le soufre néonoïde

Résumé. *Nous présentons une expérience qui met en évidence l'amplification X–UV d'un laser collisionnel pompé de manière hybride par un laser optique picoseconde se propageant dans un guide à plasma produit par une décharge capillaire. Une décharge capillaire produit une colonne de plasma de soufre avec une large population d'ions néonoïdes et un profil concave de densité électronique. Un laser intense en impulsion brève chauffe les électrons et produit une amplification sur la transition* $3p^1S_0$*–*$3s^1P_1$ *du soufre néonoïde à* 60,84 nm. *On obtient un produit gain-longueur intégré de* $\sim 5{,}5$ *en excitant une longueur de* 2 cm *de milieu actif avec une énergie laser de* 0,46 J. *La divergence du faisceau décroît avec la longueur de la colonne pour atteindre* 2,5 mrad *pour un capillaire de* 30 mm *de long. Ce nouveau laser X–UV transitoire a pompage hybride ouvre de nouvelles perspectives pour les sources X–UV cohérentes à haut rendement. © 2000 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS*

plasma / laser à rayonnement X / excitation collisionnelle / pompage hybride / guidage d'ondes par plasmas / spectroscopie X–UV / décharge dans capillaires

Note présentée par Guy LAVAL.

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1. Introduction

An interest in collisionally pumped X-ray lasers (XRLs) with a transient inversion increased enormously since the first experimental demonstration of this pumping scheme [1]. This is a result of the advantages offered by this pump method. Its involvement in experimental practice resulted in reduction in the pump energy up to two orders of magnitude and similar scale of reduction in the output pulse length. Transient inversion is now the most vigorously pursued topic within the XRLs field and has brought a few important experimental results. Using this method the germanium ($\lambda = 19.6$ nm) and titanium ($\lambda = 32.6$ nm) XRLs have been saturated and the gain coefficients of 30 and 35 cm^{-1}, respectively have been achieved with a moderate pump energy of 10–20 J [2,3]. The total laser pump energy as high as 7 J caused saturation in Ni-like Pd laser ($\lambda = 14.7$ nm) and gave maximal ever registered gain coefficient of 63 cm^{-1} [4]. However, this efficient and robust scheme is plagued by the refraction effect and works with at least two different pump pulses. As a consequence a complicated optical focusing system is required. The first, long laser pulse, usually with the length between a few hundreds of picoseconds and single nanosecond, creates the plasma with an abundance of Ne-like or Ni-like ions, while the second, picosecond pulse heats the plasma, being in the optimal ionization stage, on a very short time scale. The latter results in negligibility of the hydrodynamics und relaxation effects and the pump energy deposited is efficiently transformed into the high plasma temperature, followed by a strong collisional excitation of the laser levels. The short duration time of the gain supports a short pulse emission in the XUV spectral range but at the same time it requires complicated optical arrangement to ensure efficient extraction of the energy deposited in the active medium by the travelling wave pump regime. The last measurements on the output pulse of XRL in Ni-like Ag showed the duration time of ~ 3 ps [5]. However, more frequently the pulses with the length between 10 and 20 ps and energy up to 30 µJ were registered [2–4].

On the other hand there exists an alternative XRL-pumping scheme based on a very fast electrical discharge through a capillary. A capacitor bank stores an energy of several tens of joules which is rapidly discharged through a capillary filled with gas [6]. The capillary is usually longer than 15 cm and has diameter of 2–4 mm. The peak current achieves a few tens of kiloamps within 30–50 ns [7]. This sort of XRL delivers the XUV radiation nearly from a socket, i.e. this is a very efficient, simple and cheap pumping scheme, transforming electric energy directly in a short-wavelength radiation. Moreover, relatively low gain coefficient about 1 cm^{-1} is compensated by a very long (up to 25–30 cm) active medium and saturation of the output has been demonstrated [6]. The extremely fast electric discharge causes the plasma column to be pinched and as a result the high electron temperature and density, necessary for lasing, are achieved. The major disadvantage of the system working in a quasi-steady-state regime (QSS) is scaling this scheme to shorter wavelengths (at the moment 46.9 nm), which is a serious technological challenge. The long output pulse (~ 1 ns) is not favourable in some applications requiring high temporal resolution. However, this system is able to work with an increased (up to 7 Hz) repetition rate and delivers average energy of 0.88 mJ ($P \sim 3$ mW) with the repetition rate of 4 Hz [8]. The number of photons emitted in the form of a spatially coherent radiation exceeds that of the synchrotrons of the third generation [9]. At the moment this is the one of the brightest sources of X-ray radiation.

It is easily seen from the above that both schemes discussed are complementary to some extent. Meaning the advantages of one fit very well the disadvantages of the second. Capillary discharge is a very simple, compact and cheap source of plasma with an abundance of the Ne-like ions. Hence, this is potentially an excellent source of preformed plasma for the transient inversion pumping method and it could replace the whole optical laser system generating the nanosecond pulse. The short, guided, picosecond pulse would heat rapidly the plasma created by the discharge. Moreover, quasi-travelling wave pumping is inherent for this scheme. Additionally, the high intensity short laser pulse could easily improve the plasma ionization stage by the field ionization. Guiding in a symmetric plasma pipe reduces the problems present in the conventional scheme due to refraction. Recently, a proposal to combine both schemes in one hybrid laser system appeared and was accompanied by the initial numerical simulations [10]. The preplasma created by the discharge has to fulfil two fundamental requirements. Firstly, it has to be sufficiently dense to ensure strong energy absorption by the inverse bremsstrahlung (IB) mechanism. Secondly, the elongated plasma column should have a density profile which provides conditions for efficient guiding of the pumping radiation and possibly uniform heating over the whole plasma length. As a consequence the original capillary design used in [6–8] must be modified to make it suitable for IR-laser pumping.

2. Experimental setup

In this paper we present the results of an experiment on such a capillary, especially designed for laser pumping, if irradiated by the short CPA laser pulse. Sulphur capillaries with lengths between 10 and 30 mm and channel diameter of 0.5 mm and 1 mm have been used in the measurements. The capillary with broader channel gave no gain and will not be discussed further. The laser beam from the MBI glass laser system (maximum 10 J, 1.05 μm) was focused to a diameter of 170 μm (FWHM). This value was measured at a low signal level. The laser pulse, used in the experiment described, had length of 2 ps and delivered energy between 0.1 and 1.0 J. The plasma was created by ablation of the wall material during the discharge. A capacitor bank of 0.08 μF was charged to 3–10 kV and the peak discharge current, measured with a Rogowski coil, was kept about 3 kA, while the FWHM of the current first half-cycle was ~ 150 ns. Sulphur was used in this proof-of-priciple experiment as a lasant because its level structure is especially suitable for transient pumping, and a gain coefficient of 0.45 cm^{-1} was recently reported on the $3p$–$3s$ transition in Ne-like sulphur at 60.8 nm when a pure capillary discharge was used as a pump [11]. This laser worked in the QSS, i.e. the inversion was created by a dominant contribution of relaxation processes. The long wavelength generated was of secondary importance in this case. A sketch of the discharge unit together with a flat-field spectrograph (FFS) used in the experiment are presented in *figure 1*. The transmitted energy and beam shape of the short pumping pulse were measured using the experimental set-up shown in *figure 2*. An 8-bit CCD camera and a pyroelectric calorimeter were used to monitor the beam shape and measure the output energy, respectively. Glass wedges and a set of the neutral density filters (NG) were used to attenuate the incident beam. A plane positioned a few millimeters behind the capillary exit (marked as IP in *figure 2*) was imaged onto the CCD chip. The beam shape was modified slightly by three diaphragms installed behind the capillary to reduce the debris and make possible a differential vacuum pumping scheme. This pumping setup was necessary for the use of a double-stage multichannel plate (MCP) as an image intensifier and

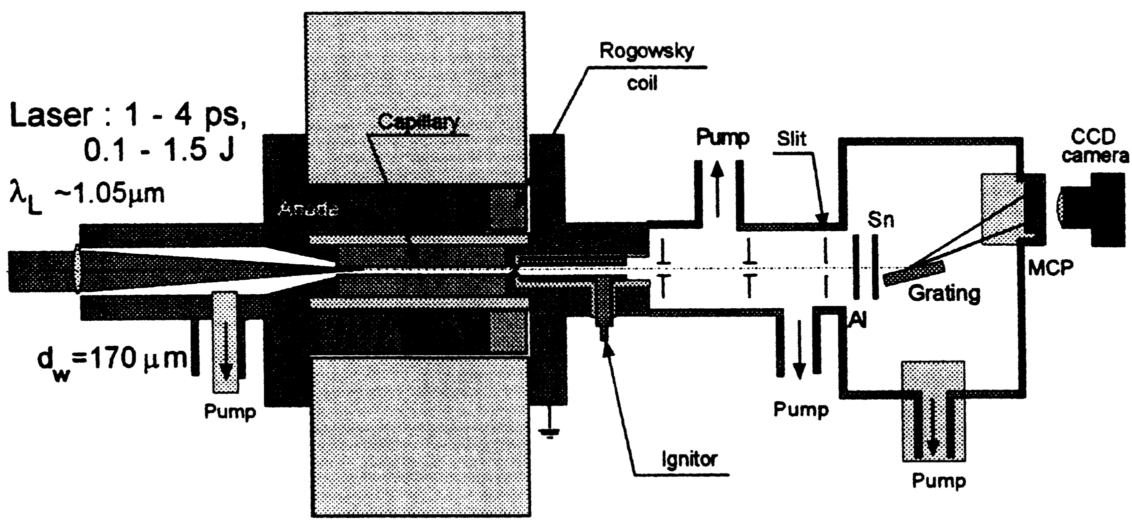


Figure 1. Capillary discharge unit with a flat-field spectrograph.

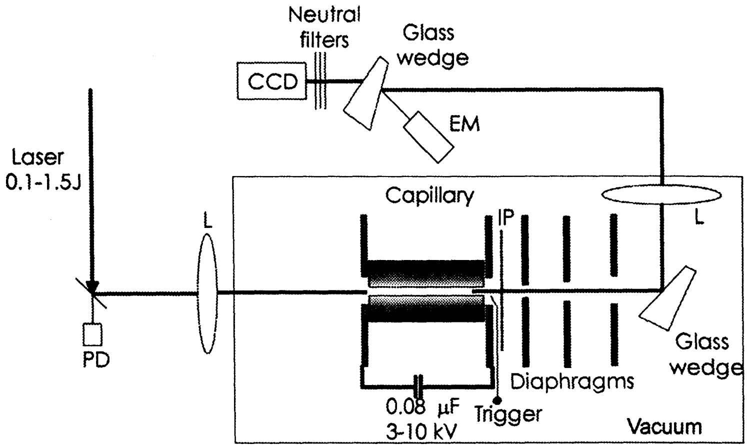


Figure 2. Experimental setup for transmission measurement and beam shape monitoring.

transformer for the detector (16-bit CCD camera) at the XUV spectrometer output. The MCP works at pressures lower than $1 \cdot 10^{-6}$ mbar while the capillary pressure increases to $\sim 1 \cdot 10^{-4}$ mbar after firing.

3. Results

The main aim of the laser transmission experiment described below was to determine the time gap in which the short pumping pulse heats the plasma due to the IB absorption but still shows a finite transmission to avoid a cold plasma at the capillary end. The guiding effect caused by the concave radial density profile of the plasma with a minimum on the axis should facilitate efficient heating along the active medium.

3.1. Laser beam transmission

The transmission curve for 10 mm capillary is presented together with the beam shape images and the discharge current waveform in *figure 3*. The beam images are related to the instantaneous current value at the moment of the laser pulse arrival. The peak current position is a reference and the laser pulse delay is calculated in respect to this moment. We determine the cut-off instant by identifying, during the beam shape monitoring, the moment at which the transmitted laser beam disappears and the discharge emission dominates the image. As a cut-off instant we understand the moment when the plasma starts to be opaque for the incident radiation. The transmission behaviour is similar for all capillary lengths used and the cut-off position does not change noticeably. This is a consequence of the constant current value used in the experiment, as the current determines the ablation process and the plasma dynamics. There is an abrupt fall in the transmission which begins near the time of the current maximum and lasts 80–90 ns. The duration of the following opacity period (in which no laser is transmitted through the plasma column) has been estimated to last between 6 and 13 μs depending on the capillary dimensions and discharge parameters. The beam shapes registered cover the whole history of the transmission phase from the beam image when the capillary is irradiated by the laser, but the discharge is not triggered, to the full opacity. These images correspond to low (energy below 1 mJ) and strong (energy 200–300 mJ) laser pump signal levels. It is worth noting that the plasma ablated from the capillary wall does not significantly affect the regular and very symmetric shape of the laser beam but significantly changes the transmission character. It is seen from *figure 3* that relatively low transmission existing without the discharge current increased with the current onset and then fell down again. Such a behaviour we ascribe an influence of a thin plasma layer created by the discharge plasma at the wall and the following inhibition in the interaction between the laser pulse and the wall. The subsequent decrease of the transmission was determined by the increase in the absorption. A small but distinct hump seen on the transmission curve between 25 and 50 ns was caused by the guiding effect which changed divergence of the transmitted beam. As a consequence the transmission

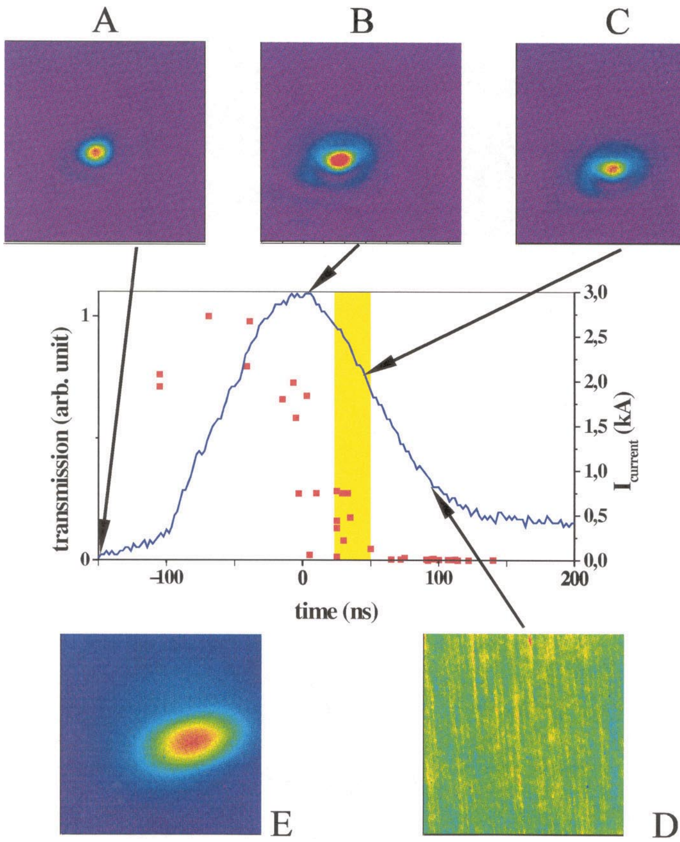


Figure 3. Transmission of the capillary discharge plasma irradiated by a picosecond laser pulse, current waveform and intensity distributions in the transmitted laser beam. $t = 0$ at the current maximum. Capillary length 10 mm. Intensity distributions: A — laser without the discharge, B — delay equal to 11 ns, i.e. laser pulse arrives 11 ns after the current maximum, C — delay equal to 51 ns, D — delay $= 91$ ns, E — discharge emission (without laser irradiation).

of the laser pulse through the diaphragms increased. This effect was more pronounced in longer capillaries. The guiding phase was observed for delays between 25 and 50 ns with optimum at 35 ns. The beam shape is highly symmetric during nearly the whole transparency phase. This evolution from an initially unperturbed laser beam into a slightly distorted one that finally evolves into a symmetric shape can be understood from a recent soft X-ray shadowgraphy study of an ablative micro-capillary discharge plasma [12]. The shadowgrams showed that in the early phase of ablative capillary discharge the plasma is non-uniform and asymmetric. This is a consequence of the fact that breakdown occurs at the walls and during the initial phase of the discharge a significant part of the current flows through a few localised surface discharge channels, creating a non-uniform plasma. However, as the plasma expands towards the evacuated center of the capillary the non-uniformities are observed to decrease. The plasma becomes very symmetric and with minimum density on the capillary axis, allowing for the propagation of the symmetric laser beam profile observed at the end of the transmission phase. As mentioned above, 80–90 ns after the current peak the pump laser is almost completely absorbed and the images become completely dominated by the plasma self-emission. We verified, using a UG8 filter (Schott, cut-off ≈ 800 nm) which is transparent to the laser, that after this time the laser is completely obscured by the plasma by. When the filter was placed in the radiation path no signal was detected by the CCD at times after the cut-off. This proves that after 80–90 ns

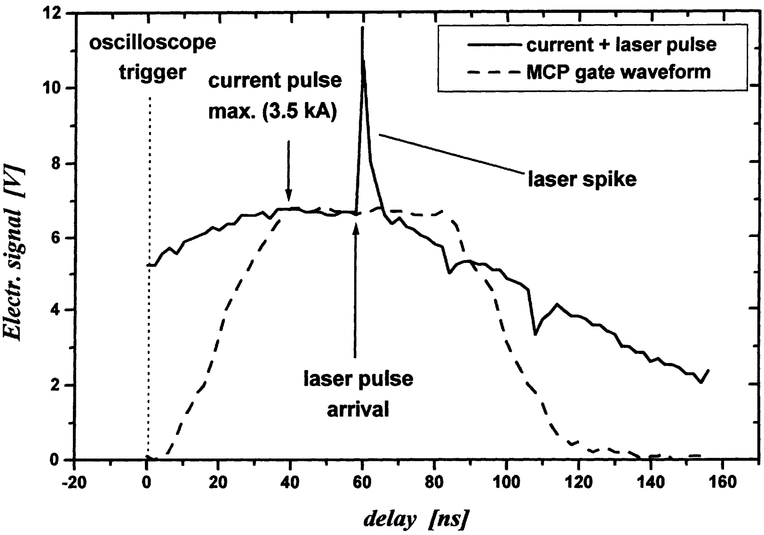
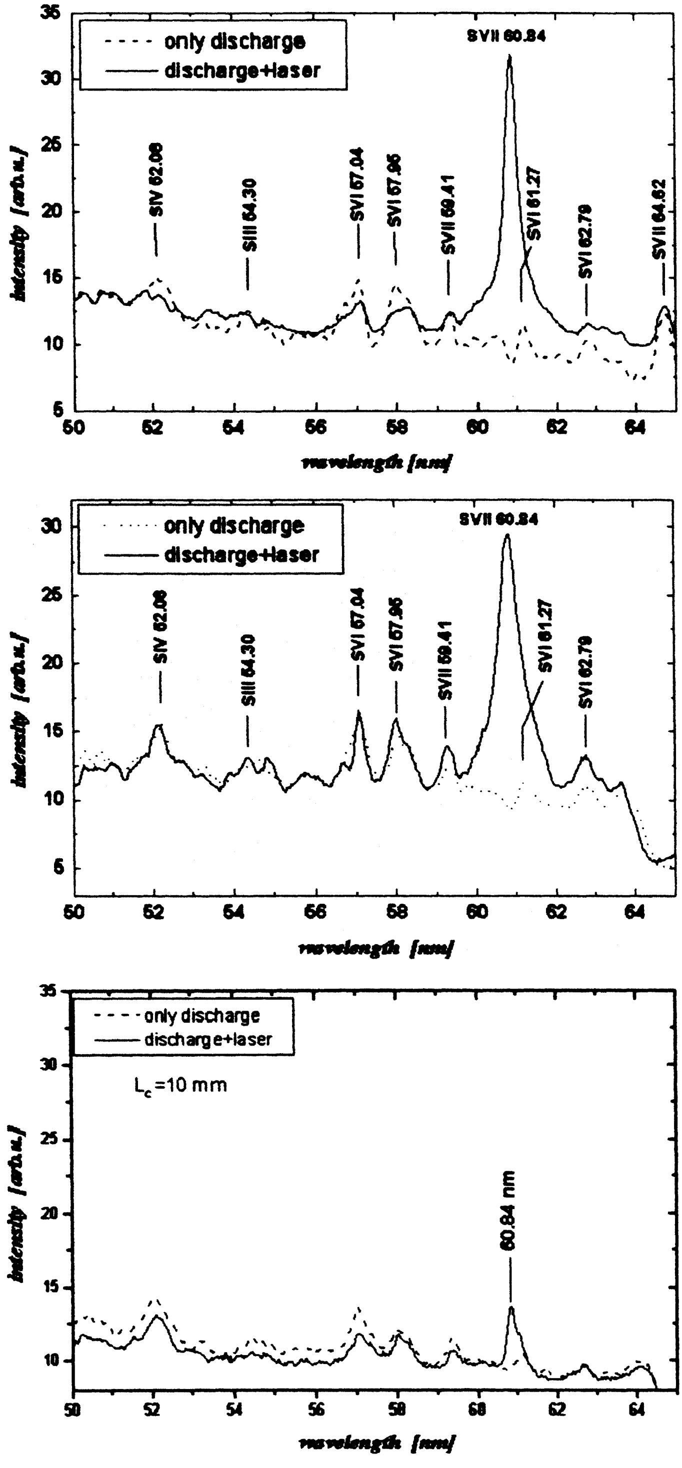


Figure 4. Timing between the discharge current, MCP gate and the laser pulse in a shot showing lasing.

no laser radiation is transmitted through the capillary discharge plasma and the same determines the upper delay limit for the short laser pulse arrival.

3.2. Spectral measurements

The arrangement of the spectral diagnostic is presented in *figure 1*. This diagnostic consists of a flat-field spectrograph (FFS) provided with a 1200 lines·mm^{-1} Al-coated, Harada-type concave diffraction grating. The radiation dispersed by the grating was recorded by a sensor consisting of a double-stage MCP, phosphor screen and a 16-bit CCD detector. The MCP was gated with a temporal window of 40 ns at the flat-top. Timing of the laser pulse, MCP gate and the discharge current is shown in *figure 4*. The input slit of the spectrograph had a width of 100 µm. This setup allowed for relatively poor spectral resolution at the wavelength of interest, as the optimal wavelength range for such a grating is far from 600 Å (5.0–30.0 nm). No filters were installed due to the limited amount of radiation available. It is seen from the spectra in *figure 5* that the pump laser radiation, at the energy level used, strongly affects the spectrum at 60.8 nm. The 60.84 nm line of Ne-like sulfur (S VII) is intensified significantly by the irradiation while the other lines are hardly changed. This influence changes with the capillary length (*figures 5* and *6*) and there is no doubt that the intensity increase of the 60.84 nm line is caused by the laser plasma heating. Moreover, the spatial separation of the line of interest from the discharge spectrum and the reduced divergence of the registered 60.84 nm radiation imply that we observed lasing (*figure 7*). We estimated the gain coefficient from the data presented in *figure 6*. These data is influenced by non-uniform heating in the axial direction. This topic requires a separate and more detailed investigation and is out of scope of this paper. However, assuming a realistic value of $2 \cdot 10^{19}$ cm^{-3} for the electron density reported earlier in other experiments on the capillary discharge plasma [13,14] and an initial electron temperature of 10 eV we can estimate the contribution of the inverse bremsstrahlung absorption using analytic formulae derived by Pert [15]. Given laser pulse intensities equal to 10^{14} W·cm^{-2} and 10^{15} W·cm^{-2}, i.e. the limits of the intensity range usually applied in the experiment, the final temperatures calculated neglecting any cooling are equal to 70 and 170 eV, respectively. These estimates correspond to the plasma temperature on the capillary axis and do not take the pump laser beam profile into account. Another simplifying assumption is a constant value of the pump laser intensity along the axis. In reality the absorption will reduce the pump intensity with the propagation distance and the electron temperature will decrease. Under these circumstaces the traditional methods of gain estimation, for example Linford formula, are no more valid. We divided the capillary into three separate sections, each with a 1 cm length and determined the gain coefficient for each



(a)

(b)

(c)

Figure 5. The spectra of the sulphur plasma measured at $\sim$30–35 ns delay relative to the current peak for pure discharge (dotted line) and discharge irradiated by a picosecond laser pulse. The data is not convoluted with the MCP gain curve.

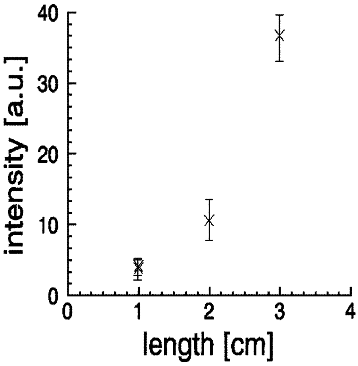


Figure 6. Maximum output signal vs. the capillary length (convoluted with the MCP gain curve).

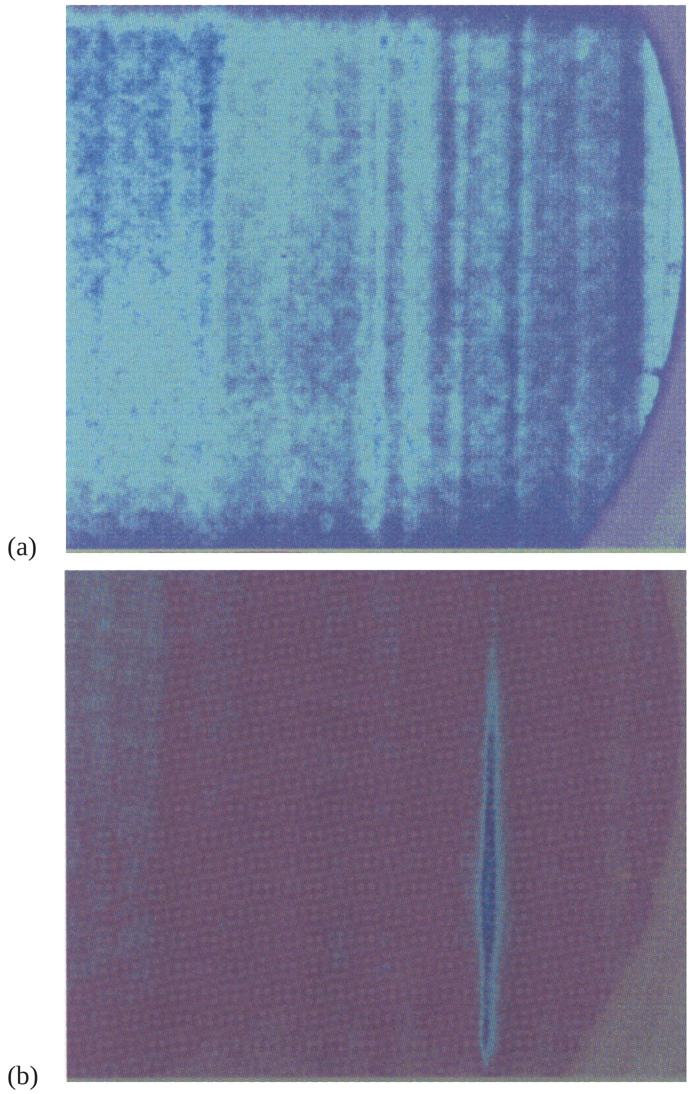


Figure 7. Spectrum image for (a) pure discharge and (b) discharge irradiated with a picosecond laser pulse.

section separately. The maximum gain, equal to 4.7 cm^{-1}, has been obtained for the 10 mm capillary. The second and third section had the gain coefficients of 1.0 and 1.1 cm^{-1}, respectively. The effective gain-length product estimated for all sections was equal to 6.8 and confirmed we observed lasing. Note, the signal from the 30 mm capillary was obtained with lower (30%) pump energy. The inversion observed (lower gain for the second stage than for the third one) could be caused by the pointing jitter or more likely by a small misalignment of the capillary. The ratio (gain-length product gl)/(pump energy E_p) used to be applied to estimate roughly the pump scheme efficiency. This factor is equal to 3.1 J^{-1} and belongs to the highest obtained for the collisionally pumped XRLs. Typical values spread between 1 and 2 J^{-1}. It is worth noting that the pump energy taken to this estimate includes the total electric energy dissipated in the discharge. There is no direct proof, that we observed transient gain. The streak camera photocathodes available during the experiment were not sufficiently sensitive, at the working wavelength, to give a clear streak of the registred signal. However, one can argue that the signal measured is significantly stronger than that obtained in the pure electric discharge plasma and within the prepulse scheme with a long laser pulse with energy of 20 J [15]. In our case, in spite of very effective plasma coupling to the bulk material of the capillary walls, plasma cooling by thermal conduction is expected to be negligible especially for very short pump laser pulses. Thus, the electron temperature can increase markedly on the short time scale and be a source of very efficient excitation and the consequent high transient gain.

4. Conclusions

We have irradiated a capillary discharge with a picosecond laser pulse of relatively low energy (320–460 mJ) and estimated the temporal dependence of the transmission as well as monitored the shape of the beam transmitted through the capillary channel during the discharge. The transmission decreases very quickly immediately after the current peak during the next 80–90 ns and the beam shape is evidently symmetrised with clear indication of the guiding effect. The corresponding spectra show significant signal increase with the medium length at 60.84 nm. We ascribe this increase to fast plasma heating by the picosecond pulse followed by lasing on the $3p$–$3s$ transition in Ne-like sulphur. The results presented are encouraging and promise a new efficient tabletop hybrid X-ray laser scheme. Other materials containing elements with higher atomic number Z, which are required to shorten the emitted wavelength are under investigation.

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