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Toward compact and ultra-intense laser-based soft x-ray lasers

S Sebban1, A Depresseux1, E Oliva2,3, J Gautier1, F Tissandier1, J Nejdl4, M Kozlova1, G Maynard2, J P Goddet1, A Tafzi1, A Lifschitz1, H T Kim5,6, S Jacquemot3,4, P Rousseau1, P Zeitoun1 and A Rousse1

1LOA, ENSTA, CNRS, Ecole Polytechnique, Université Paris-Saclay, F-91762 Palaiseau cedex, France
2Laboratoire de Physique des Gaz et des Plasmas, CNRS-Université Paris Sud 11, F-91405 Orsay, France
3Universidad Politécnica de Madrid, E-28006, Madrid, Spain
4ELI Beamlines Project, Institute of Physics of the ASCR, Na Slovance 2, 182 21 Prague 8, Czechia
5Advanced Photonics Research Institute, GIST, Gwangju 500-712, Republic of Korea
6Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 500-712, Republic of Korea

E-mail: Stephane.sebban@ensta.fr

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Abstract
We report here recent work on an optical field ionized (OFI), high-order harmonic-seeded EUV laser. The amplifying medium is a plasma of nickel-like krypton obtained by OFI when focusing a 1 J, 30 fs, circularly-polarized, infrared pulse into a krypton-filled gas cell or krypton gas jet. The lasing transition is the 3d94d(0) → 3d94p(1) transition of Ni-like krypton ions at 32.8 nm and is pumped by collisions with hot electrons. The gain dynamics was probed by seeding the amplifier with a high-order harmonic pulse at different delays. The gain duration monotonically decreased from 7 ps to an unprecedented shortness of 450 fs full width at half-maximum as the amplification peak rose from 150 to 1200 with an increase of the plasma density from 3 × 1018 to 1.2 × 1020 cm⁻³. The integrated energy of the EUV laser pulse was also measured, and found to be around 2 μJ. It is to be noted that in the ASE mode, longer amplifiers were achieved (up to 2 cm), yielding EUV outputs up to 14 μJ.

Keywords: XUV lasers, ultrafast laser, coherent radiation, optical field ionized plasmas

(Some figures may appear in colour only in the online journal)

1. Introduction
Aside from being table-top polarized coherent EUV sources [1], plasma-based EUV lasers exhibit high-quality optical beam [2] as well as a high photon number per pulse [3, 4]. Hitherto, the duration of these sources was limited to the picosecond range [5, 6], subsequently greatly reducing the field of applications. We will show here how recent work conducted at LOA allowed to overcome these bottlenecks.

The duration of the pulses emitted from a plasma amplifier is shorter than the gain lifetime and its fundamental limitation is governed by the Fourier transform of the pulse spectral line shape [7]. Collisionally-pumped plasma-based lasers are generally characterized by a very narrow intrinsic line width of the atomic laser transition (in the order of Δλ/λ = 10⁻⁴), which therefore limits their abilities to deliver ultrashort emission. Recent works demonstrated durations of emitted soft x-ray pulses between 1 and 2 ps.

To overcome this constraint, recent numerical calculations demonstrated the feasibility of a transposition of chirped pulse amplification technique to the soft x-ray range [8]. By stretching a femtosecond high-harmonic (HH) seed to a duration close to the gain lifetime, a continuous and coherent extraction of the energy stored in the plasma can be achieved. After compressing the amplified seed, this scheme theoretically inferred SXRL pulses as short as 200 fs but has not been
experimentally demonstrated so far. Other research directions have been considered to bring SXRL in the ultrafast domain, mainly based on straightforward approach capitalizing on intrinsically femtosecond population inversion schemes. The so-called recombination scheme [9] in plasmas is an attractive candidate, nevertheless it requires drastic plasma conditions, which have not been implemented to date. More recently, the inner-shell ionization scheme has demonstrated an ultrafast capability in the keV range, however this scheme requires a very intense hard x-ray pump to work efficiently [10].

An alternative approach is based on the Collisional Ionization Gating (CIG) of the gain media [11]. This method allows reducing the time window in which the lasing action takes place by quenching the lifetime of the lasing ions and therefore the gain duration. In the collisionally-pumped optical field ionized (OFI) scheme, the amplifier lifetime strongly depends on the depletion rate of the lasing ion population due to collisional ionization during the lasing process. As a consequence, a reduction in the emission duration can be expected.

2. Experimental set-up description

The figure 1 displays the experimental arrangement of the HH-seeded plasma-based soft x-ray laser chain [12, 13]. The plasma can be coherently excited using an external source, which works as an ‘oscillator’. This ‘seed’ source is synchronized with the lifetime of the population inversion achieved within the plasma. In these conditions, the seed gets amplified as it propagates into the plasma and the resulting emission is highly coherent and retains the beam spatial properties of the seed.

Because the length of gain region for longitudinally pumped gas target SXRLs is severely limited by ionization-induced refraction, a waveguide is used to maintain sufficient pump intensity over a long distance. The effective gain length for x-ray lasing can therefore be increased and the length of the under-ionized absorbing region reduced. The ‘ignitor–heater’ optically preformed plasma waveguide scheme has been used [14]. The merits of this method involve a high-density operation, guiding of pump pulse and the soft x-ray laser pulse simultaneously, and is damage-free, which caters for high-repetition-rate needed for practical applications [15].

The waveguide is implemented by focusing with an axicon lens a sequence of ignitor (130 mL, 30 fs) and ‘heater’ pulses (690 mL, 600 ps) delayed by 600 ps. The pump beam (1.36 J, 30 fs) was turned circularly polarized thanks to a quarter-wave plate. This allows production of the hot electrons that are needed to efficiently pump the laser transition. The beam is then focused into the plasma channel using a 75 cm focal length spherical mirror.

The plasma channel was tailored to operate at the highest possible electron density and thus maximize the output soft x-ray laser signal strength. At the highest reported density, appropriate conditions for guiding in terms of size and transverse density gradient were granted for the pump pulse focused about 1.55 ns after the arrival of the ‘ignitor’. In these conditions the transverse dimension of the waveguide was about 50 μm. The length of the waveguide could varied from 5 up to 20 mm using different nozzles.

The soft x-ray amplifier is an OFI [16] krypton plasma whose highly-charged and stable Kr$^{8+}$ ions display a strong lasing line at 32.8 nm for the 3d$^2$4p$_{1/2}$ $\rightarrow$ 3d$^2$4d$_{5/2}$ transition [17, 18]. In this lasing scheme, an ultrashort infrared laser pulse ($5 \times 10^{18}$ W cm$^{-2}$) was focused onto a krypton gas jet to generate the lasing ion species. The resulting electron distribution permits to achieve a population inversion by collisional pumping, leading to an ultra-intense lasing of the transition at 32.8 nm [19].

The soft x-ray seed is a HH source, implemented focusing an IR driver beam into a gas cell of adjustable pressure and length, filled with argon [20]. The linearly polarized beam was focused using a 75 cm focal length plano-convex lens. The intensity upon target is assessed at about $4 \times 10^{14}$ W cm$^{-2}$. The HH source is then image-relayed onto the plasma amplifier thanks to a set of plane and toroidal mirrors. For this purpose, the spherical, double-coated plane mirror and the axicon have been drilled (8 mm diameter hole). The grazing-incidence plane mirror is placed after the toroidal mirror and is used to control the spatial coupling conditions of the HH beam at the entrance of the plasma. A 1000 lines mm$^{-1}$ transmission grating spectrometer located 2 m away from the focal plane is used for the spectral analysis of the emission in the range 0–50 nm. The far-field profile of the SXRL beam was recorded using a CCD camera located on-axis 4 m after the plasma amplifier.

The electron density has been measured by using a imaging Mach–Zehnder interferometer. The electron density profile is reconstructed via the local modification of the refractive index (i.e. of the relative phase between the two arms of the interferometer), which imparts a modification of the interferential pattern. The phase profile has been assumed to have a cylindrical symmetry along the axis of propagation to perform an Abel inversion. The large magnification of the imaging system (of about 13), was sufficient to resolve the very thin dimensions of the waveguide structure.

3. Characterization of the amplified spontaneous emission

3.1. On-axis spectra

When no plasma channel is used to help the driving beam to propagate into the elongated plasma, no lasing line is observed, as shown in figure 2(a). Only faint unscattered light is recorded, corresponding to emission from a pre-plasma. The end of the plasma is weakly ionized because of the strong refraction of the beam at the beginning. Emission from the beginning of the plasma thus gets absorbed. We can notice the edge of the aluminum filter bandwidth, which cuts the signals below 17 nm. Advantageous guiding conditions allowed strong amplified spontaneous emission from the plasma. The recorded signal is presented in figure 2(b). It consists of a saturated zeroth-order emission line and a strong
Figure 1. Schematic of the experimental arrangement. The waveguiding beam is composed of a sequence of a short (130 mJ, 30 fs) and a long pulse (690 mJ, 600 ps). It is being focused over the whole jet length thanks to an axiconic lens and creates, following collisional ionization and hydrodynamic expansion, a plasma channel. Then, the pump beam (1.36 J, 30 fs) is being focused at the entrance of the channel with a spherical mirror and being guided afterwards. Hence, an amplifier with Kr8+ lasing ion species over the whole gas jet length is implemented. A third IR beam (16 mJ, 350 fs) is used to generate high-harmonics in an argon-filled cell. The latter are image-relayed onto the entrance of the plasma and synchronized with the gain lifetime.

Figure 2. Single-shot recorded spectra of the amplified spontaneous emission from a 5 mm long plasma operating at $n_e = 1.2 \times 10^{20}$ cm$^{-3}$ with no waveguide (a) and with a waveguide (b).
emission line in the grating first order at 32.8 nm. The secondary peaks observed on both sides of the main lines are diffraction patterns from the supporting grid of the grating. This arrangement however does not allow to resolve the very narrow linewidth of the plasma amplifier.

3.2. Far field pattern

Figure 3 shows the far-field pattern of the 32.8 nm ASE laser for a gas jet length ranging from 5 up to 20 mm. We can notice that the spatial profile is strongly divergent (over 10 mrad) and is clipped by the aperture defined by the aluminum filters’ diameter. Moreover, the ASE emission profile is inhomogenous and features ‘hot points’. Those are speckle patterns and arise from the fact that the plasma is composed of a set of secondary sources displaying high temporal but low spatial coherence. Those secondary sources interfere and give rise to those over-intensity structures.

The annular shape of the far field beam profile can be explained by refraction of the soft x-rays within the amplifier. The electron density profile indeed exhibits a high on-axis density and sharp gradients on the edges. We can notice that the fact that Kr8+ lasing ions may preferentially populate off-axis zones of the plasma amplifier cannot explain the observed profile since far-field emission from a tubular zone does not result in an annular beam profile.

The geometrical confinement of emission due to the elongation of the plasma channel while keeping a similar transverse size is highlighted with a divergence reduced from over 15 mrad down to about 8 mrad. Soft x-ray emission is essentially confined within a solid angle subtended by a circle with the transverse dimensions of the waveguide at the end of the gas jet at a point located at the gas jet entrance. This cone of emission decreases as the plasma length is expanded.

The ASE signal proportionally rises from 1 to 14.4 μJ for a gas jet from 5 to 15 mm. For the 5 mm, 10 mm, 15 mm and 20 mm long plasmas, the electron densities were respectively \( n_e = 1.2 \times 10^{20} \text{ cm}^{-3}, 9 \times 10^{19} \text{ cm}^{-3}, 5.5 \times 10^{19} \text{ cm}^{-3} \) and \( 3.4 \times 10^{19} \text{ cm}^{-3} \), while transmissions of the pump beam by the waveguide were 45%, 36%, 32% and 28% respectively.

Figure 3. Far-field of the 32.8 nm emission for a gas jet length of 5 mm (a), 10 mm (b), 15 mm (c) and 20 mm (d). The ASE signal rises from 1 to 14.4 μJ for a gas jet from 5 to 15 mm. For the 5 mm, 10 mm, 15 mm and 20 mm long plasmas, the electron densities were respectively \( n_e = 1.2 \times 10^{20} \text{ cm}^{-3}, 9 \times 10^{19} \text{ cm}^{-3}, 5.5 \times 10^{19} \text{ cm}^{-3} \) and \( 3.4 \times 10^{19} \text{ cm}^{-3} \), while transmissions of the pump beam by the waveguide were 45%, 36%, 32% and 28% respectively.

Figure 4. On-axis spectra of the high-harmonic seed (HH), the ASE emission (ASE) using a 5 mm long nozzle (b) and the seeded SXRL (SXRL) using a 5 mm long nozzle (c). The plasma density is about \( 1.2 \times 10^{20} \text{ cm}^{-3} \).
20 mm long plasmas, the electron densities were respectively \( n_e = 1.2 \times 10^{20} \text{ cm}^3 \), \( 9 \times 10^{19} \text{ cm}^3 \), \( 5.5 \times 10^{19} \text{ cm}^3 \) and \( 3.4 \times 10^{19} \text{ cm}^3 \), while transmissions of the pump beam by the waveguide were 45%, 36%, 32% and 28% respectively.

4. Seeded 32.8 nm laser operation

4.1. On-axis spectra

The figure 4 reports the spectra for HH, ASE and HH-seeded signals respectively in case of a high-density plasma amplifier with \( n_e = 1.2 \times 10^{20} \text{ cm}^3 \). The arrival of the HH signal was delayed with respect to the pump pulse. A strong amplification of the seed pulse was observed when the injection time was synchronized with the gain duration. The maximum of amplification was found for a delay of 1.4 ps between the pump and HH-driver pulses. Overall, the HH signal is amplified by a factor of about 1000.

4.2. Far field pattern and beam stability

The far-field beam profile has also been directly recorded about 4 m from the source. Figure 5 depicts the beam profile of the seeded SXRL for several consecutive shots. The \( 1 \pm 0.2 \text{ mrad} \) divergence and nearly Gaussian beam profile of HH is maintained over the plasma amplification. The amplification of the HH portion matching the laser transition at 32.8 nm corresponds to more than three orders of magnitude and the resulting SXRL signal yields about 2 \( \mu \text{J} \) per shot, which corresponds to over \( 3 \times 10^{11} \) coherent photons.

In optimal conditions, the HH-seeded SXRL source exhibits a good shot-to-shot stability. The figure 6 illustrates this over 40 shots. The energy fluctuations stand at 6.8% of the average energy (standard deviation RMS = 0.068). Regarding the beam pointing and beam divergence stabilities, they amount to RMS = 0.116 mrad and RMS = 0.39 mrad respectively.

4.3. Seeding signal strength level

Figure 7 illustrates the impact of the spectrally tuned HH seed energy at 32.8 nm on the amplified HH signal strength for \( n_e = 3.2 \times 10^{19} \text{ cm}^3 \) (black curve) and \( n_e = 7 \times 10^{19} \text{ cm}^3 \) (orange curve). The optimized HH signal energy has been decreased modifying the polarization of the IR HH driving beam. The HH generation efficiency drops sharply by turning the polarization from linear to circular. For this measurement, neither the focusing conditions of the HH driver into the gas cell nor the intensity of the IR pulse can be modified, as the spatial and spectral coupling of the HH seed into the plasma amplifier would also be changed.

The curve displayed in figure 7 shows a first phase, where the output SXRL signal rapidly rises as the HH seed energy increases. This behavior corresponds to a non-saturated regime of the amplifier. When the HH signal exceeds about 200 \( \text{pJ} \), the amplifier saturates and the output SXRL signal increases slower. The saturation regime is reached earlier for the highest electron density (orange). Furthermore, there is a threshold from which the HH gets amplified. The HH seed signal strength has indeed to overcome the ASE signal in order to be efficiently amplified. This threshold is higher at larger densities. The amplification of the...
HH seed energy is varied for a plasma amplification factor, thus revealing the actual temporal profile of the amplification. The ultrafast decay in amplification factor increases from 7 ps to an unprecedented shortness of 450 fs over 3 or 4 shots. The duration of amplification monotonically decreases from 7 ps to an unprecedented shortness of 450 fs full width at half-maximum (FWHM), by increasing the plasma densities from $3 \times 10^{18}$ cm$^3$ up to $1.2 \times 10^{20}$ cm$^3$ respectively. These measurements clearly illustrate the dramatic temporal quenching of the amplification as a result of an increase in electron density. As anticipated, the fast rise of the amplification is due to collisional excitation of the lasing transition taking place after the abrupt field ionization process. The ultrafast decay in amplification brings testimony of the CIG process at high densities. Although vital for pumping, the on-going collisional ionization also mainly contributes to shorten the gain lifetime, the number of lasing ions becoming rapidly scarce due to strong over-ionization. Moreover, the maximum amplification factor increases from $n_e = 3.2 \times 10^{19}$ cm$^3$ up to $7.9 \times 10^{19}$ cm$^3$, $n_e = 3.2 \times 10^{18}$ cm$^3$ and $n_e = 1.2 \times 10^{20}$ cm$^3$.

Changing the delay between the waveguiding beam and the IR pump beam allowed to alter the electron density of the amplifier. Indeed, the plasma expansion is characterized by a widening plasma channel with a decreasing average electron density within the waveguide transverse dimensions. The lasing conditions were optimized by tuning the distance between the jet nozzle and the optical axis to maximize the IR pump beam transmission by the waveguide. The cases figures 8(a) and (b) correspond to delays of 3 ns and 1.55 ns respectively. It should be noted that the electron density of the amplifier figure 8(b) has been recorded 10 ps after the arrival of the pump beam, whereas for case figure 8(a), the electron density was probed just after the propagation of the pump beam.

The figure 9 shows the temporal dependence of the plasma amplification with respect to the electron density. The experimental behavior of the plasma amplification has been fitted with numerical data (red curve) obtained from the time-dependent Maxwell–Bloch code DeepOne describing the amplification of HH by the plasma. The amplification factor, $A$, has been computed integrating the energy distribution of the signals using the formula:

$$A = (N_{\text{XRL}} - N_{\text{ASE}} - N_{\text{HH}})/N_{\text{HH}}.$$
150 to 1200 over nearly two orders of magnitude in electron density.

4.5. Final SXRL pulse duration

The main objective of this work is to reduce the duration of SXRL down to 100 fs. In plasma-based XRL, the duration of the lasing emission is directly linked to the temporal evolution of the gain. Knowing the gain dynamic allows to infer the SXRL pulse duration with good precision, at the only condition that the plasma dynamic is correctly modeled. The HH-seeded SXRL pulse duration is Fourier-limited and therefore shorter than the gain duration. This is due to the fact that the HH pulse

Figure 8. Measured electron density maps of the plasma waveguide (only ignitor and heater laser pulses where used) and amplifiers (ignitor, heater, and main driving laser pulse) for two different density conditions ($n_e = 3.2 \times 10^{19} \text{ cm}^{-3}$ (a) and $n_e = 1.2 \times 10^{20} \text{ cm}^{-3}$ (b)).

Figure 9. Temporal dependence of the amplification factor with respect to the seeding delay. Experimental (blue circles) and Maxwell–Bloch-modeling results (red squares) for a scan in the plasma densities.
spectral width is larger than the amplifier narrow linewidth, but also because the HH pulse duration is far shorter compared to the actual plasma temporal response. As density-induced collisional ionization strongly affects, at high-densities, the broadening of the laser transition levels and the amplification duration in the same way, we can rely on the numerical model to infer the SXRL pulse duration. The HH-seeded SXRL duration only depends on the evolution of the atomic processes regulating the laser transition populations. Therefore, one needs to get an accurate description of the broadening processes of the laser transition levels to be able to determine its final duration. Those processes include natural, Doppler and collisional broadening. In OFI plasma amplifiers, ions are relatively cold and the contribution of Doppler broadening gets negligible at high electron densities. Hence, both natural and collisional ionization broadening give the full picture of the underlying atomic processes responsible for the SXRL final duration. Experimental data were compared to results from our Maxwell–Bloch numerical modeling, which well reproduce the gain temporal quenching over a remarkably large range of electron densities covering nearly two orders of magnitude. The good agreement of the numerical fit with experimental data allows getting, besides electron density measurements, a good assessment of the actual electron density, which is pivotal to the description of the broadening effects. As density-induced collisional ionization strongly affects, at high densities, the broadening of the laser transition levels and the amplification duration in the same way, we can be confident that the numerical model reasonably well describes the atomic processes involved in the laser transition broadening. As a result, the SXRL final duration was extracted from the numerical model.

The figure 10 shows the final duration of the SXRL pulses emitted by the HH-seeded plasma for the four experimentally explored electron density and a prospective one at $n_e = 4 \times 10^{20} \text{ cm}^{-3}$. The inferred SXRL pulse duration (RMS) varies from $6.4 \pm 0.3 \text{ ps}$ for $n_e = 3 \times 10^{19} \text{ cm}^{-3}$ down to $23 \pm 6 \text{ fs}$ for $n_e = 4 \times 10^{20} \text{ cm}^{-3}$, thus breaking the decade-long picosecond barrier of plasma-based SXRL, and furthermore opening the sub 100 fs range for this type of coherent soft x-ray source. As shown in figure 10, the temporal structure of the pulse is composed of several periods of Rabi oscillations, induced by the strong amplification of the pulse (reference). In a more realistic 3D geometry, different parts of the beam would induce Rabi oscillations with slightly different periods and only the pulse envelope would be observed [22, 23].

The dramatic reduction of the final SXRL pulse duration allowed by the ‘CIIG’ process, is caused by the anticipated interruption of the gain following the overionization of the medium. To highlight this effect in force at high electron densities, numerical calculations have been carried out artificially fixing the ionization degree of the population of lasing ions.

The figure 11 brings into comparison the amplified HH pulses in the real case, when the plasma ionization degree progressively increases through collisional ionization (blue curve) and in case of an artificially blocked ionization degree (red curve). Those temporal pulse profiles are confronted to the evolution of the average ionization degree of the plasma amplifier over time (data from OFI-OD atomic code). The yellow-tinted shows the region where Kr$^{8+}$ lasing ions exist. This region defines a time window (gray-tinted area), in which lasing action occurs (blue curve). When overionization of the lasing ions population is blocked, the SXRL pulse duration is substantially longer (1.15 ps FWHM compared to 123 fs FWHM for the blue curve). Initially, a dynamic regime governed by the oscillating evolution of the population inversion under the influence of a strong amplified HH
electric field dominates. Rabi oscillations are therefore observed. After, the profile of the amplified pulse is dominated by the impact of the medium depolarization due to electron-ion collisions. The profile of the red curve shows that the pumping process continues and is not limited by overionization.

The inner envelope of the observed Rabi oscillations is the amplified wake induced by the polarization of the medium by the amplified HH field. When the ionization degree is fixed, the pumping process continues and there is a competition between this polarization induced by the HH and the medium depolarization resulting from electron-ion collisions. This phenomena is materialized by the observed ‘shoulder’ on the red curve.

5. Conclusion

A 5 mm long plasma amplifier with a density of $1.2 \times 10^{20} \text{cm}^{-3}$ was successfully seeded by a HH source and yielded a 2 $\mu$J beam displaying a high-quality 1 mrad divergence Gaussian-like beam. The seeding technique allowed to sample the gain dynamics of this amplifier and yielded a 450 fs long amplification lifetime, thus breaking the decade-long picosecond range limitation.

The time-dependent Maxwell–Bloch model was found to be in good agreement with the experimental results over a remarkably wide range of electron density, covering nearly two orders of magnitude. In case of the 5 mm long plasma amplifier at $n_e = 1.2 \times 10^{20} \text{cm}^{-3}$, a final SXRL pulse duration was extracted and assessed at 123 $\pm$ 40 fs (64 $\pm$ 21 fs FWHM).

The generation of longer high density plasmas allowed to reach ASE energies up to 14 $\mu$J and others promising prospects. However, the high signal strength of the ASE signal increases the threshold from which the HH seed can be efficiently amplified. Because of the plasma inhomogeneity, the profile of the final pulse duration is not exactly known at this stage. Further work would require the numerical model to be refined for an adequate description. Qualitatively, the pulse temporal profile is dominated by an intense and ultrashort peak emitted by the highest density regions of the plasma. This peak sits on a longer pedestal corresponding to the emission from the plasma lower densities. Considering prospective higher densities, up to 100 $\mu$J pulses of a few tens of femtoseconds are envisioned.

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References

[8] Oliva E et al 2012 Nat. Photon. 6 764