One long and two short pumping pulses control for plasma x-ray amplifier optimization

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Abstract: Development of efficient soft x-ray laser plasma amplifiers adapted to seeded operation, requires a better control over amplifier transverse spatial extent, brilliance control and gain lifetime. Here it is shown that pumping the plasma amplifier with one long and two short pump pulses (1L2S) provides advantages in terms of control for the specified parameters in the case of Ni-like Ag x-ray laser. Also, significant tunability of the gain lifetime in the 1L2S pumping scheme for Ne-like Ti x-ray laser is observed. Direct harmonics seeding and chirped harmonics seeding amplification approaches may benefit from the control of the gain lifetime, in terms of better use of the pump energy and as a way to reduce the amplified spontaneous emission in x-ray lasers.

OCIS codes: (140.7240) UV, EUV and X ray lasers; (040.7480) X-Rays, soft x-rays, extreme ultra-violet.

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1. Introduction

Plasma x-ray lasers (XRL) generate coherent x-ray emission in the range below 40nm and down to 4 nm. Their operation principle is related to generation of population inversion in laser produced plasmas. A common type of such laser system is based on population inversion generated in Ne-like and Ni-like plasmas produced with short pulse lasers, in the range of nanosecond and picosecond, on solid targets.

Recent developments of x-ray lasers based on one long and two short (1L2S) pump pulses [1–4] have demonstrated significant improvement of the laser output. In contrast with the pumping method based on the one long and one short (1L1S) pumping pulses, the 1L2S scheme allows

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to decouple and independently control the plasma expansion, ionization dynamics and electron temperature.

The enhanced plasma control and the high gain of the 1L2S scheme makes it very attractive for operation as amplifier. Amplification in plasma was first reported in [5] and subsequently addressed in seminal papers such as [6–9], as they promise higher energy, full coherence, short pulses and polarization control. In order to produce the optimal amplification, the seed spatial extent and the seed pulse duration shall match the ones of the amplifier. The 1L1S pumping scheme offers limited flexibility, in this respect. As an alternative, the 1L2S plasma amplifier is investigated here from spatial, temporal and energy output point of view. It is shown that the amplifier transverse spatial extent and brilliance (energy emitted in the unit of surface at the XRL output) can be partially decoupled. This allows better spatial matching of the injected pulse in the plasma amplifier, with subsequent efficient extraction of the energy.

Due to the short time scales of the pump process, the gain is transient. If the seed is shorter than the gain lifetime, the seed often depletes the gain; but immediately after, further upper level population is built as a consequence of high electron temperature, through collisional excitation. The recovered gain is depleted through ASE, compromising the temporal contrast, polarization and coherence properties of the resulting x-ray pulse. The 1L2S Ne-like Ti plasma amplifier is observed to work with a large range of pumping pulse durations, suggesting the possibility to control the gain lifetime. In particular, this range includes a pumping configuration leading to a short gain lifetime of the order of the gain recovery time. As a consequence, it shall be possible to extract the energy stored in the amplifier using only one short seed pulse, and to decrease significantly the parasitic amplified spontaneous emission (ASE).

2. 1L2S plasma amplifier set-up

The experimental set-up used for the studies of the 1L2S plasma amplifier was implemented at the LASERIX facility, as depicted in Fig. 1. High order harmonics were generated using one meter focal distance optics and a one centimeter long Argon gas cell having 20mbar backup pressure with a 4mJ, 40fs laser pulse at 810nm.

The plasma x-ray laser amplifier was placed 7cm away from the Ar gas cell. Two configurations were investigated, Ni-like Ag and Ne-like Ti. As the high order harmonics of the Ti:Sa laser can be easily tuned to contain Ne-like Ti frequency, Ti was chosen for amplification ex-

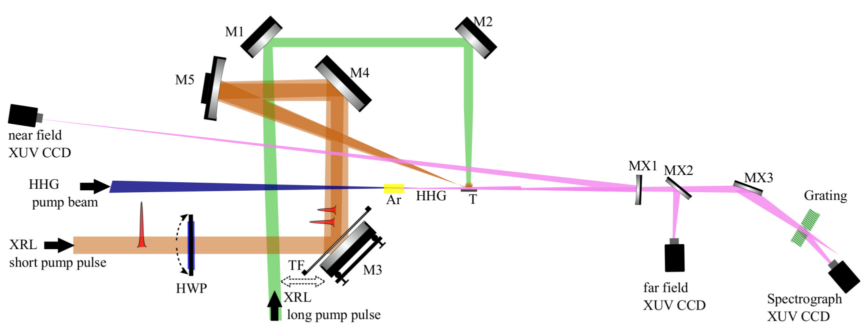

Fig. 1. Schematic diagram of high order harmonics seeded x-ray laser experiment. Ar indicates the position of the Ar gas cell where the infrared beam of 4mJ (blue on figure) is converted in high order harmonics (HHG). M1-M2 are the mirrors for the 6ns pump pulse (green on figure), T indicates the solid target position, HWP is the half wave plate, TF is the thin film beam splitter, M3-M5 are mirrors for short pump pulses, MX1-MX3 are mirrors for the x-ray laser (pink on figure).

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periments. The pumping of the amplifier was based on the 1L2S scheme using, for the long pumping pulse, a Q-switched laser synchronized with a Ti:Sapphire laser used for short pump pulses generation [4,10]. The first 6ns FWHM Gaussian pulse with 150mJ, creating the plasma, was generated with the second harmonic from the Nd:YAG laser (532nm), focused with a cylindrical lens on the target, in a 4mm$\times$ 200μm line focus.

The second pump pulse was generated with LASERIX Ti:Sapphire Chirped Pulse Amplification (CPA) system running at 810nm central wavelength, reaching, in the present experiments, up to one Joule energy on target. The pulse duration in this case was tuned from best compression at 40fs up to 20ps, by varying the grating distance in the optical compressor. The focusing optics was a tilted spherical mirror that sent the short pulse at a grazing angle of 20° on the target. It generated a line focus that was overlapped with the one from the Nd:YAG laser.

A simple modification based on a half wavelength waveplate combined with a thin film beamsplitter was implemented in order to generate two short pulses with the same duration from the short pumping pulse. The thin film is placed at a distance d_{SS} in front of a 90° deflecting mirror. The reflectivity of the beamsplitter varies from 10% to 30%, depending on the polarization of the laser on the thin film. The polarization is controlled with the waveplate, hence the ratio of the energies between the two main pulses generated changes accordingly. The temporal delay between the reflection from the thin film and the one from the mirror is controlled by varying the distance d_{SS} from 1mm to 4mm, corresponding to a temporal delay of 9ps to 36ps.

The seeded XRL is emitted along the direction of the line focus and has a privileged amplification following the direction of the traveling wave.

Final output was analysed by different systems. In the case of Ti XRL emitting at 32.6nm, an Aluminum filter with 300nm thickness was placed at 1m after the plasma amplifier to stop the IR laser. In the case of Ag XRL, Zr filters were used. A removable 45° multilayer flat mirror was employed sending the beam to the x-ray CCD and spectrometer, respectively, which was positioned at 16cm after the first Al filter. When removing the 45° multilayer mirror, the plasma emission is available for the spectrograph measurement. This implements a transmission grating (13$\times$13mm^2, 1000lines/mm) and a vacuum x-ray CCD. A spherical mirror was employed in order to deliver the XRL beam to the transmission grating.

There plasma emission is recorded with a near-field system that images the exit of the plasma amplifier. It consists in a spherical mirror (f = 0.5m), a pair of BK7 flat mirrors and two removable Al filters (1μm and 0.3μm). The spherical mirror is for the relay imaging; BK7 mirrors are used to substantially reduce the IR pump laser and the two removable filters contribute to the flexible final near-filed detection at the exit of this plasma amplifier. The size of the pixel in near field corresponds to 2μm at the object plane.

3. Results and discussion

Three key parameters for seeded XRL amplifiers will be discussed here: the spatial extent of the amplifier, the gain and the gain lifetime. When plasma amplifier is pumped with two pulses (1L1S), limited optimization can be performed, based on the pump pulses energies, durations and delay. In contrast, with 1L2S approach, two additional parameters are introduced, namely the delay between the short pulses and the energy ratio between the pulses; taking advantage of these, higher output energy was reported while the two short pulses help to control the dynamics of the plasma parameters. The direct observables related to the spatial, temporal and stored energy parameters were identified in the near field profile with the equivalent source area, the gain lifetime and the brilliance of the plasma amplifier output operated in the unseeded regime. Further parameters such as coherence, pointing stability, focused spot size are also essential for applications but they are not addressed in the present article.

Energy distribution registered with the near field imaging system allows the determination of

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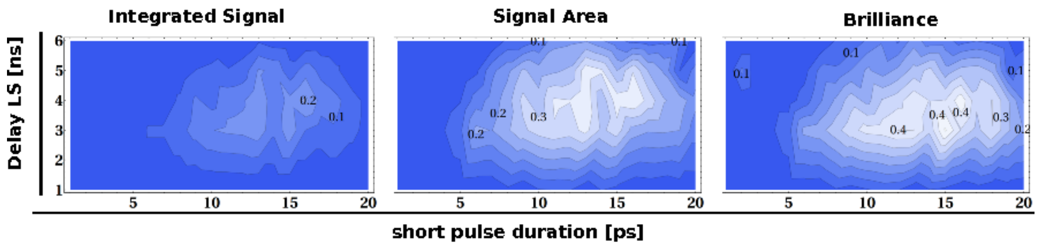

Fig. 2. Ni-like Ag measurements. Left: 1L1S output energy in unseeded operation; Middle: 1L1S unseeded spatial extent; Right: 1L1S Brilliance in unseeded operation

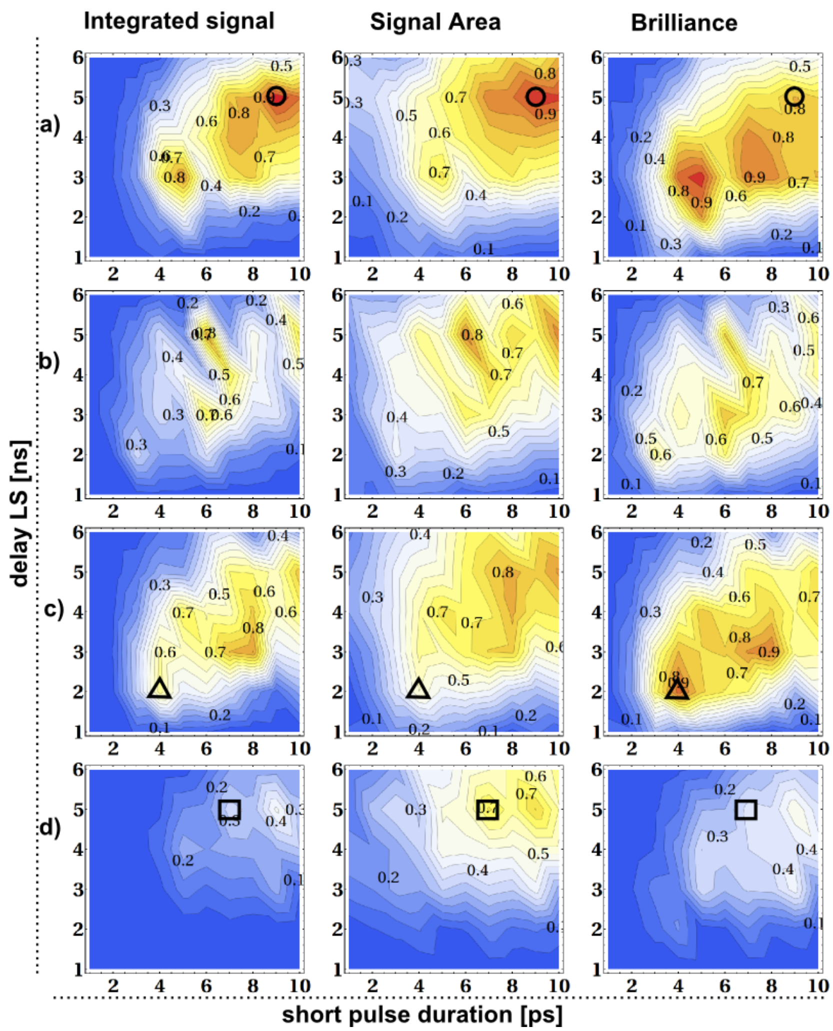

Fig. 3. Ni-like Ag measurements. Left column: 1L2S output energy in unseeded operation; Center column: 1L2S unseeded spatial extent; Right column: 1L2S Brilliance in unseeded operation for δt_{SS} of a) 14ps, b) 20.6ps c) 27.2ps and d) 33.8ps; square indicates the configuration of large near field area small brilliance (LaSb), triangle indicates the small area and large brilliance (SaLb) and circle corresponds to large area and large brilliance (LaLb)

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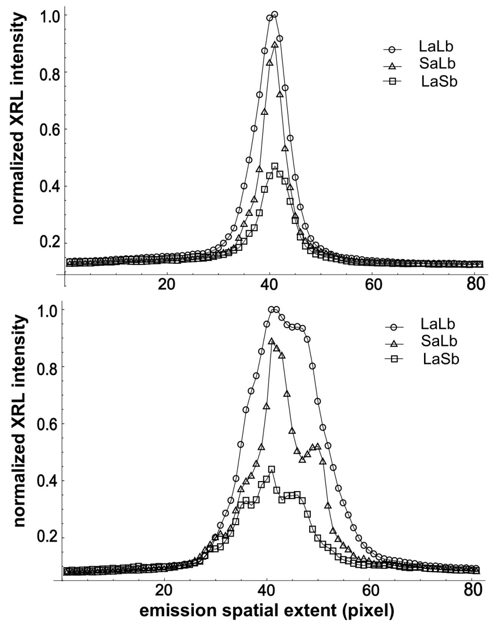

Fig. 4. Comparison of the near field profiles for 1L2S in unseeded operation. Up: along an axis perpendicular with the target; down: along a line parallel to the target. They correspond to large brilliance and large near field area (LaLb circle), to large brilliance and small near field area (SaLb triangle) and to small brilliance and large near field area (LaSb square). Horizontal axis is in pixels (2μm/pixel)

the source area at the exit of the plasma, the integrated output energy and their corresponding ratio. In order to study the source area and the gain, four main pump parameters were systematically varied: the delays between the long and the first short pulse δt_{LS}, the short pump pulse duration τ_S, the delay between the two short pulses δt_{SS} and the energy ratio between the two short pulses. The results are presented in Fig. 2 for 1L1S case and in Fig. 3 for the 1L2S case where δt_{LS} delays vary from 1ns to 6ns, for the case of 30%-50% splitting (corresponding to the highest ASE signals) and for δt_{SS} delays varying from 14ps (Fig. 3(a) to 33.8ps (Fig. 3(d). Note that in both Figs. 2and 3, the energy, laser spatial extent and brilliance are illustrated using the same normalized values and color codes,respectively, in order to make the visual comparison possible. Each of the values are the average from at least two shots. At low signal, the output was fluctuating significantly, up to 100%. At high signals, the fluctuations were smaller, within 50%.

The plasma scale length is mainly driven by the long pulse, in particular by its pumping duration which corresponds to the delays between the long and the short pulse δt_{LS}. It can be evaluated, based on analytic formula from [11], to scale with the long pump pulse duration at the power 7/9. Hence it is larger when few-nanosecond long YAG laser pulses are used for preplasma creation instead of uncompressed pulses from the Ti:Sa pump laser system in the half nanosecond range, with similar energy.

The benefit of large plasma scale length is related to the propagation of the seed in the plasma amplifier and also to the spatial extent of the amplifier. On the one hand, large plasma scale length corresponds to smooth refractive index gradients so it allows a longer propagation time for the seed pulse in the plasma before it gets out from the gain region. On the other hand,

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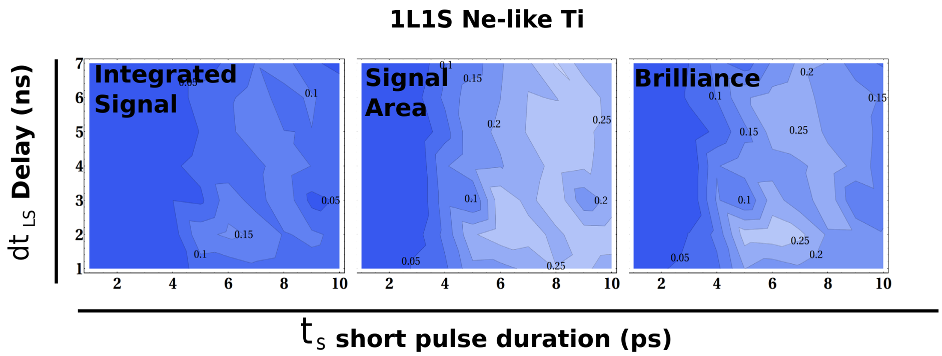

Fig. 5. Ne-like Ti measurements. Left: 1L1S output energy in unseeded operation; Middle: 1L1S unseeded spatial extent; Right: 1L1S Brilliance in unseeded operation

the large plasma scale length has the potential to host larger gain volumes, hence more energy can be extracted from the plasma amplifier.

The source size is influenced by the heating and cooling rates through thermal conductivity and expansion cooling of the plasma. Figure 2(b) indicates that the largest source size in the 1L1S case is about two to three times smaller than the largest one, obtained with 1L2S, as shown in Fig. 3 on the second column. The largest spot area is obtained for relatively large δt_{LS} of 5ns, as expected from the plasma scale length scaling law. The optimal short pump pulse duration however is smaller in the 1L2S scheme, while the output energy is four times higher, corresponding to a source brilliance two times higher in the 1L2S case. We denote this parameter region as large area large brilliance regime (LaLb) and is marked with a circle in Fig. 3 for δt_{SS} delay of 14ps.

When operating the unseeded plasma in the 1L1S configuration, the highest brilliance is obtained at δt_{LS} of about 3-4ns, as shown in Fig. 2. However, in the case of 1L2S configuration, 2.5 times higher brilliance is obtained for δt_{LS} delays varying from 2ns to 5ns, as shown in Fig. 3 for δt_{SS} delays varying from 14ps (Fig. 3(a) to 28ps (Fig. 3(c). A parameter region with small area and large brilliance (SaLb) is marked on the map with a triangle, corresponding to short pulses of only 4ps and δt_{LS} of 2ns, corresponding to smaller plasma scale lengths, as expected.

A third operation regime was identified for large δt_{SS} delays of about 34ps, as large area small brilliance (LaSb). It is marked with a square in Fig. 3(d). Again, the large δt_{LS} of 5ns indicates a large scale length of the plasma, while the large δt_{SS} delay controls the reduction in the brilliance, hence the plasma gain.

A comparison of the near field profiles along axes perpendicular to the target (up) and parallel to the target (down) are presented in Fig. 4 as profiles for the 1L2S selected pumping configurations indicated in Fig. 3. They correspond to large brilliance and large near field area LaLb (circle), to large brilliance and small near field area SaLb(triangle) and to small brilliance and large near field area LaSb (square).

Ne-like Ti corresponds to a charge state 12+ while Ni-like Ag corresponds to 19+, hence Ni-like Ag requires more energy to be produced. As we used similar pumping energy in both Ag and Ti XRL, the ionization takes more time in the case of Ni-like Ag than in the case of Ne-like Ti. Nevertheless, the experimental results for Ne-like Ti XRL are similar to the ones for Ni-like Ag XRL. The experimental results are presented in Fig. 5 for the 1L1S pumping scheme while the results corresponding to 1L2S are presented in Fig. 6. The short pump pulse duration τ_s needed to obtain strong XRL emission is reduced at least a factor of two for Ti in both 1L1S and 1L2S cases, when compared to Ag case, while the XRL output increases a factor of 6 [4].

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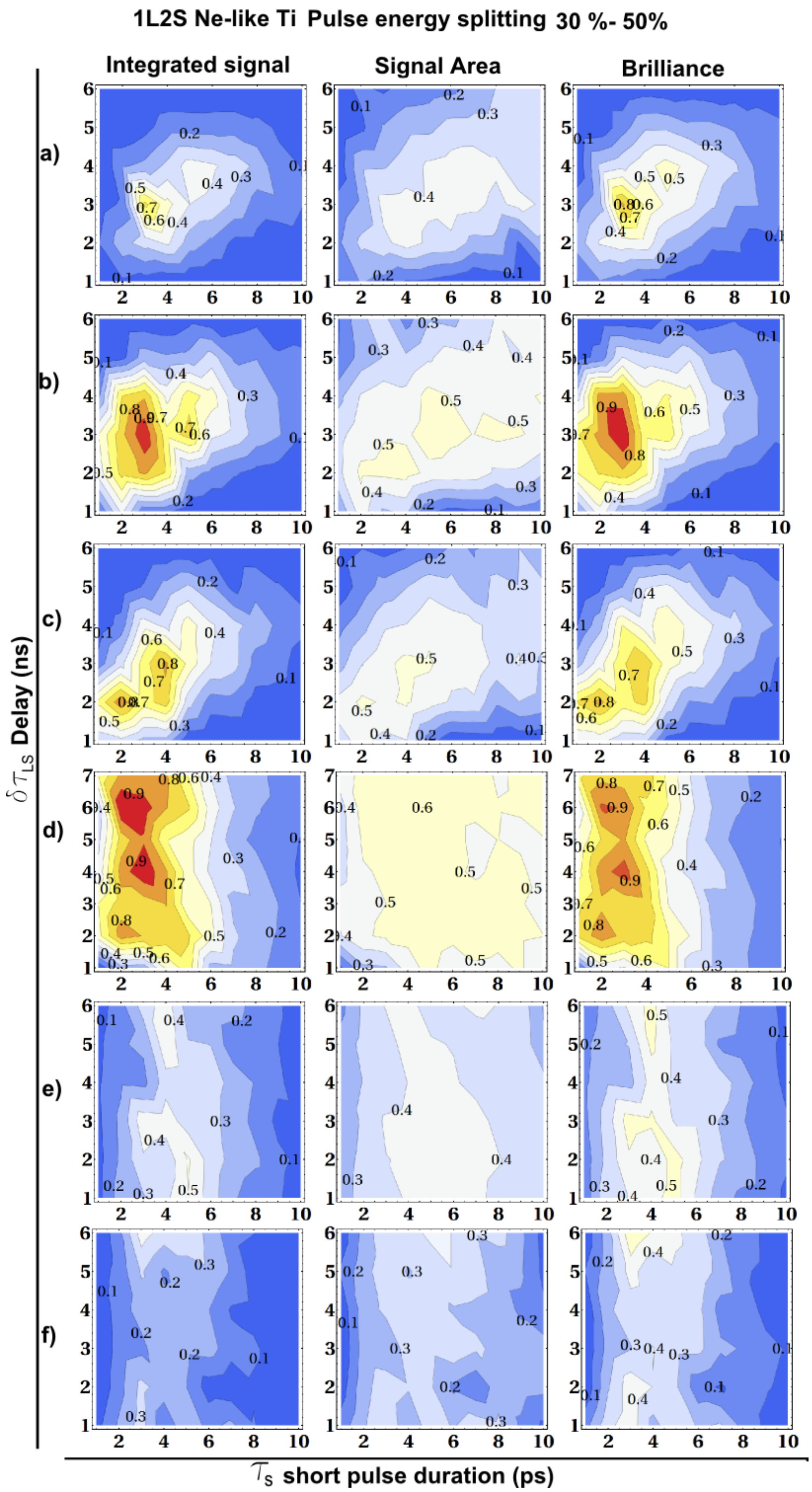

Fig. 6. Ne-like Ti measurements. Left column: 1L2S output energy in unseeded operation; Center column: 1L2S unseeded spatial extent; Right column: 1L2S Brilliance in unseeded operation for δt_{SS} of a) 14ps, b) 20.6ps c) 27.2ps and d) 33.8ps, e) 40.4ps f) 47ps

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Also, the optimal short pump pulse duration decreases from 6ps down to 3ps when going from 1L1S to 1L2S in the Ne-like XRL. It can also be noted that the area and the brilliance of the XRL across the spatial extent are linked so less tunability of the spatial extent is observed in this case. As a consequence, the high energy and high brilliance are simultaneously observed at the same pumping parameters.

The above considerations help to chose proper 1L2S configuration for seeded amplification systems where the seed pulse duration and the gain lifetime in the amplifier are similar. This condition is usually fulfilled in plasma based seeding systems as demonstrated e.g in [12] with a double target seeding configuration, or in the CPA XRL system proposed in [8] where harmonics were used instead of XRL emission as seed.

However, in the case of direct injection of high order harmonics, this is no longer the case, as the seed pulse duration is in the tens or hundreds of femtosecond range. In order to have a broader picture of the amplification issues, the temporal aspects corresponding to the gain dynamics have to be addressed. Three parameters which were systematically scanned in our experiments, the short pump pulse duration τ_S, the delay between the two short pulses δt_{SS} and the energy ratio between the two short pulses r, impact on the gain lifetime.

In a direct seeded amplifier scheme, the gain lifetime shall be shorter than the gain recovery lifetime, in order for the stored energy to be transferred only to the seed. In a similar type of seeded plasma x-ray laser experiment [9], the recovery time was measured to be about 2ps. In another experiment reported in [12], using two XRL targets in a master-amplifier configuration, the lifetime of the transient gain in a Ni-like silver medium was determined to be within the range of 3ps.

Also, several other studies indicate an unseeded TCE XRL pulse duration for scheme in the range of 1.7ps to 11ps [13–17] while for the seeded version the pulse duration goes down to the 1ps range [18].

The grazing incidence pumped XRL pulse duration decreases with the main pump pulse duration [17]. The final XRL pulse duration shall be close to the gain recovery time in order to reduce the ASE growth in the XRL plasma amplifier. As demonstrated by the seminal work of [19], ionization gating of the gain might not only help to reduce the gain lifetime to have a better matching of seed amplification and pumping dynamics but also will increase the dephasing rate and so the bandwidth of the amplifier. On the other hand, 1L1S shows optimal emission for 15ps short pump pulse duration, which is relatively large value. However, as indicated in Fig. 3, the short pulse duration can be significantly decreased down to 4ps, in the case of 1L2S scheme, for example in the case of SaLb. It is expected that also the gain lifetime is significantly reduced in this case.

In order to experimentally validate this hypothesis, injection of the harmonics in the plasma amplifier was tested. Ne-like Ti plasma was produced for these tests and 25th harmonic of the CPA laser was injected. Energy stability from shot-to-shot was obtained as $\pm16\%$ over 20 consecutive shots, which is sufficient for the input condition as coherent seed source for the XRL seeding experiment.

When 1L1S scheme was used, low amplification of the signal in the plasma amplifier and large ASE background were hindering the observation of the amplification, in spite of the very good spatial and temporal coherence of the harmonics seed pulse.

Alternatively, the 1L2S scheme was used for the amplification of the harmonics. In this case, high coherence of the emission was recorded. The gain lifetime was recorded by varying the arrival of the seed relatively to the maximum of the second short pump pulse; it is shown in Fig. 7. The maximum of the gain was obtained at zero delay to the second short pumping pulse.

The amplification factor itself was estimated to be 180 in the 1L2S optimal case. The gain lifetime was measured to be 2ps in the configuration with τ_S=4ps short pump pulses. However,

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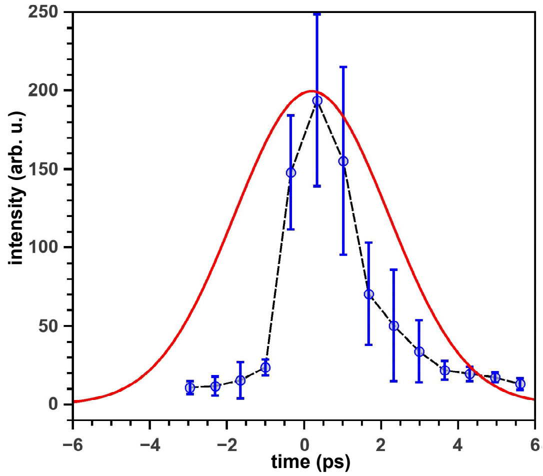

Fig. 7. Harmonic amplification factor as a function of the injection time (0ps corresponds to the main short pulse peak intensity [20]).

in the 1L1S case longer pulses are needed in order to observe the amplifier output. Here, using τ_S=9ps the measured gain lifetime was about 4ps. Even if seeding is successful in 1L1S, the resulting signal is weaker than in 1L2S and, as a consequence, sank in the ASE from the plasma amplifier. These results, discussed in [20], support the hypothesis on the gain lifetime reduction with the short pump pulse duration, in line with the previous results [14–17].

The result impacts on the way a plasma amplifier is realized. The usual choice for a plasma amplifier, 1L1S pumping scheme, does not have the flexibility to provide simultaneously both short τ_S and high gain in low energy pumping experiments. The long gain lifetime of plasma amplifier was seen as a critical problem in the scalability of XRL to higher energies through seeding [8] and an approach using stretched harmonics pulses was proposed to by-pass it. The 1L2S pumping scheme removes this issues while it allows shorter pumping pulse duration τ_S, hence smaller gain lifetime, as discussed in [20].

In conection to these results, the major issue discussed here is the operation mode for the plasma amplifier. Up to now, the injection of the seed pulses was performed in plasma amplifiers where the unseeded operation was providing the best energy output. However, if the gain lifetime is long, this operation mode corresponds to an amplifier with a large ASE as background. The 1L2S measurements in terms of brilliance, in conjunction with the gain lifetime shortening indicated by the measurements [20] indicate that the amplifier works better at lower unseeded energy outputs.

A possible example is indicated with triangles for the case of Ag XRL in Fig. 3(c) τ_S=27.2ps (SaLb). In such case, the energy output is only half when compared with the best operation mode. However, the brilliance is comparable with the LaLb case marked with circles in Fig. 3(a). The gain lifetime is expected to be further reduced for the SaLb in comparison with the LaLb, hence the ASE emission is strongly reduced, providing in this way an amplified pulse closer to the Fourier limit.

It has to be pointed out that the amplified pulse might have reduced energy, nevertheless better coherence properties. The loss of energy could be compensated by designing slightly longer plasma amplifiers, to increase the energy output. In the ideal case, when the gain depletion lifetime is smaller than the population inversion lifetime and the seed has the proper energy input, the ASE shall be completely suppressed.

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4. Conclusions and outlook

High brilliance plasma amplifier reported in literature are limited to about 2mm length, as the ASE of the plasma amplifier becomes dominant over the amplified signal when longer plasma columns are used. Control of the amplifier spatial extent, of the gain and of the gain lifetime is therefore needed for optimal amplification. The reduction of the gain lifetime, obtained with 1L2S scheme, is beneficial in the ASE reduction.

In the present work, a plasma amplifier pumped with one long and two ps short pulses was optimized for high order harmonics amplification. Using 1L2S scheme, it is shown that the volume of the gain and brilliance of the Ni-like Ag XRL amplifier in the ASE running mode can be controlled in this way.

Complementary, the gain duration lifetime was measured for different short pump pulses durations τ_S for 1L2S Ne-like XRL. The measurements are indicating that the gain lifetime is significantly reduced in this case, and also that the gain increases.

If the gain lifetime is comparable with the injected signal pulse duration, complete depletion of the population inversion in the amplifier without gain recovery can be expected, hence fully coherent beam amplification in long plasma amplifiers. As a consequence, using 1L2S amplifier with ionization gating, a matched gain lifetime can be engineered for the CPA XRL scheme, depending on the chirp of the injected harmonics. Alternatively, the gain lifetime can be shortened to values comparable with the recovery lifetime of the gain using the 1L2S pumping scheme. This would allow the construction of significantly longer plasma amplifiers with suppressed ASE emission, hence preserving the high order harmonics beam quality and increasing output energy of the XRL system.

As a final note, the plasma refractive index gradients also limit the useful length of a plasma amplifier. But also here, the large range of delays between the long and short pump pulses, achievable with 1L2S approach, correlate with the transverse spatial extension of the amplifier and indicate lower gradients at large δt_{LS} long-short delays, making possible, in this way, longer plasma amplifiers.

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