10-Hz grazing–incidence pumped Ni-like Mo x-ray laser

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The operation of a Ni-like Mo x-ray laser at 18.9 nm with a repetition rate of 10 Hz has been demonstrated. The laser has been pumped applying the grazing incidence pump arrangement, where a short (picoseconds) pulse irradiates a Mo plasma column generated by a long (a few hundred picoseconds) pulse. The delayed short pulse is incident at a grazing angle on the plasma to heat it efficiently. We used a total energy of less than 450 mJ (150 mJ in the long and 250–300 mJ in the short pulse) in a line focus of 7 mm by 50 μm.

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The GRazing Incidence Pumping scheme (GRIP) proposed and demonstrated in the proof-of-principle experiment in 2003 [1] constitutes an additional step towards a high repetition rate table-top x-ray laser. It belongs to the group of pre-pulse techniques and offers inherent travelling wave pump. Hitherto existing pump arrangements applied either lateral or longitudinal irradiation of a slab target. Only in few setups both geometries were combined in this way that the pre-plasma was created by a laterally incident beam while the heating pulse was directed nearly parallel to the target surface, i.e., along the axis of the plasma column [3,4]. In all these schemes the pumping efficiency was limited by the fact that the heating picosecond pulse either deposited its energy dominantly at the critical surface (lateral pumping) or could not uniformly heat the active medium due to significant losses for ionization and excitation in a very long active medium (longitudinal arrangement). Thus, only a limited part of the available energy was converted into useful excitation energy [1].

The pump geometry based on grazing incidence is not absolutely new as such an arrangement has been proposed by Ozaki *et al.* [5] to increase the absorption length and active medium volume. An obliquely incident beam (60°) was also applied in the experiment reported in [6]. In the GRIP geometry proposed in [1] a long (subnanosecond range) pulse is focused to a line on a polished metal slab target and after an optimized delay of a few hundreds of picoseconds to a few nanoseconds a second much shorter heating pulse with a duration between one and several picoseconds irradiates the preformed plasma column at a grazing angle (12°–17°). This angle should assure the maximum energy absorption in the area of a required plasma density. In such an arrangement a significant part of the active medium is irradiated twice. This is a result of refraction of the incident beam on the plasma density gradients. As sketched in Fig. 1 a part of the incident radiation can, after deflection, overlap the directly incident beam. This part is deflected close to the critical surface and does not traverse this high density/absorption region, as it is the case for purely lateral irradiation. Therefore, its energy is deposited by collisional absorption, dominantly in the useful, from lasing point of view, active area. Overlapping of both pulses increases the deposited energy, even if the deflected pulse is weaker due to a longer interaction/absorption path. The optimum grazing angle depends on the profile of the refraction index, i.e., on the value and position of the critical density surface and the density gradient which, in turn, depends on dynamics of plasma preforming. Due to the small grazing angle the GRIP scheme includes inherently travelling wave pumping.

In the present paper we demonstrate soft x-ray lasing at 18.9 nm obtained with a different set of pump parameters, if compared to the experiments reported in [2,7]. The goal of this experiment was giving an additional insight in the acceptable parameter range of the new pumping scheme. Such experiments are necessary as the pump drivers are at the moment not sufficiently flexible to scan the full interesting range of pump parameters with a single laser system. Any variation in energy of one pump pulse occurs at expense of the energy of the other one.

In our experiment a Ti:sapphire high power laser was used with an energy of 450 mJ. For the GRIP scheme the stretched CPA laser pulse was split before the compressor. The long (uncompressed) pulse of 150 mJ in 400 ps (measured at the target position) was coupled out and the remaining part was compressed to a pulse with an energy between 250 mJ and 300 mJ in 9 ps. The temporal delay between the two pump pulses is of fundamental importance for the scheme to work and could be adjusted between 400 ps and 1800 ps. These two pulses were focused within the GRIP arrangement onto a polished Mo slab target. The long pulse irradiated the slab target in the direction normal to its surface. It was focused with a spherical lens ($f=500$ mm) and a cylindrical lens ($f=-250$ mm). The short pulse was

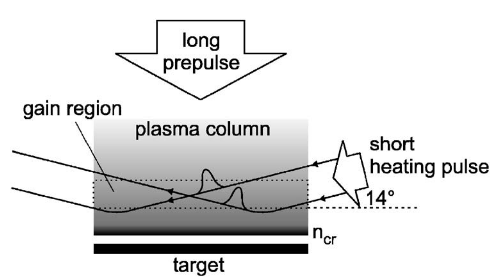

FIG. 1. Sketch explaining the GRIP principle and double irradiation of the active area by the pump beam.

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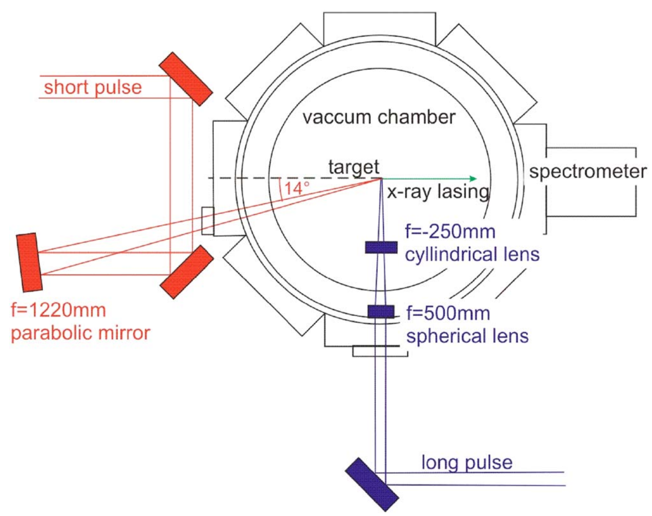

FIG. 2. (Color online) Grazing incidence pumping (GRIP) scheme.

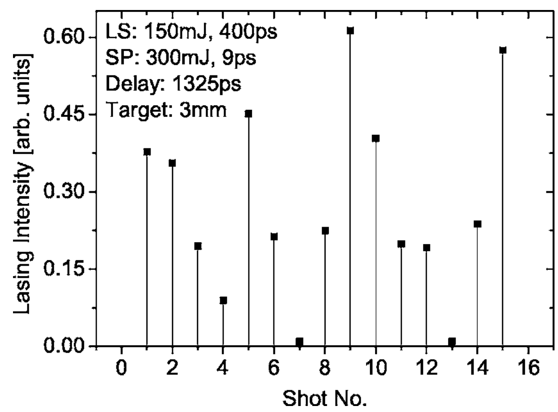

FIG. 4. Sequence of XRL pulses registered with a repetition rate of about 1 Hz.

focused with a parabolic mirror ($f=1220$ mm) at the grazing angle of 14° to the target. Both focal lines were 7 mm in length and 50 μm in width, resulting in an intensity of 1×10^{11} W/cm^2 and 9×10^{12} W/cm^2 for the long and the short pulse, respectively. Thus, our pump energy was positioned between the energies used in other two experiments [2,7], while the intensities determined by a broader focal line and pulse length were the lowest ones among the reported pump parameters and could not be increased in the applied laser configuration. Figure 2 shows a sketch of our GRIP setup.

Applying these pump conditions together with the GRIP geometry to a Mo slab target we were able to show lasing at 18.9 nm. Best lasing conditions were found at a temporal delay of 1280 ps. Lasing was obtained with a delay between 1220 ps and 1350 ps (see Fig. 3). We succeeded also in demonstration of lasing at a 10 Hz repetition rate under the same pump conditions, although target dimensions allowed only a short-term operation in this regime (about 100 shots). For quasicontinuous operation a new “refreshable” band target is in preparation. The output data was in principle acquired in a single-shot mode but the CCD camera was tested for a short time in the repetitive regime of 1 Hz (see Fig. 4). Up to 20 shots could be fired on the target without a change in its location. After that, degradation of the target affected the output in a visible way. Figure 4 shows a sequence of shots at a repetition rate of about 1 Hz and a typical scale of shot-to-shot fluctuations for a specific delay between the pump pulses of 1325 ps.

The delay has appeared to be a very critical parameter at the energy level used since the tolerance window width was just ±5%. With a delay of only 65 ps from the optimum no lasing could be detected. However, it has to be stressed that with increased energies on the target of 180 mJ in the preforming pulse and 430 mJ in the heating pulse with the length shortened to 6 ps, we could observe lasing in a much broader temporal window of 500 ps, between 650 and 1150 ps (see Fig. 5). This increase in the pump energy was possible only on a short-time scale due to technological constrains on the laser system operation.

From the spatial extension of the lasing line on the detector, we estimated the divergence of the XRL beam (Fig. 6). The CCD detector was positioned 860 mm away from the target (see Fig. 2). Starting from this data one can estimate a divergence being equal to about 3–5 mrad. This is a very

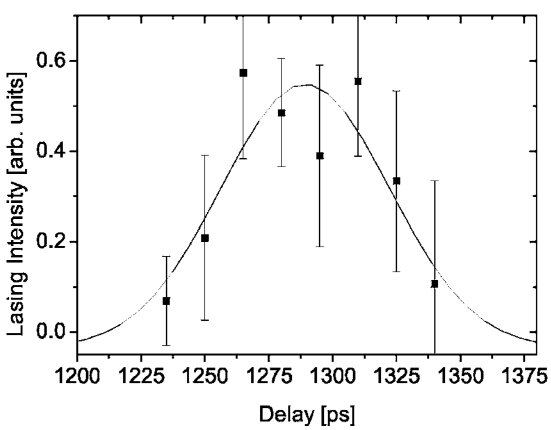

FIG. 3. Dependence of the x-ray laser output signal on the delay between both pump pulses. Each measurement point is a result of averaging over 10 shots. Parameters as in Fig. 4.

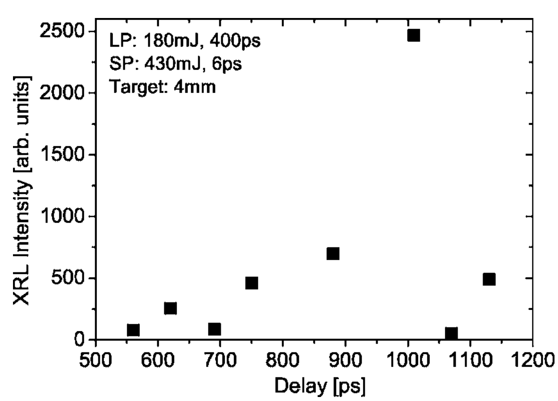

FIG. 5. Delay temporal window for lasing achieved with more energetic pumping. The best results for each delay setting are shown.

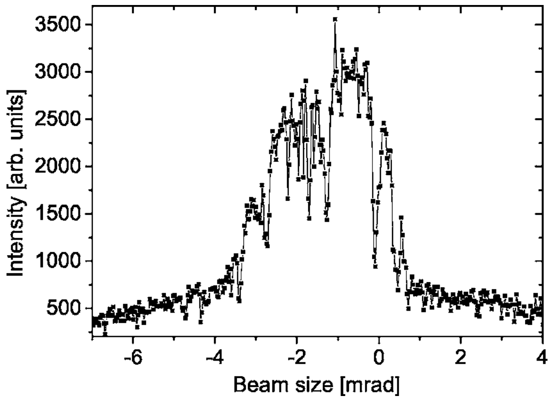

FIG. 6. Lineout of the image of lasing traced along the recorded line to determine the XRL beam divergence. The dips in the shape are caused by the supporting structure of the Al filter foil. For the pump pulse parameters, see Fig. 7(a).

small value for such a short target and suggests the existence of soft density gradients in the plasma column.

Figure 7(a) shows a typical spectrum with the Mo lasing line recorded at the optimum delay between the pump laser pulses. The small step in the spectrum at about 17.2 nm was caused by the Al absorption L edge from a 140 nm thick Al filter in front of the spectrometer. The lasing line at 18.9 nm dominates clearly the spectrum. No other line could be extracted.

Due to the high nonlinearity of the processes accompanying lasing, the output of this unsaturated x-ray laser enhances fluctuations of the pump radiation parameters. Additionally,

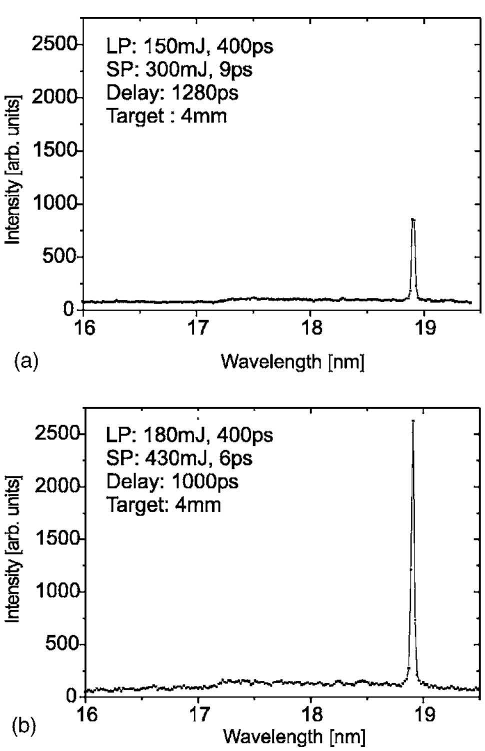

FIG. 7. Soft x-ray spectrum with dominating Ni-like Mo lasing line at 18.9 nm. The step in the spectrum at around 17.2 nm is caused by the absorption L edge of Al used as a filter.

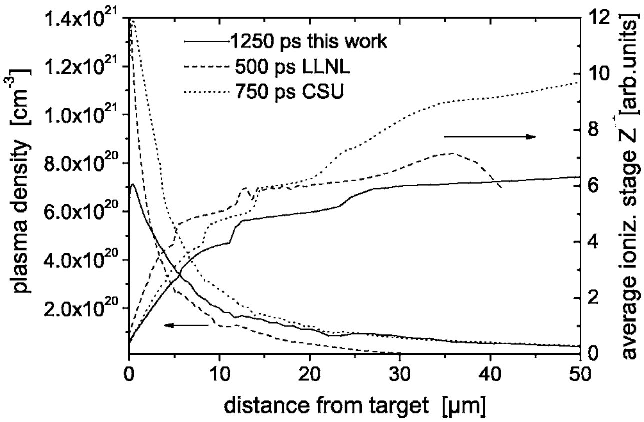

FIG. 8. Dependence of the plasma density and average ionization stage on the distance from the target surface at the time of optimum delay. The simulation was performed with the prepulse parameters of the reported experiments at Max-Born-Institute (MBI, 1×10^{11} W/cm^2, 400 ps), Colorado State University [7] (CSU, 2.4×10^{12} W/cm^2, 120 ps), and Lawrence Livermore National Lab [2] (LLNL, 5×10^{11} W/cm^2, 200 ps).

the GRIP arrangement is very sensitive to the accuracy of alignment, e.g., we could see lasing turning the target around its vertical axis by 15 arcmin. Therefore, the gain is estimated by comparing the lasing intensity for 3 mm and 4 mm target lengths. We estimated a rough gain factor of 20 cm^{-1}. One can expect considerably higher gain under harder pump conditions. This expectation is supported by two facts. Our pump parameters were very similar to those identified in [7] as slightly exceeding a lasing threshold (140 mJ in 120 ps and 310 mJ in 8 ps), and, as can be seen in Fig. 7(b), we obtained considerably stronger lasing using harder pumping conditions (180 mJ in 400 ps and 430 mJ in 6 ps).

The pump parameters in our experiment were determined by the output of the used Ti:Sa laser system and could be varied in a limited range. The parameter set was positioned energetically between those reported in other two experiments but offered the lowest intensity on the target. The mentioned experiments demonstrated either irrefutable gain saturation [7] or strong indications of the work in this regime [2]. The measured optimum delays suggest significant differences between the working regimes in all these experiments. We have simulated, using EHYBRID hydrodynamic code, the preplasma conditions expected after irradiation with the preforming pulses relevant to each of the experiments. It is fairly justified to expect that the preforming process is very important for XRL operating in the GRIP geometry as not only the state of the plasma column but also the pump pulse propagation are affected by the plasma preforming process. We concentrated our interest on the plasma density and the ionization balance. The plasma temperature is of secondary importance as the ionization balance constitutes already an expression of the electron temperature and on the other hand the parameters of the heating pulse decide about the final plasma temperature. The simulation results for the optimum delays are shown in Fig. 8. It has to be stressed that such simulations are always connected with some quantitative uncertainty of the interaction description (especially the full equation of state—here the CHART-D formulation was used) at very low fluences. However, it can be very useful for the sake of comparison. It is seen from Fig. 8 that both prepulses of higher intensity gave a steep and very similar density distribution (gradient). Our preforming pulse of lower intensity delivered a plasma plume with very soft density gradients. This explains low divergence (see Fig. 6) and small deflection observed in our shots with lasing.

A combination of the ionization balance and the plasma density traced in Fig. 8 could explain the notable differences in the output signal observed among the reported experiments [2,7]. Considering these data we found that short, intense but of low energy pre-forming pulses create rapidly a high (close to its maximum) average ionization stage (dashed line in Fig. 8). This high ionization stage can compensate some deficit in the plasma density at distances where lasing usually originates. And vice versa, short, intense but of high energy pulses ablate more plasma (density increases) and are not able to heat it sufficiently fast (dotted line in Fig. 8). As a consequence, the ionization stage increases slowly. This underionization is compensated by higher density. Both variants lead to high inversion as a notable abundance of Ni-like ions was created in both cases. There exists apparently an optimum in relation between the prepulse length and its energy/intensity assuring efficient collisional ionization. It is worth noting that in all cases the plasma is underionized and the final ionization stage will be achieved parallel to the heating process by the short pulse.

The preplasma dynamics can also be affected by the pump energy fluctuations, its distribution along the focus line and by local inhomogeneities of the target material or imperfect surface. We have tested three different prepulse energies (110 mJ, 180 mJ, and 240 mJ) with correspondingly reduced heating pulse energies and found that only the energy level between 150 and 200 mJ gave lasing. This was very likely the result of a reasonable balance between the plasma amount to be heated and the energy available in the heating process (short heating pulse). The longer delay in our experiment points to slow development of the conditions suitable for efficient excitation (lasing) but due to the decreasing density the required abundance of Ni-like ions cannot be obtained and the achieved gain is low. Additionally, lasing requires the build up of a plasma column ensuring efficient sampling of the active medium by the amplified signal and outcoupling of the extracted energy. The relatively low intensity in our experiment limited the ablation pressure, caused underionization of the optimum density plasma and resulted in the threshold-near lasing.

In summary, we have demonstrated lasing at 18.9 nm pumped by a total energy of 450 mJ. This result is supplementary to two other experiments as it shows lasing at conditions significantly different from those in the mentioned experiments. The results point to the importance of not only the pump energy/intensity but also to its temporal distribution (dynamics) in the pumping process. Having enabled lasing with the energies well below 1 J, the GRIP geometry helped to clear the way towards a repetitive, efficient x-ray laser—expanding the class of suitable laser drivers by including the laser systems working at a repetition rate of 10 Hz.

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