PHYSICAL REVIEW E **75**, 045401(R) (2007)

Optimal main pulse angle for different preplasma conditions in transient collisionally pumped x-ray lasers

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(Received 28 February 2007; published 12 April 2007)

The effects of the incidence angle of the main pump (MP) pulse in non-normal pumping geometry and the influence of the MP duration are investigated experimentally and theoretically for a transient collisionally pumped (TCE) x-ray laser in Ni-like Zr at 45° and 72° incidence angle on the target. The way they transfer to the x-ray laser output depends on the preplasma conditions, most notably on the average ionization distribution at the arrival of the MP. Moreover, contrary to previous grazing incidence pumping results, it is found that the shortest attainable MP maximizes the output. Modeling of the experimental results is performed with EHYBRID code. The results are important for scaling high repetition-rate non-normal incidence pumped lasers to sub-10 nm wavelengths.

DOI: 10.1103/PhysRevE.75.045401 PACS number(s): 52.50.Jm, 52.59.Ye, 52.38.Dx, 52.25.Jm

I. INTRODUCTION

In the history of plasma x-ray lasers a significant improvement was achieved in the 1990's with the transient excitation method [1]. This excitation scheme has several attractive properties such as (a) inversion can occur at arbitrary electron density and it increases with larger electron density and (b) the gain coefficient is several times higher, less sensitive to the details of the kinetic model. In principle, since this scheme works in the rapidly ionizing plasma where the recombination processes are weaker, there are (c) no restrictions to an active media dimension. The group at Max Born Institute in Germany reported the first transient collisionally pumped (TCE) x-ray laser (XRL) system, running at 32.6 nm in Ne-like Ti using a nanosecond long prepulse and a short MP of the order of picosecond [2]. There was a significant reduction in the pumping power needed and this approach opened the way to XRL for few Joule laser systems.

In 2003, another important step toward the reduction of the pumping energy was achieved in the grazing incidence pumping (GRIP) scheme by controlling the incidence angle of the MP on the target [3]. As a consequence, the energy of the MP can be deposited in the density region where the gain is expected (of the order 10^{20} cm^{-3}). A well known formula (see, for example, Ref. [4]) states that the turning point electron density n_e for a laser pulse propagating in a plasma with linear density profile depends on the incidence angle according to $n_e = n_{ec} \cos^2 \alpha$, where n_{ec} is the critical plasma electron density and α is the incidence angle on target. In this paper the "incidence angle" refers to the angle relative to the normal at the target, while "the GRIP angle" refers to the angle relative to the tangent at the target. With high repetition rate and higher energy pump laser systems (of the order of tens of J) being build around the world to date, the GRIP technique could be used in two major directions: first, producing higher output of similar TCE XRL as those demonstrated in the cited papers and, second, for demonstrating shorter XRL wavelengths. However, this is not a trivial task, and here are reported results concerning the implementation of the GRIP scheme in such high energy regime. The major result is that there is no absolute optimal GRIP angle while it depends on the way the preplasma is generated.

Experimental results for high energy pumped GRIP XRL in a new operation regime close to the one proposed in Ref. [1], demonstrated at the PHELIX laser facility in Darmstadt are analyzed. Lasing in Zr is demonstrated for 45° [5] and 72° incidence angle of the MP, with similar output energies, and both reaching saturation. It is found that, in contrast to the 45° case, optimal output is obtained with the highest intensity (shortest MP duration provided by the pump laser) for the GRIP geometry with 72° incidence angle on target. As shown by the EHYBRID code [6], this behavior has to be attributed to the interplay of the density, temperature, and average ionization state ($\bar{z}$) distributions: at large MP incidence angle, high $\bar{z}$ in low density region of the plasma is heated while, gradually increasing the incidence angle, the MP is heating lower $\bar{z}$ plasma with higher densities, much of the energy being spent on the ionization of a large quantity of plasma to the right ionization stage.

On the other side, the GRIP XRL systems reported to date are seemingly operating in a quasisteady state regime [7]. Their optimization has shown that the highest energy output is obtained when they are operated with more balanced pumping over a longer gain lifetime by using a MP with a duration up to 8 ps instead of subpicosecond pulses [8–10]. The apparent contradiction of the results reported here with the above cited results is elucidated in terms of the influence of the charge state distribution $\bar{z}$ at the arrival of the MP. In the results reported here, the energy used for the prepulse is

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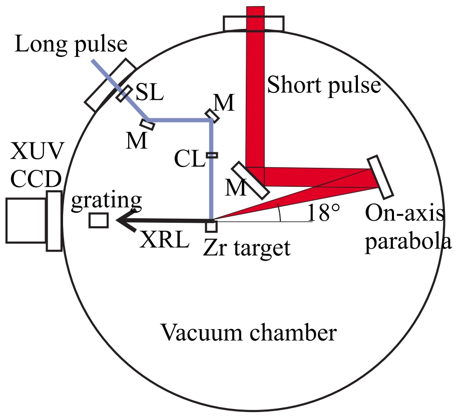

FIG. 1. (Color online) The setup for the 72° MP angle; M=flat mirror, SL=spherical lens, CL=cylindrical lens.

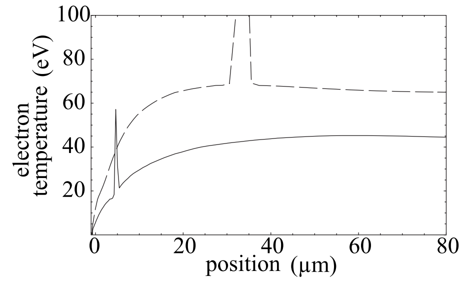

FIG. 2. Temperature distribution in the plasma at the arrival of MP as a function of the distance measured normal to the target. Target position is 0. The temperature peaks are showing the places where the MP starts to be deposited, corresponding to half of the critical density for 45° configuration (line) and to a tenth of the critical density for the 72° configuration (dashed line).

significantly higher and the average $\bar{z}$ needed (12+) is lower than in the previous work. In this way, the optimal charge state is produced deeper in the plasma, in higher electron density regions. The 45° incidence angle for MP is depositing the energy deeper in the plasma, at higher electron density regions, as needed in this case. In this way, the final answer concerning the optimal GRIP angle is obtained. The optimal GRIP angle for a given target material is not determined by the electron density distribution only but also by the charge state distribution as generated by the prepulse and corresponds to the specific experimental conditions.

II. EXPERIMENTAL SETUP

The XRL experiments in Ni-like Zr at PHELIX were performed in two campaigns with similar setups, except for the incidence angle of the MP on target. The nanosecond pulse is focused by a cylindrical lens with 250 mm focal length combined with a 1 m focal length spherical lens to a line focus of as low as (30 μm $\times$ 6 mm) onto a Zr metal target. A single, gold coated, 6 inch diameter on-axis parabola, tilted at an incidence angle of 22.5° and 9°, respectively, is used to generate a line focus of 11 and 5 mm length having the width of 30–100 μm. This geometry intrinsically leads to a tilt of the pulse front generating in this way the "traveling wave excitation" needed for the TCE XRL. The first geometry leads to an incident angle on target of 45°. In the second case the incidence angle of the MP on target is 72°. For the 72° MP angle setup see Fig. 1.

The experiments at 45° MP incidence angle used a total energy from the PHELIX preamplifier of 5 J. 67% of the energy was delivered to the 10 J optical pulse compressor, 33% was split off for the 0.8 ns prepulses. After compression a MP energy of 2.4 J was delivered on the target. The length of the line focus was 11 mm for both prepulse and MP. The peak-to-peak delay between the pulses was optimized to 0.7 ns. The incidence angle of the MP (45° on target) corresponds to a MP laser turning point density of 4.5×10^{20} cm^{-3}. The MP duration was varied from 0.5 to 6.4 ps. With a height of the focus line of 90 μm for the prepulse and 50 μm for the MP, the focused intensity was 1.2×10^{11} W/cm^2 and $0.625-7.75\times10^{14}$ W/cm^2, respectively. The optimum MP duration was identified to be around 3 ps using a 5.75 mm target. For this duration the output energy of the XRL was three times higher than for a 0.5 ps pulse. Using the same parameters the gain curve was measured at a MP intensity of 1.66×10^{14} W/cm^2.

For the experiments employing an incidence angle on the target of 72°, the output energy of the preamplifier was limited to a maximum of 3.7 J. The angle corresponds to a MP laser turning point electron density of 10^{20} cm^{-3}. The line focus generated for the prepulse had 6 mm length and 80 μm width and the pulse duration was 800 ps, corresponding to an intensity of 2.35×10^{11} W/cm^2 for the 0.9 J pulses. The line focus for the MP was 5 mm long and 35 μm width with a total energy of 1.4 J on target corresponding to 1.6×10^{15} W/cm^2 at 0.5 ps pulse duration. Optimization of the peak-to-peak delay gave a value of 200 ps. The MP duration was varied from 0.5 up to 5.5 ps, showing optimum XRL output at 0.5 ps.

The plasma x-ray laser emission was monitored with a flat field spectrograph composed of a variably spaced 1200-line/mm gold-coated Hitachi grating placed at a 3° grazing incidence angle, a 1.1 μm Al spectral filter, and a back-illuminated CCD detector.

III. RESULTS AND DISCUSSION

The parameters used for the prepulse and delay are different for the two configurations so the plasma temperature at the arrival of the MP is determined by the EHYBRID code [6] as presented in Fig. 2 (prepulse intensity for the 0.8 ns pulses of 1.2×10^{11} W/cm^2 for 45°, and 2.35×10^{11} W/cm^2, for 72°). The x-ray laser emission in both cases analyzed here was a factor up to 50 above the background emission [5,11]. In both cases saturation was reached for the optimal configuration and, in addition, the second lasing line at 26.4 nm was also visible [11].

The XRL emission for 45° and 72° incidence angles on target for various MP durations is presented in Fig. 3. For the 45° incidence angle a maximum emission intensity is identified at about 3 ps MP duration while for the 72° incidence angle the highest output obtained is for a MP duration of

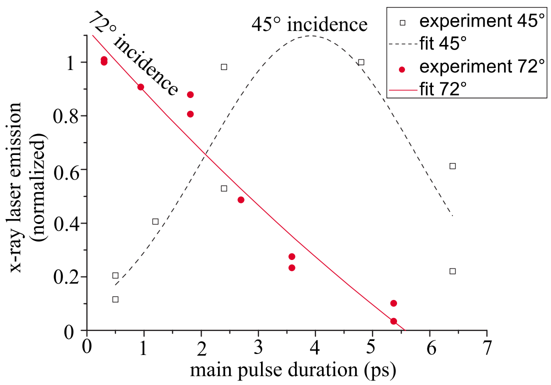

FIG. 3. (Color online) Comparison of the x-ray laser emission as a function of MP duration for 45° and 72° incidence angles on target.

0.5 ps. Shorter MP durations from the pumping laser were not possible due to bandwidth limitation of the Nd-doped glass system and the actual optimal value can be lower. The normalization of the data in Fig. 3 is made relative to the maximum signal produced on the spectrograph (no comparison of the output could be made for the two cases from the spectral data only, although there are hints the 45° configuration has higher output than 72° configuration). The result has to be compared with previous observations for Pd, for example, see Ref. [12] where an optimal pulse duration of 10±3 ps was measured with the MP having normal incidence on target.

The results can be understood in relation with the density, the charge state, and the electron temperature at the MP turning point. For the two cases, 45° and 72°, the MP is dissipated in much different regions of the plasma: the laser heating for the 45° incidence goes into a layer with an average charge state below 7, at 50% of the critical density, 7 μm away from the target, and at an electron temperature of 20 eV. In the 72° configuration, absorption appears 35 μm off from the surface, at 10% of the critical density, In this region, as can be seen in Fig. 4, the preplasma reaches Ni-like ionization state before the arrival of the MP. The drastic difference in the $\bar{z}$ in the two cases at the turning point of the MP is related to the temperature distribution at the arrival of the MP (see Fig. 2), which is reduced in the vicinity of the target, where the electron density is higher. Therefore $\bar{z}$ is

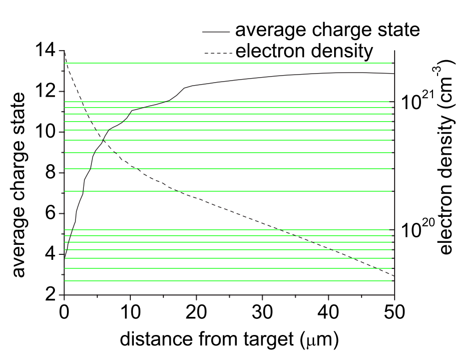

FIG. 4. (Color online) Average charge state and electron density distribution for the 72° geometry, at the arrival of the MP

lower when the MP penetrates deeper into the plasma. In turn this causes a different time for reaching the optimal Ni-like $\bar{z}$. In the case of the 72° configuration this time is 0, since the Ni-like state is already reached. In the other case it takes of the order of a few picoseconds; applying a MP of 1 ps duration, the plasma in the heated density layer will reach the Ni-like charge state only 2–3 ps after the MP. As a consequence, for other experimental configurations one can use the optimal duration of the MP to infer how far is the preplasma from the ideal Ni-like average charge state at the arrival of the MP. In most of the GRIP experiments reported to date, it is clear that the charge state at the position of the turning point density is significantly below Ni-like, and as it is in a low electron-density region, it needs a long time to reach Ni-like $\bar{z}$. In this way the hydrodynamics of the plasma comes into play and long MP is favored.

In addition to this, the better balance between the electron temperature of 60 eV at the turning point density for the GRIP case with the quiver energy of the electrons of 100 eV does not lead to a suppression of inverse Bremsstrahlung (IB) absorption even for the shortest possible pulse of our laser system. This easily explains the large difference in the optimal pulse duration of the MP. In the 72° case the shortest pulse gives still optimal absorption, and no additional time is needed for an ionization process. Under the same conditions, due to the lower electron temperature in the denser plasma layer, the inverse Bremsstrahlung correction factor would reduce the absorption by a factor of 3 in the 45° case as shown in Ref. [5]. A third effect in the determination of the optimal MP duration is the length of the optical path in the plasma. This depends on the plasma scale length and on the MP incidence angle [13]. In the case of the 45° angle, the geometrical path of the MP in the turning point density region is of the order 400 μm, while in the case of GRIP angle it is about 700 μm, assuming a plasma scale length of 30 μm. So the heating time of the plasma will be longer than the MP duration itself with more than 1 ps in the case of the 45° MP configuration and with more than 2 ps in the GRIP case.

The three processes mentioned above ($\bar{z}$, nonlinear IB, and the angle-dependent plasma heating time) have to be taken into account when scaling the non-normal incidence pumped XRL to sub-10 nm wavelengths where significantly higher laser MP intensities might be beneficial for the collisional excitation. In this case the balance between the density region where MP is deposited (determined by geometry and wavelength of the MP), $\bar{z}$ at the arrival of the MP and the MP intensity has to be taken into account. For a TCE XRL in Ni-like Sm, the optimal angle predicted is 45° [7] as in the Ni-like Zr XRL experiment analyzed here.

IV. CONCLUSION

In summary, we demonstrated a TCE Zr XRL with significantly different incidence angles of the MP, close to true TCE as proposed in Ref. [1]. Unlike the situation in most GRIP experiments, where long MP durations are optimal, it was found that here in the GRIP geometry the best MP duration is the shortest available one (0.5 ps) while in the 45° geometry this was significantly longer (3–4 ps). The strong dependence on the angle of incidence of the experimental results can be traced to the specific properties of the plasma layer where the MP is absorbed, the optimal MP duration being determined by the time needed to reach the Ni-like ionization stage.

The results are relevant for the development and application of practical high-average power lasers. They are showing that there is no optimal GRIP angle for a given element but that the MP angle can be varied according to the charge state distribution and to the density gradients. In this way, the problem is shifted to the preplasma analysis for which plasma shaping techniques have to be developed. The interdependence of the incidence angle of the MP with the $\bar{z}$ and MP propagation time in the plasma was pointed out based on the experimental results. This is critical for the generation of the gain at higher electron density regions as needed in the sub-10 nm XRL systems. In such short wavelength systems, the gain region has to be at higher electron density region, even above the critical density, in order to achieve a reasonable gain-length product. In such cases, there is no specific optimal MP angle for all the possible preplasma conditions in general, but it can vary depending on the specific pump laser parameters, largely depending on the way the preplasma is generated.

ACKNOWLEDGMENTS

We gratefully acknowledge support from the PHELIX team and discussions with LIXAM and MBI groups.

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