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Absorption Characteristics in Non-normal Incidence Pumped X-Ray Lasers

D. Ursescu[1], Vincent Bagnoud[1], Dasa Javorkova[1], Thomas Kühl[1], Paul Neumayer[1,2], Olga Rosmej[1], Klaus Witte[1], Peter Nickles[3], Bernhard Zielbauer[1,3], James Dunn[2], Kevin Cassou[4], Sophie Kazamias[4], Annie Klisnick[4], David Ros[4]

[1] *GSI, Darmstadt, Germany*

[2] *LLNL, Livermore, USA*

[3] *MBI, Berlin, Germany*

[4] *LIXAM, Paris, France*

A recent breakthrough in the development of transient collisionally excited (TCE) x-ray lasers (XRL) has been the modification of the main pumping pulse (MP) incidence angle from close to normal to **gr**azing **i**ncidence **p**umping (GRIP) combined with traveling wave excitation [1]. This technique allows to control the electron density of the plasma where the main pulse energy is deposited, leading to a significant reduction of the pump energy. Thus high-repetition rate XRL systems were demonstrated by several groups [1, 2, 3, 4]. The key to GRIP is the use of one spherical mirror for focusing the MP [5]. This generates a focal line having an intrinsic traveling wave and is flexible in the choice of the incidence angle of the MP on the target. In the experiments performed at PHELIX, a saturated TCE Zr XRL was demonstrated employing two significantly different incidence angles on target for the MP, 45° and 72°.

The main message of our experiments is that the angle of the MP affects both the absorption of the MP in the plasma generated by the pre-pulse and the XRL output. Using a simple theoretical model of the laser plasma coupling, the experimental results are qualitatively explained and the studies are extended toward the sub-10 nm XRL where for samarium and other high-Z materials incidence angles in the range from 30° to 45° are predicted. The results of the model are improving the way toward a water window TCE XRL.

The XRL experiments in Ni-like Zr at PHELIX were performed in two campaigns with similar set-ups, except for the incidence angle of the MP on target. In the first campaign the on-target incident angle was 45° for the MP and in the second campaign 72° (see fig. 1). The nanosecond pulse is focused to a line 30-μm wide and 6-mm long onto a Zr target. A single, gold coated, 6 inch diameter on-axis parabola, tilted at an incidence angle of 9° and 22.5° is used to generate a line focus of 5- and 11-mm length respectively 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.

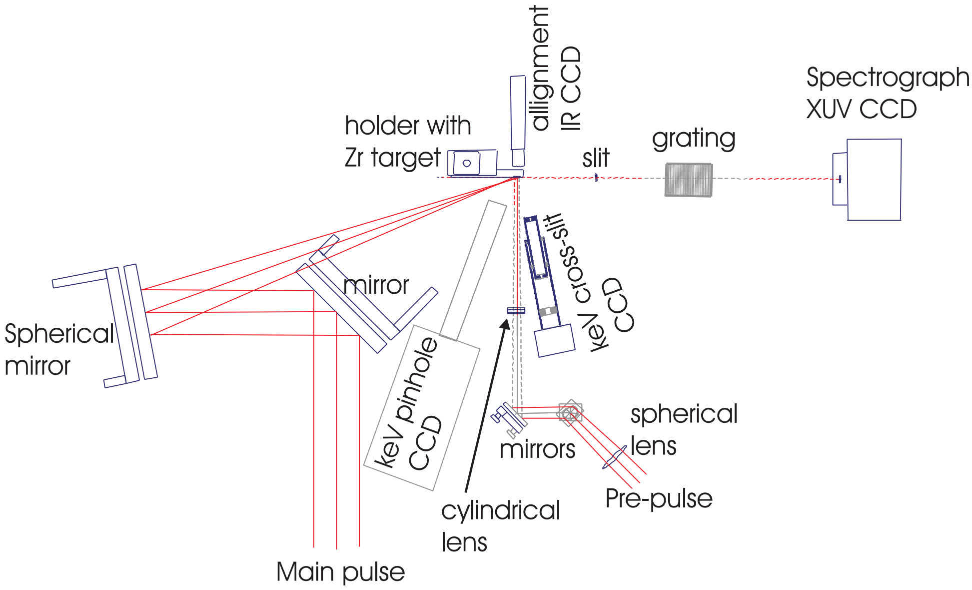

Figure 1: Schematic of the setup for the 72° MP angle Zr XRL

Employing 45° MP incidence angle, the total energy from PHELIX preamplifier was 5 J. 25% was split off for the 0.8 ns prepulses. After compression the MP had approximatively 2.4 J. The length of the line focus was 11 mm for both pulses. The peak-to peak delay between the pulses was 0.7 ns. The height of the focus lines was 90 μm for the prepulse and 50 μm for the MP. The focused MP intensity at 0.5 ps duration was 8.75 $\cdot 10^{14}$W/cm^2. The optimum MP duration was experimentally determined to be around 3 ps. For this duration the output energy of the XRL was three times higher than for a 0.5 ps pulse.

For the experiment employing an incidence angle on the target of 72°(see fig. 1), the line focus generated for the prepulse had 6 mm length, 80 μm width, the duration was 800 ps and the energy 0.9 J. 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 $1.6 \cdot 10^{15}$ W/cm^2 at 0.5 ps pulse duration. Experimental optimization of the peak-to-peak delay gave a value of 200 ps.

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

The keV emission of the plasma column generated with 72° MP angle was analyzed using an x-ray pinhole camera (Princeton Instruments, 16 bits, back illuminated, cooled with 30 μm hole diameter and a filter to suppress the radiation below 600 eV).

Alternatively an 8 bit, cross-slit camera was used for the experiments employing 45° incidence angle on target, with a transverse resolution of the images of 10 μm.

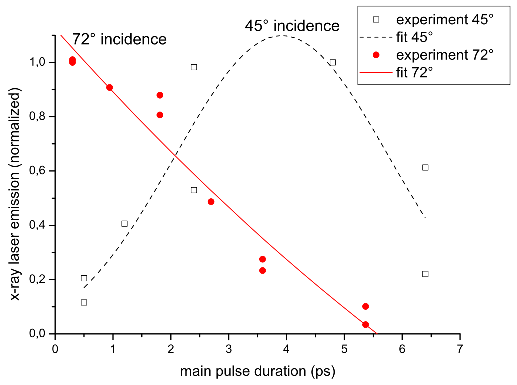

Figure 2: Comparison of the x-ray laser emission as a function of main pulse duration for 45° and 72° incidence angles on target

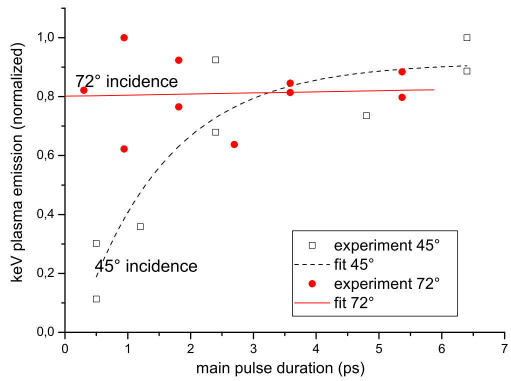

Figure 3: Comparison of the keV plasma emission as a function of main pulse duration for 45° and 72° incidence angles on target.

The XRL emission for 45° and 72° incidence angle on target for various MP durations is presented in fig. 2. For the 45° incidence angle a maximum emission intensity is identified at about 3 ps MP duration, while for the 72° MP angle, the strongest emission was measured at 0.5 ps MP duration. The result has to be compared with previous observations for Pd for example see ref. [6] where an optimal pulse duration of 10$\pm$3 ps was measured with the MP having normal incidence on target.

At the same time the keV plasma emission was monitored. The camera gives a qualitative estimation of the total amount of keV radiation emitted from the laser plasma and thus an image of the hot regions of the plasma. The puzzling result from the experiment using 45° incidence angle was that the keV signal of the plasma is smaller when short pulse durations were used. This suggests that higher temperatures are achieved using longer pulses of the same energy. A qualitative explanation was proposed in [5] considering the effect of the inverse Bremsstrahlung (IB) correction factor at high laser MP intensities, corresponding to short pulse durations. The results from the experiments using 72° MP incidence on pre-plasma show much less influence of the MP duration on the keV plasma emission. The temperature of the plasma is slowly increasing when the MP duration increases as indicated in the measurements performed with the pinhole camera (fig. 3).

Comparing fig. 3 and fig. 2 for the case of 45° geometry one can correlate the decrease in the keV plasma emission for pulses shorter than 4 ps with the decrease in the XRL emission shown in fig. 2. For the same interval at 72° geometry there is no reduction in the keV emission and the XRL output grows significantly toward shortest MP a factor of 5.

A simple theoretical model for the absorption of the MP in the preplasma was developed, which takes into account the non-linear IB mechanism. The modeling results show that in the case of the 45° geometry, the effect of the non-linear IB is extended over the whole duration of the MP while in the case of 72° geometry the electron temperature is increasing much faster in the first quarter of the MP duration to high values where this mechanism plays no role. This explains the keV emission curves presented in fig. 3 which in turn are responsible for the determination of the optimum MP duration determined in fig. 2.

The model shows that in order to scale the TCE XRL to shorter wavelengths the optimal MP incidence angle on target has to be reduced to values between 30° and 45° for Sm target and higher Z materials in order to have a good absorption of the MP energy in the plasma.

In summary, we demonstrated a GRIP TCE Zr XRL with significantly different incidence angles of the MP. The signature of the angle in the XRL output and in the plasma emission was presented. The results are significant for the development and application of practical high-average-power lasers with short pulses at wavelengths below 10 nm.

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