# Transient collisionally excited x-ray laser in nickel-like zirconium at PHELIX laser facility

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## *Abstract*

A transient collisionally pumped X-ray laser (XRL) driven by the infrared pulses from the PHELIX laser preamplifier at GSI has successfully been put into operation. Strong lasing at 22 nm has been observed in nickel-like zirconium. Experimental data from the optimization of the XRL energy output support the conclusion that inverse Bremsstrahlung plays a key role in the pumping mechanism.

Laser induced fluorescence spectroscopy in lithium-like heavy ions can be performed using narrow bandwidth light pulses with a few $\mu$J of energy in the XUV spectral region [1]. Such pulses are routinely produced in the scheme of transient collisional excitation (TCE) x-ray laser , which was first demonstrated by Nickles et al. [2]. In this scheme, saturated output can be obtained with a few J of pulse energy from the pumping laser (see e.g. [3]). A laser pulse with an energy of a few J and ns duration is focused to a line onto a solid target, creating a line-shaped plasma with a high abundance of nickel-like ions. A high intensity short ($\sim$ ps) infrared laser pulse - produced by the technique of ,,chirped pulse amplification" (CPA) - heats the plasma rapidly to a high temperature which leads to a short lived (transient) population inversion. A bright, partly coherent XUV-pulse is emitted from the end of the plasma column by amplified spontaneous emission. Due to the short life time of the transient gain [4], the pumped region has to travel with the amplified radiation, which is achieved by so called travelling wave excitation [5].

At GSI, a high intensity/high energy laser system (PHELIX) is under construction [6]. The CPA front-end together with the preamplifier and pulse compressor are well suited for pumping a TCE XRL. The front-end delivers stretched pulses of $>$ 50 mJ with a bandwidth of $\sim$ 7 nm. The preamplifier consists of three flashlamp pumped Nd:Glass rods (with 2x 19 mm and 45 mm diameter) which amplify the pulses further to an energy of several J. The pulse compressor, in a double folded single grating arrangement, is entirely housed in a vacuum chamber and is designed to compress pulses of up to 15 J to durations below 400 fs. Pulses up to 10 TW peak power have been achieved. Without the use of adaptive optics for the wave front correction the repetition rate is limited by the cooling time of the three heads to one shot every 6 minutes .

For pumping the XRL we have used 5-6 Joule pulses; 20 % of the pulse energy are split off by a beam splitter and remain uncompressed to form the prepulse. After being delayed in an optical delay line the prepulse is injected into the target chamber and focused by means of a cylindrical lens to a line focus (80$\mu$m $\times$ 10mm) to create the preplasma.

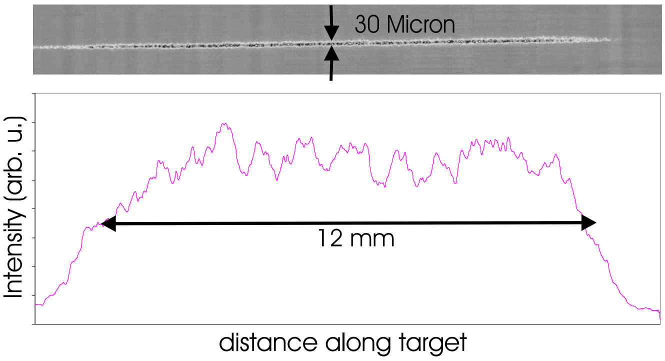

Figure 1: Line focus image and longitudinal intensity distribution for the infrared laser, obtained with the parabolic mirror

The remaining 80 % of the pulse are injected into the pulse compressor. After compression the pulse is transported under vacuum into the target chamber. A single on-axis parabola, tilted at an incidence angle of 22 degrees, is used to generate a line focus of 30$\mu$m  100$\mu$m width and over a length of 10 mm (fig. 1). The off-axis geometry intrinsically leads to a travelling wave excitation along the line focus with a close to the optimum speed of 1.4 c where c is the speed of light. The delay between the prepulse and the compressed pulse was set to 0.7 ns.

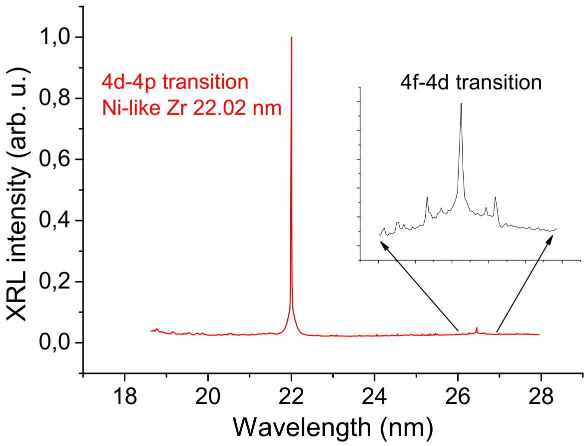

Figure 2: Typical spectrum of the Ni-like zirconium laser, corrected for the Al-filter transmission

The main diagnostics was an XUV flat-field Hitachi

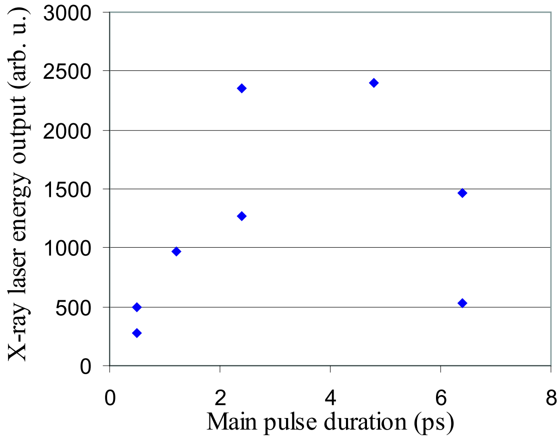

Figure 3: Energy output from the Ni-like zirconium laser for different main pulse durations at the same pumping energy

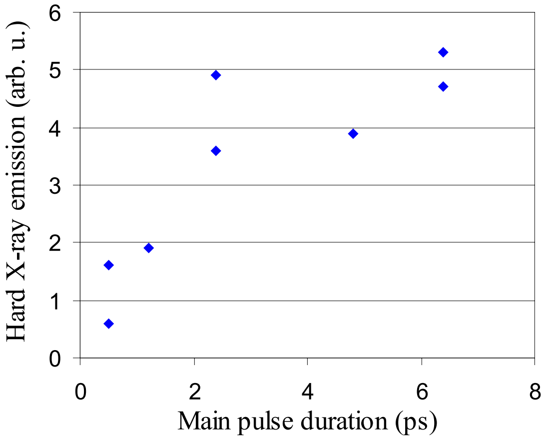

Figure 4: Integrated hard X-ray emission from the Ni-like zirconium plasma for different main pulse durations at the same pumping energy

grating spectrometer, monitored with a Princeton XUV CCD camera, with a resolution of about 0.01 nm/pixel.

The time integrated keV emission of the plasma was observed using a so called cross-slit camera. It provided a full length side view of the plasma with a transverse resolution of $10\mu$m. This helps to control the overlap of the two infrared pulses along the whole length of the plasma line.

Using a zirconium target of 4.5 mm length and a total energy of 3 Joule on target, strong lasing are obtained from the 4d-4p transition in nickel-like zirconium at a wavelength of 22.02 nm (56 eV) as well as the self photo pumped 4f-4d transition at 26.46 nm in a highly reproducible spectrum (fig. 2). The corresponding intensities of the pre-pulse and of the short pulse were $2 \cdot 10^{11}$ W/cm$^2$ and $8 \cdot 10^{14}$ W/cm$^2$, respectively. In the absence of either the prepulse or the short pulse, no line emission is observed. Still we observed the lasing transition line with ten times less intensity for the pre-pulse.

During the experiment short pulse durations of 0.4, 1.2, 2.4, 5 and 6.4 ps (see fig. 3) were used while keeping the total pulse energy constant to within 12 %. An optimum with respect to the XRL output intensity was obtained for a duration of the short pulse $\sim$ 2.4 to 5 ps for which the output of the XRL was about four times higher than for the the shortest possible pulse duration of 0.4 ps (fig. 3). Similar findings are reported e.g. in [3], however, no explanation has been given so far for this effect. Here, in addition we evaluated the brightness of the images taken by the cross slit camera for these shots (fig. 4). A strong increase of the intensity in the images from the plasma emission can be observed. The camera is protected by a thin aluminium filter which transmits mainly radiation with photon energies above 500 eV. Therefore 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. This suggests that higher temperatures are achieved using longer pulses of the same energy. Although the measurements are time-integrating and the increase in emission time could play a role [7], we propose that the reduction of inverse Bremsstrahlung absorption contributes strongly to this behavior. At conditions typical for TCE XRL, i.e. temperatures of a few tens of eV for the XRL pre-plasma and laser intensities between $10^{14}$ and $10^{15}$ W/cm$^2$ in the short pulse the process of inverse bremsstrahlung absorption strongly decreases with increasing intensity [8]. The decrease of XRL output signal for even longer pulses can be attributed to over-ionization of the Nickel-like ions. Further investigation for comparison of the theoretical model with the experiments will follow in 2004.

In conclusion we presented a new XRL system capable of routinely producing XUV-pulses at a wavelength of 22 nm at a repetition rate of 1 shot per 6 minutes. A novel short pulse focusing geometry has been used for the first time. Besides being inexpensive and easy to use, it provides a near optimum intrinsic travelling wave velocity of 1.4 $c$. The observed optimum output for the short pulse duration, in combination with the images of the keV plasma emission can be explained by a decreased inverse bremsstrahlung absorption at higher laser intensities.

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