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Transient collisionally excited X-ray laser in nickel-like zirconium pumped with the PHELIX laser facility

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ABSTRACT A transient collisionally excited X-ray laser has been put into operation using the front end of the PHELIX laser system as a pump laser. Strong lasing at 22 nm has been observed in nickel-like zirconium.

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1 Introduction

Since the first realization of X-ray lasers (XRLs) [1], considerable progress has been achieved in the improvement of beam quality as well as towards full characterization and downsizing of the required pumping demands. As XRL systems approach ‘table-top’ size, numerous applications are being proposed to use the properties of present-day XRLs such as coherence, brightness and short pulse duration [2, 3].

The narrow emission bandwidth of a plasma-based XRL is a unique property and complementary to the performance of free electron lasers facilities. Relative bandwidths on the order of 4–5 $\times 10^{-5}$ have been measured by several authors (see e.g. [4, 5]), values sufficient for laser spectroscopy.

Laser spectroscopy is the most important tool to access ground-state properties like charge radii, spin and magnetic moments of exotic nuclei, thus providing indispensable data for testing nuclear models [6]. Very interesting candidates are lithium-like ions. The electronic wave functions can be calculated to a high precision, while the lowest excitation energy from the ground state lies in the range of only 100–300 eV for nuclear charges of $50 \leq Z \leq 92$. This energy range lies within the reach of present-day XRLs.

The Gesellschaft für Schwerionenforschung (GSI, Society for Heavy Ion Research) is currently the leading facility in the production of radioactive isotopes. The unique combination of the radioactive ion beams with the experimental storage ring (ESR) offers the possibility to perform laser spectroscopy on lithium-like exotic nuclei far off stability using an XRL [7]. The main disadvantage of XRLs for their application to spectroscopy is that by their principle of operation they are not tunable. This disadvantage can be circumvented by finely varying the relativistic velocity of the ions stored in the ESR, thus tuning the wavelength in the rest frame of the ions by the Doppler shift. The total Doppler shift also boosts the XRL’s photon energy by almost a factor of three. Thus, using an XRL with a lasing wavelength around 90 eV will enable experiments for ions with $50 \leq Z \leq 92$.

The planned experiments require XRL pulse energies of several μJ, which are routinely produced in the scheme of transient collisional excitation (TCE) that was first demonstrated by Nickles et al. [8]. In this scheme a laser pulse with an energy of typically a few joules and of ns duration is focused to a line on a solid target, creating a plasma with a high abundance of nickel-like ions. A high-intensity, short ($\sim$ ps) pulse heats the plasma rapidly to a high temperature, which leads to a short-lived (transient) population inversion. By amplified spontaneous emission a bright coherent XUV pulse is emitted from the end of the plasma column. Due to the short lifetime of the transient gain the heated region has to travel with the amplified radiation, which is achieved by so-called travelling wave excitation [9]. Collimation of a TCE XRL beam over several metres with a directional stability as low as 50 μrad has been shown [10].

At GSI a high-intensity/high-energy laser system (petawatt high-energy laser for heavy-ion experiments, PHELIX) is under construction. The system consists of a long-pulse and a short-pulse front end providing up to 20-ns pulses and 130-fs pulses stretched to > 1 ns, respectively. A preamplifier section using several Nd : glass rods and a main amplifier section with large aperture disc amplifiers boost the energy to 10 J and several kJ, respectively. The system is designed to deliver in a high-energy mode pulses of energies up to 4 kJ and in a high-intensity mode recompressed pulses of powers up to 1 PW. The laser system is described in more detail in [11].

In the TCE scheme saturated output can be obtained with a few joules of pulse energy from the laser (see e.g. [12]). Therefore, the preamplifier section of the PHELIX system is an ideal XRL driver. To perform the laser spectroscopy

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experiments described above, at GSI a TCE XRL has been constructed and recently put into operation.

2 Experimental setup

For the first experiment, pulses of the short-pulse front end amplified to 5 J by the preamplifier section were used. By use of a fixed-ratio beam splitter 75% of the total pulse energy was injected into a vacuum pulse compressor. The compressor is a double-folded single-grating design and can compress pulses of up to 15 J to below 400 fs. With the total transmission of about 65% of the compressor the energy on target of the short pulse was up to 2.4 J.

The remaining 25% of the pulse energy is used as a prepulse. As the path length inside the compressor is as long as 12 m (due to the low dispersion of the 1480-lines/mm compressor grating), the prepulse is de-magnified to 1-cm diameter. In this way the delay line can be folded several times using standard 1″ mirrors and fits on 1/4 of an optical table. The prepulse is injected separately into the target chamber and focused by a simple 1″-diameter plano-convex cylindrical lens.

For the short-pulse line focusing a novel line-focusing arrangement has been used, which to our knowledge has up to now not been applied to excite TCE XRLs. It consists of a single spherical mirror used off-axis. Due to the large astigmatism, diffraction-limited line foci are generated in the sagittal and tangential planes with a very homogenous intensity distribution (Fig. 1). In our setup we use the sagittal line focus. This line focus is always parallel to the incoming beam before the spherical mirror and can easily be moved, i.e. placed onto the target by tilting of the focusing mirror. A special feature of this focusing geometry is an intrinsic travelling wave speed, which is significantly slower than that of other focusing arrangements used so far. In our experiment an incident angle of 22° onto the spherical mirror was used that yields a travelling wave speed of 1.4 times the speed of light and that varies only by 5% along the length of the line focus. Therefore, in this experiment, no additional pulse-front tilting was applied.

Alignment of the line foci as well as a direct measurement of the adjusted line-focus widths was accomplished using a specially designed microscopic imaging device, capable of operating under vacuum. In this way, line-focus quality and overlap could be checked routinely (Fig. 1). The prepulse and main pulse line foci were adjusted to widths of 80 µm and 50 µm, respectively.

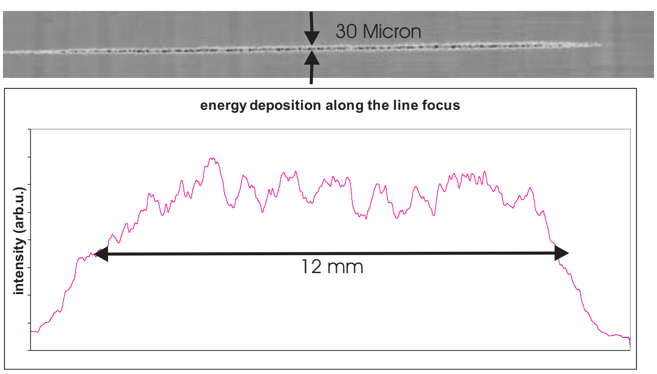

FIGURE 1 Line-focus image and longitudinal intensity distribution for the infrared laser, obtained with the parabolic mirror

XRL diagnostics in this first experiment consisted of a flat-field grating spectrometer coupled to a back-thinned XUV-CCD camera (Roper Scientific). Thin-foil aluminium filters of 1.2-µm thickness were used to protect the camera from visible light and for attenuation of the XRL output. A CCD X-ray crossed-slit camera monitored the line-focus plasma uniformity and the overlap of the laser pulses at the target surface.

3 First results

In a first experiment zirconium (Zr, $Z = 40$) was used as target material, where lasing in the transient scheme has first been demonstrated [13]. A typical spectrum obtained with the on-axis spectrometer is given in Fig. 2. The 4d–4p laser line of nickel-like Zr at a wavelength of 22 nm completely dominates the emission spectrum, which was obtained from a 4.5-mm-length target. Also, emission from the 4f–4d transition was observed (see inset in Fig. 2).

Due to the excellent stability of the pumping laser system and focusing setup a high repeatability was achieved at a repetition rate of one shot every six minutes. Even after more than 10 shots on the same location on the target no significant decrease of the obtained line intensity was observed. However, microscopic examination of the targets used showed a mean ablation depth of 3 µm/shot.

3.1 *Absorption at high laser intensities*

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 of ∼ 2.4 to 5 ps. Similar findings are reported, for example, in [12]; however, no explanation has been given so far of this effect. Here, in addition we evaluated the brightness of the images taken by the crossed-slit camera for these shots (Fig. 4). We observed a strong increase

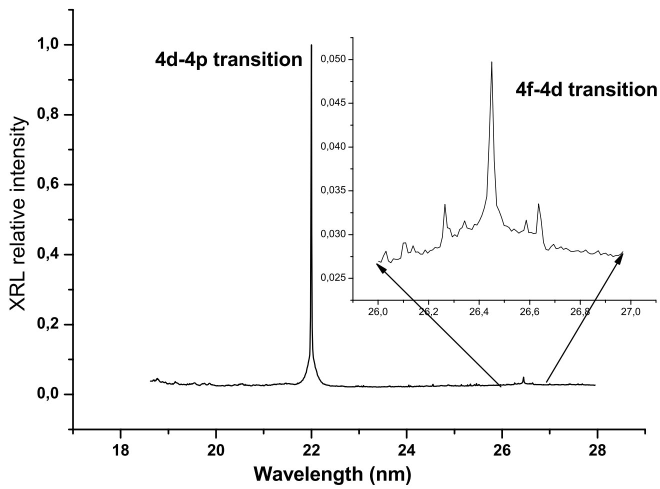

FIGURE 2 Typical spectrum from the Ni-like zirconium laser, corrected for the Al-filter transmission

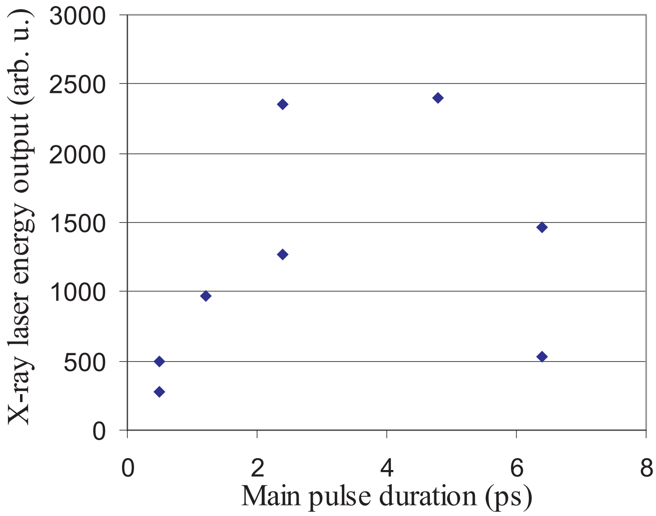

FIGURE 3 Energy output from the Ni-like zirconium laser for different main pulse durations at the same pumping energy

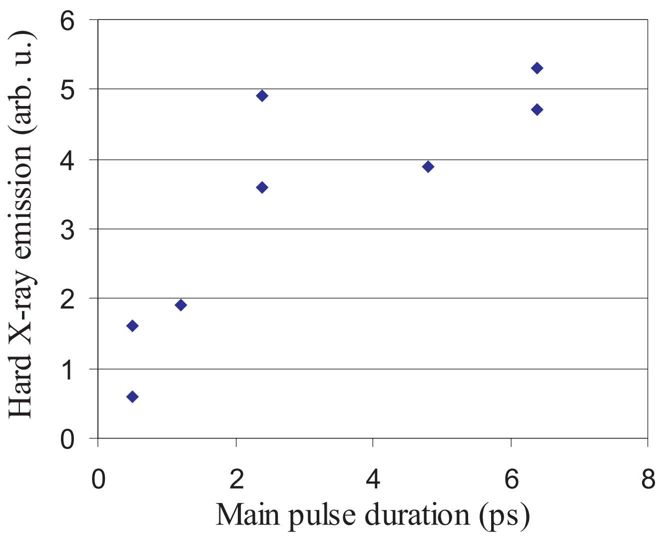

FIGURE 4 Integrated hard X-ray emission from the Ni-like zirconium plasma for different main pulse durations at the same pumping energy

of the intensity in the images from the plasma emission. 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, we propose that the reduction of inverse Bremsstrahlung absorption contributes strongly to this behaviour. At conditions typical for TCE XRLs, i.e. temperatures of a few tens of eV for the XRL preplasma 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 [14]. The decrease of the XRL output signal for even longer pulses can be attributed to over-ionization of the nickel-like ions.

4 Conclusion and outlook

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

The next experiments are aimed at measuring the pulse energy and beam quality, as well as going to shorter wavelengths. This optimized XRL system will be used to perform precision laser spectroscopy on lithium-like heavy ions.

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