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(Eds.)

X-Ray Lasers 2008

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Springer

Professor Ciaran L.S. Lewis
Department of Physics and Astronomy
Queen's University Belfast
University Road
Belfast BT7 1NN
UK

Dr. Dave Riley
Department of Physics and Astronomy
Queen's University Belfast
University Road
Belfast BT7 1NN
UK

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Preface

The 11th International Conference on X-Ray Lasers was held at the Queen's University of Belfast between 18th and 23rd of August 2008 with talks presented in the Emeleus Lecture Theatre, just off the relaxing central campus quad area. This is the second time the conference has been hosted in the UK and the first time in Ireland. In a series of oral and poster sessions, delegates reported on a wide range of developments in the area of generation and application of soft X-ray radiation sources.

The meeting was listed by the University in the programme of major events for its 2008 Centenary Year celebrations, in recognition of the importance of hosting this international conference. XRL2008 was attended by ~100 delegates from ~15 countries with many spouses, friends and children also attending and enjoying the *craic*. While for some it was an unbroken record of eleven conferences, for others it was a first time – indicating the lasting vitality of the subject area.

As reported in these proceedings, the conference covered the generation of plasma-based X-ray lasers, the traditional focus of the series, but also many evolving applications and techniques for improving beam qualities which demonstrate the maturity of the field. In addition, several contributions were included to illustrate the competing alternative approaches that are also evolving in parallel. This led to interesting and valuable discussion highlighting the special rôle each approach can play. Perhaps the most notable development is the large percentage of contributions reporting applications of X-ray lasers in a wide range of areas including plasma physics, chemistry, biology and material science.

In addition to the main science schedule, delegates survived some damp Irish weather to enjoy a wide-ranging social events programme which included a trip to the Giant's Causeway, a stroll over the Carrick-a-Rede rope bridge and an evening at the Ulster Folk and Transport Museum. There were many opportunities for renewal and forging of lasting friendships within this relatively small but always enthusiastic community. Perhaps the highlight was the Conference Dinner held in the magnificent Great Hall of the University where both young and old enjoyed demonstrations of traditional Irish music and dance as part of the after-dinner entertainment.

Many colleagues and students contributed to the successful organisation of the conference but, in particular, we wish to thank Donna Convery (Eventus-QUB), Liam McGuire (CMS-QUB) and Jenny McCabe (Physics-QUB). In addition we acknowledge generous sponsorship from Andor Technology, Coherent, Office Depot, the Institute of Physics and the Belfast Visitor and Convention Bureau.

Finally, we would like to thank the delegates and contributors, who ensure the success of this series, for their willingness to participate and comply with deadlines (for the most part!). We hope these proceedings provide a useful record of their efforts.

Ciaran Lewis
Dave Riley

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Part 1 – Progress in X-Ray Laser Facilities and Infrastructures

Recent Progress in X-Ray Laser Research in JAEA

T. Kawachi[1], M. Kishimoto[1], M. Kado[1], N. Hasegawa[1], M. Tanaka[1], Y. Ochi[1], M. Nishikino[1], M. Ishino[1], T. Imazono[1], T. Ohba[1], Y. Kunieda[1], A. Faenov[1], T. Pikuz[1], K. Namikawa[2], S. Namba[3], Y. Kato[4], H. Nishimura[5], N. Sarukura[5], M. Kando[1], Y. Fukuda[1], H. Kotaki[1], A. Pirozhkov[1], J. Ma[1], A. Sagisaka[1], M. Mori[1], J. Koga[1], S. Bulanov[1], H. Daido[1], and T. Tajima[1]

[1] Quantum Science Directorate, Japan Atomic Energy Agency (JAEA)
[2] Department of Physics, Tokyo Gakugei University
[3] Department of Engineering, Hiroshima University
[4] The Graduate School for the Creation of New Photonics Industries
[5] Institute of Laser Engineering (ILE), Osaka University

Abstract. Recent progress in x-ray laser (XRL) research in Japan Atomic Energy Agency (JAEA) is reviewed. The repetition-rate of the x-ray laser has been improved from each 20 minutes to 10 seconds (0.1 Hz) by installing new driver laser, TOPAZ, which allows us to promote the applications of fully spatial coherent 13.9 nm laser in the wide variety of research fields such as material science, single-shot x-ray holography and atomic physics. In order to improve the present performance of the x-ray lasers, we have investigated the possibilities of the enhancement of the peak brilliance using v-groove target and the generation of circularly polarized x-ray laser under a strong magnetic field. Towards shorter wavelength x-ray lasers, we have investigated several schemes. One is the use of reflection of the light by relativistic plasma mirror driven by laser-wake-field, and the other is photo-pumping scheme using Kα emission from a solid target.

1 Introduction

Advent of transient collisional excitation (TCE) laser makes it possible for us to realize compact coherent soft x-ray lasers [1-3]. The repetition-rate of these lasers in the gain-saturation regime has been improved up to 5~10 Hz [1, 2], and now we are on the stage to use this novel soft x-ray sources as powerful scientific tools in the wide variety of research fields.

In Japan Atomic Energy Agency (JAEA), we have firstly demonstrated fully spatial coherent x-ray laser beam at the wavelength of 13.9 nm by the method of double target geometry, in which the first gain medium works as the soft x-ray oscillator, and the second gain medium works as soft x-ray amplifier [4]. Succeeding optimization of the pumping condition such as the pumping intensity, traveling wave, temporal separation and shapes of the pre- and main-pulses allows us to obtain high quality, intense x-ray laser beam:

The typical parameters of the 13.9 nm laser are the beam divergence of better than 1 mrad, 1 μJ output energy and more than 10^9 photons in the coherent volume [5].

Using this high quality laser, the application experiments have been intensively promoted in the research fields of material science and atomic and molecular physics. However the extension of the applications to single-shot x-ray diffraction imaging, x-ray laser ablation and nano-fabrication, requires further improvement in the performance of the XRLs, *e.g.*, the repetition rate, output energy, controllable polarization and the lasing in the shorter wavelength region. In the following, the recent progress of XRL research program of JAEA is described in terms of these topics.

2 New Driver Laser System: TOPAZ

New driver laser system, TOPAZ stands for Two OPtical Amplifiers using Zigzag slab. TOPAZ laser consists of the oscillator, pulse stretcher, OPCPA preamplifier, prepulse generator, zigzag slab Nd:glass power amplifiers, pulse compressor, and optics for producing the line focus on the target. The two beam lines are indispensable for generating fully spatial coherent x-ray laser beam using double target geometry, and high contrast pulse is required for photo-pumping experiment using Kα line emission described later.

The oscillator is a mode-locked Ti:sapphire laser (Spectra-Physics; TSUNAMI) pumped by 10-W diode-pumped solid state laser (Spectra-Physics; Millenia). The central wavelength is 1053 nm and the spectral bandwidth is 20 nm in the full width at the half maximum (FWHM). The oscillation frequency is 80 MHz with typical power of 300 mW (~ 4 nJ/pulse). The pulse stretcher consists of a diffraction grating with 1740 grooves/mm, a spherical mirror with focal length of 1500 mm, which generate the frequency chirp of 250 ps/nm. The spectral bandwidth after the pulse stretcher is 8nm, which is limited by the optics size.

The stretched pulse is amplified by OPCPA. The pump source is 532-nm, 10Hz repetition-rate, Q-switched YAG laser with seeder (Continuum; Powerlite Precision II) with 8-ns duration and 700-mJ energy. Total amplification gain reaches around 10^6 by using four BBO crystals at the pump intensity of 100 MW/cm^2. More than 10 mJ output energy with the energy fluctuation of 7.6 % rms is obtained. The contrast ratio of the amplified laser pulse to the background is better then 10^4.

The output of OPCPA, which has circular beam profile, is cut to square shape with 10 mm x 10 mm by a serrated aperture and is amplified by the first zigzag slab 6-pass amplifier.

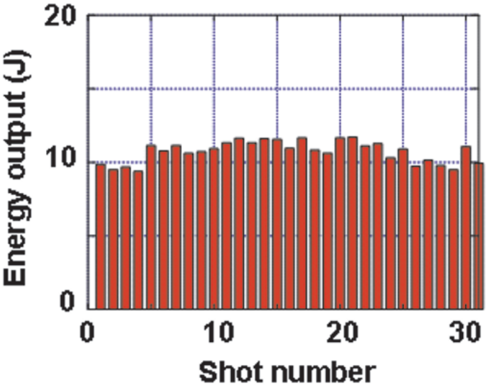


Fig. 1 Energy output and stability of TOPAZ

After the 6-pass amplifier, the height of the laser beam is expanded to 90 mm, and the laser pulse is amplified by double-pass zigzag slab amplifier. The output energy is 10 J after the final amplifier for each beam line. Figure 1 shows the output energy from TOPAZ laser under the operation of 0.1 Hz repetition-rate. From the far-field image of the beam pattern, we could not find any distortion originated from the thermal effect.

We have already demonstrated nickel-like silver laser at a wavelength of 13.9 nm using this new driver laser [6], and the preparation of application experiments using fully spatial coherent XRL driven by TOPAZ is carried on [7].

3 Application of the 13.9nm laser

In this section, we describe the application experiments using the fully spatial coherent 13.9 nm laser under the collaborations with universities, research institutes, and other research sections of JAEA.

A couple of years ago, we have taken the pico-second snap-shot of domain-structure of ferro-electric substances, $BaTiO_3$ [8, 9], by use of x-ray laser speckle technique. The following pump & probe speckle measurement revealed the temporal-correlation of “fluctuation” in the phase-transition of this materials [10]. The series of these measurements shows us that XRLs are the powerful tool to study *non-periodic* ultra-fast phenomena such as the domain fluctuation under the phase transition. The fluctuation plays a decisive role in the phase transition of the materials, and it includes the fluctuation in atomic structure, charge distribution, and spin distribution, and so on. Our next goal is to extend the observation to the fluctuation in the charge distribution of high-temperature superconductors.

The study of optical property of materials is another interesting application. In the research fields relevant to next generation lithography, the development of efficient and fast imaging scintillator devices with sufficient size is one of the key issues for lithographic applications. Zinc oxide (ZnO), a wide gap semiconductor, is one of the promising materials for the scintillators, and recent progress in the fabrication technique enables us to obtain large-size homogeneous crystal at a low cost.

Since the property of the fluorescence spectrum of ZnO for the EUV light pumping, *e.g.*, the wavelength and the lifetime, has not been well-known, therefore we tried to characterize the fluorescence by the method of soft x-ray laser induced fluorescence (X-LIF) spectroscopy. Obtained fluorescence had a peak at around 380 nm. It was sufficiently intense and the lifetime was short enough ($t \sim$ 10 ns), furthermore these optical properties were virtually the same with the case pumped by 351 nm UV laser. This implied that ZnO crystal was suitable for the fast-scintillator device for the UV-EUV region [11].

In atom and molecules physics, interaction between Xe cluster and intense soft x-ray pulse has been studies by the collaboration with Hiroshima university. The 13.9 nm laser pulse with sub micro joules and 7 ps-duration irradiated the Xe cluster target, and the production rate of several ionic stages of Xe ions were measured by the method of time of flight. Our result showed the production rate of Xe^{3+} ions dominated that of Xe^{2+}, which contradicted to the result obtained in synchrotron radiation source (SR). This was due to that XRL photon flux is larger by 6 orders of magnitude than that of the SR. Under such the condition, more than 10% of atoms in the cluster were inner-shell-ionized, and this together with the following auto-ionization process formed virtually solid state density plasma before the Coulomb explosion. Our quantitative estimation indicated that substantial ionization level lowering of Xe ions in high density plasma enhanced the production channel of Xe^{3+} ions. This study is closely connected to the physics of strongly coupled plasma or warm dense matter. [12, 13].

In the research field of x-ray laser imaging, we demonstrated single-shot Fourier transform holography. The 13.9 nm XRL beam was focused by a Fresnel zone plate (FZP) with a 50 nm-thickness Au zone fabricated on a 0.75×0.75 mm^2 silicon nitride (Si_3N_4) membrane with a thickness of 100 nm. The diameter of the FZP was 0.434 mm, and the total zone number and outermost zone width were 1700 and 64 nm, respectively. The focal length was 2 mm for the 13.9 nm laser. The focal spot size was 66 nm, and the focused beam was used as the reference beam. A test grid pattern with 2 microns period was put in the focal plane with a certain displacement (several tens of microns) from the focal position to avoid the illumination by the reference beam. The 0th order light, which was passing through the zone-plate, illuminated the test patterns, and the wave-front of the 0th-order light was distorted.

This distorted wave and the reference beam were interfered each other. The interference pattern was recorded by the x-ray CCD at the distance of 0.23 m from the sample. Figure 2 shows the image of the test patterns taken by optical microscope; (a), the raw-data of single-shot hologram; (b), and the reconstructed intensity image; (c). As shown in Figure 2 (c), the vertical and horizontal 1 μm line-and-space pattern could be virtually resolved [14]. In this experiment, the energy of the 13.9 nm laser on the FZP was 0.1 μJ due to the poor throughput (10%) of the system. Our estimation showed that in order to obtain clear single-shot hologram, at least 10^{11} photons on the sample were needed. Therefore the improvement of the output energy of the XRL was strongly desired for this purpose.

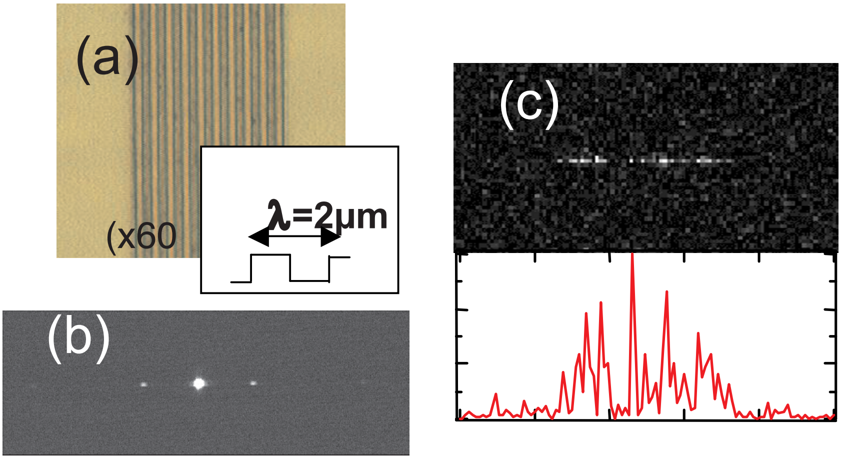


Fig. 2 Images of the test pattern taken by optical microscope; (a), single-shot Fourier transform hologram; (b), and the reconstruction image; (c).

4 Improvement of Performance of X-ray laser

4.1 Experiment towards circularly polarized x-ray laser beam

Circularly polarized soft x-ray source is promising tool to study the chilarity of stereoisomer of molecules in pharmacology and circular dichronism of magnetic substances in material science. In the collisional excitation laser, dominant lasing line is $J = 0$ to 1 transition, where J is total angular momentum quantum number of the lasing levels. Here we assume classical dipole oscillation model. If we take the quantization axis parallel to the x-ray laser propagation direction, z-direction, π-component corresponds to the electric dipole oscillation parallel to the quantization axis, and σ-components are the dipole oscillation perpendicular to z. This means that observed x-ray laser beam is the mixture of the σ-components, *i.e.*, the right-hand circular polarization component and left hand component

Consider that an external magnetic field is applied along the quantization axis. If the magnetic field is strong enough, Zeeman shift of the m_J=+1 and -1 sublevels of the lower lasing level becomes larger than the linewidth of the lasing line. Since the linewidth is typically $\Delta\lambda/\lambda \sim 10^{-4}$, the required strength of the magnetic field is ~ 40 T. This value can be achieved without any difficulties by using pulse power magnet system.

We conducted an experiment to extract the circularly polarized components of the Ni-like Mo XRL. The thin rod Mo slab target was set at the center of the magnet solenoid coil with the magnetic field of 20 T. The grazing incidence pumping (GRIP) scheme was employed to generate the XRL gain medium. The spectral profile of the XRL was measured by a high-resolution spectrometer (HIREFS) with the spectral resolution of 12.7 mA. We put an entrance slit just after the gain medium plasma, and the image of the slit was relayed to the position of x-ray CCD as the detector.

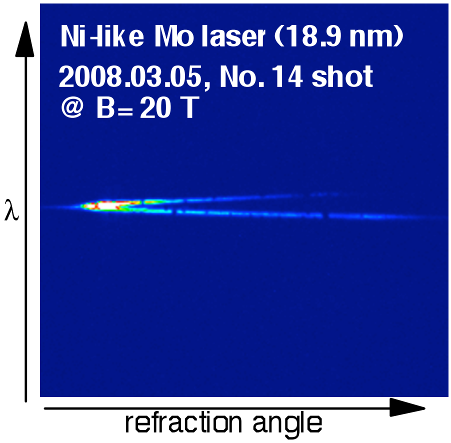


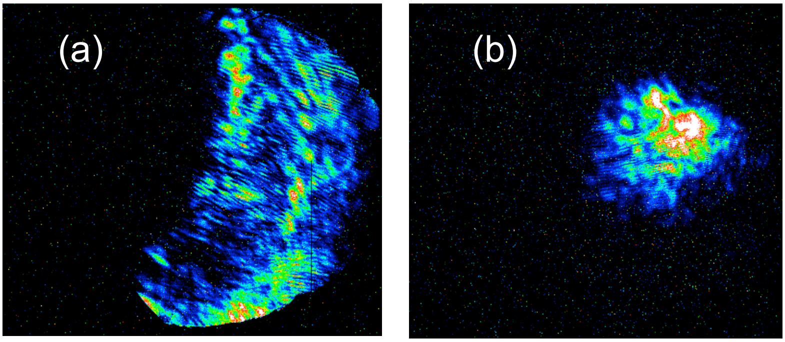
Fig. 3 Ni-like Mo XRL spectrum under the external magnetic field. Expected magnetic field strength derived from the applied voltage is 20 T.

Figure 3 shows the obtained typical spectrum of the Ni-like Mo XRL under the external magnetic field. The separation of the line is clearly shown and is a function of the refraction angle of the XRL beam. Detailed explanation of the experiment is described in another paper of this proceedings [15].

4.2 Improvement of beam divergence and pumping efficiency using v-groove target

In a view point of single-shot exposure experiments, more intense x-ray lasers are desired. For an example, in order to obtain clear image of the nano-structure by the method of single-shot soft x-ray hologram or diffraction imaging, more than 10^{11} spatially coherent photons may be required. In the TCE lasers, the output intensity under the gain-saturation regime is order of 10^{10} Wcm^{-2}, which may give the limitation of the output photon number under the typical size of the gain region. Therefore the generation of large-size gain region with a calm density gradient is key issue to increase the coherent photon number of the XRLs .

In order to increase the size of the gain region, confinement of the pumping energy into the plasma is indispensable. V-groove target may reduce the free expansion of the plasma or radiation cooling, as the result the pumping energy is confined effectively in the inside of the groove..



SN_2008021401 (flat target) SN_2008021409 (v-groove)

Fig. 4 Far-field patterns of the 13.9 nm laser with flat target (a) and v-groove target (b).

V-groove target with 150 μm-depth and 200 μm-width was irradiated by double pulses of CPA Nd:glass laser with the pumping energy of 10 J. Spatial distribution of the x-ray emission in several KeV range observed by an x-ray pinhole camera showed that the area of x-ray emission became 7 times larger, and the energy conversion efficiency was enhanced by more than one order of magnitude compared with the case of the flat target. It should be noted that in the case of v-groove target, the best result was obtained under the defocus condition, *i.e.*, the best focusing position was 800-900 μm before the groove.

With the information obtained by this preliminary test, the v-groove silver target with length of 6 mm was irradiated by our CPA Nd:glass laser. Figure 4 shows comparison of the far-field pattern of the Ni-like Ag laser with the flat target; (a) and the v-groove target; (b). The beam divergence was improved from 10 x 20 mrad^2 to 5 x 5 mrad^2, although the output energy decreases by only a factor of 2. The narrower beam divergence in Figure 4(b) may be due to that the beam propagation direction is limited by the shape of the groove and that large gain region with a calm density gradient is obtained. Present result indicates the potential of this target to improve the output energy in the double targets geometry.

4.3 New scheme for shorter wavelength x-ray lasers

In this subsection, we describe attempts towards shorter wavelength x-ray lasers. One is the frequency up-shift using the reflection from a relativistic plasma mirror, and the second is photo-pumping scheme using K-α line.

Relativistic plasma mirror is called as "Flying mirror", and the use of this mirror for generating ultra-short coherent x-ray pulse is proposed in [16]. Flying mirror is formed by a breaking wake field created by an intense laser pulse with 2TW, 76 fs-duration propagating in underdense helium plasma, and the source pulse (IR laser pulse) with the duration of 76 fs collide with the mirror in the direction of 45 deg with respect to the direction of the propagation of the mirror. Reflection of the source pulse by the moving mirror induces the frequency up-shift and pulse shortening by a factor of $\sim 4\gamma^2\cos(\theta/2)$ due to the double Doppler effect, where γ and θ is the relativistic gamma factor of the flying mirror and the incident angle, respectively.

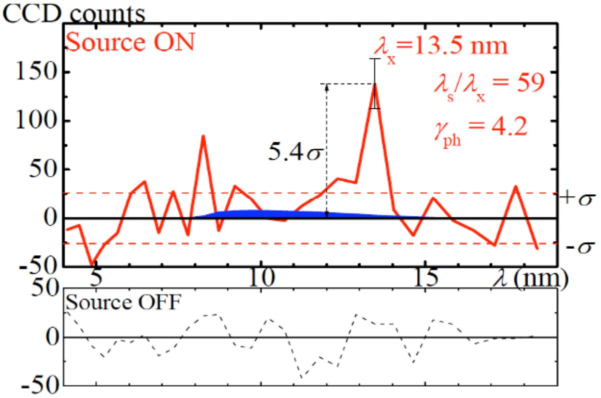


Fig. 5 Obtained spectrum of the reflected light by flying mirror.

Typical reflected spectrum of the source pulse is shown in Figure 5. Peak was obtained at around 13.5 nm, which corresponded to the upshift factor of 59 or γ= 4.2 [17]. This scheme has potential to generate atto-second coherent soft x-ray pulse by use of larger γ factor or more intense driver laser such as 100 TW class laser.

In the photo-pumping x-ray laser scheme, spectral line emission from particular ions is absorbed by different element ions to create the population inversion in the latter. The success of this scheme as an x-ray laser depends upon exact spectral matching between the emission line and the absorption line [18,19]. However, the use of "emitter" ions and "absorber" ions involves a technical difficulty: the emitter and the absorber ions should be located as close as possible so that the pumping emission reaches to the absorber ions efficiently. At the same time, the electron temperature should be high for the emitter to increase the emissivity of the ions, whereas the lower temperature is favorable for the absorber ions to avoid the "thermal" population in the lower lasing level, which reduces the amplification gain. This implies that the use of "emitter" ions and "absorber" ions is not practical under usual laser irradiation geometry [20].

We propose the use of Kα line from a solid target as the emitter coupled with the laser-produced plasma as the absorber. We focus the precise wavelength matching of aluminum Kα line (0.833816 nm) and resonance line $2p^6$-$2p^5 4d$ (J = 1) of neon-like zinc ions (0.83400 nm) and calculate the temporal evolution of the excited level population of the neon-like zinc ions. The calculated result shows that substantial amplification gain in the transition of $2p^5 3p$ – $2p^5 4d$ line at a wavelength of 3.5 nm can be generated in this scheme [21].

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Recent Advances on LASERIX Facility: Development of XUV Sources System and Applications. Perspectives from 2008 to 2010.

D. Ros [1,2], S. Kazamias [1,2], O. Guilbaud [1,2], J. Habib [1,2], B. Zielbauer [1,2], M. Pittman [1,2], G. Jamelot [1], A. Klisnick [1], J.-C. Lagron [1,2], D. Joyeux [3], S. de Rossi [3], F. Delmotte [3], S. Lacombe [4], E. Porcel [4], C. Lesech [4], A. M. Penhoat [5], A. Touati [5].

[1] LIXAM, Bât 350, Université Paris-Sud / CNRS, Orsay, France
[2] LASERIX, Centre Laser Université Paris-Sud, France
[3] LCFIO, Institut d'Optique, UMR 8501, bât 503, 91405 Orsay, France
[4] LCAM, Bât 351, Université Paris-Sud / CNRS, Orsay, France
[5] Institut de Minéralogie et de Physique des Milieux Condensés, Université Paris 6/CNRS, France.

Abstract. LASERIX is a high-power laser facility leading to *High-repetition-rate XUV laser pumped by Titanium:Sapphire laser.* The aim of this laser facility is to offer Soft XRLs in the 30-7 nm range and auxiliary IR beam that could also be used to produce synchronized XUV sources. This experimental configuration highly enhances the scientific opportunities of the facility, giving thus the opportunity to realize both X-ray laser experiments and more generally pump/probe experiments, mixing IR and XUV sources. In this contribution, the main results concerning both the development of XUV sources (in the seeded or ASE mode) and their use for applications (irradiation of DNA samples) are presented.

1 Introduction and context

Early X-ray laser actions were obtained in high-power laser facilities intended to inertial fusion studies. Since the first demonstration of the laboratory X-ray lasers 20 years ago [1], there has been significant progress in demonstration of X-ray amplification based on various pumping schemes, characterizing and improving their performances and developing XRL applications. Nevertheless, the low access and low repetition rate of the large laser facilities are not well adapted to improve the development of short wavelength lasers and those of their applications. Considering this context and the international experiment of the LIXAM team, we obtained a financial support (4.2 M€) to build a laser facility devoted to the development of XRL mainly emitting in the 30-10 nm range and of their applications, particularly investigations on XRL interaction with matter.

The main technology of the LASERIX driver is based on Ti:Sa crystals [2, 3]. Indeed, due to their large line width, Ti: Sa lasers may emit much shorter pulses (in the range of few tens of fs) than Nd-glass ones (up than 300 fs). The general architecture of the Ti:Sa laser is schematically represented in Figure 1.

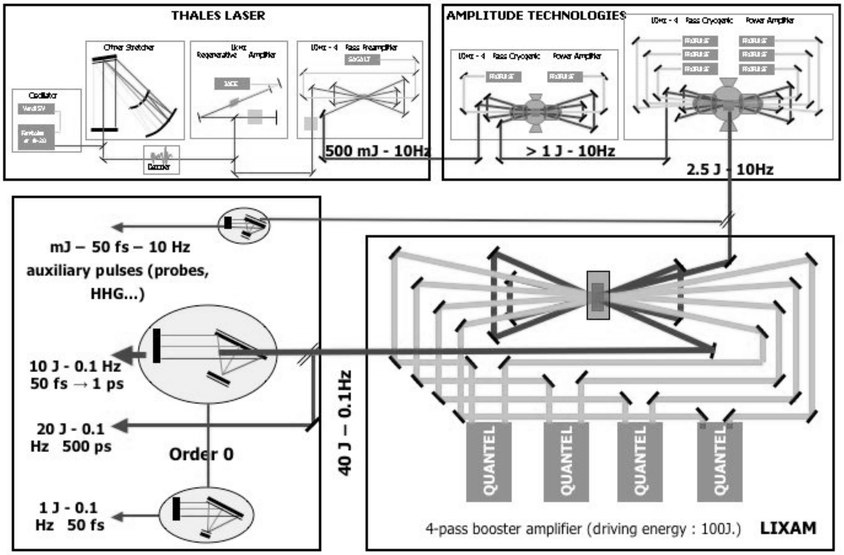

Fig. 1 Schematic view of the LASERIX driver architecture

The front-end is designed as a customized laser based on standard modules, developed by several French companies (THALES LASER and AMPLITUDE TECHNOLOGIES). It is composed by two main parts : one for the shaping and pre-amplification of the oscillator pulse, the other for two cryogenic amplifiers. The output energy at the front-end is more than 2J at the 10Hz repetition rate. The front-end beam (2.5 J) is then injected in the main amplifier, which is composed by the large Ti:Sa crystal (diameter 100 mm), shown in Figure 2. The crystal is pumped by a 4-module Nd:glass laser delivering 100 Joules of 2ω green light, developed by the French laser company QUANTEL. The energy deposition on each side of the crystal is homogenized using lens arrays. The crystal is held in a mount in which a special liquid is circulating all around to cool the crystal and limit the transverse lasing. After 4 successive passes through the crystal, the expected output before compression is ≅ 40 Joules at the repetition rate of 0.1 Hz. Basically, as shown in Figure 1, the 40-joule beam is divided in two parts, respectively 20 Joules of 500 ps and 10 Joules of 50 fs-1 ps (after compression). Besides, two more beams are offered at the final stage. Thus, the zero-order rejected by the compressor may be itself compressed to give a beam of ≅ 1 J in 50 fs.

Besides, a weak part of the energy at the exit of the front-end, ≅50 mJ in 50 fs at the repetition rate of 10Hz, can be offered to the users

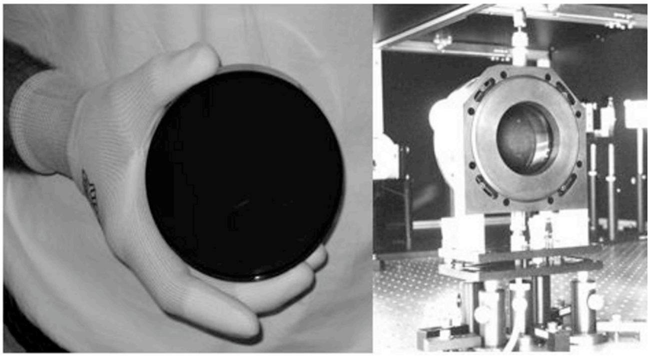

Fig. 2 The large titanium-doped sapphire crystal (diameter : 100 mm) of the LASERIX driver amplifier is shown on the left. On the right image, we can see the crystal and its mount, including a liquid all around the mount.

The first step of the development of our laser facility consisted in the production of 40 joules at 0.1 Hz repetition rate. To achieve this goal, we hardly worked both on the limitation of the transverse lasing effect and on the homogenisation of the pumping of the Ti:Sa crystals. This work has been successful and then we made in 2006 the demonstration of the production of 32 pumping Joules using 3 over 4-module Nd:glass laser [4].

Fig. 3 Picture of the “transient” experimental area.

The second step was ordered considering the status of the project in 2006. Indeed, we were supposed to move in a new building at the LOA (ENSTA, Palaiseau) especially dedicated to several laser facility programs. But due to a delay in the building’s construction, we had to stay two more years in a transient building. As shown in Figure 3, this building was just large enough for the pumping laser. Thus, we decided after the validation of the pumping system to remove the final stage of amplification to get free an area for the development of XUV sources and their uses for applications.

2 Development of XUV sources

The LASERIX configuration that was used for the development of the XUV sources is the low energy/high repetition rate part of the full system, as described on part one of this paper (see also Figure 1). Typically, we used 2 Joules of uncompressed infrared energy per pulse coming out from the last Ti:Sa amplifier stage of the front-end. The final amplified beam is equally split into two new beams. The first one remains uncompressed (700 ps) and the second one enters an in-vacuum compressor providing durations varying from 40 fs to several 10 ps.

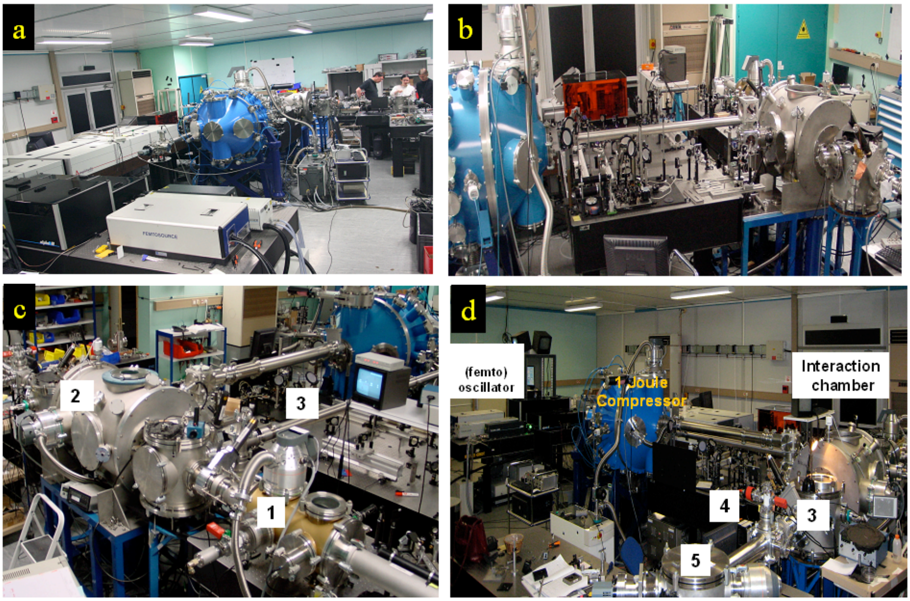

Fig. 4 Experimental set-up for the XRL generation

The Figure 4-a gives a general view of the arrangement of the experimental area, including the pumping laser until the front-end part, the compressor chamber (at the centre of the image) and the XUV sources investigations zone (at the back of the image). Different view of the experimental area for development of XUV sources are presented on Figures 4-b, 4-c and 4d.