Update on laser-driven X-ray sources at ELI Beamlines

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ABSTRACT

Three main paths have been selected within the ELI Beamlines research program for transforming driving laser pulses into brilliant beams of short wavelength radiation: High-order harmonic generation in gases, Plasma X-ray sources, and sources based on relativistic electron beams accelerated in laser-plasma. For each of these research areas, dedicated beamlines are built to provide a unique combination of X-ray sources to the user community. The employment of these beamlines has a well-defined balance between fundamental science and applications in different fields of science and technology. Besides those beamlines, a plasma betatron radiation source driven by the PW-class HAPLS laser system is being commissioned in the plasma physics platform to serve as a unique diagnostic tool for dense plasma and warm dense matter probing.

Keywords: X-rays, extreme ultraviolet, high-order harmonic generation, laser-plasma, plasma betatron, coherent diffraction imaging

1. INTRODUCTION

The mission of the ELI Beamlines center, which is a part of the pan-European ELI project, is to provide high energy beams of laser-driven X-ray sources and accelerated particles to the users from various fields of research [1]. In this paper, we provide a brief update on current and near-future experimental capabilities as well as some recent results on coherent diffraction imaging (CDI).

The main laser drivers considered for the X-ray sources are the kilohertz L1 Allegra laser system [2] and the multi-hertz petawatt-class L3 HAPLS system [3]. The L1 laser system is based on optical parametric chirped pulse amplification (OPCPA) and it is designed to provide pulse energy of 100 mJ with 15 fs pulses at 1 kHz repetition rate. This system already demonstrated operation above 50 mJ pulse energy, but the user operation is so far limited to 30 mJ with design values of pulse duration and repetition rate. The petawatt-class L3 laser is also still in the stage of ramping up its performance towards the design values. Currently, it provides pulses with the energy of 10 J and pulse length of 30 fs at a maximum repetition rate of 3.3 Hz or in the single-shot mode. The petawatt operation is expected in near future, while the 10 Hz repetition rate will most likely become available in a few years.

2. X-RAY SOURCES

X-ray sources that do not require very high energy of the driving laser pulse, such as high-order harmonic generation in gases or plasma X-ray sources, can be operated at a high repetition rate. In the case of the ELI Beamlines facility, those sources are driven by the kilohertz multi-terawatt L1 laser complemented by a commercial laser that provides 11 mJ pulses with duration of 35 fs and repetition rate of 1 kHz. On the other hand, the sources based on laser acceleration of electrons to relativistic energies, such as plasma betatron and inverse Compton source, will be exclusively driven by the multi-hertz petawatt-class L3 laser.

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2.1 HHG Beamline

The HHG Beamline (see schematics in Fig. 1), as a source of coherent XUV radiation with femtosecond pulses based on high-order harmonic generation in noble gases that is driven by kilohertz laser drivers [4],[5], has been routinely employed for user experiments. Although the beamline is designed to accommodate up to 100 mJ laser pulses, the L1 laser currently provides a maximum pulse energy of 30 mJ for HHG. Laser focusing with f-numbers 80, 200, and 500 is currently utilized enabling efficient generation in various noble gases with both kHz laser drivers. The XUV beam is directed into two end-stations: a station dedicated to atomic molecular and optical sciences and coherent diffraction imaging [6] and a magneto-optical VUV ellipsometry station [7] dedicated to material science and surface science. Since the beamline commissioning various parts of it have been upgraded with respect to the original design to increase the photon number and improve the versatility and robustness of the source as well as to improve the characterization of the XUV beam [8].
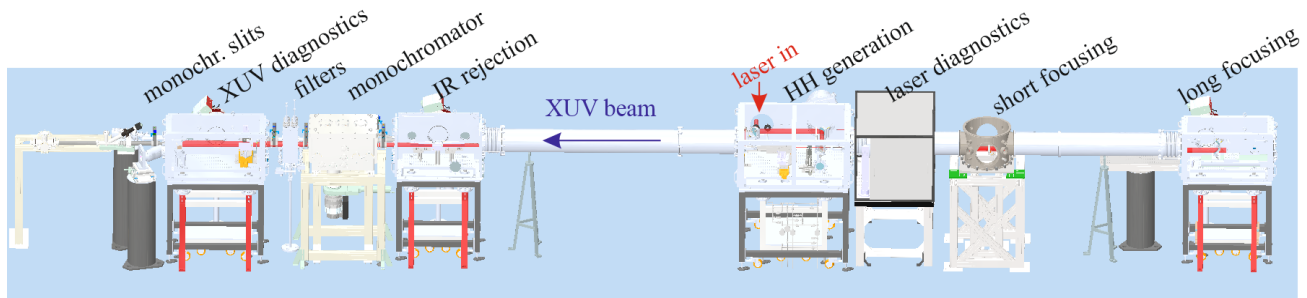

Figure 1. Drawing of the current state of the HHG Beamline with all vacuum chambers labeled by their main function. More details can be found in [4].

Recently, the grating monochromator employing a grating with 150 lines per mm was optimized to provide close to diffraction-limited image of the harmonic source on a panel with slits of various widths (50 to 400 microns) and 100, and 200 μm pinholes. Fig. 2 shows a typical image from a Ce:YAG screen located at the position of the slit panel showing positions of 21st and 19th harmonics generated by the 792 nm Ti:Sapphire laser (11 mJ, 35 fs, 1 kHz) in a Kr gas cell. The harmonics on the screen have around 200 μm in full-width at half maximum.
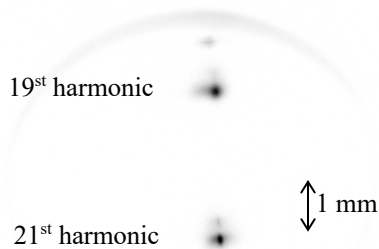

Figure 2. Negative image of the emission of the scintillator crystal that is placed in the position of exit slit of the monochromator showing 19th and 21st harmonic generated in krypton. The part of the circle at the top of the figure is caused by light coming from the edge of the scintillator.

In the following paragraph, we will describe a particular experiment, which proved the feasibility of using the beamline for monochromatic XUV coherent diffraction imaging. The monochromator slit or pinhole is imaged by an ellipsoidal mirror with demagnification factor of 5 onto a sample. The XUV focus was located 1 mm in front of the sample to ensure homogeneous illumination. A sample of 5 μm by 4 μm resembling the ELI logo was created by nano-structruring on 300 nm Au layer on a 75 nm thick Si_3N_4 substrate using a focused ion beam. For the CDI experiment, the sample was illuminated by a monochromatic XUV beam of the 21st harmonic at the wavelength of 38 nm (photon energy of 33 eV). Coherent diffraction patterns were captured using a back-illuminated CCD detector placed 50 mm behind the sample. Higher dynamic contrast of the pattern could be achieved utilizing a beam stop at 20 mm distance to the CCD sensor.

Images with and without the central beam stop were acquired and processed in order to obtain a diffraction pattern containing both the diffraction center and good signal at higher Fourier frequencies (see Fig. 3). Even though a single-shot diffraction pattern could be recorded, a typical exposure time of the camera was 100 ms to acquire the lowest spatial frequency with a reasonable signal to noise ratio. To make the highest spatial frequency visible, an acquisition time of up to 15 s is needed, leading to an overexposure of the low-frequency features. The maximum spatial frequency recorded by such system was 7300 lines/mm resulting in theoretical resolution of ~90 nm.
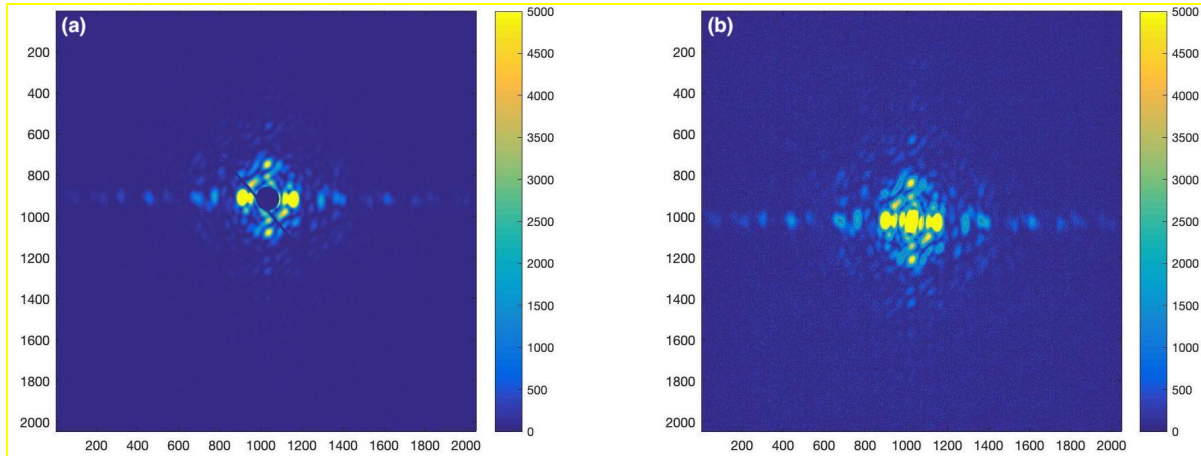

Figure 3. Raw diffraction pattern captured with beam stop (a), and post-processed, centered pattern (b) using a diffraction pattern without beam stop to reconstruct the parts of the pattern covered by the beam stop.

The applied phase retrieval algorithm is based on Fienup's Hybrid Input-Output [9][10] combined with Luke's Relaxed-Averaged-Alternating-Reflections algorithm [11] to enhance the robustness to converge to the solution by fulfilling constraints in both Fourier and real space domains. Iterative reconstructions were performed following the strategy of incrementally optimized support masks, starting with a coarse auto-correlation envelope derived from the diffraction pattern itself. The support masks are optimized continuously by adopting the shape of the reconstructed object in real space. Optimized reconstructions are therefore achieved after 35 iterations pushing the image reconstruction to an almost real-time process. A qualitative comparison between the SEM image of the actual object and the reconstruction of its XUV image (see Fig. 4) reveals a good agreement both in scale and shape.
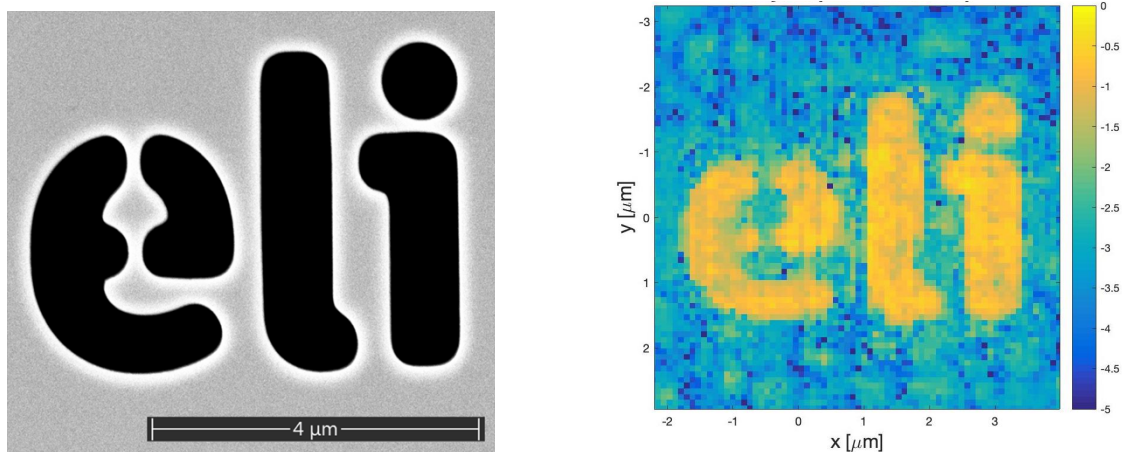

Figure 4. SEM image of ELI logo (left). Reconstructed image after 35 iterations (right). 21st harmonic of a Ti:sapphire laser monochromatized by a grating monochromator was used for illumination.

2.2 Incoherent plasma X-ray sources

There are two types of laser-plasma X-ray sources (PXS) depending on the state of the X-ray emitting material. Either it is the laser-generated plasma heated to high enough electron temperatures to generate appropriate ionization and collisional excitation of the working ion that consequently radiates through spontaneous emission, or it is the neutral target being bombarded by fast electrons from the hot plasma in its vicinity. The first type of source typically employs ns and ps lasers that are better absorbed and heat the plasma volume more efficiently resulting in ps-ns sources of XUV or soft X-ray radiation. The second type, on the other hand, employs femtosecond lasers that generate a significant population of hot electrons penetrating into the neutral material generating both a continuous X-ray spectrum (bremsstrahlung) and characteristic X-ray lines (such as K_α or L_α lines) via electron collisions with neutral atoms of the target. The later type of the source, if properly designed, is capable of providing sub-picosecond pulses of hard X-ray radiation (few keV - 30 keV) with reasonable efficiency. Therefore, this method has been chosen to be implemented at ELI Beamlines for ultrafast probing of structural and electron dynamics by diffraction methods and spectroscopy, respectively. Proper laser intensity sets a suitable electron temperature for generation in a given spectral range. The hot electron temperature scales as $T_{HOT} \sim (I\lambda^2)^{1/3}$ underlining the importance of development of long-wavelength high-peak power laser systems. Moreover, a contrast of the laser is a very important aspect, as it defines the interaction conditions of the pulse with the target.

There are three types of high-density targets being investigated for laser-plasma X-ray sources with kilohertz laser drivers (L1 and commercial kHz laser) focused by short focal-length parabolic mirror. A water jet target emitting low-energy X-ray continuum [12], metal tape target (Cu and Mo tapes) with its characteristic lines and significant bremsstrahlung in the 10-20 keV energy range [13], and liquid metal jet source [14] using Ga or Bi/In as a renewable target. While the water jet source lacks characteristic lines and therefore offers low spectral brightness, its advantage lies in its almost debris-free operation, making it an easy-to-implement/operate X-ray source for spectroscopy applications. Sufficient photon flux generated by metal target PXS systems come with debris contamination of the reaction chamber, making the sources prone to operation instability in long-term runs and flux output. Thus, each of these sources has its advantages and disadvantages. Further investigation is needed to decide which technology will become the basis for user experiments.

2.3 Laser-plasma accelerator-based X-ray sources

The Gammatron beamline, a multidisciplinary user-oriented source of hard X-ray radiation based on the laser-plasma accelerator (LPA) is being deployed in experimental hall E2 of the ELI Beamlines. The Gammatron beamline [15] consists of a broadband hard X-ray source with spectral range from a few keV to few hundreds of keV through a betatron scheme and a quasi-monoenergetic beam of hard X-rays with a spectral range of a few 100's keV in inverse Compton scheme. The mechanism of generation of these X-ray sources is based on laser wakefield electron acceleration, in which an intense ($>10^{18}$ W/cm^2) femtosecond laser pulse interacts with a gas medium. The ponderomotive force of laser drives an electron plasma wave that traps electrons and accelerates them to relativistic energies. The accelerated charge also experiences transverse oscillations due to restoring force induced by space-charge separation, which generates synchrotron like radiation. As a result, a collimated X-ray beam with bright ultrashort pulses known as plasma betatron radiation is generated [16]-[17]. Recent experimental results on Betatron show that up to 10^{11} photons/shot can be routinely delivered [18]-[19], the photon flux can be further enhanced by using the PW class lasers. Furthermore, in the inverse Compton scheme, where the relativistic electrons collide with a counter-propagating intense laser pulse, gamma radiation (100's of keV to the MeV range) can be generated as a result of double Doppler upshift of the scattered laser pulse. Both of these X-ray sources can deliver ultrashort (few fs) X-ray or gamma-ray pulses as they inherit the temporal properties of the accelerated electron pulse. Those sources represent the emergence of a new generation of bright, collimated, compact X-ray sources.

The driving laser of the Gammatron beamlines is a state-of-the-art diode-pumped Ti:sapphire L3 HAPLS laser that should deliver up to 30 J at a 10 Hz repetition rate. The schematic of the Gammatron beamline is shown in Figure 5 A. The target for the generation of relativistic electron bunches and X-rays will be either supersonic gas jet or gas cell. The typical gases for the LPA target are pure He, He with the admixture of Nitrogen, gas clusters, or dry air [20], and the plasma density for the acceleration will be in the order of 10^{18-19} cm^{-3}. The gas jets are characterized using a high resolution, high -sensitivity interferometer [21]-[22] before being placed into the experimental chamber. The ultrashort pulses (~fs) of Gammatron sources and their efficient synchronization with another femtosecond laser pulse offer a

versatile tool in studying various time-resolved experiments in ultrafast science. The major applications of the Gammatron source include X-ray phase-contrast imaging [23], radiography, time-resolved X-ray absorption spectroscopy [24], X-ray diffraction, and industrial imaging of large and dense objects.
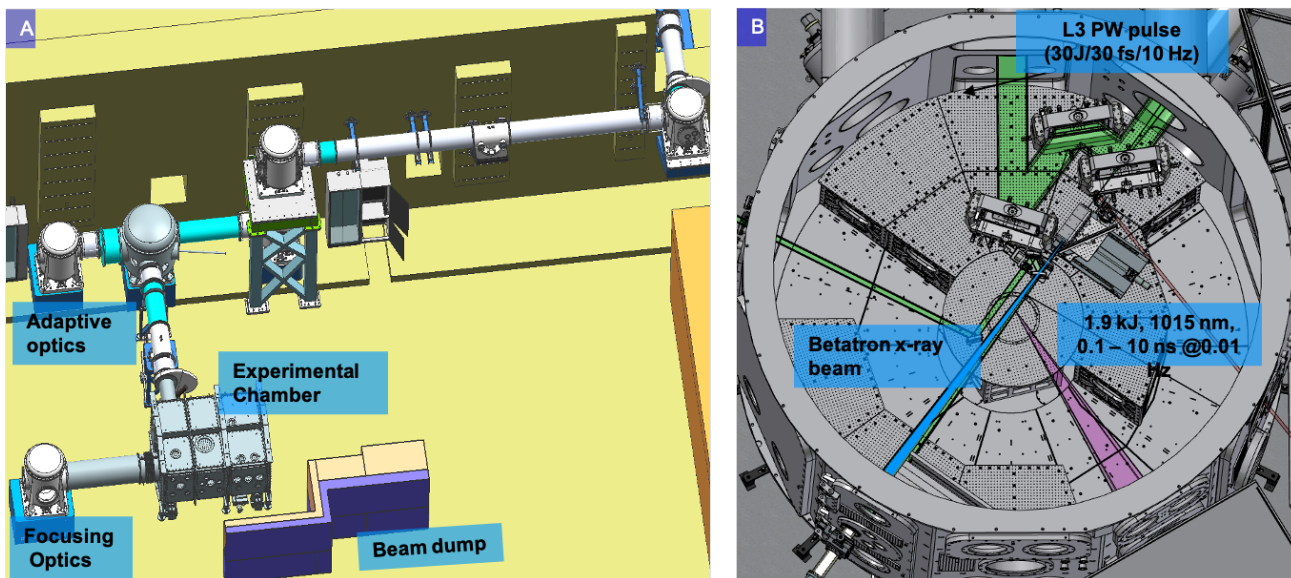

Figure 5 A) Schematic of Gammatron beamline in the E2 experimental hall at ELI Beamlines. B) Multi beams setup inside P3 chamber, a typical setup for plasma and WDM probing. The green rectangular beam is focused into a supersonic gas jet using a spherical mirror with a 5 m focal length to accelerate electrons and generate a betatron X-ray source (blue beam).

A separate betatron X-ray source [25] is being developed in the plasma physics platform (P3) [26] located in the experimental hall E3 (Fig. 5 B). The P3 facility is focused on a range of plasma physics experiments including high energy density (HED) physics, ultra-intense laser-matter interaction, laboratory astrophysics, and advanced plasma physics studies using multiple laser and particle beams [27]. Dense and highly ionized plasma can be produced during the interaction of intense laser with matter. Probing such plasmas requires a very bright hard X-ray source to overcome the plasma self-emission and to penetrate through it. Furthermore, it will be an excellent probe for many laboratory astrophysics experiments like collisionless shock or radiative shock waves [28]-[30]. In those experiments, the object moves very fast, the shock front and hydrodynamic instabilities can be very thin, i.e. requiring an ultrashort probe to resolve their structure. In laser-heated warm dense matter (WDM), the transition effects happen on timescales of the order of few tens of femtoseconds [31]. Therefore, the probing source of the WDM needs to be extremely short. The Betatron X-ray source offers X-ray pulses with a duration of tens of fs, delivers a collimated beam with a divergence less than few tens of milliradians, and small source size making the source ideal backlighting tools to study time-resolved ultrafast processes in plasma physics experiments.

3. CONCLUSION AND OUTLOOK

A new generation of X-ray sources (see also Sect. 1 and Sect. 2 [32]), driven by high power laser systems, is increasingly available for user research projects at the ELI Beamlines center. The co-existence of primary and secondary photon sources operating at a variety of energies with both monochromatic/coherent and polychromatic/incoherent operation modes allow the synergetic usage of sources and beamlines. Thus, not only classical IR-pump/X-ray-probe experiments can be carried out but also XUV/X-ray pump/probe concepts will be feasible. Covering pump/probe energies from near IR, over XUV close to the water window, and up to hard X-rays in the keV regime, the sources at ELI Beamlines offer unique experimental opportunities for the international research community. In time, we expect that these sources will outperform similar-type sources available in small laboratories not only in terms of photon flux but also in robustness, stability, and availability of well-established user end-stations equipped with extraordinary sets of diagnostics. Moreover, further development of laser-driven X-ray sources will improve the usability of their compact versions that are more generally available in small university laboratories.

Acknowledgments

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