EXTREME LIGHT INFRASTRUCTURE (ELI BEAMLINES) – RESEARCH AND TECHNOLOGY WITH NEW ULTRA-SHORT PULSE INTENSE LASER DRIVEN SOURCES OF ENERGETIC PHOTONS AND CHARGED PARTICLES

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Abstract

We are giving an overview on the development of the “Extreme Light Infrastructure (ELI) Beamlines facility”, which will be a high-energy, repetition-rate laser pillar of the ELI project, [1]. It will be an international facility for both academic and applied research, slated to provide user capability from the beginning of 2016. The main purpose of the facility is the generation and applications of laser driven high-brightness X-ray sources and accelerated particles (electrons, protons and ions).

The laser system will be delivering pulses with length ranging between 10 and 150 fs and will provide high-energy Petawatt and 10-PW peak powers.

The short photon wavelength (20 eV-1 MeV) laser driven sources are either based on direct interaction of the laser beam with a gaseous or solid target or will first accelerate electrons which then will interact with laser produced wigglers or directly injected into undulators. The main planned short pulse laser driven x-ray and charged particles sources and their parameters are presented together with basic requirements on the relevant beam detectors.

LASER SOURCES

ELI experimental area is divided into six experimental halls E1 to E6 (see Fig. 1), where a wide range of secondary x-ray or charged particle sources driven by a set of laser sources is located. The developed state-of-the-art laser sources are divided into four systems L1 to L4, each providing a specific range of pulse energies, lengths and repetition rates.

The laser system L1 involves two high-repetition-rate kHz beamlines employing the technique of Petawatt Field Synthesizer (PFS). Upon compression using chirped mirrors, each of the kHz beamlines will provide about 200 mJ, 20 fs pulses.

The 10-Hz repetition rate L2 system providing PW-class pulses (10 and 20 J) will consist of diode-pumped multislab lasers pumping a large Ti:sapphire broadband amplifier and also an OPCPA chain.

The L3 system exploits the technology of multislab Nd:glass operating at near room temperature and running at10 Hz repetition rate. The system will provide about 30 J in ~20 fs pulses at 10 Hz, corresponding to approximately 1.5 PW peak power. Additionally to the main 1.5 PW pulses the system will provide inherently jitter-free synchronized auxiliary pulses with peak power of ~50 TW.

The designed laser system finally involves a 10-PW beamline in the L4 section. The system is designed to exploit the technology of mixed Nd:glass capable to deliver CPA pulses with bandwidth >13 nm, which are

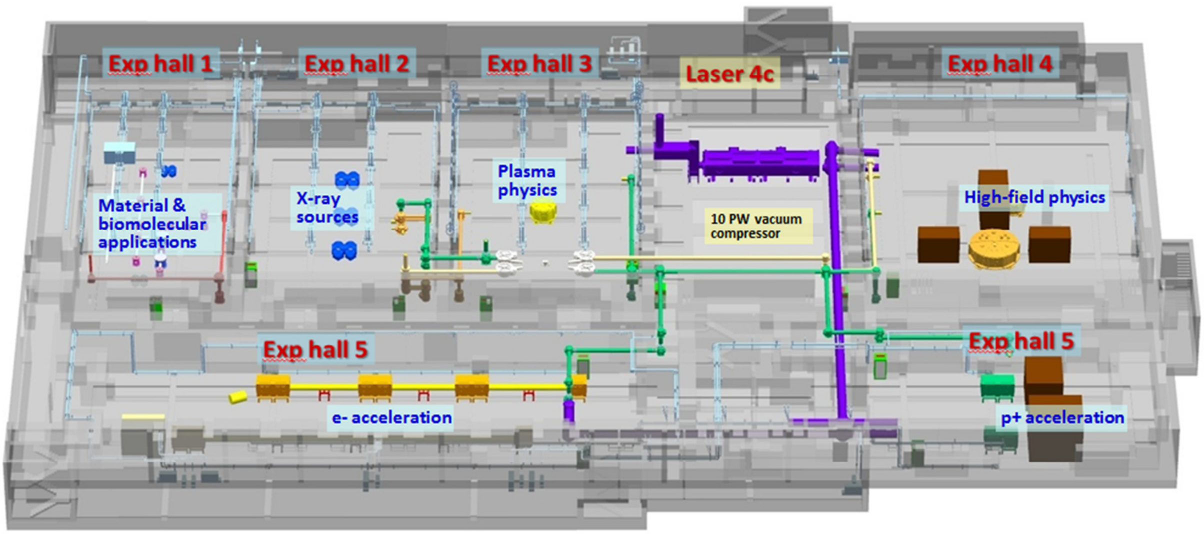

Figure 1: Overview axonometric layout of the basement floor of the ELI-Beamlines laser building showing the experimental halls E1 to E6. The halls will be equipped progressively with vacuum chambers, experimental instrumentation and beam delivery units, according to the project implementation plan. The overall footprint dimensions of the basement floor are about 110 x 65 m^2.

compressible to 130 fs. The laser chain will consist of OPCPA pre-amplifiers in the front end and of final Nd:glass slab amplifiers. This solution, designed to provide >1.5 kJ pulses, is well suitable for the ELI-Beamlines mission in generation of accelerated electrons where pulses >100 fs are required for acceleration to energies >10 GeV. The kJ energy available is also ideal for generation of plasmas for laboratory astrophysics, another mission of the ELI-Beamlines facility.

SECONDARY SOURCES

The secondary sources driven by the laser systems and housed in the experimental halls will generate short intense pulses of X-ray and charged particles. These sources will be developed in parallel with the laser systems and their parameters in various phases of the ELI project are summarized in Table 1. The detailed overview of the experimental capabilities of the secondary sources will be soon available in [2].

X-ray Sources

The short wavelength (20 eV-1 MeV) short pulse high intensity laser driven sources are either based on direct interaction of the laser beam with a gaseous target, liquid metal or solid target (High order harmonics generation (HHG), K-alpha and related laser-produced plasma sources, x-ray lasers and γ-ray flashes) or will first accelerate electrons which then will interact with laser produced wigglers (Betatron radiation) or permanent magnet undulators. In the latter case two beamlines are foreseen, the Laser Undulator X-ray source, LUX, which will be commissioned in 2016; and the X-ray Free Electron Laser Demonstrator, XFELdem, see Fig. 3, which is planned for the Phase 3. The direct interaction (collision) of laser accelerated electrons with the laser again will lead to short pulse gamma-ray beams via Compton or Thomson scattering.

Some of these sources will provide coherent radiation (High order harmonics, x-ray lasers, LUX and XFELdem).

In HHG, a focused femtosecond pulse laser beam with an intensity in the order of 10^{14} W/cm^2-10^{15} W/cm^2 enters a gas jet, and drives the electrons of a gas. The periodic recollision of the oscillating E-field driven electrons with the atomic core leads to an extremely short burst of short wavelength harmonics.

The K-alpha source employs interaction of a focused kHz short pulse laser with a metal (or cluster) target. The target should replenish (liquid metal beam system considered as nominal solution). The incident laser pulse generates fast electrons which induce K-shell vacancies, and incoherent plasma radiation is produced in the process of filling of the vacancies. Additionally, continuum radiation is emitted.

In the case of Betatron radiation source, the plasma channel is generated in a pulsed gas jet using high intensity laser pulses. The x-ray radiation is generated by betatron oscillations of off-axis electrons, see Fig. 2.

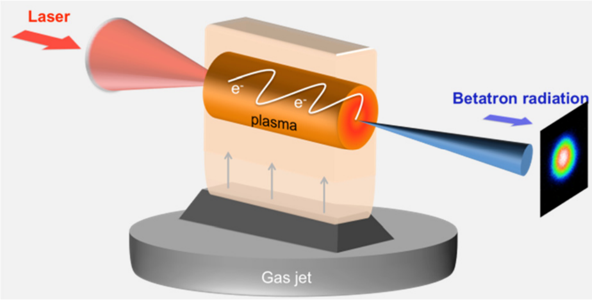

Figure 2: Generic layout of generation of x-ray radiation in plasma betatron.

The soft x-ray laser scheme will be based on amplification of HHG in an additional gas cell, which will be subsequently amplified in a laser-produced plasma column. The amplifying plasma column will be generated by kilojoule-class uncompressed pulses with duration of 0.5 to 3 ns.

Electron Acceleration

The basic electron acceleration setup is intended as a tool of investigation for the optimization of a laser-plasma accelerator (using gas-jet targets, gas-filled capillary, etc.) by using simple laser wakefield acceleration schemes. Moreover, novel techniques will also be used to control the process of electron injection into the wakefield through density ramps, double-off-axis parabola (short and long focal length) geometries, etc. The main topic will be to investigate plasma processes and laser performances able to improve the quality of the produced electron beams in order to overcome the present limits.

An advanced configuration will aim at investigating the generation of all-optical inverse Compton scattering near-monochromatic X/Gamma radiation in a counter propagating double-beam. The same configuration will be easily adaptable for various experiments which can be proposed by the laser-plasma scientific community, e.g. “flying mirror” geometry or investigations based on “radiation friction” effects. More sophisticated schemes will aim at increasing the maximum electron beam energy (mainly through a multi-staged plasma-based accelerator).

Ion Acceleration and ELIMED

In the first phase of the project the Target Normal Sheath Acceleration (TNSA) mechanism will be investigated by using micrometer-thick foils with the main goal of reducing shot-to-shot fluctuations and demonstrating the capability to work in a laser repetition rate regime (1 Hz). At the same time we aim to experimentally investigate new target geometries capable to provide much better laser driven proton/ion beam performances (increase the maximum proton energy and total number, and decrease the beam divergence) by using petawatt-class lasers. For instance, the possibility to apply structures of scale-lengths comparable with the laser wavelength (or shorter) on the thin foil surface (enhanced TNSA) will be investigated. Such laser driven ion beams will be mainly used for the ELIMED beamline with the final goal to perform proof-of-principle experiments (in 1-10 Hz laser regime) which might demonstrate the validity of new approaches for potential future applications in the field of hadron-therapy.

An important step of ELIMED will be to demonstrate that the laser-accelerated proton beams can reach energy of about 60 MeV with a proton yield (number of protons per laser pulse) at the output of the beam transport line, which is sufficient for their application in various fields (mainly radiobiology). A special attention will be devoted to dosimetry studies aimed to design an alternative treatment planning for a future application (only proof-of-principle) in treatment of eye tumors (60-70MeV, quasi-monoenergetic proton beams are needed).

Starting from the second phase of the project (2017 and later), when a 10 PW class laser is expected to considerably increase the power/intensity on target, according to numerical particle-in-cell simulations, the predominant ion acceleration regimes should be: (i) “Shock Acceleration” (for $I > 10^{20}$ W/cm^2) through the so-called “hole boring” mechanism at the target front surface or in its interior; (ii) “Radiation Pressure Acceleration” (for $I \sim 10^{21}$-10^{23} W/cm^2) when the laser electromagnetic wave directly accelerates the ions in the target with a very high efficiency through the space-charge force due to the displacement of all electrons in a thin (nm scale) foil. In the latter case few GeV proton beams with quasi-monoenergetic features are expected.

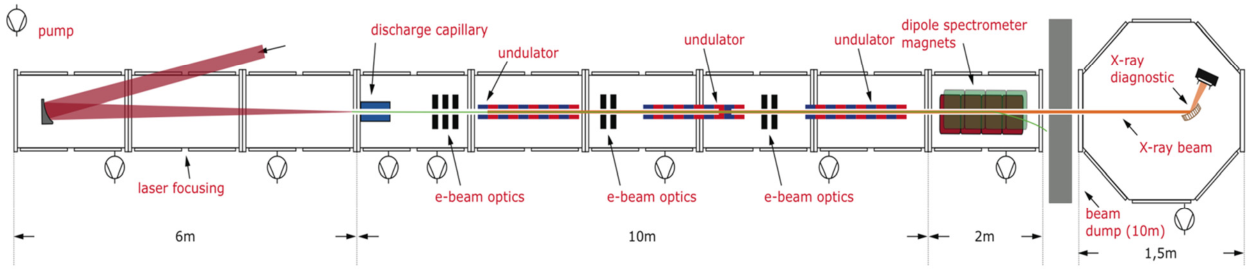

Figure 3: A conceptual scheme of one of the developed ELI beamlines (secondary sources) – XFEL demonstrator (from left to right): a petawatt-class laser beam is focused into discharged capillary, laser wakefield accelerated electrons are focused to pass through a set of undulators to induce the self-amplification spontaneous emission (SASE) process. Image by courtesy of F. Grüner.

EXPERIMENTAL END-STATIONS

Experimental end-stations for applications in molecular, biomedical and material sciences rely on synchronized laser, x-ray and charged particle sources. Several experimental end-stations are being developed within the ELI project and are mentioned below. It is also foreseen to provide a beam time to users bringing their own stations for dedicated experiments. The ELI facility will be also equipped by dedicated chemical and biological laboratories available to users to support the above mentioned and other user experiments.

Ultra-fast pulse radiolysis (PR), Fig. 4, can be in principle conducted with sub-picosecond temporal resolution at the ELI-Beamlines facility. In the Phase 1, a simple PR workstation will be installed at the K-alpha source beamline, focusing the source radiation on a liquid jet (water) target where it generates transient species and states. These transient states will be probed by measuring optical absorption of a synchronized white light flash (and later on using more sophisticated probes) at a chosen (variable) delay.

Table 1: Summary of Envisioned Parameters of the Secondary Sources

	Phase 1 (2015 – 2016)	**Phase 2 (2017 – 2019)**	**Phase 3 (2020 -)**
Energy range	100 eV - 1 MeV (photons) 0.5-3 GeV (electrons) 20-30 MeV (protons)	100 eV - 5 MeV (photons) 2-5 GeV (electrons) 60-200 MeV (protons)	100 eV - 5 MeV (photons) 2-50 GeV (electrons) 0.1-1 GeV (protons)
Yield per shot	10^4-10^6 (photons) 1-100 pC (electrons) 10^9-10^{10} (protons)	10^5-10^{10} (photons) 1-100 pC (electrons) 10^{10}-10^{11} (protons)	10^6-10^{12} (photons) 1-100 pC (electrons) 10^{11}-10^{12} (protons)

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Stimulated Raman scattering (SRS or FSRS – femtosecond stimulated Raman spectroscopy) will be used for probing ultra-fast processes initiated by UV-Vis-NIR pulses or ionizing radiation. This technique yields information not only on the formation and decay of short-living species and states, but makes possible detailed mapping of vibrational energy flows in excited molecules. In Phase 1, a proof-of-principle SRS experiment is planned. In Phase 2, it will be possible to integrate the proven SRS probe into particular pump-probe schemes dealing with ultra-fast dynamics of photo- and radiation-initiated processes in chosen (bio)molecular systems.

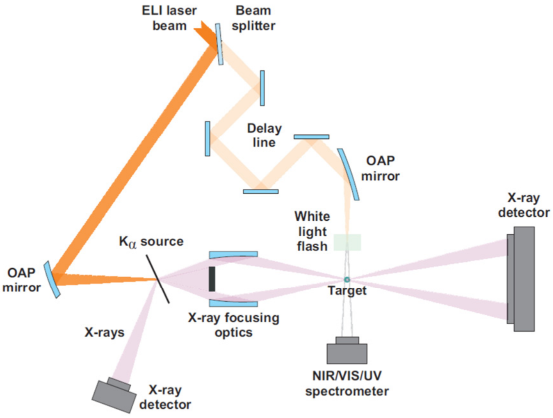

Figure 4: Scheme of pulse radiolysis layout in Phase 1 (2015 – 2016).

Time resolved diffraction end-station will be using long-wavelength pulse as a pump and X-ray pulse as a diffractive probe. Investigated will be nanocrystalline samples, superlattices, crystals, or flying micro/nanoobjects, in which different structural changes (e.g. phase transitions, non-thermal melting, excitation of coherent phonons, induced strain propagation) can be initiated. This technique allows direct probing of the structural dynamics with 100s fs time resolution and sub-Angstrom resolution.

Coherent diffractive imaging is a technique that allows to study structural dynamics of single non-periodic nanometer-sized objects (e.g. (bio)macromolecules, viruses, and cells) using a coherent X-ray pulse. The pulse has to be intense enough for the signal from a single object to be observable and it has to be short enough (10s fs) so the diffraction image is acquired before the sample is damaged. Realization of these experiments strictly depends on the availability of coherent X-ray beams at the facility. Therefore, the experiment itself (following the commissioning of the Diffractive imaging (DI) workstation) is planned in the Phase 2/3 of the project (from 2017 on). The key components of the DI workstation, especially large-area imaging X-ray detectors, sample injectors and sample state/position diagnostics, should be developed, built and tested in Phase 1. In Phase 3, multiple-beam diffractive imaging experiments will be carried out in the DI workstation.

DETECTOR REQUIREMENTS

All the above outlined laser systems, secondary sources and experimental stations will require a wide range of detectors sensitive to various particles (photons from optical down to gamma range, electrons, protons, ions, neutrons), covering intensities from single particle counting to the detection of bunches of particles with a total charge of up to 1 nC, providing outstanding time synchronization (at the level of femto seconds for dedicated pump and probe experiments), working at high repetition rate (1 kHz in some cases) and resistant against strong electromagnetic pulses (EMP) generated by the secondary laser driven plasma sources within the vacuum chambers.

The EMP causes the chambers to ring at their natural frequencies which can extend from a few MHz to many GHz. The EMP within the chambers is estimated to be about 2,500kV/m. The chamber will provide shielding but allow a significant emission of the EMP through diagnostic windows and chamber wiring. The level of EMP in the experimental halls is estimated to be about 250V/m.

SUMMARY

We have outlined briefly the laser systems, laser driven secondary sources of x-ray and charged particle pulses, experimental stations and detector requirements of the ELI Beamlines facility, which is to start the first user operation in 2016. The facility will also provide dedicated experiments for plasma, warm dense matter and high field physics, which is beyond the scope of this short overview. For more detailed information we refer the kind reader to [1] and [2].

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