OPENING UP HIGH-PERFORMANCE LASER SCIENCE TO THE WORLD AT THE EXTREME LIGHT INFRASTRUCTURE (ELI)

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The Extreme Light Infrastructure (ELI) is a research facility that provides for a wide range of scientists access to the largest and most diverse set of high-performance laser systems in the world.

The laser systems of ELI [1] are used to study the fundamentals of interaction between matter and high-intensity, ultra-fast light pulses, including plasma physics and relativistic acceleration of electrons and protons; or drive secondary sources of ultra-fast (down to attosecond pulses), high-intensity beams of light, or particles, including ions, electrons and neutrons which are used for imaging, diffraction and fast spectroscopic studies of materials and biological systems. Such technology is also developed to explore potential applications in laser-driven compact accelerators that could provide alternatives to current central facilities for synchrotron radiation and neutron beams on a scale that could be located more readily in university departments, industrial laboratories or hospitals. ELI operates as a single multi-site organisation with • • •

▲ ELI ALPS building.

▲FIG. 1: Selected laser and target areas currently offered to ELI ALPS users (from left to right): the HR (100kHz, 1 mJ) laser in combination with NanoESCA endstation, the Mid Infrared laser (100 kHz, 0.15mJ) with experimental platform (centre) and the SYLOS (1 kHz, 30mJ) driven beamline for attosecond science.

• • • complimentary facilities: (i) the ELI Attosecond Light Pulse Source (ALPS) facility in Szeged, Hungary for the exploration of ultra-fast processes with uniquely high time resolution; (ii) the high-energy ELI Beamlines facility in Dolní Břežany near Prague in the Czech Republic, with a particular emphasis on high peak intensity; and (iii) the Nuclear Physics (NP) facility in Măgurele near Bucharest in Romania for the combination of ultra-intense lasers with brilliant gamma beams. A particular feature and potential strength of ELI is the complementarity of the facilities, allowing for the support of a particularly wide range of multi-disciplinary science and enabling the co-development of new, enabling technology – for example in laser optics, diagnostics or targets for secondary sources. The three ELI Facilities have been available to user access on the basis of peer-reviewed excellence through open calls for proposals since 2022. To date the ELI facilities have attracted scientists across 27 countries requesting access to 30 different instruments.

ELI ALPS

The ELI ALPS Facility[1] is dedicated to the study of extremely fast dynamics. The parallel existence of state-of-the art lasers with secondary sources and end-stations, offers unique time-resolved investigation possibilities for nonrelativistic and relativistic interaction of light. Installation of research technology started in 2017, when the specially engineered buildings were completed, including 4,000 m^2 cleanroom facilities with vibration isolation, thermal and humidity control and radiation protection. In 2023, the main construction phase of ELI-ALPS is being concluded. The priority focus is shifting from installation to commissioning and user offers. ELI ALPS provides beamtime as well as technical and scientific support for the experiments. To support a wide variety of laser based fundamental and applied research in physical, biological, chemical, medical and materials sciences, the facility hosts a combination of eight specialised primary lasers, operating in NIR and MIR regimes, from 10 Hz to 100 kHz in few cycle pulses. The laser combination drives nonlinear frequency conversion and acceleration processes in twelve different secondary sources. The attosecond secondary sources are based on advanced techniques of high-order harmonic generation in optically ionised gases or oscillating surface plasmas. Other secondary sources provide THz radiation via optical rectification or electron beams via laser wakefield acceleration for spectroscopic and structural studies, plasma physics or radiobiology. End-stations enable investigation techniques to be applied for the study of various samples: *e.g.* a reaction microscope enables the measurement of momenta of photo-fragmented molecules in coincidence; the NanoESCA characterises photoelectrons from surfaces in real and k-space, and spin. Furthermore, high-field physics experiments with the PW laser, particle irradiation of radiobiological samples, photochemical studies or time resolved nanoscience are enabled in advanced setups. Thus at ELI ALPS a uniquely broad spectral range of the highest average and peak power and shortest light pulses with specialised end-stations and a wide portfolio of diagnostics devices becomes available for the study of dynamic processes on the attosecond and femtosecond timescale in atoms, molecules, condensed matter and plasmas.

ELI Beamlines

The combination of high repetition rate capability and high energy in a single pulse of the laser systems at the ELI Beamlines facility[2] is a unique feature which allows users to explore the interaction of light with matter (plasma) at relativistic and ultra-relativistic intensities and simultaneously sustain unprecedently high repetition rate operations of about 10^{23} W/cm^2 at 1 shot/min, about 10^{22} W/cm^2 at 10 Hz, and more than 5×10^{18} W/cm^2 at 1 kHz. Such cutting-edge technologies enable pioneering research in plasma physics, nuclear fusion, strong-field physics, and laboratory astrophysics. Experiments on nonlinear quantum electrodynamics, positron, muon and gamma-ray beam generation, and planetary science are conducted by users or planned in the near future. Furthermore, laser driven particle accelerators have gained interest in recent years thanks to their versatility and innovative features, which has pushed forward the development of beamlines

[1] https://www.eli-alps.hu

[2] https://eli-beams.eu

The scientific breakthroughs on which ELI's transformative technology is based have now been recognized by two recent Nobel Prizes in Physics: in 2018 to Mourou and Strickland for Chirped Pulse Amplification, and in 2023 to Agostini, Krausz and L'Huillier for experimental methods generating attosecond pulses.

where users can exploit the unique parameters such as ultrashort bunch duration and ultrahigh dose rate of laser-driven particle (ion and electron) and radiation (XUV to gamma-ray) sources for a wide range of applications in material science, AMO (atomic, molecular and optical) science, chemistry, biology, medicine, and pump-probe capabilities for high energy density physics. User experiments on probing ultrafast relaxation dynamics of atoms, irradiation of cancer cells, mimicking space radiation for testing electronics, and non-destructive surface analysis techniques for cultural heritage are conducted at the facility. The potential combination of optical, X-ray, and particle beams is also offered to users to conduct experiments related to inertial confinement fusion and shock physics thanks to the availability of a unique kJ-class, nanosecond laser beam operating at unprecedented repetition rate of about 1 shot/min and having temporal shaping capability and narrow/broad band options. A range of advanced target delivery solutions and diagnostics in operation under extreme laser-plasma conditions and unprecedented repetition rates is in continuous development and is provided to ELI Beamlines users.

ELI NP

The focus of the ELI-NP research infrastructure[3] is on research activities of laser- and gamma-ray driven nuclear physics and ultra-high intensity laser interaction and related applications. The facility aims to deliver secondary high energy radiation and particle beams with unprecedented brightness suitable for studying fundamental processes of relevance for domains such as high-energy-density physics, light sources such as betatron, Compton and FEL (Free Electron Laser), and nuclear physics. ELI-NP consists of two major divisions with state-of-the-art equipment: one related to the gamma beam system in which the radiation source is generated from Compton backscattering of laser light on a very intense beam of electrons accelerated to relativistic velocities for high sensitivity nuclear physics studies; the second one related to the high-power laser system for Ultra-High Field science studies aims at the exploration of relativistic laser-matter interaction in a range of extreme laser power and intensity; here new phenomena become significant dominated by the radiation pressure such as the acceleration of the extreme thin foil that allows for the production of a quasi mono energetic ion beam or by the radiation reaction force that affects the dynamics of charged particles and its efficient conversion to γ photons. In the last week of October 2023, a symposium was held to celebrate the 10 years of ELI-NP that is now delivering the most powerful laser beams in the world with two arms of 10 PW each that are reaching intensities of more than 10^{23} W/cm^2. The different *modi operandi* of the laser system allow users to propose a large diversity of experiments. The commissioning of the laser experimental areas was carried out through several experimental campaigns by the ELI-NP teams with the support of expert users from institutions abroad. Many challenges have been successfully tackled resulting in the delivery of multi-GeV electron beams, proton beams with energy over one hundred MeV, and bright gamma beams. ■

[3] https://www.eli-np.ro

▼ FIG. 2: (Top) Selected lasers currently offered to ELI Beamlines users in connecting experimental areas: the L1 5TW (1kHz) laser, the L3 1PW (10Hz) laser (centre), and the L4n kJ (ns) laser. (Bottom) The laser bay at ELI-NP housing lasers capable of delivering up to 10 PW.