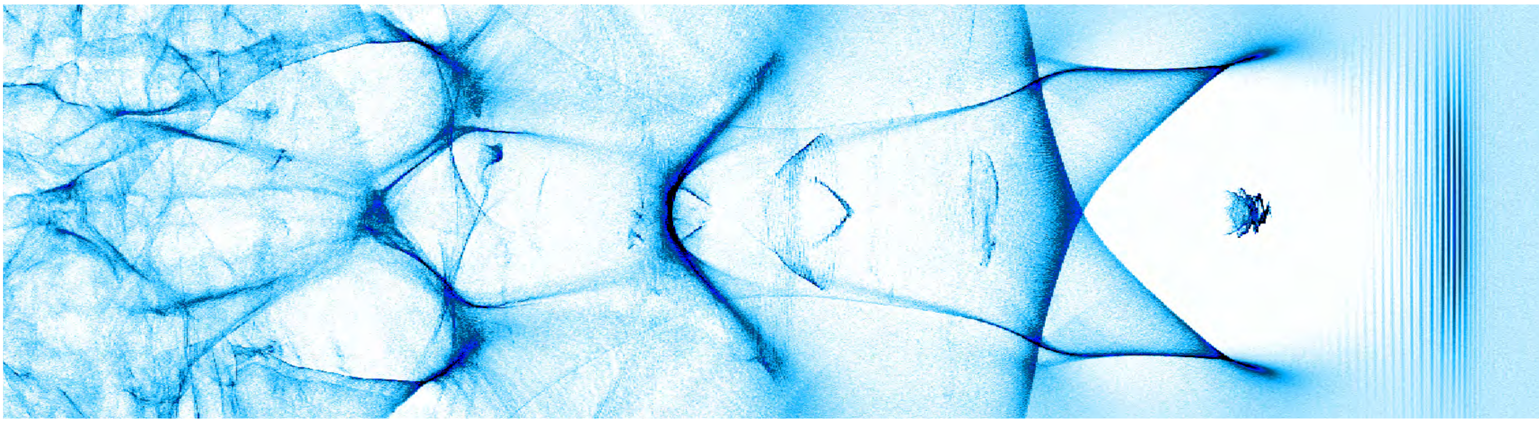


Information on Scientific Programs and Experimental Capabilities of ELI Beamlines

for the Research, Development and Innovation Council

Version 1.0 | April 2017

Fyzikální ústav
Akademie věd ČR, v. v. i.

MŠMT
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

Contents

1. Executive Summary ... 4
2. Facility Overview ... 5
3. Research Programs ... 9
   - 3.1. Overview ... 9
   - 3.2. **RP1** Lasers ... 10
   - 3.3. **RP2** X-Ray Sources Driven by Ultrashort Laser Pulses ... 15
     - 3.3.1. Scientific-technological infrastructure in the experimental halls E1, E2 and E5 ... 15
     - 3.3.2. List of present collaborating institutions and potential future users ... 18
     - 3.3.3. Scientific highlights – selected publications of the research program ... 19
   - 3.4. **RP3** Particle Acceleration by Lasers ... 19
     - 3.4.1. Scientific-technological infrastructure in the experimental halls E4 and E5 ... 20
     - 3.4.2. List of present collaborating institutions and potential future users ... 23
     - 3.4.3. Scientific highlights – selected publications of the research program ... 23
   - 3.5. **RP4** Application in Molecular, Biomedical and Material Sciences ... 24
     - 3.5.1. Scientific-technological infrastructure in the experimental hall E1 ... 24
     - 3.5.2. Major research topics ... 25
     - 3.5.3. Present research linked to future activities ... 25
     - 3.5.4. Scientific highlights – selected publications of the research program ... 26
     - 3.5.5. List of potential future users ... 26
   - 3.6. **RP5** Plasma and High Energy Density Physics ... 27
     - 3.6.1. Scientific-technological infrastructure in the experimental hall E3 ... 27
     - 3.6.2. Major research topics ... 28
     - 3.6.3. Present research linked to future activities ... 29
     - 3.6.4. Scientific highlights – selected publications of the research program ... 30
     - 3.6.5. List of potential future users ... 30
   - 3.7. **RP6** Exotic Physics and Theory/Simulation ... 31
     - 3.7.1. Major research topics ... 31
     - 3.7.2. Present research linked to future activities ... 31
     - 3.7.3. Scientific highlights – selected publications of the research program ... 32
     - 3.7.4. Active collaborations in theory/simulation ... 33
     - 3.7.5. Technological infrastructure ... 33
   - 3.8. **ELIBIO Project:** Future Biology with High-Power Lasers ... 34
     - 3.8.1. Specific research objectives of the project ... 34
     - 3.8.2. Key investments ... 35
4. Worldwide Cooperation ... 37
5. Conclusion: ... 40
6. Annex No. 1 – ELI Beamlines Facility Start up Period Schedule ... 42

1. Executive Summary

A competitive research program on the international level

ELI-Beamlines is the largest and most ambitious scientific initiative in the Czech Republic and also one of the largest financed by the European Union. The expectations in Europe and the rest of the world are correspondingly high. ELI-Beamlines has to and will deliver a unique, open laser-based research infrastructure for the scientific community in Europe and the rest of the world. The specific nature of the ELI-BL user facility is its multi-disciplinary features as far as its laser systems and corresponding usage is concerned.

A cosmopolitan team for operation

From the beginning of the project the outlook as far as staff recruitment is concerned has been cosmopolitan. ELI-Beamline employees originate from 24 nations. It is a truly universal endeavor. At present, the team consists of 280 FTE, of which 75 FTE are foreigners. In the research and experimental programs, their share exceeds 50%. ELI-Beamlines has become a global point of attraction for scientific and technical/engineering staff. Due to the attraction of the project itself and the location ELI-Beamlines is able to establish a diverse operation team which will play to its advantage once an international user community will be conducting its experiments here.

Scientific output

Even though the research team has as pre-dominant obligation the design and construction of the technological and scientific infrastructure, it is nevertheless very active as far as publications and patent applications is concerned. The publications of the research teams appear in high-impact journals and their scientific production is acknowledged by the worldwide scientific community in the field. As for the year 2016 ELI Beamlines has produced more than 200 high impact publications.

International cooperation

International cooperation have been established via dedicated Memoranda of Understanding (MoU, see detailed list provided in Annex 1). MoUs have been concluded not just with European installations but with worldwide facilities. This clearly shows that the interest in ELI-Beamlines is not just a European affair. The unique potential of the installation under construction has been recognized globally.

The prospective user community

The future user community is of national, European and international origin. Contacts with the potential future users have been established via scientific collaborations, exchange of personnel, presentations at international conference in order to attract the attention of the scientific community to the ELI-Beamlines project, and dedicated user workshops. A large but non-exhaustive list of prospective users is provided in Annex 2.

2. Facility Overview

ELI Beamlines is the largest research facility of FZU and also the largest scientific initiative in the Czech Republic. The main goal of ELI-BL is to build one of the most advanced laser resources in the world and implement research projects covering the interaction of light with matter at intensities many times higher than the currently achievable values. ELI-BL will produce ultra-short laser pulses of a few femtoseconds (10-15 fs) duration at the peak power of up to 10 PW. Technologies of ELI-BL will enable creation of new techniques, including those for time-resolved spectroscopy, scattering, and diffraction techniques, medical imaging, display, diagnostics, and radiotherapy, tools for design, development, and testing of new materials, improvements of X-ray optics. ELI-BL will also be an attractive platform for educating a new generation of scientists and engineers.

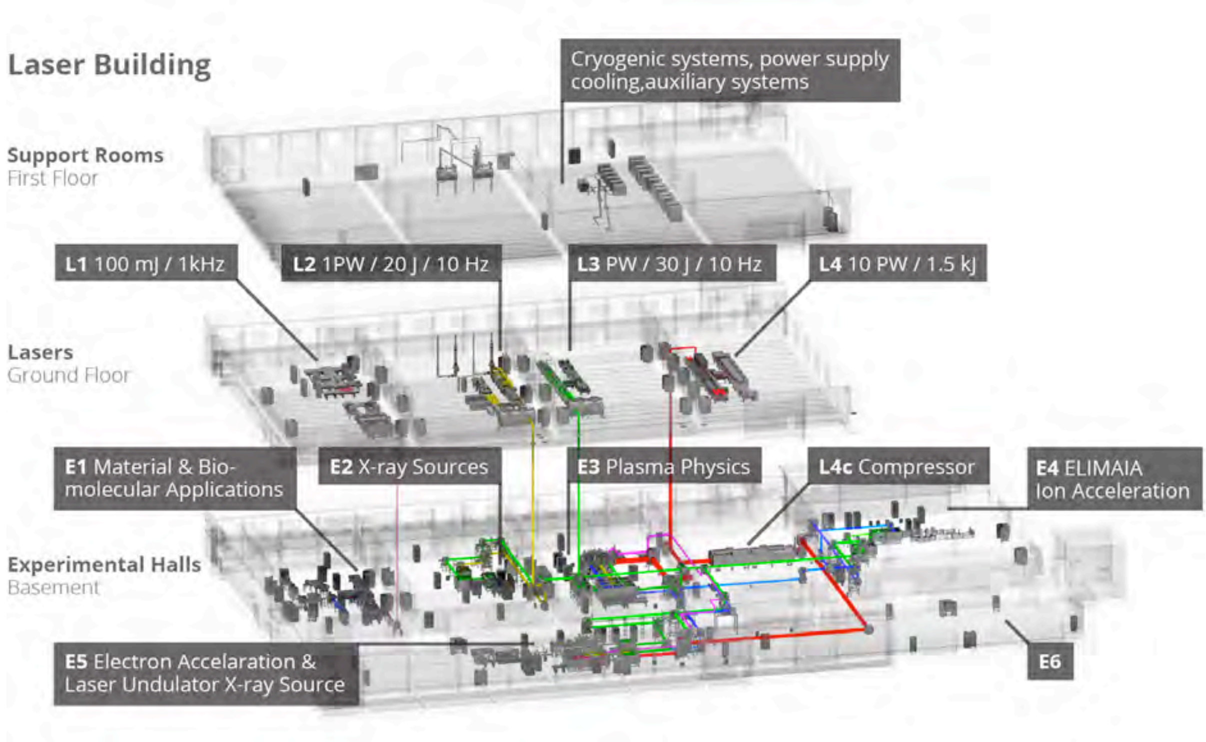
The implementation of ELI-Beamlines represents a unique opportunity for the Czech Republic to host a major international research infrastructure which will provide facilities for national researchers and industry and attract international researchers at the forefront of their fields to the country as facility users. There are expected to be more than 2200 researcher days per year at the facility providing an additional local economic impact through the associated accommodation and travel costs. With a projected workforce of more than 250 employees, ELI-Beamlines will generate high-level long-term career opportunities for researchers, engineers and technicians, primarily but not exclusively those involved in optics and laser science, in electronics, in mechanical engineering, and material sciences. In addition, the Czech optics and photonics industry is expected to take a significant part in the technological developments required for the construction of ELI and its further maintenance, thus demonstrating and acquiring know-how.

The research and development at ELI-BL has been performed continuously in six research programs (RPs) over last four years:

- **RP1** Lasers Generating High Repetition-rate Ultrashort Pulses and Multi-petawatt Peak Powers
- **RP2** X-ray Sources Driven by Ultrashort Laser Pulses
- **RP3** Particle Acceleration by Lasers
- **RP4** Applications in Molecular, Biomedical, Material Sciences
- **RP5** Plasma and High Energy Density Physics
- **RP6** Exotic Physics and Theory/Simulation

Primarily ELI-Beamlines will provide expertise in laser development, diagnostics, short pulse X-ray generation and acceleration of particles and their applications.

The laser system will constitute a specific unit, which must be implemented and managed as a major single instrument within the Research Program 1: Lasers generating repetition-rate ultrashort pulses and multi-petawatt peak powers. The Research Programs 2 to 6 will jointly exploit the capacity of this instrument to carry out scientific, application and technology development projects using ultra-intense light pulses. The Research Programs 2 to 6 will use pulses with various parameters generated by the laser system and will effectively share the capacity provided by this system. Each of the Research Programs 2 to 6 is centered on a specific field of research and technologies and involves a specific expertise, using the laser as a resource delivered by the expertise of the Research Program 1.



The facility will provide Beamlines for a variety of research programs which will by their nature require interdisciplinary cooperation. In particular, for RP4 - Applications in molecular, biomedical, and material sciences where work will draw upon structural sciences, biology, atomic and plasma physics, optics and mathematics. Each research program leader is charged with managing their programs to foster interdisciplinary research.

The facility will enable developments in a wide range of research areas, for example biological imaging at or near atomic resolution is probably the most challenging of all experiments that have been proposed for X-ray lasers, and it requires a detailed understanding of photon-material interactions on ultra-short time scales at very high X-ray intensities. Resolution in single-particle experiments does not depend on sample quality in the same way as in conventional crystallography, but is a function of radiation intensity, pulse duration, and wavelength, which are factors controlling ionisation and sample movement during exposure.

The potential for breakthrough science is great with impact not only in biology or physics but wherever dynamic structural information with high spatial and temporal resolution is valuable.

Commercial sector areas most closely related to the development of the facility are those of laser development. In particular, the investment in advanced DPSSL laser technology represented by ELI Beamlines will bring opportunities to European industry which will be incentivized to gear up for high volume production of DPSSL laser systems. This will put Europe in a strong position to benefit from laser energy projects world-wide and to exploit DPSSL technology in other market sectors. The research is expected to have impact in the following areas:

Engineering and electronics industry:

- Non-destructive diagnostics of high speed processes in industrial devices and their visualization or simulation
- Testing of resistivity to extreme fields – e.g. simulation conditions on the orbit
- New method of preparation of special material structures – development and testing
- Elimination of thermal effects for special application
- Particle interactions and material treatment, change of basic material parameters
- Application of new principles in control and diagnostics
- New construction material with unique parameters
- Increasing possibilities in communication technology using the knowledge from the laser beam transport

Life-Sciences (medical, pharmaceutical):

- Diagnostics and interaction of molecular samples – biological labs BSL1 – BSL3 background
- Induction and visualization of photochemical processes – chemical labs background
- Development new diagnostics method for tissues and live organisms, in-situ observation of interactions between samples and additives
- Accelerated particles – development of new diagnostic and therapeutic methods
- Application of different types of radiation (light) with defined time delay – theragnostic methods
- Targeted focus of the effectiveness of the applied radiation – superficial or deep, no/desirable thermal effects, bragg peak, no/desirable absorption
- Controlled ablation of biological samples
- Advanced Imaging - especially in “water window”

Fundamental research:

- New radiation sources and their unique combination with defined and tunable time delay
- High intensity of radiation for exotic field of physics, laboratory simulation of astrophysics conditions

- Unique combination of accelerated particles with radiation sources in common laboratory
- Research of subatomic and sub-nuclear level – alternative to large accelerators

More information about the ELI-BL center can be found on the web site: **www.eli-beams.eu**

3. Research Programs

3.1. Overview

The following presents a very brief summary of each of the research programs which are subsequently developed in some more detail.

RP1 Lasers

RP1 develops the short-pulse laser system used for all applications at ELI-BL. This work is of both fundamental and applied nature including development, implementation and optimization of the laser systems, their components and subsystems. Short term activities: Development and implementation of the four main laser systems of the ELI-BL facility. Long term activities: Ongoing development of the laser systems to reach world leading intensities and pulse parameters at high repetition rates.

RP2 X-Ray Sources Driven by Ultrashort Laser Pulses

RP2 develops a new generation of laser driven secondary light sources covering the VUV (vacuum UV) to gamma-ray energy range. These are based on plasma effects in gases and solids as well as relativistic electron acceleration and the research is both fundamental and applied. Short term activities: Provide the national and international user community access to ultrashort pulses in the VUV to gamma-ray energy range for applications in molecular, biomedical and materials science. Long term activities: Continuous source development, in particular the development of a laser driven X-ray Free Electron Laser.

RP3 Particle Acceleration by Lasers

RP3 develops versatile and stable sources of high-energy electrons, protons and ions driven by various laser-acceleration mechanisms. The research is both fundamental and applied. Short term activities: Develop laser driven ion and electron sources with world-leading beam parameters. Long term activities: A possible future application for the ion source is compact and low-cost laser driven proton and ion sources for cancer therapy. Laser driven electron acceleration is the basis for the development of laser driven X-ray Free Electron Lasers (FELs).

RP4 Application in Molecular, Biomedical and Material Sciences

RP4 develops a unique set of capabilities for time-resolved experiments using high power lasers, secondary light-sources and a comprehensive set of pump beams. The research is both fundamental and applied. Short term activities: 1) Implement capabilities in the VUV and soft X-ray range for time-resolved materials science, Coherent Diffractive Imaging and Atomic Molecular and Optical science. 2) Implement X-ray instruments for time-resolved scattering, diffraction, absorption spectroscopy, phase contrast imaging and pulse radiolysis. 3) Use the high intensity lasers directly for advanced optical spectroscopy applications such as fs stimulated Raman scattering and 2D spectroscopy. Long term activities: Combine these methods with perfect synchronization for complete investigations of complex phenomena.

RP5 Plasma and High Energy Density Physics

RP5 explores both fundamental science and possible applications in the field of high-energy and high-intensity laser-plasma interaction. Research activities concentrate on ultra-high intensity, laboratory astrophysics, warm dense matter and plasma optics. Short term activities of RP5: implement the technological infrastructure around P3. Long term activities: perform experiments for new unexplored extreme states of matter and ultra-high intensity interaction.

RP6 Exotic Physics and Theory and Simulation

RP6 explores theoretical and experimental aspects of the exotic physics expected in the so-called ultra-relativistic regime (above 1022 W/cm2) of laser-matter interaction. Predictive simulations are performed for future high-field experiments. RP 6 also runs the ELI-BL 1300 cores ECLIPSE computing cluster. Short term activities of RP6: simulation support for experimental programs in high-energy and high-intensity laser-matter interaction. Long term activities: Explore new horizons in the physics of laser matter interactions under extreme conditions.

3.2. **RP1** Lasers

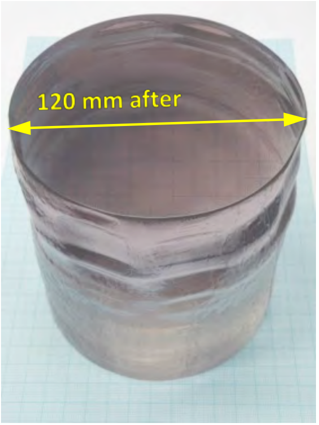
The ELI-Beamlines facility will be a high-energy, high repetition rate laser pillar of the ELI (Extreme Light Infrastructure) project. The facility will provide pulses from four laser systems. To meet the requirements for high repetition rates, three of these lasers will employ the emerging technology of diode-pumped solid state lasers (DPSSL) for pumping broadband amplifiers. The fourth, the kilojoule laser, will use advanced flashlamp technology with actively cooled gain medium.

The DPSSL technology represents a paradigm change in the current cutting edge laser technologies, making it possible to deliver the laser pulses at much higher repetition rate than current systems and also to achieve higher pulse-to-pulse stability, higher robustness, lower maintenance, higher level of automation, and much higher scalability to higher peak power and repetition rates. ELI-Beamlines will be the first laser facility in the world that will programmatically exploit this emerging technology.

The laser systems are development both by in-house efforts of ELI-Beamlines and in cooperation with strategic partners, namely Lawrence Livermore National Laboratory, National Energetics (USA), and Rutherford Appleton Laboratory (UK). Since its beginning the ELI-Beamlines project has formed a dedicated team of about 50 laser scientists, optical and optomechanical designers, technicians and specific technology specialists. This team is developing the L1 and L2 systems, and plays also a significant role in development of specific subsystem of the L3 and L4 systems.

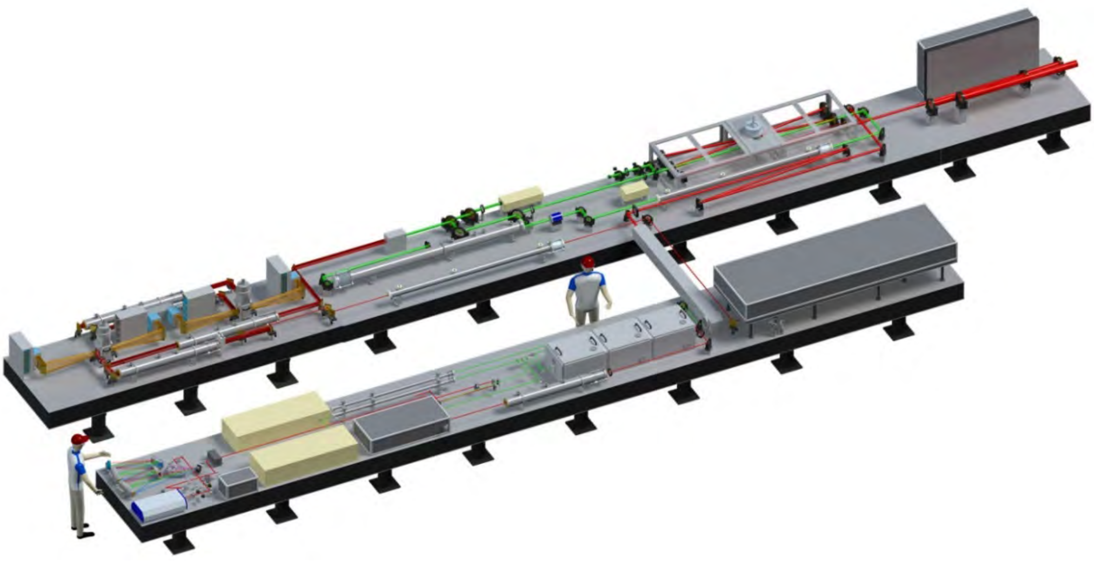
Assembling of the L1 laser system in the cleanroom development premises of the Institute of Physics: shown in the picture is internal optomechanical structure of the L1 vacuum compressor of picosecond pumping pulses.

The L1 laser is being developed in house by the ELI-Beamlines laser team. The laser system is designed to generate <20 fs pulses with energy exceeding 100 mJ per pulse at a very high repetition rate (1 kHz). The concept of the laser is based entirely on amplification of frequency chirped picosecond pulses in an optical parametric chirped pulse amplification (OPCPA) chain consisting of a total of seven amplifiers. The OPCPA amplifier stages are pumped by precisely synchronized picosecond pulses generated by state-of-the-art thin-disk-based Yb:YAG laser systems obtained both from industry and developed



Large monocrystals developed in cooperation with Czech industry within the ELI-Beamlines project. The core-free Yb doped YAG crystals with up to 5’ in diameter and 6’ long are the largest of its kind in the world.

The L2 beamline is designed to provide ultimately PW-class peak power at 10 Hz repetition rate. The short-pulse amplification chain will be based on OPCPA. In the current phase of the project the first stage of the L2 laser is developed, including the 10 J pump engine using cryogenic He gas cooling. Several new technologies were developed in cooperation with the Czech industry, specifically large laser YAG crystals (see Figure above) and also an advanced system of cryogenic gas cooling of the gain medium to temperatures of about -130° C.



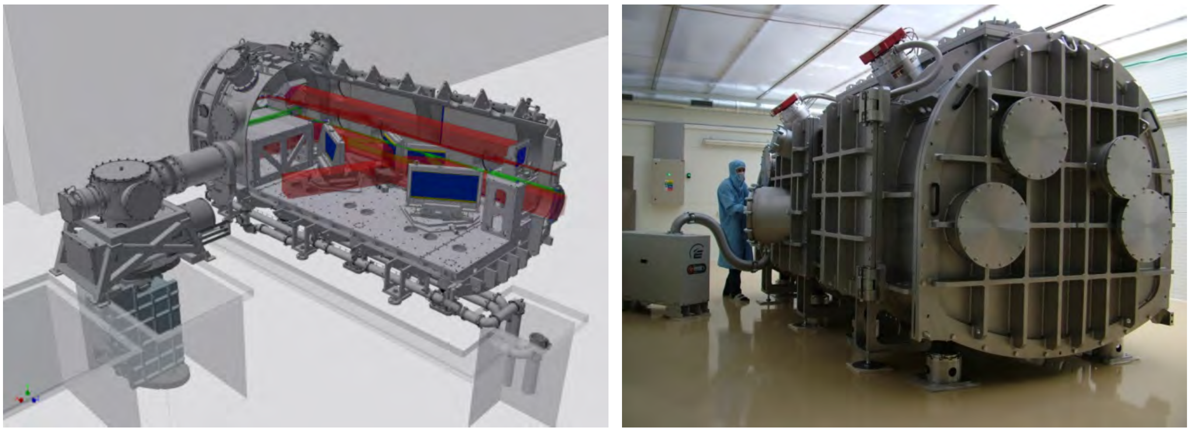
Layout of the L3-HAPLS (High-Repetition-Rate Advanced Petawatt Laser System) developed for ELI-Beamlines by Lawrence Livermore National Laboratory, with participation of the ELI-Beamlines specialists on implementation of several subsystems.

The L3 laser system called HAPLS (The High-Repetition-Rate Advanced Petawatt Laser System), seen in the Figure above, is designed to deliver PW pulses with energy of at least 30 J and durations <30 fs, at a repetition rate of 10 Hz. It is the first all diode-pumped, high-energy femtosecond PW laser system in the world. The laser was developed at the Lawrence Livermore National Laboratory, with ELI-Beamlines cooperating on the development of the short-pulse diagnostics and of the short-pulse subsystem controls and timing.

During initial testing the L3-HAPLS has recently demonstrated continuous operation setting a world record for diode-pumped Petawatt lasers, delivering pulses with energy reaching 16 J and a 28 femtosecond pulse duration, equivalent to ~0.5 PW/pulse at a 3.3 Hz repetition rate.

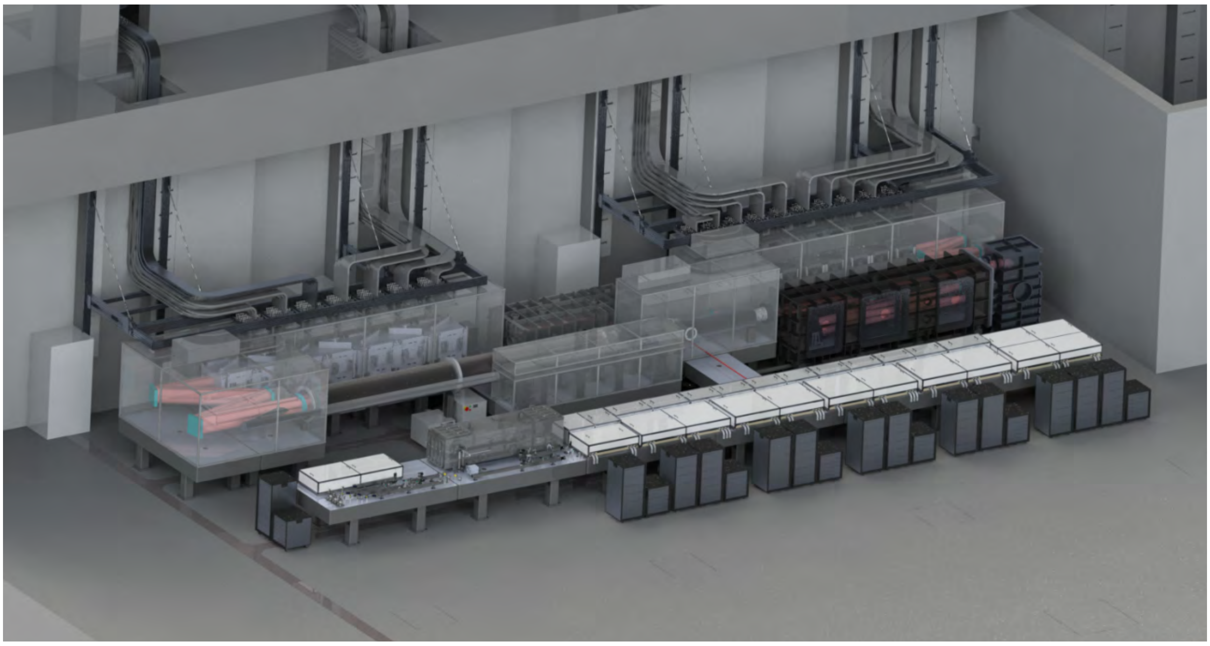
L3-HAPLS laser system during testing in the development premises in the Lawrence Livermore National Laboratory.

ELI-Beamlines has designed for the L3-HAPLS system the vacuum compressor of PW laser pulses, see Figure below. The compressor has size of approximately 5.2 x 2.4 x 2.2 m and includes a highly complex structure of optical, optomechanical and electronic elements. The compressor is being built and integrated in cooperation with the Czech SME industry.



Structure of the L3 compressor of PW laser pulses (left) and the vessel of the compressor during vacuum testing at the supplier's cleanroom (right).

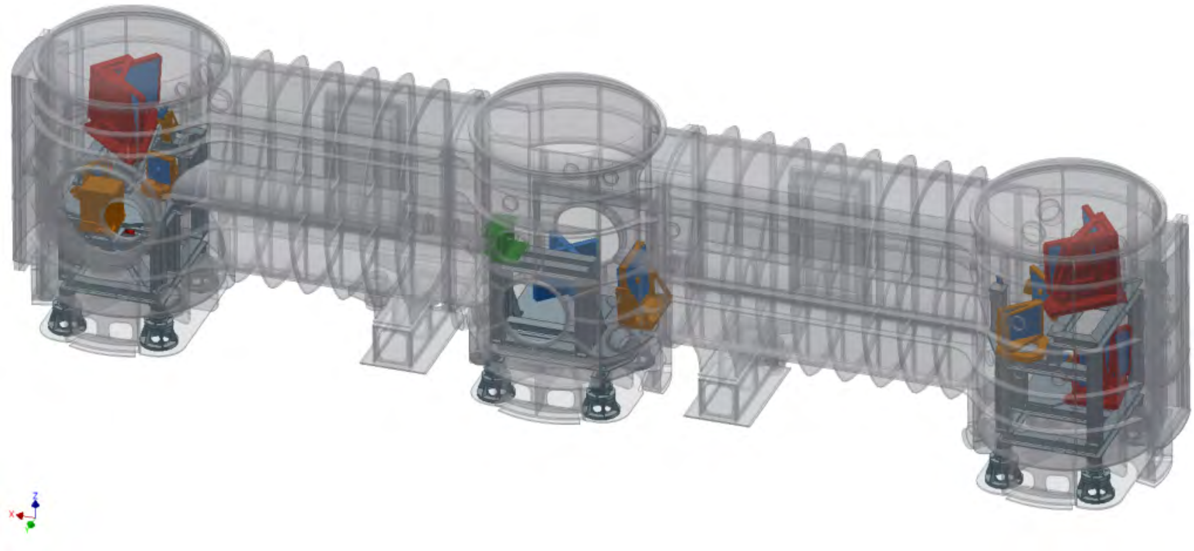
The L4 laser beamline will deliver pulses with energy of 1.5 kJ, lasting about 150 fs. The system will thus generate peak power of 10 PW, which will be the highest value ever achieved by a high-power laser. A number of innovative technologies used will make it possible to achieve a shot rate of 1/min, which is unprecedented in the in the field of kJ-class lasers. The L4 system architecture exploits a combination of different Nd:glass slab amplifiers using innovative liquid cooling.



Layout of the L4 kilojoule laser system integrated in the L4b laser hall of the ELI-Beamlines facility. Upon compression of the pulses in the compressor the laser will generate 10PW laser pulses.

Laser L4 chain in the development laboratories at National Energetics (USA), with the front end of the system seen in the forefront.

The compressor of the 10 PW pulses, see Figure below, will employ large diffraction gratings and large aperture mirrors to compress the L4 output beam with size 650x650 mm, and to generate pulses with about 150 fs duration. The structure of the compressor with a length of about 18 m (see Figure below) has been designed by the ELI-Beamlines laser technical team. The compressor vessel will be supplied by the L4 supplier, while the ELI-Beamlines team will be responsible for development and construction of the internal optomechanical systems and of the control electronics.



Designed structure of the compressor of 10PW pulses, developed by the ELI-Beamlines technical team.

3.3. **RP2** X-Ray Sources Driven by Ultrashort Laser Pulses

One of the main goals within the ELI scientific community is to produce X-ray beamlines with ultrashort pulses, both coherent and incoherent, to pave the way towards exploring nature with atomic spatial resolution and femtosecond temporal scales. Applications range from structure analysis in solid-state, atomic physics and molecular chemistry via imaging applications in medicine and life sciences through studying basic building blocks of life.

The laser-driven X-ray sources developed at the ELI-Beamlines facility have the capability, unlike large-scale facilities such as third-generation synchrotrons or X-ray free-electron lasers (XFELs), to offer much broader accessibility due to their compactness and reduced cost. Moreover, various combinations of fully synchronizable femtosecond pulses from extremely broad spectral range (from VUV to gamma radiation) combined in one experiment and complemented by optical pulses (from THz to UV) originating from the same laser will open a gateway to science that has not yet been accessible.

3.3.1. Scientific-technological infrastructure in the experimental halls E1, E2 and E5

Four paths have been developed within this research program for transforming laser pulses into brilliant bursts of X-rays:

High-order harmonic generation in gases (E1 hall, 1 kHz L1 laser driver)

Generation of high-order harmonics (HHG) of an intense laser pulse is now widely used as an efficient source of coherent ultra-short pulses (tens of femtoseconds down to tens of attoseconds) in the spectral range from EUV to soft X-rays. The atoms of noble gases interacting with a strong laser field (10^{14}-10^{15}Wcm^{-2}) are partially ionized and the freed electrons are first accelerated and then rescattered from the parent ion while generating radiation of short wavelength in attosecond bursts repeating every laser cycle. The coherent addition of this radiation from significant target volume through phase matching (or quasi-phase matching) leads to a substantial increase in the power of the generated radiation.

We plan to extend the capabilities of recently commissioned HHG Beamline by implementing advanced techniques to reach high flux generation regime using loose focusing of the high power laser driver (L1 laser system having 100 mJ <20 fs at 1 kHz rep. rate). Particularly the implementation of two-color driving field is proposed to enlarge the accessible wavelengths, increase the conversion efficiency through enhancement of the single atom response and generating any polarization state of the XUV beam, particularly the circular polarization. Meanwhile we plan to employ advanced target geometries with modulated gas density and/or various gases combined with plasma waveguiding techniques to enable so called quasi-phase matching. Using this method, we foresee to overcome the phase mismatch in highly dispersive plasma medium for generation in soft X-ray range and also to enable efficient generation of a single harmonic of the laser driver. This approach would allow avoiding lossy XUV monochromator that is needed for certain class of applications.

Incoherent plasma X-ray sources (E1 hall, 1 kHz L1 laser driver)

In a plasma X-ray source, laser pulses are tightly focused on a renewing solid-density target and produce non-equilibrium plasma with significant population of hot electrons. Those electrons are then, similarly to medical X-ray tube, responsible for generation of hard X-rays from both plasma and cold part of the target. The emitted spectrum contains continuum part as well as characteristic X-ray lines of the atoms in the target, and pulses are of duration of 100s femtoseconds. Such short X-ray probe pulses in combination with laser pump pulses will allow scientists to resolve the kinetics of chemical reactions on atomic scales via ultrafast hard X-ray diffraction and X-ray absorption spectroscopy techniques to study artificial photosynthetic systems or photoactive biological molecules.

Betatron/Compton radiation sources (E2 hall, 10 Hz L3 laser driver)

Relativistic interaction of short-pulse lasers with underdense plasmas has recently led to the emergence of a novel generation of femtosecond X-ray sources. Based on radiation from electrons accelerated in plasma, these sources are compact generators of femtosecond pulses in narrow beams. Electrons transversally oscillating during their acceleration by the plasma wave emit broadband X-ray betatron radiation. The inverse Compton radiation source on the other hand relies on scattering of a counter-propagating laser pulse on laser-driven relativistic electrons and it can produce tunable quasi-monochromatic radiation from X-rays to gamma radiation.

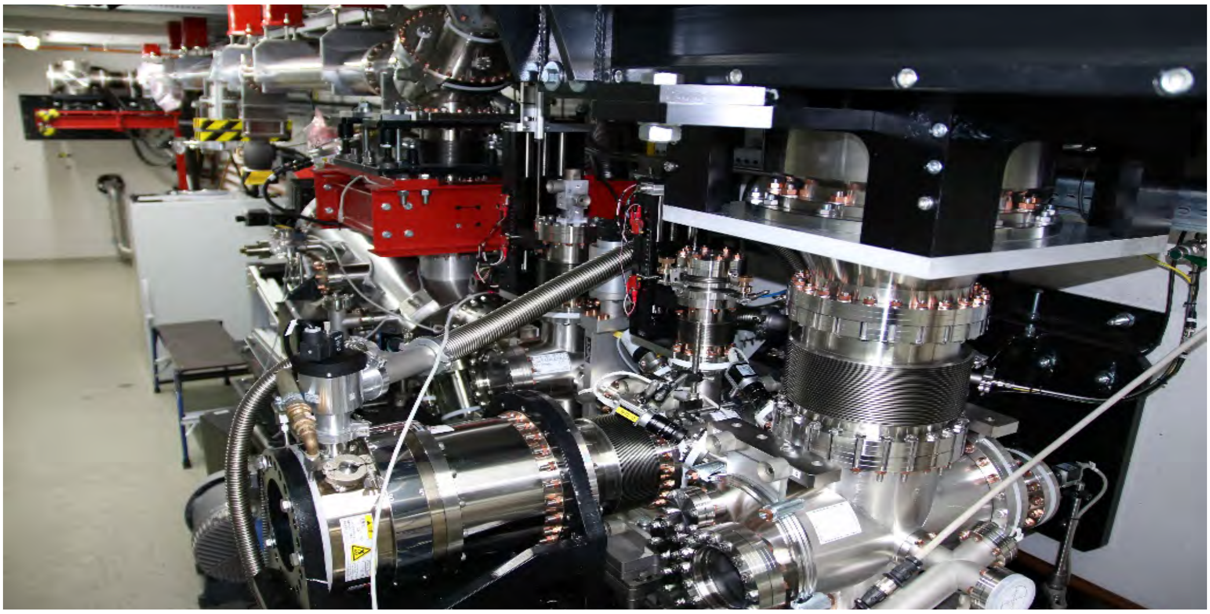
Broadband femtosecond X-ray radiation is desired to study warm dense matter, effective small size of the source is beneficial to perform high-resolution imaging of biological samples with phase-contrast.

Laser-driven X-ray free-electron lasers (E5 hall, 10 Hz L3 laser driver)

Laser wakefield acceleration will be used to provide high-quality relativistic electron bunches passing through an undulator formed by a periodic magnetic structure. This Laser-driven Undulator X-ray source (LUX) is designed to provide users with few-nm, few-fs X-ray pulses. The main challenge in this research and development is the long-term stability of the X-ray pulses that are generated. The development of the LUX beamline is one of the steps toward stable laser-driven free-electron lasers where coherent emission in undulator is achieved boosting the number of generated photons by many orders of magnitude.

The teams of University of Hamburg (UHH) and ELI develop the LUX beamline in collaboration with the main goal to serve as a synchrotron like source for user experiments at ELI Beamlines facility, providing soft X-ray pulses with 106 photons in 1% bandwidth with tuneable mean wavelength in the range of 4.2 down to 0.4 nm. Such a radiation is suitable for studying biological samples in the water window region and, with additional auxiliary beams, for studying molecular processes with temporal resolution better than 10 fs.

The LUX beamline development is already very advanced. In June 2016, ELI and University of Hamburg teams successfully accelerated the first electron beams with LUX, reaching the design energy of 400 MeV (See figure below for the first part of the setup). The beamline is currently ready for the production of first photons taking place in the following weeks.

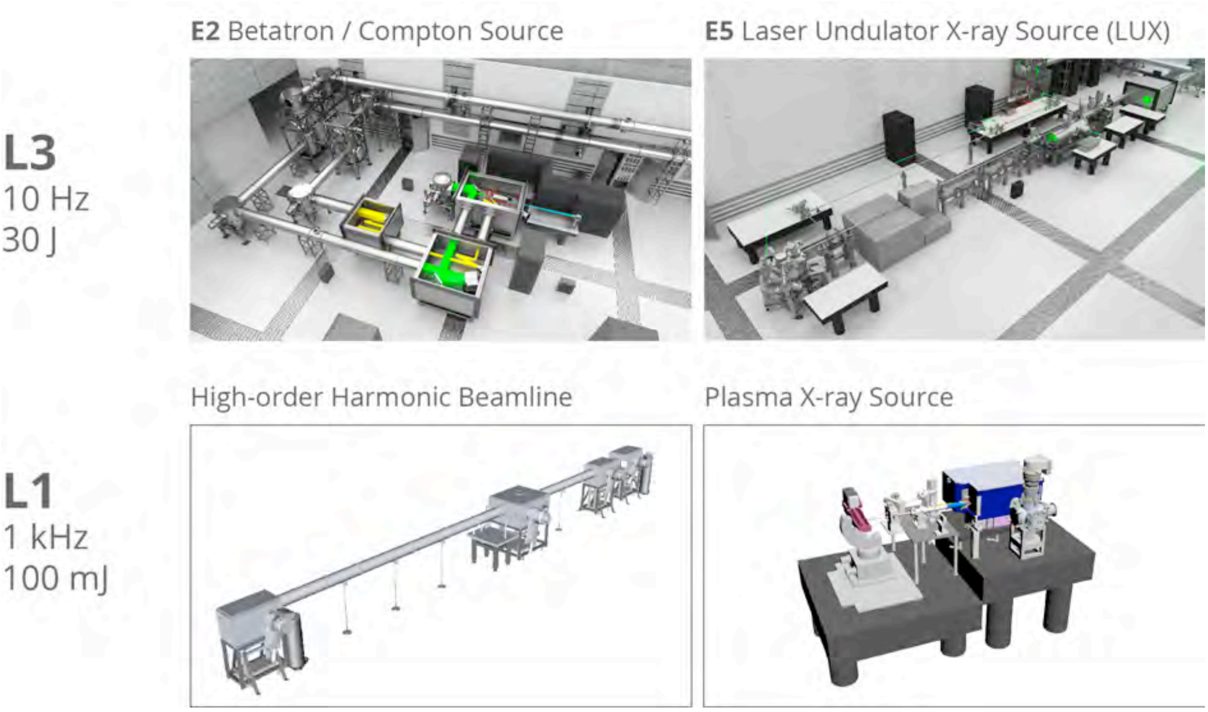


From left to right: A laser beam transport, the final focusing and laser diagnostics sections and the LUX plasma target section as installed at DESY laboratory, Hamburg.

In addition, the LUX is a crucial development step towards a much brighter laser-driven Free Electron Laser (FEL). Both UHH and ELI teams collaborate on the preparation of a demonstrator FEL experiment to take place in 2018. UHH team has designed a dedicated cryogenic undulator enabling reaching FEL gain in the number of radiated photons and ELI team has designed advanced electron beam optics to provide a sufficiently focused and stable beam for the novel undulator.

Moreover, ELI team collaborates with DESY (group J. Osterhoff) on LUX plasma diagnostics (Stark broadening plasma density measurement) and with University of Strathclyde (group D. Jaroszynski) on pepper pot electron beam diagnostics.

In the following years (after the first LUX user experiment scheduled on November 2017), the ELI team will focus on the FEL demonstration experiment, moving of the LUX beamline from DESY to ELI Beamlines experimental hall E5, and commissioning it for a regular user operation, and further advancing towards a full scale laser driven soft X-ray FEL in collaboration with UHH and DESY.



Visualization of four different sources developed by RP2with indicated laser drivers. The Plasma X-ray source and HHG Beamline will be installed in E1 and the 1 kHz 5 TW "L1" laser driver will be used. The Betatron/Compton and LUX beamlines will be installed in E2 and E5, respectively, all driven by 10 Hz 1 PW "L3" laser driver.

3.3.2. List of present collaborating institutions and potential future users

- LOA, ENSTA, France
    - Development of X–ray sources from relativistic electrons accelerated by lasers (betatron, inverse Compton source) and their applications (phase contrast imaging).
    - Development of plasma based X–ray lasers their diagnostics and applications

    - High-order harmonic generation from gases
- University of Postdam, Germany – plasma X–ray source and its applications
- Brown University, USA - plasma X–ray source and its applications
- CELIA, Univ. Bordeaux, France – High-order harmonic generation and applications
- University of Hamburg – Development of laser-driven free electron lasers and applications

3.3.3. Scientific highlights – selected publications of the research program

The most important publications with the impact factors (given in brackets) are the following:

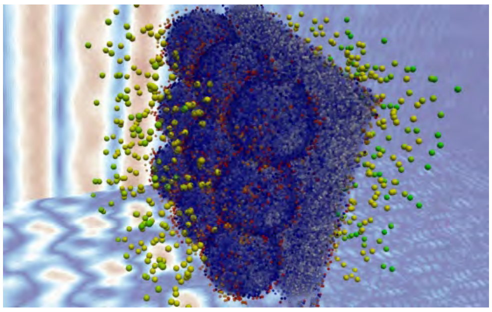
- V Nefedova et al, ***Development of a high-flux XUV source based on high-order harmonic generation***, Journal of Electron Spectroscopy and Related Phenomena 2017 (published online) **[1.7]**
- Depresseux et al., ***Table-top femtosecond soft X-ray laser by collisional ionization gating***, Nature Photonics **9**, p. 817 (2015). **[34.2]**
- Depresseux et al. ***Demonstration of a Circularly Polarized Plasma-Based Soft-X-Ray Laser***, Phys. Rev. Lett. **115**, 083901 (2015). **[7.6]**

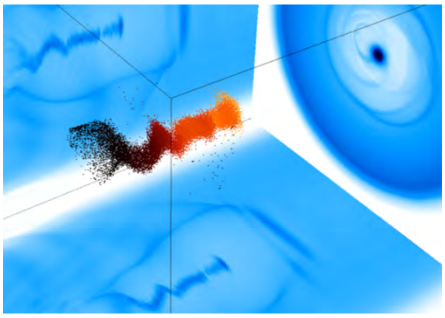
3.4. RP3 Particle Acceleration by Lasers

ELI-Beamlines offer the prospects of producing and studying versatile and stable particle (ions and electrons) sources at high repetition rates, while simultaneously enhancing the high energy tail of the spectrum, the beam monochromaticity and the laser-to-particle conversion efficiency, all of which are crucial points for the production of additional secondary sources.

The Research Program 3 (RP3) will also focus on the demonstration of proof-of-principle experiments aimed at envisioning future societal applications in various areas with special attention paid to biomedical ones. Thus, the optimization of particle beam quality and reproducibility (spatial profile, pointing, divergence and energy stability) will be a crucial issue. In order to realize such a challenging and wide range of envisioned activities, two scientific groups are currently working on the implementation of two different target areas, the **ELIMAIA** ion acceleration beamline and the **HELL** electron acceleration platform, with the main goal being to fulfil the expectations of the scientific user community.

Laser-driven particle acceleration is a new field of physics that is rapidly evolving thanks to the continuing development of high power laser systems, thus allowing researchers to investigate the interaction of ultrahigh laser intensities (> 1019 W/cm2) with matter. As a result of such interaction, extremely high electric and magnetic fields are generated. Such tremendous fields, which can be supported only in plasmas, allow for the acceleration of particles at relativistic energies by way of very compact approaches. In particular, spectacular progress in the acceleration of electrons and protons has been achieved. On the one hand, electrons are currently being accelerated to very high energies (several GeV) from gas targets, which are transformed in plasma by high intensity laser pulses. On the other hand, 100-MeV-class protons are presently being accelerated in thin solid targets through the energy transfer of high energy electrons.





3D numerical simulations showing laser-accelerated ions from a thin nanostructured target (left) and laser-accelerated electrons in a gas target (right)

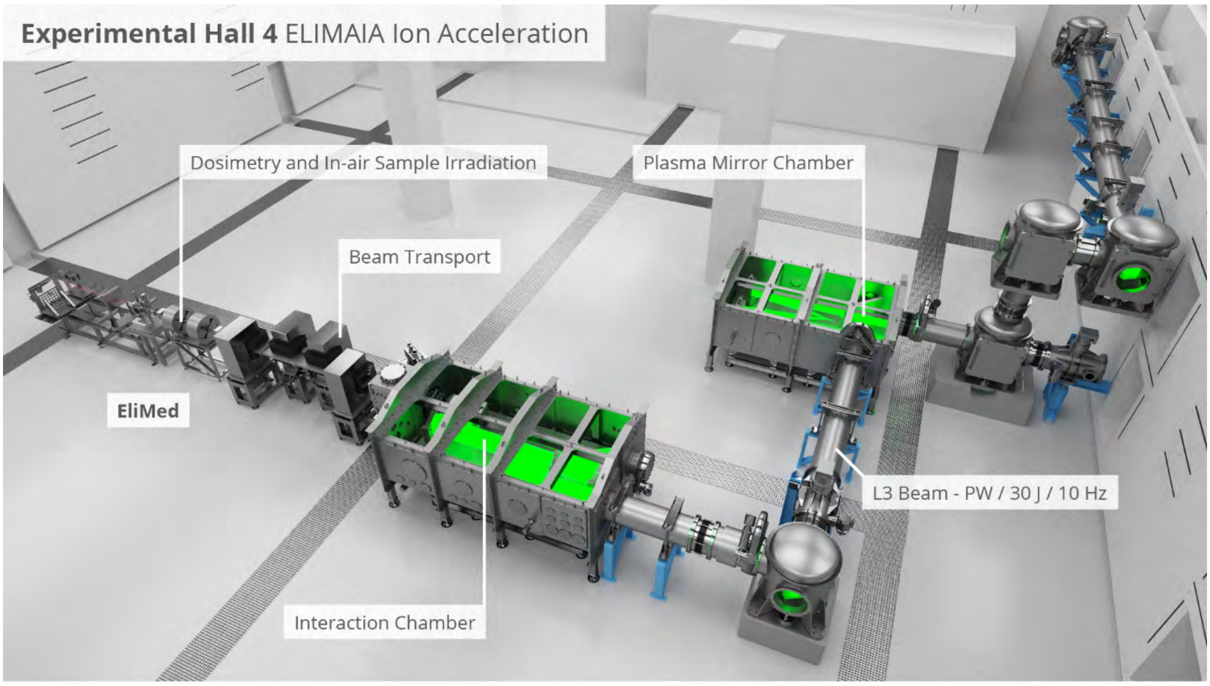
3.4.1. Scientific-technological infrastructure in the experimental halls E4 and E5

Two main different beamlines are developed within the Research Program 3 one dedicated to proton and ions acceleration (ELIMAIA in E4) and another dedicated to high energy electrons (HELL in E5).

ELIMAIA Beamline in E4

ELIMAIA will be one of the key secondary source target areas of the ELI-Beamlines facility. The proposed technological and scientific solutions for the implementation of the ELIMAIA beamlines is the result of a complex investigation carried out in the last several years with the main goal of fulfilling the specific requirements that have been coming from the international user community.

The general philosophy for the design, development, and implementation of the ion beam line in the ELI-Beamlines building is based on three key features: a user friendly approach, accurate monitoring and reliability of the accelerated ion beams, and flexibility for a future upgrade of the beam line. A complete beam line (ion source, in-vacuum ion beam transport, different dosimetric endpoints, and in-air sample irradiation end-station) will be available for users to enable them to apply laser-driven ion beams in multidisciplinary fields.



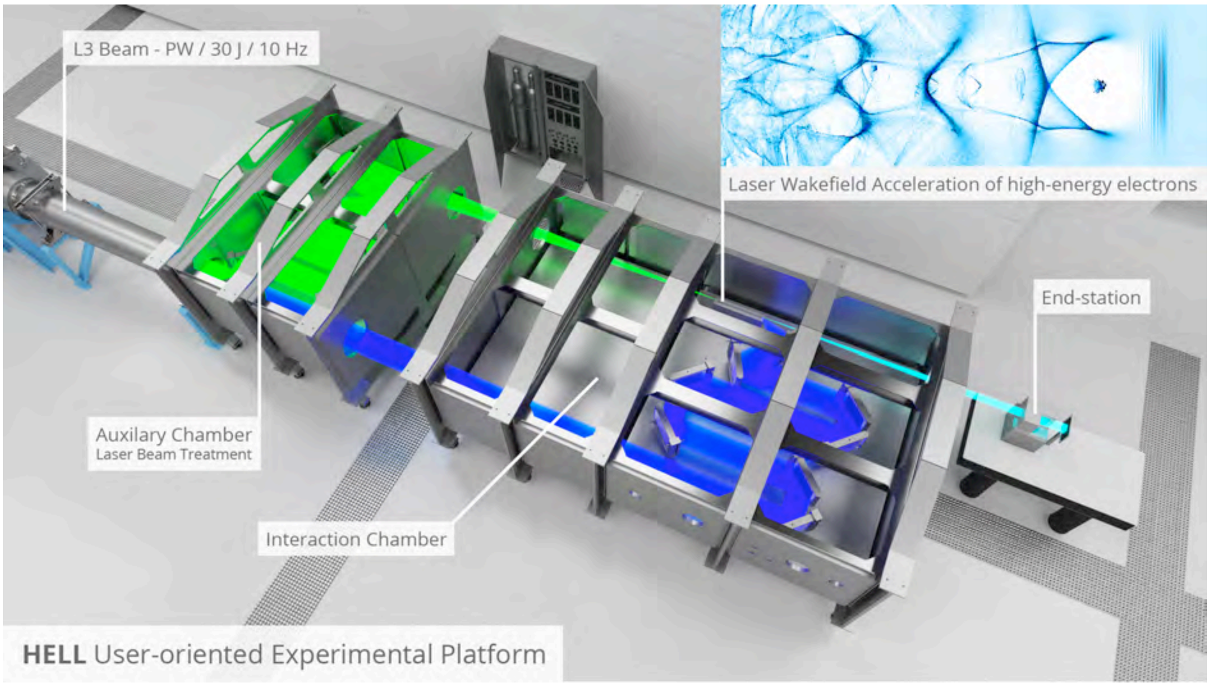
A 3D design of the ELIMAIA beam line in E4 is shown in the figure above. The ELIMAIA beam line is located in the northern part of experimental hall 4 (E4). The available laser beams are L3 and L4 (both at 1 PW power level) coming from the western wall. The ELIMAIA beam line consists of two main subsystems: **Ion accelerator** and **ELIMED.**

The aim of ELIMAIA will be to demonstrate that the overall cost of the standard acceleration facilities can be drastically reduced by using innovative compact approaches based on high power laser-matter interaction. In fact, the main goal of the ELIMAIA beamline is to provide stable, fully characterized, and tunable particle beams accelerated by PW-class lasers and to offer them to a broad national and international community of users for multidisciplinary applications, as well as fundamental science. An international scientific network, called ELIMED (ELI MEDical applications), that is particularly interested in future applications of laser-driven ions for hadrontherapy has already been established. However, this is only one of the potential applications of the ELIMAIA beamline, which will be open to several proposals from a multidisciplinary user community. These proposals will be for areas such as non-conventional ion acceleration, radiobiology, time-resolved radiography of different materials, and beam-target nuclear reactions generating isotopes for positron emission tomography or producing high brilliance secondary radiation sources (e.g., neutrons and alpha-particles).

HELL Platform in E5

Electron acceleration driven by high peak power femtosecond lasers was theoretically predicted in 1979 by Tajima and Dawson [5]. The brilliant idea to use laser-driven plasma-waves was experimentally demonstrated more than a decade ago, and presently this technique is used on a daily basis in many laboratories worldwide. Laser-accelerated electron beams can potentially be used for various societal applications (e.g. through the generation of x-ray and gamma ray secondary sources) and, at the same time, enable and validate innovative physical mechanisms proposed by the scientific community, as extensively described in the ELI-White Book [1] . The high energy electron acceleration program being implemented at ELI-Beamlines is conceived to accommodate, in a long term perspective, experiments covering both aspects. Thus, the HELL (High-energy Electron by Laser Light) platform under construction at ELI-Beamlines will facilitate the performance of experiments oriented to the use of secondary sources (thanks to the user-friendly "beamline" features that will be focused on user needs), as well as advanced experiment that will require the use of the main electron source (thanks to the flexible "platform" features) to develop and test innovative schemes, in order to improve acceleration techniques and to verify new models.

The development activity of the HELL platform already resulted in filing of a Luxembourg patent application, where the European patent office as a search and examination authority acknowledged, besides the others, its novelty, inventiveness and industrial applicability for an advanced "laser-based radiotherapy machine" provided by means of electrons.



The double scope of the HELL platform is guaranteed from one side thanks to the flexible setup that enables the possibility to use a wide range (from 4m to 30m) of focal lengths of the focusing optics obtainable modifying the distance between the Auxiliary and Main interaction chamber thus allowing the use of a wide range of interaction regimes for new acceleration scheme and counter-propagating basic experiments. On the other side the presence of a dedicated and flexible end-station enables the user-oriented needs to irradiate samples at pre-defined accelerator parameters in the range available from the main LWFA (from 10MeV to multi-GeV).

3.4.2. List of present collaborating institutions and potential future users

Ion Acceleration (ELIMAIA)

- Queen's University (Belfast, UK): laser driven proton/ion acceleration, neutron sources, particle diagnostics, future hadron therapy applications.
- INFN-LNS (Catania, Italy): ion beam transport and dosimetry for multidisciplinary applications, including radiation biology, pulsed radiolysis, hadron therapy.
- LBNL (Berkley, US): innovative schemes for laser driven ion acceleration from advanced targets.

Electron Acceleration (HELL)

- Strathclyde University (Glasgow, Scotland): experiments on capillary at 1J-level as partners of the project "Lab. in a bubble".
- IPPLM (Warsaw, Poland): ultra-stable pointing and applications.
- MUT (Warsaw, Poland): ns-channels and a Joint-Proposal for defense.
- Imperial College: R&D on new diagnostics, grant proposal, student training.
- Biological Center (Pilsen, Czech Republic).
- BIOCEV (Vestec, Czech Republic).
- CNR (Italy): implementation of new ideas for deformable mirror optimization aiming at low cost large size mirrors.
- GIST (Sud-Korea): Ultrahigh Intensity Laser-Matter Interaction.
- LOA (Palaiseau, France) for medical applications of laser driven electron beams.
- ELETTRA/FERMI (Trieste, Italy): electron diagnostics development and testing.

3.4.3. Scientific highlights – selected publications of the research program

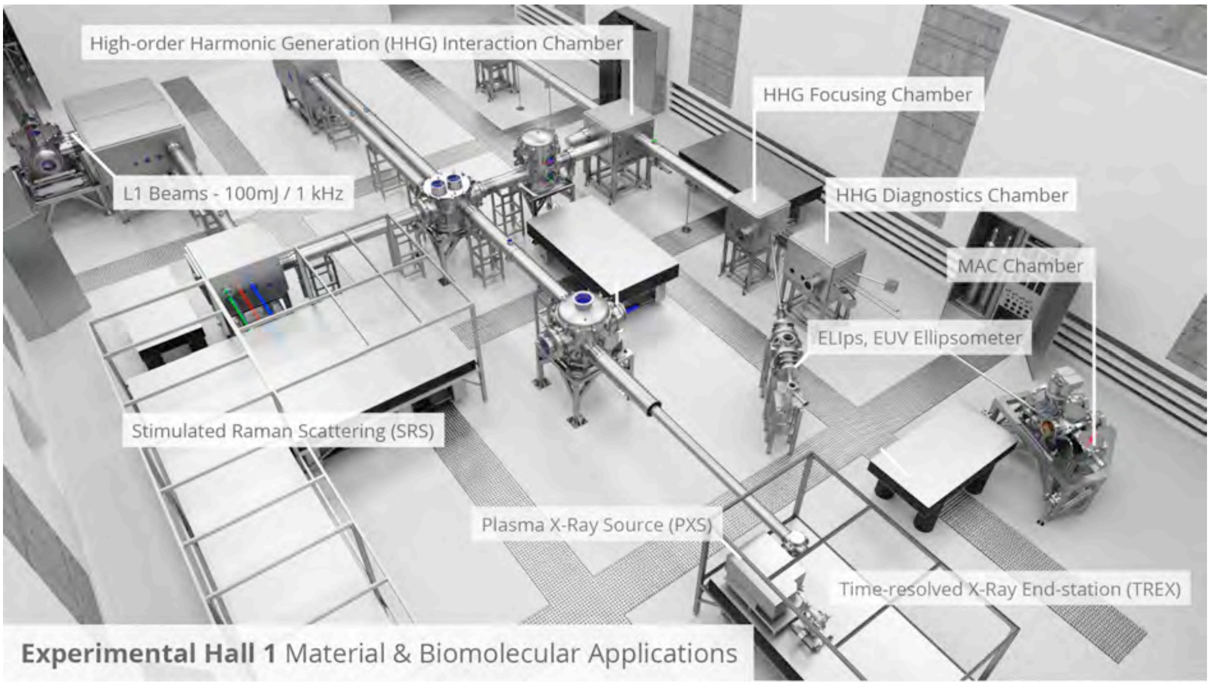
Several publications and patent have been produced during the implementation phase. A few selected key works are listed below:

- D. Margarone et al., "Proton Acceleration Driven by a ns laser from a cryogenic thin solid hydrogen ribbon", Phys. Rev. X 6 (2016) 041030.
- D. Margarone et al., "Laser-Driven Proton Acceleration Enhancement by Nanostructured Foils" Phys. Rev. Lett. 109 (2012) 234801
- D.Margarone, G. Korn, A. Picciotto, P. Bellutti, "Laser fusion system and method", European Patent Application No. EP2833365 (already granted in CZ)
- Grittani, Levato, Lazzarini, Korn, EU-patent submission (accepted recently) for an advanced "Laser-based radiotherapy machine with real time"

3.5. **RP4** Application in Molecular, Biomedical and Material Sciences

3.5.1. Scientific-technological infrastructure in the experimental hall E1

Research program 4 (RP4) at ELI Beamlines develops “Applications in Molecular, Bio-medical and Material Science” utilizing mainly the L1 laser developed by RP1 and the laser driven light (VUV and X-ray) sources developed by RP2. Scientific activities are focused in the E1 experimental hall where the high repetition rate (1 kHz) L1 will be converted to the requested pulse parameters and used to study ultrafast processes of electronic, molecular and magnetic dynamics.



Planned structure of the E1 experimental hall. A high vacuum beam transport system brings the L1 beams to the VUV and X-ray sources (HHG and PXS). Scientific end stations are located behind the sources. Note that the PXS station will be located in a radiation safety hutch that is not shown for clarity.

Four experimental stations are developed for E1. Two of these are optimized for the vacuum Ultra-violet (VUV) pulses from the HHG source. One (the MAC chamber) is dedicated to the study of ultrafast dynamics in isolated atoms, molecules, clusters as well as nanoparticles and nano-bio-particle complexes. This station can also be used for imaging application through coherent diffractive imaging. Although initially deployed in E1, this station is also suitable for use at the LUX source in E5 once it becomes available. The other end station at the HHG source will offer to the material science community unique ways to study dynamics in solid state materials (including new physics at interfaces and surfaces) through time resolve magneto optical ellipsometry extending into the soft X-ray range. Next to the HHG source the PXS source will serve a modular end station for jitter-free time-resolved X-ray diffraction, spectroscopy and pulse radiolysis experiments. In addition to the experimental stations at the laser driven X-ray sources (HHG and PXS) E1 will also be equipped with a station for advanced time-resolved optical spectroscopy techniques. This station includes a wide range of pulse conversion instruments including methods to generate pulses in the UV to IR range (including THz), as well as temporally shaped and ultra-short (~5 fs) pulses. The beam transport system is developed to allow the beams from all light sources in E1 to be overlapped in both space and time, thus allowing unique experimental combinations.

3.5.2. Major research topics

The choice of technologies for development recognizes a number of fundamental aspects of photon science. First, as in every-day flash photography, the duration of the light flash limits the temporal resolution that can be achieved. With femtosecond (fs) flashes (pulses) from the L1 laser it is possible to study fs dynamics. This is exactly the time scale where a great part of interesting properties in Molecular, Bio-medical and Material Science have their origin. Furthermore, the wavelength of the light sets a fundamental limit to the spatial resolution that can be obtained. In particular, to study atoms and molecules directly, you need light with a wavelength of that same scale (that means X-rays). The fact that X-ray diffraction can provide spatial resolution on the atomic and molecular scale, where motion happens on the fs time scale makes ultrashort X-ray pulses extremely suitable to study structural dynamics. Finally, the energy of the photons determines what type of properties in the sample the pulse will either activate or probe. It is said that when the photon energy is the same as that of a specific excitation/property in the sample they are in "resonance". Ultrafast resonance spectroscopy, is a very powerful way to selectively activate and study diverse properties in applied science.

In E1 RP4 develops the unique possibilities that come from having synchronized high repetition-rate light-sources covering a wide range of the electromagnetic spectrum available in one location. This will allow us to selectively chose how to activate and probe sample dynamic in ways that are beyond the present state-of-the-art. Research and development will focus on ultrafast dynamics and cover interactions between electronic, structural, magnetic and optical properties. Samples cover atoms, molecules, clusters and nanoparticles (including bio-particles and bio-nano complexes) as well as thin films, multilayers and bulk materials (including powders and single crystals for time-resolved X-ray diffraction). In a close collaboration with the ELIBIO team RP4 develops unique strengths in the investigations of complex and sensitive bio-molecular targets (like dynamics in membrane proteins). Time-resolved research will cover both studies of the effects of photo-activated charge transfer processes as well as processes that are not explicitly photo activated ("dark" reactions) which are particularly important to biological systems and catalysis since very few of these processes are photo-activated in nature.

3.5.3. Present research linked to future activities

A long term strategy in RP4 has been to be actively involved in X-ray science at international user facilities such as X-ray Free Electron Lasers (FELs) and modern synchrotrons as well as in optical labs of strategic international collaborators. As an example, in 2017 RP4 researchers are scheduled to participate in at least three X-ray FEL beamtimes at DESY in Hamburg and SLAC in the USA. Since December 2016 the international user community is also working with the RP4 team on user assisted methods development projects at the ELI

BL facility. A particularly successful example is the development of time resolved spectroscopic ellipsometry that has already attracted significant interest from international and national users. Both of these activities represent important preparations for the future user activities. A topic of significant present importance is the co-development of RP4 and the ELIBIO Excellent Research Team headed by Professor Janos Hajdu since Dec. 2016. RP4 has a unique opportunity to utilize the synergy effects from having a world leading team in bio-molecular dynamics being realized at the very facility where RP4 is developing scientific instruments for in-house research and user operation.

3.5.4. Scientific highlights – selected publications of the research program

The publications with the highest impact factors (given in brackets) are the following:

- Shirly Espinoza, et al., ***User oriented end-station on VUV pump-probe magneto-optical ellipsometry at ELI beamlines,***
  Applied Surface Science (published online) **[3.15]**
- B. J. Daurer, et al., ***Experimental strategies for imaging bioparticles with femtosecond hard X-ray pulses,***
  IUCrJ, v. 4, part 3 (May 2017) **[5.32]**
- G. Van der Schot, et al., ***Open data set of live cyanobacterial cells imaged using an X-ray laser,***
  Nature SCIENTIFIC DATA | 3:160058 | DOI: 10.1038/sdata.2016.58,
  Journal does not yet have an Impact Factor
- Anna Munke, et al., ***Coherent diffraction of single Rice Dwarf virus particles using hard X-rays at the Linac Coherent Light Source,***
  Nature Scientific Data 3, Article number: 160064 (2016),
  Journal does not yet have an Impact Factor
- D. Rath, et al., ***Explosion dynamics of sucrose nanospheres monitored by time of flight spectrometry and coherent diffractive imaging at the split-and-delay beam line of the FLASH soft X-ray laser,***
  Optics Express, Volume: 22, Pages: 28914-28925 (2014) **[3.75]**

3.5.5. List of potential future users

The following list of potential/likely international users represents a selection of researchers and institutions RP4 have worked with during the instrument and methods development process. In many cases they represent long term scientific collaborators of senior RP4 researchers.

AMO science and Coherent Diffractive Imaging

- Technical University Berlin, Berlin, Germany (M. Krikunova)
- Molecular Biophysics, Uppsala University, Uppsala, Sweden (F. Maia)
- Molecular and Condensed Matter Physics, Uppsala University, Uppsala, Sweden (N. Timneanu)

Material science, in particular time-resolved ellipsometry extending into the VUV range

- Leipzig University, Leipzig, Germany (R. Schmidt-Grund)
- Hamburg University and CFEL and DESY, Hamburg, Germany (M. Rübhausen)
- Magdeburg University, Magdeburg, Germany (M. Feneberg)
- New Mexico State University, New Mexico, USA (S. Zollner)
- Institute of Physics, Prague, Czech Republic (A. Dejneka)
- Masaryk University/CEITEC, Brno, Czech Republic (Joseph Humlicek)

Hard X-ray science (diffraction, scattering, spectroscopy and imaging)

- Potsdam University, Potsdam, Germany (M. Bargheeer)
- Molecular Biophysics, Uppsala University, Uppsala, Sweden (I. Lundholm)
- Göteborg University, Göteborg, Sweden (G. Katona)
- Uppsala University/Polish Academy of Science, Uppsala/Warsaw, Sweden/Poland (J. Sa)
- Jan Kochanowski University, Kielce, Poland (J. Szlachetko)

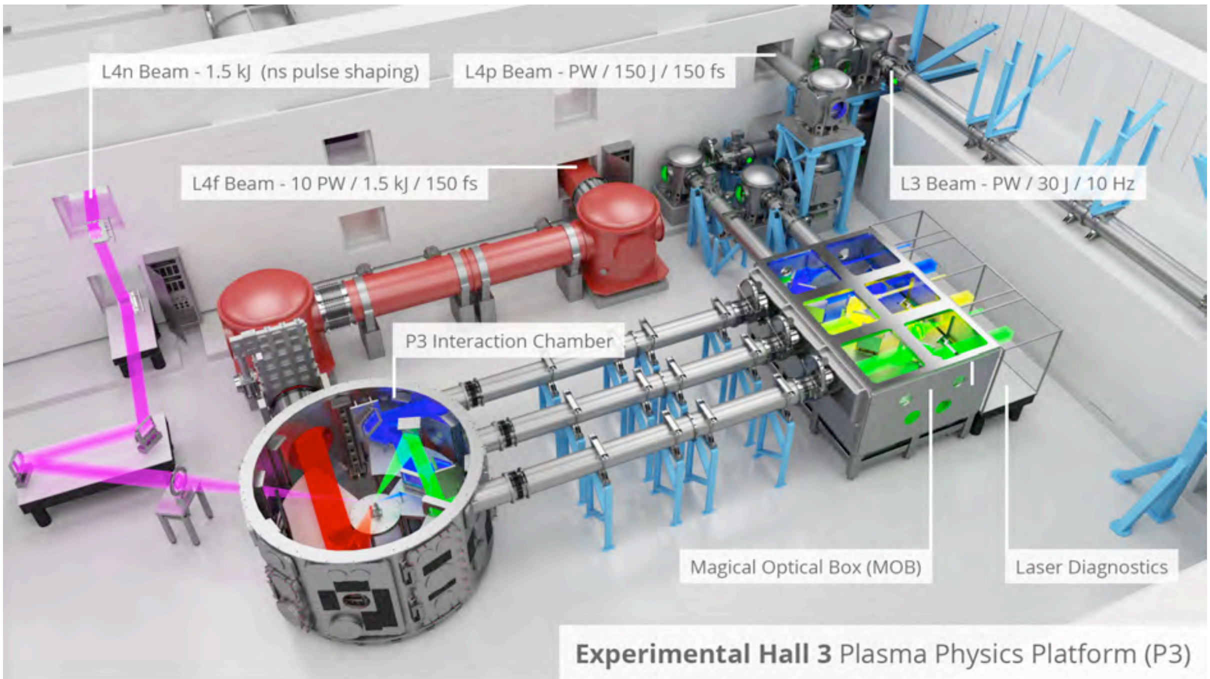
Optical spectroscopy (fs Stimulated Raman Scattering and 2D spectroscopy)

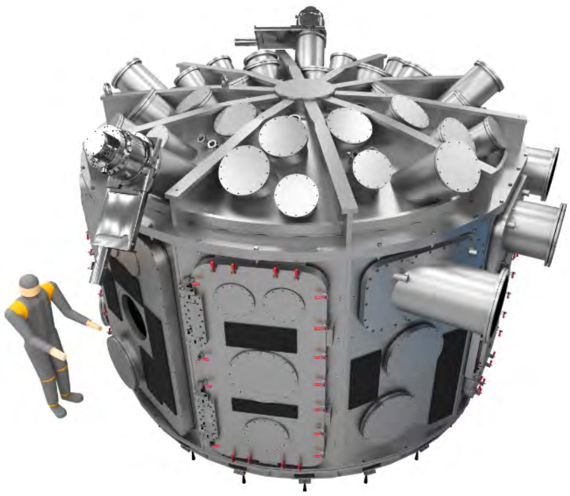
- Univ. of South Bohemia, České Budějovice, Czech Republic (T. Polivka)
- Chalmers University of Technology, Göteborg, Sweden (M. Karlsson)
- Free University Amsterdam, Amstedan, Netherlands (R. Croce, J. Kennis)

3.6. RP5 Plasma and High Energy Density Physics

3.6.1. Scientific-technological infrastructure in the experimental hall E3

The experimental hall E3 is dedicated to the study of high-energy-density physics and ultra-high intensity laser-plasma interaction. The most important elements of the technological infrastructure are the plasma physics platform (P3) and the optical switchyard (MOB). The infrastructure is designed to handle multiple, synchronized laser beams in the same interaction chamber, covering a wide range of pulse lengths and energy. It is not a dedicated beamline providing optimized secondary sources but rather a platform for fundamental and applied research allowing for very flexible setups. On a smaller scale there will be additional scientific equipment such as a betatron for new sophisticated plasma diagnosing and a pulsed power device for the study of magnetized plasmas. The main vacuum chamber can accommodate the 10 PW beam as well as the uncompressed nanosecond beam. It is therefore dedicated to high-intensity as much as high-energy laser-plasma interaction. This variety of laser configurations allows the study of a wide range of laser-plasma phenomena. The main interaction chamber is with about 50 m3 one of the largest civilian vacuum chamber for laser-based experiments.





P3 Chamber: manufactured parts (left), visualization of complete chamber (right).

3.6.2. Major research topics

The research program R5 is covering a very wide range of topics in the field of lasers interacting with plasmas/matter:

- Laboratory astrophysics: collisionless shocks, magnetic reconnection, radiation hydrodynamic phenomena, jet formation, magnetized laser-plasma interaction
- High-energy-density physics and warm dense matter: planetary cores, shock waves, opacities, equation of state etc.
- Ultra-high intensity interaction: electron-positron pair creation, radiation damping, γ-ray flashes, relativistic flying mirror etc.
- Plasma optics: plasma amplification, plasma focusing, manipulation of coherent light by plasmas, new schemes for future high-power laser pulses etc.

- Laser-plasma interaction: e.g. for shock-ignition approach to ICF, parametric instabilities, soliton formation, laser absorption etc.

The P3 research infrastructure with its wide range of possibilities is of strong interest to the academic research community. However, the research program is also strongly engaged in the development of possible new secondary sources which will benefit the other beamlines and provide eventually societal benefits.

3.6.3. Present research linked to future activities

Members of the R5 team engage actively in experimental campaigns in Europe and USA as well as develop new scientific technology for the future user community of P3. Some of them are presented briefly in the following.

Technology development activities:

- **Gamma-ray spectrometer:** Gamma-photons are generated by nonlinear inverse Compton scattering in ultra-high intensity laser-matter interaction. A prototype instrument was developed operating in the 5-20 MeV range with 2 MeV resolution. The spectrometer has been calibrated at HZDR-ELBE beamline.
- **Betatron:** Laser wakefield acceleration of electrons provide an efficient way to generate betatron radiation of a few keV. This radiation is a diagnostic for warm dense matter studies, e.g. XANES etc. The approach is being fine-tuned on installations such as PALS and Lund Laser Center.
- **Pulsed Power Device:** Up to 30 kJ of stored energy are released in a few milli-seconds to generate quasi-static magnetic fields (~40 Tesla). This allows the study of magnetized laser-plasma interaction for astrophysical applications and warm dense matter studies.
- **Ellipsoidal Plasma Mirrors:** EPMs are required for refocusing the 10 PW laser beam of ELI-BL. Development work is taking place to optimize the EPMs for proof-of-principle experiments before being deployed in P3.

Experimental campaign activities:

- **Magnetic field generation:** Capacitor coil experiments for generating Mega Gauss fields were performed at PALS laser facility. This method is complimentary to a PPD as the fields are very short-lived but much more intense.
- **Warm dense matter & betatron:** Several experimental campaigns were conducted in the context of WDM on such installations as OMEGA in Rochester and Trident at LANL. These experiments investigated electron preheat, novel X-ray sources and electron diffraction.
- **Plasma amplification:** Over the last few years several campaigns were conducted on plasma amplification leading towards control and optimization of the interaction process. The robustness and energy-efficiency of the Brillouin-based process was clearly proven.

- **Hot electron generation & diagnosing:** In a series of experiments, generation of suprathermal electrons has been studied at conditions relevant for the development of a shock ignition driven inertial confinement fusion. A novel approach to suprathermal electron production in laser-irradiated Cu targets characterized by combined methods of x-ray imaging and spectroscopy is being developed.

3.6.4. Scientific highlights – selected publications of the research program

The publications with the highest impact factors (given in brackets) are the following (in chronological order):

- B. Albertazzi et al., ***Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field,***
  Science **346**, 325 (2014) **[33.61]**
- L. Lancia et al., ***Signatures of the Self-Similar Regime of Strongly Coupled Stimulated Brillouin Scattering for Efficient Short Laser Pulse Amplification***,
  Phys. Rev. Lett. 116, 075001 (2016) **[7.645]**
- U. Zastrau et al., ***Tracking the density evolution in counter-propagating shock waves using imaging X-ray scattering***,
  Appl. Phys. Lett. 109, 031108 (2016) **[3.142]**

A detailed reference article on the P3 scientific and technological infrastructure has been accepted for publication in Matter and Radiation at Extremes (Elsevier journal). It describes in some detail on almost 30 pages the most important scientific and technological aspects of the Plasma Physics Platform (P3):

- S. Weber et al., ***P3: an installation for high-energy density plasma physics and ultra-high intensity laser-matter interaction at ELI-Beamlines,***
  Matter Rad. Extremes (accepted for publication) (2017)

3.6.5. List of potential future users

R5 is in contact with a large number of institutes/laboratories and universities worldwide who are either already collaborators of the project or expressed interest as future user. In the following overview only the major institutions are listed together with a contact person or collaborator.

EUROPE:

- LULI/APOLLON, Ecole Polytechnique, Palaiseau, France (J. Fuchs)
- University of Strathclyde, Glasgow, UK (P. Mckenna)
- XFEL, Hamburg, Germany (M. Nakatsutsumi)
- HZDR, Dresden, Germany (T. Cowan)
- Technische Universität Darmstadt, Darmstadt, Germany (M. Roth)
- RAL, Didcot, UK (D. Neely)
- Queen’s University Belfast, Belfast, UK (M. Borghesi)

- Lund Laser Center, Lund, Sweden (O. Lundh)
- GSI, Darmstadt, Germany ()
- Friedrich-Schiller University Jena, Jena, Germany ()

Outside EUROPE:

- SIOM, Shanghai, China (J.-Q. Zhu)
- University of Texas, Austin, USA (G. Dyer)
- LLNL, Livermore, USA ()
- Rochester University, Omega, Rochester (USA)
- Weizmann Institute of Science, Israel ()
- Osaka University, Osaka, Japan (Kodama)

It is to be expected that any research group worldwide active in the domain of high-energy and/or high-intensity laser-matter interaction will be interested to become future user of P3 as the proposed scientific and technological infrastructure will be unique in the European landscape of laser-based research.

3.7. **RP6** Exotic Physics and Theory/Simulation

3.7.1. Major research topics

The research program R6 has the character of a theory & simulation group as the experimental part, high-field research, was transferred to R5. In addition, R6 is responsible for the high-performance computing center. Its main activities are the following:

- Predictive simulations of future high-field laser-matter interaction experiments
- Start-to-end simulation work up to the detector response signal
- Investigating new possible signatures of high-field interaction for diagnostic means
- Optimizing the computing cluster for specific simulation activities
- Code development activities for high-field as well as pre-pulse physics
- Simulation support and data analysis for experimental activities
- Define possible high-field flagship experiments for the ELI-BL 10 PW laser
- Development of the Virtual Beamline (VBL) for the experimental programs and the ELI facility as a whole

The actual physics topics overlap strongly with the ones presented for the R5 program.

3.7.2. Present research linked to future activities

The present research activities have resulted in a large number of peer-reviewed articles investigating mostly the following topics:

- **Electron-positron pair creation using the Breit-Wheeler process:** Detailed studies are under way to optimize the interaction process and to determine amount and geometry of the release process.
- **Magnetic reconnection in the relativistic collisionless regime:** MR is a ubiquitous process in astrophysics and can be studied with laser in the short-pulse regime. For UHI the reconnection process is no longer driven by collisions as for example in tokamaks.
- **Plasma amplification:** The use of 3-wave coupling processes in plasmas is investigated for the generation of high-intensity laser pulses. Plasmas allow to overcome the usual damage threshold consideration of standard solid-state-based optical materials. This might be one way for future Exawatt laser systems.
- **Pre-pulse physics: Any laser has a limited contrast.** As a consequence, the pre-pulse generates a plasma corona in front of the solid material. A detailed understanding and possible subsequent control of the coronal plasma is of vital importance for ICF applications as well as for making possible the interaction of solid density with the highest possible laser intensity.
- **Gravitational wave generation by high-power lasers:** A study investigated the possibility to generate gravitational waves in a controlled laboratory environment. Although possible in principle, the achievable space-time perturbations are beyond present detector limits.
- **Attosecond physics:** Studies are under way to understand laser-induced atto-second physics on the nano-scale for possible future applications.
- **Parametric instabilities in the context of the shock-ignition scenario for ICF:** Parametric instabilities are detrimental to the ignition process in thermonuclear fusion. They are responsible for energy loss due to backscattering and can generate hot electrons which induce preheat. The intricate interplay of the various instabilities and their control is far from understood.

3.7.3. Scientific highlights – selected publications of the research program

The publications with the highest impact factors (given in brackets) are the following (in chronological order):

- S. Weber et al., ***Amplification of Ultrashort Laser Pulses by Brillouin Backscattering in Plasmas,***
  Phys. Rev. Lett. **111**, 055004 (2013) **[7.645]**
- T.-M. Jeong et al., ***Spatio-temporal modification of femtosecond focal spot under tight focusing condition,***
  Optics Express **23**, 11641 (2015) **[3.148]**
- M. Chiaramello et al., ***Role of Frequency Chirp and Energy Flow Directionality in the Strong Coupling Regime of Brillouin-Based Plasma Amplification,***
  Phys. Rev. Lett. 117, 235003 (2016) **[7.645]**

- Y.-J. Gu et al, ***High density ultrashort relativistic positron beam generation by laserplasma interaction,***
  New J. Phys. **18**, 113023 (2016) **[3.570]**
- M.F. Ciappina et al., ***Attosecond physics at the nanoscale,***
  Rep. Prog. Phys. 80, 054401 (2017) **[13.857]**

3.7.4. Active collaborations in theory/simulation

R6 is engaged in several very productive collaborations with specialists inside and outside Europe which help to define the future research activities:

- LULI-UPMC, University Pierre et Marie Curie, Paris, France (C. Riconda)
- MEPhi, Moscow, Russia (E. Gelfer)
- CELIA, University of Bordeaux, Bordeaux, France (V.T. Tikhonchuk)
- Kansai Photon Science Institute, JAEA, Kyoto, Japan (S. Bulanov)
- FNSPE, Czech Technical University, Prague, Czech Republic (O. Klimo)
- Forschungszentrum Jülich, Jülich, Germany (P. Gibbon)

3.7.5. Technological infrastructure

The research program R6 is in charge of building up a local high-performance computing center. The first element was the acquisition of a cluster of about 1400 cores and 1 Peta-Byte disk space. The peak performance is of the order of 100 Tera-Flops. The dominant purpose of the machine is multi-dimensional, kinetic simulation work for the interpretation of experimental data, predictive modeling of future high-field experiments and numerical support work such as Monte Carlo simulations for radiation protection etc. Due to a recently awarded ERT grant the machine is expected to undergo a considerable upgrade in 2018.

The high-performance computing cluster ECLIPSE.

3.8. **ELIBIO Project:** Future Biology with High-Power Lasers

The European Development Fund and the Czech Ministry of Education, Youth and Sports has awarded over 250 million CZK to the ELIBIO project at the new ELI Beamlines laser facility of the Institute of Physics of the Czech Academy of Sciences. The project explores new frontiers in light and optics to create breakthrough science in biology, chemistry, and physics. The project brings world-leaders in photon science and structural biology to the Czech Republic, and creates an interface between two complementary research centres of the Czech Academy of Sciences: the ELI-Beamlines (ELI-BL) facility and the Institute of Biotechnology (IBT) of the BIOCEV Centre. IBT is focused on biomedical and biotechnological research while ELI-BL is a leader in photon physics with high-power lasers.

The ELIBIO team is headed by Prof. Janos Hajdu, who is developing the research strategy and sets the scope of the experimental work. Prof. Hajdu has a rich scientific career. He started his X-ray work in Oxford, U.K., was Professor of Photon Science at Stanford University in the USA, and Professor of Molecular Biophysics at Uppsala University in Sweden. He also served as advisor to the Directors of the European X-ray Free-Electron Laser (XFEL) in Hamburg. The "Excellent Research Team" (ERT) to be established in this project includes scientists at all professional levels and is expected to enhance the research performance of the partner organizations. Senior ERT members include Prof. Bohdan Schneider (IBT), Prof. Jan Dohnalek (IBT), and Prof. Maria Krikunova (ELI-BL). A particularly close collaboration has been established with Dr. Jakob Andreasson from ELI-BL, who heads the ELI-BL research programme for applications in molecular, bio-medical and material sciences.

One of the aims of the ELIBIO project is to establish an Interdisciplinary Centre of Excellence at the European Extreme Light Infrastructure in Dolní Břežany near Prague. This centre will combine biology, chemistry and physics, and will exploit some of the most powerful photon beams in the world at the ELI-Beamlines facility. ELIBIO will use these beams to perform breakthrough studies in life sciences.

3.8.1. Specific research objectives of the project

Biomolecular interactions and charge transfer studied by ultrafast spectroscopy.

We will trigger charge transfer reactions with extremely short photon pulses to study ultra-fast processes in a broad spectrum of radiation from THz to UV and X-ray radiation. Synchronized multidimensional spectroscopy will be used to characterise the dynamics of the systems under investigation. We plan to address three issues: (1) fingerprinting of biomolecules by Raman spectroscopy at up to attosecond resolution. (2) studying transient protein-protein or protein- nucleic acid interactions by combined vibrational and UV/fluorescence spectroscopy; (3) light-driven nano-manipulation of molecules and their assemblies.

Diffraction-based imaging of crystalline and non-crystalline nano-material on ultrashort time scales.

We will create a sample environment and pipeline to perform such experiments at ELI-BL and work with other scientists at ELI-BL in pioneering efforts to use multiple beams to obtain super-stereo images. Initially, this work will mainly be carried out at the LCLS and the European XFEL and then moved to ELI-BL as the operational parameters of the facility approach requirements.

Studies of photon-material interactions on ultrashort time scales and high intensities.

Biological imaging exploits the high-frequency and high-energy density regime of photon science, which has not been accessible to research so far. The dominant interaction of X-rays with atoms is through K- shell photoionization. Relaxation of the resulting hollow ions proceeds through the emission of Auger electrons in biologically relevant light elements. Shake-up and shake-off excitations, initial- and final- state configuration interactions and interference between decay channels will modulate this picture. Electrons ejected from atoms cause further ionization by eliciting secondary electron cascades in condensed materials. With very short X-ray pulses (shorter than about 10 femtoseconds), most of these processes will have no time to develop, and the photoionisation cross-sections drop. We will investigate: (i) primary and secondary ionisations as a function of photon energy and pulse intensity. (ii) time-dependent X-ray absorption and scattering, and (iii) perform experiments at ultra-high energy densities.

Development of experimental methods.

A biology support laboratory will be created at ELI-BL during this project and research infrastructure of IBT at BIOCEV will be upgraded. We will work on improving sample delivery to reduce sample consumption when introducing living cells, viruses or biomolecules into the beams of ELI for spectroscopy and imaging. We will develop advanced pump-probe methods for time-resolved spectroscopy at ELI-BL.

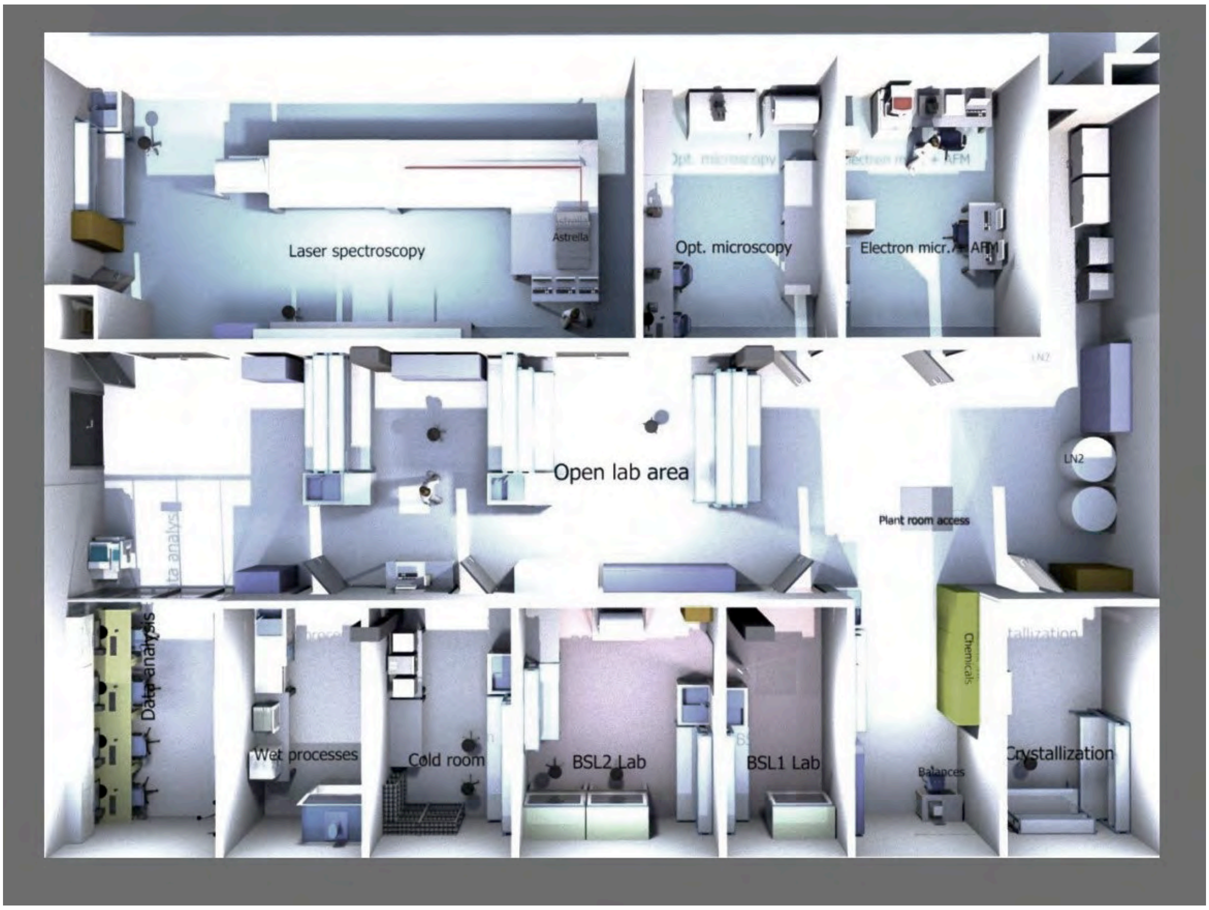
Education of Czech and foreign students.

Students will benefit tremendously from participating in revolutionary new experiments. We intend to set up a Masters Programme and a Graduate Programme in Photon Science and continue teaching of structural biology at Charles University and South Bohemian University. Our links to various X-ray lasers and advanced photon sources offer new dimensions and opportunities through joint courses and joint M.Sc. and especially Ph.D. projects.

3.8.2. Key investments

The Bio-lab complex

The main infrastructure upgrade will be the realization of a bio-lab complex at the ELI-BL facility. The building for the bio-lab complex has been constructed in at ELI-BL and within the ELIBIO project we will develop 373 m2 of this area into a fully functional bio-lab equipped to perform preparatory and complementary measurements to experiments at ELI-BL and X-ray Free Electron Lasers. It will also support the IBT labs in sample preparation.



Schematic layout of the ELIBIO Laboratory area.

The construction of the bio-lab complex is expected to start in month 12 of the project and finish in month 24 (with the commissioning of all major systems). Estimated cost: 59.34 M CZK (excl. VAT).

A designated pump-pulse laser

This laser will be installed in the ELI-BL E1 experimental hall to deliver the pulses used to initiate the sample dynamics that will be probed by the X-ray sources driven by the powerful ELI-BL main lasers. This laser should have an oscillator that can be synchronized to the ELI-BL main lasers on the femtosecond level and a capability of picking pulses with arbitrary delays for amplification, thus allowing high resolution pump-probe experiments in the femtosecond to millisecond range. This upgrade will start in month 9 of the project and finish in month 15. Estimated cost: 14.16 M CZK (excl. VAT).

Sample preparation and characterization facility at IBT

The capabilities for sample preparation and characterization at IBT will be upgraded. Significantly a SAXS beamline will be added to the X-ray scattering and diffraction instrument. In addition, the capabilities for protein expression and purification will be improved and the mass spectroscopy instrument upgraded. These upgrades will start in month 9 of the project and finish in month 36. Estimated cost: 20.65 M CZK (excl. VAT).

The ELIBIO project will be embedded into an international framework of research infrastructures, including the European XFEL and the Linac Coherent Light Source at Stanford (California, USA). A Memorandum of Understanding with the European XFEL will be signed on 28 April 2017 in Dolní Břežany. The inflow of talent and expertise through this project, combined with the foundation of a centre of excellence will leave a legacy of a strengthened Czech research environment.

4. Worldwide Cooperation

From 2007 to 2010, more than 40 research institutions coming from 13 EU member States contributed to the ELI Preparatory Phase, with the objective of bringing the initial concept of ELI to a level of maturity allowing its implementation. The ELI Beamlines will be one of the three initial facilities of the future infrastructure.

Already now , more than 30 agreements and contracts have been concluded to fix the terms of such cooperations. In most cases, these contracts have the form of a special Memorandum of Understanding for a scientific and technological collaboration.

MoUs ELI-Beamlines

- **Institute for Materials Research,** Tohoku University, Japan
- **Keldysh Institute of Applied Mathematics (KIAM)**, Moscow, Russia
- **Institute of Plasma Physics and Laser Microfusion (IPPLM)**, Warsaw, Poland
- **The Institute for Solid State Physics**, The University of Tokyo, Japan
- **Institute of Experimental Physics II**, Leipzig University, Leipzig, Germany
- **Korea Basic Science Institute (KBSI)**, Daejeon, Republic of Korea
- **Elettra-Sincrotrone Trieste S.C.p.A.**, Trieste, Italy
- **Deutsches Elektronen-Synchrotron DESY**, Hamburg, Germany
- **University of Rochester (UR), Laboratory for Laser Energetics (LLE)**, Rochester, USA
- **Jan Kochanowski University in Kielce**, Poland
- **Institute of Physical Chemistry, Polish Academic Sciences**, Warsaw, Poland
- **Laboratori Nazionali del Sud (LNS)**, of the Instituto Nazionale di Fisica Nucleare, Catania, Italy
- **EUROPEAN SYNCHROTRON RADIATION FACILITY**, Grenoble, France

- **Faculty of Nuclear Sciences and Physical Engineering**, Czech technical University in Prague, Czech Republic
- **Helmholtz-Zentrum Berlin für Materialien und Energie GmbH**, Berlin, Germany
- **Centre National de la Recherche Scientifique**, Grenoble, France
- **Extreme Light Infrastructure - Attosecond Light Pulse Source**, Hungary
- **Extreme Light Infrastructure- Nuclear Physics**, Romania
- **Center for Physical Sciences and Technology**, FTMC, Vilnius, Lithuania
- **Technische Universität Darmstadt (TUDA)**, Darmstadt, Germany
- **Shanghai Institute of Optics and Fine Mechanics (SIOM)**, Shanghai, Jiading, China
- **The French National Center for Scientific Research (CNRS) & The French Alternative Energies and Atomic Energy Commission (CEA),** Paris, France
- **Universität Hamburg, the Faculty of Mathematics**, Informatics and Natural Sciences (MIN), Germany
- **Institut National de la Recherche Scientifique (INRS)**, Quebec, Canada
- **Masarykova univerzita, Ústav výpočetní techniky**, Centrum CERIT-SC, Brno
- **Section of Radiological Sciences of the Department of Biomedical Sciences and of Morphologic and Functional Imaging of the University of Messina**, Italy
- **Pierre et Marie Curie University**, Paris, France
- **The European Organization for Nuclear Research (CERN)**, Geneva, Switzerland
- **Strathclyde Intense Laser Interaction Studies Group of Strathclyde University (SILISSTRATH)**, Glasgow, UK
- **European Organization for Nuclear Research (CERN)**, Geneva, Switzerland
- **National Research Nuclear University**, Moscow, Rusko
- **The Helmholtz-Zentrum Dresden-Rossendorf (HZDR),** Germany
- **APRI-GIST**, Repulic of Korea
- **The Queen´s University of Belfast**, Belfast, UK
- **The Laboratori Nazionali del Sud (LNS), The National Institute for Nuclear Physics (INFN),** Catania, Italy

User Community

5. Conclusion:

ELI-BL in the European and Worldwide Laser-based Research Landscape

High intensity lasers are proposed to drive advanced short pulse optical, IR, x-ray and particle beams (secondary sources) beyond state of the art by controlling and extending the parameters of lasers and secondary sources concerning their intensities, stability, synchronization, quality, energy range and repetition rates. This allows performing new investigations spanning the range from fundamental to applied sciences and medicine, ultimately leading to a better understanding of nature and providing future societal benefits. The proposed upgrade of the existing facility will extend the scope of societal and fundamental applications and widen the potential user base, in particular from the industrial sector, while continuing to provide a unique research platform for the academic sector. ELI's worldwide competitiveness will increase considerable, making it the foremost user installation in the European landscape and at the same time positioning the Czech Republic at the forefront of photonic research.

The projected center development is thus two-fold: enhancing the capabilities and versatility of the laser systems and subsequently use these improved lasers for new experimental possibilities. There is therefore a strong interconnectivity/interdependence of lasers and experimental applications. Improving the lasers leads directly to improving the endstations, beamlines and platforms of ELI-Beamlines.

The ELI-BL project is a unique endeavor in the field of photonic-based research worldwide and also the first large-scale user facility in this domain. By construction it will serve the academic research community as much as the applied research community, which is oriented towards industry, societal benefits and medicine and health sector. By its very nature, projects on the scale of ELI-BL are many years in the making. During this construction, installation and commissioning period new technological developments take place, which are of prime importance to the project especially in such unexplored field of physics. Any facility, which intends to remain state-of-the-art has therefore to upgrade continuously, even before commissioning is over. In order to remain competitive ELI-BL has to innovate in parallel to construction and commissioning. ELI-BL cannot afford to be out-of-date the moment it opens its doors to the prospective user community. The present technological infrastructure is designed in such a way as to allow a very efficient and rapid upgrade within the existing building layout. Any upgrade will therefore be very cost-effective, as almost all expenditure goes directly into equipment destined for the users and only minimally into adjusting the building infrastructure.

The specific nature of the ELI-BL user facility is its multi-disciplinary features as far as its laser systems and corresponding usage is concerned. The planned upgrade will affect each of the dedicated experimental target areas in the infrastructure in a particular way. Nevertheless, the specific upgrades are not completely independent and have to be considered interconnected since both the laser development and the fundamental science new achievements will allow enhancing the features of the developed secondary radiation and particle sources, thus, as a consequence, the user capabilities at the end-stations.

The trend in laser-based research are sophisticated pump-probe experiments which require synchronized multiple laser beams. The scope of experimental possibilities is enhanced considerably by increasing the wavelengths available as well as variability of pulse lengths and number of beams.

The excellent research, which will become possible, will give consequently excellent scientific achievements. New paths of applied and fundamental research will be opened.

6. Annex No. 1 – ELI Beamlines Facility Start up Period Schedule

RP2 X-ray Sources - HHG Beamline

<table>
<tr><th>Stage</th><th><u>Pre-commissioning</u>
(Hardware and Basic Functionalities)</th><th><u>Commissioning</u>
(Laser-target Inter. & second. source)</th><th><u>Enabling</u>
(Initial User Experiments)</th><th><u>Flagship</u>
(Advanced User Experiments)</th></tr>
<tr><td>Scope</td><td>Acceptance of the delivery from the supplier in hall E3 at HiLASE
Optimization of the source with the alignment laser</td><td>Installation of the HHG beamline in E1 (ELI BL)

Optimized generation of a single beam from 120 nm down to 10 nm</td><td>Optimized generation of a single (double) HHG beam with single (double) driver beam from 120 nm down to 5 nm</td><td>Two color driving scheme option to enable more accessible wavelengths and various polarization states</td></tr>
<tr><td>Enabling technology</td><td><u>Basic supporting technologies:</u>
Primary vacuum
cooling water (closed circuit with local chiller)
cleanroom ISO 7 tent
<u>Alignment laser</u> (>5 mJ, <50 fs, 1 kHz)</td><td><u>All supporting technologies in E1 and beam transport for alignment laser</u></td><td><u>Alignment laser + L1 at PL3 (>30 mJ, <20 fs)</u></td><td><u>single L1 beam with >60 mJ</u>
<u>And possibility of having 2 beams of L1 laser (>30 mJ each)</u></td></tr>
<tr><td>Timeline</td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>Installation of the supporting technologies</td><td></td><td>9-11/2016 (3 mons)</td></tr>
<tr><td>Installation of the HHG beamline</td><td></td><td>11/2016-1/2017 (3 mons)</td></tr>
<tr><td>Verification of the HHG beamline</td><td></td><td>1/2017-2/2017 (2 mons)</td></tr>
<tr><td>Optimization of the source</td><td></td><td>3/2017-5/2017 (3 mons)</td></tr>
</table></td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>Installation of the HHG beamline</td><td></td><td>7-9/2017 (3 mons)</td></tr>
<tr><td>Optimization of the source</td><td></td><td>9-12/2017 (4 mons)</td></tr>
</table></td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>Optimization of the source with L1 laser</td><td></td><td>6-12/2018 (7 mons)</td></tr>
<tr><td>Upgrade of the diagnostics and DAQ systems</td><td></td><td>6-12/2018 (7 mons)</td></tr>
<tr><td>Regular user operation (with Astrella and later with L1)</td><td></td><td>10/2017 (unk.)</td></tr>
</table></td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>Optimization of the source (with two-color pumping)</td><td></td><td>1/2019-2020 (12 months)</td></tr>
</table></td>
</tr>
</table>

RP2 X-ray Sources - Plasma X-ray source

Stage	**Pre-commissioning** (Hardware and Basic Functionalities)	**Commissioning** (Laser-target Inter. & second. source)	**Enabling** (Initial User Experiments)	**Flagship** (Advanced User Experiments)
Scope	Acceptance of the delivery from the supplier at PALS Optimization of the source with the 10 Hz laser driver	Installation of the PXS in E1 (ELI BL) Optimized generation in 3-20 keV (10.8 keV line)	Optimized generation in 3-80 keV (10.8 keV line)	Optimized generation in 3-80 keV (10.8 keV line)
Enabling technology	Basic supporting technologies and laser available at Ti:S laboratory at PALS	All supporting technologies in E1, alignment laser and beam transport for the alignment laser	Alignment laser + L1 at PL3 (>30 mJ, <20 fs) Beamtransport for L1 laser	single L1 beam with >60 mJ

Timeline

Pre-commissioning:

Activity	System	Timing (duration)
Installation of the source		3/2017 (1 mon)
Verification/acceptance		3/2017 (1 mon)
Optimization of the source		3/2017 (1 mon)

Commissioning:

Activity	System	Timing (duration)
Installation of the PXS		4/2017 (1 mon)
Optimization of the source		6-9/2017 (4 mons)

Enabling:

Activity	System	Timing (duration)
Optimization of the source with L1 laser		6-12/2018 (7 mons)
Upgrade of the diagnostics and DAQ systems		6-12/2018 (7 mons)
Regular user operation (with Astrella and later with L1)		10/2017 (unk.)

Flagship:

Activity	System	Timing (duration)
Optimization of the source (with two-color pumping)		1/2019-2020 (12+ months)

RP2 X-ray Sources - Betatron & Compton source

Stage	**Pre-commissioning** (Hardware and Basic Functionalities)	**Commissioning** (Laser-target Inter. & second. source)	**Enabling** (Initial User Experiments)	**Flagship** (Advanced User Experiments)
Scope	BETATRON Basic functions ("Electron Accelerator" and "X-ray photon source" hardware and vacuum chamber installed in E2 and E3): • Vacuum systems (Installation and tests in E2) • Electrical systems (Installation and tests in E2) • Control system - Manual + remote (installation and operation E2) • Targetry systems (Installation and alignment E2 and E3) • Diagnostic systems (Installation and alignment in E3) •	Plasma/electron/betatron generation on gas target with L3 in the vacuum chamber in E2 • Alignment of L3 (low power mode) on target (laser team) • Alignment of Electron/plasma/X-ray diagnostics • Focusing of L3 (high power mode) on target • Electron/plasma/X-ray characterization; long-term betatron beam stability tests	X-ray beam generation <20keV photon beam	**10-100 keV photon generation** 1. for pump probe probing WDM using XANES/EXAF technics with fs time resolution and µm spatial resolution in cooperation with plasma Physics, P3 chamber 2. for phase contrast imaging **100 keV – 200 keV later up to 1MeV photon generation, if science case is identified or users ask for it** 3. for pump probe probing WDM using XANES/EXAF technics with fs time resolution and µm spatial resolution 4. for phase contrast imaging of macroscopic materials 5. medical imaging above 100 keV, bandwidth control will be investigated

Enabling technology	• Central vacuum piping; ECU chambers
	   • Central hubs-to-service channels; service channels-to technologies
	• Electrical and network cables
	   • Betatron-to-racks; racks-to-control room
	• Software for remote control (control system)
	• Local alignment laser; optics and optomechanics
	   • including focusing optics in the ECU chambers
	• Target positioner and alignment system
	• Electron/plasma/X-ray diagnostics
	• Demineralized water
		• L3 BT systems in E2
		   • vacuum, optics, optomechanics
		• L3 laser alignment mode in E2
		• L3 laser in E2
		• L3 diagnostic systems in E2 (near/far field, wavefront, pulse duration)
		• Electron/plasma/X-ray real-time diagnostics
		   • remote controlled
			• L3, single shot, 100 TW-300TW ramping
			• Electron, plasma, X-ray diagnostics (10Hz)
				• L3 + L3 aux, 10 Hz, 1 PW
				• L3 aux with fs synchronization and spatial overlapping within radius of L3 focus

Timeline

Pre-commissioning:

Activity	System	Timing (duration)
Installation and tests	Vacuum systems	3-7/2017 (4 months)
Installation and tests	Electrical systems	7-10/2017 (3 months)
Installation and operation	Manual + remote control system	7-10/2017 (3 months)
Installation and alignment	Targetry systems	10-11/2017 (1 month)
Installation and alignment	Diagnostic systems	11-12/2017 (1 month)

Commissioning:

Activity	System	Timing (duration)
Alignment of L3 (low power mode) on target	L3	1-2/2018 (1 month)
Alignment	Electron/plasma/X-ray diagnostics	2-3/2018 (1 month)
Focusing of L3 (high power mode) on target (single shot)	L3	3-4/2018 (2 months)
Electron/plasma/X-ray characterization;	X-rays	4-8/2018 (4 months)

Enabling:

Activity	System	Timing (duration)
Enabling exp. – stage 1		
Generation of stable electron beam	Plasma Accelerator	9-12/2018 (3 months)
Enabling exp. – stage 2		
Betatron photon beam	Plasma Accelerator + Betatron	1-8/2019 (8 months)

Flagship:

Activity	System	Timing (duration)
Flagship exp. – stage 1		
Generation of tunable photon beam	Plasma Accelerator + Compton	9-12/2019 (3 months)
Flagship exp. – stage 2		
Pump probe experiments	Compton	1-7/2019 (7 months)

RP2 X-ray Sources – Laser Driven Undulator X-ray source

<table>
<tr><th>Stage</th><th><u>Pre-commissioning</u>
(Hardware and Basic Functionalities)</th><th><u>Commissioning</u>
(Laser-target Inter. & second. source)</th><th><u>Enabling</u>
(Initial User Experiments)</th><th><u>Flagship</u>
(Advanced User Experiments)</th></tr>
<tr><td>Scope</td><td>Pre-commissioning at DESY finished.
The current plan counts on further developments of LUX towards higher photon counts per bunch and towards FEL at DESY and installation of LUX or upgraded LUX at ELI by the end of 2018 or in 2019.</td><td>First electrons with 400 MeV energy accelerated with LUX and 200 TW laser system at DESY in June 2016. The energy of electrons is sufficient to reach water window region with photons. The LUX beamline setup for the first photons to be finalized by December 2016 or January 2017.</td><td>First pump and probe and first user experiments will take place in 2017 at DESY. Preparations on-going with the first user group (L. Juha et al.).</td><td>Upgrade to soft X-ray Free Electron Laser in collaboration with University of Hamburg and DESY. FEL demonstration experiment preparation in progress.</td></tr>
<tr><td>Enabling technology</td><td></td><td></td><td></td><td>Required laser system with pointing stability RMS on OAP < 200 nrad (nanorad)
Required laser system peak power: 200 – 400 TW
Required three (or more) cryogenic undulators</td></tr>
<tr><td>Timeline</td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>Installation and commissioning</td><td>LUX components target to X-ray spectrometer</td><td>until 2016/12 to 2017/1</td></tr>
<tr><td>First photons</td><td>Depends on new laser gratings availability</td><td>2017/1 till 2017/4</td></tr>
</table></td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>Experiments - reaching nominal X-ray beam values</td><td>Complete LUX beamline</td><td>2017/1 till 2017/6</td></tr>
<tr><td>Installation and commissioning</td><td>Auxiliary beams and synchronization</td><td>2017/3 till 2017/6</td></tr>
<tr><td>Pump and probe experiments</td><td>Complete LUX beamline with auxiliary beams</td><td>2017/6 till 2017/8</td></tr>
</table></td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>User experiment preparation</td><td>X-ray optics, user chamber and detectors, sample preparation and characteristics, simulations</td><td>2017/1-2017/6</td></tr>
<tr><td>First user experiment</td><td>Complete LUX with X-ray optics and user chamber</td><td>2017/6 till 2017/9</td></tr>
</table></td>
<td><table>
<tr><th>Activity</th><th>System</th><th>Timing (duration)</th></tr>
<tr><td>FEL demonstrator experiment</td><td>LUX with upgraded electron beam optics and new undulator (property of UHH, not part of LUX contract)</td><td>estimated 2017/9 till 2018/3</td></tr>
</table></td></tr>
</table>

RP3 Particle Acceleration – ELIMAIA ion accelerator

Stage	**Pre-commissioning** (Hardware and Basic Functionalities)	**Commissioning** (Laser-target Inter. & second. source)	**Enabling** (Initial User Experiments)	**Flagship** (Advanced User Experiments)
Scope	ELIMAIA Basic functions ("Ion Accelerator" and "ELIMED" hardware and main instrumentation installed in E4): • Vacuum systems (Installation and tests) • Electrical systems (Installation and tests) • Control system - Manual + remote (installation and operation) • Targetry systems (Installation and alignment) • Diagnostic systems (Installation and alignment) • ELIMED beam transport and dosimetry line (Installation and tests)	Plasma/Ion generation on solid targets (µm-thick) with L3 in the ELIMAIA chamber • Alignment of L3 (low power mode) on target (laser team) • Alignment of ion/plasma diagnostics • Focusing of L3 (high power mode) on target • Plasma/Ion characterization; long-term ion beam stability tests	Enabling exp. – stage 1 ("Ion Accelerator"): Generation and detection of protons in the ELIMAIA target chamber using various targets. • 10-30 MeV protons • ±50% energy spread • 10^{9}-10^{10} protons/pulse (10% BW) Enabling exp. – stage 2 ("Ion Accelerator + ELIMED"): • Dose delivery to sample; long-term dose delivery stability tests	Flagship exp. – stage 1 ("Ion Accelerator + ELIMED"): • Delivery of "online" tunable dose on biological samples (in vitro and in vivo) of interest in medical research, possibly combining treatment and diagnostics (XUV) Flagship exp. – stage 2 ("Ion Accelerator"): Generation and detection of record energy protons in the ELIMAIA target chamber using advanced targets. • 60-250 MeV protons • ±5% energy spread • 10^{9}-10^{11} protons/pulse (10% BW)

Enabling technology	• Central vacuum piping; ECU chambers
	  • Central hubs-to-service channels; service channels-to technologies
	• Electrical and network cables
	  • ELIMAIA-to-racks; racks-to-control room
	• Software for remote control (control system)
	• Local alignment laser; optics and optomechanics
	  • including focusing optics in the ECU chambers
	• Target positioner and alignment system
	• Ion/plasma diagnostics
	• ELIMED beam transport and dosimetry line
	• Demineralized water
		• L3 BT systems in E4
		  • vacuum, optics, optomechanics
		• L3 laser alignment mode in E4
		• L3 laser in E4
		  • 50, 100, 200, 300 TW, 5 µrad, single shot
		• L3 diagnostic systems in E4 (near/far field, wavefront, pulse duration)
		• Ion/plasma real-time diagnostics
		  • remote controlled
			• L3 laser (~1PW, 5 µrad, 0.01-0.1 Hz)
			• Ion beam transport systems
			• Ion beam dosimetry and sample irradiation (user station)
				• L3 laser (~1PW, 2 µrad, 1-10 Hz)
				• L4 (≥PW, 5 µrad, single shot)
				• sub-µm-thick foils and cryogenic targets.

Timeline

Pre-commissioning

Activity	System	Timing (duration)
Installation and tests	Vacuum systems	3-7/2017 (4 months)
Installation and tests	Electrical systems	7-10/2017 (3 months)
Installation and operation	Manual + remote control system	7-10/2017 (3 months)
Installation and alignment	Targetry systems	10-11/2017 (1 month)
Installation and alignment	Diagnostic systems	11-12/2017 (1 month)
Installation and functional tests	ELIMED beam transport and dosimetry line	10-12/2017 (2 months)

Commissioning

Activity	System	Timing (duration)
Alignment of L3 (low power mode) on target	L3	1-2/2018 (1 month)
Alignment	ion/plasma diagnostics	2-3/2018 (1 month)
Alignment	ELIMED ion/plasma diagnostics	2-3/2018 (1 month)
Focusing of L3 (high power mode) on target (single shot)	L3	3-4/2018 (2 months)
Plasma/Ion characterization; long-term ion beam stability tests	Ion beam	4-8/2018 (4 months)

Enabling

Activity	System	Timing (duration)
Enabling exp. – stage 1		
Generation and detection of protons in the ELIMAIA target chamber using various targets	Ion Accelerator	9-12/2018 (3 months)
Enabling exp. – stage 2		
Dose delivery to sample; long-term dose delivery stability tests	Ion Accelerator + ELIMED	1-8/2019 (8 months)

Flagship

Activity	System	Timing (duration)
Flagship exp. – stage 1		
Delivery of "online" tunable dose on biological samples (in vitro and in vivo) of interest in medical research, possibly combining treatment and diagnostics (XUV)	Ion Accelerator + ELIMED	9/2018-3/2019 (6 months)
Flagship exp. – stage 2		
Generation and detection of record (60-250 MeV protons) energy protons in the ELIMAIA target chamber using advanced targets and L3/L4.	Ion Accelerator	3-9/2019 (6 months)

RP3 Particle Acceleration - HELL platform

Stage	**Pre-commissioning** (Hardware and Basic Functionalities)	**Commissioning** (Laser-target Inter. & second. source)	**Enabling** (Initial User Experiments)	**Flagship** (Advanced User Experiments)
Scope	HELL Basic functions ("Electron Accelerator" and "End-Station" hardware and main instrumentation installed in E5): • Vacuum systems (Installation and tests) • Electrical systems (Installation and tests) • Control system - Manual + remote (installation and operation) • Targetry systems (Installation and alignment) • Diagnostic systems (Installation and alignment) • EndStation (Installation and tests)	Plasma/Electron generation on gas targets with L3 in the HELL chamber • Alignment of L3 (low power mode) on target • Alignment of electron/plasma diagnostics • Focusing of L3 (high power mode) on target • Plasma/Electron characterization; long-term electron beam stability tests	Enabling exp. – stage 1 ("Electron Accelerator"): Generation and detection of electrons in the HELL main chamber using various targets in NOT guided regime. • 100 MeV-1GeV electrons • 5% energy spread • 1-100pC bunch/shot Enabling exp. – stage 2 ("Electron Accelerator + EndStation"): • Electron bunch delivery to sample; long-term dose delivery stability tests • 1-20 MeV, 100pC-10nC.	Flagship exp. – stage 1 ("Electron Accelerator + EndStation"): Generation and detection of electrons in the HELL main chamber using various targets ALSO in guided regime. • 1-5GeV • 10% energy spread, • 1-10 pC, • 250 MeV into the EndStation Flagship exp. – stage 2 ("Counter-propagation"): (*IF FUNDED*) Acceleration in guided regime and 10^{20}W/cm^2 additional laser beam for counter-propagation experiments with L3 only. • 1-5GeV • 0.5-1% energy spread • 0.1-10pC

Enabling technology	• Central vacuum piping; ECU chambers
	  • Central hubs-to-service channels; service channels-to technologies
	• Electrical and network cables
	  • HELL-to-racks; racks-to-control room
	• Software for remote control (control system)
	• Local alignment laser; optics and optomechanics
	  • including focusing optics in the ECU chambers
	• Target positioner and alignment system
	• Electron/plasma diagnostics
	• Pure gases (N, He, others)
		• L3 BT systems in E5
		  • vacuum, optics, optomechanics
		• L3 laser alignment mode in E5
		• L3 laser in E5
		  • 10-50, 100, 200, 300 TW, 5 μrad, single shot
		• L3 diagnostic systems in E5 (near/far field, wavefront, pulse duration)
		• Electron/plasma real-time diagnostics
		  • remote controlled
			• L3 laser (~1PW, 5 μrad, single-shot / 10Hz)
			• Electron beam transport systems
			• Electron beam sample irradiation (user station)
				• L3 laser (~1PW, 2 μrad, 1-10 Hz)
				• L4 (≥PW, 5 μrad, single shot)

Timeline

Pre-commissioning:

Activity	System	Timing (duration)
Installation and tests	Vacuum systems	3-7/2017 (4 months)
Installation and tests	Electrical systems	7-10/2017 (3 months)
Installation and operation	Manual + remote control system	7-10/2017 (3 months)
Installation and alignment	Targetry systems	10-11/2017 (1 month)
Installation and alignment	Diagnostic systems	11-12/2017 (1 month)
Installation and functional tests	HELL beam transport and focal optimizations	10-12/2017 (2 months)

Commissioning:

Activity	System	Timing (duration)
Alignment of L3 (low power mode) on target	L3	1-2/2018 (1 month)
Alignment	Electron/ plasma diagnostics	2-3/2018 (1 month)
Alignment	EndStation diagnostics	2-3/2018 (1 month)
Focusing of L3 (high power mode) on target (single shot/10Hz)	L3	3-4/2018 (2 months)
Plasma/Electron characterization; long-term electron beam stability tests	Electron beam	4-8/2018 (4 months)

Enabling:

Activity	System	Timing (duration)
Enabling exp. – stage 1		
Generation and detection of electrons in the HELL target chamber using various targets	Electron Accelerator	9-12/2018 (3 months)
Enabling exp. – stage 2		
Electron delivery to sample; long-term dose delivery stability tests	Electron Accelerator + EndStation	1-8/2019 (8 months)

Flagship:

Activity	System	Timing (duration)
Flagship exp. – stage 1		
Delivery of "online" tunable electron bunches on samples	Electron Accelerator + End Station	9/2018-3/2019 (6 months)
Flagship exp. – stage 2		
Generation and detection of record (multi-GeV) energy electrons with optimized energy spread and pointing stability for the use in a counter-propagation experiments with an high intensity laser pulse (L3 split). *IF FOUNDED*	Electron Accelerator + counter-propagation setup	3-9/2019 (6 months)

RP4 Applications in Molecular Bio-medical and Material science

Stage	**Pre-commissioning** (Hardware and Basic Functionalities)	**Commissioning** (Laser-target Inter. & second. source)	**Enabling** (Initial User Experiments)	**Flagship** (Advanced User Experiments)
Scope	ELIps: Installation and pump down (UHV) in E1. Either near the Astrella laser or at the HHG beamline 2. • ELIps operational, including cryostat, magnetic field head and auxiliary light source (Installation and tests) • X-ray diffraction: Installation of X-ray diffraction equipment on the PXS optical table in E1. • Diffractometer with Eiger detector operational using the conventional X-ray source included in the diffractometer (Installation and tests) • Optical spectroscopy: Installation of initial pump beam and optical spectroscopy capabilities (SRS station) in E1. • SHG and THG operational (Installation and tests) • OPAs and DFGs operational (Installation and tests) • UV to IR detection systems operational (Installation and tests) • Optomechanics operational (Installation and tests)	ELIps commissioning experiment; Instrument throughput in the NIR to UV range at 60°, and 75° angles . *In situ* characterization of all optical elements in the VUV range (around 20 eV). • Establish that all mechanical and optical elements work and are characterized in their respective operational ranges. X-ray diffraction commissioning experiment: Absolute scattering intensity calibration and sample-detector distance calibration using glassy carbon and silver behenate (or other standards). • Verify function of the X-ray diffraction systems with the pulsed PXS. • Verify the operational function of the radiation safety hutch. • Optical spectroscopy: I) Transient absorption of carotenoid-phthalocyanine dyad, Pump: 400 nm (2nd harm), Probe: Visible continuum. • Integration between pre-commissioning items • Timing/trigger with Astrella	ELIps: I) Time-resolved ellipsometry experiments in the ELIps instrument with pump and probe in the UV to NIR range. One suitable target is Ge (others are: GaAs, ZnO and GaN). II) Time-resolved VUV reflectivity on test sample (one potential candidate is monoclinic β-Ga_2O_3). • Verify timing/trigger with Astrella • Verify function of VUV spectrometer and Andor camera X-ray diffraction: Metal/Dielectric oxide superlattices, e.g. LSMO/STO superlattices and a double layer of these materials. • Verify timing/trigger with Astrella • Establish function of X-ray cryostat • Find spatio-temporal overlap at low and high temperatures • Optical spectroscopy: Femtosecond Stimulated Raman Scattering (FSRS) on photoactive proteins in a large temporal window (fs - ms) • Establish necessary sample handling at the SRS station • Establish initial distribution of pump beams to X-ray end staions	ELIps: I) VUV Time-resolved ellipsometry experiments on GaN (pump: visible, probe: VUV). II) Charge dynamics in complex oxides and heterostructures (e.g. $LaAlO_3/SrTiO_3$) • Prove unique/state-of-the-art capabilities X-ray diffraction: I) THz pump X-ray diffraction probe on e.g. Lysosyme (or other suitable protein crystal). II) Study of lattice effects of charge transfer processes in complex materials. • Prove unique/state-of-the-art capabilities Optical spectroscopy: I) FSRS on DNA or RNA samples studying early events of DNA photo-damage II) Implementation of 2D spectroscopy • Prove unique/state-of-the-art capabilities
Enabling technology	• Electrical and network systems to Astrella, ELIps, X-ray diffraction and optical spectroscopy locations (Installation and tests) • Astrella laser up and running (Installation and tests) • Local trigger from Astrella laser to ELIps, X-ray diffraction and optical spectroscopy locations (Installation and tests) • Local laser safety around Astrella and the SRS station (Installation and tests) • Central roughing/backing vacuum to ELIps location (Installation and tests) • Central DAQ at ELIps and Diffraction stations (Installation and tests) • Central cooling water to ELIps and diffraction station (Installation and tests) • Radiation safety hutch in place at diffraction station (Installation and tests)	• HHG source available, driven by Astrella (Installation and tests) • PXS source available, driven by Astrella (Installation and tests) • Initial beam transport system available with capacity to switch the Astrella beam between end stations. (Installation and tests) • Vacuum control system for beam transport, HHG, PXS and ELIps (incl. safety and interlock),	• Cryostat for material science samples (Installation and commissioning) • Initial beam distribution system for pump beams from SRS table to X-ray end stations (Installation and commissioning)	• L1 available for PXS and HHG as well as at the SRS table. • BT system with full flexibility, switching L1 between end stations and switching between L1 and Astrella. • Full implementation of pump beam capabilities (including beam transport for all generated pulses). Specifically including THz and ultrashort pulses. (Installation and tests) • High energy (HE) OPA (commissioning) • ELIps sample load lock system (commissioning) • VUV monochromator (commissioning) • Integration between local and central control and DAQ systems.

Timeline

Pre-commissioning:

Activity	System	Timing (duration)
Installation and tests	Vacuum systems	3-7/2017 (4 months)
Installation and tests	Electrical systems	3-6/2017 (3 months)
Installation and operation	Manual + remote control system	3-12/2017 (9 months)
Installations and tests	ELIps instrument	3-6.2017 (3 months)
Installations and tests	Diffractometer	5-7.2017 (2 months)
Installations and tests	Pulse conversion and optical spectroscopy instruments	3-7.2017 (4 months)

Commissioning:

Activity	System	Timing (duration)
Commissioning	ELIps	6-12.2017 (6 months)
Commissioning	X-ray diffraction station	6-12.2017 (6 months)
Installations, tests and commissioning	X-ray optics	6-12.2017 (6 months)
Commissioning	Optical spectroscopy and pump beams	6-12.2017 (6 months)

Enabling:

Activity	System	Timing (duration)
Commissioning	Beam transport of pump beams	01-04.2018 (3 months)
Commissioning	Diffraction cryostat	01-04.2018 (3 months)
Enabling experiment	ELIps	01-06.2018 (5 months)
Enabling experiment	X-ray diffraction	01-06.2018 (5 months)
Enabling experiment	Optical spectroscopy	01-06.2018 (5 months)

Flagship:

Activity	System	Timing (duration)
Commissioning	Remaining pump beam devices	04-08.2018 (4 months)
Commissioning	VUV monochromator	02-06.2018 (4 months)
Commissioning	Permanent pump beam transport	06-12.2018 (6 months)
Flagship experiments	ELIps, X-ray diffraction, optical spectroscopy	04-12.2018 (8 months)

RP5 Plasma Physics

Stage	**Pre-commissioning** (Hardware and Basic Functionalities)	**Commissioning** (Laser-target Inter. & second. source)	**Enabling** (Initial User Experiments)	**Flagship** (Advanced User Experiments)
Scope	P3 Basic functions: Plasma physics platform for high intensity, warm dense matter and laser plasma experiments. Hardware and main instrumentation installed in E4: • Vacuum systems (Installation and tests) • Electrical systems (Installation and tests) • Control system - Manual + remote (installation and operation) • Experimental Diagnostic systems - (Tests on other facilities) • SAFETY – Basic vacuum interlocks	Plasma generation on solid targets with L3/L4 in the P3 chamber • Alignment of L3/L4 (low power mode) on target (laser team) • Implementation of elementary plasma diagnostics (interferometry, pyrometry, particle diagnostics) • Focusing of L3/L4 (high power mode) on target • Secondary source characterization; protons, electrons, K-alpha • Targetry systems (Installation and alignment)	Enabling exp.: • TNSA protons for laser contrast estimation • Experiments for commissioning advanced diagnostics for e.g., gamma ray detectors, VISAR, etc. • HHG measurements for pre-pulse characterization	Flagship exp.: • Splitting L3: betatron source (x-rays, electrons) + proton heating • L4f on thin solid targets for gamma-ray generation • Multiple beam operation: Shock generation (L4n) + backlighter (L4f, L4p)

Enabling technology	• Central vacuum piping; P3 chambers
	    • Cable trays, EMP shielded racks
	• Electrical and network cables
	    • P3-to-racks; racks-to-control room
	• Software for remote control (control system)
	• on/plasma diagnostics
	• Demineralized water
		• L3/L4 BT systems in E3
		    • vacuum, optics, optomechanics
		• L3/L4 laser alignment mode in E3
		• L3/L4 laser in E3
		• L3/L4 diagnostic systems in E3 (near/far field, wavefront, pulse duration)
		• Local alignment laser; optics and optomechanics
		    • including focusing optics
		• Target positioner and alignment system
			• L3 laser (~1PW, 5 µrad, 0.01-0.1 Hz)
			• L4 laser (~10PW, single shot)
			• Probe beam (possibly L2 pump)
				• L3 laser (~1PW, 5 µrad, 1-10 Hz)
				• L4 (10 PW, 5 µrad, single shot)

Timeline

Pre-commissioning:

Activity	**System**	**Timing (duration)**
Installation and tests	Vacuum systems	4-8/2017 (4 months)
Installation and tests	Electrical systems	1-2/2017 (2 months)
Installation and operation	Manual + remote control system	9-10/2017 (2 months)

Commissioning:

Activity	**System**	**Timing (duration)**
Alignment of L3 (low power mode) on target	L3	1-2/2018 (1 month)
Focusing of L3 (high power mode) on target (single shot)	L3	3-4/2018 (2 months)
Alignment of L4 (low power mode) on target	L4	11-12/2018 (1 month)
Focusing of L4 (high power mode) on target (single shot)	L4	12/2018 (1 month)

Enabling:

Activity	**System**	**Timing (duration)**
Plasma/secondary source characterization;	P3	3-4/2018, 5-6/2019 (4 months)
TNSA	L3/L4	3-4/2019 (2 months)
Commissioning diagnostics	L3/L4	5-8/2019 (4 months)
HHG	L3/L4	9-10/2019 (2 months)

Flagship:

Activity	**System**	**Timing (duration)**
Flagship exp.		
Betatron	L3/L4	11-12/2019 (2 months)
Gamma ray flash	L4	1-2/2020 (2 months)
Multiple beam experiments	L3/L4	3-4/2020 (2 months)

www.eli-beams.eu