Extreme Light Infrastructure Preparatory Phase
(ELI-PP)

Final Report

1.11.2007 – 31.12.2010

28th February, 2011

I EXECUTIVE SUMMARY

The first laser shot in 1960 was a Copernican event that touched all parts of science and technology. In science, the laser has been extremely effective to improve our understanding of the atomic and molecular structure of matter and the associated dynamical events. However, it was quite inefficient in probing the subjacent strata formed by the nucleons and their components the quarks or to dissociate the vacuum in its elements. Nor the laser photon energy or its electric field were large enough or its pulse duration sufficiently short to conceive decisive experiments.

A few years ago, a new type of large-scale laser infrastructure specifically designed to produce the highest peak power and focused intensity was heralded by the European Community. The Extreme Light Infrastructure (ELI) will host the first exawatt (one billion times GW) class laser, where this gargantuan power will be obtained by producing kJ of energy over a pulse duration of 10 fs. Focussing this power over a micrometer size spot, will bring forth the highest intensity. By producing, first, the highest electric field, second, the shortest pulse of high energy radiations in the femto-zeptosecond (10^{-15}-10^{-21} s) regime and third, electrons and particles with ultrarelativistic energy in the GeV regime, the laser signals its entry into Nuclear Physics, High Energy Physics, Vacuum Physics and in the future Cosmology and Extradimension Physics.

In October 2009, only two years after the launch of the preparatory phase, the ELI-PP consortium made landmark decisions on the conditions of implementation of the project. The Steering Committee decided that ELI would be implemented in two phases as a distributed infrastructure. First, the Czech Republic, Hungary and Romania will commission by end 2015 facilities specialised in three of the four scientific pillars of the project identified during the preparatory phase. The “Attosecond Light Pulse Source” facility (Szeged, Hungary) will be designed to make temporal investigation at the attosecond scale of electron dynamics in atoms, molecules, plasmas and solids; the “Beamlines” facility (Dolni Brzezany, Czech Republic) will mainly focus on the production of ultra intense and ultra short sources of electrons, and ions, coherent and energetic X rays; the “Nuclear Physics” facility (Magurele, Romania) will be dedicated to laser-based photonuclear physics and will allow combined experiments with high-power lasers and a very brilliant γ beam. The aim of these facilities is to construct ultra-high-power lasers with focusable intensities and average powers far beyond the levels reached by the laser systems currently under construction (APOLLON, Vulcan, PFS). In the second phase, the location of the fourth and emblematic pillar devoted to Extreme Field Science will be decided in 2012 upon review of the performance of the technological solutions available at that time. The scientific and technological developments undertaken for the implementation of the first phase will make significant contributions to this ultimate objective of the project. This fourth facility will explore laser-matter interaction up to the non-linear QED limit and allow the investigation of vacuum structure and pair creation. The four facilities will be jointly operated in conditions offering excellent standards of access for external users for revolutionary experiments unconceivable up to now.

The successful development of ELI from a concept to a mature project on the verge of being implemented results from a particularly fruitful environment characterised by the considerable attention of European nations to optics, photonics and lasers, by very productive scientific communities in these areas, and certainly by the international coordination triggered and funded by the EC. All this contributes to strengthening Europe’s leading position in high-intensity laser research and will give new opportunities to the European photonic industry. Finally, the location of the ELI facilities in Central and Eastern European countries represents a remarkable contribution to the development of the European Research Area promoted by the European Commission. It builds on the scientific and technological potential of new EU-member countries and will lead to immense improvements of their research capacities, while supporting the European integration process and mobility of researchers.

II PROJECT CONTEXT AND THE MAIN OBJECTIVES

II.1 Project context

Today’s top specifications of high power pulsed laser systems are characterized by a peak power between one and two petawatts at very low (sub Hz) repetition rates, this being unchanged over more than one decade now. The majority of high intensity systems, however, still rests at the 100 TW level. ELI and its national predecessor projects like ILE and Vulcan-10 PW will boost the peak power of single lasers (modules) into the 10 PW or multi-10 PW regime at much higher repetition rates, constituting an evolution of more than one order of magnitude in both of these parameters. In addition, the high intensity pillar of ELI aims at another order of magnitude in peak power, into the 100 PW regime, by coherent combination of several such modules. With these parameters ELI will certainly lead the international high power laser scenario. ELI is, however, means much more than a world recorder facility. It is the chance to test a new paradigm where for the first time nuclear physics, high energy physics, vacuum physics could be done using the laser field amplitude and not high energy particles as it has been the case until now. If this challenge were to be met the 21th century would be the photon century, even for high energy physics which has usually been dominated by particles. In this sense ELI is in science a serious game changer. In this context the the interesting questions to be asked are: Why now? And why in Europe?

The answers to these questions appear to be strongly correlated. They both lie in the observation that *ELI will be the first laser research infrastructure which is the result of a co-ordinated effort of a multi-national scientific laser community*. Other communities (high energy physics, synchrotrons, astronomy etc.) have long standing traditions in the operation of international user facilities. Lasers, having evolved 50 years ago from small table-top devices, are only now at the edge of such mode of operation, and ELI is the first installation world-wide to make that step.

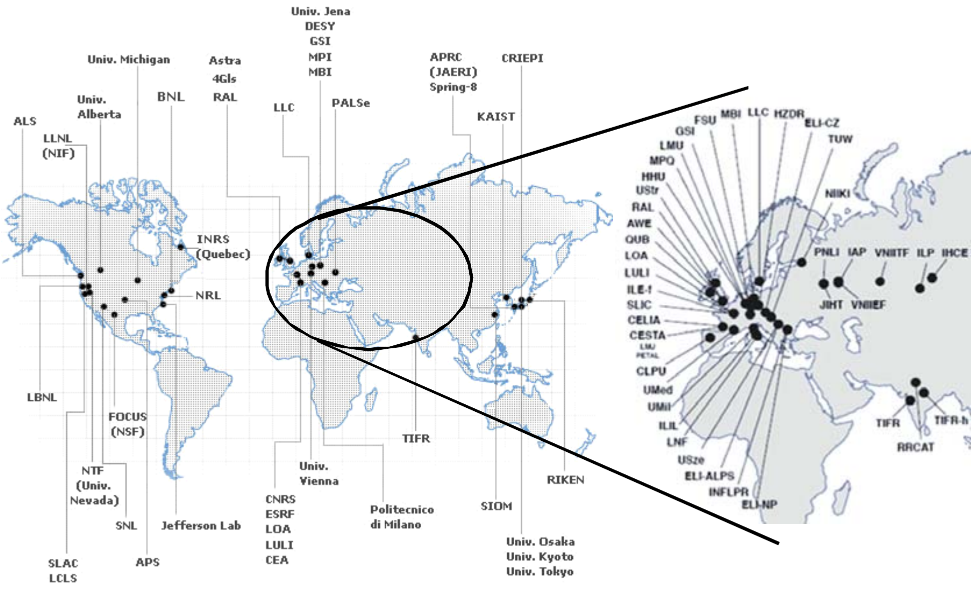

Fig. II.1: World map of high intensity systems in 2006 (left) and the current situation in Europe, Russia and India by the end of 2010 (right). Taken from the “International Committee on Ultra-High Intensity Lasers” (ICUIL, www.icuil.org).

In this context it is illustrative to view the global distribution of high-power laser systems beyond 100 TW peak power, and its temporal evolution, particularly in Europe. Figure II.1 shows the world map of high intensity systems in 2006 and the current situation in

Europe, Russia and India by the end of 2010. The left part of the figure shows that high power lasers are pre-dominantly located in three global regions at moderate northern latitudes: North America (US and Canada), Europe (including Russia), and the Asian-Pacific region (including India). This general feature has not changed since 2006 except that now (in 2010) the overall number of such systems has considerably increased (c.f. www.icuil.org). The increase, however, was most dramatic in Europe (c.f. right part of figure II.1).

Perhaps not surprisingly, the recent increase in European high-power laser systems parallels the increase in national laser laboratories within the EC-funded European network LASERLAB-EUROPE (www.laserlab-europe.net), now comprising 27 of Europe's most important laser research infrastructures from 19 EU countries. It shows (and this is part of the answer to the above questions) that the European nations and the European Commission both pay particular attention to the scientific field of lasers, optics and photonics. In fact, besides operating a multitude of national laser research infrastructures several European nations have large funding programs in optics and photonics. The EC has recently counted optics and photonics as one of the five key enabling technologies to tackle the Grand Societal Challenges of the 21st century.

Hence, Europe appears as a particularly fertile ground for laser technologies, laser development and laser applications at the national level. ELI, however, goes beyond the national capabilities of most countries. Here it helps that the European Commission has, over more than a decade now, established and funded networks of large national research infrastructures with three essential elements: 1) Joint Research Activities (including device development), 2) Trans-national Access to the benefit of a broad user community, and 3) Networking among national infrastructures. In laser science the relevant network is LASERLAB-EUROPE which, during its current funding period, concentrates its research activities among others on the development of high-power lasers (including those with high average powers), attosecond physics and applications. There is a coordinated approach to meet these challenges by investigation of new techniques as for example the development of high average power diode pumped solid state laser, parametric conversion to high peak power and coherent multiple aperture beam combination. While this research was mostly carried by the top national laboratories with their individual funding, it was the co-ordination through LASERLAB-EUROPE which added considerable value to these efforts and lifted them beyond the national level. Hence, the ground was laid for revolutionary new laser projects like ELI and HiPER when the European nations, as the final ingredient to the process leading to ELI, called for proposals for pan-European Research Infrastructures in the context of the ESFRI process.

What is ELI's future within this international context? Given the dynamic evolution of European and global national laser facilities as shown in fig. 1 it is not surprising that they continue to develop top-of-the-line laser facilities themselves. Figure II.2 shows the European state projects (already under development) towards the PW regime; similar projects exist in the other global regions. The following conclusions may be drawn from this observation:

(i) the top-of-the-line in high power lasers is slowly, but steadily shifting from the 100 TW to the 1 PW level, while singular projects (especially the ELI predecessor projects) attain similar powers as the ELI 10 PW modules. ELI's multi-100 PW facility seems to remain largely unchallenged for the next one-two decades.

(ii) Such a development, although tending to close the gap between ELI and its national companions and competitors, is much more of an opportunity than a threat. Without the availability of a large number of comparable high-power systems (even if an order of magnitude less powerful) the international user community could not be sustained which is necessary to exploit all the new physics that ELI provides.

(iii) The only threat, however, may lie in the lack of human resources needed to complete all these projects in time. This is why ELI, together with LASERLAB-EUROPE and other allies (HiPER, EOS, Photonics21) is actively working to develop the international community of laser scientists, engineers and technicians.

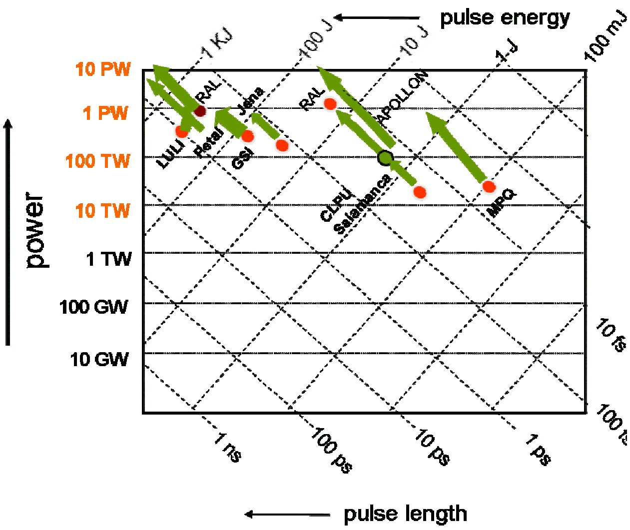

Fig. II.2: European state projects (already under development) towards the PW regime

II.2 Main objectives of the project

The Extreme Light Infrastructure is a major breakthrough compared with any other large-scale facility worldwide. Indeed, there is no such an integrated, multi-site laser facility dedicated to multi-disciplinary studies and secondary sources production and applications worldwide. Therefore the governance, financial, legal issues relating to this new type of facility is far from other operating laser infrastructures, and will eventually operate under the European law of European Research Infrastructure Consortium (ERIC). The technical aspects that have been sorted out during the ELI Preparatory Phase (ELI-PP) were also quite different since each laser chain represents a major leap forward in the development of technologies associated with Optical Parametric Chirped Pulse Amplification (OPCPA) and Ti:Sapphire amplification. In addition, the safety issues (radio-protection) is apart from other operational laser facilities owing to the high repetition rate of ELI, the novelty of the laser-based particle accelerators and the uniqueness of the combination of photons from lasers and gamma rays from a linear accelerator.

One of the most important objectives of the ELI project was to ensure that the site selection process would come to a decision during the time frame of the Preparatory Phase. Once a conclusion was found on 1 October 2009, the other objectives of the Preparatory Phase had to be adapted to the new distributed scheme of ELI. Indeed, while ELI was initially envisaged as a single-site infrastructure, the site selection process and the discussions that took place during more than a year led to landmark decisions of the Steering Committee reflecting a major evolution in the definition of the conditions of implementation of the project. ELI was decided to be a distributed facility consisting of three specialised facilities located in the Czech Republic, Hungary and Romania to be commissioned by end 2015 and complemented in a second phase by a fourth facility dedicated to the ultra-high intensity pillar of ELI, the location of which should be decided in 2012 upon a review of the performance of the various technological solutions. The location of the first three ELI facilities in new EU member States of Central and Eastern Europe represents a major contribution to the development of the European Research Area and to Europe's integration and cohesion in general. Accordingly, below we mention the already adapted objectives of the period.

Through the ***Support Actions***, which have been the **central part of this project**, we worked out the basic questions about legal (WP2), organizational (WP3), strategic (WP4A), site choice (WP4B) and financial (WP5) aspects of the Extreme Light Infrastructure. The work was divided into three main parallel parts. First, the countries that expressed their interest in hosting ELI prepared a comprehensive site implementation study including all the aspects relevant to the future operation of ELI. Meanwhile, the ELI-PP team dealt with the issues that were not site-dependent such as the type and number of personnel required for the operation of ELI, the general safety (radio-protection + laser) issues, the general building design etc. Second, after the conclusion of the site selection procedure, the legal, governance and financial studies were completed and adapted under the leadership of representatives of the designated ELI host countries. In particular, from the laser characteristics, the equipment of the experimental rooms, the personnel required for the operation of ELI, a detailed implementation budget was estimated covering both investment and start-up costs, and a first evaluation of the running costs was performed. In a third stage, the legal framework, internal organization and missions of the ELI Delivery Consortium (ELI-DC) were laid down, under the leadership of the plenipotentiaries for ELI appointed by the Czech, Hungarian and Romanian governments, to ensure the continuity of the project at the European level, while local implementation teams were gradually being developed in the three host countries. ELI-DC will be the structure ensuring a coordinated approach to the implementation activities that will be carried out in the three host countries in particular with the aim of optimizing the use of resources; ELI-DC will also have a leading responsibility in preparing and organizing the negotiations with the funding agencies interested in contributing to the establishment of the European Research Infrastructure that will be in charge of operating ELI.

Safety **and radioprotection issues** (WP6) are a priority of ELI since high intensity lasers are mixed with secondary sources of energetic particles, x-rays and even gamma rays. The choices made are having a strong impact on the building design and on its costs. In the first half term, the ELI team defined the so-called "source term", i.e. the characteristics of the source that emits the harmful radiation. In the second half of the project we have completed a set of radioprotection rules, which take into account the European regulations and recommendation as well as the national rules prevailing in the ELI-host countries.

Regarding the ***Technical*** work package, it focused on the preparation of the construction of ELI. Major parts of the research on laser (WP7A) and secondary sources (WP7B) were performed through various national projects. In the first term of the project the major objectives were the specification of the laser architecture and the purpose of the target areas. During the second term, the layout of both the primary and secondary sources have been laid down, along with the complete IR beam distribution including remote control. On the basis of the conclusions of the work carried out by WP6 (Safety), the design of the buildings were started in WP7C and reached at various levels, which provided us with a fair estimate of the total construction and operating costs of ELI.

The ***networking*** tasks of the ELI-PP served two objectives. First, it has been the glue within ELI to ensure that all the technical work done in different countries efficiently converges to the ELI machines. Different approaches towards the same technical point have been undertaken simultaneously by several groups for the sake of cross-comparison, which have been done through regular, small, targeted meetings. Networking activities have also been used to advertise ELI and its progress in Europe and worldwide, to facilitate the future recruitment of the best researchers through the promotion of the career opportunities ELI will create, and to enlarge the user community by highlighting the revolutionary research opportunities it will open.

III MAIN SCIENTIFIC AND TECHNICAL RESULTS

ELI will extend the field of laser-matter interaction, now limited to the relativistic regime (a_0~1-10, which corresponds to intensities 10^{18}W/cm^2 - 10^{20}W/cm^2), into the ultra-relativistic regime a_0 ~10^2-10^4. By means of relativistic effects, these extreme intensities will provide access to extremely short pulse durations in the attosecond or zeptosecond regime. ELI will comprise 4 branches: **Ultra-High-Field Science** centred on direct physics of the unprecedented laser field strength, **Attosecond Laser Science**, which will capitalize on new regimes of time resolution, **High-Energy Beam Facility**, responsible for development and use of ultra-short pulses of high-energy particles and radiation stemming from the ultra-relativistic interaction, and **Nuclear Physics Facility** with ultra-intense laser and brilliant gamma beams (up to 19 MeV) enabling also brilliant neutron beam generation with a largely controlled variety of energies.

By relativistic pulse compression, the femtosecond high energy pulses could be further compressed to the attosecond range and the laser power boosted accordingly. ELI will open the possibility of taking snap-shots in the attosecond or zeptosecond scale of the electron dynamics in atoms, molecules, plasmas and solids. ELI will afford new investigations in particle physics, nuclear physics, gravitational physics, nonlinear field theory, ultrahigh-pressure physics, astrophysics and cosmology. Besides its fundamental physics mission, a paramount objective of ELI will be to provide ultra-short energetic particle (10-100 GeV) and radiation (up to few MeV) beams produced from compact laser plasma accelerators.

ELI will make its scientific, engineering and medical missions for the benefit of industry and society. For instance, the secondary sources expected in the project will provide X-ray technologies to clarify the complete time history of reactions such as protein activity and protein folding, radiolysis, monitoring of chemical bonds and catalysis processes. This will lead to a better understanding and control of key events during chemical bond formation and destruction. A high impact on society and on new technologies for industry is then expected since these processes will play a major role in creating new drugs or in improving their efficiency.

The new Gamma source to be built within the ELI Nuclear Physics branch will help to produce new medical radioisotopes to determine the efficiency of chemotherapy for tumors and the optimum dose by nuclear imaging. New `matched pairs' of isotopes of the same element become available, one for diagnostics, the other for therapy, allowing to contol and optimize the transport of the isotope by the bioconjugate to the tumor. Emitters of low-energy Auger electrons for highly efficient targeted tumor therapy may be generated for clinical use. Investigations in this "medical technology direction"will open up absolutely new important perspectives for the society.

In collaboration with medical doctors, laser driven ion beam therapy will be developed with this novel source. In material science ELI will make it possible to clarify the mechanisms leading to defect creation and aging of materials in nuclear reactors. It should be emphasised that the optical, x-ray and particle beams provided by ELI-lasers will be perfectly synchronized due to their way of generation from the high power optical laser pulses.This enables pump-probe investigations in a very broad range of energies for the photon (eV-MeV) and particle beams (eV-GeV) with very high accuracy.

III.1 ELI Science

III.1.1 Electron Acceleration

ELI will be the ideal harbor for a development program of laser-plasma electron accelerators including the use of the current state-of-the-art acceleration techniques in new applications such as the generation of coherent XUV radiation in a compact free-electron-laser, electron cancer therapy or electron radiography, as well as the development of new acceleration techniques to improve this source to the level required by many present and future applications.

The concept of laser-plasma wake-field electron accelerator was proposed in 1979 by T. Tajima and J.M. Dawson [1]. In a laser-plasma accelerator (LPA), a plasma medium (e.g., fully stripped helium or hydrogen ions surrounded by free moving electrons) is used to transform electromagnetic energy from a laser pulse into kinetic energy of accelerated electrons by exciting high amplitude plasma density waves. An intense laser pulse causes the plasma electrons to move out of its path through the “photon pressure”. The much heavier ions barely move and as a consequence are left unshielded. Some distance behind the laser pulse, the electrostatic force exerted by the ions on the electrons pulls them back to the axis, creating an electron density peak. The pattern of alternating positive and negative charges is referred to as a plasma wave or laser wake and supports an electric field. The wave oscillates at the plasma frequency, which scales as the square root of the plasma density, and has a wavelength typically around 10 to 100 μm. This is several orders of magnitude shorter than the typical RF period used in conventional accelerators. The amplitude of the plasma wave or strength of the electric field is proportional to the square root of the plasma density (number of free electrons per unit volume) and proportional to the laser intensity (for intensities $\geq 10^{18}$W/cm^2). For typical densities (10^{18}– 10^{19} electrons/cm^3) used in experiments, fields ranging from 10–100 GV/m are produced, three orders of magnitude greater than with conventional technology. The wave’s phase velocity is near the speed of light and electrons injected at the proper phase can be accelerated to high energies. To reach the same particle energy, plasma accelerators can then, in principle, be three orders of magnitude shorter than their conventional counterparts. The wavelength of the plasma waves is also around three orders of magnitude smaller than the wavelength of the radiofrequency used in conventional accelerators. The generation of low energy dispersion electron bunches requires that the length of the bunch to be a small fraction of these wavelengths and/or the use of complex techniques only compatible with a large facility.

In the case of plasma accelerators this condition implies the use of electron bunches shorter than 10 fs to get an energy dispersion bellow 10% typically. So far these short pulses were produced by controlling the wavebreaking of the plasma waves or by using laser beam collision in the acceleration zone to produce a strongly localized injection.

The present state-of-the-art of laser-plasma accelerators combined with a stable laser systemand a well engineered facility allows to start an experimental program of beam time for users requiring the advantages of laser-plasma accelerators (short pulse duration, high current, synchronization with intense laser pulses or other laser secondary sources) and tolerating the present limitations (high energy dispersion, low repetition rate, reproducibility, moderate bunch charge). However, since the specifications of the ELI lasers are a major leap in the laser landscape new developments on the laser-plasma accelerator are needed to take advantage of this type of lasers. These developments include long plasma channels with adequate plasma profiles to guide the laser beam during the acceleration length overcoming the diffraction, robust techniques to inject short electron bunches into the accelerating plasma structure leading to mono-energetic and usable electron beams, multiple acceleration stages to reduce the length of the accelerator and improve the energy dispersion, robust and practical laser beam coupling to the plasma channels, radiation protection and adequate diagnostics.

The ELI laser is uniquely suited to explore electron acceleration in plasmas in that it can span all parameter regimes of interest. This includes the quasi-linear wakefield regime, typically characterized by laser intensities on the order of 10^{18}–10^{19} W/cm^2, and the highly nonlinear blowout (or bubble) regime, typically characterized by intensities greater than 10^{19} W/cm^2. The quasilinear regime has the advantage of being nearly symmetrical for acceleration of both electrons and positrons, since the wakefield is nearly sinusoidal. The highly nonlinear bubble regime has the advantage of extremely large accelerating fields, but due to the highly nonlinear structure, the wake is highly asymmetric, with a small phase region available for positron acceleration.

The ELI laser could explore electron acceleration to 100 GeV in a single stage or in multiple stages. In addition, ELI could explore a quasi-1D wakefield regime, by using large spot sizes(and large powers), which would have the advantage of greater amounts of accelerated charge. The general physics issues that could be explored with ELI include study of the quasi-linear, blowout, and quasi-1D wakefield regimes, the maximum charge that could be accelerated in the wake, beam loading (the effect of the accelerated charge on the wake structure), the quality (energy spread and emittance) of the accelerate bunch, pump depletion (loss of laser pulse energy to the wake), dephasing (the accelerated particles outrunning the wake and laser pulse), electron injection techniques, stability of the both the laser pulse and electron bunch within the plasma (hosing instabilities), and the efficiency of the acceleration process.

III.1.2 Ion sources

By directing a high power ultra-short laser pulse onto a thin target, it has been found in 2000 that beams of high-energy ions and protons could be produced. These beams have intrinsic, unique, qualities (extreme laminarity [~0.0025mm.mrad for a current ~kA], ultra-short duration [ps] and high particle number per bunch [10^{11}–10^{13}]) that distinguish them from beams produced by conventional sources (e. g. accelerators) and that have already lead to innovative applications of these beams. Moreover, these sources are extremely compact (the acceleration occurs over a distance of about tens of microns). Fast recent progress, both experimental and theoretical (studying new interaction regimes), has hinted that the extreme parameters of ELI will allow the production of ultra-high energy ions (GeV and beyond). This will open the door to future unique applications like time and space resolved radiography of dense matter, injectors study for medical applications, for ion beam physics, spallation, or transmutation. The multi-beam capability of ELI will be moreover in a position to grasp the opportunities for pomp probe experiment offered by combining the produced ion beams with the range of other ELI-based radiation sources (e. g. X-rays, electrons, high harmonics).

ELI, in its various stages, will allow exploring new, efficient, ion acceleration regimes that have been observed in numerical simulations. As a result, and as shown in Fig. III.1, several hundred MeV up to a few GeV protons could be achievable with the planned on-target intensities within reach of ELI in its final stage (i. e. on target intensities of up to 10^{25} W/cm^2). Supposing that the proton number would be similar to what obtained currently (~10^{10}) on existing facilities and considering a higher repetition rate (e. g. 10Hz), we could then obtain currents of up to a few tens of nA, comparable with a conventional accelerator. According to simulations, the predominant ion acceleration regime should be, when increasing the laser intensity, first (i) shock accelerated at the target front surface or in its interior for I> 10^{21} W.cm^{-2} [2], followed by (ii) radiation pressure acceleration (RPA), when I~ 10^{23} W.cm^{-2}. In the latter case, at such high intensities, the electromagnetic wave is directly converted into ion energy via the space-charge force related to the displacement of all electrons in a thin (nm scale) foil, allowing to reach GeV-scale energies . As mentioned above, this regime can be already explored at more moderate intensities (10^{20}–10^{21} W/cm^2). For this, TNSA is intentionally suppressed by using circularly polarized laser light in order to avoid producing hot electrons [3].

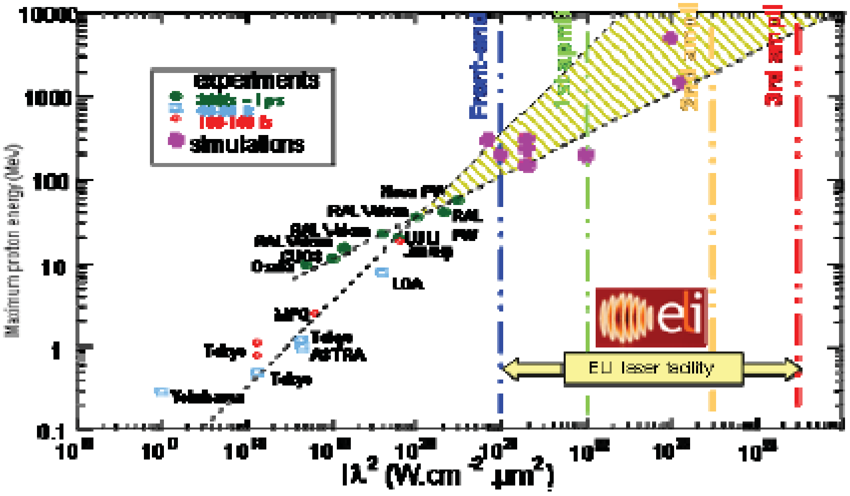

Fig. III.1 Review of cut-off maximum proton beam energy, as a function of laser intensity, as reported from published data. Experimentally measured data are small dots, boxes and crosses corresponding to three pulse duration ranges shown. Simulations performed at higher laser intensities planned for ELI are reported as big purple dots. Note that, as experimentally proven up to 10^{20} W.cm^{-2}, the maximum proton energy for the extreme short pulses is ~I, whereas for the longer pulses ~$I^{1/2}$.

Multiple stage acceleration using stacked foils [4] would offer the additional prospect of further energy increase of the ion maximum energy. However, further simulations and benchmarking experiments are necessary in order to investigate the influence of radiation losses appearing at such ultrahigh intensities. RPA would impose constraints on the facility, namely an extremely high temporal contrast for the laser pulse and circular polarization for the wave interacting with the plasma. At a similar intensity regime, other simulations have also shown that ions could be accelerated to > 10GeV in the “bubble” regime of wakefield acceleration using near-critical density plasmas and mixed ions [5]. Such underdense plasma targets would have the benefit of allowing high repetition rate operation. ELI will thus offer the prospect of producing and study a versatile ions source, at high repetition rate, while enhancing simultaneously the high-energy end of the spectrum, the beam monochromatization and the laser-to-ions conversion efficiency, all of which being crucial points for the development of applications in various areas. The possibility to vary the pulse duration of the ELI laser beam lines offer also a way to create proton/ion bunches of different durations, offering a way to adapt the emission optimal to the various envisioned applications.

ELI offers a versatile proton/ion source emitting in an unprecedented energy range but moreover it is worth noting that the facility with its unique variability in the parameter range given by the optional different laser beam parameters would not exclusively be interesting for basic science studies. The proton/ion “beam lines” with the concomitant environment (diagnostics, radiation protection etc) would also allow to accomplish more technically relevant applications, which are already in the focus of present day activities. ELI will be a demonstrator of these possibilities and prepare integrated designs of specific lasers facilities for many applications ranging from medical to industrial ones.

III.1.3 Neutron sources

Neutron beamlines at ELI will enable a broad range of both fundamental and applied science. Thermal neutron sources (meV–eV) are widely used for diffraction and spectroscopy experiments, (see e. g. Ref. [6]) and fast neutrons (MeV) can be applied to radiography, medicine and material damage studies [7]. Laser generated sources of neutrons hold the advantages of a small source size and pulse duration and synchronicity with other secondary sources at ELI. Imaging using combined sources can yield information about the composition of materials as well as their density [8]. The intense source of γ-radiation planned at ELI-NP also opens up the possibility of a revolutionary thermal neutron source generated through neutron halo isomers. This scheme avoids the need for moderation of the neutron energy and is predicted to generate neutron fluxes orders of magnitude higher than at existing spallation sources [9].

At ELI-NP the source produced using neutron halo isomers will provide unprecedented fluxes of polarized thermal neutrons. There is a wealth of scientific applications for these beams as evidenced by the extensive programs pursued by researchers at current facilities (e. g. Ref. [6]). These areas include studies of soft condensed matter, including polymer structure, surface adsorption and intermolecular interaction. Neutron sources are also used in solid state chemistry, to probe material structure and magnetic ordering within solids and also in Earth Sciences and Engineering.

The availability at ELI-Beamlines of a short pulse (<nanosecond) laser-driven fast neutron source inherently synchronized to other high quality radiation and particle beams will be ideal for pump-probe type experiments. Spectral and spatial control will offer access to regions of warm dense matter, high energy density plasmas and shocked materials not achievable by other means. There are also applications for fast neutron beams which address some key societal issues in security, medicine and energy [7].

Soft errors occur in electronic equipment as a result of bombardment from neutrons produced as a secondary effect of cosmic rays impinging on the atmosphere. The neutron flux increases with altitude so is of particular concern for aircraft. Intense neutron sources are used to perform *single event effect* tests to determine the response of electrical equipment to the neutron flux.The fast neutron spectrum obtained from a white beam spallation source is very similar to that encountered in the atmosphere [10].

Neutrons are a very useful tool for radiography, since they are complementary to x-ray sources because neutrons are attenuated by low-*Z* materials, whereas x-rays are attenuated by high-*Z*. Using either source independently gives a map of the density of the sample, but combining γ and neutron beams provides an image of the *composition* of the sample as well as its density. The ratio of the attenuation factor of the two gives a ratio which can be attributed to a certain material and shown in false colour [8].

With realistic plans in place for a demonstration nuclear fusion reactor within the next 20 years, it is imperative to study the effects of neutron bombardment on the materials which will be used for these devices [11]. The damage processes occur on a sub-nanosecond timescale, so to perform pump-probe experiments requires a short-pulse neutron source synchronized to a sampling secondary source. A laser-based facility would thus be ideal for this application. There must also be a concurrent program to build and test the many detectors needed to operate such reactors.

Obtaining cross-section data for neutron capture and neutron induced fission reactions is crucial for exploring options for alternative nuclear fission reactor designs and for radioactive waste management. Many of these cross-sections are poorly known at high incident neutron energy. Currently these experiments take place at the n_TOF facility at CERN which uses a 20 GeV proton beam to generate a white spectrum from 1 eV to 250 MeV [12].

Neutron sources also offer certain advantages for *cancer therapy treatments* and the technology for patient treatment is well established [13]. Some tumours can be treated with neutrons, which would be either resistant to or would reoccur with conventional therapy. The biological effectiveness of neutrons is high (they have a high rather than a low linear energy transfer) and so the required tumour dose is lower than with photons, electrons or protons.

III.1.4 Teraherz sources

There is huge potential for ELI to generate intense sources of terahertz radiation (0.1–10 THz, 30–3000 μm, 3.3–333 cm^{-1}) through laser-driven processes. Because this frequency range lies above the capabilities of traditional electronics but below the range of optical and infrared generators, bright THz sources of any kind have only become available in recent years in an attempt to cover the "terahertz gap" [14-15].

This range of frequencies has many scientific applications because it contains, for example, the rotation frequency of large molecules and the characteristic frequencies of high temperature superconductors. The THz absorption spectra of important biological molecules are sensitive to the conformation of these molecules. In the last two decades THz pulses were used in a vast number of spectral measurements. Since the penetration depth of THz radiation is relatively high for insulators, semiconductor structures, plants and biological tissues, an important application of this radiation is imaging. Many applications of THz pulses exist, since (in contradiction to the visible electromagnetic pulses) not only the temporal shape of their intensity, but the temporal shape of its electric field strength can be measured by (for example) electro-optic sampling [16]. Using time domain spectroscopy it is possible for example to measure simultaneously the real and the imaginary part of the dielectric constant of materials in the far-infrared range. Because of these applications it is important to explore this spectral range. However, at room temperature the maximum of the blackbody radiation is at about 4 THz. To suppress the strong background noise, intense coherent THz sources are needed.

The interest in such radiation has led to the design and construction of numerous large-scale facilities optimized specifically for high power THz operation [17–20]. Synchrotrons are the leading sources of high average power THz radiation (~ 100 W) because of the very high repetition rate (~GHz) whereas the highest peak powers (~ 100 MW) have been obtained using linear accelerators [21] and free electron lasers [19]. High THz pulse energies up to 100 μJ have been produced using coherent transition radiation from a linear accelerator [21]. High demand and high cost limits the available access to such large machines and laser based sources offer an attractive alternative.

Although generation of THz pulses by photoconductive switches with useful spectral content in the 1–20 THz range has also been reported [22], no data are available concerning the THz pulse energy, which is expected to be small because of the small area between the electrodes of the used switch. Recently, ultrashort THz pulses up to 5 μJ energy have been generated from two-color-pumped plasma sources driven by femtosecond lasers. Another table-top method is optical rectification of femtosecond pulses. By using the tilted-pulse-front pumping technique in LiNbO3 ultrashort THz pulses with energies in the 10 μJ range (up to 50 μJ) have been demonstrated [23-24].

In high power laser interaction research, emission in the THz region is less well characterized than is short wavelength radiation (x-rays and γ-rays). Unlike other secondary sources there is also a lack of a strong theoretical and numerical basis for the expected scaling of THz parameters using the next generation of intense lasers. There are various options for producing intense THz sources using petawatt class lasers. These consist of harvesting radiation from relativistic electron beams, driving solid surface plasma process and direct conversion of the laser light through optical rectification. We discuss the scalability of the THz emission and re confident that ELI has the capability for highest energy THz pulses so far available.

III.1.5 Ultrafast-laser driven X-ray sources

One of the main goals within the ELI scientific community is to produce ultrashort X-ray beamlines, both coherent as well as non-coherent, paving the way towards imaging nature with atomic resolution both in space and time – with university-lab sized devices. In fact, the discovery of X-rays by W.C. Roentgen in 1895 [25] has been one of the most important driving forces to push forward understanding and knowledge in many kinds of scientific areas. Applications range from structure analysis in solid-state, atomic physics and molecular chemistry via imaging applications in medicine and the life sciences to the discovery of the basic building blocks of life, in particular the DNA, and more generally the structure of proteins and other macromolecules. Having access to the spatial resolution of molecular structure and electron orbitals is only one side of the coin to be explored by X-rays. It took about one century to flip the coin to the other side showing the temporal resolution of the atomic and molecular motion, making it possible to monitor the dynamics of molecules and electrons on their natural time scale, which is now in the attosecond range. The early X-ray generation devices and techniques such as X-ray tubes, electrical discharges or the first synchrotron sources have not been able to deliver X-ray pulsesthat had durations of less than several nanoseconds and thus could not be used to gather both types of information, spatial and temporal, simultaneously.

An insight into the temporal dynamics of quantum systems was first gained by using probes of much larger wavelength than the one of X-rays: namely infrared (IR), visible (VIS) and ultraviolet (UV) laser pulses. Today, the fundamental limit of ultrashort laser pulses is one single optical cycle, lasting about 1 fsin the UV to several femtoseconds in the IR spectral region [26-27]. Having at hand the possibility of monitoring molecular and electronic motion, unfortunately it is not possible to use these lasers to directly image molecular structure at atomic resolution due to the large wavelength of the laser photons. The principal solution to this problem is to transform the coherent long-wavelength laser pulses into coherent/incoherent X-ray pulses via several techniques to be explored within ELI. These laser-based sources have, in contrast to large-scale facilities suchas third-generation synchrotrons or X-ray Free-Electron-Lasers (XFELs), the great perspective of having only university-lab size and can, thus, offer a much broader accessibility as only few large-scale facilities exist world-wide. Another added value besides reduction in size and costs is the intrinsic synchronization between the (optical) driver laser and the generated X-ray pulses as well as the spectrum of different X-ray sources each delivering another specific feature – from single attosecond spikes to coherent X-ray bursts with peak brilliances competitive with large-scale XFELs. For transforming optical driver laser pulses into brilliant bursts of X-rays four paths will be developed within this ELI research area: X-ray plasma lasers, laser-driven XFELs, Thomson backscattering, betatron radiation, and, to some extent, Kα sources. The pre-requisite for this research branch is ELI's pursuit of high-energy/high-peak power lasers with high repetition rate and high average power. X-ray lasers can be realized through the production of very short lived, high temperature laser plasma. Such X-ray bursts may be used to study ultrafast structural dynamics in solids and complex molecules like proteins. In fact, intense attosecond X-ray pulses will enable study of them movement of electrons in an atom or molecule as it undergoes a quantum or chemical transition. In particular, coherent X-rays present a very important secondary source perfectly suitable for the nano-scale metrology due to its very short wavelength combined with coherence. X-ray interferometry with X-ray lasers can be an excellent method to measure the surface properties with nm-scale resolution, thanks to the fact that X-ray lasers are extremely monochromatic sources. Possible applications thus include X-ray holography, coherent imaging or measurementof fine structures on any solid surface. It may be also used for inspection of defects in lithography masks having thus great impact on the industry.

Recent advances in laser wakefield accelerators have allowed the production of electron beamswith energies ranging from tens of MeV to more than 1GeV within a centimeter scale, and with an intrinsic pulse duration of few femtoseconds only. The enormous progress in improving the beam quality and stability makes them serious candidates for driving the next generation of compact light sources. The versatile laser-based radiation sources range from infrared to X-ray energies. They attract a large user community, because they are ultra-short, brilliant sources tunable up to keV photon energies with an intrinsic synchronization to the IR driver laser, making them useful for time-resolved structural analysis of matter with atomic resolution. The development of FELs has led to an enormous increase of brilliance and coherence. However, accelerator technology currently limits the pulse duration of synchrotron sources just under a picosecond and demands large and expensive facilities due to the accelerating field gradients of conventional accelerators, which are restricted to 20–100MV/m by radiofrequency-cavity electrical breakdown. In contrast, a plasma, which is already fully broken down, can sustain electric fields that are 3–4 orders of magnitude higher, exceeding 100GV/m. Thomson backscattering of laser pulses from relativistic electron bunches is an alternative technique of producing high-energy incoherent X-ray pulses, with relatively broad spectral bandwidth and low efficiencies, using current Ti:sapphire lasers. A source of broad-bandwidth X-ray radiation is also the betatron-like wiggler radiation from electrons undergoing transverse motion in the accelerating potential of the wakefield. Both sources will be able to deliver the highest X-ray energies, even MeV photons.

III.1.6 Attophysics

High photon energy, high brilliance radiation sources, such as synchrotron installations, have been proven instrumental in structural studies encompassing several disciplines including physics, chemistry, material sciences, biology and medicine. Recent pioneering developments in intense, coherent XUV/x-ray radiation sources, with ultra-short pulse duration are for the first time close to offering the possibility of complete four dimensional (4D) studies in light matter interactions, at the unprecedented A3 spatial and sub-fs temporal resolution. These sources may be classified in i) free electron laser (XFEL) based installations [28-29] and ii) laser based sources utilizing non-linear laser frequency up-conversion processes, such as higher order harmonic generation (HOHG) in gas [30-31] or on solid surface [32–36] targets. XFEL and HOHG sources are at the moment complementary sources, with the XFEL providing today substantially higher brilliances, while HOHG sources hold by far the record in ultra-short pulse durations of 80 attoseconds (1 atto = 10^{-18}) [37]. Real time studies of dynamic processes involving electronic motion in all states of matter, from atoms and molecules to macromolecules, liquids or condense matter, require temporal precision of the scale of the atomic unit of time (24.1889 asec). Indeed, since few years, progress in the field of attoscience has culminated, for the first time, the direct observation of ultra-fast processes in atoms, molecules and condensed mater on the sub-femtosecond regime [38–40].

Current and future efforts in attosecond pulse engineering are focusing on the progress in laser technology. Systems emitting pulses of few 100 of mJ and sub-10 fs durations are operational (e.g. the LWS 10 beam line at MPQ). The under construction PFS system at MPQ and the forefront laser system at ELI are challenging the few cycle pulse PW range (5 fs, 1-5

J). Utilizing such systems at intensities exceeding 10^{20} W/cm^2, intense attosecond pulses are predicted to reach the water window and beyond, while in the XUV region focused intensities of 10^{23} W/cm^2 may become achievable. Developments in the generation process are following two directions: I) Use of gas targets and highly loose focusing geometries (sub-20 m focal lengths) and II) Use of solid targets and ultra-high contrast laser beams. Such an evolution is subject to profound developments in short wavelength optics and filters mentioned in the previous section. Table III.1 summarizes some specifications of current and future, including ELI, attosecond radiation sources.

Source	$\eta\omega$	τ	E (@ the source)	$I_{\max}$ (@ the target)
Gas HOHG single pulse	20–100 eV	$\sim$ 100 asec	$\leq$ 1 nJ	$<10^{11}$W/cm^2
Gas HOHG pulse trains	10–100 eV	$\geq$ 300 asec $\geq$ 10 fs envelope	$\leq$ 1 μJ	$<10^{14}$ W/cm^2
Surface HOHG (current)	10 s of eV –few keV	$\sim$ 900 asec $\sim$40 fs envelope	$\leq$ 1 μJ	$<10^{12}$ W/cm^2
Surface HOHG (future, i.e., ELI)	10 s of eV – few keV	100–5 asec	$\leq$ 100 mJ**	$<10^{23}$ W/cm^2 **

** Predictions based on PIC simulations.

Table III.1 Specifications of current and future laser-based attosecond radiation sources.

Since the source is dedicated to users, its specifications have to be user oriented. Thus a central parameter in defining specifications is the requirements set by users. The spectrum of users of such a source is very broad and the adjacent requirements rather diverse. On the other hand resources are limited and thus encompassing tendencies have to be avoided and optimal compromises have to be made. The source parameters to be defined are the pulse duration, energy, central wavelength and spatio-tempotral coherence as well as the average power that directly relates to the repetition rate of the source and the beam divergence. Depending on the specific application the required specifications are diverse and often in partial conflict. An assessment of the user requirements in conjunction with the available technologies and the infrastructure scale has led to the specifications listed in Table III.2.

Source target	1. Solid density plasma 2. Gas jet
Photon energy	10 eV–5 KeV
Pulse duration	300–10 asec
Photon flux	10^{16}- 10^{12} Photons/pulse
Repetition rate	1 kHz
M^2	1.5

Table III.2 Attosecond source specifications.

ELI's light sources will provide a unique variety of ultrashort, brilliant X-ray beams, which are all complementary to each other, at one single site – hence providing users the possibility of addressing complex studies with different and well-synchronized probes. The X-ray lasers are coherent X-ray sources with high photon flux at moderate energies. XFELs are the most brilliant X-ray sources in the range of several keV photons and even sub-femtosecond time resolution. Thomson backscattering will yield the highest photon energies, even up into the MeV range. Among all sources, betatron radiation is the most compact one, it is incoherent, however, its flux can already be used for medical imaging. The above aspects can specifically impact the following R&D areas with certain commercial potential: material science, medical imaging, attosecond time resolved studies, ultrafast radiation biology, single molecule imaging and high-resolution atomic physics.

The advanced X-ray and attosecond sources at ELI will be unique and complementary to existing large-scale facilities, as it combines many different sources with their specific parameters at one single site. In this sense ELI will advance the development of fifth-generation light sources with a broad and substantial impact on various fields of technology and research.

III.1.7 ELI Nuclear Physics

For ELI-NP the extreme light is realized in a twofold way: by very high optical laser intensities of high power laser and by the very short wavelength beams with very high brilliance. This combination allows for three types of experiments: stand-alone high power laser experiments, stand-alone γ beam experiments and combined experiments of both facilities. Here the low repetition rate (1/min) of the high power laser requires the same low repetition rate for the γ beam in combined experiments. While the stand-alone γ beam will be used with typically 120 kHz the low repetition mode requires few very intense γ pulses.

With the high power laser we do not plan to interact with nuclear dynamics directly, but we use the laser for ion acceleration or to produce relativistic electron mirrors by laser acceleration followed by a coherent reflection of a second laser beam in order to generate very brilliant X-ray or γ beams. We plan to use these beams later to produce exotic nuclei or to perform new γ spectroscopy experiments in the energy or time domain.

The production of heavy elements in the Universe, a central question of astrophysics, will be studied within ELI-NP in several experiments. While we want to address the s-process and p-process with the γ beam, we also plan to study the r-process at the N = 126 waiting point (Fig. III. 2) by producing these neutron-rich nuclei via fission-fusion reactions with the high power laser. This close interaction between nuclear physics and astropyhisics will be very productive.

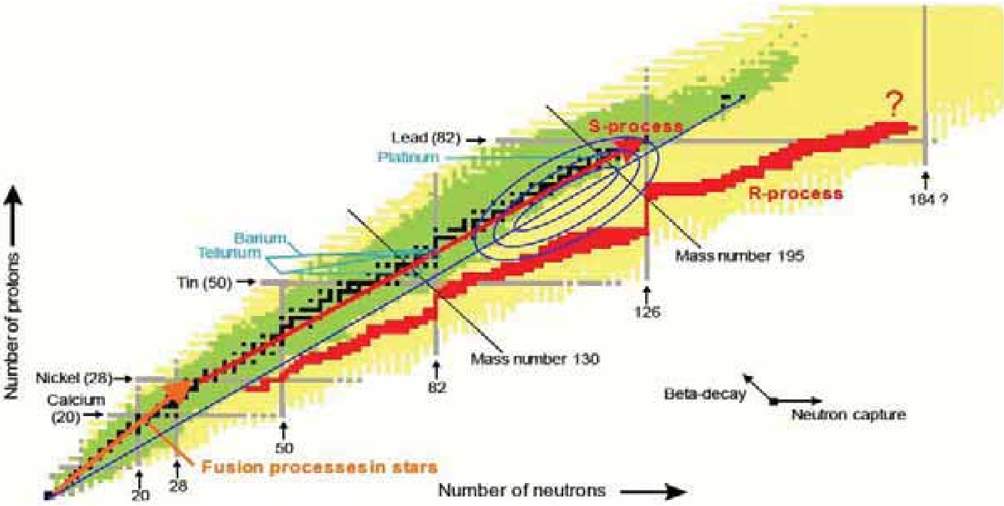

Fig. III.2: Nuclidic chart, showing the different nucleosynthesis processes like the R-process, the S-Process or the fusion processes in stars together with conture lines of the new fission-fusion process for producing very neutron-rich nuclei close to N = 126 waiting point of the R-process.

III.1.8 Physics of dense plasmas

The “Extreme Light Infrastructure” (ELI) will open a possibility to study previously inaccessible states of matter and interaction regimes of laser, X-ray and charged particle beams with various targets. The basic advantages of the ELI will be the unprecedented focused laser intensity and the synergy of laser and secondary sources. Additionally, repetition rate will be superior to the present high-power installations, as the ELI is proposed as a high repetition facility. On the other hand, relatively low laser energy due to a very short pulse may present a limitation for some types of experiments.

In the initial phase, the ELI will be built to the second stage which assumes 50 J laser pulses of the duration going down to 15 fs. The focused intensity may reach as high as 10^{23} W/cm2 in an ideal case, while a focused intensity of a few times 10^{22} W/cm^2 seems to be realistic. At least 2 beamlines should run at the 10 Hz repetition rate. Later, when the third, high intensity stage is completed, ELI will achieve 3–5 kJ and over 200 PW. The focused intensity will reach 10^{24} W/cm^2 opening the era of new exotic physics experiments. ELI will be a unique user facility and the experimental studies of plasma and interaction physics and of high energy density physics will be proposed and guided by user teams. Consequently, the research topics proposed here cannot be complete by any means, and they are not intended for setting any limitations on the future research. They can only serve as guidelines setting an insight that is required for the design conceptions of the interaction and diagnostic complex. The infrastructure ELI must provide very flexible environment that will enable very broad range of experimental set-ups. Though studies of dense plasma physics on the ELI will be oriented mainly to gaining the knowledge of the interaction and properties of the studied systems, the results will find applications in various fields of science. First, the development of the secondary sources (X-ray and charged particle beams) of ELI will benefit from the research of laser-target interactions. There is still a vast space for an improvement of the existing schemes for X-ray sources and charged particle acceleration, and innovative schemes will be proposed based on the laser-plasma interaction research. Second, plasma is a suitable medium for parametric amplification and compression of laser pulses. It can sustain much higher intensities than any other medium and applications of stimulated Raman (SRS) and Brillouin (SBS) scattering are currently being explored experimentally. Third, the envisioned research will have impact on many other physics and science fields. For example, novel fusion schemes will be proposed and explored. High energy density systems will be formed with parameters near to or scalable to those important for astrophysics and thus the basic data for modeling certain astrophysical systems will be obtained. Laser-produced plasmas may be also utilized in the technology of the classical accelerators as ultraintense electric or magnetic lenses focusing intense particle beams (e.g. Large Hadron Collider) to a focal spot significantly narrower than via classical technology.

ELI will be a versatile facility for dense plasma studies. It offers an unprecedented range of laser intensities together with a variety of secondary sources that can enable a variety of interaction and diagnostics set-ups. We have mentioned here only a few important research fields, but many others will be proposed by the facility users. It is worth to note that the facility with its unique variability in the parameter range given by the optional different laser beam parameters will not be exclusively used for basic science studies, but it will also allow accomplishing more technically relevant applications, which are already in the focus of present day activities.

III.1.9 Investigation of Vacuum Structure – Towards Schwinger Fields: QED effects and Particle Physics at ELI

An overview of QED and particle physics effects relevant for the fundamental physics potential of the Extreme Light Infrastructure (ELI) project is presented. This includes processes at tree level such as nonlinear Compton scattering and Unruh radiation as well as loop effects associated with strong-field vacuum polarisation. The latter come in two classes, dispersive and absorptive, as described by the real and imaginary parts of the vacuum polarisation tensor, respectively. Dispersive effects comprise modifications of photon propagation in strong laser fields due to vacuum birefrigence and diffraction. Absorption implies the 'disappearance' of photons due to pair production. We discuss a variety of pair creation processes differing in their characteristic energies and intensities and/or the presence or absence of stimulating probes. In contrast to standard weak field vacuum polarisation effects (Lamb shift, $g\ -2$) the processes discussed here are nonperturbative: they either involve an infinite number of diagrams to be summed or do not have a perturbative expansion at all. Examples are spontaneous vacuum pair creation via the Schwinger mechanism and laser photon merging in laser-proton collision. Moreover, we give a brief overview of the particle physics potential of the ELI facility. This includes the concept of a laser-driven collider and physics beyond the Standard Model, i.e. potential discovery of new particles such as axion-like and minicharged particles.

III.1.10 Laboratory astrophysics

The development of superintense lasers with parameters in the ELI range will provide the necessary conditions for experimental physics where it will become possible to study ultrarelativistic energy of accelerated charged particles, superhigh-intensity EM wave and the relativistic plasma dynamics. A fundamental property of the plasma to create nonlinear coherent structures, such as relativistic solitons and vortices, collisionless shock waves and highenergy particle beams, and to provide the conditions for relativistic regimes of the magnetic-field line reconnection, makes the area of relativistic laser plasmas attractive for modeling of processes of key importance for relativistic astrophysics.

III.2 Applications in multidisciplinary sciences

III.2.1 Biomedical imaging with laser-driven brilliant X-ray sources

Since its discovery more than a hundred years ago X-ray radiation has become an indispensable tool in medical diagnostics. Despite its invaluable contribution to patient care, for example in imaging bone structure, X-ray diagnostics ultimately reaches its limits in the examination of soft tissue, such as tumors embedded in healthy tissue. Modern X-ray imaging methods, which explicitly utilise the wave character of X-ray light, promise a significant improvement in image quality and reduction in patient-delivered dose over conventional, absorption-based approaches. The requirements on the X-ray beam brilliance mean, however, that presently the applications of such innovative methods are restricted to large-scale synchrotron facilities.

Visible light microscopy is a standard and widely utilized tool with a broad range of applications in science, industry and everyday life. Besides standard bright-field imaging, many more contrast mechanisms have been developed, and dark-field imaging, phase-contrast, confocal and fluorescence microscopy are routine methods in today's light microscopy applications [41]. It is not surprising that this development has stimulated a similar progress in imaging applications with other forms of radiation. In electron microscopy, for example, where the initial electron microscope image was produced in the early thirties, dark-field imaging was introduced in the late thirties [42], and imaging based on phase contrast in the forties [43]. In X-ray microscopy, or more generally, X-ray imaging, the development of a similar range of contrast modalities proceeded much more slowly and is still a very active field of research. Despite the early pioneering work on X-ray interferometry by Bonse et al. in the sixties [44], the majority of phase-contrast imaging [5,6] and dark-field imaging [47–50] methods were introduced in the late nineties. The development of such advanced imaging methods is particularly difficult for hard X-rays (with energies in the multi-keV range), because of the lack of efficient X-ray optics. Most existing hard X-ray dark-field and phase-contrast imaging methods, for example, work best with a narrow energy band-width (typically between 0.01 and 1%) and a very small source size (typically between 10 an 100 μm) of the radiation [44, 47–58], and this effectively restricts their use to highly brilliant and well-collimated large-scale X-ray synchrotron sources. Medical imaging applications, on the other hand, would require a more compact and costeffective solution, which could be integrated into a clinical environment.

Following the initial exploitation of the exisiting prototype and its optimisation, further developments in the direction of MegaWatt laser resonator cavity systems and higher electron beam energy (> 100 MeV) in the storage ring could be anticipated in ELI. This would open the door to clinical diagnostics applications in the X-ray energy range of 80–150 keV and potentially even allow for advanced radiation treatment procedures, such as micro-beam radiation therapy using X-ray energies in the range of a few hundred keV.

III.2.2 Biological imaging with intense and ultra-short X-ray sources

Theory predicts that with an ultra-short and very bright coherent X-ray pulse, a single diffraction pattern may be recorded from a large macromolecule, a virus, or a cell before the sample explodes and turns into a plasma. The over-sampled diffraction pattern permits phase retrieval and hence structure determination. The interaction of an intense X-ray pulse with matter is profoundly different from that of an optical pulse. A necessary goal at ELI is to explore photonmaterial interactions in strong X-ray fields. The aim in structural biology is to step beyond conventional damage limits and develop the science and technology required to enable highresolution studies of single biological objects near the physical limits of imaging. Eligible targets include nanocrystals, cells, cell organelles, single virus particles and isolated macromolecules. The challenges engage an interdisciplinary approach, drawing upon structural sciences, biology, atomic and plasma physics, optics and mathematics. 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. The overall relevance of such a program at ELI extends beyond basic science, to technologies of essential importance to a future Europe.

III.2.3 Life Sciences

Besides surgery, radiation therapy is a key method for treating tumour patients with localized disease. Over the last years, advances in research and technology led to significant improvements in various fields of radiotherapy, resulting in higher cure rates and less side effects in normal tissue. The majority of radiation treatments for tumours in humans is currently done by ultrahard X-ray beams generated by clinical linear electron accelerators.

Within the last decade, the clinical interest in high-energy protons or heavier ions as a promising alternative has risen clearly (see for example [59-61]). Compared to the standard X-ray treatment, this particle or ion- beam therapy can deliver better dose distributions with less dose burden in normal, healthy tissue. The therapeutical use of ion beams was proposed by Wilson in 1946, and the first patients were irradiated in the 1950s and 1960s in the USA (Berkeley and Harvard), Sweden (Uppsala) and the former Soviet Union (Dubna and Moscow). Since then, more than 70 000 tumour patients have been treated with ions all over the world (85% with protons, 15% with heavier ions, mainly carbon). The number of ion beam facilities is increasing, and especially in the last few years several new hospital based ion accelerators started their operation (e. g. the Heidelberg Ion Beam Therapy Center HIT), while some more are under construction. Rather than the high energy physics laboratories, where the first patients were treated, these new therapy units are dedicated to medical applications only and provide a patient friendly environment, higher patient throughput and research facilities in the fields of oncology and medical physics. Turn-key solutions are available from several commercial vendors.

The ELI high energy electron beamline is designed for energies in the range of 10–15GeV of the accelerated particles. The planned laser driver for this application is a 15–20 fs laser with a peak-power of 1 PW. The diode pumped frequency doubled pump laser will enable repetition rates in the range of 10Hz–20 Hz depending on the required output energy or peak-power of the short pulse laser. The estimate for the necessary driver laser power to generate protons in the range of 200–250MeV shows that the laser (approximately 1PW, 10 Hz) planned for ELI electron acceleration posses the necessary parameters for laser based ion beam therapy investigations. The high intensity interaction and ion irradiation investigations will be performed with an especially devoted beam line in the same shielded area as the electron acceleration experiments. Different kinds of renewable targets will be developed and investigated for Laser Driven Ion Acceleration (LDIA) at repetition rates between 1–10Hz in the required therapy energy range. The short pulse CPA driver laser will allow changing the irradiation conditions of the targets for an efficient conversion of the laser energy in to ions with the necessary energy spectrum. It should also be mentioned that for applications in eye tumor therapy much lower proton energies in the order of 70MeV are necessary due to the reduced penetration depth (24–25mm, eye ball length) of the protons.

LDIA –technology offers a novel technical approach for ion beam therapy. By replacing the conventional particle accelerators by less spacey and expensive laser units. But the major challenge that should be addressed in the ELI project is not only to reach the required maximum energies of 200MeV for protons and 400MeV/ u for carbon. In addition the beam application system like the scanning system and the control monitors have to be adapted to the short beampulses expected by LDIA in order to achieve the required dose homogeneity and distribution.

For the realization of the medical application of ELI, several further topics should be treated, from the extension of the energy spectrum to 200 MeV for protons, production of a pencil beam having a defined diameter and direction through production of a homogenous intensity between the two cut off points till development of new concepts for high repetition rate renewable targets and debris handling.

III.2.4 Material sciences

Material sciences have come to extremes: while many static material properties are defined by the collective behaviour of electrons and atoms in a solid, on the ultrafast time scale, highly non-equilibrium conditions in condensed matter can be achieved. The primary response of materials to optical excitations is electron dynamics on the attosecond timescale. The subsequent structural response is driven and controlled by this transient, non-equilibrium electronic structure. The ultrashort and ultraintense light sources that will be available at ELI allow for unprecedented studies of primary attosecond electron dynamics as well as for the generation of controlled extremely short-lived states of matter, which will enable us to study the complex interplay between electronic and structural dynamics.

Fundamental processes on these extreme timescales start to play a role in electronics and other applications of material sciences. One is attosecond electron dynamics, where fundamental electronic effects in condensed matter occur on the attosecond timescale [62-63], including time-resolved view of many-body response in condensed matter, charge transfer dynamics and resonant photoemission and scattering experiments and dynamics of band structure build-up. The other aspect is the behaviour of materials at intense electromagnetic fields.

Insight into the fastest processes in materials will have a huge impact on the future developments in material sciences. For investigating and understanding these processes the attosecond time structure of the ELI light sources is highly desired and needed. Especially, attosecond pulses at photon energies in the keV range as will be provided by ELI are a key for future success in material sciences at the extremes.

III.2.5 Industrial Applications for the Management of Nuclear Materials

A resonant excitation of definite nuclear states of a nucleus occurs when the nucleus absorbs an electromagnetic radiation equal to the excitation energy. This excitation state instantaneously decays mainly to a lower state with re-emission of the radiation equivalent to the absorbed radiation. This process is nuclear resonance fluorescence (NRF). The energy width of resonance is determined by the lifetime of excited nuclear states, which is of the order of 10−10 second. The absorption and re-emission of electromagnetic radiation by nuclei occurs only at exact resonance with tiny energy width, typically $\Gamma \sim 10-5$ eV. This resonant interaction is a unique property of NRF, while other nuclear absorption phenomena such as photo-nuclear reactions and the giant dipole resonance involve the continuum states of nuclei and show broad absorption spectra. Nuclear resonance fluorescence provides important information about the nuclear structure, the energies of the excited states, their lifetimes (equivalent to energy widths), their angular momenta and their parities, which are relevant to the fundamental forces between the nuclear constituents.

Radioactive wastes are produced from a nuclear fuel cycle, decommission of nuclear facilities, and the use of radionuclides for research and medical purpose. At the final disposal, the radioactive wastes are segregated, according to the amount of the activity concentration of the radionuclides, into categories - geological disposal, subsurface disposal, concrete pit disposal, trench disposal. Since the disposal cost depends on the disposal category, the appropriate classification of the radioactive waste by accurate measurements of the radioactivity concentration is a key issue for the efficient management of the radioactive waste. The non-destructive assay based on the high-brightness γ-rays can be applied to the management of radioactive wastes. This method has advantages: (1) non-destructive identification of radioactive and stable nuclides is possible, (2) a quasi-monochromatic γ-ray tuned at a fluorescence energy improves signal-to-noise ratio in the energy-resolved γ-ray detection, (3) detecting many kind of nuclides is practically possible by scanning the γ-ray energy.

Generation of energy-tunable and quasi-monochromatic γ-rays via laser Compton scattering makes it possible to detect or measure radioactive nuclides in an object non-destructively, which is a key technology for nuclear industrial applications such as management of radioactive wastes, nuclear material accounting and safeguards.

III.2.6 Ultrafast molecular dynamics

The ELI XUV/x-ray light sources allow to develop novel strategies for studying chemical reaction dynamics with the potential to significantly advance molecular physics. These novel strategies benefit from two characteristics of the ELI light sources, namely the unique *attosecond time structure* and the unique *wavelength structure.*

The *attosecond time-structure* of the ELI light sources allows unprecedented access to the ultrafast electronic dynamics that constitutes the primary response of molecular systems to incident light. The coupling of this electronic response to the nuclear degrees of freedom sets the stage for studies of nuclear motion that have been pursued in the context of femtochemistry research, notably through the pioneering efforts of Ahmed Zewail [64]. Nuclear motion is always preceded by an electronic response, which not only couples to nuclear degrees of freedom, but to other electronic degrees of freedom as well. As has been recently predicted in several theoretical works, intense attosecond light sources allow to induce a purely electronic response in molecules [65-66]. This purely electronic response may lead to ultrafast electron transfer in extended systems on the attosecond or few-femtosecond timescale. Visualizing this electronic response should be one of the "holy grails" pursued at the ELI-HU facility. In addition to ultrafast intra-molecular electronic responses, ELI will allow to study inter-molecular electronic responses, such as in the ubiquitous ICD (interatomic Coulombic decay) process, that has recently been observed [67-69]. The *wavelength structure* of the ELI light source allows to develop completely novel strategies for probing nuclear motion that significantly go beyond the methods of femtochemistry. In femtochemical experiments, photo-absorption by a pump laser pulse induces nuclear motion that is typically probed by monitoring the evolution of photo-absorption spectra (either directly, or indirectly as part of a high-order non-linear optical scheme). Although proven to be powerful in smaller systems, these methods depend in an undesirable way on ones' ability to know, calculate or infer the dependence of the absorption spectrum on the instantaneous molecular structure. This implies that a time-resolved study of the molecular structure is only possible when it includes a detailed understanding of the electronic structure (including excited states) of the molecule. The ELI light sources allow to probe molecular structure without a prior knowledge of the electronic structure. With the short wavelengths offered by ELI, photoelectrons can be ejected from molecules that carry a de Broglie wavelength that is comparable to the internuclear distances that occur in the molecule, inducing diffractive structures in the photoelectron angular distributions that are reminiscent of the structures in the photoionization efficiency that are measured in EXAFS experiments [70-71].

The main advance offered by the ELI-HU facility is that both of the advances described above can be pursued as part of one and the same experiment. With weaker attosecond light sources that are based on lab-scale femtosecond lasers, on the one hand, and with Free Electron Lasers like FLASH and LCLS on the other, the two aspects described above (i.e. inducing ultrafast electron dynamics by ionization, and probing molecular dynamics using XUV/x-ray ionization) have recently been separately pursued and demonstrated in two-color XUV+IR, resp. IR+XUV experiments. In the former first hints of the coupling of electronic and nuclear degrees of freedom, and of coupling of multiple electronic degrees of freedom have been observed [72], while in the latter, first indications of the manifestation of the molecular structure in the photoelectron angular distribution have been obtained [73].

III.3 Layout and planned performance of the facilities

III.3.1 General laser layout

In order to reach the unprecedentedly high peak power for ELI, modern laser technology has to be pushed to its limits by both implementing many new concepts and optimizing tried state-of-the-art technology. In general, the desired peak powers require the creation of high-energy laser pulses with ultra-short duration. However, the direct amplification of short pulses to high energies is limited by constraints for size and damage threshold of the optical components in the laser. Moreover, owing to the nonlinear response of optical materials at high intensities, upon propagation in matter such as transparent optical components the laser pulse itself will experience spatial and temporal phase distortions, leading to a degradation of the beam quality and eventually a loss of coherence in both time and space. Therefore, safe direct amplification in a single amplifier without detrimental effects is only possible up to a maximum intensity of ~ 1 GW/cm^2 [74-75]. If a laser chain is considered aiming for producing energetic short laser pulses, then the overall effect of the amplifier gain media, transmission optics and air has to be considered. Thus, the general rule of thumb in designing laser systems is that the so called break-up integral calculated (and first measured in [76]) for the entire laser system has to be kept below 1 to avoid considerable deterioration of the focused pulses.

To overcome the nonlinear effects in a high power laser chain, an obvious solution is to increase the beam diameter and also to multiply the pulses. These routes were, however, soon blocked by technological and economical constraints. The breakthrough came with the proposal to decrease the peak pulse power in the laser chain by stretching the pulse duration prior to amplification, and temporally compress the pulses again just before the target. The idea how to stretch and compress light pulses was inspired by radar technology and adopted into optics, is dubbed chirped pulse amplification (CPA) [77] and has been the key for the realization of a dramatic increase in laser power and focused intensity over the last 25 years.

The basis of realization lays in the fact that short laser pulses consist not of a monochromatic wave, but a broad range of colors. This provides a handle for stretching a short laser pulse into a long one (and vice versa) by sending the different colors in the pulse over different optical paths, hence dramatically lowering its peak power during amplification.. It is schematically shown in Fig. III.3. A low-energy ultra-short pulse is first stretched in time, then amplified and finally temporally compressed in an all-reflective setup to allow for an ultra-short, high-energy pulse.

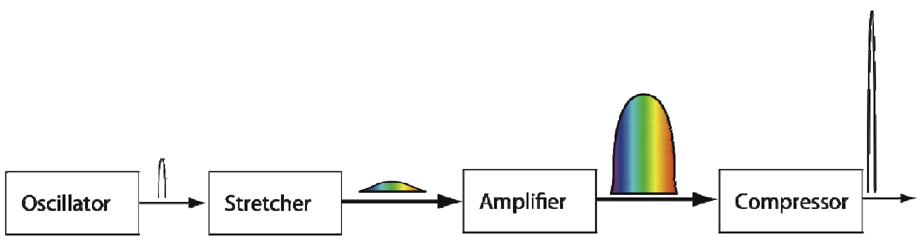

Fig.III.3: Principle of Chirped Pulse Amplification (CPA): An ultrashort laser pulse is temporally stretched, amplified at low peak intensity and temporally re-compressed.

High-power lasers usually consist of a chain of separate amplifiers with increasing size and energy level. In the first amplifiers, the gain factor is very large (10^6), while the overall energy level is rather low (mJ). The architecture of such low-energy, high-gain amplifiers is particularly vulnerable to photon noise, prepulses from multiple passes, and phase or gain nonlinearities. These effects may lead to the emission of substantial amounts of light nanoseconds to picoseconds before the main pulse has reached its maximum power, hence lowering the “temporal contrast”, i.e. the ratio of background light to peak power.

As solid targets become ionized above a threshold of around 10^{10} W/cm^2, in a laser system such as ELI, a high temporal contrast is of utmost importance for applications. Hence, with an envisioned peak focal intensity of 10^{24} W/cm^2, ELI calls for temporal contrast of greater than 10^{14} outside the last picosecond before the main pulse. Otherwise, solid targets would not stay solid for the main pulse, but expand into a low-density plasma, altering the interaction characteristics in an unpredictable manner. These high contrast values up to now cannot even be measured with state-of-the art devices.

Since all important contrast degradation effects occur in the first high gain amplifier stages (commonly dubbed “frontend”), it is necessary to clean the temporal shape of the pulses after these stages by filtering the pulses in the temporal domain. The so far most successful architectural solution is the double CPA (DCPA) scheme [78], where the pulses from the frontend are fully compressed and the prepulses cut away by an ultrafast optical “switch”. Instantaneous effects triggered by the laser pulse itself and displaying strong intensity dependence, such as cross-polarized wave generation (XPW) [79-80], are ideal for pulse cleaning. Afterwards, the clean, intermediate energy pulses are stretched again, amplified in low-gain, high-energy amplifiers with low distortions and finally compressed. To compensate for gain narrowing in laser materials and hence keep the eventual pulse duration from a DCPA laser the shortest, the scheme of negative and positive CPA (NPCPA) calls for opposite sign of chirping in the first and second CPA parts [81].

As a different approach to keep the bandwidth broad along the laser chain, optical parametric devices were suggested to replace some amplifiers in high power laser systems [82]. These OPCPA stages could be located either in the front end part where the gain is very high in order to reduce the gain narrowing, or in the power section where the available size of amplifier materials is the limiting parameter (KDP crystals exist in very large dimensions). In order to prevent from parametric superfluorescence in these optical parametric chirped pulse amplification (OPCPA) lasers, however, the pump sources shall be short (i.e. picosecond) pulsed lasers [83-84], which circumvents most of the contrast problems inherent of high-gain, multiple-pass laser amplifiers by providing high, ultrabroadband gain in a single pass [85].

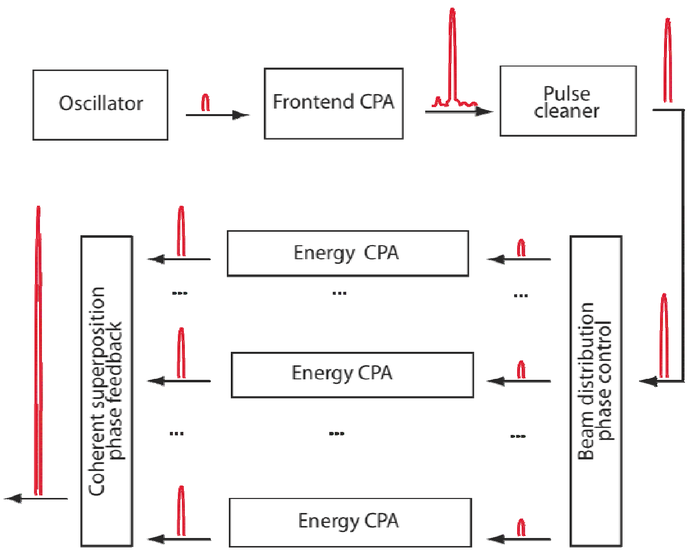

Fig.III.4: Beam multiplexing: A sophisticated real-time phase control loop has to stabilize the coherent superposition of up to ten 20 PW-laser beams, all derived from a common frontend.

Ultimately, the output of a high-power laser reaches a technological limit through availability of large optics, in particular the laser crystals and pulse compression gratings.

Recent progress in manufacturing appears to predict that limit to be somewhere around 10-20 PW for a single beam laser within the temporal limits of the ELI project. This assumes that optics currently at the prototype stage can be commercialized within the next 2-3 years. However, for the ultimate goal of ELI to reach a level of 200 PW, a single beam laser will not be the most cost-effective solution. Combining multiple powerful laser beams onto a common target is not a new technology, but has become state-of-the-art for many fusion research facilities around the world since the 1970's. However, also in this field ELI will have to break new ground. In contrast to a fusion machine that aims at smoothly distributing a large amount of energy onto a target much larger than the light wavelength, ELI wants to concentrate the energy of multiple large-scale single-beam lasers onto a spot with a size on the order of one laser wavelength (Fig.III.4).

III.3.2 Attosecond Light Pulse Source

The primary mission of the ELI Attosecond Light Pulse Source (ALPS) (Fig. III.5) is to provide the international scientific community a broad range of ultrafast light sources, especially with coherent XUV and X-ray radiation, including single attosecond pulses, to enable temporal investigations of electron dynamics in atoms, molecules, plasmas and solids on femtosecond and attosecond time scales. The secondary purpose is to contribute to the scientific and technological development towards generating 200 PW pulses, being the ultimate goal of the ELI project. ELI-ALPS will be operated also as a user facility and hence serve basic and applied research in physical, chemical, material and biomedical sciences as well as industrial applications.

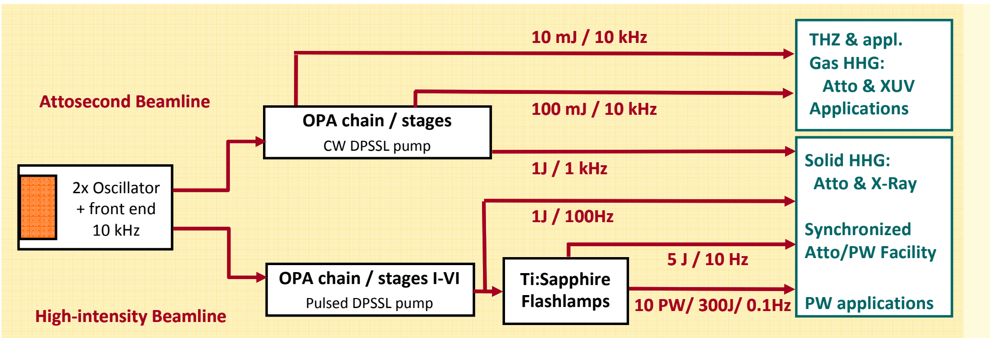

Fig. III.5: Current schematics of the laser systems of the ELI-ALPS Research Infrastructure with a list of secondary sources and applications.

To fulfil the primary mission of ELI-ALPS, PW-class driving lasers providing few-cycle, carrier-envelope phase (CEP) stabilised laser pulses are necessary to be operated at unprecedentedly high repetition rate. These pulses enable the utilization and scaling of all known methods of attosecond pulse generation. i) The well-established method of high harmonic generation in rare gases (GHHG) will be pushed to its ultimate limits by a loose focusing geometry, aiming at producing attosecond pulses with tens of μJ pulse energy. ii) It is anticipated that much more energetic and shorter attosecond pulses can be generated on solid surfaces (SHHG) reaching the X-ray domain. This method is not yet fully explored, so research will also be directed for the full exploitation of the technique. These two methods are offering complementary parameters to deliver a versatile atto-source for users. New methods of attosecond pulse generation utilizing field enhancement at nanostructured surfaces or dc-like external fields will be tested to enhance the harmonic generation process. Partly for this purpose, intense, synchronized THz pulses will be generated and their use for atto pulse generation will be implemented.

The high-intensity, multi-PW beamline will serve as a testbed for scientific and technological researches towards the 200 PW laser and also as a driver source for versatile radiation and particle secondary sources. The unique feature of these sources will be their broad spectrum in terms of available photon and particle energy.

In order to satisfy all the basic design criteria driven by applications, the scheme in Fig. 1 is proposed. A separate channel is devoted to user facility experiments, primarily based on CEP-stabilized, few-cycle laser pulses in near-IR and mid-IR domains at 10 kHz repetition rate to drive the GHHG source. The laser beamlines has identical early front ends, so that synchronisation will be ensured. The optical parametric (chirped pulse) amplifier stages are pumped with diode-pumped solid-state lasers, while the duty end of the high intensity beamline may retain flashlamp pumped Ti:S amplifiers. The workhorse of the attosecond beamline will provide 1J, CEP-stabilized few-cycle laser pulses at 1 kHz with two outputs.

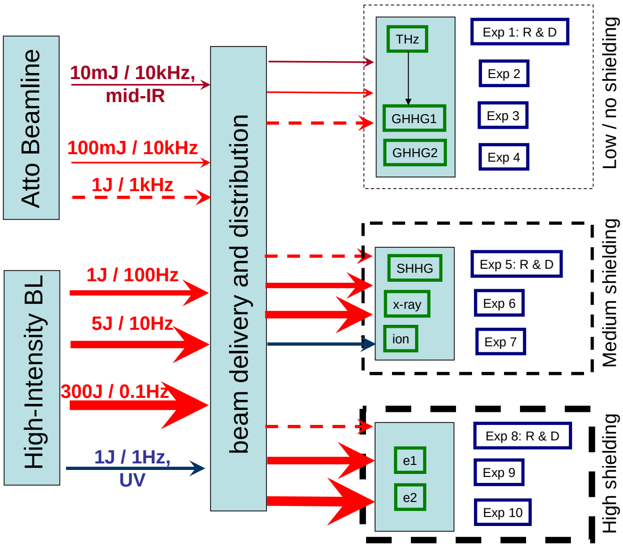

Fig. III.6: Layout of the target areas.

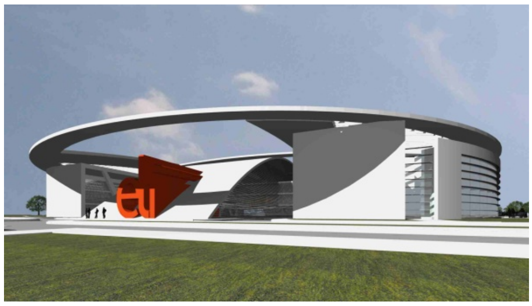

Fig. III.7. Conceptual building plan.

A target area (TA) layout corresponding to the laser system described above is shown in Figure III.6. According to the expected radiation dose and the required shielding, three groups of target areas In each group of TAs one of the experimental areas is devoted to source development supporting future updates of the secondary sources and the implementation of new technologies.

III.3.2 High Energy Beam-Line Facilitiy (Prague, Czech Republic)

The beamline facility will exploit the PFS technology in the front end up to a few 100 mJ and will use amplification techniques exploiting repetition-rate pumping (especially cryogenic multislab pump systems) to provide ultrashort petawatt-class pulses with up to 50 J of energy, at a repetition rate of up to 10 Hz. As emphasized by the ELI-PP consortium, ideally all the beamlines should run at 10 Hz repetition rate, in order to enable ELI to become, amongst other, a highly competitive source of accelerated electrons or protons for applications. The contribution of ELI-Beamlines to the development of high-intensity facility will consist in two laser blocks providing each 10 PW. The design options for laser high-intensity systems, as well as techniques of coherent combination of their pulses, will be prototyped and tested at ELI-Beamlines.

The laser of the ELI Beamline Facility (Fig. III.8) consists of a front end including the oscillator section and the three booster amplifiers, beamlines with output energy 10 J, including pulse compressors, beamlines with output energy 50 J, including pulse compressors, and high intensity 2x10 PW section, including pulse compressors.

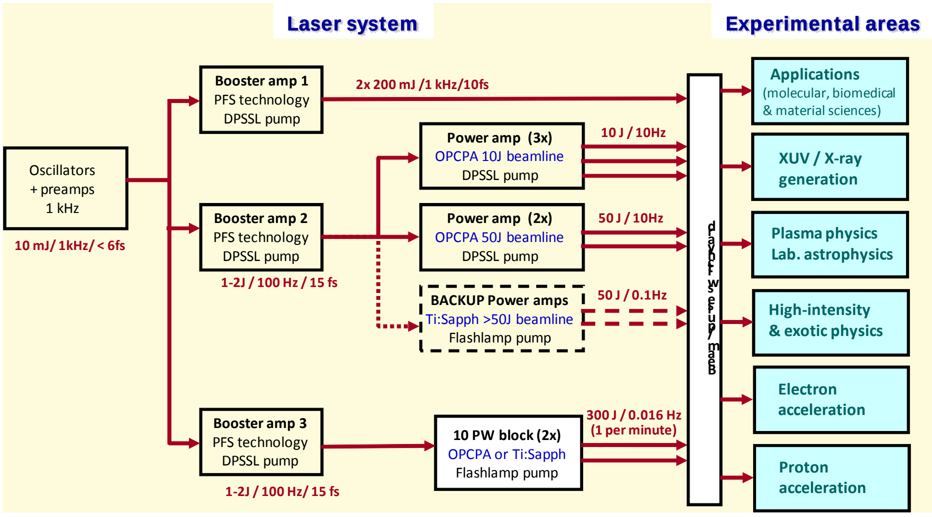

Fig. III.8: Schematic layout of laser chains of ELI-Beamlines.

Fig. III.9: Proposed layout of the internal structure of ELI-Beamlines facility.

Fig. III.10: Artist impressions of the high energy beam line facility near Prague

The facility (Fig. III.9) is designed to feature six Experimental Halls (E1 to E6). These experimental halls are supplied with laser beams generated by the laser systems L1 to L4. Laser systems L1 (oscillator and booster amplifiers), L2 (diode-pumped 10 J / 10 Hz beamlines) and L3 (diode-pumped 50 J / 10 Hz beamlines) are placed in the ground floor, whereas the 10-PW laser units spreads over the three floors (pump system on the first floor (4a), broadband amplifiers on the ground floor (4b) and optical compressors in the basement(4c)). Support technology systems located in the first floor include heat exchangers of the cryogenic circuits, capacitor banks, and power supplies for the diode-pumped repetition laser blocks L2 and L3.

III.3.4 Nuclear Physics Facility (Magurele, Romania)

The ELI-NP facility will generate laser and gamma beams with unique characteristics suited to perform frontier laser, nuclear and fundamental research. The core of the facility is a double multi-PW chain laser system. In order to perform cutting edge photo-nuclear physics experiments, a complementary high brilliance gamma beam, very performant low bandwidth, energies in the 15 MeV range, will be generated via the laser interaction with a brilliant bunched electron beam. Thus ELI-NP will allow either combined experiments using the high power laser beams and the γ beam or stand-alone experiments. The design of the facility is modular, reserving the space for further extension of the laser system and allowing the extension later of the experimental area, according to the needs.

The basic objectives of the ELI-RO Nuclear Physics (NP) pillar are (i) precise diagnosis of the laser beam interaction with matter using nuclear methods and techniques; (ii) photonuclear reactions for nuclear structure studies and for applications; (iii) exotic nuclear physics and astrophysics; and (iv) frontier fundamental physics based on high intensity laser and very brilliant γ beams.

The ELI-NP high power laser system (Fig.III.11) consists of two 10 PW-class Apollon type lasers coherently added to the high intensity of 10^{24} W/cm^2. At higher repetition rate, 100 TW and 1 PW laser pulses will be also available for experiments.

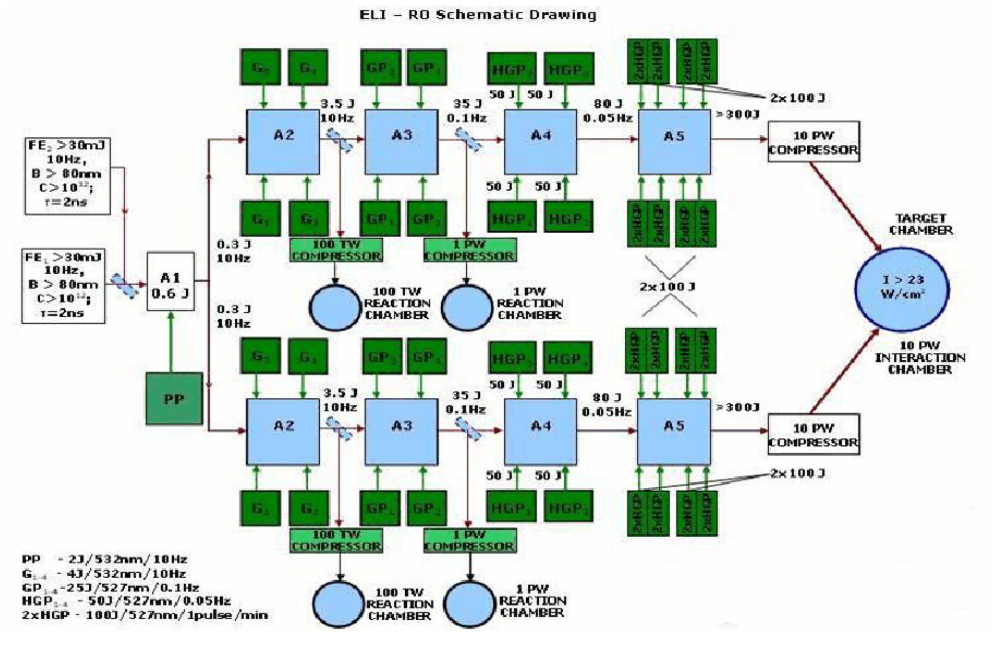

Fig. III.11 The ELI-NP multi-PW laser system conceptual design: FE1, FE2 - Font-End based on OPCPA. A1-A5 - Ti:sapphire amplifiers.

Concerning the gamma beam part, the scientific community decided that the gamma beam should be generated by a X-band ‘warm’ LINAC coupled to a 10 J/120 Hz diode pumped solid state laser system This choice ensures that ELI-NP will be the world-leading gamma beam facility at the time of its start of operation. A laser pulse recirculation system synchronized to a train of electron bunches allows to increase by a factor of 100 the effective gamma pulse rate up to 12 kHz. The characteristics of these systems are adapted to produce gamma beams with variable energy up to 19 MeV, 10^{-3} energetic width, 10^{13} photons/second total flux and a peak brilliance larger than 10^{21} photons/sec/mm^2/mrad^2/0.1%BW. After a first stage of acceleration up to 400 MeV, a similar laser-electrons interaction system is installed such that intermediary energies gamma beams are available in two additional experimental halls increasing the experiments preparation flexibility and, consequently, the total beam time is effectively used.

Coupling a high power laser with a gamma beam will confer ELI-NP facility a truly unique character in the world. Indeed, none of the many existing new projects, lasers with powers similar to those proposed for ELI-NP, will not be able to benefit from the gamma beams synergy proposed here. Technically, the temporal and spatial superposition of ultra-short laser and gamma pulses will be for the first time implemented and demonstrated at ELI-NP.

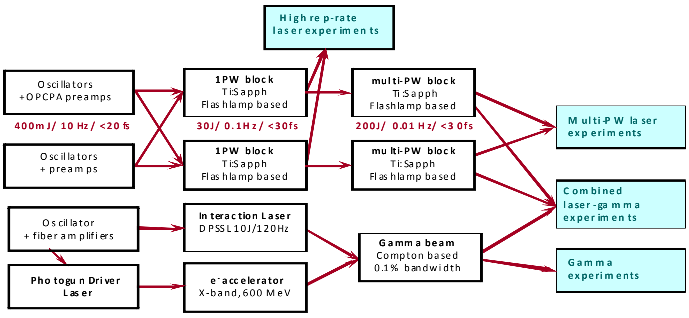

Fig. III.12: The schematic layout of ELI-NP facility.

Fig. III.13: general architectural concept of ELI-NP.

The layout of the facility is presented schematically in Fig. III.12, together with the general architectural concept. Experiments will be distributed in eight experimental halls, reconfigurable with the use of movable concrete blocks, having main primarily thematic assignment as follows: E1 - laser induced nuclear reactions; E2 - nuclear resonance fluorescence and applications; E3 - positrons source and experiments; E4 / E5 - accelerated beams induced by high repetition 100 TW/1 PW pulses; E6 - intense electron and gamma beams induced by high power laser beams; E7 - experiments with combined laser and gamma beams; E8 - nuclear reactions induced by high energy gamma beams.

References

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979)
[2] L.O. Silva et al., Phys. Rev. Lett. **92**, 015002 (2004).
[3] B. Qiao et al., Phys. Rev. Lett. **102**, 145002 (2009).
[4] S. M. Pfotenhauer et al., New J. Phys. **12**, 103009 (2010).
[5] B. Shen, Y. Li, M.Y. Yu, and J. Cary, Phys. Rev. E **76**, 055402 (2007).
[6] http://www.isis.stfc.ac.uk.
[7] J. Blomgren, Proceedings of Science (FNDA 2006) 022.
[8] J. Rynes *et al*., Nucl. Instrum. Meth. A **422**, 895 (1999).
[9] D. Habs, M. Gross, P. G. Thirolf and P. Boni, Appl. Phys. B (accepted 2010).
[10] C. Slayman, Proceedings of the SELSE6 conference, paper 16 (2010).
[11] D. Ridikas and X. Ledoux, Proceedings of Science (FNDA 2006) 021.
[12] P. F. Mastinu *et al*., J. Phys.: Conf. Ser. **41**, 352 (2006).
[13] http://www-bd.fnal.gov/ntf/index.html.
[14] G. P. Williams, Rep. Prog. Phys. **69**, 301 (2006).
[15] K. Reimann, Rep. Prog. Phys. **70**, 1597 (2007).
[16] Q. Wu and X.-C. Zhang, Appl. Phys. Lett. **71**, 1285 (1997).
[17] J. M. Byrd *et al*., ICFA Beam Dynamics Newsletter **35**, 71 (2004).
[18] F. Sannibale, A. Marcelli, and P. Innocenzi, J. Synchrotron Rad. **15**, 655 (2008).
[19] A. F. G. Van der Meer, Nucl. Instrum. Meth. Phys. Res. A **528**, 8 (2004).
[20] S. Casalbuoni *et al*., Phys. Rev. ST Accel. Beams **12**, 030705 (2009).
[21] Y. Shen *et al*., Phys. Rev. Lett. **99**, 043901 (2007).
[22] Y. C. Shen, P. C. Upadhya, E. H. Linfield, H. E. Beere, and A. G. Davies, Appl. Phys.Lett. **83**, 3117 (2003).
[23] K.-L. Yeh, M. C. Hoffmann, J. Hebling, and K. A. Nelson, Appl Phys Lett. **90**, 171121 (2007).
[24] A. Stepanov, L. Bonacina, S. V. Chekalin and J-P. Wolf, Opt. Lett. **33**, 2497 (2008).
[25] W.C. Roentgen, Nature 53, 274 (1896).
[26] B. Schenkel et al., Opt. Lett. 28, 1987 (2003).
[27] K. Yamane et al., Opt. Lett. 28, 2258 (2003).
[28] R.H. Pantell, Y. Soncini, and H. E. Putoff, IEEE Quantum Electronics **4**, 905 (1968).
[29] D.A.G. Deacon et al., Phys. Rev. Lett. **38**, 892 (1977).
[30] A. McPherson, G. Gibson, H. Jara, U. Johann, T.S. Luk, I. McIntyre, K. Boyer, and C. K. Rhodes, J. Opt. Soc. Am. B **4**, 595 (1987).
[31] M. Ferray, A. L' Huillier, F. X. Li, L. A. Lompre, G. Mainfray, and C. Manus, J. Phys. B **21**, L31 (1988).
[32] S. V. Bulanov, N.M. Naumova, and F. Pegoraro, Phys. Plasmas **1**, 745 (1994).
[33] R. Lichters, J. Meyer-ter-Vehn, and A. Pukhov, Phys. Plasmas **3**, 3425 (1996).
[34] G. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, and F. Krausz, New J. Phys. **8**, 19 (2006).
[35] F Quere, C. Thaury, P. Monot, S. Dobosz, Ph. Martin, J.-P. Geindre, and P. Audebert, Phys. Rev. Lett. **96**, 125004 (2006).
[36] A. Dromey et al., Nat. Phys. **2**, 456 (2006).
[37] E. Goulielmakis et al., Science **320**, 1614 (2008).
[38] A. L. Cavalieri et al., Nature **449**, 1029 (2007).
[39] M. Uiberacker et al., Nature **446**, 627 (2007).
[40] M. Drescher, M. Hentschel, R. Kienberger, M. Uiberacker, V. Yakovlev, A. Scrinzi, Th. Westerwalbesloh, U. Kleineberg, U. Heinzmann, and F. Krausz, Nature, **419** 803 (2002).
[41] Murphy DB. Fundamentals of Light Microscopy and Electronic Imaging (Wiley & Sons, New York, 2001).
[42] von Ardenne M., Z. tech. Phys 19:407–416 & Z Phys 1938;109:553–72.
[43] Ramberg EG., J Appl Phys 1949;20:441–4.
[44] Bonse U, Hart M., Appl Phys Lett 1965;6:155–6.
[45] Fitzgerald R., Physics Today 2000;53:23–7.
[46] Momose A., Jap J Appl Phys 2005;44:6267–355.
[47] Pagot E, Fiedler S, Cloetens P, Bravin A, Coan P, Fezzaa K, et al., Appl Phys Lett 2003;82:3421–3.
[48] Levine LE, Long GG., J Appl Cryst 2004;37:757–65.
[49] Ando M, Hashimoto E, Hashizume H, Hyodo K, Inoue H, Kunisada T, et al., Nucl Inst Meth A 2005;548:1–16.
[50] Shimao D, Sugiyama H, Kunisada T, Ando M., Appl Rad Isot 2006;64:868–74.
[51] Davis TJ, Gao D, Gureyev TE, Stevenson AW, Wilkins SW., Nature 1995;373:595–8.
[52] Ingal VN, Beliaevskaya EA., J Phys D 1995;28:2314–7.
[53] Chapman D, Thomlinson W, Johnston RE, Washburn D, Pisano E, Gmuer N, et al., Phys Med Biol 1997;42:2015–25.
[54] Beckmann F, Bonse U, Busch F, Gunnewig OJ., J Comput Assist Tomogr 1997;21:539–53.

[55] Pfeiffer F, Weitkamp T, Bunk O, David C., Nature Phys 2006;2:258–61.
[56] Pfeiffer F, Bunk O, David C, Bech M, Le Duc G, Bravin A, et al., Phys Med Biol 2007;52:6923–30.
[57] Pfeiffer F, Kottler C, Bunk O, David C., Phys Rev Lett 2007;98:108105.
[58] Pfeiffer F, Bech M, Bunk O, Kraft P, Eikenberry EF, Broennimann C, et al., Nature Mat 2008;7:134–7.
[59] Schulz-Ertner D., Jakel O., Schlegel W., 2006 Semin. Radiat. Oncol. 16(4):249–59.
[60] De Laney TF, Kooy HM, 2007 Proton and Charged Particle Radiotherapy, Lippincott Williams & Wilkins, Philadelphia.
[61] Durante M, Loeffler JS, 2010 Nat Rev Clin Oncol. 7(1):37–43.
[62] A.Cavalieri, F. Krausz, R. Ernstorfer, R. Kienberger, P. Feulner, J. Barth, D. Menzel, "Attosecond Time-Resolved Spectroscopy at Surfaces", in "Dynamics at Solid Surfaces and Interfaces, Vol.1", U. Bovensiepen, H. Petek, M. Wolf (eds.), (Wiley-VCH, 2010).
[63] A.L. Cavalieri et al., Nature **449**, 1029 (2007).
[64] A. H. Zewail, Journal of Physical Chemistry A **104**, 5660 (2000).
[65] J. Breidbach and L. S. Cederbaum, Journal of Chemical Physics **118**, 3983 (2003).
[66] F. Remacle and R. D. Levine, PNAS **103**, 6793 (2006).
[67] R. Santra, J. Zobeley, L. S. Cederbaum, et al., Physical Review Letters **85**, 4490 (2000).
[68] M. Mucke, M. Braune, S. Barth, et al., Nature Physics **6**, 78 (2010).
[69] N. Sisourat, N. V. Kryzhevoi, P. Kolorenc, et al., Nature Physics **6**, 508 (2010).
[70] A. Landers, T. Weber, I. Ali, et al., Physical Review Letters **8701** (2001).
[71] F. Krasniqi, B. Najjari, L. Struder, et al., Physical Review A **81**, 033411 (2010).
[72] G. Sansone, F. Kelkensberg, J. F. Perez-Torres, et al., Nature, 763 (2010).
[73] F. Kelkensberg, A. Rouzee, W. Siu, et al., (2010 (in preparation)).
[74] S. Backus, C. G. Durfee III, M. M. Murnane, H. C. Kapteyn, Rev.Sci.Instr. 69, 1207 (1998)
[75] Mourou, G. A., T. Tajima, and S. V. Bulanov, Rev. Mod. Phys. 78, (2006) 309.
[76] D. Villate, N.Blanchot, C.Rouyer, Opt.Lett. 32, 524 (2007)
[77] Strickland, A. D., and G. Mourou, *Opt. Commun.* 56, (1985) 212.
[78] M.P. Kalashnikov, E. Risse, H. Schönnagel, W. Sandner, Opt. Lett. **30**, 923 (2005)
[79] N. Minkovski, G. I. Petrov, S. M. Saltiel, O. Albert, J. Etchepare, J. Opt. Soc. Am. B **21,** 1659 (2004).
[80] A. Jullien, O. Albert, F. Burgy, G. Hamoniaux, J.-P. Rousseau, J.-P. Chambaret, F. Augé-Rochereau, G. Chériaux, J. Etchepare, N. Minkovski, S. M. Saltiel, Opt. Lett. **30**, 920-922 (2005).
[81] M.P. Kalashnikov, K. Osvay, I. M. Lachko, H. Schönnagel, W. Sandner, Appl. Phys. B **81**, 1059 (2005)
[82] I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, Opt. Commun. **144**, 125 (1997)
[83] G. Cerullo, S.DeSilvestri, Rev.Sci.Instr. **74**, 1 (2003)
[84] A. Dubietis, R. Butkus, A. P. Piskarskas, IEEE J. Sel. Top. Quantum Electron. **12**, 163 (2006)
[85] Z. Major, S. A. Trushin, I. Ahmad, M. Siebold, C. Wandt, S. Klingebiel, T.J. Wang, J.A. Fülöp, A. Henig, S. Kruber, R. Weingartner, A. Popp, J. Osterhoff, R. Hörlein, J.Hein, V. Pervak, A. Apolonski, F. Krausz, S. Karsch, Rev.Las.Eng. **36**, 431 (2009)

IV POTENTIAL IMPACT, DISSEMINATION AND EXPLOITATION OF THE RESULTS

IV.1 ELI and European Research Installations

The ecosystem of the EU embraces three types of research installations: European Research Infrastructures (ERI), Regional Facilities and National Facilities (which can also operate as Regional Facilities). The EU envisages actions integrating all three types and establishing close links, networking and synergy.

The initial plan called ELI to be under one roof in one location, while the final design is to build ELI as a distributed pan-European infrastructure with four pillars. After careful consideration and discussion it was found that although more expensive such solution would have a considerably stronger impact on the structure of European research infrastructures and on the development of local scientific and industrial communities than if ELI were built on a single site. Analysis of user statistics of Laserlab-Europe seems to imply that the existence of large research infrastructures within a country is indispensable for the creation of a productive national scientific community. On the educational and technology transfer ground, it is expected that it will be more effective in attracting students and creating spinoff companies. This is all the more important as optics and photonics is considered as one of the five key enabling technologies (KET) by the European Commission. The four pillars, the *Attosecond Light Pulse Source facility in Hungary,* the *Beamline facility in Czech Republic,* the *Nuclear Physics facility in Romania* and the *Ultra High Field Science (site to be decided in 2012)* will be under one unified governance and specialized according to the selected themes.

IV.1.1 ELI Delivery Consortium

On 1 October 2009, the Steering Committee of the ELI Preparatory Phase Consortium decided that ELI would be implemented as a distributed research infrastructure. It gave to the Czech Republic, Hungary and Romania the mandate to build by end 2015 three specialised facilities dedicated to three of the four “Grand Challenges” of ELI, the decision on the location and technology specifications of the fourth pillar being expected in 2012. In addition, the delegates of the 13 funding agencies represented in the Committee entrusted the hosting countries with the responsibility to negotiate the establishment of a European Research Infrastructure Consortium (ERIC) that would jointly operate the facilities and be as inclusive as possible.

In order to promote the pan-European character of ELI and ensure consistency between the three project teams during the implementation phase, the three hosting countries have established an interim organisation, the *ELI Delivery Consortium*, entitled with two essential responsibilities. On the one hand, the ELI Delivery Consortium will be in charge of defining a single delivery plan for the whole project making optimal and coordinated use of the expertise and financial and human resources available in Europe. On the other hand, the Consortium will negotiate and submit to the European Commission the application for establishing the European Research Infrastructure Consortium (ELI-ERIC) on the basis of a detailed definition of the governance and financial scheme of the future infrastructure. For that purpose, the hosting countries have invited all funding agencies represented in the ELI Preparatory Phase Consortium to join the Delivery Consortium.

On 16 April, 2010, the plenipotentiaries of Czech Republic, Hungary and Romania signed a Memorandum of Understanding forming ELI Delivery Consortium. This was the first joint legal and political commitment of the three hosts to work together on the establishment of ELI as a single-governance infrastructure. The Czech Republic, Hungary and Romania commited to work in common on the establishment of ELI-ERIC that will operate three facilities with missions in the beamline, attosecond and photonuclear applications of ELI, respectively. Regarding the construction of the ultrahigh-intensity pillar, the document confirms the intention of the three countries to participate in co-ordination with other partners in the development required for its fulfilment.

The activities of the ELI Delivery Consortium will be carried out by a team of full-time employees supported by the local implementation teams and external experts and advisory bodies. The consortium is currently established as a structure with no legal personality on the basis of a Memorandum of Understanding signed in April 2010 by the Czech, Hungarian and Romanian plenipotentiaries for ELI. To provide the ELI Delivery Consortium with more stability, visibility and financial capacity, the three founding countries intend to establish it as a legal person, most probably in the form of an international non-profit association under Belgian law. Several countries have already expressed their intention to take part in the discussions and negotiations to be organized by the ELI-DC, namely Armenia, Bulgaria, France, Germany, and Greece. Other countries such as Italy, Poland, Portugal and the UK are also likely to join.

IV.1.2 Elements on the funding scheme of the implementation phase

Unprecedentedly in the history of the European Union, the three facilities located in the Czech Republic, Hungary and Romania will be funded by structural funds. Structural funds represent the main financial instrument used by the European Union to address economic and infrastructural imbalances across the community and promote cohesion. The European Regional Development Fund (ERDF) is a key component of this policy, and makes funds available to regions that have a per capita GDP lower than 75% of the EU average. Funds are allocated on the basis of a strategic plan defined by each member state in cooperation with the European Commission and translated into specialised ‘operational programmes’.

The three ELI facilities will be funded under three different “Operational Programmes” co-funded by the European Regional Development Fund (ERDF) up to 85% and by national budgets. A specific evaluation process organised by the relevant national Managing Authority decides on the allocation of funding in each of these Operational Programmes. Given the level of funding – over € 50 million – the three facilities are considered *major projects* and have to be approved by the European Commission under the conditions set in the applicable European Regulation (Council Regulation n°1083/2006). The three Operational Programmes are neither synchronised nor interdependent.

The ERDF grants cover most of the costs related to the construction, research and development, setting-up, assembling, testing and commissioning of the three ELI facilities until December 2015. The rules conditioning the use of the European Regional Development Fund in the three host countries exclude the possibility of having a non-national entity as the applicant for funding or beneficiary of the grant. This precluded in particular having an international Consortium or even the ELI-ERIC as the applicant or direct beneficiary of the funds. In the three hosting countries, national entities – existing entities or *ad-hoc* legal vehicles – will be in charge of preparing the application for funds and of managing all activities related to the implementation of the ELI Project.

IV.1.3 Regional facilities

In the European spirit of integrating the European, Regional and National Research Facilities with establishing close links, networking and synergy, Annex 1 of the Grant Agreement of the ELI preparatory phase (ELI-PP) has foreseen and later the preparatory phase has elaborated the scheme of Regional Partner Facility (PRF) complimenting the landscape of the ELI pillars. RPFs facilitate optimal integration and exploitation of existing pan-European expertise in the ELI project. They make active involvement of institutions and scientists in ELI more attractive and sustainable, promote regional development, support and serve simultaneously European, regional and national needs and enhance synergy with existing European Research Facilities operating in other locations than the regions hosting the ELI facilities.

RPFs are auxiliary facilities of the three (four) ELI pillars, located in other countries (or regions) and providing on demand long term support and services to the ELI pillars. They are small and flexible operational units integrated in the - through them - strengthened operation of the ELI pillars. RPFs operate under the label the central ELI. Upon establishment of the planned ELI-ERIC they operate as part of it. Their mission is:

- To fill gaps and provide, on demand, transfer of knowledge, training, support and services of any kind, such as technical, technological, scientific, computational, managerial and educational, to the ELI pillars.
- To act as facilities in which methods, technologies and special instrumentation to be exploited by the ELI pillars will be designed and/or developed.
- To act as facilities for testing instrumentation and devices to be used at the ELI pillars, or for feasibility studies of experiments to be implemented at the ELI pillars.
- To act as an incubator of the ELI pillars, in which a number of technological and technical problems may be defined and/or solved.
- To possibly prepare and foster future experiments to be conducted in the main ELI.
- To act as training sites of personnel and users of the ELI pillars.

All costs related to the RPFs are considered to be covered regionally and thus they may act as National Facilities. Upon negotiation, it will be decided whether the investment of the hosting country towards the operation of the established facility as an RPF can be accounted, if requested by the hosting country, as part of the country's contribution to the ELI-ERIC. The ELI pillars may sub-contract the RPF to realize specific projects. The management of the RPFs will be on local basis in collaboration with the central ELI management. Before the establishment of the ELI-ERIC they will operate under national law. The governance of the RPFs will be part of the ELI governance scheme.

During the ELI PP three institutions have expressed their interest in hosting an RPF:

- CLPU, Salamanca: The Petawatt laser Science and Technology training RPF.
- IST, Lisbon: The High Field Computational Sciences RPF.
- FOTH-IESL, Heraklion: The Attosecond Science and Technology RPF.

ELI-PP has endorsed the development of these three RPFs and has handed over the issue to the Delivery Consortium thus becoming part of the negotiations between funding agencies and ELI towards the establishment of the ELI-ERIC. Upon establishment of the ELI-ERIC, it may invite in the future other facilities to become an RPF.

IV.1.4 National research programs and facilities

Several countries have launched national programs in a range of ten million Euros to enhance national R&D activity related to ELI. The DiPOLE program in the UK, aiming at the development of high-energy diode laser based pump lasers, has started recently. The APOLLON program in France, one of the technical predecessors of ELI, has very recently been donated an excellent site, the former linear accelerator L'Orme des Merisiers, Saclay. The HiLASE program of the Czech Republic is reaching now the public announcement stage and will concentrate on development of diode pumped solid-state lasers for application in industry and applied researches. In the frame of the national preparation program for ELI-Ro a 1 PW laser has been launched. A project is expected also in Hungary.

IV.2 Impact on science and industry

A few years ago, the Extreme Light Infrastructure, ELI, was proposed under the aegis of the ESFRI (European Strategy Forum for Research Infrastructure). It was largely inspired by a paper by T. Tajima and G. Mourou [1]. It was a new type of infrastructure designed to produce the highest peak power possible in the sub-exawatt regime or about 1000 times the NIF or the Laser Megajoule power. These gargantuan powers are obtained by packing the laser energy in extremely short pulses measured in femtoseconds or few optical periods. When focused to a spot size of about the size of the laser wavelength, i.e. few micrometers, extraordinarily large intensities will be produced, in the 10^{25} W/cm^2 range. This is the gateway of a new type of interaction that will make possible for the first time the possibility to penetrate beyond the stratum of atomic physics to explore subsequent matter strata relevant to nuclear physics, particle high energy physics, astrophysics, field traditionally studied with high energy particle accelerators. ELI may bring a completely new approach to the investigation of fundamental physics where massive and charged particle; electron, ion are replaced by the massless and chargeless photon, announcing a shift from the traditional paradigm based on momentum to one based on energy.

The laser ultra-relativistic intensity is ELI's quintessence. It underpins the following features that form its foundation. In particular it leads to:

1) the highest electromagnetic field,
2) the possibility for light to move matter, electrons and ions at relativistic velocity.
3) The generation of coherent or incoherent high energy radiation, X or γ,
4) the possibility to produce much shorter pulse than the initial one, reaching the zeptosecond-yoctosecond range.

These four unique features alone or combined offer a new set of powerful structural dynamic tools. They define the adopted ELI's four-pillar architecture.

IV.2.1 ELI, as technology booster

The ELI program is scientifically ambitious and demands the most challenging technical specifications. In particular it will require the highest peak power, in the 200PW range necessary to produce the highest single shot signal. However, we will need the highest average power or repetition rate to maximize signal-to-noise ratio. Sub-exawatt can not be reached by a single beam. Therefore, the current design calls for the development of laser pulses of 10PW peak power. This power could be produced by Ti:Sapphire (Apollon) but also by Optical Parametric Chirped Pulse Amplification (OPCPA). The pulses with an energy of 300 J and duration 30fs, must be immaculate in time with an excellent intensity contrast greater than 10^{15} for solid target experiments. The final decision between the two technologies will be done in 2012. The ultrahigh peak power pillar will require the phasing of at least 10 beams of 10 Petawatts. This challenge has never been attempted. It will require an excellent mechanical stability and optical pump stablity (1%). The 10 optical arms have to be maintained within $\lambda/20$ accuracy to provide the sought after coherent addition. Even if we can produce extremely high peak power, it is still difficult to produce large average power above the 100W. This is due in large part to the overall mediocre laser efficiency in the 1% range.

IV.2.2 Society and industry

A large effort largely based on solid state diode pumped lasers is undertaken in Czech Republic, Germany and the United Kingdom to bring the efficiency to the 10% level. The CPA (chirped pulse amplification) approach requires large Ti:sapphire crystals of around 20 cm diameter. Because of the ELI program, an American company has been already able to produce high quality crystals of this dimension and is trying to grow it to 25 cm diameter. The most important hurdle in getting ultrahigh peak power is improving the diffraction grating optical damage threshold. At the moment diffraction gratings have a damage threshold at least 10 times less than other system components. A higher damage threshold would reduce the surface grating area and will reduce overall system cost and size. The ELI program is working on new grating designs that will lead to a large improvement in grating damage size and cost.

ELI will make its scientific, engineering and medical missions for the benefit of industry and society. For instance, the secondary sources expected in the project will provide X-ray technologies to clarify the complete time history of reactions such as protein activity and protein folding, radiolysis, monitoring of chemical bonds and catalysis processes. This will lead to a better understanding and control of key events during chemical bond formation and destruction. A high impact on society and on new technologies for industry is then expected since these processes will play a major role in creating new drugs or in improving their efficiency.

The new Gamma source to be built within the ELI Nuclear Physics branch will help to produce new medical radioisotopes to determine the efficiency of chemotherapy for tumors and the optimum dose by nuclear imaging. New `matched pairs' of isotopes of the same element become available, one for diagnostics, the other for therapy, allowing to contol and optimize the transport of the isotope by the bioconjugate to the tumor. Emitters of low-energy Auger electrons for highly efficient targeted tumor therapy may be generated for clinical use. Investigations in this “medical technology direction“will open up absolutely new important perspectives for the society.

In collaboration with medical doctors, laser driven ion beam therapy will be developed with this novel source. In material science ELI will make it possible to clarify the mechanisms leading to defect creation and aging of materials in nuclear reactors. It should be emphasised that the optical, x-ray and particle beams provided by ELI-lasers will be perfectly synchronized due to their way of generation from the high power optical laser pulses.This enables pump-probe investigations in a very broad range of energies for the photon (eV-MeV) and particle beams (eV-GeV) with very high accuracy.

IV.2.3 Long term vision

Already now it appears as if ELI during its preparatory phase has created “new physics” in many areas, most notably in those which did not use lasers before. Examples which are already foreseen are nonlinear QED in strong laser field, laser-particle acceleration, and new ways to produce ultra-short wave length radiation in the hard x-ray or gamma-ray regime, frequently associated with ultra-short pulse durations. Other examples will inevitably arise from experiments once ELI goes into operation.

ELI’s long-term vision is certainly to become the world’s first and the world’s best user facility to utilize the power of today’s most advanced lasers for the advancement of fundamental science and applications in many areas of societal relevance, including the Grand Challenges of the 21st century. In addition, if ELI as an exawatt machine turns out to be an effective tool to address fundamental physics, it would help us to plan experiments at much higher peak power in the zettawatt regime. This type of power could, for instance, be obtained by harnessing already built megajoule systems. From the evolution of the laser intensity over the years, there seems to be the possibility to go beyond the exawatt using already built megajoule large scale systems like the NIF and the Laser Megajoule. These machines could become available for basic science within 10 to 20 years, once the campaign to demonstrate inertial fusion is concluded. If that were the case a new life could be given to these machines, for the benefit of science, by providing Schwinger-size fields from the laser directly. In addition, from the relationship between input intensity and output pulse duration [2], extremely short duration pulse below the zeptosecond regime could be produced. This, however, may only be one of many ways to achieve the next level of laser powers, others may arise due to new and unexpected progress in laser technology as we have seen it frequently during the last decades. In any case, the next level of high power laser infrastructures beyond ELI could deliver simultaneously extremely high field with Schwinger magnitude, particles with PeV energy, and coherent bursts of gamma radiation with zeptosecond pulse duration tying the three distinct disciplines of science, i.e. ultrafast science, high field science, and large-energy laser science together with a single stroke.

IV.2.4 Integrating scienctific communities

During the short life time of the Preparatory Phase we could already observe that ELI did not grow only by involving and increasing the optics community, but rather by integrating other communities associated with new physics disciplines like Plasma-, Nuclear-, and High-Energy physics, General Relativity and the like. This was particularly tangible upon the creation of the Nuclear Physics Pillar in Romania.

IV.3 Impact on geopolitical science

Immediately after its inclusion into the ESFRI Roadmap, ELI aroused scientist's and technologist's interest as a laser that would deliver the most powerful burst of energy with the capability to federate a number of scientific and technological disciplines, combined with a tantalizing societal application offering, in material science and medicine. The numerous meetings among the 13 countries partners held during the Preparatory Phase have led to the inception of ELI and contributed to shape and unify the European science and technology landscape. The ELI Preparatory Phase of three years, culminated by the astonishing choice of three countries (the Czech Republic, Hungary, and Romania) that did not had no experience of collaboration as the hosts of the first three pillars. Now they have been given the considerable challenge of establishing, in the central-eastern part of Europe not only the first ESFRI infrastructure, but also the first and largest civilian laser infrastructure.

The implementation of ELI helps strengthening the leading European position in high-intensity laser research and will give new additional opportunities to the European photonic industry. The location of the ELI facilities in central and Eastern Europe utilizes the scientific and technological potentials of the involved new EU-member countries, accelerates the European integration process and will lead to immense improvements of their research infrastructures. ELI will provide new educational and training perspectives for the younger generation of students and scientists in the field of lasers, laser-matter interaction and photonics.

However, the ELI's construction activity will not take place only in these three countries alone. It will spill over all the partner countries expected to bring considerable contribution by lending expertise, workforce and equipment. ELI by its science but also by its pan-European character is becoming a recognized model and a beacon for the rest of the world. Today, because of ELI, the ultra relativistic interaction and Exawatt systems are on the agenda of most scientifically inclined countries, especially the USA, Russia, China, Japan, India.. The fact that Europe is leading this development may be the result of a long-standing tradition in networking among national laser laboratories within the EC-funded network LASERLAB-EUROPE. It has prepared the laser community to segue from university-size systems to large-scale infrastructure so new scientific challenges can be addressed. ELI, the world's first truly international laser research infrastructure, appears as the natural culmination of this development. ELI will also be the first large-scale infrastructure that will propel the laser beyond the atomic physics frontier which has been hitherto, the laser privileged domain to penetrate into the deeper strata of nuclear physics and vacuum physics. This will be ELI's primary goal. Having with ELI such a control of space, time, amplitude and polarization, nuclear reaction, nonlinear QED interaction could be produced and studied with minute accuracy as it is the case today in photochemistry or solid state physics. ELI will make possible to scout a field that could only be explored until now using pertubative theory.

IV.4 Exploitation of the results

During the project, altogether ***449 papers*** (Fig. IV.1) have been published in peer reviewed international journals and ***12 patents*** (Fig. IV.2) have been submitted (all of them pending). The number of publications in the second half of the project showed an almost 40% increase compared to the first period, while the patent activity is basically at the same level. The large majority of the scientific and technical results behind the publications and patents have been supported by national funding agencies.

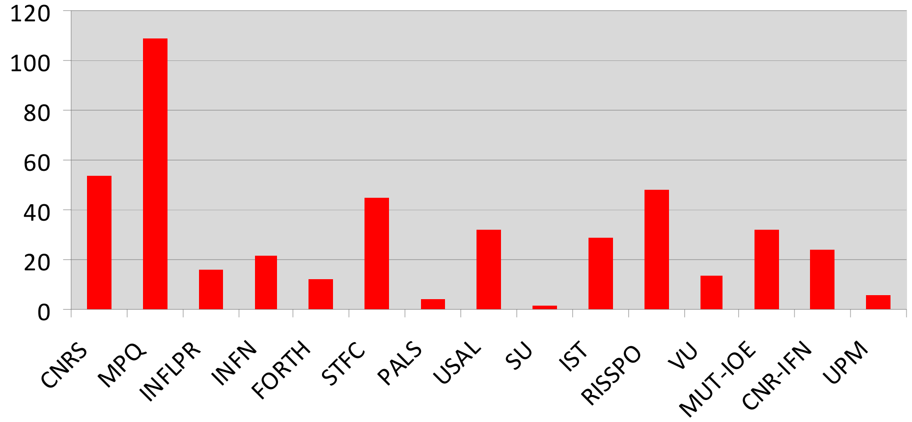

Fig. IV.1: Number of papers in peer-reviewed journals by Beneficiary during the project.

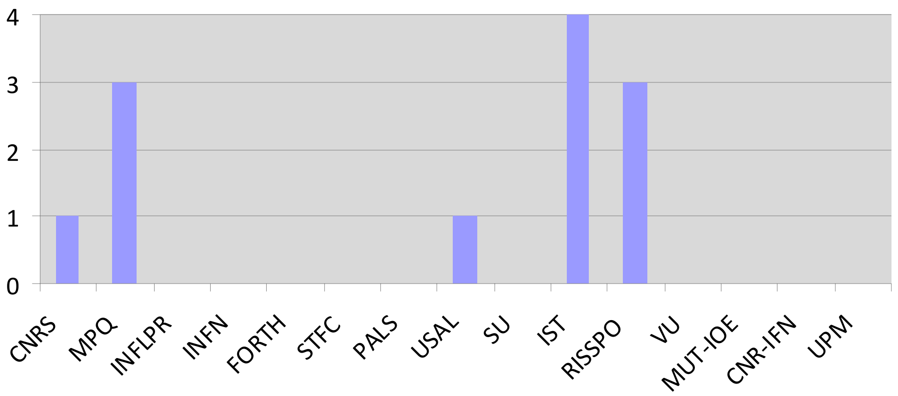

Fig. IV.2: Number of patents by Beneficiary during the project.

From the graphs we can conclude, that the beneficiaries' publication activity more or less corresponds to their EC funding. Among the beneficiaries with modest budget, the contributions of IST (Portugal), MUT-IoE (Poland), RISSPO (Hungary), and U.Salamanca (Spain) are at a considerably higher level than expected from their EC support. In the case of the lead beneficiary CNRS, however, one has to take into account that the cost of the overall management of the project is included in its EC funds.

IV.5 Dissemination of the results

IV.5.1 Web-sites of the project

www.eli-laser.eu
The first version of the project website was created already when the ELI-PP proposal was submitted. Since then it has been considerably enlarged and improved. Now it provides information on the aim of ELI-PP, on its organization including management and provides basic description on the laser as well as the five major scientific pillars addressed. The news section provides the ELI community as well as the interested colleagues and civilians with most recent information on achievements and meetings, while the Calendar section is kept updated with all events related to ELI. The last major upgrade happened during the last months of 2009 to reflect the October 2009 decision on the implementation of ELI as a distributed infrastructure based in three new member States (Fig. IV.3).

Fig. IV.3: Snapshot of the project web page.

Upon and after the site selection process, the host countries have developed the web pages of their ELI site as

www.eli-beams.eu; www.eli-hungary.hu; www.eli-np.ro .

In order to keep the internet information continuous, ELI-DC would keep the address of the central web page as it was in the ELI-PP, that is, www.eli-laser.eu. The transfer of contents and the re-direction of the addresses would be made gradually, probably during the second half of 2011.

IV.5.2 Newsletter – ELI Courier

The *ELI Courier*, the quarterly newsletter of ELI, sent out to institutions, media, policy makers and researchers of each beneficiary country, was distributed to about 30 countries woldwide altogether to more than 1100 addresses. The newsletter had a big success all around

Europe and the world. Thanks to this dissemination effort, a strong awareness of ELI within different target audiences has been achieved.

It is worth mentioning that the ELI Delivery Consortium has already expressed its strong willingness to keep the newsletter alive. It is expected that the next issue edited and published by ELI-DC will appear during the first half of 2011.

IV.5.3 National and local communication events

The national communication events, which are aiming by definition the scientific and general public of a given country mostly in the vernacular language, have been an essential part of the ELI-PP communication. One cannot overestimate its importance, since the willingness of a national funding agency to take part in the ELI Delivery Consortium and eventually in the future ELI-ERIC depends strongly on the *present* visibility of the ELI project at the national level.

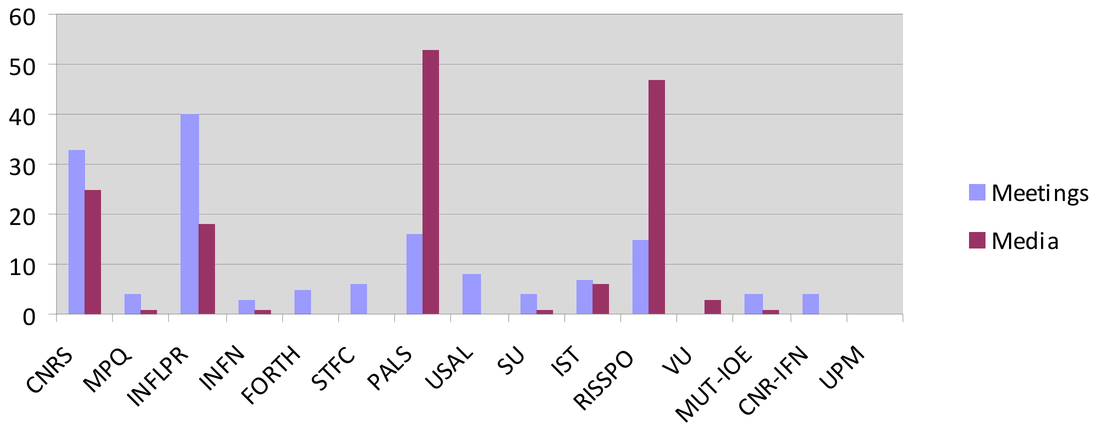

Fig. IV.4: National communication activities by Beneficiary during the project.

During the lifetime of the project, ***149 meetings*** were held and ELI appeared ***in local media*** (TV, Radio, newspaper, etc.) on ***156 occasions***. From the number of reported events per beneficiary (Fig. IV.4), one can conclude that ELI was mainly communicated in the coordinating country (CNRS - France,) and in the ELI host countries (INFLPR-Romania, IoP-PALS-Czech Republic and RISSPO-Hungary).

References

[1] T. Tajima, G. A. Mourou, *Phys. Rev. STAB* **5**, 031301 (2002).
[2] G. A. Mourou and T. Tajima, *Science* **331**, 41 (2011).