Invited Paper

Extreme Light Infrastructure Nuclear Physics (ELI-NP): present status and perspectives

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ABSTRACT

Extreme Light Infrastructure (ELI) Pan-European facility initiative represents a major step forward in quest for extreme electromagnetic fields. Extreme Light Infrastructure – Nuclear Physics (ELI-NP) is one of the three pillars of the ELI facility, that aims to use extreme electromagnetic fields for nuclear physics and quantum electrodynamics research. At ELI-NP, high power laser systems together with a very brilliant gamma beam are the main research tools. Their targeted operational parameters are described. The related experimental areas are presented, together with the main directions of the research envisioned.

Keywords: Ultra intense laser pulses, laser facility, nuclear physics, gamma source, Thomson backscattering, laser-driven particle acceleration

1. INTRODUCTION

Proposed in early 20th century by Albert Einstein, the laser was experimentally demonstrated in late 50es. Since then they become ubiquitous, from communication fibers, to material processing and from printing technologies to medical surgery. The laser provides outstanding power and control of the electromagnetic fields at the micrometer scale and below, making it the ultimate electromagnetic field source.

While in the first decade, the lasers were merely laboratory devices, with the advent of the technology, ultra-intense laser systems are now climbing the path towards research facility following a development path similar with the one from nuclear physics facilities. Availability for users of devices with unprecedented parameters and reliability are the key aspects of such facilities.

Extreme Light Infrastructure (ELI) project, funded through European Union FP7 Programme, started in 2007 with a preparatory phase that decided the places and the directory lines for the project. ELI will be a pan-European distributed facility with three research pillars: laser driven secondary radiation sources in Czech Republic, attosecond pulses and related developments in Szeged, Hungary and nuclear science in Magurele, Romania ([1],[2],[3]).

The Extreme Light Infrastructure – Nuclear Physics (ELI-NP) in Romania will be an European research center for ultra-high intensity lasers, laser matter interaction, nuclear science and material science using laser driven radiation sources. The laser intensities at ELI-NP will be in the range of 10^{23} W/cm^2. This multidisciplinary facility will provide completely new opportunities to study fundamental processes that occur in ultra-intense laser fields during light-matter interaction.

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The ELI-NP research center will be located in Magurele, a town few kilometers away from Bucharest, Romania. ELI-NP will host two 10PW class lasers and a Gamma beam system producing gamma beams with parameters beyond those available at the present state of the art machines. The facility, worth 295 million euro, will be developed in two phases and will be available for the users in 2017.

This paper presents the planned high power laser system and the gamma beam system parameters. It also gives a glimpse in the scientific program associated with the ELI-NP facility [4].

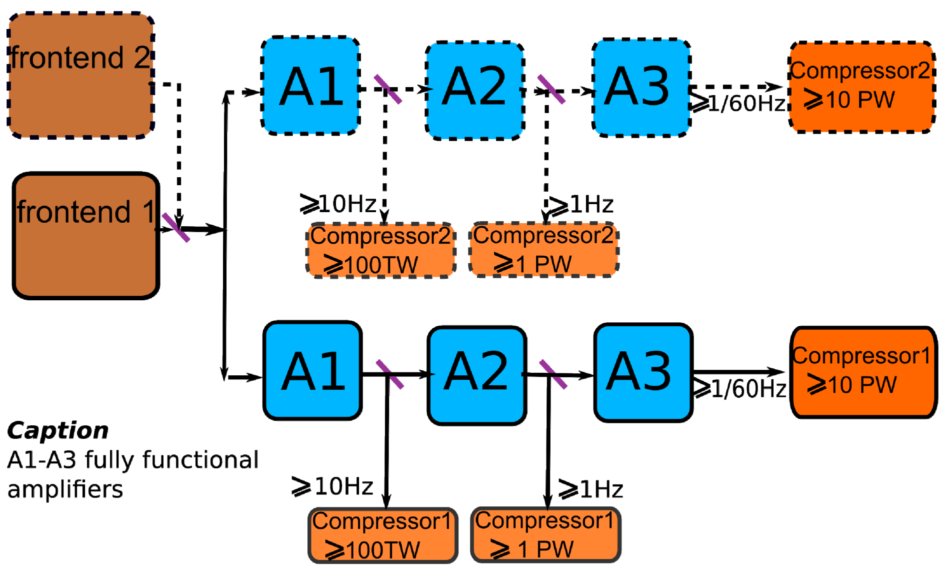
2. ELI-NP HIGH POWER LASER SYSTEM

The high power laser system (HPLS) at the core of ELI-NP facility is a dual front-end system with two parallel amplification arms, each of them with three outputs, as sketched in figure 1. Only one front end will run at a time, while the second front end represents a back-up solution that minimizes the down-time of the facility.

HPLS will serve several experimental areas in parallel, delivering pulses with different power levels, as follows: the main two of the outputs, one for each amplification arm, are specified to reach 10PW at a repetition rate of at least one shot/minute; two more outputs are extracted at the 1PW level from the amplification chains at the place where the repetition rate of the system is 1Hz; two more outputs, at 10Hz and 0.1PW are extracted at earlier amplification stages from the two arms. Each output will have its optical pulse compressor. The duration of the pulses from each of the 6 outputs of the HPLS shall be tunable from the best compression level to at least 5 ps pulse duration, with both positive and negative chirp.

The HPLS outputs will be synchronized with accuracy below 200 fs. On the long run, coherent combination of the outputs with the same output power levels is envisaged. The laser system will deliver pulses synchronously with the Gamma Beam System electron and gamma bunches. The synchronization system will be implemented at the HPLS front-end level.

Figure 1. The HPLS architecture



The key parameters that define the range of experiments that can be approached at ELI-NP, to be delivered by the HPLS system are detailed in Table 1. The pulse duration was chosen to be below 50 fs. A small focal spot is essential for experiments, in order to reach highest intensities on the target. As a consequence a Strehl ratio of at least 0.7 is specified.

Temporal contrast of the pulses is a critical parameter at the very high field intensities to be generated on targets. The specified temporal contrast at the 0.1 PW output level is specified to be in the range of 10^{11}:1, for both nanosecond temporal range and picoseconds temporal range. This value is placed at the limit of the existing temporal contrast measurement devices. For the temporal contrast at the higher intensity outputs, the extrapolated temporal contrast shall reach at least 10^{12}:1, for both nanosecond temporal range and picoseconds temporal range. The high temporal contrast is essential in order to avoid the target destruction before the arrival of the laser pulse, by the optical noise emitted in front of the pulse.

Another critical parameter is the pointing stability of the laser pulses, specified to be better than 2μrad. Such angular stability will allow the realization of experiments that involve targets with small dimensions or also realization of experiments that involve overlap of two synchronous, focused laser pulses.

The specified parameters for the high power laser source are listed in the table below.

Table 1. Specified parameters for the high power laser source:

Parameter	Range
Available outputs power and repetition rate	Two outputs with 0.1PW at 10Hz two outputs with 1PW at 1 Hz two outputs with 10PW at 1shot/min
Pulse duration	<50 fs
Strehl Ratio	>0.7
Pointing stability	<0.2 microrad
Temporal contrast in the nanosecond range	10^{11}:1 for the 0.1PW outputs 10^{12}:1 extrapolated for the 10PW outputs
Temporal contrast in the picosecond range	10^{11}:1 for the 0.1PW outputs 10^{12}:1 extrapolated for the 10PW outputs
External clock synchronization jitter	<200fs

3. ELI-NP GAMMA BEAM SYSTEM

The ELI-NP Gamma Beam System (GBS) will enable the production of a brilliant, highly collimated beam of radiation in the gamma ray domain, through the Compton backscattering of a laser beam off a beam of accelerated electrons. This will ensure the possibility to tune with very high precision the energy of the gamma radiation produced in a range that is relevant for the scientific case of ELI-NP. Electrons will be accelerated up to 700MeV by means of a warm Linac.

The minimum output specifications for the Gamma beam (see Table 2) were established in a series of workshops and meetings organized with the scientific community interested in ELI-NP and industry, in order satisfy the need of the scientists for the progress of their research but also to have realistic expectancies that are technically feasible within the time frame of project implementation. During the public purchase procedure for the acquisition of the GBS, tenderers may commit for values of these parameters above the minimum required specifications.

The GBS will open new possibilities for high resolution spectroscopy up to high nuclear excitation energies, leading to a better understanding of nuclear structure at higher excitation energies. An important research topic at ELI-NP will be nuclear astrophysics, the characteristics of the gamma beam (bandwidth, spectral density) permitting the study of reaction cross-sections relevant for the p- and r- nucleosynthesis processes.

At the lower end of the energy range, the high resolution of the beam is very important for protein structural analysis. Applied research and development will be enabled by the very high degree of collimation and the intensity of the gamma beam, allowing studies in materials science. A relevant example is the investigation of new methods to produce thermal neutrons, through photonuclear reactions (γ,n). These will be used in the study of bio-proteins, nano-composites, fullerenes, and magnetic materials, to name a few. Another example would be the creation of an intense positron source by means of the (γ,e^+e^-) reaction ([4], [5]), very useful in materials science.

One of the areas of research that will be tackled with the help of the gamma beam will be the mapping of the isotope distribution of nuclear materials or radioactive waste remotely via Nuclear Resonance Fluorescence (NRF) measurements.

The investigation of new production schemes of medical isotopes (e.g., ^{99}Mo – currently used in therapies, ^{195m}Pt – nuclear imaging to determine efficiency of chemotherapy, ^{117m}Sn – emitter of low energy Auger electrons for tumor therapy) via (γ,n) processes are also among the proposed areas of study of ELI-NP.

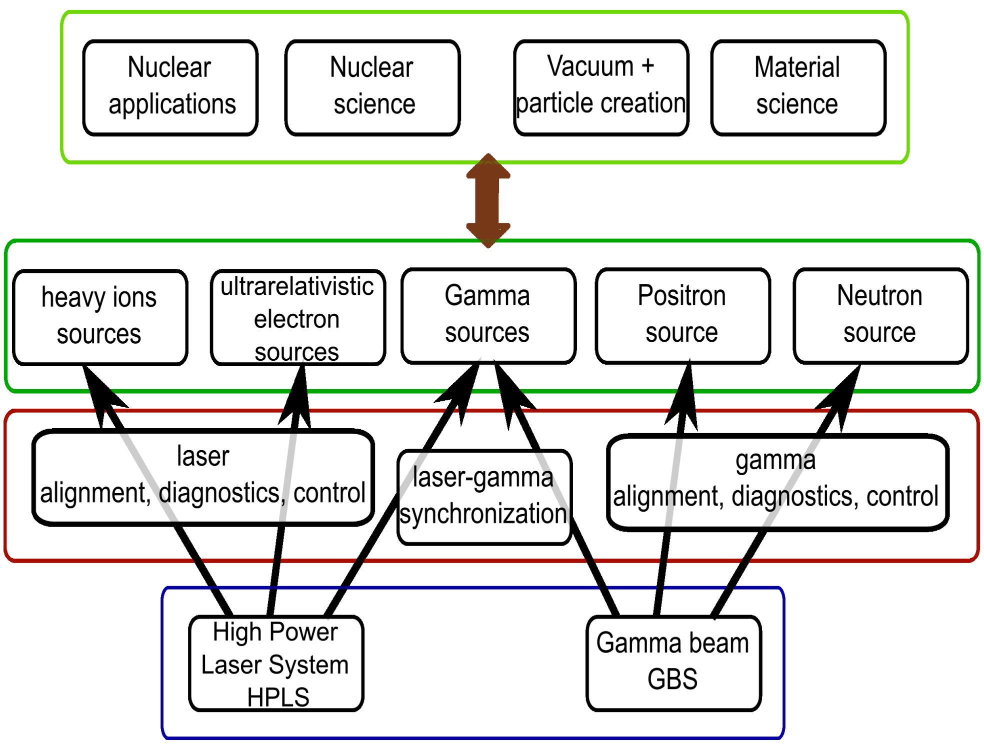
Table 2. Specified parameters for the gamma beam source:

type	Units	Range
Photon energy	MeV	0.2 – 19.5
Divergence	Rad	$\leq 2.0 \times 10^{-4}$
Average Relative Bandwidth of Gamma-Ray Beam		$\leq 5.0 \times 10^{-3}$
Time-Average Spectral Density at Peak Energy	1/(s eV)	$\geq 5.0 \times 10^{3}$
Time-Average Brilliance at Peak Energy	1/(s mm^2 mrad^2 0.1% $\eta_{,\gamma}$)	$\geq 1.0 \times 10^{11}$
Minimum Frequency of Gamma-Ray Macropulses	Hz	≥ 100

4. EXPERIMENTAL PROGRAM

The experimental proposals in the White Book of ELI-NP can be gathered in the following synthetic description:

Figure 2. From facilities to science: the steps



At the bottom of the diagram there are the main tools of the ELI-NP facility, namely HPLS and GBS. An interface layer is then defined, as a buffer between the facility and the experiments, consisting in the laser alignment, diagnostics and control package, HPLS-GBS synchronization package and GBS alignment, diagnostics and control. The next layer includes the scientific and technical developments that form the foundation of the mission-critical experiments of the facility.

The experiments related to the HPLS are based on three major laser driven radiation sources developments, namely laser accelerated heavy ions, laser accelerated electrons and laser driven gamma sources. Besides, further experiments were proposed that involve only the HPLS or a combination of HPLS and GBS. As a consequence, three associated technical experimental design reports (TDR) are now in preparation for the three directions of research.

The first one has as a perspective ion driven nuclear reactions where the ions are produced with the laser. Among the important scientific goals there is the production of super-heavy elements in the region Z>116. Such experiments require a huge experimental development in the field of laser driven ion acceleration according to new acceleration mechanisms, to be tested for the first time at ELI-NP.

The second TDR aims to develop ultra-relativistic electron sources, and subsequently, gamma sources for nuclear physics experiments. Complementary strong field quantum electrodynamics studies at the interaction between ultra-intense laser pulses and solid targets were proposed within this TDR framework.

The third TDR aims to make prospective studies based on the combination of HPLS 10PW beams with the GBS pulses. Thus, dynamics of the electrons in tightly focused, ultraintense laser fields, modifications of the vacuum constants and gamma beam assisted electron-positron production experiments were suggested in the ELI-NP White Book.

All three development directions above will use, at the intermediate step, the high repetition experimental areas E4 and E5 where 0.1PW at 10Hz and 1PW at 1Hz beams will be available. Besides, the experimental area E1 will be prepared to host the ion driven experiments, E6 will host QED-related experiments and E7 will host the combined HPLS-GBS experiments.

The other major instrument of the ELI-NP facility is the intense, brilliant γ beam, which is envisaged to provide a photon flux of $I = 10^{13}/[s\ (100\ \mu m)^2]$. The research program of ELI-NP Science case for GBS combines two aspects:

- Basic science – fundamental physics of perturbative and non-perturbative high-field quantum electrodynamics, high-resolution nuclear spectroscopy and astrophysics of the r-, s- and p-processes in nucleosynthesis.
- Applications – developing nuclear resonance fluorescence for nuclear materials and radioactive waste management, brilliant gamma, X-ray, neutron, positron and electron microbeams in material and life science, and techniques of laser acceleration and of a brilliant gamma beam.

The main achievements with the γ beam facility are likely to occur as a result of the high resolution at higher nuclear excitation energies in studies related to collective modes in nuclei. For example, identifying the predicted neutron halo isomers closely below the neutron binding energy would open a new field of nuclear spectroscopy. Major advances are expected in the fields of photonuclear reactions related to nuclear astrophysics, as well as to photofission studies. Thus the nuclear physics experiments in the different experimental areas have to be carefully designed.

The γ beam will have unique properties in worldwide comparison and opens new possibilities for high resolution spectroscopy at higher nuclear excitation energies. They will lead to a better understanding of nuclear structure at higher excitation energies with many doorway states, their damping widths, and chaotic behaviour, but also new fluctuating properties in the time and energy domain. The detailed investigation of the pygmy dipole resonance above and below the particle threshold is essential for nucleosynthesis in astrophysics.

Besides a wide range of fundamental physics projects, a variety of applied research will also be enabled at ELI-NP. The project aims at the development of techniques for remote characterization of nuclear materials or radioactive waste via NRF will gain large importance for society in Europe. The unsolved problems of long-term storage of radioactive waste from reactors, while having to deal with large amounts of old, insufficiently characterized radioactive waste, requires a precise isotopic characterization in the first place. The new production schemes of medical isotopes via the (γ,n) reactions might also reach socio-economical relevance. The realization of intense positron sources may reach large importance in material and life sciences.

The experimental areas will accommodate three types of experiments: laser driven experiments will be performed at E1, E4, E5 and E6 experimental areas; gamma experiments will be performed at E2, E3 and E8 experimental areas, while combined experiments are planned at E7 experimental area, as summarized in table below. A lay-out of the experimental areas is displayed in figure 3, while their use is summarized in table 3.

Figure 3: Lay-out of the experimental areas of the ELI-NP facility, as of year 2012, with the dimensions specified in meters.

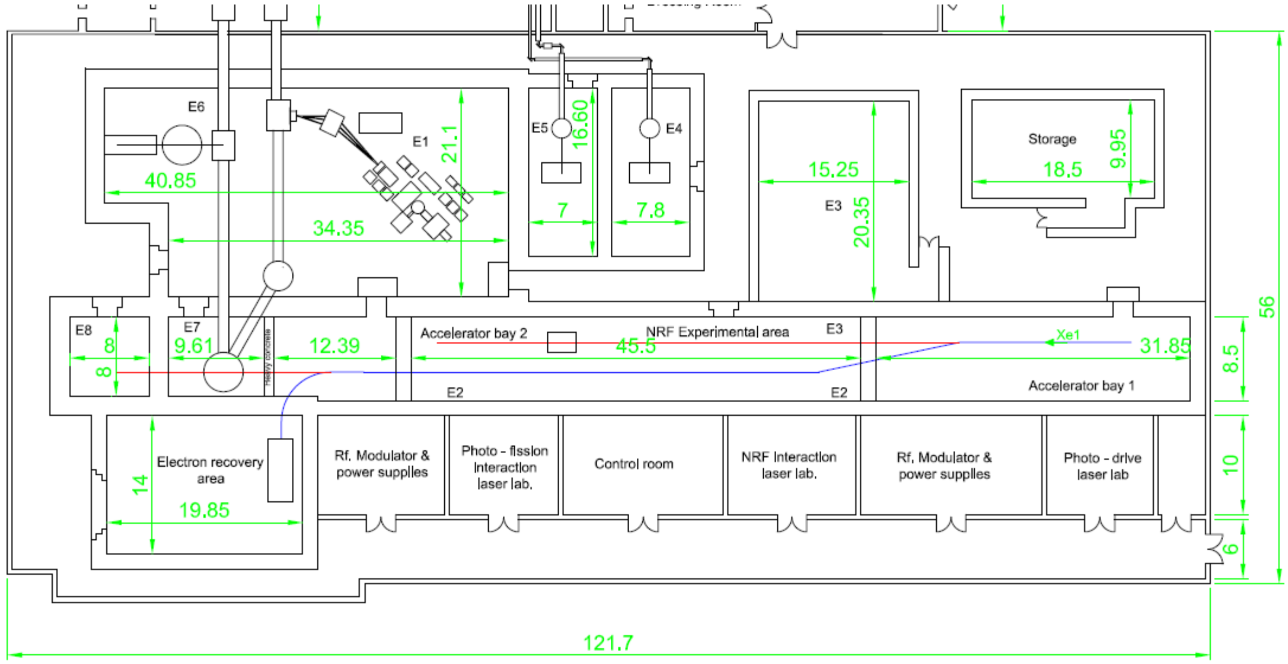


Table 3. Experimental areas at ELI-NP

Acronym	Subject	Available beams
E1	Ion acceleration for nuclear science experiments	Laser, 10 PW
E2	Nuclear Resonance Fluorescence Gamma-beam experimental area	Gamma, 4.5 MeV
E3	positron source experimental area	positrons
E4	0.1PW@10Hz, intermediate developments for laser driven experiments	Laser, 2 x 0.1 PW
E5	1PW@1Hz, intermediate developments for laser driven experiments	Laser, 2 x 1 PW
E6	Gamma and electron beams production for QED and nuclear physics studies	Laser, 10 PW
E7	Combined laser-gamma experiments related to vacuum structure	Laser, 2 x 10 PW, electron and gamma beams
E8	Nuclear reactions induced by high energy gamma beams and material science experimental area	Gamma, 19MeV

5. CONCLUSIONS

ELI-NP facility mixes two research facilities with parameters beyond the state of the art, namely a high power laser system with two amplification arms to deliver 10PW and intensities on the target in the range of 10^{23} W/cm^2 at least every minute, and a gamma beam system to deliver up to 19 MeV photons. Their outstanding performances will allow to approach a virgin science field, at the frontier between the strong field QED and nuclear physics.

Acknowledgments

The general presentation of the Laser and Gamma Beam systems, and of the experiments to be pursued at the ELI-NP facility is based on the ELI-NP White Book [4] and its subsequent refinements, which converged in an international scientific collaboration effort. The ELI-NP project is co-funded by The European Union through the European Regional Development Fund.

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