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Extreme Light Infrastructure – Nuclear Physics

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Abstract. The Extreme Light Infrastructure (ELI) is an ESFRI-listed distributed facility that entered the implementation phase. The Romanian pillar will focus on the field of nuclear physics research, performed with the help of an ultra-short-pulse, multi-petawatt scale laser system and a brilliant, tuneable and highly collimated gamma beam system. ELI-Nuclear Physics, an open-access facility, shall become operational and receive the first visiting research teams in 2017. We report herein on the status of the implementation and some of the research topics proposed for ELI-NP.

1. Introduction

The Extreme Light Infrastructure (ELI), listed on the ESFRI (European Strategic Forum for Research Infrastructures) road-map and distributed among three European countries (the Czech Republic, Hungary and Romania), entered the implementation phase in 2011, when the Czech pillar, ELI-Beamlines, received the approval from the European Commission for funding from Structural Funds. The location of a fourth pillar, dedicated to a significant increase in laser power with respect to the first three pillars, will be decided at a later stage.

The Nuclear Physics pillar, ELI-NP, located near Bucharest, Romania, in the Măgurele Physics research campus, is scheduled to enter operation in 2017.



Figure 1. Rendered image of the main buildings complex at ELI-NP: laser building, accelerator and experiments building, laboratories building.

At the time of entering operation, ELI-NP will be the most advanced research infrastructure in the world focused on photonuclear physics studies and applications, with the help of a pair of 10PW, ultra-short pulse lasers and the most brilliant tuneable gamma-ray beam in the world. The infrastructure will be built between 2012 and 2016. The facility will cover frontier fundamental physics, new nuclear physics and astrophysics as well as applications in nuclear materials and radioactive waste management, materials science and life sciences.

The policy of access to ELI-NP, as well as to the other ELI centers, will be open access, free of charge for members of the scientific community. Paid access will be granted to companies.

2. Scientific Equipment

Two large, cutting-edge pieces of equipment will promote ELI-NP to the forefront of scientific research at international level: the laser system and the Gamma ray beam. It will be the first time in Europe the combination of these two types of radiation sources, at very high intensities, will be available for use concurrently in experiments.

2.1. Multi-Petawatt Laser System

The technical specifications for the laser system were derived from the analysis of the most advanced ultra-intense laser technologies and their associated risks. At the time of the analysis in 2009, during the ELI Preparatory Phase, three advanced technologies were considered mature enough for the ELI-NP facility. They can be classified according to their active amplification media and central emission wavelength as follows:

1. Ti:Sapphire/~800nm
2. Nd:Glass/~1050nm
3. Optical parametric chirped pulse amplification (OPCPA) in non-linear crystals/~900nm

These technologies are in an advanced development stage, namely there are already demonstrations of laser systems with peak powers of at least half a PW. Several studies from the research community sustain the idea that new facilities in the range of 10PW, based on these three technologies, are feasible.

A comparison of the main advantages and disadvantages of the three technologies was synthesized in the ELI-NP White Book [1] – see Table 1.

Table 1. Comparison of advantages and disadvantages for the three proposed laser technologies; (+) denotes an advantage while (–) denotes a disadvantage.

Main characteristics	1		2		3	
	Ti:sapphire Nd:glass		DKDP Nd:glass		Mixed Nd:glass Nd:glass	
Gain medium	Ti:sapphire		DKDP		Mixed Nd:glass	
Stored energy medium	Nd:glass		Nd:glass		Nd:glass	
Pump wavelength	2 ω Nd	(–)	2 ω Nd	(–)	<i>No additional</i>	(+)
Pump duration, ns	>10	(+)	1	(–)	<i>pump laser</i>	(+)
Amplifier aperture, cm	10	(–)	40	(+)	>40	(+)
Minimum duration, fs	25	(+)	15	(+)	150	(–)
Efficiency (1 ω Nd \rightarrow fs), %	15	(–)	10	(–)	100	(+)
Repetition rate (determined by available pump lasers)	0.1 Hz	(+)	1pulse/20min	(–)	From 1/20min up to 1 / min	(–)
Number of PWs from a 1kJ 1 ω Nd	6		4		6	
Max. power obtained, PW	0.85		0.56		1.10	

In order to fulfil the requirements in terms of power and pulse duration, the most promising solutions are Ti:Sapphire and Nd:Glass. A number of general and specific bottlenecks, and also

engineering challenges were subsequently identified for these technologies, as illustrated in Table 2, for the development of a 10PW-class laser.

Table 2. Overview of the technical bottlenecks and engineering challenges for the Ti:Sa and Nd:Glass technologies

	1. Ti:Sa	2. Nd:glass
Architecture dependent Bottlenecks	a) High damage threshold broad-band large size gratings b) Pump lasers: general design, SHG crystals, Homogenizers c) Large size Ti:Sa crystals d) High damage threshold broad-band HR coating on large size optics	a) Tiled compressor b) Rep. rate & slab cooling
Engineering challenges	e) OPCPA front-end: Synchronization & Pumps f) Contrast: ASE + pre-pulses g) Back-reflection isolation h) Strehl ratio & adaptive optics	c) Contrast: ASE + pre-pulses d) Strehl ratio & adaptive optics
Architecture independent bottle-necks	Beam transportation Coherent combination of the ultrashort pulses	

However, due to the recent R&D and industrial developments, it is expected that all the architecture dependent bottlenecks will become engineering challenges before the end of 2012, when the decision on the laser system architecture is expected.

The final decision concerning the system architecture will be taken using the legal competitive procedures for public procurements, in order to deliver a laser system that fulfils the following requests:

- Peak pulse power of the order of 10 PW or more for each of the two amplifier chains;
- Pulse duration of the amplified and re-compressed pulse: 15-100 fs;
- Repetition rate at full energy in the range 1/10 Hz – 1/60 Hz;
- ns & ps contrast: $>10^{12}$;
- Focused laser intensity: $\geq 10^{23}$ W/cm² (laser beam focused near the diffraction limit).

2.2 Gamma Ray Beam System

The brilliant Gamma ray beam, with energy tuneable up to 20 MeV, is obtained by back-scattering of optical photons on electrons from a warm LINAC beam with energies up to 720 MeV. It will open new possibilities for high resolution spectroscopy up to high 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 output specifications for the Gamma beam (see Table 3) were established in a series of workshops and meetings organized with the scientific community interested in ELI-NP, in order to satisfy the needs of the scientists for the progress of their research but also to have realistic expectancies that are technically feasible within the timeframe of project implementation. The main characteristics of the gamma beam that will make it unique will be the very narrow relative bandwidth (of the order of 10^{-3}), one order of magnitude better than present-day machines, and the extremely high brilliance – at least two orders of magnitude better than present state-of-the-art machines.

Consequently, very good energy level selection capabilities and reduced irradiation times will be possible in experiments, making possible experiments that were not feasible before.

The Gamma Beam System will have two gamma-ray outputs available for use independently, one for the lower part of the energy range (up to approximately 3.5MeV) obtained using the first half of the accelerator, and a second one for higher energies, with the laser-electrons interaction point located at the end of the accelerator.

Table 3. Main specifications for the Gamma-ray beam.

Quantity	Symb	Unit	Specification
Photon Energy Range	E_γ	[MeV]	0.2 – 19.5
Frequency of Gamma-Ray Macropulses	Ω_γ	[1/s]	$\geq 1.0 \times 10^2$
Divergence	$\Delta\theta$	[rad]	$\leq 2.0 \times 10^{-4}$
Average Bandwidth of Gamma-Ray Beam	η_γ		$\leq 3.0 \times 10^{-3}$
Time-Average Spectral Density at Peak Energy	Φ_γ	[1/(s eV)]	$\geq 1.0 \times 10^4$
Time-Average Brilliance at Peak Energy	B	[1/(s mm ² mrad ² 0.1% η_γ)]	$\geq 1.0 \times 10^{11}$
Peak-Brilliance at Peak Energy	B _p	[1/(s mm ² mrad ² 0.1% η_γ)]	$\geq 1.0 \times 10^{19}$

The acquisition of the gamma ray machine, as well as that of the multi-petawatt system, will be done through international open tender procedures.

2.3 Experimental areas

Due to the preparation time needed for each laser and nuclear physics experiment, in order to optimize the use of equipment, the facility was designed in such a way as to permit the simultaneous use of several experimental rooms. ELI-NP will feature eight experimental rooms, located in the gamma beam and experiments building, out of which six will be used simultaneously.

These experimental areas, organized as shown in Figure 2, are:

- E1: laser induced nuclear reactions;
- E2: nuclear resonance fluorescence and applications;
- E3: positrons source;
- E4 / E5: accelerated particle beams induced by high power laser beams (0,1/1 PW) at high repetition rates;
- 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.

Due to the high radiation doses that might be produced during experiments (especially when using the 10PW laser beams), all experimental areas will be confined by 1.5 or 2.0 meter thick radioprotection walls. Some of these walls are modular, so they can be moved with the help of the crane installed in the area. This will allow for more flexibility in the setup of experiments.

The detailed design for the equipment in the experimental areas will be performed by working groups established during the ELI-NP science meetings and comprising researchers from organizations around the world, who already proposed or intend to propose experiments to be performed at ELI-NP.

Therefore, the purchase of equipment for the experimental areas will begin after the completion of the ELI-NP main buildings, in the end of 2014, and will continue until the end of the implementation phase of the project.

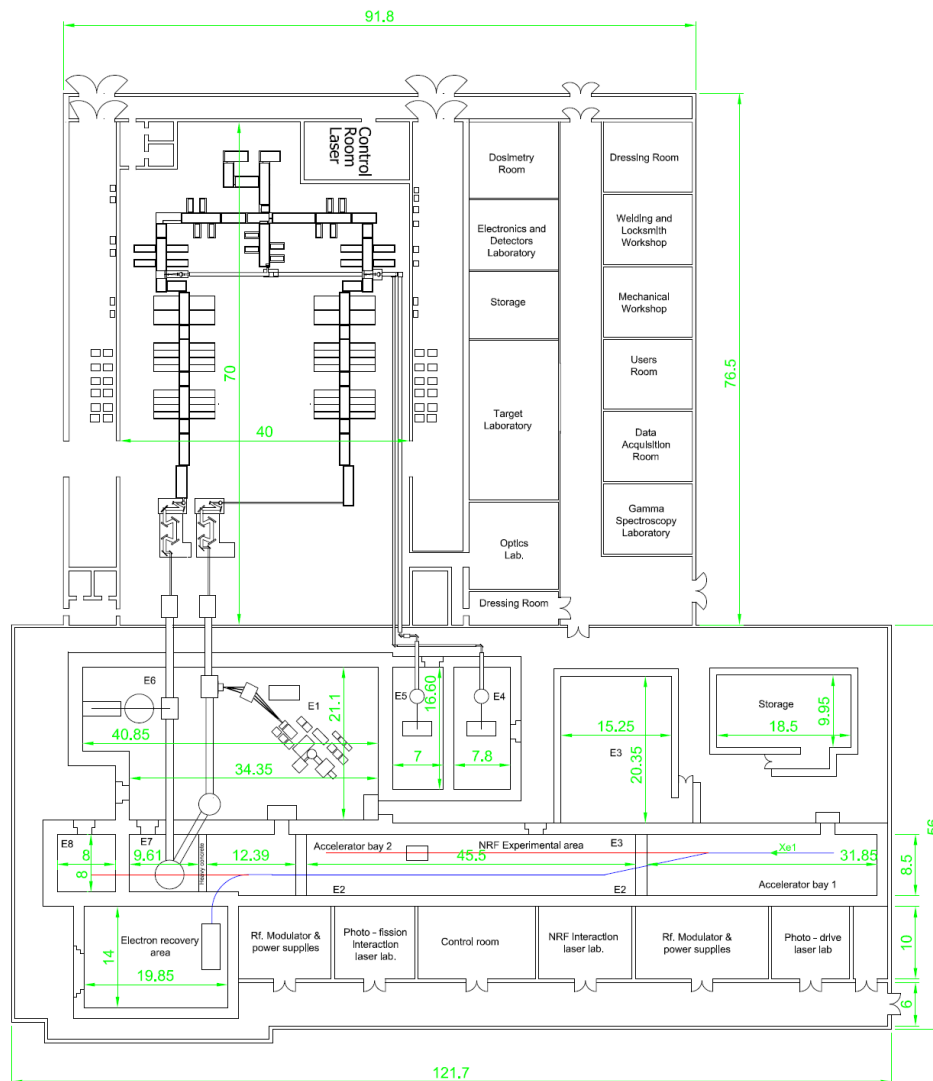


Figure 2. The experimental areas at ELI-NP (E1 – E8). Descriptions in the text. A possible setup for the laser system and the gamma beam are also figured.

3. Experiments

3.1. Laser-based Experiments

The powerful lasers will be used 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 to produce exotic nuclei or to perform new γ spectroscopy experiments in the energy or time domain.

The acceleration of particles using lasers can occur following several mechanisms, depending on the characteristics of the incident beam and target:

- Wake-Field acceleration [2]: charge separation occurs when electrons move due to the Lorentz force, forming a very intense electric field;
- Target normal sheath acceleration [3]: the accelerating electric field generated by hot electrons is stationary and ion acceleration is spatially separated from laser absorption into electrons; protons are preferentially accelerated;

- Radiation pressure acceleration [4]: much thinner foil targets of only nanometers are used so that the laser transfers energy to all electrons located within the focal volume; a localized longitudinal field enhancement is present that co-propagates with the ions as the accompanying laser pulse pushes the electrons forward.

The acceleration of particles using laser beams is of great interest nowadays, because of the plethora of applications it may trigger in a number of fields, from medicine (compact and more versatile accelerators for ion-therapy) to homeland security (scanners).

The study of the interaction of radiation with matter by means of nuclear physics techniques is one of the new areas where ELI-NP will mark a leap ahead with respect to existing facilities. Interaction of the high power (PW) laser radiation with the solid state matter produces specific effects, not completely known, on the structure and composition of the irradiated materials. The detailed knowledge of these effects has a fundamental interest for understanding the material behaviour in extreme conditions of irradiation. On the other hand, study of the irradiation effects significantly helps to optimization of the materials and components operating in the laser beam.

One of the experiments proposed in the ELI-NP White book aims to the production of neutron-rich nuclei around the $N = 126$ waiting point of the r-process via the fission-fusion reaction mechanism. The origin of the heaviest elements is still standing as one of the 11 greatest unanswered questions of modern physics [5].

3.2. Experiments Based on the Gamma Beam

The gamma beam can be used to study new techniques to map the isotope distributions of nuclear materials or radioactive waste remotely via Nuclear Resonance Fluorescence (NRF) measurements. At lower energies, around 100 keV the high resolution of the beam is very important for protein structural analysis. In addition it will be produced low energy, brilliant, intense neutron and positron beams, which will open new fields in materials science and life sciences.

The new production schemes of medical isotopes (e.g., ^{99}Mo – currently used in therapies, $^{195\text{m}}\text{Pt}$ – nuclear imaging to determine efficiency of chemotherapy, $^{117\text{m}}\text{Sn}$ – emitter of low energy Auger electrons for tumour therapy) via (γ, n) processes may also reach socio-economical relevance.

Laboratory astrophysics experiments aiming at explaining the nucleosynthesis processes will be possible, through direct or inverse reactions. Reactions relevant for the p- and r-processes will be investigated, to advance the explanation of the formation of a large part of the known elements in the Universe.

Compared to former gamma-ray facilities, the much improved bandwidth is decisive for this new facility, because an important factor in this type of experiments is the energy bandwidth of the beam, which should be smaller than the normal energy gap between nuclear levels. Several experiments, like the parity violation experiment, only become possible due to this much better bandwidth.

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 methods new methods to produce thermal neutrons, through photonuclear reactions (γ, n) . Another example would be the creation of an intense positron sources by means of the (γ, e^+e^-) reaction ([1], [6]).

3.3. Experiments Employing Lasers and Gamma Beam

The possibility to study the same target with these very different brilliant beams will be unique and shall advance science much faster. Laser radiation and gamma radiation may be used as pump and probe, in order to excite processes and observe the subsequent evolution of the systems.

Nuclear levels have lifetimes down to the zeptosecond range once one reaches excitation energies beyond the particle emission threshold, while nuclear levels have lifetimes longer than typically 10 fs below the particle threshold [7]. We plan to study this drastic change in lifetime and predicted changes in decay laws for the first time. We modulate the energy of emitted conversion electrons in a phase-locked laser field and carry over the technique used to measure as lifetimes of atomic levels [8] to

nuclear systems. Ultrashort light pulses offer the possibility to study photonuclear reactions up to 10 or 15 MeV from a different and completely new perspective.

Among other experiments proposed by the scientific community for ELI-NP there are: Compton Scattering and Radiation Reaction of a Single Electron at High Intensities; Cascades of e^+e^- Pairs and Gamma Rays triggered by a Single Slow Electron in Strong Fields; The Real Part of the Index of Refraction of the Vacuum in High Fields: Vacuum Birefringence.

In fundamental physics, ELI-NP will approach the field intensity boundary from which the observation of the first catalysed pair creation from the quantum vacuum should be achievable.

4. Conclusions

The ELI-NP project is the result of a pan-European collaborative effort that extended beyond the borders of the European Union. Research communities in more than 20 countries actively contributed to the definition of the project. The present report is a short, updated synthesis of these efforts. Extended list of ELI-NP contributors and description of the details can be found in two public reference documents: ELI-NP White Book [1], and [9].

ELI-NP will host two cutting edge infrastructures, namely 2×10 PW laser systems and a brilliant gamma source. They will allow applied research and development in unmatched conditions, relevant also for companies acting in the fields of medicine (radionuclides and hadron-therapy), telecommunications (materials in high intensity radiation fields), engineering industry (non-destructive testing), security (scanners based on nuclear resonance fluorescence of sensitive nuclear materials) – to name just a few.

Collaborations with universities in Romania and abroad already exist or will be established, for the mutual benefit of the community and of the infrastructure, through the access to a cutting-edge facility offered to the staff and students of academic institutions, and the implementation of training programs with specializations within the scope of ELI-NP. Highly skilled personnel will thus be trained and will ensure part of the staff at the facility.

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 [1], which emerged in an international scientific collaboration effort.

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