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The Extreme Light Infrastructure– Nuclear Physics Facility (ELI-NP): Project implementation and overview of the scientific program

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Abstract: The European Strategic Forum for Research Infrastructures (ESFRI) has selected in 2006 a proposal based on ultra-intense laser fields with intensities reaching up to $10^{22\text{-}23}$ W/cm^2 called "ELI" for Extreme Light Infrastructure. The construction of a large-scale laser-centred, distributed pan-European research infrastructure, based on three pillars received the approval for funding in 2011-2012.
The three pillars of the ELI facility are being built in Czech Republic, Hungary and Romania. The Romanian pillar is ELI-Nuclear Physics (ELI-NP). Its mission covers scientific research at the frontier of knowledge involving two domains. The first one is laser-driven experiments related to nuclear physics, strong-field quantum electrodynamics and associated vacuum effects. The second is based on a Compton–backscattering high-brilliance and intense low-energy gamma beam (<20 MeV), a marriage of laser and accelerator technology. These two installations will allow us to investigate nuclear structure and reactions as well as nuclear astrophysics with unpreceded resolution and accuracy. In addition to fundamental themes, a large number of applications with significant societal impact (energy, biology, medicine, material sciences) are being developed.
The ELI-NP project is implemented by "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH) at Magurele near Bucharest, Romania. The project started in January 2013 and the new facility will be operational by the end of 2018.
During the last three years, a significant fraction of the international scientific community contributed to the shaping of the ELI-NP facility science program through a series of international workshops**.** The ELI-NP White book and the Technical Design Reports (TDRs) for the proposed experiments envisage a very wide range of experiments in 8 experimental areas. A description of the present status of the implementation of the ELI-NP project and an overview of the proposed experiments will be presented.

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1. Introduction

The European Strategic Forum for Research Infrastructures (ESFRI) has selected in 2006 a proposal based on ultra-intense laser fields with intensities reaching up to 10^{22-23} W/cm^2 called "ELI" for Extreme Light Infrastructure. The construction of a large-scale laser-centred, distributed pan-European research infrastructure, involving beyond the state-of-the-art ultra-short and ultra-intense laser technologies, received the approval for funding in 2011-2012. The three pillars of the ELI facility are built in Czech Republic, Hungary and Romania [1].

The Romanian pillar is ELI-Nuclear Physics (ELI-NP) [2]. The new facility is intended to serve a broad national European and International science community. Its mission covers scientific research at the frontier of knowledge involving two domains. The first one is laser-driven experiments related to nuclear physics, strong-field quantum electrodynamics and associated vacuum effects. The second is based on a back Compton –scattering high-brilliance and intense low-energy gamma beam (<20 MeV), a combination of laser and accelerator technology which will allow us to investigate nuclear structure and reactions, as well as nuclear astrophysics with unpreceded precision and accuracy [3-7]. In addition to fundamental themes, a large number of applications with significant societal impact are being developed. These applications extend from the nuclear power plant waste management to new radio-isotopes for medicine and cancer therapy and from space science to material and nanoscience using for example new powerful probes like a brilliant positron beam.

The ELI-NP research centre will be located in Magurele near Bucharest, Romania. The facility, worth more than 310 million euros, is financially supported by European Regional Development Fund in two phases: 134 million euros in 2013-2015 and the rest in the next in the 2014-2020 cycle of the European Funds. The project is implemented by "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH). The project started in January 2013 and the new facility is planned to be operational by the end of 2018. The civil engineering construction has started in June 2013 and has been completed in September 2016. During the last three years, a significant fraction of the international scientific community contributed to the shaping of the ELI-NP facility science program through a series of international workshops. As a result, these scientific meetings led to the definition of about ten new development directions for the experiments to be carried out at the future facility. For each of them, writing of Technical Design Reports (TDRs) by specialized working groups of international scientists and coordinated by ELI-NP physics team, was triggered and further developed during the workshops. Final version of the TDR's were presented and discussed by the ELI-NP International Scientific Advisory Board in June 2015 [8]. In the following, we will present the status of the implementation of the ELI-NP project as well as new research areas at reach and/or to be revisited using the unique features of High Power Laser System (HPLS) up to 2x10PW and of the brilliant and monochromatic Gamma Beam System (GBS) in the energy range 0.2-20 MeV.

2. Technical description and implementation status of the ELI-NP facility

The major milestones in the constrcution of the facility so far are:

2.1 Civil enginering

Civil engineering was a major challenge with the construction of the ELI-NP buildings, a total surface of 34000 m2 and three main components (HPLS hall and services, Gamma beam linac hall, 8 experimental areas with a total surface of about 7000 m2, office building and the guesthouse (see Fig.1). They are now completed and checking procedures to insure that the very tigh specifications in terms of both dimensions, utilities, and vibrations are taking place. We hope to start the installation on site of the first components of lasers and gamma beams by the end of November 2016.

2.2 Besides the construction of the buildings, the ELI-NP project consists of two main components

The High power Laser System (HPLS) and the Gamma Beam System (GBS). For each of these components, important milestones have been achieved beetween the end of 2015 and the summer of 2016.

Figure 1. Image of the ELI–NP building site taken as of July 2016.

2.2.1 High-Power Laser System.

We are installing two 10 PW lasers, which are developed by a consortium consisting of Thales Optronique France and Thales Romania. The high-power laser system (HPLS) of ELI–NP consists of two 10 PW class lasers based on Optical Parametric Chirped Pulse Amplification (OPCPA) and driven by a dual front-end system with two parallel amplification arms. Each amplification arm will have three outputs each with its own optical pulse compressor. The three outputs will provide different power levels. Besides the 10 PW output at a repetition rate of 1/60 Hz there will be two other outputs of 100 TW and 1 PW at repetition rates of 10 Hz and 1 Hz, respectively.

Out of the six possible outputs on the two arms, two of them, one from each arm, can be provided simultaneously for experiments, combined in the same experimental setup or to be used independently in two different setups. For the two 10 PW outputs an unprecedented level of intensity of about 10^{23}–10^{24} W/cm2 will be achieved. The main parameters characterizing the ELI– NP HPLS are summarized below:

<u>Main parameters of the ELI–NP high-power laser system</u>

Outputs: 2 outputs: 10 PW @ 1 shot/min, 2 outputs: 1 PW @ 1 shot/s, 0.1 PW@ 10 shot/s

Pulse duration < 50 fs

Strehl ratio > 0:7

Pointing stability < 0.2 μrad

The laser research activities have registered a major milestone in the end of 2015, with the delivery of the first HPLS 10PW arm. One of the major challenge in developing the laser is that we need a 200 mm large very pure Titanium-Sapphire crystal to amplify the light. It is a real challenge to grow such a crystal, without introducing any defects. This challenge was overcome last November by our industrial partners and our first HPLS up to 1,3 PW was assembled and tested with success in the Thales Optronics premises in France. The integration of the final amplifiers up to the 10PW level will be done at the ELI-NP location in Magurele, Romania. Activities related to the technical specifications for the Laser Beam Transport System continued and a new tender procedure for the public purchase contract is underway.

2.2.2 Gamma Beam System (GBS)

The GBS is developed by a consortium consisting of research institutes and high tech companies from 8 European countries led by Istituto Nazionale di Fisica Nucleare (INFN), Italy. Production of gamma beams at ELI-NP is based on the inverse Compton scattering (ICS) of high-repetition laser pulses on a low-emittance relativistic electron beam. The solution adopted for the Gamma Beam System (GBS) at ELI-NP will provide gamma beams with energy continuously tunable between 200 keV and 19.5 MeV, with a relative bandwidth better than 0.5% and a spectral density higher than 0.5 x10^3 photons/s/eV. The layout of the ELI–NP GBS can be divided in several main components as follows:
a) a warm RF linac for the acceleration of electrons to relativistic energies; the accelerator is designed in two stages: one to deliver electrons with energies up to about 300 MeV and a second one to further accelerate the electrons to energies higher than 720 MeV. Electrons are produced by a laser–driven multi–bunch RF photogun at a repetition rate of 100 Hz in 32 bunches of 250 pC each and separated at 16 ns;
b) Two interaction lasers of cryo-cooled Yb: YAG J-class type (200mJ) at 100 Hz repetition rates one of the lasers will be used for the low–energy interaction point and both of them for the high–energy interaction point.
c) Two laser beam circulators to ensure the interaction of the laser pulses provided at 100 Hz repetition rate with the 32 electron bunches delivered by the RF linac every 10 ms
d) gamma beam collimators for low– and high–energy gamma beams consisting of 14 vertical Ti dual-slit elements rotated at 25.7 degrees one respect to the other; the collimators take advantage of the angular dependence of the photons energy after the inverse Compton scattering to filter–out the low–energy distribution of the Compton scattered photons and select the bandwidth of the gamma beams.
e) Diagnostics stations to characterize the gamma beams are placed after the interaction points; they will provide information on the energy, bandwidth, intensity and spatial profile of the gamma beams after the collimators.
The delivery of GBS at ELI-NP is phased in four stages. The first stage, aiming at delivering a subsystem able to produce gamma rays of at least 1 MeV energy, was successfully completed in October 2015 by the EuroGammaS. This first part of the accelerator and the first interaction point were then established. The 1 MeV gamma-ray subsystem consists of a high luminosity radio frequency (RF) electron photo–injector, one C-band accelerating structure, and an interaction laser. The main components are completed. All these components are waiting to be shipped. Presently the Gamma Beam System of ELI-NP is in the implementation phase of Stage II at the end of which the EuroGammaS Association will deliver all the components necessary to produce gamma beams with energy of at least 3 MeV.

3 ELI-NP: experimental lay out, science program and day-one experiments

The lay out of the 8 experimental areas and electron linac hall are shown in figure 2.

3.1 Laser Driven Nuclear Physics – Day one experiments

The experimental plan has as focus roughly the first two years of operation at ELI-NP (starting nominally at the end of 2018- beginning of 2019). The experimental goals follow the strategy detailed below for the first stage of ELI-NP operation:
i) Demonstrate the performance of the 10 PW lasers
ii) Develop intense particle beams for nuclear physics with lasers
As target in the first 10 PW experiments we propose to use a high density He or H jet, instead of a solid plastic foil. This is first motivated by concerns about the safety of the expensive focusing

mirrors, for which we will have no replacement in Day-1. A gas target will eliminate all risk to mirrors, as well as the need for very high contrast, and for target change at high repetition rate. High density gas jets can be obtained commercially. Proton acceleration to very high energy is predicted in dense gas jets [9], raising the possibility to achieve the milestone of 200 MeV proton acceleration. Conversely, we will use sub-μm thick CH foils as targets, recently predicted to enable high energy proton acceleration at intensities around 10^{22} W/cm^2 [10,11].

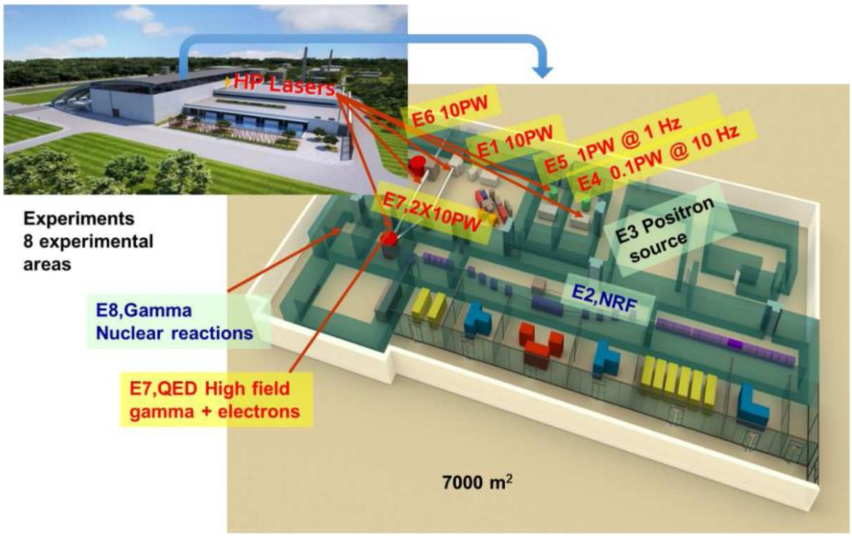

Figure 2. 3D sketch of the layout of the experimental areas

Lastly, we propose to accelerate the development at 10 PW of dense heavy ion beams relevant to nuclear physics experiments (i.e. having ~10 MeV/nucleon). This is motivated by recent predictions that the efficiency of heavy ion acceleration from thin foils scales favorably with laser intensity [12], as well as by promising recent results of heavier ion acceleration from thin foils at the TRIDENT laser [13]. Out of the eight experimental areas at ELI-NP (see fig.2), four are devoted to laser-based experiments at the three power levels available.

The E1 and E6 experimental areas feature both 10PW beams. In E1 it is foreseen the acceleration by RPA of protons and heavy ions, up to 500MeV (protons) or 50MeV/A (heavy ions), and their use in Laser-Driven Nuclear Physics experiments. Accelerated proton bunches should have more than 10^{10} p/pulse, energy FWHM of 10% and divergence better than 5°. The E6 area aims fundamental physics research topics involving intense electron and gamma beams induced by the high power lasers. Electrons will be accelerated up to tens of GeV, with very good divergence (#1°) and energy spread (FWHM few MeV).

The E7 experimental area is devoted to experiments in fundamental physics with combined laser and gamma or electron beams. The laser- accelerated electron beams envisaged to be used in radiation reaction, pair creation and vacuum birefringence experiments will have energies up to 5 GeV and low divergence (less than 0.3 deg) and energy spread. These beams will be used for the generation of gamma photons in the GeV range by Compton backscattering effect.

The experiments at E4 and E5 employing 0.1 and 1PW laser beams at higher repetition rates are covering a wide range of topics, from materials science to the quest for dark matter candidates. Protons up to 60MeV in large bunches of 10^{10} to 10^{12}, and electrons in the range of 50 to 2000 MeV and intensities of up to a few 10^{10} / pulse are foreseen to be produced.

From the multitude of proposals employing the acceleration of particles with the high power laser beams three cases are briefly discussed below:

3.1.1 Enhanced decay of ^{26}Al in hot plasma environments

The 26Al nucleus was the first radioisotope detected in the interstellar medium, by the observation of the characteristic 1809 keV-emission associated with the decay of its ground state [14]. There is still a debate regarding the production sites of this isotope that is a marker of ongoing nucleosynthesis. Moreover, in stellar conditions (temperatures up to about 0.4GK), it is predicted through theoretical calculations [15] that the effective life time of 26Al would be reduced by many orders of magnitude due to a variety of physical processes.
At ELI-NP there is the possibility to produce plasma conditions similar to the ones in various astrophysical setups, and thus the population of the states of interest will provide a disintegration rate closer to the true astrophysical one [16]. The fact that the radiation pulses are ultrashort in time and synchronous will provide good conditions for the resolution of ps timescales.

3.1.2 Production of Extremely Neutron-Rich Isotopes

The waiting point around N=126 is extremely important for the r- process nucleosynthesis, and presently very little is known about the nuclei in this area. The proposal aims producing these nuclei by the fission of a dense thorium ion bunch with about 7 MeV/u in a thick thorium target (covered by a thin carbon layer), where the light fission fragments of the beam fuse with the light fission fragments of the target. The accelerated ^{232}Th bunches of solid state density are produced via the RPA process with a high intensity laser pulse (in the range of 10^{23}W/cm2) produced by one of the 10PW HPLS arms. These bunches pass through a thin carbon layer and disintegrate into light and heavy fission fragments. In addition light ions (H, C) from the CH2 backing of the first (thin) Th target will be accelerated as well, inducing the fission process of 232Th in the second, thick Th foil. A detailed discussion of the achievable fission-fusion reaction yield is given in Ref. [17]

3.1.3 Electron Screening in Astrophysical Plasmas

The measurement of rates and cross-sections (S-factors) in conditions close to the astrophysical ones (extremely low energies and including plasma effects) in the laboratory has been a great challenge for the experimental nuclear physics for many decades. A setup is proposed based on two high power laser beams generating, by interaction with a solid and a gas target, two colliding plasma bunches. The study of the role played by free and bounded electrons on the Coulomb screening is one of the first topics to be investigated.

3.2 Gamma beams- Day one experiments

Nuclear physics experiments with gamma beams will be performed in the experimental areas E2 and E8. The E2 area will host low-energy (up to 3.5 MeV) gamma beams while in the E8 area both low- and high-energy (up to 19.5 MeV) gamma beams will be available (see Fig.2)
Features of the gamma beams available at ELI–NP (high brilliance and small transversal diameter) will provide an increased sensitivity of the measurements leading to a drastic reduction of the material quantities required for the construction of the targets. This allows for the study of nuclei available in nature only in very limited quantity such as p-nuclei or nuclei producing large radiation background such as actinides.

3.2.1 Photo-nuclear reactions below and above the particle separation threshold

Nuclear Resonance Fluorescence (NRF) experiments will be used to study the low-lying dipole strength distribution in nuclei. NRF experiments with quasi-monochromatic gamma beams were performed previously at the High Intensity γ-ray Source (HIγS) [18,19] characterized by a

3% bandwidth and spectral density of about 10^2 photons/s/eV demonstrated the possibility to determine branching ratios and total transition widths. The self-absorption method [20, 21] allows for a model independent determination of the absolute ground-state transition widths C0.
The NRF method will provide important information about the nuclear structure of the irradiated nuclei allowing for the study of their dipole response and the understanding of phenomena such as scissors mode and quadrupole–octupole phonon coupling in nuclei (Fig.3)
Pygmy Dipole Resonances (PDR) can be investigated above and below the particle threshold, which is essential for nuclear synthesis in astrophysics. PDRs occur close to the neutron emission threshold and their decay is governed by the coupling to the large number of states around the threshold. The use of ELI–NP gamma beam provides the possibility to reveal possible fine structures/ splitting of PDRs the excitation function with high resolution for (γ, n) and (γ, charged particle) channels, allowing for the determination of the branching ratios for various decay channels.

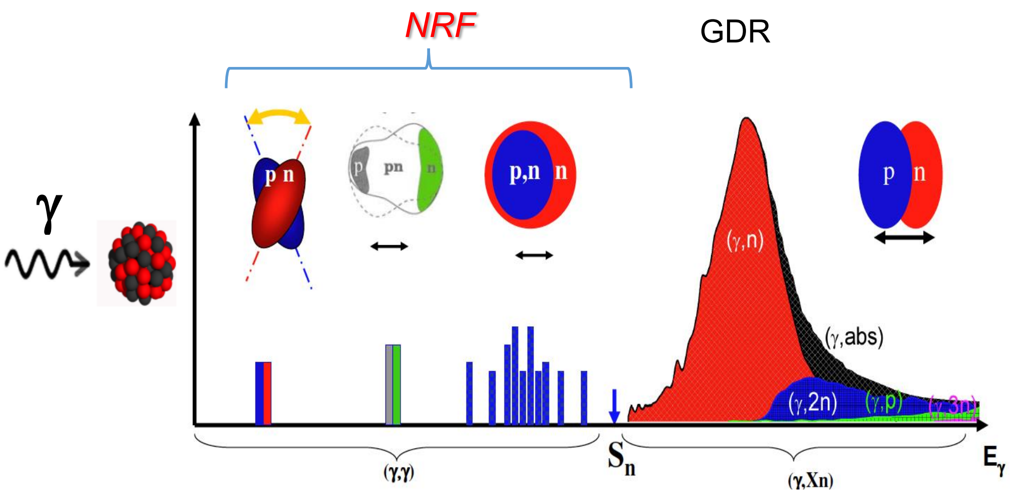

Figure 3. Schematic representation of the Dipole response function in nuclei. (adapted from ref.22)

The linear polarization of the beam will allow for the determination of the E1 or M1 type of excitation for the observed structures. The study of PDRs can show neutron skin effects and set constrains on the equation of state of neutron-rich matter [23-24].
In stable nuclei low-energy isovector excitations with mixed proton-neutron symmetry will be ideally investigated at ELI-NP, together with a variety of elementary collective excitations: quadrupole shape vibrations, double scissors mode, rotational states built on the scissors mode, the M2 twist mode, spherical/deformed octupole vibrations, as well as hexadecapole vibrations.
At higher excitation energy the study of the particle and gamma decay of the Giant Dipole Resonance is also of major importance. Among the key topics to be investigated we will mention the GDR neutron decay and measurements of (γ, xn) cross sections with x = 1–2 for a new compilation of total and partial photoneutron cross sections to be pursued as a Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) and to measure exclusive neutron decays of GDR to the ground state and excited states in residual nuclei. Last but not least direct gamma decays of GDR to the ground state with branching ratios of the order of 1% will be also carried out [25].

3.2.2 Photo-fission studies

In the actinides, investigation of the second and third potential minima, angular and mass distribution measurements of fission fragments, measurements of absolute photo-fission cross sections, studies of rare photo-fission events, such as triple fission, highly asymmetric fission, etc. are considered for investigation with the gamma beams at ELI–NP.
The capabilities of the gamma beams in terms of high spectral density and narrow bandwidth of the next-generation facility ELINP will allow for the identification of sub-barrier transmission resonances in the fission decay channel with integrated cross- sections down to $\Gamma\sigma \sim 0.1$ eV·b, where Γ is the resonance width. In addition the GBS facility at ELI-NP will be used for the first time to search for rare fission modes such as true ternary fission. Nuclear fission accompanied by light charge particle emission will be studied. As ternary particles are released close to the scission point they provide valuable information about the scission point and fission dynamics.
The use of linearly polarized gamma beams has the advantage to fix the geometry of the fission process and facilitate a detailed study of it.
Low-energy gamma beams are fully efficient at 15 MeV for producing short-lived and refractory elements in thin U targets using a gas-cell catcher (IGISOL technique [26]) with high efficiency. IGISOL technique using dedicated gas-cell catcher [27] allows us to investigate properties of neutron rich refractory elements with limited investments and in the mean time minimizing radioactivity production: a real niche! After their separation, the nuclei of interest will be transported to different measurement stations for mass , lifetime and decay spectroscopy measurements.

3.2.3 Nuclear astrophysics

Nucleosynthesis research based on gamma-induced reactions, (γ, n) or (γ, charged particles), with very low cross sections will largely benefit form the use of the high intensity gamma beams at ELI–NP. The availability of high-brilliance narrow-bandwidth gamma beams, will provide new opportunities for photonuclear reaction studies with high resolution. One flagship study is that of the important $^{12}C\ (\alpha,\gamma)\ ^{16O}$ reaction. Understanding and modelling the evolution and explosion of massive stars requires a 10% uncertainty on the $^{12}C\ (\alpha,\gamma)\ ^{16O}$ reaction cross section at helium burning energies around 300 keV. Due to the extremely small cross section at such low energies, the $^{12}C\ (\alpha,\gamma)$ reaction has been studied experimentally only down to energies around 1 MeV [28]. The detailed measurement of the reaction cross section and angular distributions for the inverse photodisintegration reaction $^{16}O\ (\gamma,\alpha)\ ^{12C}$ is one of the high priority experiments at ELI-NP. The measurement of cross section and angular distributions with precision better than 3% at higher energies, all the way to 14 MeV excitation energy reduce the uncertainty of cross-section extrapolations.
Other gamma capture reactions are under investigation like the ones relevant for p-nuclei resulting from the destruction of s- and r-type nuclei through a combination of (p,γ) capture reactions and (γ,n), (γ,p) or (γ,a) photo-reactions [29].

3.2.4 Applications of GBS at ELI-NP

A variety of applied research with ELI-NP gamma beams are also considered:
The tunability of the gamma beam energy makes such that NRF can be used for applications in the characterization of samples content in given isotopes. This technique is useful for the management of sensitive nuclear materials and radioactive waste characterization. It will allow for the scan of containers for nuclear materials or explosives. By combining the NRF method with gamma-ray computerized tomography techniques one can also establish the location of the identified materials inside the containers. For example. highly efficient and accurate nuclear waste content characterization for determination of the $^{235}U/^{238}U$ ratio in spent fuel rods or determination of ^{239}Pu content will become possible.

The use of high-energy gamma beams can open new opportunities in radioisotopes production schemes for medicine by following (γ, n) reactions [30]. One of the candidates considered at ELI–NP is the 195mPt isotope that is a promising imaging agent to determine the efficiency of some chemotherapy procedures in cancer treatment.

4. Conclusions

ELI–NP is a new research infrastructure, part of the pan-European Extreme Light Infrastructure- ELI initiative, under construction and dedicated to nuclear physics driven by an ultra high-power laser system composed of two 10 PW lasers and by a brilliant, high intensity gamma beam system. The unique features of the available laser and gamma beams will open new opportunities in fundamental physics, nuclear physics, nuclear instruments, diagnostics tools development and applied physics research.

During the last 4 years **building the ELI-NP R&D team** was also a very important milestone. At the moment, over 140 specialists are working on the implementation of the project from the management, administrative and research perspective. We selected more than one hundred Romanian specialists returning from countries where they had worked in last-generation labs or research facilities, but also foreign experts from France, Italy, Great Britain, Germany, Spain, Bulgaria, Turkey, China, India, the United States, Canada and Japan.This brain gain is exactly one of the reasons ELI will be stationed in Eastern Europe. At the same time, we are constantly focused on the new generations of physicists from Romanian universities. Recently, we launched an internship program in which students in their final year, or doing their master's, have the opportunity to undertake a research internship at the ELI-NP.

In parallel with building the ELI-NP R&D team and the technical implementation of the main systems for the production of the laser and gamma beams, an important activity is going on for the definition of the experimental setups necessary to investigate the proposed physics cases. The effort to prepare the technical specifications of the experimental setups is supported by a large international collaboration including Universities and research institutions from all over the world.

Acknowledgment

The ELI-NP project is the result of an international collaborative effort of scientists from more than 20 countries and their contribution to this the project is gratefully acknowledged. The essential contribution of all my colleagues from the ELI-NP team at Magurele in the preparation and implementation of the project is also deeply acknowledged. The ELI–NP project is co-funded by the European Union through the European Regional Development Fund.

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