The ELI–NP facility for nuclear physics

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**Abstract**

Extreme Light Infrastructure–Nuclear Physics (ELI–NP) is aiming to use extreme electromagnetic fields for nuclear physics research. The facility, currently under construction at Magurele–Bucharest, will comprise a high power laser system and a very brilliant gamma beam system. The technology involved in the construction of both systems is at the limits of the present-day’s technological capabilities. The high power laser system will consist of two 10 PW lasers and it will produce intensities of up to $10^{23}–10^{24}$ W/cm$^2$. The gamma beam, produced via Compton backscattering of a laser beam on a relativistic electron beam, will be characterized by a narrow bandwidth (<0.5%) and tunable energy of up to almost 20 MeV. The research program of the facility covers a broad range of key topics in frontier fundamental physics and new nuclear physics. A particular attention is given to the development of innovative applications. In the present paper an overview of the project status and the overall performance characteristics of the main research equipment will be given. The main fundamental physics and applied research topics proposed to be studied at ELI–NP will also be briefly reviewed.

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1. Introduction

Extreme Light Infrastructure (ELI) [1] is a pan-European research initiative aiming at the foundation of a worldwide laser physics research infrastructure. Extreme Light Infrastructure–Nuclear Physics (ELI–NP) [2] is one of the three pillars of the initiative and it is dedicated to laser-based nuclear physics research. ELI–NP is under construction on the Magurele Physics Platform in southern Bucharest. The implementation of the ELI project started in 2011 and the ELI–NP pillar is expected to enter operation in 2017.

Two scientific communities, high-power laser physics and nuclear physics, have joined their efforts to develop new interdisciplinary research opportunities with lasers and secondary radiation produced by them. The major equipment hosted by ELI–NP, two 10 PW lasers producing intensities of up to $10^{23}–10^{24}$ W/cm$^2$ and a high brilliance gamma beam system with narrow bandwidth (<0.5%), tunable energy from 200 keV up to about 20 MeV and linear polarization higher than 95%, will provide to the users laser and gamma beams with unprecedented performances allowing the facility to cover frontier fundamental physics, new nuclear physics and astrophysics as well as applications in material and life sciences, industrial tomography, nuclear waste management. The scientific case of ELI–NP was elaborated by an international collaboration of more than 100 scientists from 30 countries and it was published as the ELI–NP White Book [3]. At present, in parallel with the building of the main equipment, the efforts of the ELI–NP scientific team are focused on the selection and refinement of the first-day experiments and the definition of the experimental setups needed to carry on the proposed scientific cases.

The new facility in Bucharest will extend over a surface of about 33,000 m$^2$ and it will comprise the main experimental building, an office building, a guesthouse and a canteen. The largest area, about half of the total surface, is dedicated to the experimental building that will host: the main research equipment, the experimental rooms, laboratories and workshops, control rooms and user rooms. Civil engineering construction has started in June 2013 and should be completed in 2015. The picture shown in Fig. 1 illustrates the construction status of the facility as of October 2014.

2. Research infrastructure at ELI–NP

2.1. The high-power laser system

The high-power lasers, based on Optical Parametric Chirped Pulse Amplification (OPCPA) [4,5], will be provided by Thales Optronique (France) in collaboration with Thales Systems Romania. The lasers are driven by a dual front-end system with two parallel amplification arms, each arm delivering three outputs of different powers 10 PW, 1 PW and 0.1 PW. The corresponding

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laser pulses repetition rates for the three outputs are 1/60 Hz, 1 Hz and 10 Hz, respectively. Only one front-end will be used at a time, the other one being used as back-up in order to minimize the down time of the system. The successful implementation of the 10 PW lasers is conditioned by the development of solutions to several critical problems, such as: high order phase dispersion compensation with acousto-optic filters, achievement of high temporal contrast, limit the Strehl ratio decrease due to the thermal loading of the Ti:sapphire crystals, parasitic transversal lasing in large aperture Ti:sapphire crystals. At the high-field intensities to be achieved at ELI–NP high temporal contrast is necessary to avoid target deterioration before the laser pulse reaches the target. Large Strehl ratio is important for obtaining a small spot focused on the target. The main characteristics of the 10 PW high-power lasers system under construction at ELI–NP are summarized in Table 1. The system can provide in parallel two laser beams by combining any of the outputs from each of the amplification arm. The two laser beams can be used in parallel, in separate measurement setups, or combined together in one single setup. Synchronization to better than 200 fs of the laser beams provided by the two amplification arms is ensured by their common front-end. More technical details on the high-power lasers of ELI–NP are given in Ref.[6]. The Laser Beam Transport System (LBTS) was designed by the ELI–NP scientific team such to optimize the use of the available laser beams based on the proposed experiments [3]. Fig. 2 shows a schematic of the proposed LBTS aiming to serve the experimental halls. The LBTS has to transport the laser pulse every 10 ms at the interaction point for 32 times without a sensitive degradation of the pulse intensity and duration and preserving the number of electron–photon interactions while maintaining the quality of the electron and laser beams to ensure a high spectral density of the gamma beam. The solution adopted for the building of the gamma beam system (GBS) at ELI–NP is based on the use of: a warm RF linac producing high-intensity, low emittance electron beams; very brilliant, high-repetition interaction lasers; a small collision volume. The design and the construction of GBS is being performed by EuroGammaS [7], a European Association of academic and research institutions (INFN – Italy, Sapienza University – Italy, CNRS – France) with industrial partners (ACP Systems – France, ALSYM – France, COMEB – Italy, SCANDINOVIA – Sweden) and several sub-contractors with expertise in the field. The GBS at ELI–NP is designed in two stages: a low-energy stage delivering gamma-ray beams with energies up to 3.5 MeV and a high-energy stage providing gamma-ray beams with energies up to 19.5 MeV. The main components of the GBS are [7]: the RF linac, the lasers, the laser circulators and the collimators. The layout of the GBS is shown in Fig. 3.

2.2.1. RF linac

The electron accelerator is built of an S-band photo-injector and C-band accelerating structures. In the low-energy stage the electrons are accelerated up to 300 MeV while in the high-energy stage up to 720 MeV. A multi-bunch photo-cathode RF gun [8] will provide 32 bunches of electrons of about 250 pC separated by 16 ns with a repetition rate of 100 Hz. The electron beam at the interaction point will be delivered with advanced features such as normalized emittance of about 0.2–0.6 mm mrad, bunch energy spread of 0.04–0.1%, time arrival jitter of less than 0.5 ps and pointing jitter of 1 micron.

2.2.2. Lasers

The photo-cathode laser is a 100 Hz repetition UV laser combination with a multi-pulse cavity for the generation of 32 pulses separated by 16 ns. There will be two J-class high-quality Yb:YAG interaction lasers with similar characteristics: photons of 515 nm, energy of 0.2 J, repetition rate of 100 Hz. One of them will be used for the low-energy interaction point and both of them for the high-energy interaction point.

2.2.3. Laser beam circulators

To ensure the collision of the laser pulses with a repetition rate of 100 Hz with the corresponding 32 micro-bunches of electrons repeating every 10 ns, a laser pulse circulator is under development [9]. The role of this device is to transport the laser pulse every 16 ns at the interaction point for 32 times without a sensitive degradation of the pulse intensity and duration and preserving the polarization of the photons. The system allows for a sizeable increase of the number of gamma-ray photons.

2.2.4. Collimators

The principle of operation of the collimators is based on the energy-angle dependence of the gamma-rays following ICS to select the requested bandwidth (better than 0.5% in the case of ELI–NP). Due to the small transversal dimensions of the gamma beam a dedicated collimator system was designed for the GBS at ELI–NP based on the configuration reported in [10]. In designing the collimator system one had to consider the following advantages for the production of quasi-monochromatic high brilliance gamma beams: (1) it provides the most efficient frequency amplifier process for the incident laser radiation (more than one million times in the case of ELI–NP); (2) the energy of the scattered photons is correlated with the scattering angle; (3) strong forward focusing of the scattered radiation. The drawback of the method is the low cross-section of the ICS process of the order of $10^{-25}$ cm$^2$.

To produce high-intensity gamma beams one has to maximize the number of electron–photon interactions while maintaining the quality of the electron and laser beams to ensure a high spectral density of the gamma beam. The solution adopted for the building of the gamma beam system (GBS) at ELI–NP is based on the use of: a warm RF linac producing high-intensity, low emittance electron beams; very brilliant, high-repetition interaction lasers; a small collision volume. The design and the construction of GBS is being performed by EuroGammaS [7], a European Association of academic and research institutions (INFN – Italy, Sapienza University – Italy, CNRS – France) with industrial partners (ACP Systems – France, ALSYM – France, COMEB – Italy, SCANDINOVIA – Sweden) and several sub-contractors with expertise in the field. The GBS at ELI–NP is designed in two stages: a low-energy stage delivering gamma-ray beams with energies up to 3.5 MeV and a high-energy stage providing gamma-ray beams with energies up to 19.5 MeV. The main components of the GBS are [7]: the RF linac, the lasers, the laser circulators and the collimators. The layout of the GBS is shown in Fig. 3.

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requirements: low transmission of gamma-ray photons, continuously adjustable aperture to ensure the required bandwidth for the whole range of energies, minimization of secondary radiation production.

The gamma beam system under construction for ELI–NP will provide beams with unprecedented brilliance and spectral density. The main features of the gamma beams to be delivered at ELI–NP are listed in Table 2. With these parameters the ELI–NP GBS will become the most advanced gamma beam system in the world. Parameters such as bandwidth, brilliance at peak energy, spectral density will be orders of magnitude better than what is presently achieved with the state-of-the-art systems [11,12].

3. Experiments at ELI–NP

The scientific program of ELI–NP is focused on nuclear physics research with high-power lasers and gamma beams. The

![Fig. 2. Preliminary Laser Beam Transport System in the areas for experiments with high-power lasers. The experimental areas are marked on the figure. The E1, E4, E5 and E6 areas are dedicated to experiments with laser beams only while the E7 area will be used for experiments with combined laser and gamma beams.](image1)

![Fig. 3. General layout of the gamma beam system at ELI–NP. The main components of the system are indicated on the figure.](image2)

<table>
<thead>
<tr>
<th>Gamma beam parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td>0.2–19.5</td>
</tr>
<tr>
<td>Spectral density [ph/s/eV]</td>
<td>0.8–4 × 10⁴</td>
</tr>
<tr>
<td>Bandwidth (bdw) rms [%]</td>
<td>≤0.5</td>
</tr>
<tr>
<td>Source rms size [μm]</td>
<td>≤8.3 × 10⁻⁶</td>
</tr>
<tr>
<td>Source rms divergence [μrad]</td>
<td>10–30</td>
</tr>
<tr>
<td>Pulse length rms [ps]</td>
<td>0.7–1.5</td>
</tr>
<tr>
<td>Linear polarization [%]</td>
<td>≥99</td>
</tr>
<tr>
<td>Macro repetition rate [Hz]</td>
<td>100</td>
</tr>
<tr>
<td>Number of pulses/macropulse</td>
<td>32</td>
</tr>
<tr>
<td>Pulse-to-pulse separation [ns]</td>
<td>16</td>
</tr>
<tr>
<td>Brilliance at peak energy [1/s mm² mrad² 0.1%bdw]</td>
<td>10²⁰–10²²</td>
</tr>
<tr>
<td>Source position transverse jitter [μm]</td>
<td>≤5</td>
</tr>
<tr>
<td>Energy jitter pulse-to-pulse [%]</td>
<td>≤0.2</td>
</tr>
<tr>
<td>Number of photons jitter pulse-to-pulse [%]</td>
<td>≤3</td>
</tr>
</tbody>
</table>
opportunities to study new physics and exotic phenomena with the ELI–NP laser and gamma beams were discussed in the ELI–NP White Book [3]. The present paper will briefly review some of the physics cases identified by the international ELI–NP working groups as first-day experiments for the new facility.

3.1. Experiments with high-power laser system

Nuclear physics research at high-power lasers is still at the beginning. Several research laboratories around the world are implementing PW class lasers and investigate their potential. A review of the nuclear physics applications of high-power lasers can be found in Ref. [13]. Laser-driven ions acceleration is one of the main research topics at ELI–NP as a possible compact and lower cost alternative to the present acceleration facilities. Pioneering work [14,15] performed at the VULCAN facility of Rutherford Appleton Laboratory (UK) showed the possibility to achieve heavy ion acceleration following the interaction of an ultra-high intensity laser with solid targets. Experiments and theoretical works are supporting the idea of two mechanisms responsible for the acceleration of ions: Target Normal Sheath Acceleration (TNSA) [16] in micrometers thick targets and Radiation Pressure Acceleration [17] in sub-micron thick targets. These mechanisms are still not fully understood and ELI–NP will contribute to their investigation and understanding. Laser-driven heavy ions acceleration will be also investigated from the point of view of its use for initiating nuclear reactions. The high density of accelerated ions following the interaction of high-power lasers with solid targets will open the possibility to investigate exotic processes such as the 2-steps fission-fusion reaction [18]. One proposal [19] is to accelerate $^{232}\text{Th}$ nuclei at several MeV/u followed by their fission and to induce the fission of $^{232}\text{Th}$ nuclei in a subsequent target. The population of the beam- and target-like light fission fragments will lead to the fission of $^{232}\text{Th}$ nuclei in a subsequent target. The population of the beam- and target-like light fission fragments will lead to the fusion with high yields of neutron-rich nuclei around the $N = 126$ waiting point of the $r$-process.

The E4/E5 experiment areas will be reached by the higher repetition laser beams with powers of 0.1 PW (10 Hz) and 1 PW (1 Hz). The secondary laser-driven radiation produced by these beams (electrons, protons, neutrons, gamma rays) will be used to study materials behavior under extreme conditions of radiation with application in the selection and development of materials for fusion devices, fission reactors or space science. Materials used traditionally for the building of targets, beam protection elements, beam pipes, windows are exposed to extreme thermo-mechanical loads and radiation fields at the high-power accelerators such as FAIR or LHC. The measurements proposed at ELI–NP aim to estimate the lifetime of these elements and to provide realistic input data for simulation calculations.

3.2. Experiments with gamma beams

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. 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 $\gamma$-ray Source (HiS), characterized by a 3% bandwidth and spectral density of about $10^9$ photons/s/MeV 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 $I_0$. Features of the gamma beams available at ELI–NP such as 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.

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.

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.

Photo-nuclear reactions with high-energy gamma beams above the particle separation threshold will mainly excite collective state such as the Giant Dipole Resonance (GDR). Recently it was shown that GDRs show a discrete sub-structure that can be investigate with the narrow bandwidth gamma beams available at ELI–NP. At excitation energies close to the particle separation threshold another type of excitation mode corresponding to the oscillation of the neutron skin against the core nucleus was identified [22]. It was called Pygmy Dipole Resonances (PDR). PDR can be investigated at ELI–NP above and below the particle threshold to reveal essential information for the understanding of the nucleosynthesis process in astrophysics. The study of PDRs can show neutron skin effects and set constrains on the equation of state of neutron-rich matter [23,24].

Nuclear astrophysics and nucleosynthesis research based on gamma-induced reactions, $(\gamma,n)$ or $(\gamma,\text{charged particles})$, with very low cross sections will largely benefit from the use of the high intensity gamma beams at ELI–NP. The p-nuclei resulted from the destruction of s- and r-type nuclei through a combination of $(p,\gamma)$, $(\gamma,n)$, $(\gamma,p)$ or $(\gamma,\alpha)$ photo-reactions [25].

Photo-fission represents an important category of experiments to be carried-out at ELI–NP. There are three types experimental directions considered: studies of photo-fission barriers, cross sections and rare fission modes such as ternary fission or highly asymmetric fission; separation, manipulation and experiments with fission fragments; in-beam $\gamma$-ray spectroscopy of fission products. Production and study of refractory elements in thin U targets following photo-fission is proposed. For a highly efficient extraction of the photo-fission products the IGISOL technique [26] with gas-cell catcher is proposed.

The use of high-energy gamma beams can open new opportunities in radioisotopes production schemes for medicine by following $(\gamma,n)$ reactions [27]. One of the candidates considered at ELI–NP is the $^{195}\text{Pt}$ isotope that is a promising imaging agent to determine the efficiency of some chemotherapy procedures in cancer treatment.

3.3. Experiments with combined high-power laser and gamma beams

Both the high-power lasers and the gamma beams can reach the E7 area. This particular configuration of the experimental area opens unique possibilities to study the same target with these very different brilliant beams and to reveal new phenomena. Production and photo-excitation of isomeric states in nuclei is one of the proposed experiments. Isomeric states will be excited by the $2 \times 10$ PW lasers and subsequently photo-excited with the gamma
beam just above the neutron threshold. Detection of the resulting photo-neutrons will be a signature of the isomer excitation.

4. Conclusions

At ELI–NP two main research systems, an ultra high-power laser system composed of two 10 PW lasers and a brilliant, high intensity gamma beam system, with features well beyond the present-day state-of-the-art, are presently under construction. The facility is dedicated to nuclear physics research based on lasers and the unique features of the available laser and gamma beams will open new opportunities in fundamental physics, nuclear physics, nuclear instruments and diagnostics tools development and applied physics research. In parallel with the construction and installation 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 [3]. 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.

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References