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Perspective

New light in nuclear physics: The extreme light infrastructure

D. L. Balabanski, R. Popescu, D. Stutman, K. A. Tanaka, O. Tesileanu, C. A. Ur, D. Ursescu and N. V. Zamfir

Extreme Light Infrastructure-Nuclear Physics (ELI-NP)/Horia Hulubei National Institute of Physics and Nuclear Engineering - Reactorului St., 30, PO Box MG-6, 077125, Bucharest-Magurele, Romania

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Abstract – Extreme Light Infrastructure-Nuclear Physics (ELI-NP), to become operational in 2019, is a new Research Center built in Romania that will use extreme electromagnetic fields for nuclear physics research. The ELI-NP facility will combine two large equipments with state-of-the-art parameters, namely a 2×10 PW high-power laser system and a very brilliant gamma-beam system delivering beams with energies up to 19.5 MeV. The laser and gamma-beam systems under construction and typical proposed first-phase experiments are described.

Introduction. – Extreme Light Infrastructure-Nuclear Physics (ELI-NP) [1], under construction near Bucharest in the Magurele Physics Research Campus, will host two major facilities: a high-power laser system consisting of two 10 PW ultra-short pulse lasers and the most brilliant tunable gamma-ray beam machine currently unavailable in the world. Not only will both these types of photon beams be available in the same infrastructure, but also the characteristics of each of these beams are unique and beyond state-of-the-art worldwide at the moment of starting operation, allowing to approach a field of science not yet explored, at the frontier between laser, plasma and nuclear physics.

The intense electromagnetic fields are promising to produce the experimental platform for expanding the scientific horizon of nuclear physics. Using these systems, unique and original experimental designs have been proposed in the field of new frontiers in nuclear physics and astrophysics, photonuclear reactions, strong field non-linear quantum electrodynamics (QED) effect, and dark-matter physics. The highlights of the ELI-NP experimental program were recently reviewed [2]. The Technical Design Reports for the future experiments are presented in ref. [3], and in this article we will outline the "first day" experiments. The ELI-NP laboratory complex will have eight experimental halls (fig. 1)

Ultra-high intensity laser and high-brilliance gamma-beam systems. – The high-power laser system (HPLS) of ELI-NP is built by Thales Optronique France in collaboration with Thales Systems Romania. The central wavelength was chosen to be around 815 nm, as it efficiently amplifies in Ti:Sapphire. The system shall reach 10 PW peak power in pulses of durations below 22 fs, with a contrast of 10^{13}:1 at 100 ps ahead of the pulse peak. Figure 1 shows the laser beam system configuration. HPLS has two arms, operated by a common front-end, thus being intrinsically synchronous. Each arm has three dedicated optical compressors allowing compressed pulse extraction at different amplification levels, *i.e.*, at 100 TW it operates at 10 Hz, at 1 PW at 1 Hz and at 10 PW at 1 shot/minute. The pointing, spatial, temporal, spectral, and polarization properties of the pulses are essential to various experiments implementation. The pointing stability of the system is achieved with a ground floor specified to have the power spectral density of the vibrations at the level of 10^{-10} g^2/Hz in a frequency range from 1 Hz to 200 Hz. The measurements performed during building commissioning confirm the stability of the floor. With this parameter achieved, the expected pointing fluctuations shall remain below 3 μrad root mean square In order to avoid the long-term drift of the pointing, the temperature in the laboratory building is 22 °C and is stabilized to ±0.5 °C.

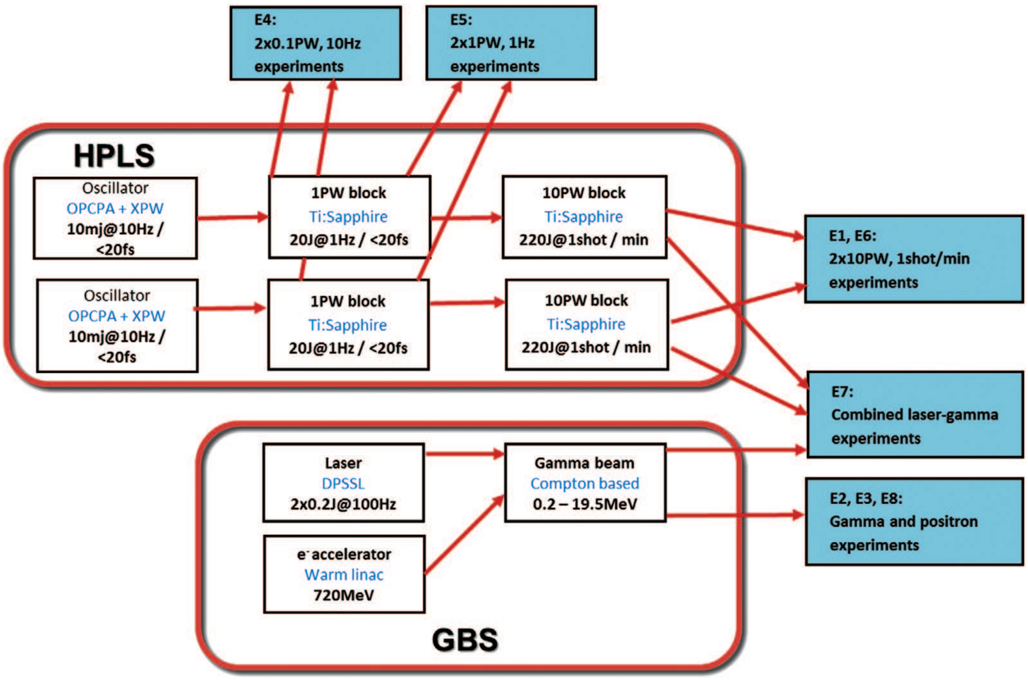

Fig. 1: (Color online) Sketch of the ELI-NP systems (HPLS and GBS) and the experimental areas.

The collimated laser beam diameter at full peak power after compression will reach 45 cm full width at half-maximum (FWHM) assuming super-Gaussian intensity profile and 55 cm diameter hard aperture clip. The optics for beam transportation shall be designed to remain better than $\lambda/20$ in order to secure proper beam transportation and focusing on the target. In order to reach high power and high intensity, each pulse shall be kept as short as possible. This implies that the amplification bandwidth shall be large and all the optics in the amplification chain shall support pulses with broad bandwidth of at least 170 nm. The targeted temporal contrast of at least 10^{13}:1 at 100 ps ahead of the pulse peak is a challenge in both reaching it and measuring it. To date, there is no measurement device with a dynamic range better than 10^{12}:1 and thus the evaluation of the contrast is made by more indirect means, evaluating the temporal contrast enhancement induced by various specific subsystems such as cross-polarized wave (XPW) system or optical parametric amplification system.

The HPLS beams will be delivered to the various experimental areas, identified in fig. 1. There will be one dedicated experimental hall for the two 100 TW pulses (E4) and one for the two 1 PW pulses (E5). There, testing of components and instrumentation for the facility at intermediate power levels will be done, prior to their transfer to the 10 PW experimental areas E1, E6 and E7.

The 100 TW and the 1 PW beams will be delivered through vacuum pipelines, as part of the HPLS. A laser beam transport system (LBTS) is designed now for the transport of the 10 PW beams to the three experimental areas. The beam transport system will take the compressed pulses at the output of the optical compressors and will transport them through vacuum specified to reach 10^{-6} mbar residual pressure. The main features of the LBTS is the ability to deliver two synchronized 10 PW beams on the target in each experimental area. This will be a unique feature of the facility, allowing a range of pump-probe experiments at unprecedented levels of power. The synchronization level is foreseen to be realized at sub-ps level using a delay line that balances the optical path difference between the laser arms from the splitting to the target. The estimated length of the delay line is 15 m.

ELI-NP will benefit also from a very bright gamma-beam system (GBS) [4]. The system was conceived as a dedicated device based on the inverse Compton backscattering of high-intensity laser pulses off high-brightness relativistic electron bunches and able to provide gamma beams with unprecedented features: continuous tunable gamma-ray energy over a broad range (from 200 keV to 19.5 MeV), high spectral density (about 10^4 photons/s/eV), small relative bandwidth (lower than 0.5%), high degree of linear polarization (higher than 95%), and high peak brilliance. The high brightness electron beam is to be provided by a compact linear RF electron accelerator composed of a S-band photoinjector and a new concept of damped C-band accelerating structures. Electrons will be provided as trains of 32 micropulses of 250 pC each, separated at 16 ns from each other, repeating every 10 ms. To achieve a small emittance of the electron beam (0.2–0.6 mm mrad) with energy spread below 0.1%, when designing the accelerator a particular care was paid to the damping of higher-order modes (HOM) to reduce

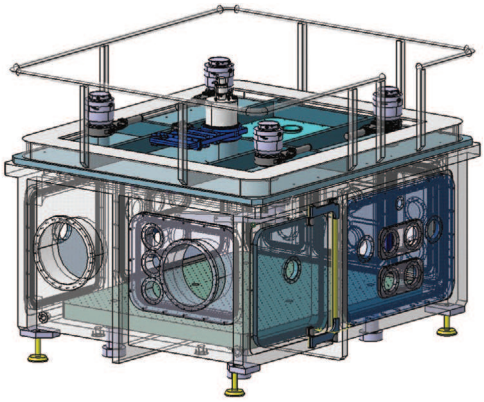

Fig. 2: (Color online) Design of the 10 PW interaction chamber.

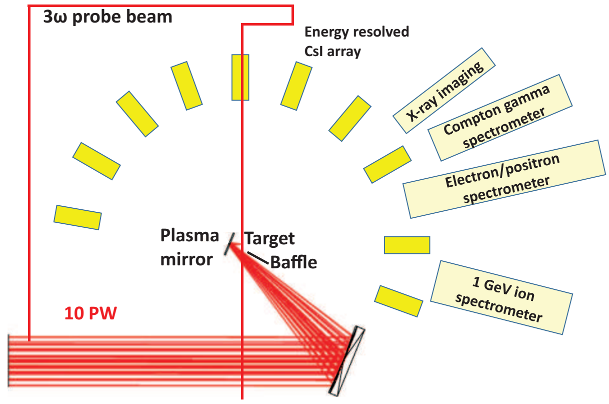

Fig. 3: (Color online) Layout of the laser-gamma conversion experiment.

the beam break-up (BBU) effects and to the reduction of beam loading effects of the cavities due to the short-time separation between the electron micropulses [5]. The electron accelerator is designed to be operated in two stages: one providing electrons with energies up to 300 MeV and a second one where electrons are further accelerated up to more than 720 MeV. Green light at the wavelength 515 nm laser pulses will be provided at the interaction points at 100 Hz repetition rate by J-class cryo-cooled Yb:YAG lasers. There are two interaction points, one for each stage of the electron accelerator, providing gamma beams with energies up to 3.5 MeV and up to 19.5 MeV, respectively. To ensure the interaction of the laser pulses generated at 100 Hz with the 3.2 kHz electron microbunches, optical cavities for the recirculation of the laser pulses were foreseen at the interaction points. Each laser pulse will be re-circulated between two parabolic mirrors for 32 times without significant degradation of the pulses quality [6]. The whole system is time synchronized to an accuracy better than 0.5 ps. The small energy bandwidth of the gamma beam is obtained by using custom-developed collimation systems with continuously adjustable aperture [7].

First-phase experiments. – The extreme light intensity achievable with the 10 PW ELI-NP lasers will enable producing extreme electric fields of over 10^{15} V/cm, and extreme light pressures of over 10^{13} bar. To accommodate the 2×10 PW experiments at 1 pulse/min, two large ($\sim 4 \times 3.5 \times 2$ m), nearly identical experimental chambers, E1 and E6, have been designed. We chose a large chamber setup because the footprint of the parabolic mirrors which focus the 60 cm diameter laser beams is of the order of $1 \times 0.8 \times 0.5$ m, with mounting frame and positioning stages. The design of the E6 chamber, shown in fig. 2, will enable easily changing the diagnostic views, adding extensions to the interaction chamber, and even changing the distance between the laser beams if necessary. In addition to the 2×10 PW experimental areas, a 2×1 PW at 1 pulse/s experimental area E5 has been designed, dedicated to studies of materials under simultaneous irradiation with multiple types of laser-produced nuclear radiation.

A mirror-based circular polarization system is being developed for studies of ion acceleration with different laser polarization states. Helical-phase beams will also be studied for improved ion acceleration regimes [8] and as a possible substitute for circular polarization, since for large diameter laser beams it is much less costly to shape the phase of the beam instead of its polarization. The most important characteristic of the 10 PW lasers is the extreme intensity achievable at the focus (in the range $\sim 10^{23}$ W/cm^2 with $f/3$ focusing optics). The first commissioning experiment at experimental area E1 will thus aim to demonstrate focal intensity in this range through efficient conversion of the laser light into gamma rays. The theory predicts that in dense targets up to tens of % of the laser energy can be converted to MeV gamma rays through synchrotron radiation. To eliminate the problem of target debris we consider using a high-density He or H jet as a target in the first experiments. Recent calculations show that 45% of the laser energy can be converted to gammas in a gaseous hydrogen target having four times the critical electron density, n_c [9]. GeV energy protons might also be produced in a gaseous hydrogen target having $2 \times n_c$ electron density [10]. Alternately, μm thick plastic foils can be used for intense gamma-ray generation.

The conceptual setup for the laser-gamma conversion experiment is shown in fig. 3. An array of energy-resolved CsI scintillator detectors will measure the gamma output as a function of intensity at several angles, while Compton and electron/positron spectrometers will measure the spectrum up to a few tens MeV. An important element in the setup is a plasma mirror having primarily the role of preventing laser back-reflection into the expensive 10 PW beam transport and amplification system. A preliminary design for a multi-shot plasma mirror/target system is shown in fig. 4. Parabola protection from debris is also achieved using a baffle. Following the gamma conversion experiment we will utilize the extreme light pressure of the 10 PW laser for acceleration of dense ion bunches to energies of the order of 10 MeV/nucleon, in preparation for nuclear-physics experiments.

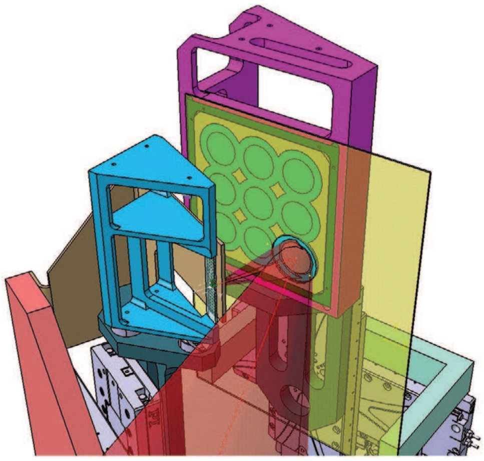

Fig. 4: (Color online) Preliminary layout of multi-shot 10 PW plasma mirror and target system.

The potential for producing near-solid density ion bunches is one of the main attractions of laser-driven acceleration for nuclear physics, because it opens the possibility of producing exotic nuclear reactions, which either require chains of interactions, or have very low cross-sections. A typical example is the production of neutron-rich nuclei around the $N = 126$ waiting point through fission-fusion reactions, for studies of heavy-element nucleosynthesis.

In a parallel commissioning experiment at area E6, we will utilize the extreme laser electric field to study strong-field QED (quantum electrodynamics) phenomena such as non-linear inverse Compton scattering, radiation reaction, and Breit-Wheeler pair production. To this end, fs duration and sub-nC charge electron bunches will be accelerated to a few GeV by wakefield acceleration in gas with one laser focused at $f/20$, then collided at $135\,^\circ$ with an extreme-intensity light pulse from the second laser focused at $f/4$. The electron acceleration to ultra-relativistic energies has the role of increasing the electric field seen by the electron in its rest frame, to values approaching the Schwinger field. With later upgrade of the wakefield parabola to $f/80$, electron bunches could be accelerated to over 10 GeV energy.

The experimental program at the GBS of ELI-NP benefits from the availability of gamma beams with high spectral density, 10^4 ph/(s $\cdot$ eV), narrow bandwidth, $\geq$0.5%, and high polarization, >95%, and is directed towards photonuclear studies of the structure and reactions of atomic nuclei and development of gamma-beam applications. Few research fields are considered, *e.g.*, nuclear resonance fluorescence experiments (NRF), nuclear astrophysics studies, photonuclear reaction and photofission measurements and experiments involving excitations above the particle-emission threshold. For the realization of the NRF experiments, a γ-ray spectrometer, the ELI-NP array of Ge detectors (ELIADE), is under construction. It consists of eight segmented Ge Clover detectors and uses digital data-acquisition system. Experiments with γ-beams above the neutron separation threshold will be carried out with the ELIGANT-GN array, which consists of 30 large $LaBr_3$:Ce and $CeBr_3$ detectors, 20 ^{6}Li-glass detectors and up to 60 liquid scintillator detectors. The array allows simultaneous measurement of the gamma and the neutron decay of excited states. The positioning of the two arrays in the E8 experimental area of the ELI-NP laboratory complex is presented in fig. 5.

The availability of high-brilliance gamma beams and of the high-efficiency ELIADE detector array will provide the possibility to push further several frontiers of NRF experiments, *e.g.*, increase of the sensitivity of the experiments by measuring weak-decay channels and improvement of the precision of the experiments due to better statistics. These experiments will take advantage of the narrow-bandwidth pencil-size beams at ELI-NP, which provide the possibility for studies of low-abundance targets, *e.g.*, NRF studies in the actinide nuclei.

The first-phase experiments under consideration involve studies of the distribution of the E1 strength in the region of the pigmy dipole resonance (PDR) and the giant dipole resonance (GDR). These studies will shed light on the origin of the PDR excitations. The high polarization (>95%) of the ELI-NP gamma beams, combined with the high intensity and the narrow bandwidth, will provide optimal experimental conditions for studies of the E1 strength in atomic nuclei. The use of mono-energetic gamma beams guarantees a very accurate determination of the E1 strength and its fragmentation. Due to the high brilliance of the beam, selection of either individual excited states, or very narrow averaging bins can be achieved, revealing information on the fine structure of the E1 strength distribution. In such a way, it will be possible to evaluate accurately the dipole polarizability, whose determination can constrain the neutron skin thickness and the symmetry energy of the nuclear equation of state (EoS). The use of polarized gamma rays guarantees to separately and unambiguously resolve the E1 and M1 resonances, coexisting in the low-energy region.

The p-process ^{180}Ta(γ, n)^{179}Ta and ^{138}La(γ, n)^{137}La reactions, which are of high interest for nuclear astrophysics calculations [11], will be studied with the ELIGANT-GN array in the first phase. For studies of (γ, α) and (γ, p) reactions an array of Si strip detectors, ELISSA, is under construction, which consists of 35 single-side position-sensitive silicon detectors, with four strips 10 mm wide and 75 mm long and eight annular segmented double-sided detectors that extend the angular coverage of the array. The expected precision in position of the event is of 1 mm. In the first-phase experiments, the array will be used for measuring the photodisintegration of ^{7}Li, a measurement which is of importance for understanding the Big Bang nucleosynthesis.

According to systemic calculations, the (γ, α) cross-sections and reaction rates are very sensitive to the optical-model potential of the α-particle. Precise experimental

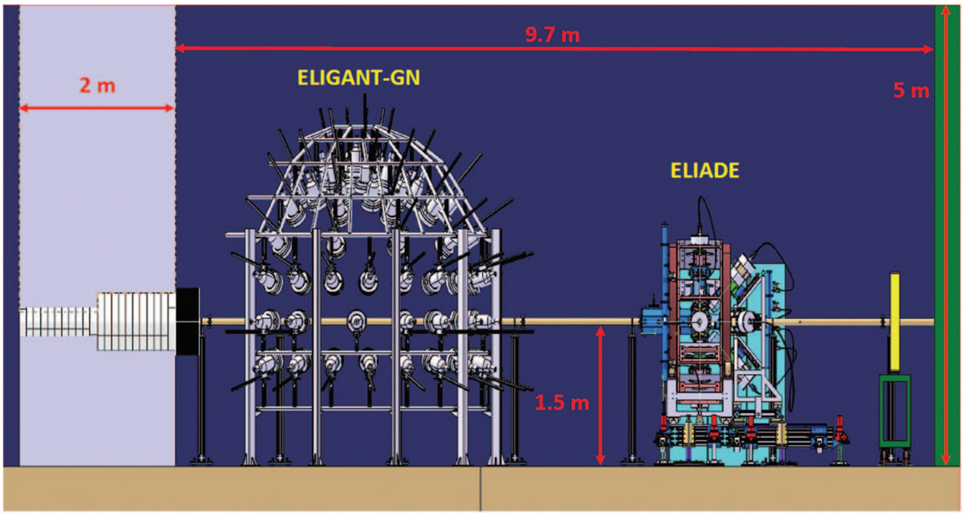

Fig. 5: (Color online) Positioning of the ELIADE and ELIGANT-GN arrays at the GBS high-energy beam line in the experimental area E8 of the ELI-NP laboratory complex.

studies of (γ, α) reactions will be possible at the ELI-NP facility. The astrophysically important nuclei for (γ, α) reactions include ^{74}Se, ^{92,94}Mo, ^{96,98}Ru, and ^{148}Gd, which are proposed as first-phase studies at ELI-NP. Furthermore, by combining the detection systems for both charged particles and neutrons, which are under construction at ELI-NP, the simultaneous measurement of $(\gamma, \alpha)/(\gamma, \mathrm{n})$ and $(\gamma, \mathrm{p})/(\gamma, \mathrm{n})$ branches would be possible. Especially, the branching ratios of $(\gamma, \alpha)/(\gamma, \mathrm{n})$ on ^{146}Sm and $(\gamma, \mathrm{p})/(\gamma, \mathrm{n})$ on ^{139}La are of significant importance for the determination of the nucleosynthesis and reaction path flow of both the s- and the p-process.

In addition, an electronic-readout time projection chamber (ELITPC) is under construction. The electronic readout, for which GEM detectors will be used and the signals will be processed with GET electronics, allows more flexibility in the choice of gas mixtures and higher resolution, and, in this way, the detector will be used for different active-target experiments. The ELITPC active volume will have dimensions of $35 \times 20 \times 20\,\mathrm{cm}^3$ and it will run at 100 mbar. In the first experiments it is planned to measure the cross-section of $^{16}\mathrm{O}(\gamma, \alpha)^{12}\mathrm{C}$, the time reverse of the $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ reaction relevant for the stellar helium burning process.

First-phase research in photofission will be directed on studies of transmission resonances in the light actinide nuclei, which will provide an insight into the multi-humped fission barriers. First measurements will be done on ^{238}U, which was recently measured at the HIγS facility at Duke University, as a preparatory experiment for ELI-NP [12]. At ELI-NP the experiments will benefit from the improved resolution, which is due to the narrow bandwidth of the gamma beam, as well as from the much higher intensity and the pencil size of the gamma beams.

In addition, a research program directed to different nuclear science applications is in preparation. These include the development of gamma-ray imaging techniques and methods for 3D industrial tomography and radiography, production of new medical radioisotopes, such as ^{195m}Pt, development of NRF analytical techniques for cultural heritage studies.

After the low-energy interaction point of the GBS, a positron-production chamber will be mounted. Positrons will be produced through pair creation, moderated in the target material and after DC field extraction, electrostatic and RFQ focusing, positron beams with intensity of 10^6 positrons/s will be delivered to different experimental stations for material science studies.

One of the main characteristics of ELI-NP that makes this facility unique worldwide is the possibility to use in experiments, simultaneously, two high-power laser beams and a high-intensity gamma radiation beam or accelerated electron beam. Pump-probe experiments were proposed, in nuclear physics and fundamental physics, to study the QED effects in ultra-intense fields. The experimental area E7 is where the two 10 PW laser beamlines intersect the gamma photons or electron beams. In fig. 6 (left), a configuration using one multi-PW laser beam and the accelerated electrons beam from the ELI-NP linac is presented. A gradual approach for the various experiment ideas was adopted, starting with the simpler setups as "commissioning experiments". In E7, a first-phase commissioning experiment will be the production and photoexcitation (PPEx) of isomers. The first-phase experiments for the E4 area, where two high-repetition rate 100 TW laser beams are available, proposes the four-wave mixing, by focusing in ultra-high vacuum two laser beams of different wavelengths [13]. A further experimental proposal at E4 is the study of photon-photon interactions at MeV energies [14].

In a second stage of the experiments, the accelerated electron beam from the linac will be extended to E7 and used in the experiments of radiation reaction [15–17] and

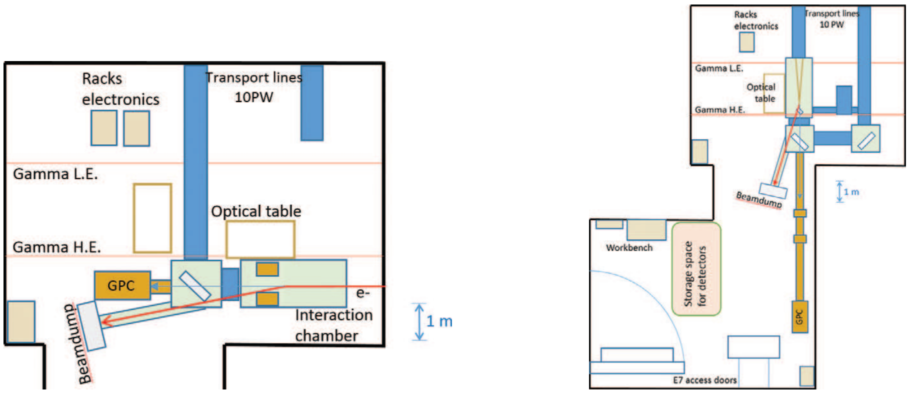

Fig. 6: (Color online) Experimental area E7. Left: setup for the radiation reaction studies Right: setup for the vacuum birefringence studies.

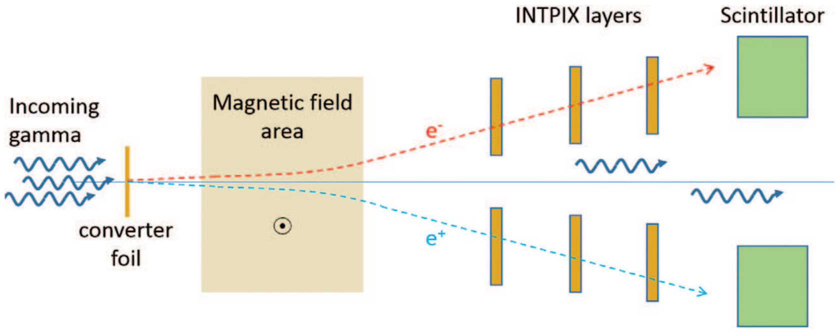

Fig. 7: (Color online) Block diagram of the GPC detector under development.

pair creation [18,19]. The most complex experiment foreseen for the E7 area is the study of vacuum birefringence [20], for which the block diagram is presented in fig. 6 (right). This experiment uses both multi-petawatt laser beams, synchronized at a femtosecond level, for the laser acceleration of electrons to multi-GeV energies, subsequent generation of polarized GeV gamma photons through Compton backscattering, and then detection of the residual polarization after these photons pass through the ultra-intense field generated in the short focus of one of the multi-PW beams. The experiment aims to verify the theories of the birefringence property of the vacuum in fields of unprecedented intensities.

In order to better understand astrophysical environments essential for nucleosynthesis, where conditions are extreme, it is important to study the properties of nuclei in isomeric states [21]. The basic idea of the PPEx experiment is to excite the target nuclei in isomeric states through gamma inelastic scattering, where the gamma photons are produced via bremsstrahlung from laser wakefield accelerated electrons. Then, the gamma beam from the ELI-NP GBS, appropriately tuned in energy, will be used to produce photo-neutron emission from the isomeric states (and not from the ground state). A combination of gamma-ray and neutron detectors will be employed to study the properties of the isomeric states. Preliminary calculations and simulations have been performed in order to select the best candidates for the targets, from the point of view of astrophysical relevance for nucleosynthesis and production yields.

In order to optimize the performance of the proposed experiments, several R&D activities were initiated: ultra-high vacuum, laser wakefield acceleration of electrons, the development of a new detector (GPC —gamma polari-calorimeter), synchronization between the beams.

A preliminary design of the GPC detector is shown in fig. 7. It will be used for the measurement of energy, momentum and polarization of the high-energy photons, using the pair creation in a converter foil. After passing through an area with intense magnetic fields, generated by configurations of permanent magnets, the electron and positron will intersect three layers of pixelated silicon detectors for the identification of the direction of propagation and will end up in a scintillator for energy measurement. Numerical simulations have been performed and testing experiments for the setup will be performed at collaborating laboratories before implementation at ELI-NP.

The vacuum levels needed close to the laser focus for the photon-photon experiment are extremely high, the sensibility of the measurements depending on them. Collaborations are in place now for the study of innovative methods of differential pumping and special materials to increase the level of vacuum to be attained tackling the main bottleneck, which is the fact that no material window can be inserted in the way of the laser beam.

Summary. – The two major equipment at ELI-NP have been described: the 10 PW laser and the up-to-19.5 MeV gamma beam systems. Typical first-phase experiments are presented with the use of 1) 10 PW laser, 2) 3.5 and 19.5 MeV gamma beams, and 3) combined laser and gamma-beam systems. Utilizing the full capabilities of these systems, totally new and unique physics will be studied for the first time: non-linear QED, and vacuum effects, nuclear resonance fluorescence, photonuclear reactions, etc. Novel nuclear-science applications have also been developed.

* * *

We acknowledge the contribution of the entire ELI-NP team. The design of the first-phase experiments is the result of a broad collaboration with scientists from research and academic institutions from all over the world. This work is supported by Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase II, a project co-financed by the European Union through the European Regional Development Fund through the Comptitiveness Operational Programme "Investing in Sustainable Development" (1/07.07.2016, COP ID 1334).

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