Extreme Light Infrastructure – Nuclear Physics

A New Research Infrastructure at the Interface of Laser and Subatomic Physics

Daniel URSESCU,1,2 Ovidiu TESILEANU,1 Mihail O. CERNAIANU,1 Syony GALES,1,3 and Nicolae V. ZAMFIR1
1ELI-NP, “Horia Hulubei” National Institute for Physics and Nuclear Engineering, 30 Reactorului Street, RO-077125 Măgurele, jud. Ilfov, Romania;
2National Institute for Lasers, Plasma and Radiation Physics (INFLPR), Atopești 409, 077125 Măgurele, jud. Ilfov, Romania;
3IPN Orsay/IN2P3/CNRS and University Paris XI, 91406 Orsay cedex, France

(Received October 8, 2013)

Extreme Light Infrastructure (ELI) is a pan European research initiative selected on the European Strategy Forum on Research Infrastructures Roadmap that aims to build a European Large-scale Facility devoted to ultra intense laser and gamma beams interaction with matter. We report on the status of Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility, one of the three ELI pillars under construction, to be operational in 2018. Placed in Romania, ELI-NP has as core elements a new generation 10 PW laser systems and a narrow band width Compton backscattering gamma source with photon energies up to 19 MeV. ELI-NP will address nuclear photonics, nuclear astrophysics and quantum electrodynamics involving extreme photon fields. Applications in nuclear medicine, in detection and characterization of nuclear materials and in material science with positron sources are foreseen.

Key Words: High power laser, Nuclear physics

In an effort spread over more than 60 years, nuclear physics communities across the world developed research facilities for specific domains of research, from synchrotrons and free electron lasers to neutron spallation sources and ion acceleration facilities for cancer treatment.

Ultraintense laser fields with intensities reaching up to $10^{22}$ W/cm², are now able to produce typical radiation formerly used in nuclear facilities, as demonstrated in laboratories across the globe. The emerging laser driven technologies are very promising in terms of cost, size and available parameter range. However, the vast majority of the experiments were performed in labs where the operation of the laser system did not reach the reliability of the nuclear facilities counterparts. The construction of a large scale laser-centered, distributed pan-European research infrastructure, involving beyond the state of the art ultrashort and ultraintense laser and gamma source technologies, was triggered through the Extreme Light Infrastructure project.

The three pillars of the ELI facility are built in Czech Republic, Hungary and Romania. The first one, ELI-Beamlines is dedicated to the construction and characterization of secondary radiation sources, such as electrons, x-rays and protons, driven by high repetition rate ultraintense lasers.1 The second one is dedicated to the generation and use of attosecond electromagnetic pulses.2,3 The third pillar is ELI-Nuclear Physics (ELI-NP). Its mission covers scientific research involving two domains where only very few experimental results were reported until now: laser-driven experiments related to nuclear physics, strong field quantum electrodynamics with associated vacuum effects, and nuclear photonics.

ELI-NP hosts two major research infrastructure instruments. A high power laser system (HPLS), with two arms, reaching up to 10 PW for each arm and a gamma beam system (GBS) that will provide a very intense and narrow-band gamma rays with energies up to 19 MeV. Eight experimental areas will be available for performing experiments, among which one experimental area will allow combined experiments. Figure 1 presents the block diagram of the facility.

The high power laser system HPLS of ELI-NP will be constructed by an association between Thales Optronique SA France and Thales Romania. It consists of a chirped pulse amplification system at about 820 nm central wavelength, with a dual front-end architecture, in order to minimize down-time for the laser facility. Each of the identical front-ends can provide a high contrast broadband laser pulse with energy in the tens of mJ range that is split and injected into the two parallel amplification chains. Each of the two parallel chains includes Ti:Sapphire amplifiers to bring the final output energy to the few hundreds of Joule level. Subsequently, the pulses are compressed to around 22 fs pulse duration that implies a peak power of 10 PW for each of the two arms. The repetition rate for the two 10 PW outputs is one shot per minute. The general layout of the HPLS laser system is similar to the one under development in France for CILEX-APOLLON facility.4

Along the two amplification chains, additional outputs with corresponding optical compressors will be installed. Their corresponding power levels are 0.1 PW and 1 PW at repetition rates of 10 Hz and 1 Hz, respectively. The pre-pulse temporal contrast for all the outputs is specified to be better than $10^{12}$:1 both at picosecond and nanosecond delays and the requested Strehl ratio is 0.9. The intensity in reach is $10^{23}$ W/cm², thus securing a properly defined laser pulse in both space and time for interaction with thin targets. Further specifications are considering the reproducibility of the laser pulse parameters.
in terms of energy and pointing stability. The first parameter is expected to reach 5% RMS while the second one targets less than 5 microrad RMS for both axes. The pointing stability specifications are based on the very tight specification for building vibration, where static damping of the floor is secured across the entire laser area and experiments area.

Synchronization of the laser pulses delivered from the parallel amplifiers is secured by the use of the common front-end. The front ends will incorporate the needed electronic parts in order to realize the synchronous operation of the laser system and the GBS with better than 200 fs precision at the laser oscillator level.

The overall control command of the HPLS will be TANGO based. TANGO is a distributed control system, used for controlling any kind of hardware or software systems that is working based on the client-server model. The software is developed by the European Community of Synchrotrons: ESRF, SOLEIL, ALBA, ELETTRA, etc. and is also used in other major projects like Laser Megajoule and Cilex - Apollon from France. The programming can be done using C++, Java and Python but TANGO also allows bindings with several commercial scientific software programs: LabVIEW, Matlab, Igor Pro, etc. The involved community has also written hundreds of device classes that implements the hardware access to different devices.

In the ELI-NP HPLS, TANGO will be used in controlling the access rights to the system, configuration (active front end, selection of the laser power, number of shots, etc), management of the system according to different states and transitions, system analyze, local control of devices, logging management, display trending and providing the data interface - Ethernet - to transmit the data.

In addition, because specific laser based experiments typically use an increased number of motors, actuators and cameras, a modular user friendly interface will be built using 3rd party software that will allow the user to generate in an easy manner different working scenarios. This application will be integrated with TANGO and will also permit the use of specific developed control algorithms and feedback loops to conduct experiments in an autonomous way.

The laser beam transport for the laser pulses to five experimental areas has to be built. The main technologies under scrutiny are relay imaging, plasma mirror for temporal contrast enhancement, mirror based polarization control and adaptive optics for high quality focus on target.

The gamma beam will be produced by the Compton backscattering of light photons on accelerated electrons. The photons are provided by an average power, high-repetition rate laser. No restrictions were imposed in the tender on the laser technology to be used for the GBS but laser technologies similar to the ones reported in are expected. The pulse energy is expected to be in the few hundreds of mJ range and frequency doubling of such laser pulses would provide green photons to be frequency up-shifted through the Compton backscattering process to 19 MeV. The pulse duration shall stay above 1 picosecond, as imposed by the narrow bandwidth condition imposed to the backscattering gamma rays, namely, relative bandwidth smaller than 0.5%.

The electron accelerator will be a warm linac, with two acceleration stages of 360 MeV each. Thus, the highest electron energies reachable will be of 720 MeV, allowing the production of up to 19 MeV gamma photons. A lower energy gamma output (up to about 3.5 MeV) will be also available, with similar beam characteristics with the high-energy output.

Through a public tender procedure, the development of the gamma beam will be awarded to a company or consortium. The implementation will have three phases, with two intermediate deliveries before the final commissioning.

The minimum output specifications for the Gamma beam (see Table 1) were established in a series of workshops and meetings organized with the scientific community interested in ELI-NP and industry, in order to satisfy the need of the scientists for the progress of their research, but also to have realistic expectations that are technically feasible within the time frame of project implementation. During the public purchase procedure for the acquisition of the GBS, tenderers may commit for values of these parameters above the minimum required specifications.

There are eight experimental areas of ELI-NP. Three of them are dedicated to GBS-only experiments, while four of the areas are using only the HPLS. There is also one experimental area, E7, dedicated to combined HPLS-GBS experiments. A significant fraction of the international scientific community contributed to the shaping of the ELI-NP facility is a series of workshops. The latest ones, held in 2013, were centered on laser driven experiments and on nuclear science with gamma beams and defined eight development directions for the facility. For each of them, technical design reports writing was triggered during the workshops.

Dosimetry, ionizing radiation metrology and radiation in-
duced damage are major active research areas in nuclear physics and engineering. Their applications extend from the nuclear power plants to medicine and from space science to material science and to accelerators engineering. As a leading facility in laser-driven nuclear physics, ELI-NP will take advantage of the specific properties of laser-driven radiation production, such as ultrashort time scale and the relatively broadband spectrum of secondary radiation at the experimental areas E4 (two 100 TW pulses at 10 Hz) and E5 (two 1 PW pulses at 1 Hz). Further specificity of the proposed experimental environment at ELI-NP is to simultaneously provide two or more types of radiation on the same target (e.g. laser accelerated electrons and laser accelerated ions). All these aspects will allow top class research with specific types of laser-produced radiation.

Ion driven nuclear physics research will be performed at the E1 experimental area. Here, laser accelerated heavy ions will drive nuclear reactions and further experiments related to astrophysics. The flagship experiment involves production of neutron rich isotopes using fission of Thorium and subsequent fusion process, to shed light on one of the most important questions in today’s physics on super-heavy elements formation. Such experiments require significant experimental development in the field of laser driven ion acceleration according to new acceleration mechanisms, including radiation pressure acceleration\(^1\) and breakout afterburner.\(^2\)

The experimental area E6 will host experiments related to strong field quantum electrodynamics. High intensity on solid targets, up to \(10^{23} \text{W/cm}^2\) is intended. The type of experiments will imply a different set of diagnostics tools, compared to the ones at E1 where ion-driven nuclear physics experiments will be performed. Here, electron-positron production in laser irradiated solid targets and their subsequent behavior will be the main object of study\(^3\).

The combined experiments from E7 area will host a vacuum chamber where one pulse from each 10 PW HPLS output will be focused. The two pulses will be synchronous, allowing both laser-laser experiments but also laser-gamma. The envisaged experiments are related to studies of the vacuum in strong fields, such as studies of vacuum birefringence, gamma-assisted pair creation in strong laser field and dark matter studies.\(^4\)

A series of workshops related to nuclear science with the ELI-NP gamma beam that took place in Bucharest-Magurele, gathered the support of the scientific community. In June 2013 several main aspects were discussed, as follows.

One of the workgroups started with that occasion focuses on the gamma beam delivery and characterization. Many of the proposed experiments for the gamma beam are highly sensitive to the accurate knowledge on the gamma beam parameters and consequently standardized reliable methods must be devised to characterize the beam on target.

The low energy gamma experiment area E2 shall be mainly dedicated to Nuclear Resonance Fluorescence (NRF) experiments and applications\(^5\). Due to the brilliance of the gamma-ray beam, significantly increased with respect to existing facilities, experiments on materials whose availability is very limited will become feasible.

The E8 experiment area at ELI-NP is dedicated to experiments that can use the entire range of gamma ray energies, but mainly the higher energies 3-19 MeV. Phototisation and photodisintegration experiments are foreseen for this area, three TDR workgroups being involved in the design of the equipment to be placed here. The first one focuses on phototisation, topic where ELI-NP gamma beam will bring significant advances, due to the brilliance, large energy range and very good bandwidth\(^3\). The second has as main topic the photonic reactions above the particle threshold, very important for astrophysics studies (nucleosynthesis)\(^6\) but also for applications and new generation nuclear reactors. The third one aims to prepare the detection of charged particles resulting in nuclear reactions of the proton and alpha burning processes that are essential for stellar evolution theory, and most importantly the measurement of cross sections of the \(^{12}\text{C} (\alpha, \gamma)\) reaction relevant for stellar helium burning.\(^7\)

ELI-NP will feature a brilliant positron beam, the E3 experiment area being dedicated to research based on this beam, including imaging and applications.\(^8\) The realization of intense positron sources may reach large importance in material and life sciences.

A variety of applied research proposals have been received by ELI-NP. The project aims at the development of techniques for remote characterization of nuclear materials or radioactive waste via NRF which will be of increasing importance in the future. New production schemes of medical isotopes via the \((\gamma, n)\) reactions might also reach socio-economical relevance.\(^9\)

**Outlook**

Benefiting from the support of a large number of specialists across the globe, the ELI-NP facility is on track with the technical design reports and construction of the experimental areas. Commissioning is expected to take place in the end of 2017. This work is supported by Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase I, a project co-financed by the Romanian Government and European Union through the European Regional Development Fund.

---

Table 1 Specified output parameters for the gamma beam system:

| Type                              | Units | Range      |
|-----------------------------------|-------|------------|
| Photon energy                     | MeV   | 0.2-19.5   |
| Divergence                        | Rad   | \(\leq 2.0 \times 10^{-4}\) |
| Average Relative Bandwidth of Gamma-Ray Beam | –     | \(\leq 5.0 \times 10^{-3}\) |
| Time-Average Spectral Density at Peak Energy | \(1/(s \text{ eV})\) | \(\geq 5.0 \times 10^3\) |
| Time-Average Brilliance at Peak Energy | \(1/(s \text{ mm}^2 \text{ mrad}^2 0.1\% \eta_{\gamma})\) | \(\geq 1.0 \times 10^{21}\) |
| Minimum Frequency of Gamma-Ray Macropulses | Hz    | \(\geq 100\) |

---

1. ELI-NP Whitebook, http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf
References

1) B. Rus, P. Bakule, D. Kramer, G. Korn, J.T. Green, J. Novák, M. Fibrich, F. Batysta, J. Thoma, J. Naylon, et al.: 87801T (May 7, 2013), doi:10.1117/12.2021264.
2) S. Banerjee, M. Baudisch, J. Biegert, A. Borot, A. Borzsonyi, D. Charalambidis, T. Ditmire, Z. DIVEKI, P. Dombi, and K. Ertel: CLEO: 2013, OSA Technical Digest (online) (Optical Society of America, 2013), paper CTu2D.6.
3) C. L. Arnold, F. Brizuela, A. Borot, and F. Calegari: CLEO: 2013, OSA Technical Digest (online) (Optical Society of America, 2013), paper JTh2A.13.
4) G. Cheriaux, F. Giambruno, A. Freneaux, F. Leconte, L.P. Ramirez, P. Georges, F. Druon, D.N. Papadopoulos, A. Pellegrina, C. LeBlanc, et al.: AIP Conference Proc. on Light at Extreme Intensities 1462 (2012) 78.
5) Nexeya Systems: Control Systems for Experimental Physics Facilities: Know how & References (March 2013).
6) F. J. Furch, B. A. Reagan, B. M. Luther, A. H. Curtis, S. P. Meehan, and J. J. Rocca: Opt. Lett. 34 (2009) 3352.
7) J. Tümmler, R. Jung, H. Stiel, P. V. Nickles, and W. Sandner: Opt. Lett. 34 (2009) 1378.
8) A. Macchi, M. Borghesi, and M. Pascoli: arXiv:1302.1775.
9) L. Yin, B. J. Albright, B. M. Hegelich, and J. C. Fernandez: Laser and Particle Beams 24 (2006) 291.
10) E. Esarey, C. B. Schroeder, and W. P. Leemans: Rev. Mod. Phys. 81 (2009) 1229.
11) A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel: Rev. Mod. Phys. 84 (2012) 1177.
12) U. Kneissl, N. Pietralla, and A. Zilges: J. Phys. G 32 (2006) R217.
13) P. G. Thirolf, L. Csige, D. Habs, M. Günther, M. Jentschel, A. Krasznahorkay, D. Filipescu, T. Glodariu, L. Stroe, O. Tesileanu, et al.: EPJ Web of Conferences 38 08001.
14) K.-L. Kratz, J. P. Bitouzet, F.-K. Thielemann, P. Moeller, B. Pfeiffer: Astrophys. J. 403 (1993) 216.
15) R. Wallerstein, I. Iben, P. Parker, A.M. Boesgaard, G. M. Hale, A. E. Champagne, C. A. Barnes, F. Kappeler, V. V. Smith, R. D. Hoffman, et al.: Rev. Mod. Phys. 69 (1997) 995.
16) W. A. Fowler: Rev. Mod. Phys. 56 (1984) 149.