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EXTREME LIGHT INFRASTRUCTURE – NUCLEAR PHYSICS (ELI-NP) PROJECT AND RESEARCH PROGRAM

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An overview of ELI-NP facility under construction and the parameters of its two main machines, the High-Power Laser System (HPLS) and the Gamma Beam System (GBS), are presented along with the broad fundamental and applied research program they will enable. More details are given for the high-power laser driven nuclear physics experiments and the instrumentation required by them.

Keywords: high power laser, gamma beam, nuclear physics, nuclear astrophysics.

Sunt prezentate facilitatea ELI-NP aflată în construcţie şi parametrii celor două principale instalaţii ale sale, Sistemul Laser de Mare Putere şi Sistemul pentru Fascicul Gamma, împreună cu programul larg de cercetări fundamentale şi aplicative pe care acestea îl deschid. Mai multe detalii sunt date privind experimentele de fizică nucleară bazate pe laseri de mare putere şi instrumentaţia necesară acestora.

Cuvinte-cheie: laseri de mare putere, fascicul gamma, fizică nucleară, astrofizică nucleară.

INTRODUCTION

ELI-NP [1] project will create in Măgurele, Romania a new European laboratory aiming to investigate a very broad range of science domains, from new fields of fundamental physics, new nuclear physics and astrophysics topics, to applications in material science, life sciences and nuclear materials management. It is one of the three pillars of Extreme Light Infrastructure (ELI), a large-scale laser-centered, distributed pan-European research infrastructure, involving beyond the state-of-the-art ultra-short and ultra-intense laser technologies. While the Romanian pillar is focused on nuclear physics, the ELI-Beamlines [2] facility in Czech Republic is dedicated mainly to secondary (X-ray, electron, proton) sources and ELI-ALPS [3] in Hungary is devoted to generation and applications of ultrashort pulses down to attosecond duration.

ELI-NP is a complex facility which will host two machines of extreme performances:

- a very high intensity laser system with two arms of 10 PW each and a repetition rate of 1 pulse per minute
- a very intense (4×10^4 γ/s/ev), brilliant γ beam, 0.5% bandwidth, with variable energy up to E_γ^{max} = 19.5 MeV.

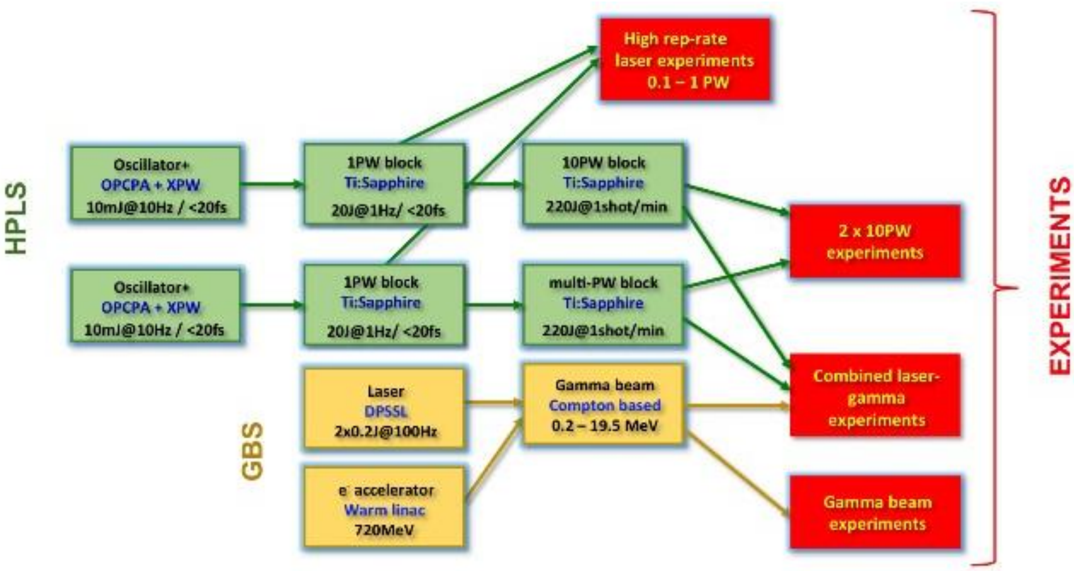

Fig. 1. Block diagram of the ELI-NP facility. Notations are explained in the text

The scientific program at ELI-NP has been defined with contribution of a broad international community, initially in the form of ELI-NP White Book [4] and recently elaborated within ELI-NP Technical Design Reports [5] together with experimental instrumentation needed for the proposed studies.

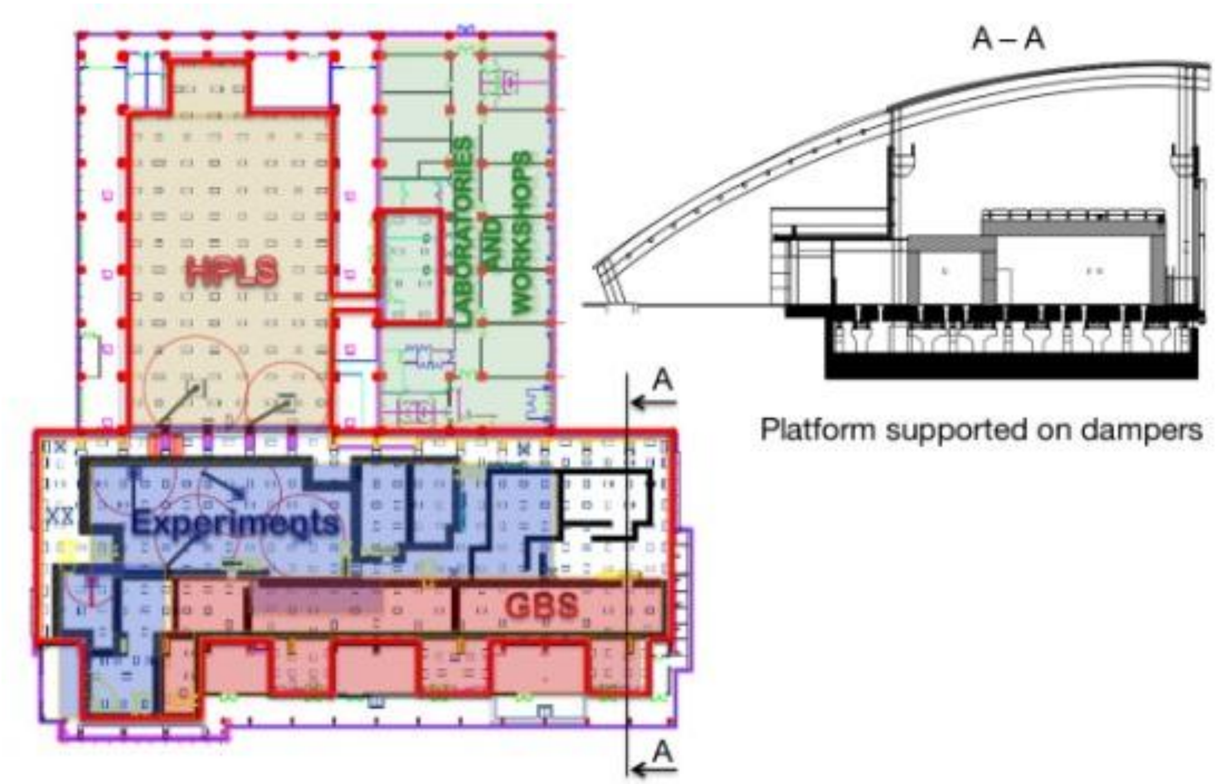

Fig. 2. The layout of ELI-NP experimental building and space allocation for various systems and activities. The approximate dimensions are 135 m ×120 m

ELI-NP FACILITY OVERVIEW

In the Figure 1 the concept of the ELI-NP facility is presented as a block diagram. The layout of experimental building is shown in the Figure 2. Other buildings for offices, guesthouse, conference hall, and cafeteria will complete in a modern design the ELI-NP site.

The high power laser system is currently built by French company Thales. At Front End level, above 10 mJ energy pulse at 10 Hz repetition rate, with large bandwidth and high temporal contrast of 10^{12}:1 are achieved starting form a Ti:Sapphire oscillator and employing XPW (cross-polarized wave) filtering [6], OPCPA (Optical Parametric Chirped Pulse Amplification) and other technologies. In order to increase the system availability two Front End modules are foreseen, working one at once. Each can feed two parallel Ti:Sapphire amplification chains increasing the pulse energy to more than 200 J and producing, after temporal compression, two synchronized 10 PW pulses with repetition rate as high as one pulse per minute. Outputs from intermediary amplification stages can be compressed to deliver two 100 TW or 1 PW pulses, at 10 Hz or 1 Hz, respectively.

The High-Power Laser System (HPLS) will be installed in a clean room with surface of more than 2500 m^2, excluding the adjacent technical corridors. Vacuum chambers for all the six compressors mentioned above are placed also in this clean room. As the10 PW laser beam has a diameter of more than 50 cm, large diameter vacuum tubes are further used to distribute the laser pulses in different interaction chambers installed in the experimental area marked in blue in Figure 2.

The Gamma Beam System (GBS), currently being built [7] for ELI-NP by EuroGammaS Consortium, is based on Compton inverse process, the high energy γ-rays being produced by scattering of visible photons (515 nm wavelength) off the high energy electrons accelerated by (warm) linear accelerator. Laser pulses of picosecond duration with energy in 100's of mJ range and repetition rates of 100 Hz are generated by a Diode Pumped Solid-State Laser (DPSSL). They are collided with electron pulses of up to 720 MeV energy originating from a photo-gun driven synchronously by another similar laser system converted to shorter (ultra-violet) wavelengths. Thus, γ-rays with tunable energy up to 19.5 MeV are produced. As the energy of the γ-rays depends on the scattered angle, adequate collimation allows to select only highest energies produced at a given electron energy with a resolution of $\Delta E_\gamma/E_\gamma$ (RMS) = 0.5% and a spectral density of about 10^3 ph/eV/sec. These figures are determined by both laser pulses and electron bunches quality in terms of divergence, emittance, bandwidth, energy/charge, etc., integrating the results of several state-of-the art technologies in laser and accelerator science. In order to increase the photon number, a recirculation of the laser pulse at the interaction point is provided by multi-pass reflective optics and similar temporal structure of accelerated electron bunches. A gain factor of up to 32 can be obtained, resulting a time structure of the gamma beam of 100 macropulses per second each consisting of 32 micropulses (separated by 16 ns) and total flux of about 10^9 ph/sec. within FWHM.

The linear accelerator and the interaction point are placed in the area marked as GBS in the Figure 2. As gamma beam cannot be manipulated after production, the experimental room making use of it is positioned in the same direction as the linac. In order to provide some operational flexibility, a second interaction points is foreseen at a mid-point along the accelerator followed by a translation of few meters of acceleration direction. Here up to 3.5 MeV γ-ray will be produced with similar flux and bandwidth as at high energy interaction point.

Both HPLS and GBS, as well as experiments using HPLS, have to be operated in very demanding environments. First, low vibration condition is achieved by installing all the equipment on a thick concrete platform supported by dampers and decoupled from the rest of the building (see vertical section view in Figure 2). The stability of the air temperature is important not only for laser rooms where the pulses are propagating in air, but also in all other areas since the temperature drifts implies dilatations and deformations changing the optical paths which should be kept constant at micrometer level. Therefore a strong HVAC (heating, ventilation and air conditioning) system is installed at ELI-NP powered by an impressive network of geothermal heat pumps.

Safety and Radioprotection have been integrated in all the relevant aspects of the building and equipment design. The pulsed and mixed radiation fields expected at ELI-NP have imposed specific calculations and detector systems for area monitoring. The uncertainties in radiation fields that will be generated by high power laser pulses are large because no simple extrapolation can be made from the existing measurements at 1 PW level to unprecedented 10 PW level. Consequently conservative radiation source terms have been taken as starting point in shielding calculations. Additionally, high power laser interaction with mater is expected to generate Electromagnetic Pulses (EMP) of high amplitude in the frequency range of 10 MHz – 30 GHz, which may affect humans or equipment. Again, a full range of protective measures have been integrated in the building and equipment design to assure that EMP outside experimental area are attenuated by more than 60 dB.

HIGH POWER LASER EXPERIMENTS

The laser pulses delivered by HPLS are distributed in five experimental rooms (areas). These rooms and the main equipment installed in this area are shown in the Figure 3.

The E1 area is devoted to laser driven nuclear physics experiments, its interaction chamber will enclose focusing mirrors of the two 10 PW beams in various configurations with options to bring in also the 1 PW pulses at higher repetition rate. Details on physics cases to de addressed in E1 area and experimental equipment to be installed here will be presented further below.

The E6 experimental area will be used mainly for laser wakefield electron acceleration using a long focal length parabolic mirror and probing the high field created by tightly focusing the second 10 PW beam. Although the Schwinger field E_S= 1.31×10^{18} V/m required for spontaneous electron-positron pair creation out of the vacuum requires a laser intensity of 2.3×10^{29} W/cm^2, which is still far beyond reach, several high-field QED processes will be accessible at ELI-NP at expected laser intensities of 10^{22}–10^{23} W/cm^2. The use of solid target will allow to study the same phenomena in a high-density but lower energy regime of accelerated electrons. A large electron-spectrometer is proposed for up to 40 GeV electrons together with an adapted beam dump. Other diagnostics are requested for: gamma-rays, electrons and positrons, protons and ions, plasma characterization, as well as for laser beam parameters

The two 10 PW pulses are also send in the E7 where the high intensity laser field can be probed with gamma beam or high quality electron pulse delivered by the linear accelerator. Radiation reaction, electron-positron pair production in tunneling regime, vacuum birefringence and polarization properties of emission field in strong laser fields are other types of experiments proposed in this area [8]. Some other will be discussed in the end of next section.

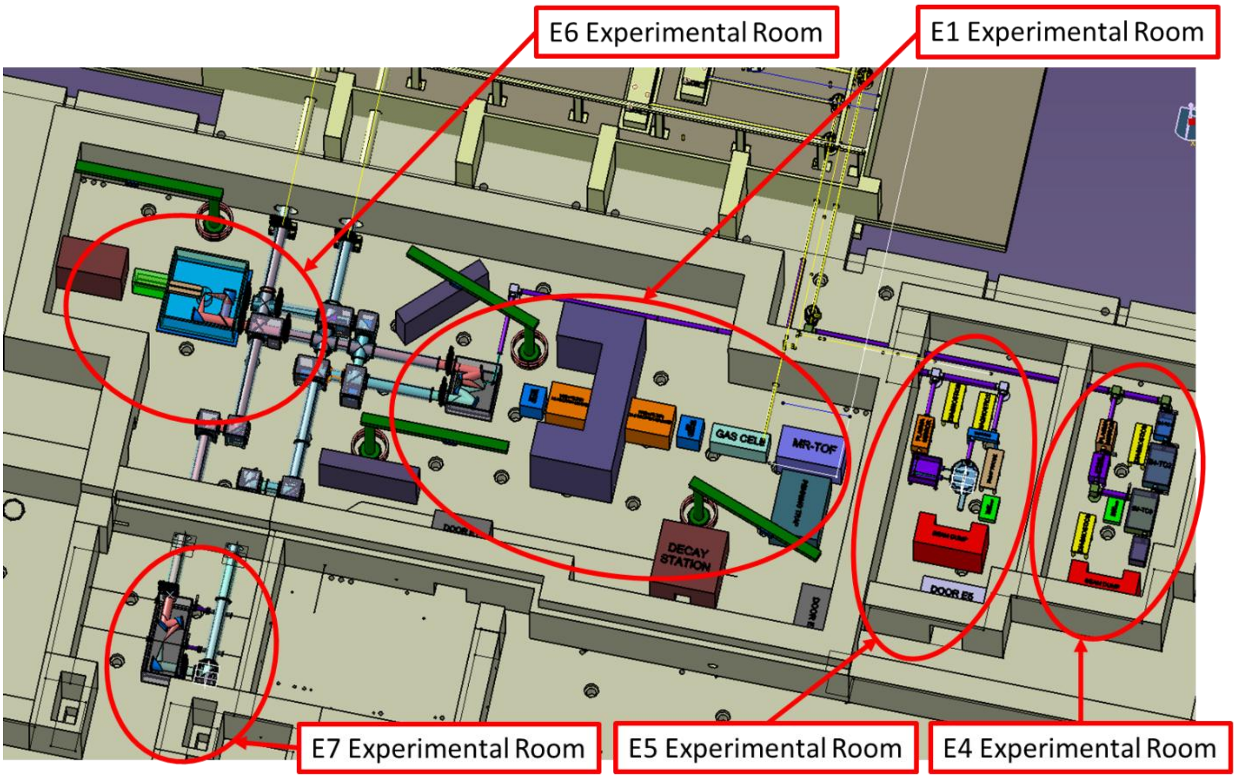

Fig. 3. The 3D model of high-power laser experimental rooms and associated equipment

The intermediary outputs of 1 PW and 0.1 TW are sent in the E5 and E4 experimental rooms, respectively. In E5 area, existing and future optimization of ionizing radiation production at 1 PW level will be used to study the mixed field short duration and high intensity pulses irradiation effects on materials. Laser induced shock acceleration will complete the type of extreme condition that can be created in E5 area for testing materials such as:

- accelerator components
- electronics for space science
- material science research (surface and volume modification, nanotechnology)
- biomedical samples (radiation effects on cells, tissues, organisms)
- radiation detectors
- optical components

E4 area is intented to be used for new diagnostics and measurement methods development. Also, high repetition (10 Hz) of 100 TW may be very convenient for some studies demanding acceleration at moderate energies and searching for low cross section reactions. Another type of studies proposed in

E4 is the search for dark matter and sub-eV particles, associated with breaking of fundamental symmetries in the context of particle physics and cosmology, through multi-color quasiparallel photon collisions [9-11].

In the remaining of this section we will focus on E1 experimental area. The proposed nuclear physics studies will take advantage mainly by high density of laser accelerated particle bunches, one of the parameters exceeding by order of magnitudes the values currently available in accelerator facilities. At intensities approaching 10^{23} W/cm^2 achievable at ELI-NP, the dominance of RPA (Radiation Pressure Acceleration) mechanism for ion acceleration over TNSA (Target Normal Sheath Acceleration) is expected [12]. Especially in the “light sail” regime of RPA, quasi-neutral quasi-monoenergetic bunches with solid state density are predicted opening up the possibility for interaction between unstable reactions products, which is exploited in the proposed fission-fusion scenario [13] to access the region of neutron rich N~126 nuclei. This region of nuclear chart represents a waiting point in astrophysical r-process and therefore is very important in understanding the nucleosynthesis of heavy elements. A staged approached is taken into consideration: *i)* demonstrate the RPA for very heavy ions up to Thorium, *ii)* induce fission reactions in enough high density to produce fusion of fission products, *iii)* separate the nuclei of interest using electromagnetic spectrometers, *iv)* measurement of their β-decay properties in a decay station, *v)* measurement of masses with high accuracy devices, for example a Multi-Reflection Time-of-Flight (MR-TOF) Mass Spectrometer [14] or a Penning Trap [15,16]. Each of these devices are shown in Figure 3. The C shape big item represents the beam-dump required for energetic protons that can be created in high intensity laser interaction with solid target due to their surface contamination with hydrogenated volatile compounds present in the residual vacuum inside interaction chamber.

Another type of nuclear studies aims to measure the cross section for nuclear reactionz of astrophysical interest in hot plasma conditions similar, to some extent, to stellar environments. Indeed, screening effects due to electrons around nuclei are changing the cross section compared to the case of bare nuclei [17], however nuclear reactions cross sections were not measured in plasma conditions. Such plasma target can be created by laser pulses in gas target at various densities. A second laser pulse incident on a solid target could produce a high intensity bunch of accelerated ions inducing reactions before the expansion of plasma target. This scheme is proposed in E1 in order to benefit of high energy of uncompressed laser pulses but it could be done also at higher repetition rate with 0.1 PW pulse in E4 area, because the energies relevant for astrophysics are low.

Hot and dense plasma conditions are modifying not only nuclear reaction cross sections, but also the lifetime of nuclear states and other observables. Changes with factors as high as to 10^9 are predicted [18] for example in the case of ^{26}Al lifetime for plasma temperature range from 0.15 GK to 0.4 GK. A large number of mechanisms could be responsible for such modifications: photoexcitation, electron inelastic scattering, internal conversion and its inverse process called Nuclear Excitation through Electron Capture (NEEC), or resonant process between nuclear transition and atomic transitions call bound internal conversion and respectively Nuclear Excitation through Electron Transitions (NEET). However the NEEC process has never been observed while NEET was measured only in normal (cold target) conditions [19-21].

In some cases nuclear isomeric states with long lifetime can be excited to upper excited states decaying much faster to ground state and releasing the energy [22], an effect with possible application in high density energy storage and release on demand. To study such cases, the nuclear states of interest are proposed to be produced in the reactions induced by laser accelerated nuclei and then plasma will be created by a second laser pulse.

Special gamma detectors capable to measure in-situ the gamma ray emitted by nuclear states as soon as possible after the laser shot are currently under development.

Among the applications foreseen to be developed here using high power laser we can mention the high energy neutron generation for imaging, and carbon acceleration for hadron therapy.

The design of E1 vacuum interaction chamber that should host several configurations of focusing optics with large dimensions as well as many types of detectors and diagnostics is shown in Figure 4. It has an inside volume of about 24 m^3.

The optical table supporting the focusing optics and the target system is directly connected to the anti-vibrational floor and decoupled with bellows from the vacuum enclosure.

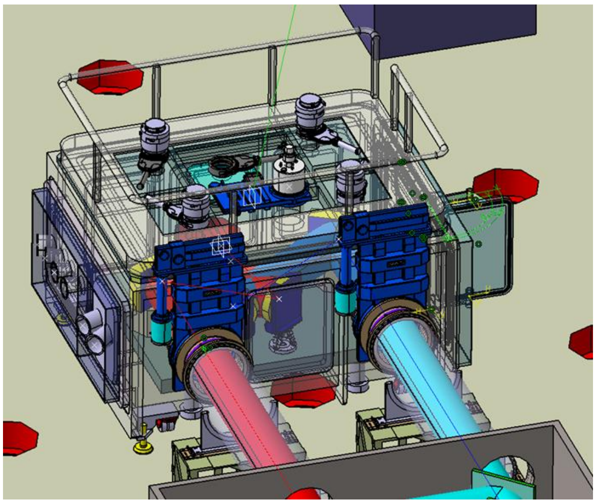

Fig. 4. The E1 Interaction chamber design. The two laser beams are shown in red and blue

In order to minimize the number of venting-pumping cycles, especially in case of solid targets that are destroyed at each laser shot, a target exchange system is foreseen to be installed on top of chamber.

It can be also used for insertion/extraction of passive diagnostics such as Radiochromic Films (RCF) or Image Plates (IP) that can give very valuable information additionally to active diagnostics which are more adapted for high repetition rate laser experiments.

GAMMA BEAM EXPERIMENTS

Nuclear physics program addressed by high intensity gamma beams at ELI-NP is very broad. For energies below the nuclear separation energy, the absorbed photon is re-emitted with same energy or a smaller. This process, called Nuclear Resonance Fluorescence (NRF), gives access to a multitude of information on studied nuclei: γ–ray transition energies, level energies, angular momentum quantum numbers, parity quantum numbers, resonant photon scattering cross sections, level lifetimes and decay widths, γ–decay branching ratios, *K*–quantum numbers, transition multipolarities and multipole mixing ratios, monopolar partial decay widths, and monopolar reduced transition rates. They will help collecting new nuclear structure data and understanding various phenomena: scissors mode in nuclear, parity violation, study of pigmy dipole resonance (PDR), dipole response and parity measurements in low abundancy isotopes. For applications, an energy–tunable and quasi–monochromatic γ beam makes possible to detect and measure non–destructively any isotope in a material using NRF, due to the fact that the energy levels and γ transitions are unique isotopic fingerprints. This a key technology for nuclear industrial applications such as management of radioactive wastes, nuclear material accounting and safeguards, analysis of spent nuclear fuel and others.

At higher γ-ray energies, photonuclear reactions with particle (neutrons, protons or other charged particle) emission will be possible to be studied at ELI-NP with accuracy beyond any other existing γ-ray beam facility. Highly relevant for nuclear astrophysics, these studies are also important for understanding nuclear phenomena as Giant Dipole Resonance (GDR) or clusterization. The proposed studies of photofission of actinide targets will allow to get information both on fission products and on the fission process itself: fine structure of cross section resonances in relation with predicted super- and hiper-deformed states (before fission), ternary fission channels, etc.

Another type of application related to gamma beam is the production of a positron beam. Expected positron beam intensity is 2×10^6 e^+/sec. generated by an intense *γ*-beam of 2.4×10^{10} *γ*/sec. with energies up to 3.5 MeV. In applied physics studies of Fermi-surfaces, defects, interfaces etc. positrons offer excellent diagnostics tools. Using fully circularly polarized γ-beam we aim to obtain an intense, polarized positron beam with a polarization degree of 31-45%. Thus, the beam will have the world highest intensity of polarized positrons for material science studies and therefore it will become a unique tool for the investigation of magnetic samples.

CONCLUSION

ELI-NP project, currently under implementation in Romania, will create a unique open access laser facility offering to the international user community unprecedented light sources starting with 2019. While centered on nuclear physics research and applications, the 2x10 PW laser system and the high intensity 20 MeV γ beam of ELI-NP will be used also for research in many other domains such as material science, life science, strong-field quantum electrodynamics or astrophysics.

BIBLIOGRAPHY

1. http://www.eli-np.ro
2. http://www.eli-beams.eu
3. http://www.eli-hu.hu
4. ELI-NP WhiteBook, http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf
5. http://www.eli-np.ro/2015-tdr-final/
6. Jullien A. et al, Appl. Phys. B 102, 769 (2010)
7. Adriani O. et al., Technical Design Report; EuroGammaS proposal for the ELI–NP Gamma beam System, arXiv:1407.3669v1 [physics.acc-ph].
8. Seto K., Prog. Theor. Exp. Phys 2015, 023A01 (2015).
9. Tajima T. and Homma K., Int. J. Mod. Phys. A vol. 27, No. 25, 1230027 (2012).
10. Homma K., Habs D., Tajima T., Appl. Phys. B 106:229-240 (2012).
11. Homma Kensuke, Hasebe Takashi, Kume Kazuki, Prog. Theor. Exp. Phys. (2014) 083C01.
12. Robinson A.P.L. et al., New J. Phys. 10 (2008) 013021.
13. Habs D. et al., Appl. Phys. B 103 (2011) 471.
14. Plass W.R. et al., Nucl. Instr. Phys. Res.. B 266 (2008) 4560.
15. Block M. et al., Eur. Phys. Jour. A 25 (suppl. 1) (2005) 49.
16. Mukherjee M. et al., Eur. Phys. J. A 35, 1-29 (2008).
17. Salpeter E.E., Australian Journal of Physics 7(3) (1954) 373.
18. Coc A. et al., Phys. Rev. C 61, 015801, 1999.
19. Kishimoto et al., Phys. Rev. Lett, 85, 1831 (2000).
20. Ahmad et al., Phys. Rev. C, 61, 051304 (2000).
21. Kishimoto et al., Nucl. Phys. A, 748, 3 (2005).
22. Gosselin G., Méot V., and Morel P., Phys. Rev. C 76, 044611 (2007).

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