Laboratory Astrophysics at Extreme Light Infrastructure: Nuclear Physics

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1 Introduction

The buildings of ELI-NP and a significant part of the equipment are completed [1, 2] in Magurele, Romania, where a large fraction of the Physics research institutes of the country are located.

The High Power Laser System, to provide two beams with the highest laser pulse power in the world, of 10 PW, is already installed and in an advanced testing stage. The system will be commissioned at full power in the first half of 2019.

This facility will break new ground in the peak laser intensities attained worldwide, going beyond 10^{23} W/cm^2 for the 10 PW beams in tight focus. In order to achieve this, a commissioning (ramp-up) period is needed, for which we have an already proposed experimental programme, endorsed by an International Scientific Advisory Board, that will demonstrate the top-notch capabilities.

Among the proposed experiments there are many relevant for astrophysics, but since ELI-NP will be a user-facility, receiving applications for beamtime from any research team worldwide, we will make in the following sections an overview of the beam capabilities and interaction areas available.

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2 The Laser Beams

The European distributed research infrastructure ELI aims to push ahead the power of the laser pulses available for experiments beyond the 10 PW mark, implementing in the three centers in Romania, Hungary and the Czech Republic high power lasers based on different technologies.

In Romania, at ELI-NP, the laser system is developed on the Ti:Sapphire solid state technology, for this purpose the largest such crystals, of 200 mm diameter, being grown. 48 pump lasers at 532 nm increase the energy of the stretched laser pulse with center wavelength at 810 nm along the two beam lines. The final amplification stage, featuring the large Ti:Sapph crystals, is pumped by very stable 100 J pump lasers developed specifically for this project. The pulses are then compressed to a duration below 25 fs in vacuumed compressors with large optical gratings. The 10 PW pulses will be delivered at a repetition rate of one pulse per minute.

Responding to the call for research in applied physics, that could transfer benefits back to society in short periods of time, but also to the need of gradual increase in laser pulse power for some experiments, outputs at intermediate powers of 100 TW and 1 PW are available. The pulses have in these cases the same ultra-short duration of 22–25 fs, but higher repetition rates of 10 and 1 Hz, respectively.

After the compressors, the ultrashort pulses will travel in the vacuum pipes of the beam transport system. The 10 PW pulses have 55 cm diameter in full aperture (and the beam transport pipes 800 mm), so the mirrors for the transport system will have dimensions close to one meter. Extremely good quality of the optics, allowing no more that $\lambda/20$ RMS deviations, is also required in order to keep the characteristics of the laser pulse until it reaches the focusing mirror.

The laser beams are transported to five experimental areas that will be described in the next section.

Due to the large distances of propagation of the laser beams from the laser bay to the experimental areas, amounting to 30–60 m, the pointing stability and the divergence parameters of the laser where very strictly controlled.

3 Experimental Highlights

The eight experimental halls of ELI-NP are grouped on a vibration-stabilized 1.5 meter-thick concrete platform together with the bays for the gamma beam system with radiation-protection provisions, high dose rates being produced in the interaction between the intense focused laser pulses and solid or gas targets. In Fig. 1, an overview of the radiation-protected bunkers is shown.

On the other hand, in short-pulse laser-based experiments very intense electromagnetic pulses (EMP) may be produced. In order to protect the equipment from these, several layers of protection have been set – beginning with a minimum 60 dB

Fig. 1 View of the hall of the experimental areas at ELI-NP

damping of the vacuum interaction chambers themselves, continuing with the EMP filters for all cable or pipe ducts and ending with the insulation embedded in the concrete radioprotection walls and the conductive cover on top of the removable ceiling of the experimental areas.

Five of the experimental areas get access to the ultrashort laser pulses, one of them being at the crossroads between the 10 PW laser beams and the high intensity gamma ray beam.

For the main topics of the experimental research at ELI-NP (starting from the more detailed description of the first, commissioning experiments), Technical Design Reports (TDRs) have been devised covering each experimental area.

3.1 Laser-Based Experiments Relevant for Astrophysics

One of the main research aims of ELI-NP is to combine the precise methods of measurement of Nuclear Physics with the novelty of the high power laser experiments. There are two ways in which the ultrashort laser pulses can help performing experiments in the area of “laboratory astrophysics”.

The first one is the acceleration of high density bunches of particles up to relativistic energies, over short distances, these bunches being then collided with secondary (and sometimes tertiary) targets producing the nuclear reactions of interest. As an example of nuclear astrophysics experiment, at ELI-NP is foreseen (as presented in the TDR [3]) the acceleration and fission of heavy nuclei (such as ^{232}Th) in a double-layer solid target, and then obtaining very neutron-rich isotopes from the fusion processes of the fission fragments in a secondary double-layer target. This is a typical experiment which could not be done at classical accelerators due to the very low rates involved, but fusion products could become detectable at the very high densities in laser-based acceleration. The very neutron rich isotopes are a still unknown area of the chart of nuclides, but important for the nucleosynthesis of heavy elements in the Universe. The experimental area E1 is foreseen for this type of experiments, featuring a big 24 m^3 vacuum interaction chamber that can accommodate two short-focus off-axis parabola mirrors for the focusing of the 10 PW laser beams.

A second way of performing astrophysically-relevant experiments is to obtain the extreme plasma conditions encountered in astrophysical scenarios such as heavy stars or supernova explosions. One could then get information on the thermally-populated nuclear states in these conditions, and study effects such as electron screening, that may impact on the real reaction rates.

Another proposal in the ELI TDRs foresees the use of both the laser pulses and the gamma radiation pulses in a same nucleosynthesis experiment – the laser pulses being used for the creation of the extreme conditions and the population of excited (isomer) states in some nuclei of interest, and the gamma photons exciting nuclear transitions departing from the isomer states [4]. The experimental setup for this experiment (see Fig. 2) has been designed and comprises large volume vacuum enclosures in Aluminium alloy (to minimize nuclear activation over time) in the E7 experimental area.

The two-beam configuration available in each experimental area (for 100 TW, 1 PW and 10 PW power) allows for an extremely broad range of geometries for interaction, making possible experiments of simulation in laboratory of astrophysical jets. Studies of the scaling laws for MHD systems [5] are promising. In this respect, there have been experiments performed at existing facilities [6–8] and simulations [9], which are a natural evolution after the experiments of plasma jets at Imperial College London [10] initiated in the framework of the JETSET project [11]. The possibility to employ both ultra-short and longer laser pulses at ELI-NP is investigated.

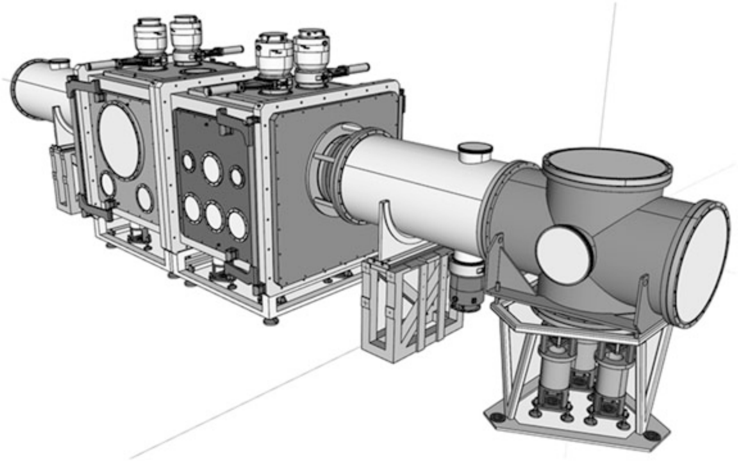

Fig. 2 Vacuum interaction chamber for experiments with combined laser and gamma radiation pulses

3.2 Gamma-Based Experiments of Nuclear Astrophysics

The gamma radiation beam at ELI-NP will have unparalleled characteristics – the possibility to continuously tune the photon energy in a broad range, from 0.2 up to 19.5 MeV, with a very narrow bandwidth of less than 0.5% and high brilliance, of more than 10^3 ph/eV/s. A broad range of detectors are in advanced stages of development at ELI-NP for taking advantage of these characteristics in new experiments [12].

The narrow bandwidth of the gamma beam and good collimation (due to the method of producing the gamma photons, namely Compton backscattering of a pico-second laser pulse on relativistically accelerated electrons) allows a great increase in the signal-to-noise ratio for the study of nuclear reactions of interest. Therefore, experiments of measuring reaction rates relevant for the $s - process$ branching points in nucleosynthesis, as well as photodisintegrations important for the $r - process$, have been already planned [13]. Neutron and gamma detector arrays are constructed at ELI-NP for these studies, for rates and time-of-flight measurements: a 30 ^{3}He counters array, a hybrid gamma-neutron detector array of 3 m diameter and a segmented clover detector array.

Charged particle detectors, both for gas targets (an electronic-readout Time Projection Chamber [14]) and solid targets (a Silicon-Strip Detectors array [15]) with high resolution were designed and are now under development. They will allow the more precise study of reactions of great importance for astrophysics, such as, for example, the $^{12}C(\alpha, \gamma)^{16}O$ reaction through inverse kinematics [16].

4 Conclusions

The ELI-NP project in Romania implements now the base equipment of the experimental areas and is close to commissioning the high power laser system. A first call for experiment proposals to the international community is due in 2019.

Thanks to the various multi-beam configurations that will be available, a wide range of astrophysically-relevant experiments will be possible. Applications in the "laboratory astrophysics" of stellar and extragalactic jets are thought to be possible and will be a great test-bench for the numerical simulations and for the theories on the formation and evolution of these fascinating structures in the Universe.

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