About the Author



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OPPORTUNITIES FOR NEW SCIENCE AT ELI

A. Arefiev[1], Mihail Cernaianu[2], Florian Condamine[3] and Balázs Major[4] – DOI: https://doi.org/10.1051/epn/2023509

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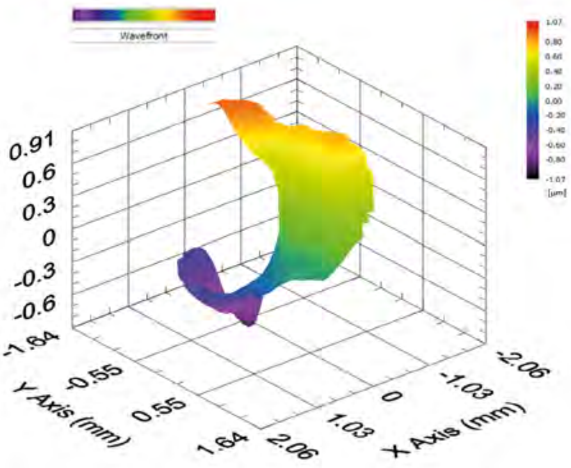
The technology that ELI provides and is developing at a very rapid pace, so the opportunities to study new phenomena in a wide range of scientific areas are also advancing very quickly[4].

High-intensity laser-plasma interactions

Mihail Cernaianu, ELI-NP

The extraordinarily high power of the lasers and associated equipment at the ELI-NP Facility offers exceptional opportunities to explore the fundamentals of laser plasma interactions for ion acceleration and applications. Energies up to hundreds of Joules, delivered in pulses of the order of tens of femtoseconds and focused down to a few microns provide intensities of more than 10^{22} W/cm^2. However, reaching clean and controllable interaction conditions with a dense target at such intensities is very challenging due to the difficulty of achieving high temporal contrast, in which the intense peak in intensity has minimal pre-peak intensity that might stimulate undesirable phenomena. Understanding how this influences the laser-plasma interaction and finding means to control it is crucial to achieving efficient laser – plasma coupling, and will ultimately unlock the potential of high power lasers for applications such as cancer therapy involving tumour irradiation. A particular area of research into laser-plasma interactions is the production and exploitation of beams with a helicoidal phase structure – so called Laguerre - Gaussian beams. The helicity of such beams could influence and perhaps even control aspects of laser – plasma interactions [1], and nuclear physics, for example by conferring some aspects of the helicity to beams produced. Here the need to have a "clean" temporal contrast profile over many orders of magnitude in intensity

[4] Scientific publications at http://www.eli-np.ro/scientific_papers.php



◂ **FIG. 1:** Measurement of a laser pulse wavefront that is compressed down to 25 fs (FWHM) pulse duration. The laser pulse possesses a helical wavefront with topological charge 3 (*i.e.* three twists in one wavelength), generated by the novel technique at ELI-NP.

is even more acute, to help distinguish between the influence of the helicity of the beam on the laser-plasma interactions and potential effects due to deviations from a clean profile.

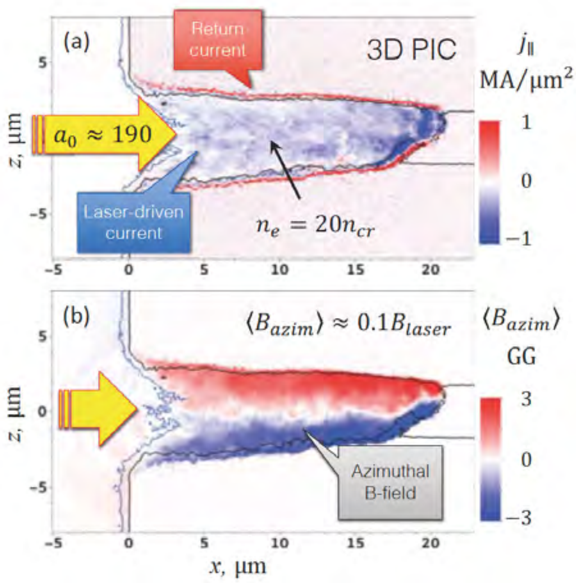
ELI-NP provided the right facilities and environment to perform such high-risk, high-gain experiments. A novel approach to produce helical laser light that could be used for multi-PW ultra-short pulse laser beams was first tested with simulations and then experimentally with some of the very first shots of the ELI-NP lasers. This work also took advantage of the very diverse skills and experience of staff and collaborators at the facility, bringing together scientists from a wide range of physical and engineering sciences, stimulated by the prospect of playing a role in ground-breaking research. The complex measurements require the support of large teams with complementary knowledge for designing and building optical setups, plasma diagnosis, detectors, controlling laser parameters, analysing data or performing simulations to understand the underlying physics and optimize the experiments. This exciting period was rewarded after four years of research with vindication of theoretical work and simulation of the nature of Gaussian-Laguerre beams on laser-plasma interactions and pointed to further improvements to experimental set-ups to control and improve the laser contrast to better understand and improve the laser – target interaction. It also became apparent that helical beams could also be used to provide further control of the parameters of the accelerated particles produced in plasmas. In addition to the significance of this fundamental science, the research also has important applications based on the improvements it could make to the technology of laser accelerated particles or secondary radiation (X-rays) for biomedical research (*e.g.* cell irradiation or hadron therapy) or applications such as X-ray imaging.

Study of gamma-ray generation in multi-PW laser-plasma interactions

Florian Condamine and Alex Alefiev

The development of high-power lasers and pulsed power devices has advanced experimental plasma physics research into regimes relevant to astrophysics. Among many topics, the direct creation of matter and antimatter from light remains elusive in laboratory research [2] This process is crucial for various phenomena, from filling the magnetosphere of a pulsar with plasma to determining the opacity of our universe. To achieve this process, a high photon density of at least multi-MeV energy (known as gamma-rays) is needed. The most suitable mechanism involves deflecting ultra-relativistic electrons (E > 100 MeV) with a strong static magnetic field, leading to the emission of MeV photons. The advent of ultra-high intensity (UHI) lasers offers a promising approach. By driving a strong magnetic field in a dense, laser-irradiated plasma, an optical laser with a peak intensity of 5.10^{22} W.cm^{-2} can induce the generation of tens of MeV photons. The field is generated through a high electron current density $|j|$ within the plasma through relativistically induced transparency a regime, accessible by UHI lasers. Figure 2 illustrates a 3D Particle-In-Cell (PIC) simulation of a plasma penetrated by a the beam and the resultant strong current and magnetic field.

In such magnetic fields, electrons are radially confined and accelerated after being injected into the the laser beam from the ambient plasma. This process, called Direct Laser Acceleration (DLA) assisted by the plasma magnetic field leads to the emission of synchrotron radiation with typical critical energies in the order of several MeVs. Considering the high density of gamma-rays generated, the two-photon process for pair production becomes achievable and measurable at state-of-the-art UHI facilities such as ELI Beamlines. Indeed, the • • •



◂ **FIG. 2:** 3D PIC simulation of a UHI laser propagating through a plasma-filled channel (a) driving a strong current and (b) generating a static magnetic field.

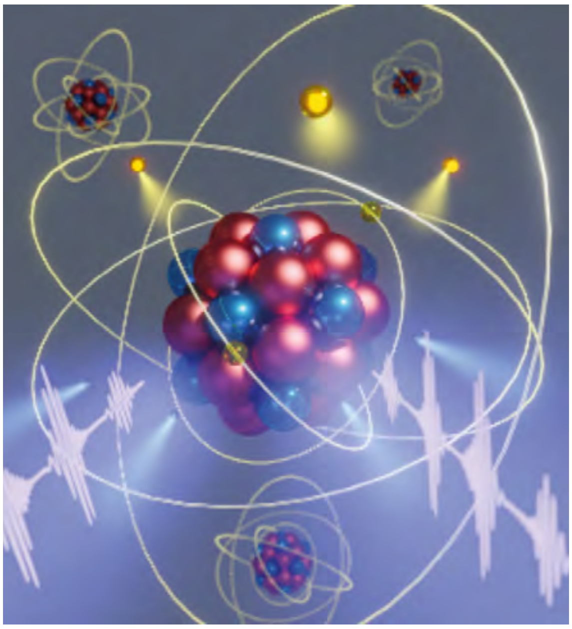
●●● L3-HAPLS (1 PW, 3.3 Hz repetition rate) and L4-ATON (10 PW, 1/min repetition rate) offer ultra-high intensity levels on target, up to 10^{23} W.cm^{-2}, while their repetition rates enable significantly increased statistics. This is an entire change of paradigm compared to what high-power lasers were able to provide before. But, many experimental challenges must be solved in order to generate gamma-ray beams in a reliable and reproducible way. First, the higher repetition rate necessitates mass production of targets. Very low density solid targets are required, leading to the use of complex foams to ensure known interaction parameters. While these targets reduce the number of shots per experiment, ELI Beamlines also offers a multi-beams configuration where the L3 laser is coupled with the L4 ns-kJ class laser. In this setup, the ns-kJ pulse creates a low-density plasma, into which the PW laser pulse is shot with adjusted delays to scan various densities and plasma sizes. Also, implementing active gamma-ray diagnostics in highly constrained environments (*e.g.*, EMPs, radiations) presents challenges. One solution involves using scintillators coupled with a CCD camera to capture the light emitted by gamma-rays upon interaction with the scintillators. Utilising different layers and types of scintillators, it is possible to deduce the MeV photon spectrum through unfolding techniques.

In conclusion, cutting-edge, ultra-high-intensity laser sources pave the way for studying physics phenomena encountered in the most extreme environments in the universe, such as pulsars and the gamma-ray induced pair creation mentioned here. Many challenges have to be solved to use the full-potential of such lasers. In the next decade, combining sophisticated 3D PIC simulations and complex engineering, these technologies will undoubtedly usher in a new era for laser-matter interaction studies.

Selected directions in current attosecond science

Balázs Major, ELI ALPS

The use of laser pulses to capture snapshots of superfast processes is the underlying principle of the technique of pump-probe spectroscopy at femtosecond (10^{-15}s) timescale, and was recognised with a Nobel prize in 1999. ELI ALPS aims to push the limits and applications of this method up to three orders of magnitude further – into the attosecond (10^{-18}s) regime – and make it accessible to users from around the world. This will take dynamic studies of materials well beyond following the nuclear motion that occurs in a chemical reactions as the atoms rearrange within molecules. Rather, it will allow scientists to follow the reorganisation of the electrons associated with the atoms during such processes, as the much lighter electrons move considerably faster. Understanding their motion is critical to understanding the reaction paths molecules are taking and key to answering important open questions in attochemistry.



▲ **FIG. 3:** Schematic illustration of an attosecond experiment: two intense attosecond pulse trains (white) interact with an atom, resulting in the emission of three electrons (yellow); during this process four photons (blue) are absorbed.

Attosecond pump –probe measurements nowadays allow one to study directly what happens when one or more electrons are removed from an atom through the absorption of extreme ultraviolet photons. First a train of attosecond pulses – the pump – excites the material, while the second train of pulses, each with a short, variable delay compared to the initial pulses – the probe – provides information about the resulting processes through changes in their spectral content. Such experiments have recently been carried out that even revealed multi-electron multi-photon dynamics (Figure 3) [3]. Of course, the world surrounding us does not only consist of gas-phase atoms or molecules. We should not forget about condensed phase materials, in which although different bonds are making the connection in between atomic elements, the cohesive force is also formed by the electronic cloud. Since the velocity with which particles travel is strongly correlated with their mass, the mechanisms through which condensed matter reacts to its environment happens on a time scale defined by the electron motion. As a result, the same "cameras" can be used to gain new insights in surface science or nanophysics.

A common feature of all the above is quantum phenomena. With the faster and faster measurements, one may observe the dynamics of yet smaller physical entities. The dynamics of these are inherently governed by quantum physics, and a brand new direction of science starts to blossom as the quantum aspects of attoscience begin to be unraveled. While one of the first quantum optical signatures in a strong laser pulse after interaction with semiconductors were measured in a user experiment at ELI ALPS, most recent experiments are working with non–classical light states, like squeezed light, having important potential applications in quantum information science or detection of gravitational waves. It is generally true - independent of the research field - that underlying technologies always limit what can be measured, achieved or resolved. By pushing the frontiers of ultrafast laser science ELI also extends the parameter range in which its secondary sources – such as femtosecond-laser driven attosecond beamlines – can operate. Substantial work is also put into improving the capabilities of existing attosecond beamlines at ELI ALPS and providing access to so far unobservable dynamical phenomena in all types of matter regardless of whether it is organic or inorganic. And as a user facility ELI is particularly distinctive in offering advances in cutting-edge tools for attosecond science to researchers around the world, whether they are expert in such techniques or not.

About the Authors

Alexey Arefiev is Professor at the University of California San Diego where his group studies high-intensity laser-plasma interactions using supercomputer simulations.

Mihail Cernaianu joined ELI-NP in 2013 and is responsible for the 1 PW laser driven experimental area. His research interests are in the field of laser – solid plasma interactions and applications.

Florian Condamine is an instrument scientist at the plasma physics and ultra-high intensity interaction platform at ELI Beamlines. Since 2022 he is co-PI with A Arefiev on a project to study gamma ray sources using multi-PW beams.

Balázs Major is senior research fellow, group leader at ELI ALPS, and assistant professor at University of Szeged. He chairs the Short Wavelength Sources and Attosecond/High Field Physics Technical Group of Optica.

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