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Review

Nuclear Physics with 10 PW laser beams at Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

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Abstract. The field of the uncharted territory of high-intensity laser interaction with matter is confronted with new exotic phenomena and, consequently, opens new research perspectives. The intense laser beams interacting with a gas or solid target generate beams of electrons, protons and ion. These beams can induce nuclear reactions. Electrons also generate ions high-energy photons via bremsstrahlung processes which can also induce nuclear reactions. In this context a new research domain began to form in the last decade or so, namely nuclear physics with high power lasers. The observation of high brilliance proton beams of tens of MeV energy from solid targets has stimulated an intense research activity. The laser-driven particle beams have to compete with conventional nuclear accelerator-generated beams. The ultimate goal is aiming at applications of the laser produced beams in research, technology and medicine. The mechanism responsible for ion acceleration are currently subject of intensive research in many laboratories in the world. The existing results, experimental and theoretical, and their perspectives are reviewed in this article in the context of IZEST and the scientific program of ELI-NP.

1 Introduction

The dramatic increase of laser power [1], since the invention of Chirped Pulse Amplification (CPA) [2] and Optical Parametric CPA [3], catalyzed a new field of research: the high-intensity laser interaction with matter. New exotic phenomena have generated a burst of theoretical and experimental studies and many reviews, even textbooks, have already being dedicated to this subject [4].

The charged particles accelerated by petawatt lasers and secondary radiation makes nuclear physics one of the various disciplines participating in the consortium of contributing (and beneficiary) fields to the new field of high-intensity laser interactions with matter.

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The present paper is far from being a comprehensive review of nuclear physics applications of high-intensity laser interaction with matter. For a review of this subject see for example Ref. [5]. This present paper is intended only as a glance at the most recent studies with ultraintense lasers and perspectives of nuclear physics studies with petawatt lasers.

There is at present an impressive number of either planned or running projects based on high power laser installations, including both large international facilities, which will provide the highest laser intensities ever produced, and smaller scale systems that bring petawatt power to national facilities. In this context, one pillar of the Extreme Light Infrastructure (ELI) European project is dedicated to Nuclear Physics. The construction of this pillar, the Extreme Light Infrastructure – Nuclear Physics (ELI-NP), began in 2013 in Bucharest-Magurele, Romania and will be operational in 2018. The 2 lasers of ELI-NP, each with 10 PW of power, will produce intensities in the range of 10^{23} W/cm^2. It will be a European research centre for ultra-high intensity lasers, laser matter interaction, nuclear science and material science using laser driven radiation beams [6,7]. This multidisciplinary facility will provide completely new opportunities to study fundamental processes that occur in ultra-intense laser fields during light-matter interaction. The present paper outlines the rationale for this pillar and a summary of the scientific program presented in the ELI-NP White Book [8].

2 Particle acceleration

One of the most exciting driving forces behind the numerous studies of the high-intensity laser interaction with matter, greatly stimulating the efforts, is the perspective of obtaining laser-driven particles beams with characteristics similar to those obtained with conventional accelerators but, potentially, much less expensive. The present energy frontier of high energy physics is several TeV, but colliders capable of reaching this regime, such as the Large Hadron Collider (LHC), are costly and time-consuming to build. Relatively expensive are also the accelerators used for science, medicine (hadron-therapy) or synchrotrons for material studies. Virtually all of today's accelerators accelerate charged particles in the electric field generated between conducting electrodes or in electromagnetic cavities. In this approach electrical breakdown limits the maximum field to less than 100 MV/m. Laser-based accelerators have the potential to deliver accelerating gradients more than 1000 times higher than in conventional accelerator technology, reducing the required accelerator length by the same factor. This large increase in accelerating gradient for laser technology is the key to reducing the size up to a tabletop scale and reducing associated cost over conventional accelerators. An ultra high intensity laser interacting with matter accelerates electrons to nearly the speed of light. These, in turn, can be used to accelerate protons and heavier ions. It is expected that the compact, high repetition rate, tabletop lasers with comparable intensities with classical accelerators will define the future for laser-driven nuclear and particle phenomena [9]. The observation of high brilliance beams of multi-MeV protons from solid targets has stimulated an enormous amount of studies. However, the laser-driven beams have yet to achieve the quality of conventional accelerator beams and, consequently, systematic studies should be performed. This novel technology must be followed by the development of laser-driven particle accelerators providing mono-energetic particle beams as well as diagnostics and suitable detectors for such beams with 10^8–10^{12} particles in 1 ps particle pulse at 1–200 Hz repetition rate. For this purpose, typical nuclear physics studies, with specific methods and tools, are extremely important for the development of this new field.

2.1 Electrons

By far the largest effort expended on laser-produced particle beams has been to generate electron beams. The pioneering work on "laser electron accelerator" by Tajima and Dawson [10] proposed to accelerate the electrons with an intense laser pulse producing a wake of plasma oscillations due to localized volumes of low and high densities of electrons. The wakefield generated by an intense laser pulse propagating in an underdense plasma exerts on electrons a ponderomotive force in the longitudinal direction. Exploiting the laser wakefield acceleration mechanism acting on gas jet targets, electron beams up to GeV energies have been realized with typically pC charges per laser pulse, an energy spread of 1–2% and an excellent emittance of 10^{-5} mm mrad. Despite the successes, it is still necessary to demonstrate beam quality, including low-energy spread and low emittance beams and the pulses need to be reproducible in energy. The ultimate utility of plasma accelerators will depend on sustaining ultrahigh accelerating fields over a substantial length in order to attain a significant energy gain. For a review of the tremendous evolution of the research on laser wakefield accelerators that led to the production of high quality electron beams beyond the GeV level, see for example Ref. [11].

2.2 Protons and heavy ions

Most of the experimental and theoretical studies on laser-driven ion acceleration are based on solid density targets. Two major and promising acceleration mechanisms have been identified in this density regime: Target Normal Sheath Acceleration (TNSA) [12] and Radiation Pressure Acceleration (RPA) [13].

The interest in ion acceleration in the super-intense regime has been greatly boosted since the year 2000 when three experiments reported on the observation of collimated proton beams with multi-MeV energies from the rear (non-irradiated) side of solid targets [14–17]. The first proton (18 MeV) and heavy ion beams were obtained at VULCAN at the Rutherford Appleton Laboratory, UK, by Clark and col. [14, 15] from an ultra-intense laser 5×10^{19} W/cm^2 interaction with solids. The acceleration mechanism for rather thick solid targets (micromiters foils) is TNSA. The details of the interaction physics are not yet fully understood although, probably, Wilks et al. [12] have offered the most viable model to date. In TNSA the acceleration of the ions is due to the strong fields set up by a sheath of laser accelerated relativistic electrons. The electrons are generated by the laser at the front surface and transported to the rear side of the target, establishing, by charge separation, a sheath electrostatic field there. The electric fields then drag the ions through the target. Proton beams have been observed both in front of the target and behind the target. Where the proton beams originate from is still a major area of debate. The protons are either from the bulk hydrocarbon molecules or from water vapors and hydrocarbon impurities on the target surfaces. Proton beams with energies ∼60 MeV have been produced within TNSA regime, yet with large energy spreads. The sheath field of order 10^{12} V/m can accelerate the ions on the target back surface to MeV/nucleon level. However, in order to study them, the elimination of parasitic proton beams produced by contamination layers of hydrocarbons and water vapors on the surfaces of the presently used targets is necessary. In the TNSA mechanism the ion energy scales with the laser intensity I, as $(I)^{1/2}$. The conversion efficiency from laser to ion energy scales rather inefficiently with $\epsilon \sim \sqrt{I}$, consequently reaching barely $\epsilon \sim 1\%$. The need to reach both the high energies (>100 MeV) and the beam quality required by most applications has further stimulated the search for alternative schemes of ion acceleration beyond the TNSA model.

A different mechanism, RPA, driven directly by the radiation pressure exerted by superintense laser pulses on overdense plasmas is currently attracting a substantial amount of experimental and theoretical attention due to the predicted and experimentally proven superior scaling in terms of ion energy and laser-ion conversion efficiency. Recent experiments have shown that the maximum energy and the number of ions generated by the interaction of a high-intensity laser pulses with solid targets can be improved significantly if targets with thickness below the colissionless skin depth of the laser, i.e. partly transparent targets are employed. In contrast to experiments carried out in the parameter range of TNSA, where the laser energy is inefficiently transferred to electrons of an underdense plasma at the target front side and most of the laser pulse is reflected, the experiments in the transparent regime enable the participation of the whole focal volume in the acceleration. In RPA the electrons are driven out of the foil via the light pressure, dragging the ions behind in the resulting dipolar field. The momentum of the laser is imparted directly to the object to be accelerated. Analytic models based on momentum conservation indicate that the final energy simply scales as $(\mathrm{I}\tau/\sigma)^{\alpha}$ where I is the intensity, τ is the pulse duration and σ is the areal mass of the foil. The exponent α is equal to 2 for $v << c$ and is approaching 1/3 in the ultrarelativistic limit [18]. The first acceleration using the radiation pressure from a laser beam was reported in 1970 [19] for micron-sized particles. It was mentioned that similar accelerations could be possible with atoms and molecules. Theoretical studies [13, 20, 21] have shown that for the interaction of laser beams of intensities exceeding $10^{23}\,\mathrm{W/cm^2}$ with ultra-thin (sub-micrometric) foils the dominant mechanism is RPA instead of TNSA. In Ref. [18] it was demonstrated, based on a semi-analytic model and on simulations, that RPA is dominant at lower intensities, around 10^{20}–$10^{21}\,\mathrm{W/cm^2}$ using high contrast, circularly polarized beams on sub-micron foils. A. Henig and colleagues [22] presented for the first time experimental studies of ion acceleration from ultra-thin diamond-like carbon (DLC) foils of thickness 2.9–40 nm irradiated with ultra-high laser pulse contrast with intensities of $5 \times 10^{19}\,\mathrm{W/cm^2}$. A polarization-dependent of the carbon ion spectral profile was observed. Using circularly polarized laser beams on 5.3 nm foil, C beams of $\sim 10^7$ particles/msr at $\sim$30 MeV and an energy spread of around 20% were obtained. RPA is currently attracting a substantial amount of experimental and theoretical attention due to the predicted superior scaling in terms of ion energy and laser-ion conversion efficiency. The conversion efficiency with the RPA scheme is estimated to be more than 40 times higher than TNSA [22]. In Ref. [23] the acceleration of ions from ultra-thin foils by using 250 TW, sub-picosecond laser pulses focused to intensities of up to $3 \times 10^{20}\,\mathrm{W/cm^2}$ was investigated. Ion beams of C, Cu and Al of 10^{12}–10^{13} particles/MeV/sr centered at energies of a few MeV/nucleon were measured. The spectral features scale with the laser and target parameters. The route towards the current optimum of laser generated ion beams was outlined in Ref. [24], by subsequently changing the important parameters such as target thickness, laser pulse contrast, angle of incidence and laser pulse polarization. It is possible to achieve spectral peaks beyond 100 MeV/nucleon by tuning currently achievable laser and target parameters. A number of different approaches have been attempted to monochromise these beams using sophisticated shaped targetry, specially controlled chemic treatment of high Z metal foils and the use of micro-lens technology requiring a second laser beam. These approaches have had some success, but at the expense of increased complication. Experimental evidence of RPA is however scarce, as TNSA dominates in standard interaction conditions. In addition, the maximum ion energy observed seems to have saturated and remains too low for many applications.

A new laser-driven ion acceleration mechanism has been identified using particle-in-cell (PIC) simulations [25]. This mechanism, dubbed "Laser Break-out

Afterburner" (BOA), allows ion acceleration to GeV energies at lower laser intensities compared with earlier acceleration schemes [26–28].

Other promising mechanisms of generating ion beams are collisionless shock acceleration (see for example [29], coulomb explosion [30] or Skin-layer ponderomotive acceleration S-LPA [31].

Various other studies attempt to improve the generation of proton and ion beams. For example, in recent studies, the acceleration of protons to energy up to 21 MeV by a modest power (~5 TW) laser and structured dynamical plasma targets [32] or to energies ~200 MeV by irradiating a two-layer target [33] were experimentally demonstrated. The proton beams reached tens of MeV or even higher, but the proton yields are still small compared with conventional accelerators. In addition, the question of how to make the beams highly monoenergetic is still unresolved. A detailed account of experimental research proposed schemes for particle laser acceleration may be found in recent reviews [34, 35].

2.3 Laser nuclear physics

The existing high power short-pulse lasers, at the level of hundreds of terawatt or, recently, petawatt, producing focal intensities of 10^{18}–10^{21} W/cm^2, are able to produce a variety of secondary radiation, from relativistic electrons and multi-MeV/nucleon ions to relatively large intensity X-rays and γ-rays These laser-driven particle beams have encouraged many to think of carrying out experiments normally associated with conventional nuclear accelerators. A list of the nuclear physics studies envisaged to be performed following the high intense laser interaction with matter, far from being exhaustive, is:

- Nuclear processes induced by the primary beams of electrons, protons and ions, and secondary beams of X-rays, γ-rays, neutrons and positrons. Neutron production is based mainly on the secondary reactions (γ, n), (γ, fission), (p,n), $\mathrm{d(d,n)^3He}$, and $\mathrm{d(t,n)^4He}$,
- Positron production based on the generation of electron-positron pairs by ultraintense laser beams. The process has been reviewed in Refs. [36, 37]. At 10^{21}–10^{22} W/cm^2 large number of electron-positron pairs are generated, either through direct high-energy electron interaction with a high-Z nucleus (Trident process), or through the interaction of bremsstrahlung produced gamma rays with the high Z nucleus (Bethe-Heitler process) [38],
- Determination of the characteristics (temperature, energy distribution) of the deuterium plasmas [39],
- Nuclear excitation of isomers by intense beams of electrons and X-rays has not yet been established unambiguously but the subject is sufficiently important to merit further studies,
- Direct laser nuclear reactions. At extremely high field strengths, 10^{28} W/cm^2, the laser can directly interact with the nucleus,
- Plasma-based schemes have been proposed to compress in time and space laser pulses achieving extremely high field strength, approaching the Schwinger limit at which the vacuum becomes unstable for pair production,
- Relativistic electron mirrors from nanoscale foils for coherent frequency upshift to the extreme ultraviolet [40]. Reflecting light from a mirror moving close to the speed of light has been envisioned as a route towards producing bright X-ray pulses,
- Unique perspectives open up for the use of laser-driven ion beams, particularly for nuclear astrophysics in view of the solid-state density of these beams, thus

exceeding the density of the ion beams from conventional accelerators by about 14 orders of magnitude. This ultra-high density ion beams will give rise to effects which lead to drastic deviations from classical expectations (the Bethe-Bloch formula for individual ions), when considering the specific energy loss of such a beam bunch hitting a secondary target. The unprecedented density of laser-driven ion beams will allow for a novel reaction scheme that promises to generate much more neutron-rich isotopes than accessible with conventional techniques, especially targeting the region of the r-process waiting point at N = 126 region, which is crucial for understanding the nucleosysthesis of the heaviest elements. Habs, Thirolf and col. [41,42] proposed to produce neutron-rich nuclei in the range of the astrophysical r-process (the rapid neutron capture process) around the waiting point N = 126 by fissioning a dense laser-accelerated Th ion bunch on a Th target, where the light fission fragments of the beam fuse with the light fission fragment of the target,

– Proton acceleration by the interaction of an ultra high intensity laser beam with matter has several wide prospective applications in medicine, astrophysics, nuclear physics, and material science (see for ex. Refs. [5,34]). Applications for laser-driven photon and particle beams include transmutation studies and medical applications as PET isotope production, radiotherapy and radiography, hadron therapy. A very special application of the high intensity laser matter interaction is the inertial confinement fusion, a subject too vast to attempt to review in the present paper. This is just to name a few of the possible experiments to be performed with the state-of-the-art equipment available at ELI-NP and other future high-intensity laser facilities.

3 Conclusions

The ELI-NP facility mirrors the birth of the new field of high- intensity laser interactions with matter mixing two research communities, the intense laser community with the nuclear physics community. As a result, a virgin science field, which can be called Laser Nuclear Physics, and new scientific frontiers will be reached.

The ELI-NP project is the result of an international collaborative effort of scientists from more than 20 countries and their contribution to the definition of the project is gratefully acknowledged. The essential contribution of my enthusiastic and tenacious colleagues from Magurele in the implementation of the project is also deeply acknowledged. The ELI-NP project is co-funded by The European Union through the European Regional Development Fund.

References

1. See the review article by G. Mourou, T. Tajima, S. Bulanov, Rev. Mod. Phys. **78**, 309 (2006)
2. D. Strickland, G. Mourou, Opt. Comm. **56**, 219 (1985)
3. I.N. Ross, et al., Opt. Commun. **144**, 125 (1997)
4. See for example: Paul Gibbon, *Short Pu]lse Laser Interaction with Matter* (Imperial College Press, 2005), Andrea Macchi, *A Superintense Laser-Plasma Interaction Theory Primer* (Springer Briefs in Physics, 2013)
5. K.W.D. Ledingham, W. Galster, New J. Phys. **12**, 045005 (2010)
6. D. Habs, T. Tajima, V. Zamfir, Nuclear Phys. News **21**, 23 (2011)
7. N.V. Zamfir, EPS Web Conf. INPC2013 **66**, 11043 (2014)

8. *ELI-NP White Book* (eds.), D. Habs et al. (2010), `http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf.`
9. G.A. Mourou, C.P.J. Barry, M.D. Perry, Phys. Today **51**, 22 (1998)
10. T. Tajima, J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979)
11. V. Malka, Phys. Plasmas **19**, 055501 (2012)
12. S.C. Wilks, et al., Phys. Plasmas **8**, 542 (2001)
13. T. Esirkepov, M. Borghesi, S.V. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. **92**, 175003 (2004)
14. E.L. Clark, et al., Phys. Rev. Lett. **84**, 670 (2000)
15. E.L. Clark, et al., Phys. Rev. Lett. **85**, 1654 (2000)
16. A. Maksimchul, et al., Phys. Rev. Lett. **84**, 4108 (2000)
17. R.A. Snavely, et al., Phys. Rev. Lett. **85**, 2945 (2000)
18. A.P.L. Robinson, et al., New J. Phys. **10**, 013021 (2008)
19. A. Ashkin, Phys. Rev. Lett. **24**, 156 (1970)
20. T. Esirkepov, M. Yamagiwa, T. Tajima, Phys. Rev. Lett. **96**, 105001 (2006)
21. F. Pegoraro, S.V. Bulanov, Phys. Rev. Lett. **99**, 065002 (2007)
22. A. Henig, et al., Phys. Rev. Lett. **103**, 245003 (2009)
23. S. Kar, et al., Phys. Rev. Lett. **109**, 185006 (2012)
24. S. Steike, et al., Contrib. Plasma Phys. **51**, 444 (2011)
25. L. Yin, et al., Laser Part. Beams **24**, 291 (2006)
26. B.M. Hegelich, et al., New J. Phys. **15**, 085015 (2013)
27. D. Jung, et al., Phys. Plasmas **20**, (2013) 083103
28. D. Jung, et al., New J. Phys. **15**, 023007 (2013)
29. L.O. Silva, et al., Phys. Rev. Lett. **92**, 015002 (2004)
30. see for ex. S.S. Bulanov, et al., Phys. Rev. E **78**, 026412 (2008)
31. J. Badziak, et al., Appl. Phys. Lett. **89**, 061504 (2006)
32. A. Zigler, et al., Phys. Rev. Lett. **110**, 215004 (2013)
33. H.Y. Wang, et al., Phys. Plasmas **20**, 013101 (2013)
34. H. Daido, M. Nishiuchi, A.S. Pirozhkov, Rep. Prog. Phys. **75**, 056401 (2012)
35. A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys. **85**, 751 (2013)
36. J. Galy, et al., New J. Phys **9**, 23 (2007)
37. M. Marklund, P.D. Shukla, Rev. Mod. Phys. **78**, 591 (2006)
38. H. Chen, et al., Phys. Rev. Lett. **102**, 105001 (2009)
39. W. Bang, et al., Phys. Rev. Lett. **111**, 055002 (2013)
40. D. Kiefer, et al., Nature Commun. **4**, 1763 (2013)
41. D. Habs, et al., Appl. Phys. B **103**, 471 (2011)
42. P.G. Thirolf, et al., Acta Physica Polonica B **42**, 843 (2011)