LASER PARTICLE ACCELERATION: STATUS AND PERSPECTIVES FOR NUCLEAR PHYSICS*

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High power short-pulse lasers with peak powers presently reaching Terawatts and even Petawatt levels routinely reach focal intensities of 10^{18}–10^{21} W/cm^2. These lasers are able to produce a variety of secondary radiation, from relativistic electrons and multi-MeV/nucleon ions to high-energetic X-rays and γ-rays. In many laboratories world-wide large resources are presently devoted to a rapid development of this novel tool of particle acceleration, targeting nuclear, fundamental and high-field physics studies as well as various applications *e.g.* in medical technology for diagnostics and tumor therapy. Within the next 5 years a new EU-funded large-scale research infrastructure (ELI: Extreme Light Infrastructure) will be constructed, with one of its four pillars exclusively devoted to nuclear physics based on high intensity lasers (ELI-Nuclear Physics, to be built in Magurele/Bucharest). There the limits of laser intensity will be pushed by three orders of magnitude to yet unprecedented 10^{24} W/cm^2.

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1. Status of Laser-Particle Acceleration

Since the invention of the laser in 1960 drastic progress has been achieved in the increase of laser power and focal intensities, basically due to a continuous reduction of the laser pulse length from μs to nowadays femtoseconds. With the advent of new technologies (chirped pulse amplification CPA [1]

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and optical parametric CPA [2]) periods of saturation were overcome, thus paving the road towards the nowadays prospering field of laser particle acceleration. Fig. 1 gives an overview of the development of laser powers and focal intensities, nowadays routinely reaching up to PW powers and intensities up to 10^{21} W/cm^2. Details of this plot are discussed in the review article by Mourou *et al.* [3].

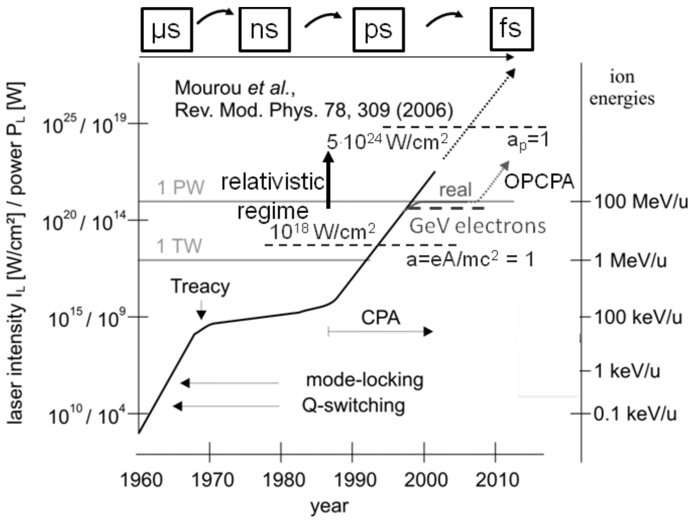

Fig. 1. Overview of the development of laser power and focal intensity together with the energy of laser-accelerated electrons and ions. Details are discussed in the quoted article by Mourou *et al.* [3].

Exploiting the extremely large accelerating fields of high-power, short-pulse lasers in the regime of TV/m up to PV/m together with the effects of relativistic laser–plasma interaction allow for electron and ion acceleration on a mm scale to energies so far provided only by large conventional accelerators. Exploiting the laser wakefield acceleration mechanism acting on gas jet targets [4], 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 $\sim 10^{-5}$ mm mrad [5]. Until recently laser ion acceleration was limited to thermally shaped, continuous energy spectra, using the 'target normal sheath acceleration' mechanism (TNSA) acting on rather thick solid targets ($\sim \mu$m foils). The conversion efficiency from laser to ion energy ϵ in this scenario scales rather inefficiently with $\epsilon \propto \sqrt{I_{\rm L}}$, with $I_{\rm L}$ being the laser intensity, reaching barely $\epsilon \sim 1\%$. Recently a new ion acceleration mechanism, 'Radiation Pressure Acceleration' (RPA) was introduced first theoretically [6], where circularly polarized laser light interacts with a very thin (few nm) (diamond-like) carbon foil, driving the electrons out of the foil via the light pressure and dragging the ions behind in the resulting dipolar field. It is essential that the electrons will experience cold compression, forming a dense, relativistic electron sheet, and that electrons and ions will be accelerated together as a neutral bunch, thus avoiding Coulomb explosion. This opens the possibility to generate quasi-monoenergetic ion beams with much improved conversion efficiency (scaling $\propto I_{\mathrm{L}}$) of up to 10–20%. Ion energies up to 50 MeV/u have been reported so far (with an energy spread of presently 10–20%, leaving much room for improvement) and recently the first experimental observation of the RPA mechanism was achieved [7].

2. Ultra-dense laser-accelerated ion beams for nuclear astrophysics: the 'fission–fusion' mechanism

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 ion beams from conventional accelerators by about 14 orders of magnitude. This ultra-high density of laser-accelerated ion beams will give rise to collective effects, which lead to drastic deviations from classical expectations, when *e.g.* considering the specific energy loss of such a beam bunch hitting a secondary target. For individual ions the Bethe–Bloch equation, describing the specific energy loss, contains two contributions, one addressing binary collisions and another one describing the energy loss by long-range collective interactions. Since in the envisaged laser-based scenario the plasma wavelength (*ca.* 5 nm) will be significantly shorter than the bunch length of the accelerated ions (*ca.* 200 nm), only binary collisions will contribute to the specific energy loss. When hitting the target, the first layers of the ultra-dense accelerated ion bunch will remove the electrons of the target foil like a snowplough, thus drastically reducing the electron density seen by the rest of the bunch. So the energy loss in the target will be drastically reduced, thus allowing to use much thicker targets [10].

The unprecedented density of laser-driven ion beams will allow for a novel reaction scheme that holds promise to generate much more neutron-rich isotopes than accessible with conventional techniques, especially targeting the region of the r-process waiting point at $N = 126$, where presently the last known isotope is 15 neutrons away from the r-process path. This region is crucial for understanding the nucleosynthesis of the heaviest elements [8, 9]. In the 'fission–fusion' reaction scenario we propose to produce exotic nuclides in this mass range by fissioning a dense laser-accelerated thorium ion bunch in a second thorium target, where the light fission fragments of the beam will fuse with the light fission fragments of the target.

Fig. 2 shows a sketch of this reaction scenario for two different situations, (a) for the case of normal electronic stopping as described by the Bethe–Bloch equation and (b) for the case of reduced stopping due to collective effects in the target induced by the ultra-dense ion beam discussed above.

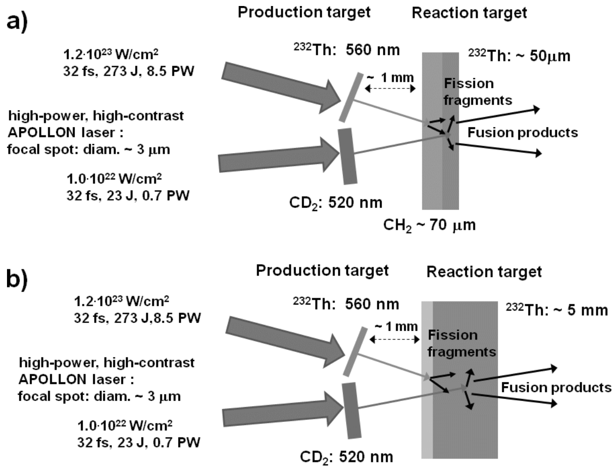

Fig. 2. Target arrangement envisaged for the 'fission–fusion' reaction process based on laser-ion acceleration. (a) illustrates the situation in case no collective effects on the electronic stopping are taken into account. (b) depicts an alternative scenario, where we consider collective effects in the reaction target induced by the ultra-dense ion bunches, leading to a reduced electronic stopping and allowing for a larger target thickness (see text).

The target arrangement consists of two targets: 'production' target and 'reaction' target. The first is composed of two spatially separated foils, one made from ^{232}Th and the other from deuterated polyethylene, CD_2. They serve for the generation of a laser-accelerated thorium ion beam and a beam containing carbon ions and deuterons. The reaction target has a sandwich structure. The first layer is made from CH_2 and serves a twofold purpose: Primarily it is used to induce fission of the impinging Th ion beam, generating the beam-like fission fragments. Here polyethylene is advantageous compared to a pure carbon layer because of the increased number of atoms able to induce fission on the impinging Th ions. In addition, the thickness of this CH_2 layer has been chosen such that the produced fission fragments will be decelerated to a kinetic energy which is suitable for cold fusion with the target-like fission fragments generated by the light accelerated ions in the Th layer of the reaction target. The second layer of the reaction target is a pure thorium film. The accelerated carbon ions and deuterons lead to fission of these thorium nuclei. Fusion of the (light) fragments created in both layers generates neutron-rich nuclei in a mass range towards the waiting point $N = 126$. This reaction scheme works best when the thorium and carbon ions and the deuterons each have an energy of about 7 MeV/u, which can be selected by choosing appropriate target and laser focus conditions. While so far (as shown in Fig. 2(a)) 'conventional' stopping was assumed, Fig. 2(b)) takes into acount collective events of stopping reduction. We now propose to abandon the front CH_2 layer of the reaction target and use only a homogeneous, 5 mm thick Th target as indicated in Fig. 2(b)). We now use the first part of the target (marked by the lighter colour in Fig. 2(b)) primarily as stopping medium for the incoming Th ions in order to decelerate them to about 3 MeV/u for subsequent cold fusion with target-like fragments. The drastic increase of the reaction target thickness now results in a full conversion of the Th beam into fission fragments.

Based on a laser energy of 300 J and a pulse width of 32 fs (as envisaged for the APOLLON laser [11] planned for the ELi-Nuclear Physics project in Bucharest [12]), an order-of-magnitude estimate gives a yield of neutron-rich fusion products in the mass range of $A = 180$–190 of about 10^3 per laser pulse in the scenario with collectively reduced electronic stopping. While presently the laser repetition rate is limited to about 1 pulse/min., extensive efforts are ongoing to reach about 100 Hz within the next few years. A detailed study of this scenario can be found in Ref. [10].

Fig. 3 displays a closer view into the region of nuclides around the $N = 126$ waiting point of the r-process, indicated are the key bottleneck r-process isotopes at $N = 126$. The elliptical contour lines show the range of nuclei expected to be accessible with our new 'fission–fusion' scenario on a level of 50%, 10% and 10^{-3} of the maximum fusion cross-section between two neutron-rich light fission fragments.

An important experimental task will be the subsequent separation of the fusion reaction products with about 2–3 MeV/u from faster beam-like fission fragments with about 7 MeV/u, or target-like fragments with about 1 MeV/u, which could be achieved with a (gas-filled) recoil separator. In first studies, a tape station could be used to transport the reaction products to a remote, well-shielded detector system, where the characterization of the implanted fusion products could be performed *e.g.* via β-decay studies. Since most of the fusion products will have typical lifetimes of ≈ 100 ms, they will survive the transport to a secondary target and/or detector station. In a later stage, the fusion products may be stopped in a buffer gas stopping cell [13], cooled and bunched in, *e.g.*, a radiofrequency quadrupole ion guide before then being transferred to a Penning trap system for high-accuracy mass measurements.

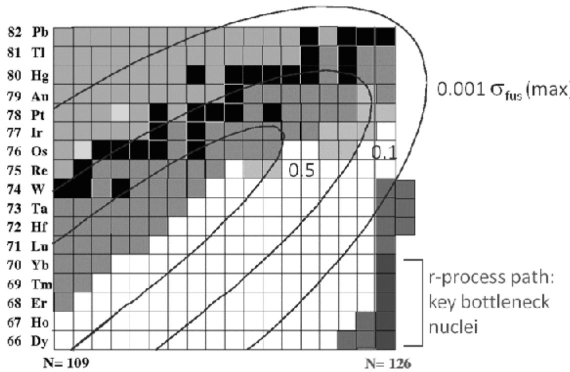

Fig. 3. Chart of nuclides around the $N = 126$ waiting point of the r-process path. The ellipses denote the expected range of isotopes expected to be accessible via the 'fission–fusion' process. The indicated lines represent 0.5, 0.1 and 0.001 of the maximum fusion cross-section after neutron evaporation. The $N = 126$ nuclides relevant for the r-process are marked, with the dark colour indicating the key bottleneck nuclei for the astrophysical r-process.

3. Perspectives for Brilliant, Intense Gamma Beams

Photo-nuclear transitions can be probed by γ rays in the range from a few 100 keV to multi-MeV that are presently available from various sources: tagged photons from electron scattering can be obtained *e.g.* in an energy range from 6–20 MeV from the NEPTUN facility of the S-DALINAC electron linac in Darmstadt [14] with an average γ rate of about 10^5/s and a band width of $\Delta E/E \sim 3 \times 10^{-3}$. At the presently leading photonuclear facility 'HIγS' at Duke University (USA) [15] a high energy electron storage ring ($E_e = 0.3$–1.2 GeV) is combined with an XUV Free Electron Laser, whose photons are backscattered from the electron beam, thus via the Compton upshift of $4\gamma^2$ ($\gamma = 1/\sqrt{1-(v/c)^2}$) being able to provide γ beams from 2–50 MeV with an intensity of about 10^7/s and a bandwidth of ca 2%. The same principle of Compton backscattering of laser photons off fast electron beams is used at the MeGaRay facility (Lawrence Livermore Natinal Laboratory) [16] and at LCLS (SLAC, Stanford) [17]. The first one will provide photons up to 2 MeV, while the X-ray laser facility LCLS concentrates on the X-ray regime below 10 keV. For the upcoming laser-based Extreme Light Infrastructure (ELI) facility with its nuclear physics pillar (ELI-NP) envisaged for construction in Bucharest [12], a high-intensity, high-brilliance γ beam is foreseen with $> 10^{13}$ photons/s and $\Delta E/E \sim 10^{-3}$, based on Compton-backscattering of laser photons from a 600 MeV electron beam. In the future laser-particle acceleration may allow even to surpass the brilliance of the unprecedented γ beam of ELI-NP. Fig. 4 displays the concept of a fully laser-driven γ-ray source.

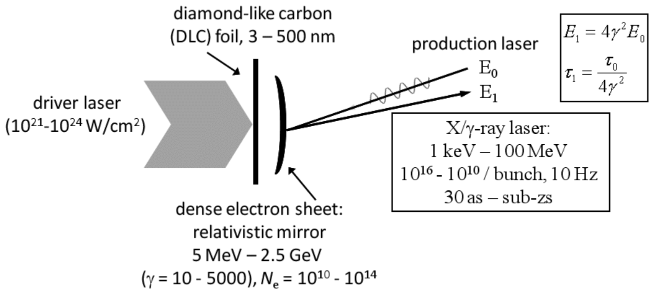

Fig. 4. Schematical description of a laser-driven relativistic electron sheet used as mirror to generate ultra-short, high-energy photons via Compton-backscattering.

A high-power driver laser (up to 10^{24} W/cm^2 as envisaged for ELI) hits a thin diamond-like carbon (DLC) foil. Via the radiation pressure laser acceleration mechanism the electrons in the foil are compressed and driven out of the foil as a dense, relativistic electron sheet that can act as a relativistic mirror when it is hit by photons from a second counter-propagating laser beam. Via the Doppler-upshift of $E_1 = 4\gamma^2 E_0$ high photon energies can be achieved, while the already ultrashort laser pulse (*ca.* 20 fs) will be further shortended by $\tau_1 = \tau_0/4\gamma^2$. Up to 10^{15} photons per second with a band width of about 10^{-2} are expected from this scenario. It will have to be experimentally tested whether this relativistic mirror will even be able to *coherently* reflect the optical photons. However, already incoherent reflection would provide a multi-MeV γ-ray source with a peak brilliance far beyond all presently existing or planned light sources, as can be seen from Fig. 5.

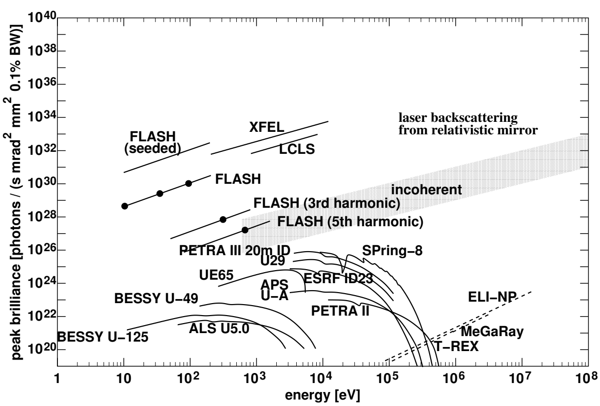

Fig. 5. Overview of peak brilliances from conventional light sources compared to the facilities based on Compton-backscattering (MeGaRay, ELI-NP) and indicating the potential when using a relativistic laser-driven electron mirror.

Here the peak brilliances of existing and planned light sources are included, impressively illustrating that laser-backscattering sources able to produce multi-MeV γ beams (T-REX and its successor MeGaRay in Livermore, ELI-NP in Bucharest) exhibit unrivaled properties, with the perspective of laser backscattering from a laser-driven relativistic electron mirror marking the ultimate goal (shown is only the scenario for incoherent reflection). Perspectives for applications of these novel γ beams are outlined at the end of the next chapter.

4. ELI-Nuclear Physics: New Research Facility for laser-based Nuclear Physics

The European Strategy Forum on Research Infrastructures (ESFRI) and its roadmap [18] aim to integrate national resources into a common, pan-European effort. Currently the ESFRI roadmap, as updated in 2008, lists 43 large-scale projects selected from all science and engineering areas. Under the 7th Framework Programme the European Commission has funded the preparatory phases for 34 projects included in the initial 2006 ESFRI roadmap. In the area of physical sciences besides the two RIB facilities FAIR (GSI/Germany) and SPIRAL2 (GANIL/France) also the project 'Extreme Light Infrastructure' (ELI) [19] was selected. A decision was made in October 2009 to build ELI by a joint European consortium of 17 nations as consisting of three individual laser facilities that will be consolidated under the joint ELI project. The prime objective is to build a unified infrastructure based on (initially) three pillars. One pillar will be located in Prague (Czech Republic), focusing on providing a novel generation of secondary sources from high energy laser beams for interdisciplinary applications in physics, medicine, biology, and material sciences. The second pillar, concentrating on the physics of ultrashort optical pulses on the attosecond scale, is planned for location in Szeged (Hungary). Finally, the third pillar will be built in Magurele, close to Bucharest (Romania) and will be dedicated to (photo-)nuclear physics [12], therefore termed ELI-Nuclear Physics (ELI-NP). With the termination of ELI's Preparatory Phase end of 2010 and with funding of 280 million Euros in the process of being allocated from EU structural funds for ELI-NP, ground breaking for ELI-NP could start as early as 2011. The laser backbone of ELI-NP will consist of initially two arms of high-power, short-pulse lasers, each of them providing 10 Petawatt laser power. These 'APOLLON'-type lasers are currently being developed by the group of Mourou and coworkers at the École Nationale Supérieure de Techniques Avancées (ENSTA) in Paris [11]. Here, a future fourth pillar of ELI is prepared, where several (up to ten) APOLLON lasers are envisaged to be combined for high-field science. The second source of ELI-NP, the γ-beam facility, will be developed and provided by the group from Lawrence

Livermore National Laboratory (LLNL, C. Barty *et al.*). Brilliant, intense and energetic photon beams will be generated via Compton backscattering of laser photons from a high-quality 600 MeV electron beam [20]. The Livermore group is presently building a similar facility called MeGa-ray [16], with a normal-conducting electron linac based on X-band technology. This facility is a continuation of their previous γ-ray facilities PLEJADES [21] and T-REX [22]. Hence, the longterm expertise of the groups responsible for the key components of ELI-NP raise confidence for a timely completion of its main driver facilities. Thus a world-leading laser-based facility is scheduled to become operational in 2015, opening intriguing perspectives for novel experiments in photonuclear and astrophysics, fundamental and high-field science as well as for a variety of applications with high societal impact (*e.g.* R&D for nuclear waste management and the identification of shielded nuclear materials, novel types of radioisotope production for nuclear medicine, soft matter and material sciences and many others). Via the (γ, n) reaction also a highly brilliant neutron source can be created, opening up new perspectives of neutron physics as outlined in [23]. The full scope of the ELI-NP project is described in detail in the ELI-NP Whitebook [24].

5. Conclusion

The fast-developing field of laser-particle acceleration has matured in recent years to a level, where electron as well as ion acceleration can be envisaged to be used also in nuclear physics and related fields. Ultra-dense laser-accelerated ion beams allow for exploiting new reaction schemes like 'fission–fusion' involving fusion of two light fission fragments, potentially leading to extremely neutron-rich species towards the r-process waiting point at $N = 126$, crucial for improving our understanding of the nucleosynthesis of the heaviest elements. Highly brilliant γ beams from back-scattering off either high-quality 'conventional' fast electron beams or maybe in the future from a laser-driven relativistic electron mirror will allow for unprecedented intensity and resolution for photonuclear physics. Finally we gave a brief outline on the perspectives of the upcoming first laser-based large-scale research facility 'ELI-Nuclear Physics' that will allow to open new horizons for photon physics in Europe in the coming decade.

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