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Physics Procedia 00 (2012) 000–000

UCANS III

Laser Driven Neutron Sources: Characteristics, Applications and Prospects

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Abstract

The basics of laser driven neutron sources, properties and possible applications are discussed. We describe the laser driven nuclear processes which trigger neutron generation, namely, nuclear reactions induced by laser driven ion beam (ion n), thermonuclear fusion by implosion and photo-induced nuclear (gamma n) reactions. Based on their main properties, i.e. point source (<100 μm) and short durations (< ns), different applications are described, such as radiography, time-resolved spectroscopy and pump-probe experiments. Prospects on the development of laser technology suggest that, as higher intensities and higher repetition rate lasers become available (for example, using DPSSL technology), laser driven methodologies may provide neutron fluxes comparable to that achieved by accelerator driven neutron sources in the near future.

Keywords: laser; neutron; source; acceleration; ion; Gamma ray; laser fusion

1. Introduction

Apart from all nuclear energy related applications, neutrons are acquiring an important role in very diverse fields such as material science, biology, medicine, security and industrial engineering. Its ability to probe matter mostly by interaction with the nuclei, make them particularly suitable to investigate structural properties as well as functional ones in which light atoms are present. As the number of neutron applications increases, so does the need of neutron sources. A 2010 report estimated the total number of neutron sources around the world to be around a thousand, predicting an increase of 50 new units every year [Hamm,2010; Hamm, 2008]. For obvious reasons, this demand cannot be fulfilled with new fission reactors or spallation facilities. Therefore, more affordable neutron sources, in particular for moderate fluences, must be designed. Back in 2005, a technical report of the International Atomic Energy Agency [IAEA 2005] encouraged the construction and use of small and medium scale accelerators driven neutron sources, ADNS, as adequate installations with a wide range of potential applications, for example as a test-bench for components and instrumentation designed for large neutron facilities, as “cheap” education and training tools or as home-lab sources for medium and small neutron flux applications. A more recent and thorough description of other opportunities can be found in [Mank 2011]. With the present conditions, ultraintense laser driven neutron sources, in particular those with a reduced “table-top” size, may have a word to say. Laser technology to amplify and compress pulses has evolved dramatically since the first evidences of neutron production by lasers [Floux 1970] and at present, TW or PW systems can easily trigger nuclear reactions with the resulting production of millions or billions of neutron per laser shot. At present, large laser laboratories are able to produce 10^{10} n/shot whereas table-top systems generate a more modest fluence of some 10^{6} n/shot. Although those values may not look impressive compared to the current ADNS, laser systems provide several characteristic advantages which make them an interesting option of choice for some applications, namely, very directional and short neutron pulses and a cheap and compact system.

This paper aims at introducing the basics of laser driven neutron sources and their present and anticipated performance in the future, in order to report on the potential applications of this technology. In the next section, the authors briefly describe the two main types of lasers according to their energy and pulse duration. In the section three, the three main mechanisms of neutron production by lasers ((ion,n), implosion and (gamma,n)) are discussed. Based on the characteristics of the laser driven neutron sources, section four enumerates some of the most promising applications. Finally, section five overviews the current and future laser developments which could increase the neutron yields. In summary, laser systems may still be a young technology but, after the proper dedicated efforts, it might end up as a competitive source of neutrons.

2. Types of ultraintense lasers

With the advent of the Chirped Pulse Amplification (CPA) technology [Strickland and Mourou 1985], lasers are capable of delivering intensities significantly higher than 10^{18}W/cm^2, the electric and magnetic fields of which are so high that charged particles reach an energy regime in which the production of neutrons via different nuclear processes is highly probable. How lasers achieve those intensities allows us to distinguish between the two kinds of systems. On one side, there are the so called “table-top” lasers which are based on very short pulses, in the range of femtoseconds, and a few J of energy. These systems, due to their reduced size (they can be installed in a room) and cost (a few million euros) are suitable for small research centers and universities. On the other hand, there are large laser infrastructures which deliver hundreds of J per shot in a picosecond or nanosecond scale. These facilities require tens of meters of amplification bays and only highly funded institutions, typically in connection with laser confined fusion experiments, can have access to. A quite complete list of both types of lasers can be found in https://lasers.llnl.gov/map/ which, at present, counts with a total of roughly 65 facilities around the world.

Although, the laser induced mechanisms to produce neutrons are the same for both types of ultraintense lasers, there are three important factors to be taken into account:

i) Neutron generation by implosion of fusile capsules can only be produced at large facilities with tens or hundreds of laser beams due to the illumination configuration and the total laser energy required.

ii) Total number of neutrons produce, in particular by laser-ion acceleration, seem to follow a laser energy squared relationship [Ellison 2010], which implies that large systems typically produce three to four orders of magnitude more neutrons than table-top systems (10^9-10^{10} n/shot versus 10^6 n/shot).

iii) The laser repetition rate at a large facility is limited to a few shots per hour at best, whereas for small systems the shot rate is typically 1-10 Hz.

Having those differences in mind, in the following section we address experiments either in one or the other laser type.

3. Production of Neutrons by Laser and Characterization

In short, the current production of neutrons by ultraintense lasers is either based on the acceleration of light ion species (hydrogen isotopes) or on the generation of Gamma rays to induce nuclear reactions. In the future, one could also think on directly triggering the nuclear reactions by the intense electric and magnetic field of the laser but for that to occur intensities of $5x10^{28}$ Wcm^{-2} need to be achieved. In the following subsections, we will concentrate on the laser ion/gamma driven neutron sources via some of the most investigated nuclear reactions such as (p,n), d(d,n)^{3}He, d(t,n)^{4}He, Li(p,n), Li(d,xn), (γ,n) and (γ, fission).

3.1. Neutron Production by Laser Produced Ion Beams

There are different laser driven processes to accelerate ions from solid targets: laser breakout afterburner [Yin 2007], directed Coulomb explosion [Bulanov 2002], the radiation pressure acceleration (RPA) [Henig 2009], and the Target Normal Sheath Acceleration, TNSA, mechanism [Borghesi 2006, Badziak 2007]. The TNSA is one of the most employed mechanisms by the laser neutron community for ion acceleraion due to its more relaxed experimental requirements. In short in TNSA, an ultraintense laser pulse focused on a solid target accelerates electrons to relativistic energies by the ponderomotive force, creating strong sheath electrostatic field (TV/m) on both front and rear surfaces which in turn pulls out and accelerate ions from the target. The ions accelerated from the rear surface are more preferred due to their better beam properties in terms of directionality and bunch density. The duration of the ion bunch is directly related to the electrostatic field at the rear side which depends on the duration of the laser pulse and the motion of the electrons. Thus, the ion pulse can be as short as some picoseconds long at its origin. Typically, the generated ions show a broad spectral energy distribution extended up to several tens of MeV, where the peak ion energy and particle flux depend on various laser and target parameters [Zeil 2010].

There are numerous examples of generation and acceleration of high fluxes of energetic proton and deuteron beams in literature, many of them related to the induction of fusion reactions and neutron production. For a review, the reader is referred to the work of [Ledingham and Galster 2010]. The most representative examples rely on D samples: solid CD_2 target [Youssef 2005], deuterated plastic targets [Izumi 2002] and heavy water (D_2O) sprayed target [Ter-Avetisyan 2005]. In most cases, the experimental set-up used for the neutron generation falls in the following generic description: a target with H or D content is irradiated by an ultraintense laser pulse. By TNSA, H or D ions are accelerated from the rear side and impact on a second target where the nuclear reaction and the production of neutrons takes place. This scheme, also called pitcher-catcher set-up (see Figure 1a), can sometimes be substituted by a single thicker target in which both the acceleration of ions and nuclear reactions take place in the same material but at different depths [Willingale 2011]. For gaseous or cluster targets with D content, coulomb explosion plays a dominant role towards acceleration of ions which trigger the neutron generation by interaction with other D ions and neutral atoms from neighboring clusters [Ditmire 2000, Parks 2001, Madison 2003, Madison 2004] (see Figure 1b).

Experimentally, neutron production by laser irradiation of clusters has reached values of 5.5 $x10^6$/shot [Lu 2009].

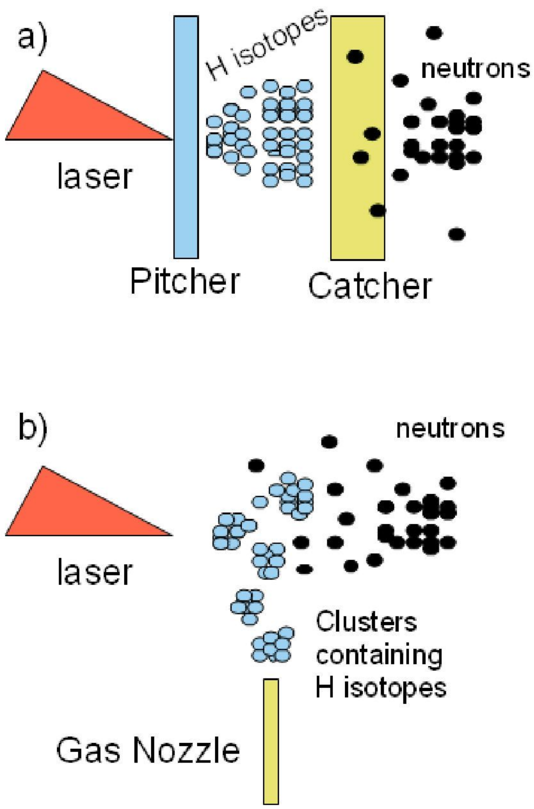

Figure 1 - Scheme of laser driven (ion, n) nuclear reactions. a) Neutron production by irradiation of solid targets based on TNSA mechanism in the Pitcher-Catcher configuration. b) Neutron production by irradiation of gas phase targets (clusters) based on Coulomb explosion.

Note that ion-fission and spallation [McKenna 2005] reactions with laser accelerated ions can also be a source of neutrons. However, because the stringent safety measures and complexity of using fissile elements in the former and the high energies ions required for the latter case (hundreds of MeV which are far from the current energies of laser driven ions) make these options less attractive.

At present, the neutron production numbers per laser shot range from 10^{5-6} in a table top system up to 10^{10} in large laser facilities [Ellison 2010, Ledignham 2010, Galy 2009]. Typically, the high neutron fluxes have been observed by deploying light ions (protons and deuterium) accelerated by the TNSA mechanism in either d-d or p-Li reactions. However, the acceleration of ions by the TNSA mechanism is probably not the most efficient process, and better neutron yields are expected with some of the other acceleration mechanisms mentioned above, with thinner targets and more optimized set-ups.

3.2. Neutron generation by laser implosion

Another process to produce neutrons by intense pulse lasers is through thermonuclear fusion by the implosion of a micro capsule containing fusion fuel, like deuterium (D) and tritium (T) [Nuckolls 1972]. The neutron generation by laser implosion have been demonstrated experimentally in various single shot lasers [Nakai 2004, Meyerhofer 2011, Azechi 2009] being the number of neutrons generated per one pulse much higher than those of the other laser driven cases. Therefore, the implosion neutron source is in principle the most intense among the various laser neutron sources.

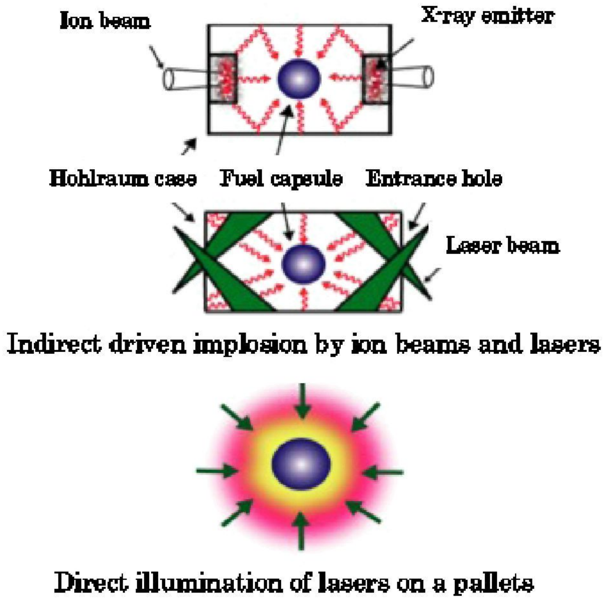

Figure 2. Implosion schemes

There are two laser implosion pathways namely, the direct drive [Eliezer 2008] and the indirect drive implosions [Lindl 1998]. The concepts of them are schematically shown in Figure 2. In the direct drive implosion, the surface of a fuel pellet is directly irradiated by laser beams. In contrast, in indirect-drive implosion, the driver energy is converted into soft x-rays, which fill a cavity as quasi-black body radiation. The soft x-rays are absorbed on the surface of the pellet to generate ablation pressure to drive the implosion.

In a thermo-nuclear scheme, the fuel number density n is depleted due to the nuclear reaction as

$$dn/dt = -n^2 \langle \sigma v \rangle /2$$

where, σ is the fusion cross section and $\langle \sigma v \rangle$ is the average over the energy distribution of D and T. For a constant $\langle \sigma v \rangle$ over time, one can write the expression for the fuel density as

$$n = n_0/(1 + n_0 \langle \sigma v \rangle t/2)$$

Therefore, the burning fraction Φ is given by

$$\Phi = 1 - n/n_0 = (n_0 \langle \sigma v \rangle t/2) /(1 + n_0 \langle \sigma v \rangle t/2)$$

The fusion reaction time t is given by the time of sustaining the plasma confinement. In the case of Inertial Fusion Energy (IFE), $t \sim R/4C_s$, where R is the plasma radius and C_s is the sound speed. Then, the burning fraction is given by the function of ρR as follows,

$$\Phi = \rho R/(A + \rho R)$$

where A is the function of temperature and approximately equal to $10/(T/10\ keV)^2\ g/cm^2$ for DT reaction. So, the neutron yield is $Y = N\ \Phi/2$, for $N = n_0\ (4\pi R^3/\ 3)$. If the laser pulse energy which heats the DT fuel *is* E_L and η is the energy coupling efficiency of laser to the reacting plasma, we can write $\eta E_L = 3NT$.

When $\rho R << A$, $Y \sim N\rho R/A$, which is proportional to $(E_L/T)^{4/3}(\rho_{\square}/\rho_S\ \ )^{2/3}$, where $\rho_S = 0.2\ g/cm^3$ is the initial DT density, and the temperature T is 10 keV. For T=10 keV and η=0.1, Y ~ $10^7(E_L/1.0J)^{4/3}$ which is shown in the Figure 3 by a solid line.

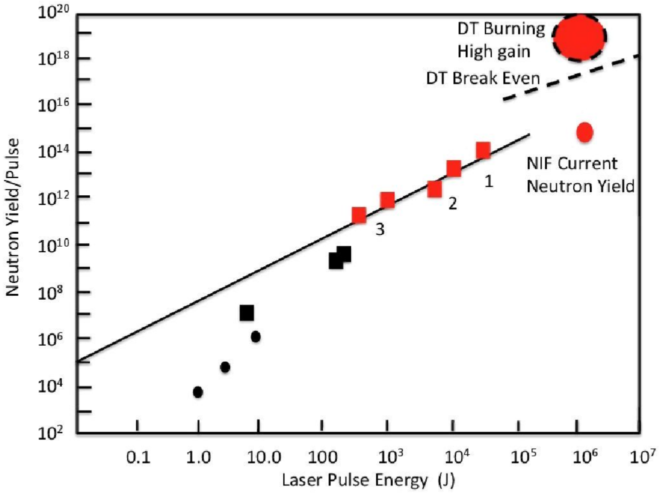

Figure 3. Laser energy dependence of neutron yield. Red squares, black squares, and red circle correspond to implosion experiment neutron yields for LHART (Large High Aspect Ratio Target) [Yamanaka 1986], exploding pusher target [Storm 1978], and NIF indirect drive [Lindl 1998], respectively. Small black circles are for the cluster fusion by using JanUSP [Madison 2003] (This figure is an update of the figures presented in previous papers by one of the authors [Nakai 2008, Nakai 2010]).

Figure 3 shows the compiled data of neutron generation as a function of injected laser energy with different pulse width depending on the related implosion processes and the cluster Coulomb explosion. The data points are basically single shot results. Since high repetition-rate operation is needed for its applications as a neutron source, repeatable target feeding and high average power pulse laser must be developed. When the neutron production shots are repeated at 10 Hz to 1 kHz, the neutron flux could be higher than 10^{15} n/sec. It should be also noted that fusion ignition can enhance the neutron production beyond the broken line in Figure 3 (that line corresponds to the breakeven condition, Q=1, where the fusion energy is equal to the incident laser energy). Once the ignition is achieved with high gain, as expected to be demonstrated in near future (2013~2015) by the NIF [Glenzer 2010], the neutron yield will be as high as indicated by the broken line circle – in excess of $10^{18\text{-}19}$/pulse.

3.3. Neutron Production by N-Gamma Processes

Photo-induced nuclear (gamma, n) and (gamma, fission) reactions can also be triggered by ultraintense lasers. As in the case of ions, the process relies on the initial acceleration of electrons from a solid target to relativistic speeds. When these relativistic electrons are decelerated during their interaction with the bulk material, Bremsstrahlung radiation is emitted in the Gamma ray range of the EM spectrum. In turn, the generated Gamma rays can excite the surrounding nuclei and produce neutrons. However, if compared with ion driven neutrons, this approach is far less effective. The conversion efficiency of laser energy to photon via Bremsstrahlung is lower than one percent, while the efficiency of laser energy to proton can reach up to 10%. In addition, cross-sections are higher for (p,xn) reactions than they are for (gamma,f) or (gamma, xn) reactions [Galy 2009]. Thus, this procedure to generate Gamma rays and latter neutrons has been set aside and other ways are being explored. Energy shift of laser pulses to lower wavelengths via Compton scattering with accelerated electron beams is a well established technique and high intensity gamma-ray sources as HiγS are based on it. Based on the same concept and using the ability of ultraintense lasers of producing an accelerated dense electron sheet, Dr. Habs and his group have proposed to create very bright Gamma ray pulses using the electron sheet as a relativistic mirror (energy $E = \gamma mc^2$). In this case the oscillating electron sheet coherently reflects a second laser pulse of photon energy ω, which by the Doppler boost, will turn into a high-energy photon beam with energy $\hbar\omega' = 4\gamma^2\hbar\omega$ [Habs 2009]. Among the applications of such a bright Gamma source, Dr. Habs' team proposes the production of thermal neutrons in a micro size scale.

4. Overview of applications

As previously mentioned, neutron sources have found applications in many scientific, technological and industrial areas. In particular, some possible applications of laser neutron sources were already identified in previous reports by some of the authors [Nakai 2008, Nakai 2010]. These reports have mentioned the use of neutrons in probing energy storage systems like Li-ion batteries and fuel cells, in nuclear energetics (fission and fusion reactor materials), in medical therapy like BNCT cancer therapy, and as a new tool in diagnostics, especially in measurements of light elements. Depending on the application, the required neutron energy and flux were evaluated and the design of energy moderation and guiding systems are mentioned. A summary of those studies can be found in Table 1 for the different applications in industry.

In broader sense, the possibility of developing an ultra-short source of thermal neutrons opens the territories of ultrafast dynamic studies in a wide range of disciplines such as material science, condensed matter and biology. For example, in fusion energy research, ultrafast studies may allow to trigger and visualize in real time the production and evolution of radiation damage at the atomic scale. Short bursts of neutrons would also be a powerful probe to obtain crucial information about equation of state of matter under extreme conditions, such as those found in inertial confinement fusion or planetary cores.

Another interesting application would be the use of compact source of pulsed, mono-energetic MeV neutrons delivering above 10^{10} n/cm^2 for security measures at checkpoints for investigation of large cargo containers by fast neutron radiography technique, where the nature and location of the threat can be identified by simultaneously measuring scattered neutrons and time of flight of the induced gamma radiations.

Table 1. Applications and Required Neutron flux

Application	Required Neutron Flux
Diagnostics	**10^{11} - 10^{12} /s**
Li-ion batteries, Fuel Cells,	

Combustion Engine (Fuel nozzle), Hydro storage Engineering	
Medical applications	
BNCT	**10^{12} - 10^{13} /s**
(Boron Neutron Cancer Therapy)	
Power Electronics	**10^{13} - 10^{14} /s**
Silicon Doping	
Material Processing and Nuclear Material R&D	
Transmutation of radiation	**≥ 10^{15} /s**
Fusion Reactor Engineering	
Fission Reactor Engineering	

5. Propects

In light of rapid developments in laser technology and intrinsic advantages in terms of low cost and compactness, reduction of radioactive pollution and ability of radiation confinement by close-coupled experiments, significant attention is being paid in the development of laser driven neutron sources. Among the mentioned possible laser energised nuclear phenomena, the most investigated route to create a neutron source is employing laser accelerated ions. At present, neutron fluences are limited 10^{10} W/cm^2 using the TSNA mechanism. However, with the prospects of high repetition (0.1-100 Hz) 1- 100 PW lasers based on Diode Pumped Solid State Lasers, DPSSL, one can envisage boosting the average power of the neutron source by some orders of magnitude in the near future. Ongoing projects such as ELI [ELI web page], APOLLON [LULI web page], Mercury [LLNL Lasers web page] and Dipole [CLF web page] aim at intensities > 10^{23} W/cm^2 at a shot repetition rate of few Hz which should already increase the neutron fluence in one order of magnitude [Ellison 2010].

For what concerns the achievable neutron yield, various schemes mentioned in the section 3 appear promising for the emerging state-of-the-art lasers. Work aimed to their experimental validation, comparative characterization and optimization at currently accessible laser facilities will help setting milestones on the way to future developments. Exploring the potential of different approaches is important as the choice for one of the schemes over another can be biased depending on the parameters required by a specific application, for instance, neutron energy.

6. Conclusions

The second generation of neutron sources (spallation based) has won popularity over the reactor based sources due to their high flux and pulsed (ms) nature. However, the scale and operational cost involved in such accelerator based facilities not only limits their availability to the scientific community, but also are a bottleneck for the wide promotion of industrial, technological and healthcare applications. Several of such studies are feasible employing moderated neutron flux of the order of ~10^{10} n/cm^2 from accelerator driven neutron sources (ADNS) or, as it has been discussed here, by laser driven neutron sources. In the present work, different mechanisms to generate neutrons have been discussed ((ion n), fusion implosion and (gamma n)), and their current developmental status, and their pros and cons summarized.

From the point of view of applications, the two main advantages from laser sources are the small size and the short duration of the neutron pulses. These two characteristics can greatly improve the present spatial and time resolution of neutron based measurements. From the point of view of logistics and as long as the provided flux is adequate, "table-top" laser neutron sources can also be attractive to universities, small research departments and nuclear medicine centers due to their relative low cost, more relaxed shielding demands and compact size. Large laser facilities pursuing fusion might be as expensive as large fission or spallation based neutron sources but, if ignition is reached, they may produce neutron fluxes in unprecedented quantity in the form of short bursts.

At present, the quality and flux from laser neutron sources, in particular "table-top" systems, may be below the ones required for conventional applications of neutrons. However, as it has been described, there are strong reasons to believe that the ongoing developments in laser amplification technology will overcome those limitations in the near future. As any other not-yet mature technology, it will require more dedicated efforts but the foreseeable applications might well pay the toll.

Acknowledgements

J. Alvarez thanks the Spanish MINECO for economical support via the ACIPROMOCIONA program 2011 (AIC-A-2011-0718), and the previous Ministry of Science and Innovation for the research contract under the Especialización en Infraestructuras Científicas y Organismos Internacionales Subprogram 2010 (SEII-2010-00267). S. Kar would like to acknowledge the support from EPSRC - UK reseach grant - EP/J002550/1.

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