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Recent advances in laser-driven neutron sources

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Summary. — Due to the limited number and high cost of large-scale neutron facilities, there has been a growing interest in compact accelerator-driven sources. In this context, several potential schemes of laser-driven neutron sources are being intensively studied employing laser-accelerated electron and ion beams. In addition to the potential of delivering neutron beams with high brilliance, directionality and ultra-short burst duration, a laser-driven neutron source would offer further advantages in terms of cost-effectiveness, compactness and radiation confinement by closed-coupled experiments. Some of the recent advances in this field are discussed, showing improvements in the directionality and flux of the laser-driven neutron beams.

1. – Introduction

An ultrashort, directional burst of fast neutrons, produced by laser-driven, compact ion accelerators, would have wide ranging applications including material testing for fusion energy research [1], fast neutron radiography [2], neutron resonance spectroscopy [3], and fast neutron therapy [4, 5]. In addition, with the possibility of moderating the laser-driven fast neutrons using closely coupled moderators, compact thermal and epithermal neutron sources can be developed for a wide range of neutron science and medical applications [6]. The growing interest in laser-driven neutron sources is also based on further advantages in terms of cost-effectiveness, compactness and radiation confinement by closely coupled experiments. In light of the rapid progress in laser technology, and particularly the development of diode-pumped solid-state lasers capable of delivering high-power lasers with high repetition rates [7], laser-driven sources may provide, in a near future, neutron fluxes on samples comparable to those delivered at conventional facilities.

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In this paper we briefly review three neutron generation mechanisms currently being investigated. Neutron fluxes reported in the literature are reviewed and discussed along with the results obtained from a recent experimental campaign. The focus here is on providing an overview of the improvements achieved in this area and their importance towards the development of compact neutron sources for potential applications.

2. – Laser-driven neutron generation

There are three main mechanisms capable of producing high neutron fluxes: spallation reactions, photo-neutron generation and nuclear fusion reactions. Although the spallation of a heavy nucleus produces multiple neutrons, it requires highly energetic (hundreds of MeV) ions. Therefore, this mechanism is currently limited to large neutron facilities employing conventional ion accelerators. For example, the ISIS facility in the UK [8] produces neutrons by bombarding tungsten targets with 800 MeV protons accelerated by a synchrotron ring of 163 m circumference. Since such high energy ions are beyond what can be currently achieved by laser-driven acceleration, for currently accessible laser intensities, the on-going research on laser-driven neutron sources mainly relies on the other two mechanisms.

2·1. *Photo-nuclear reactions.* – The photo-neutron generation is based on the interaction of high-energy γ photons with heavy nuclei (such as ^{208}Pb, ^{209}Bi, ^{231}Th), which excite the nuclei to high-energy states leading to the emission of protons or neutrons, depending on the nuclear structure. The cross-section of the photo-nuclear reactions usually peaks at photon energies of the order of MeV. Therefore, one can take advantage of the highly energetic electron beams produced via laser-plasma interaction. In this case, the neutrons are generated via a double conversion in a secondary converter target (fig. 1(a)). Energetic photons are produced via Bremsstrahlung, as the high energy electrons are slowed down inside the high-Z converter. This is followed by the interaction of the photons with the heavy nuclei in the same converter, allowing the photo-nuclear reaction to take place.

Highly energetic electrons from laser-plasma interactions are mainly produced via two mechanisms, viz. Laser Wake Field Acceleration (LWFA) [9-11] from underdense plasmas, and via the $J \times B$ mechanism during the interaction of intense lasers with overdense plasmas [12, 13]. Although electron energies from hundreds of MeV to GeV energies can be produced by the LWFA mechanism, the total charge in the accelerated electron bunch sets a limitation in terms of the achievable neutron yield. On the other hand, interaction of intense lasers with solid targets allows efficient coupling of laser energy into the hot electrons, even though a broad quasi-Maxwellian electron spectra is produced with temperature of the order of the Ponderomotive potential of the laser (maximum energy typically of the order of tens of MeV [14]). The potential of using these high-flux, moderate-energy electrons towards developing a credible neutron source was recently demonstrated experimentally by using Cu converters [14]. A total neutron yield (in 4π and full spectrum) of the order of 10^9 neutrons/shot was produced isotropically with a neutron bunch duration shorter than 50 ps, as estimated from the transit time of the relativistic electrons interacting with the converter.

2·2. *In-target reactions.* – An alternative route to generate a high flux of fast neutrons is to deploy laser-accelerated light ions in fusion reactions. One can use the dense bunch of ions accelerated from the front-surface of a laser irradiated target, through the

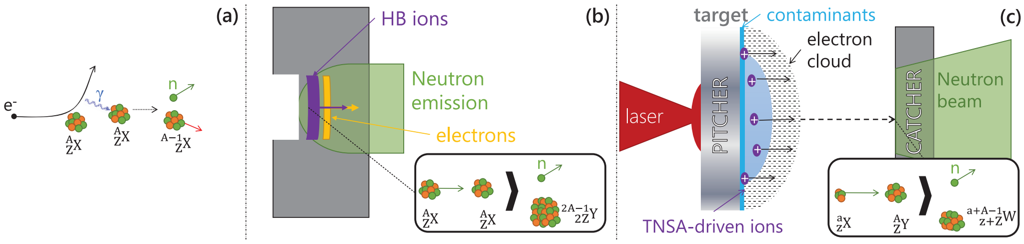

Fig. 1. – Schematic showing the three neutron generation mechanisms using high-power lasers, as discussed in the text.

so-called "*Hole-Boring (HB)*" mechanism [15,16] (fig. 1(b)), to produce neutrons via fusion reactions initiated by the ions travelling through the target bulk. Efficient neutron production in this case requires a large fusion cross-section at relatively modest (MeV range) ion energies. Therefore d(d,n)^{3}He reaction has been considered as the ideal candidate, and can be implemented by irradiating deuterated plastic or heavy water targets with intense lasers.

2˙3. *Beam-target fusion.* – While the HB mechanism produces a dense bunch of low energy (MeV) ions suitable for the d(d,n)^{3}He reaction, other promising high-yield fusion reactions, such as ^{7}Li(p,n)^{7}Be, require higher energy projectiles. Low atomic mass nuclei, such as protons and deuterons, can be efficiently accelerated to tens of MeV energies by a number of ion acceleration mechanisms, an avenue of laser-plasma interaction that has been very actively investigated over the last decade. Among several laser-driven ion acceleration mechanisms explored so far, Target Normal Sheath Acceleration (TNSA) [17-21] has been established as one of the most robust processes (fig. 1(c)). Other mechanisms such as Radiation Pressure Acceleration [22-24] and Break-Out Afterburner [25, 26] are currently being investigated as they are predicted to produce significantly higher ion energies compared to the TNSA mechanism with next generation lasers.

An appealing source of neutrons can be developed by employing these high-energy ions (protons and deuterons) in a pitcher-catcher scenario. In this double-target configuration, the first target (pitcher) is irradiated by the laser and is the source of the projectile light ions, whereas fusion reactions take place in the second target (catcher), initiated by the projectile ions from the first target. The higher the energy of the projectiles, the deeper they propagate into the catcher, producing a higher number of neutrons per incident ion. Due to the kinematics of the beam-target reaction, the neutrons in the laboratory frame are emitted with strong anisotropies in their flux and energy distribution, both peaked along the axis of the projectile ions [27]. Such a beamed neutron source would be highly useful for their direct applications, or further transport and moderation.

3. – State of the art

An overview of experimental results obtained from the different types of laser-driven neutron sources is presented. Here we focus on the on-axis flux, since an isotropic emission would show higher numbers for the total yield, nonetheless neutrons directed along a given direction would be of interest for most of the applications.

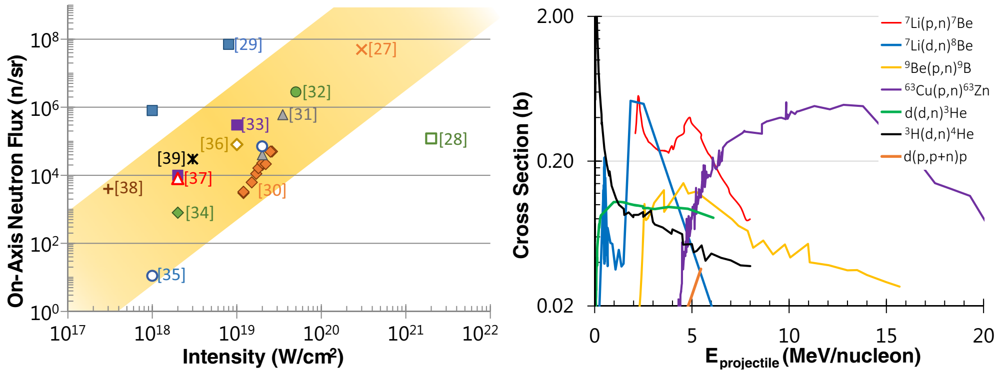

Fig. 2. – (a) Overview of measurements reported in the literature for on-axis neutron flux from in-target mechanism, as a function of laser intensity on the target. For more information see refs. [27-39]. (b) Comparison between reaction cross-sections suitable for neutron generation using laser-driven low-Z projectile ion species.

The neutron source based on photo-neutron reaction is currently at an early stage of development and the only reported data [14] has been discussed in sect. **2**˙1. Figure 2(a) compares data obtained from the "in-target" type of neutron sources (as discussed in sect. **2**˙2). As can be seen in fig. 2(a), one can find a broad, general trend of increasing the on-axis neutron flux with the increase in laser intensity. The few deviant data points in this graph are likely due to differences in laser conditions or target parameters (thickness and composition). For example, the data point from the ref. [28] was obtained using

TABLE I. – *List of recently published results using pitcher-catcher configuration. N.S. in the 6th column stands for "not specified" for the cases where the range of neutron energies is not explicitly specified in the reference. The diagnostics used for the flux measurement are mentioned within brackets in the column 6, while neutron Time of Flight was used when the range of neutron energies is specified. BD stands for Bubble Detector dosimeters, sensitive to neutrons of energy in the range* $\sim 100\,keV$*–tens of* MeV [45]. *CR39 is a nuclear track detector capable of detecting neutrons over a broad range of energies* [46].

Ref.	E_{laser} (J)	I_0 (W cm^{-2})	Nuclear reaction	On-axix neutron flux (n/sr)	Neutron energy (E_n) range (MeV)	On-axis flux/E_{laser} (n sr^{-1}/J)
[28]	1.1	$2.0 \cdot 10^{21}$	^{7}Li(d,n)^{8}Be	$3.0 \cdot 10^6$	$0.5 < E_n < 20$	$2.7 \cdot 10^6$
[30]	6.0	$2.0 \cdot 10^{19}$	d(d,n)^{3}He	$1.2 \cdot 10^4$	$1 < E_n < 5$	$2.0 \cdot 10^3$
[40]	6.0	$2.0 \cdot 10^{19}$	d(d,n)^{3}He	$4.0 \cdot 10^5$	N.S. (BD)	$6.7 \cdot 10^4$
[41]	69.0	$2.5 \cdot 10^{19}$	^{7}Li(p,n)^{7}Be	$2.0 \cdot 10^8$	N.S. (CR39)	$2.9 \cdot 10^6$
[42]	80.0	$2.0 \cdot 10^{20}$	d breakup & ^{9}Be(d,n)^{10}B	$1.0 \cdot 10^{10}$	N.S. (BD)	$1.3 \cdot 10^8$
[43]	127.0	$7.0 \cdot 10^{20}$	^{7}Li(d,n)^{8}Be	$3.5 \cdot 10^8$	N.S. (CR39)	$2.8 \cdot 10^6$
[27]	150.0	$2.0 \cdot 10^{20}$	d(d,n)^{3}He & d(p,p+n)p	$1.0 \cdot 10^9$	$2.5 < E_n < 20$	$6.7 \cdot 10^6$
[44]	360.0	$2.0 \cdot 10^{19}$	^{7}Li(d,n)^{8}Be	$7.5 \cdot 10^8$	N.S. (CR39)	$2.1 \cdot 10^6$

a laser with significantly shorter ($\sim$ 30 fs) pulse duration compared to the rest, and a higher density target(C_8D_8 polystyrene) was used in ref. [29] than in other experiments shown here, typically carried out with CD targets. Nonetheless, the increase in neutron flux with the incident laser intensity, as suggested by fig. 2(a), can be explained in terms of the ion energy scaling ($E_{\mathrm{ion}} \propto I/\rho$, where I and ρ are laser intensity and target mass density, respectively) for the HB mechanism [16]. In fact, a higher ion energy would lead to a deeper penetration into the bulk, and to a larger number of fusion reactions.

Some of the recent data reported in literature using a pitcher-catcher configuration are listed in table I. As it can be seen, a direct comparison between the different experiments is difficult, not only due to the limited number of data points available to date, but also due to the large variations in laser and target parameters, as well as the different fusion reactions involved in those data points. However, using higher energy/intensity laser pulses would in principle lead to a significant increase in neutron flux due to the expected improvements in the projectile ion beam parameters. For a given pulse duration and focal spot size, increasing the laser energy (and intensity) on target, generally leads to higher flux of higher energy ions via the TNSA mechanism. Where a higher flux of ions would increase the neutron flux commensurately, higher energy ions will also lead to a substantial increase in the neutron flux due to their deeper penetration inside the catcher.

Neutron flux can be optimised further by selecting suitable nuclear reactions for a given projectile ion species. For instance, since the TNSA mechanism can efficiently produce beams of low-Z ions, such as protons and deuterons (by using either deuterated targets [27] or a deuteron rich coating at the rear side of the target [21]), there are several fusion reactions that can be of interest as shown in fig. 2(b). While the typical reaction used so far in the literature has been the ^{7}Li(p,n)^{7}Be, some recent publications have investigated possible enhancement in neutron flux by using the ^{7}Li(d,n)^{8}Be reaction [28, 43, 44].

In a recent experimental campaign, we studied the neutron source from nuclear reactions involving low-Z nuclei, such as protons and deuterons. Neutrons were produced by irradiating, on a deuterated plastic catcher, high energy beams of protons and deuterons produced from a sub-petawatt laser interaction with deuterated plastic targets. A neutron flux of the order of $1 \cdot 10^9$n/sr along the ion beam axis was obtained from a combination of d(d,n)^{3}He, D(p,p+n)p reactions. The neutron beam displayed a near-gaussian flux profile of $\sim 70^\circ$ FWHM [27]. Further increase in neutron flux is anticipated by optimising the incident ion beam and catcher combinations in future experiments.

4. – Conclusions

The scale and operational costs associated with the conventional accelerator-driven neutron facilities can be a bottleneck for the wide promotion of neutron sources in science, industry and healthcare sectors. An overview of different approaches pursued for developing laser-driven neutron sources and results reported in the literature are discussed. There is significant scope for optimising the neutron beam flux and directionality by varying the laser-plasma interaction regimes, as well as by an appropriate choice of nuclear reactions. The upcoming facilities aimed to deliver higher laser powers and intensities will also support the development of laser-driven neutron sources by increasing further the peak neutron fluxes.

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