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► **To cite this version:**

Ronan Lelievre, E. Catrix, S. Vallières, S. Fourmaux, Amokrane Allaoua, et al.. High repetition-rate 0.5 Hz broadband neutron source driven by the Advanced Laser Light Source. *Physics of Plasmas*, 2024, 31 (9), pp.093106. 10.1063/5.0218582 . hal-04797682v2

**HAL Id: hal-04797682**

**<https://hal.science/hal-04797682v2>**

Submitted on 13 Jan 2025

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RESEARCH ARTICLE | SEPTEMBER 24 2024

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R. Lelièvre ; E. Catrix ; S. Vallières ; S. Fourmaux; A. Allaoua; V. Anthonipillai; P. Antici ; Q. Ducasse ; J. Fuchs 



*Phys. Plasmas* 31, 093106 (2024)

<https://doi.org/10.1063/5.0218582>



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# High repetition-rate 0.5 Hz broadband neutron source driven by the Advanced Laser Light Source

Cite as: Phys. Plasmas **31**, 093106 (2024); doi: 10.1063/5.0218582

Submitted: 28 July 2024 · Accepted: 18 August 2024 ·

Published Online: 24 September 2024



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Export Citation



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## ABSTRACT

Neutron beams are an essential tool to investigate material structure and perform nondestructive analysis, as they give unique access to element composition, thus ideally complementing density analysis allowed by standard x-rays investigation. Laser-driven neutron sources, though compact and cost-effective, currently have lower average flux than conventional neutron sources, due to the limited repetition rate of the lasers used so far. However, advancements in laser technology allow nowadays to address this challenge. Here, we report results obtained at the Advanced Laser Light Source characterizing stable production of broadband (0.1–2 MeV) neutrons produced at a high repetition rate (0.5 Hz). The interaction of laser pulses of 22 fs duration and 3.2 J on-target energy with 2- $\mu\text{m}$ -thick tantalum targets produced protons in the Target Normal Sheath Acceleration (TNSA) regime up to 7.3 MeV. These protons were subsequently converted into neutrons by (p,n) reactions in lithium fluoride (LiF). Activation measurements and bubble detectors were used to characterize neutron emissions, with a neutron fluence of up to  $\sim 1.4 \times 10^5$  neutrons/shot/sr and energies mainly between a few hundred of kilo-electron volt and 2 MeV. The total neutron yield was  $\sim 5 \times 10^5$  neutrons/shot. This paves the way for numerous applications, e.g., in homeland security, materials science, or cultural heritage.

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## I. INTRODUCTION

Neutrons offer two unique characteristics when used as probes of matter: not only can they penetrate deeper into matter than charged particles (of the same energy), but due to their direct interaction with nuclei they also provide unique insights, through elemental and temperature analysis, of the properties of materials, well beyond the capability of charged particles or x-rays. Laser facilities are now recognized as new particle sources, including the possibility to generate neutron fields<sup>1–4</sup> with very short duration neutron bunches (picosecond<sup>5</sup>–nanosecond<sup>6</sup>) and record peak brightness.<sup>7–10</sup> These characteristics make laser-driven sources complementary to conventional sources, from very compact, hand-held monochromatic fusion sources STA,<sup>11</sup> to large-ones like fission reactors producing continuous neutrons or

accelerators, producing longer neutron pulses (microsecond at best).<sup>12</sup> Moreover, the best conventional sources, having a much higher average but lower peak neutron fluxes than the laser-driven sources, have a much larger footprint and cost compared to the latter.

These characteristics are particularly interesting for applications in astrophysics, e.g., by opening up the possibility of characterizing multiple neutron captures,<sup>13,14</sup> in nondestructive material analysis for industry,<sup>15</sup> or contraband detection,<sup>16–18</sup> or for heritage science by performing Neutron Resonance Spectroscopy (NRS),<sup>19,20</sup> or Instrumental Neutron Activation Analysis (INAA),<sup>21</sup> thus complementing Prompt Gamma-ray Activation Analysis (PGAA).<sup>22,23</sup>

However, to improve the prospects of these applications, it is necessary to increase the flux of laser-driven neutron sources by moving

to high-repetition rate operation, and to ensure their stability shot after shot. Indeed, most of the characterization of laser-driven neutrons was performed until now using large-scale, high-energy (tens or hundreds of Joules) lasers, such that the neutron flux could be large. However, the yield of the protons used to generate the neutrons is very non-linear with respect to the input laser energy.<sup>24</sup> Hence, an important aspect of evaluating the usefulness of high-repetition rate table-top lasers as neutron drivers is to measure how the neutron yield is affected by moving from high-energy lasers to such lasers having much more moderate energies, in the few Joules range. This is the main endeavor of the present work. Here, we present the first measurements of broadband neutron emissions generated repetitively with a laser at a repetition rate of 0.5 Hz. Note that two recent separate works have also investigated high-repetition rate laser-driven neutron sources. The first<sup>25</sup> was conducted at 1 Hz repetition rate, but using much lower laser energy and hence producing a much lower neutron fluence. The second<sup>26</sup> was conducted at a higher high-repetition rate (1 kHz) and yielded a similar average flux as reported here, but with monochromatic fusion-based neutrons. Here, we used the Advanced Laser Light Source (ALLS), a laser source characterized by a good shot-to-shot laser repeatability.<sup>27</sup> The neutrons were produced by the interaction of protons accelerated from tantalum foils via the Target-Normal Sheath Acceleration (TNSA) mechanism<sup>28–30</sup> and subsequently converted through (p,n) reactions in a LiF converter, in the so-called pitcher-catcher scheme.<sup>3</sup>

Section II details the experimental setup for performing laser-driven proton acceleration and neutron production. Section III shows the results of the experimental characterization of neutron emissions, in comparison with simulations performed using the Monte Carlo transport codes Geant4<sup>31</sup> and MCNP6.<sup>32</sup> Finally, Sec. IV delves into the results obtained and provides perspectives induced by this study.

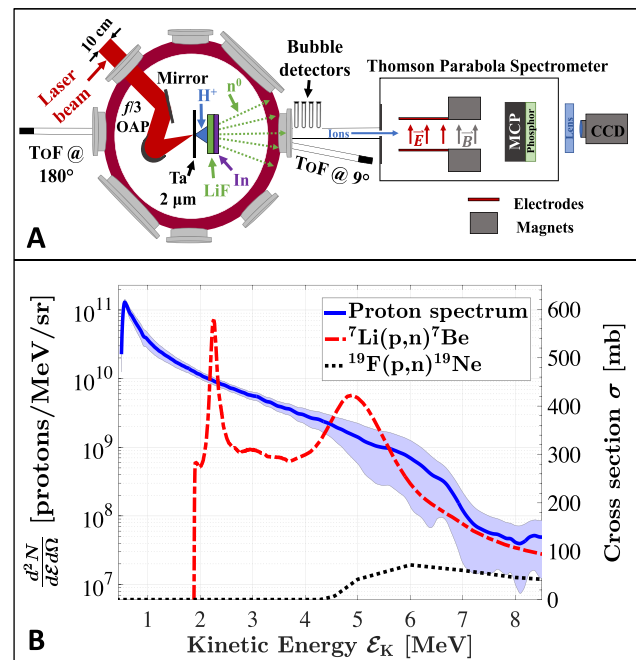
## II. EXPERIMENTAL SETUP

### A. ALLS 150 TW Ti:Sapphire laser

The experiments were carried out on the laser-driven ion acceleration beamline at the Institut national de la recherche scientifique (INRS) in Varennes, near Montréal, Canada. We used the ALLS 150 TW Ti:Sapphire laser<sup>33</sup> based on a double Chirped Pulse Amplification (CPA) system, delivering 3.2 J on target with a pulse duration of  $\tau_{\text{FWHM}} = 22$  fs at full-width-half-maximum (FWHM) and with a central wavelength of  $\lambda_0 = 800$  nm. The experimental setup, shown in Fig. 1(a), uses an  $f/3$  off-axis parabola (OAP) to focus the  $95 \times 95$  mm square beam (at  $e^{-2}$ ) down to a spot size of  $w_{\text{FWHM}} \sim 5 \mu\text{m}$ . Parabola alignment and wavefront optimization, using a feedback loop between a wavefront sensor and a deformable mirror, are both performed at full laser power, which allows to compensate aberrations arising from thermalization in the laser system. This results in a peak intensity  $I_0$  around  $1.3 \times 10^{20}$  W/cm<sup>2</sup>. Prior to entering the second CPA amplification stage, a cross-wave polarizer (XPW) and a booster stage relying on saturable absorber are employed to clean the incoming laser beam, achieving an Amplified Spontaneous Emission (ASE) pre-pulse contrast  $< 10^{-10}$  at  $-100$  ps before the main pulse, along with a steep power rise with contrast  $< 10^{-6}$  at  $-3$  ps.

### B. TNSA-based proton acceleration

The p-polarized laser pulses are incident at an angle of  $20^\circ$  with respect to the target-normal on  $2\text{-}\mu\text{m}$ -thick tantalum foils [see



**FIG. 1.** (a) Top-view of the experimental setup for the laser-driven neutron generation. (b) Mean proton spectrum averaged over 38 shots using a  $2\text{-}\mu\text{m}$ -thick tantalum foil (full blue). The shaded area is delimited by one standard deviation. The cross sections for the nuclear reactions  ${}^7\text{Li}(p,n){}^7\text{Be}$  (dashed red) and  ${}^{19}\text{F}(p,n){}^{19}\text{Ne}$  (dotted black) are also shown, as given by the ENDF/B-VIII.0<sup>34</sup> and TENDL-2019 libraries,<sup>35</sup> respectively.

Fig. 1(a)] to produce ion beams using the TNSA regime, allowing for 400 consecutive shots by using a custom-made target holder. The experiment is conducted in a ‘multi-shot mode’ where all target positions are pre-set in the software controlling the motorized stages. The software is synchronized with the laser trigger at 0.5 Hz.<sup>27</sup> The energy distribution of the accelerated ions (mainly protons and carbon ion species) is measured using a calibrated Thomson Parabola (TP) spectrometer positioned at  $0^\circ$  with respect to the target-normal axis, employing a microchannel plate (MCP) detector allowing to acquire the images of the ion spectra for each laser shot. A mean proton spectrum (averaged over 38 shots) is shown in Fig. 1(b), characterized by  $\sim 10^{11}$  protons/sr/shot and an energy cutoff of 7.3 MeV. Additionally, two time-of-flight (ToF) spectrometers are deployed, one positioned at  $9^\circ$  and the other at  $180^\circ$  from the main axis, to monitor the number of protons and their energies in correlation with the TP spectrometer. The latter spectrometer is primarily utilized when the LiF converter is inserted into the ion beam path to verify that the TNSA acceleration occurs efficiently.

### C. Neutron emissions

For the neutron generation, we selected LiF as the converter material in order to maximize the neutron production. Indeed, since the maximum proton cutoff energy is limited to about 7.3 MeV and since the proton spectrum has a typical decreasing exponential shape, LiF is optimum due to its high cross sections of (p,n) reactions for low-energy protons. Further, it has a threshold energy of about

1.9 MeV and a specific resonance at 2.2 MeV of the  ${}^7\text{Li}(p, n){}^7\text{Be}$  reaction [see Fig. 1(b)]. Thus, a 1-mm-thick, 1-inch-diameter LiF converter was placed 20 mm behind the target holder [see Fig. 1(a)], ensuring that all protons interact with it.

1. Diagnostics

Several techniques were employed to characterize the neutron emissions,<sup>36,37</sup> including bubble detectors<sup>38</sup> and activation measurements.<sup>39</sup> Bubble detectors are composed of droplets of a superheated liquid contained in an elastic polymer. These droplets become visible bubbles when neutrons lose their energy inside the detector and, by counting the number of bubbles and considering an appropriate calibration, neutrons doses can be determined. Two types of bubble detectors, supplied by *Bubble Technology Industries*, were used during this experiment: type BD-PND and type BDT. BD-PND detectors are sensitive to neutrons from ~200 keV to more than 15 MeV, while BDT detectors are sensitive to thermal neutrons.

An activation diagnostic composed of a 1-in.-diameter and 6-mm-thick pure indium sample, placed right behind the LiF converter [see Fig. 1(a)], was also used during the experiment. The interaction of neutrons with this sample can cause two main reactions:  ${}^{115}\text{In}(n, n'){}^{115m}\text{In}$  and  ${}^{115}\text{In}(n, \gamma){}^{116m}\text{In}$ . As shown in Fig. 2(b), the cross sections of the first reaction are significant between 2 and 10 MeV,

allowing to detect neutrons in this energy range, while the second reaction is more sensitive to neutrons from the thermal region to few mega-electron volt and serves as a qualitative low-energy neutron diagnostic.

Finally, as the neutrons are produced through the  ${}^7\text{Li}(p, n){}^7\text{Be}$  reaction only (see below), the total number of neutrons can be determined by measuring the  ${}^7\text{Be}$  nuclei created in the converter. This radioisotope emits a gamma-ray of 478 keV with an intensity of 10.44% and a half-lifetime long enough ( $T_{1/2} = 53.22$  d) to be easily measured using gamma spectrometry.

2. Monte Carlo simulations

To predict the characteristics of the neutron emissions, Geant4 simulations were made using the averaged proton spectrum shown in Fig. 1(b), injected into the LiF converter within a half angle of  $21^\circ$  to reproduce the beam divergence of a TNSA proton beam.<sup>41</sup> These considerations and the use of the ENDF/B-VIII.0 and TENDL-2019 libraries allow to faithfully reproduce the experimental conditions and the nuclear reactions inside the converter.

Figure 2 presents the simulated angular distribution of neutron emissions and the associated neutron spectra obtained at different angles, from  $0^\circ$  to  $180^\circ$ . These simulation results show that more neutrons, with higher energies, are emitted in the forward direction than in the backward direction. This implies that within the converter, not only compound nuclear reactions occur but also direct nuclear reactions, contributing to the distinctive emission anisotropy. However, the large angular distribution of protons induces a smoothed angular distribution of forward-directed neutron emissions and similar neutron spectra between  $0^\circ$  and  $45^\circ$ .

Additional simulations show that the  ${}^7\text{Li}(p, n){}^7\text{Be}$  reaction is responsible for all neutron emissions. This is due to a much lower cross section for the  ${}^{19}\text{F}(p, n){}^{19}\text{Ne}$  reaction and a higher threshold energy of 4 MeV, and to the fact that protons above 4 MeV represent only around 3% of the total number of protons emitted.

Thus, the total number of neutrons calculated by the simulations is  $5.44 \times 10^5$  neutrons/shot, corresponding to a simulated  ${}^7\text{Be}$  activity of 0.082 Bq/shot. The simulations also yield a fluence of up to  $9.20 \times 10^4$  neutrons/sr/shot at  $0^\circ$  and a mean value of  $5.42 \times 10^4$  neutrons/sr/shot in the specific solid angle covered by the indium sample ( $\sim 2\pi$  sr). This value and the corresponding neutron spectrum were then used to perform activation simulations of the indium sample, using MCNP6 with the IRDFF-II library, as it is more suitable for such modeling than the libraries available in Geant4, leading to a  ${}^{115m}\text{In}$  activity of 0.025 Bq/shot and a  ${}^{116m}\text{In}$  activity of 0.274 Bq/shot.

III. ASSESSMENT OF NEUTRON EMISSIONS

A. Activation measurements

A  $2 \times 2''$  NaI gamma spectrometer, shielded by 10-cm-thick lead bricks, was used to experimentally measure the activation of the converter and indium sample. The efficiency calibration of this spectrometer was performed with a  ${}^{152}\text{Eu}$  calibration point source and extrapolated to the geometries of the LiF converter and indium sample using Geant4 simulations and the efficiency transfer method<sup>42,43</sup> based on the Moens concept.<sup>44</sup> This allows to take into account the sample geometry and the self-attenuation effects of gamma rays on the measurements.

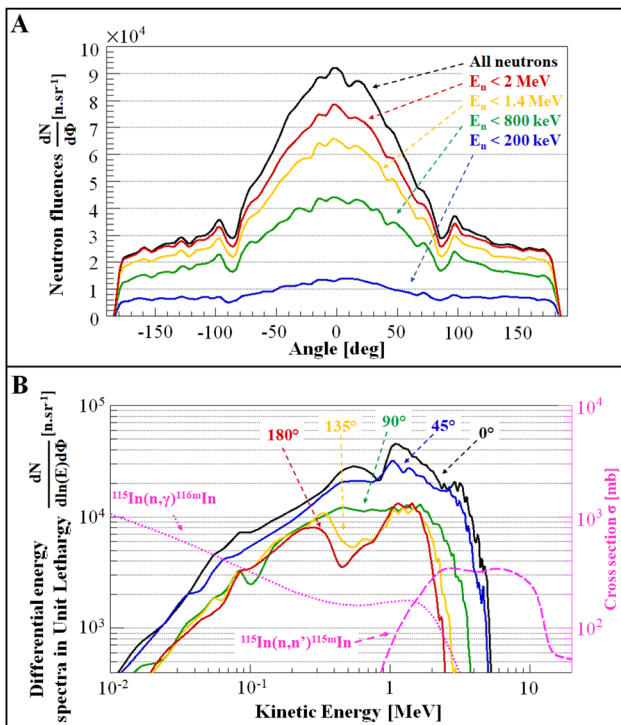


FIG. 2. (a) Simulated angular distribution of the neutron emissions recorded in the equatorial plane and passing through the converter center, and (b) differential energy spectra, in unit lethargy, obtained at different angles from Geant4 simulations. Overlaid are the cross sections (in pink) of the  ${}^{115}\text{In}(n, \gamma){}^{116m}\text{In}$  and  ${}^{115}\text{In}(n, n'){}^{115m}\text{In}$  reactions, according to the IRDFF-II<sup>40</sup> library. These are used for the activation simulations.



### 1. Direct measurement of the LiF converter

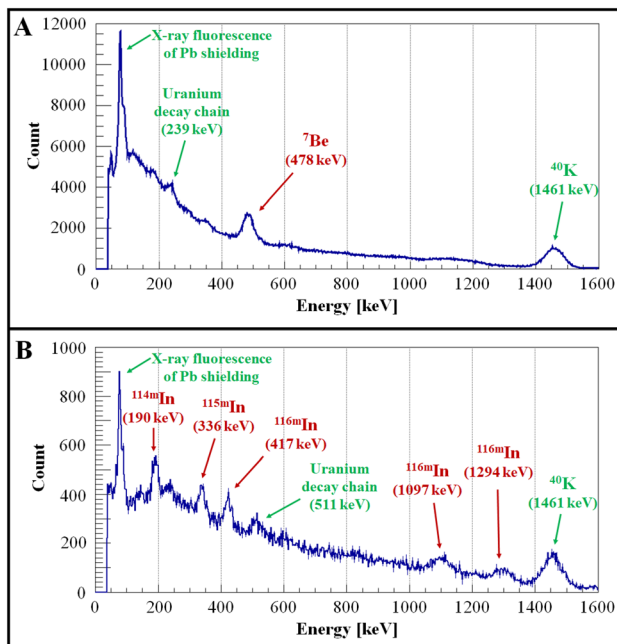
The LiF converter was used during a series of 292 shots to accumulate a measurable  ${}^7\text{Be}$  activity [see Fig. 3(a)]. The gamma spectrometry measurement revealed an activity of  $0.072 \pm 0.009$  Bq/shot, and the number of  ${}^7\text{Be}$  nuclei being equivalent to the number of neutrons emitted, we can thus infer a total neutron production of  $(4.76 \pm 0.62) \times 10^5$  neutrons/shot, which is 12.5% lower, but close, to the value predicted by the Geant4 simulations.

### 2. Indium sample

The indium sample was placed behind the LiF converter [see Fig. 1(a)], during the same series of 292 shots. Both  ${}^{115\text{m}}\text{In}$  and  ${}^{116\text{m}}\text{In}$  activities were measured by gamma spectrometry [see Fig. 3(b)], resulting in  $7.89 \pm 2.47$  and  $39.56 \pm 11.68$  Bq, respectively. Considering the almost flat cross section profile of the  ${}^{115}\text{In}(n, n'){}^{115\text{m}}\text{In}$  reaction between 2 and 10 MeV [see Fig. 2(b)], a neutron fluence in this energy range can be evaluated using the following equation:

$$N_{\Omega} = \frac{A_{\text{mes}}}{\lambda \times n_{\text{shot}}} \times \frac{1}{\bar{\sigma} \times t \times n \times \chi} \times \frac{1}{\Omega} \quad (1)$$

with  $N_{\Omega}$ , in units of neutrons/sr/shot,  $A_{\text{mes}}$ , the measured activity (in Bq),  $\lambda$ , the decay constant ( $\text{s}^{-1}$ ),  $n_{\text{shot}}$ , number of shots,  $\bar{\sigma}$ , the average cross section ( $\text{m}^2$ ),  $t$ , the sample thickness (m),  $n$ , number



**FIG. 3.** Gamma-ray spectra emitted from the LiF converter (a) and indium sample (b), as measured by a  $2 \times 2'$  NaI gamma spectrometer. The peaks pointed to by a green arrow come from the background noise, due to the presence of uranium and potassium in the soil and in the concrete used in the facility, as well as from the excitation of the lead shielding by the gamma-rays. In the following analyses, the  ${}^{114\text{m}}\text{In}$  nuclei were not considered since this radioisotope can be created from two reactions  ${}^{113}\text{In}(n, \gamma){}^{114\text{m}}\text{In}$  and  ${}^{115}\text{In}(n, 2n){}^{114\text{m}}\text{In}$ , with the inability to discriminate between their respective contributions.

**TABLE I.** Comparison between the simulated activities,  $A_{\text{sim}}$ , and the measured activities,  $A_{\text{mes}}$ , after the last laser shot of the series.  $\epsilon$  gives the corresponding experimental uncertainties. The simulated activities of the  ${}^{115\text{m}}\text{In}$  and  ${}^{116\text{m}}\text{In}$  were normalized by the  ${}^7\text{Be}$  activity measurement (i.e., by a factor 0.875), to take into account the real production of neutrons.

Reaction	$A_{\text{sim}}/\text{shot}$ (Bq)	$A_{\text{mes}}/\text{shot}$ (Bq)	$\epsilon$ (%)
${}^7\text{Li}(p, n){}^7\text{Be}$	0.082	0.072	13.0%
${}^{116}\text{In}(n, \gamma){}^{116\text{m}}\text{In}$	0.240	0.065	29.5%
${}^{115}\text{In}(n, n'){}^{115\text{m}}\text{In}$	0.022	0.013	31.3%

density ( $\text{m}^{-3}$ ),  $\chi$ , the isotope abundance, and  $\Omega$ , the solid angle covered by the sample (sr).

Thus, the  ${}^{115\text{m}}\text{In}$  measured activity of 0.013 Bq/shot would correspond to a neutron fluence of  $(6.99 \pm 2.19) \times 10^3$  neutrons/sr/shot between 2 and 10 MeV, in the specific solid angle covered by the indium sample, which is very close to the fluence of  $6.76 \times 10^3$  neutrons/sr/shot predicted by the simulations (and normalized by the  ${}^7\text{Be}$  activity measurement) in the same energy range and solid angle. The measurement therefore confirms the proportion of around 1.45% of neutrons above 2 MeV obtained by the simulations.

However, as shown in Table I, the  ${}^{115\text{m}}\text{In}$  simulated activity (0.022 Bq/shot) is roughly a factor of 2 higher than the measured value, which is not consistent with the good agreement between the evaluated and simulated fluences. This is due to an erroneous evaluation of the cross sections of the  ${}^{115}\text{In}(n, n'){}^{115\text{m}}\text{In}$  reaction by the IRDFF-II library for neutrons below 2 MeV, resulting in an overestimation of the activity. This was confirmed for this particular cross section by an experiment we performed at the AMANDE facility<sup>45</sup> (IRSN, Cadarache) where indium samples were irradiated by monoenergetic neutrons. A comparison between measured and simulated activities revealed an overestimation of the simulated activities, especially for neutrons between 0.565 and 1.2 MeV. Furthermore, if only neutrons above 2 MeV are considered in the activation simulations, we obtain a  ${}^{115\text{m}}\text{In}$  activity of 0.011 Bq/shot, which is more consistent with the measured activity.

The comparison between the measured and simulated  ${}^{116\text{m}}\text{In}$  activities is also shown in Table I. The measured activity is about four times lower than expected which means that, considering the cross section distribution of the  ${}^{115}\text{In}(n, \gamma){}^{116\text{m}}\text{In}$  reaction, the actual low-energy part of the neutron spectrum seems reduced compared to what is predicted by the simulations. In summary, these activation measurements show that fewer neutrons are emitted in the lower energy part of the neutron spectrum, while the proportion of high-energy neutrons ( $>2$  MeV) is in a good agreement with the simulations.

### B. Bubble detectors

BDT and BD-PND bubble detectors were also used to characterize the emissions of thermal and fast neutrons, respectively. They were placed outside the target chamber, on the target normal axis ( $0^\circ$ ), at 60 cm from the LiF converter [see Fig. 1(a)] and during the same series of 292 laser shots as before.

BDT detectors revealed no bubble, meaning that thermal neutron emissions are negligible, which is consistent with the simulated neutron spectra showing a significant and continuous decrease in the spectrum when the neutron energy decreases.

On the other hand, bubbles were observed in the BD-PND detectors. Considering their energy independent response to neutrons from 200 keV to around 15 MeV, the bubble counting leads to a neutron fluence of  $(1.37 \pm 0.15) \times 10^5$  neutrons/sr/shot in this energy range. This neutron fluence is 70% higher than the expected fluence obtained with the Geant4 simulations (normalized by the  $^7\text{Be}$  activity measurement). The neutron emissions seem therefore more forward-directed than predicted by the simulations.

#### IV. DISCUSSION

In summary, the use of these three diagnostics (bubble detectors, gamma spectrometry of the LiF converter and of the indium sample) allowed us to conduct the first characterization of neutron emissions generated, using the pitcher-catcher technique, in a high repetition-rate TNSA regime operating at 0.5 Hz, which produces laser-based ion acceleration through the interaction of a high power laser and thin-foil solid targets. The measurement of the  $^7\text{Be}$  activity produced by the interaction of the protons with the LiF converter led to an estimation of the total neutron production of  $(4.76 \pm 0.62) \times 10^5$  neutrons/shot, which is 12.5% lower than the simulation predictions.

The indium sample, measured by gamma spectrometry, presented an activation inducing a neutron fluence of  $(6.99 \pm 2.19) \times 10^3$  neutrons/sr/shot between 2 and 10 MeV and fewer emissions of low-energy neutrons compared to the simulations. This observation was confirmed by the absence of bubble inside the BDT detectors. However, the BD-PND detectors showed bubbles from which a neutron fluence of  $(1.37 \pm 0.15) \times 10^5$  neutrons/sr/shot was measured, in the range of 200 keV to around 15 MeV, along the normal axis ( $0^\circ$ ). These quantitative results, summarized in Table II, suggest a higher neutron emission than expected in the forward direction and a more sharp energy distribution between a few hundred of kilo-electron volt and 2 MeV.

The number of neutrons per shot obtained here is about  $10^5$  lower than what could be obtained using much higher energy lasers,<sup>19,46,47</sup> delivering on-target energies of several tens or hundreds of Joules, but which have a very poor repetition rate (with typically one shot per several hours). We also note that the present number of neutrons per shot is around 100 times lower than that measured<sup>37</sup> with a twice higher energy laser, having otherwise shorter pulses at very high contrast, but also limited to one shot per minute. All these point out to the strong nonlinearity of the neutron yield with respect to the input laser parameters (energy, laser pulse duration, and temporal contrast). It also shows that using laser-based neutrons for the applications demonstrated with the high-energy lasers (i.e., thermal neutron radiography or NRS) is

**TABLE II.** Summary of the measurement of neutron emissions by the three diagnostics used (gamma spectrometry of the LiF converter and of the indium sample, and bubble detectors), showing the simulated  $\Phi_{\text{sim}}$  and measured  $\Phi_{\text{meas}}$  total neutron yield and neutron fluences in different energy ranges.  $\epsilon$  gives the corresponding experimental uncertainties.

Quantity	Energy range	$\Phi_{\text{sim}}$	$\Phi_{\text{meas}}$	$\epsilon$ (%)
Total neutron yield (n/shot)	All neutrons	$5.44 \times 10^5$	$4.76 \times 10^5$	13.0%
Neutron fluences (n/sr/shot)	$\sim 0.025$ eV	0	0	...
	(2–10 MeV)	$6.76 \times 10^3$	$6.99 \times 10^3$	31.3%
	(0.2–15 MeV)	$8.05 \times 10^4$	$1.37 \times 10^5$	10.9%

not favorable in the conditions demonstrated here, as this would entail accumulating the neutron signal over tens of hours.

Nonetheless, other applications requiring lower neutron fluxes can be considered using the presently demonstrated high-repetition rate, low-yield source. The significant activation of the indium sample measured by gamma spectrometry reveals indeed the possibility of carrying out INAA measurements for the elemental analysis of objects composed of elements whose neutron interaction cross sections are similar or higher to those of indium. This points to a significant advantage of using a laser-based source, since, on the same facility, a range of nondestructive elemental analysis techniques could be deployed, e.g., INAA, but also x-ray fluorescence (XRF) and particle-induced x-ray emission (PIXE) measurements.<sup>48</sup> This is in contrast to conventional accelerators-based sources, where x-ray and neutron sources are produced by different machines.

Fast neutron radiography could also be considered with the neutron flux demonstrated here because, unlike thermal neutron radiography, it does not require to use a moderator to thermalize the neutrons, which usually reduces the neutron flux. Such an application was already performed<sup>49–51</sup> using conventional neutron sources with neutron fluences of about  $10^{7–8}$  neutrons/cm<sup>2</sup>. Considering the neutron fluence measured here between 2 and 10 MeV by the indium sample and extrapolating it to the whole spectrum, a total neutron fluence of around  $6 \times 10^4$  neutrons/cm<sup>2</sup>/shot can be inferred. Thus, we estimate that fast neutron radiography could be performed using the ALLS laser by cumulating several hundreds of shots, which represents only a few minutes of irradiation.

#### ACKNOWLEDGMENTS

The authors would like to acknowledge the staff of the ALLS facility: Joël Maltais, William Lévesque and Mandy Doly for their technical assistance during the experiment, and LaserNetUS for the beamtime provided under Proposal No. K173. This work was supported by the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program (Grant Agreement No. 787539), by CNRS through the MITI interdisciplinary programs and by IRSN through its exploratory research program, and by the National Sciences and Engineering Research Council of Canada (NSERC) (Grant Nos. RGPIN-2023-05459, ALLRP 556340-20), Compute Canada (Job: pve-323-ac). The ALLS facility and its ion beamline are funded and supported by the Canadian Foundation for Innovation (CFI), Institute for Quantum Computing, University of Waterloo, INRS, and Ministère de l'Économie, de l'Innovation et de l'Énergie (MEIE) from Québec. This work was supported by the U.S. Department of Energy Office of Science, Fusion Energy Sciences under Contract No. DE-SC0021246: the LaserNetUS initiative at the Advanced Laser Light Source.

#### AUTHOR DECLARATIONS

##### Conflict of Interest

The authors have no conflicts to disclose.

##### Author Contributions

**R. Lelièvre:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Resources

(equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **E. Catrìx:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Resources (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **S. Vallières:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Resources (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **S. Fourmaux:** Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **A. Allaoua:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **V. Anthonipillai:** Methodology (equal); Software (equal); Writing – review & editing (equal). **P. Antici:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Q. Ducasse:** Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **J. Fuchs:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

#### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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