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Numerical study of neutron beam divergence in a beam-fusion scenario employing laser driven ions

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Abstract

The most established route to create a laser-based neutron source is by employing laser accelerated, low atomic number ions in fusion reactions. In addition to benefiting from the high reaction cross-sections at moderate energies of the projectile ions, the anisotropy in the neutron emission is another important feature of beam-fusion reactions. Using a simple numerical model based on neutron generation in a pitcher-catcher scenario, anisotropy in the neutron emission was studied for the deuterium-deuterium fusion reaction. Simulation results are consistent with the narrow-divergence ($\sim 70^\circ$ full width at half maximum) neutron beam recently obtained from an experiment employing multi-MeV deuteron beams of narrow divergence (upto 30° FWHM depending on the ion energy) accelerated by a sub-petawatt laser pulse from thin deuterated plastic foils via the Target Normal Sheath Acceleration mechanism. By varying the input ion beam parameters, simulations show that a further improvement in the neutron beam directionality (i.e. reduction in the beam divergence) can be obtained by increasing the projectile ion beam temperature and cut-off energy, as expected from the interactions with higher power lasers at upcoming facilities.

Keywords: laser, neutron, beam fusion

1. Introduction

Fast neutron sources driven by high-power lasers have gained substantial interest over the last decades for a range of potential applications in medicine [1], security [2, 3], material science [4] and high energy density physics research [5]. Furthermore, deploying compact moderators closely coupled to laser-driven fast neutrons sources would allow the development of intense sources of thermal and epithermal neutrons, which would extend the range of applicability of laser-based sources. With the rapid progress in laser technology, aiming towards developing higher repetition rate lasers of higher powers, laser-driven neutron sources can, in principle, complement the research activities currently pursued at conventional accelerator-driven spallation sources. Although these large scale facilities produce substantially higher fast neutron fluxes, a key interest for laser-driven neutron sources lies in the neutron burst duration, which is substantially shorter than that produced at spallation facilities.

With the current laser systems, neutron yields up to of the order of 10^{10} neutrons/shot have been shown experimentally ([6, 7] and references therein) , by employing laser driven ions to generate neutrons from secondary catcher targets via beam-fusion reactions. In addition to the advantage of the ultra-short pulse duration, directionality/anisotropicity in the neutron emission is another important characteristic resulting from the beam-fusion reactions. The total neutron yield from a fusion reaction scales with the product of fusing ion densities and cross-section σ, which, for the most common reactions, reaches high values for centre-of-

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mass energy in the MeV-10s of MeV range [8]. In a pitcher-catcher scenario, where neutrons are produced by bombarding the laser-driven ions on a suitable converter target, anisotropy arises from the nuclear reaction kinematics, which strongly depends on the atomic mass of the fusing nuclei and velocity of the projectile ions [6]. In addition, the strong angular dependence of the differential cross-section for light nuclei reactions helps producing neutron fluxes strongly peaked along the incident ion-beam direction, even while using moderate energy (10s of MeV) ions as accelerated at currently available laser intensities [9]. In this context, fusion reactions based on low atomic mass nuclei, such as ^{7}Li(p,n)^{7}Be, ^{9}Be(p,n)^{9}B, ^{13}C(p,n)^{13}N, d(d,n)^{3}He, T(d,n)^{4}He, ^{7}Li(d,xn), ^{7}Be(d,xn), are particularly relevant, which would not only allow obtaining higher neutron yield, but higher peak flux by producing a narrow cone beam of neutrons. A highly beamed neutron flux would be extremely helpful towards improving transport capabilities as well as efficient moderation of the neutrons to thermal and epithermal energies by using compact, closely-coupled, directional moderators.

Anisotropic emission of the neutron beam is starting to be realized in experiments. In addition to the anisotropicity intrinsic to the beam-fusion, as discussed above, the neutron beam divergence from a typical laser-driven pitcher-catcher source also depends strongly on the divergence of the projectile ions - the final neutron beam divergence from the catcher will be a convolution of the divergence of the input ion beam and the neutron beam divergence expected for a collimated beam of ions.

In this paper we show a simple model for simulating the neutron production from light nuclei reactions in a pitcher-catcher scenario, and to study the effect of ion beam parameters (divergence and spectrum) on the neutron generation. The neutron beam divergence estimated by our model from d(d,n)^{3}He reaction in a beam-fusion scenario, while using laser-driven deuterium beam produced via the Target Normal Sheath Acceleration (TNSA) mechanism[9], compares well with the data obtained from a recent experiment [6]. A systematic study show that the neutron beam divergence can be reduced significantly (to a few tens of degrees) by increasing the input ion beam temperature, which, according to the current understanding of the TNSA mechanism, is achievable using the intense lasers that will be available at the upcoming facilities[10, 11].

2. Simulation design and method

Alternative to the usual Monte-Carlo approach [12, 13] to simulate neutron generation in a beam-fusion scenario, the model described in this paper (as discussed below) takes advantage of the tabulated angularly-resolved neutron yield, that can be found in the literature, obtained for a mono-energetic, pencil beam of ions impinging onto a catcher at normal incidence. The main interaction that is taken into account in our simple model is the effect of a multi-energy, divergent beam of ions, as typically produced by the TNSA mechanism, towards the angular distribution of emitted neutrons from a secondary catcher target. The schematic of the setup used in our model is shown in Fig. 1.

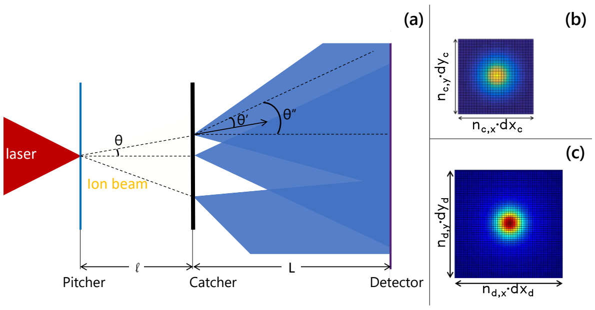

Figure 1: **(a)** Schematic of the neutron generation process in the pitcher-catcher scheme. An ion beam is generated by the interaction of the laser with the target (pitcher), which then reaches the secondary converter (catcher), leading to the neutron emission. **(b)** and **(c)** depict the grids representing the catcher and the detector, respectively.

The input for the projectile ion beam in our model is the angularly-resolved ion spectra. This information can either be obtained numerically, by performing multi-dimensional PIC simulations of the laser-foil interaction, or experimentally, by using for example angularly distributed high-resolution Thomson Parabola Spectrometers (TPS) [14]. The angularly resolved ion spectra can be represented by a function $\frac{d^2N_{ion}}{dE\,d\Omega}(E,\theta,\varphi)$, where E is the ion energy, (θ,φ) are the angles defining the direction of a given beamlet of ion, and Ω stands for solid angle. For simplicity, one may assume the ion beam produced by the laser-foil interaction to be cylindrically symmetrical about θ.

The catcher in the model was designed as a two dimensional matrix ($n_{c,x} \times n_{c,y}$ cells), where the grid size ($dx_c \times dy_c$) can be chosen depending on the desired resolution and accuracy, being $dx_c = dy_c = 200$ µm the resolution for the simulations here shown. The spectrum of ions arriving at each grid point on the catcher ($dN_{ion,(x,y)}/dE$) is calculated from the input ion spectrum to the code (as mentioned above) for a given pitcher-to-catcher distance (l). In order to obtain the neutron flux distribution across a plane parallel to the catcher, the detector in the code was modelled as a two dimensional array of $n_{d,x} \times n_{d,y}$ cells of size $dx_d \times dy_d$. This detector configuration mimics the response of CR39 nuclear track detectors typically used in neutron generation experiments [6**?** , 15], allowing for a direct comparison between the simulations and the experimental data.

Neutron generation from each grid point of the catcher was calculated by using the tabulated data for the angularly-resolved neutron yield, that can either be found in the literature, or be obtained by running Monte Carlo simulations [12, 13] for different ion energies. In this paper we used the tabulated data for d(d,n)^{3}He reaction provided by Davis *et al.* [12], which was one of the main reactions producing neutron in the experiment reported in [6]. The d(d,n)^{3}He reaction is also an efficient fusion reaction for moderate-energy deuterons, which is suitable for studying the effect of the input ion beam spectrum and divergence on the neutron beam divergence. The tabulated neutron yield per incident ion, given in Ref. [12], along different angles of neutron emission and for different projectile ion energies were interpolated to obtain a function $Y_n(E, \theta')$, where θ' is the neutron emission angle with respect to the incident ion beam. Using this function, the neutron flux at a given pixel of the detector ($F_{n,(x_d,y_d)} = N_{n,(x_d,y_d)}/dx_d dy_d$) is calculated as the sum of the fluxes reaching that pixel, generated at each point on the catcher. This can be expressed mathematically as

$$N_{n,(x_d,y_d)} = \sum_{(x_c,y_c)} \sum_{E} Y_n(E, \theta'') \cdot N_{ion,(x_c,y_c)}(E)$$

where, $\theta'' = \tan^{-1}\left(\sqrt{(x_d - x_c)^2 + (y_d - y_c)^2}/L\right)$ and L is the catcher-to-detector distance.

3. Results

In order to study the beamed neutron emission observed in our experiment [6] employing the petawatt arm of the VULCAN laser at Rutherford Appleton Laboratory (RAL), STFC, UK[16], we used the experimentally measured deuteron spectrum as the input to our model. The ion beams in the experiment were produced by irradiating 10 μm-thick deuterated plastic foils with a p-polarised laser pulse of $\sim$ 200 J energy and $\sim$ 750 fs duration, focussed down to a spot of $\sim 6\,\mu$m (FWHM) on the target, reaching a peak intensity in excess of 10^{20} W cm^{-2}. The ion beam spectrum was diagnosed along different emission angles (-8°, 0°, 21° and 32°) with respect to the target normal by employing Thomson Parabola Spectrometers (TPS)[14]. Due to the limitation of TPS in retrieving the spectrum of overlapping species, a differential filtering technique [17] was implemented to discriminate the deuterium ions from the overlapping species with equal charge-to-mass ratio, such as C^{6+} and O^{8+} originated from the target and hydrocarbon contaminant layers. A typical raw data obtained along the target normal direction is shown in Fig. 2(a). A comparison between on-axis proton and deuteron spectra obtained from the TPS data is shown in Ref. [6]. The deuteron spectra obtained from the different TPS were used to reconstruct the full beam profile, as shown in Fig. 2(b), while assuming an axis-symmetrical beam profile. The data shows a divergent ($\sim 30^\circ$ FWHM, $\sim 60^\circ$ full cone) beam of deuterons with an exponential spectrum, with the highest energies produced along the target normal direction with a narrow ($\sim 15^\circ$ full cone) beam divergence, as expected from the TNSA mechanism for such laser and target parameters [18].

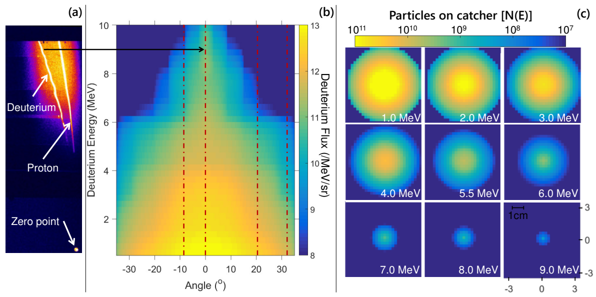

Figure 2: **(a)** A typical raw data obtained by a TPS diagnosing ion spectrum along the target normal direction. **(b)** Angularly resolved deuteron spectrum reconstructed from the data obtained by four TPS measurements along different angles (as shown by the dashed line) with respect to the target normal direction. **(c)** Spatial profiles of deuteron beam for different energies at the catcher plane.

The angularly-resolved deuteron spectra shown in Fig. 2(c) was used in our code to simulate the neutron generation in the catcher placed at a distance of l = 5 mm from the ion source (which represents the point of laser interaction with the pitcher target). The flux distribution of the deuterons of different energies at the front surface of the catcher are shown in Fig. 2(c), which was obtained by using the beam profile shown in Fig. 2(b).

Despite of the moderate energies of the ions and the broad emission angle produced in the experiment, the simulation shows a directional beam-like emission of neutrons from the catcher target, as shown in Fig. 3 (showing neutron flux distribution across the detector plane placed at a distance $L = 15$ mm from the catcher), with a Full Width at Half Maximum (FWHM) divergence of $\sim 62°$ and maximum flux along the ion beam axis. The simulated neutron beam profile is similar to that obtained from the experiment (FWHM of $(70 \pm 10)°$ [6]). Since the simulated neutron beam profile was obtained by considering only the d(d,n)^{3}He reaction, the residual difference between the simulated and experimental neutron beam profile is most likely due to a range of additional nuclear reactions taking place in the catcher in the latter case. As discussed in Ref. [6], due to the higher flux and higher energy protons produced from the pitcher target (as can be seen in Fig. 2(a)), the proton-induced deuteron breakup reaction (d(p,n+p)^{1}H) contributes significantly towards the total neutron yield. Due to the reaction kinematics, this nuclear reaction is expected to produce a narrow neutron beam divergence, similar to that obtained for the d(d,n)^{3}He reaction. However, a detailed simulation for the d(p,n+p)^{1}H case could not be carried out due to the insufficient reaction cross-section available in the literature.

In order to study the effect of the projectile ion beam parameters on the neutron beam divergence, we carried out a set of simulations by varying the input spectrum of the ions, as expected to be produced by TNSA mechanism at different laser intensities. The ion temperature and the cut-off ion energy in the TNSA mechanism scale with the temperature of the hot electrons

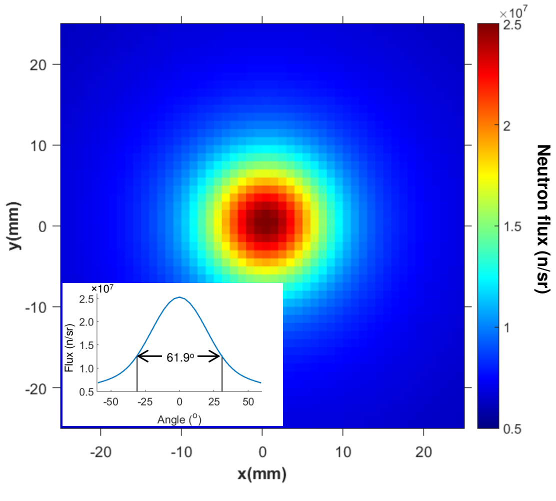

Figure 3: Simulated neutron beam reaching a flat detector in front of the catcher. Inset shows the lineout of the neutron beam profile across the detector, which also represents the emission angle of neutrons with respect to the ion beam axis. The divergence of the neutron beam (FWHM) is $\sim 62°$.

produced by the interaction, which broadly scales as $\sqrt{I_L \lambda^2}$ [9, 19, 20, 21], where I_L and λ stand, respectively, for the intensity and the wavelength of the incident laser. The divergence of the ions produced by the TNSA mechanism also varies within the beam depending on its energy [18] - ions with higher energy are emitted with a lower divergence. Assuming a flat-top flux profile within the ion beam divergence, and the following divergence profile as a function of ion energy (as reported for ~ps lasers in Ref. [18], which closely matches with the observed divergence shown in Fig. 2(b)),

$$\theta_D(E, E_{max}) = \begin{cases} 62 & E < E_{max}/2 \\ 107.4 - 90.9 \cdot \frac{E}{E_{max}} & E \geq E_{max}/2 \end{cases}, \quad (1)$$

we modelled an input TNSA beam profile for our simulations as a function of laser intensity, as given by

$$\frac{d^2 N_{ion}}{dE\, d\Omega} = \left.\frac{dN_{ion}}{dE}\right|_{\substack{E<E_{max} \\ \theta<\theta_D}} \propto \exp\left(-\frac{E}{k_B T(I_L)}\right) \quad (2)$$

A set of simulations were carried out by varying the ion beam temperature $k_B T(I_L)$. The cut-off energy for the deuterons as a function of laser intensities was assumed as $E_{max}(I_L) \propto 10^{-9} \sqrt{I_L}$ MeV, where the proportionality constant was calculated using the maximum deuteron energy obtained in our experiment, shown in Fig. 2(b).

The FWHM divergence of the neutron beam obtained from the simulations is shown in Fig. 4. One can see how the neutron beam divergence reduces significantly with an increase in the ion beam temperature. While a nearly isotropic emission for low ion temperatures is produced, the neutron beam divergence can be reduced below 50° using higher power lasers than that used in our experiment. Intense lasers will produce ions at higher energies, which will provide two-fold enhancement to the on-axis neutron flux - (1) neutron yield per incident ion will increase significantly due to their deeper penetration into the catcher, (2) higher anisotropicity due to differential cross-section and kinematics (see Eq. 2 in Ref. [6]). An alternative approach for increasing the flux and energy of ions other than protons, which are preferentially accelerated by the TNSA mechanism, would be to use some special technique to eliminate the hydrogen contamination layer at the rear side of the pitcher target, such as depositing a layer of heavy water contamination for enhancing the deuteron acceleration [22].

The rate of decrease in the neutron beam divergence slows down towards the higher temperatures, as visible in Fig. 4. The nearly constant divergence of $\sim 30°$ obtained for the high ion temperatures is due to the, albeit

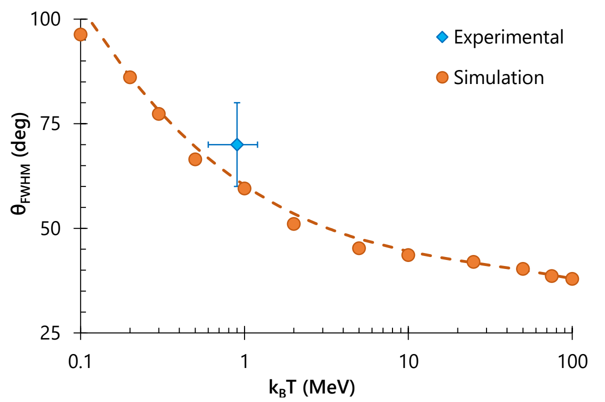

Figure 4: Neutron beam divergence (FWHM) as a function of the ion beam temperature obtained from our simulations. The blue point shows the beam divergence obtained for the d(d,n)^{3}He reaction using the deuteron beam profile obtained from our experiment discussed above.

small, intrinsic divergence ($\sim 15^\circ$) of the highest energy ions produced by the TNSA mechanism. This limitation in the neutron beam divergence can be easily eliminated by focussing the ion beams on the catcher, for example by using one of the several schemes reported in literature, such as permanent/pulsed magnetic focusing devices [23, 24, 25], laser-driven micro-lens[26], hemi-spherical targets [27], shaped targets [28] etc. Using a focussed beam of ions with narrow energy band can also help reducing the pulse duration of emitted fast neutrons, as recently reported by Higginson *et al.* [29].

4. Conclusions

We presented results obtained from a numerical model simulating the neutron beam generation by laser-driven ions in a pitcher-catcher scenario. Simulation results are broadly consistent with the neutron beam profile observed in the experiment while using the experimentally measured ion beam profile in the simulation. By varying the ion beam parameters, simulations predict improvement in the neutron beam divergence with an increase in the ion beam temperature and cut-off energy, as expected from the TNSA mechanism at higher laser intensities. Further experimental measurements with improved ion beam parameters would be required to benchmark the simulated trend for neutron beam divergence.

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