Micro-size pico-second duration fast neutron source driven by laser plasma wakefield electron accelerator

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Abstract
Pulsed fast neutron source is critical for the applications of fast neutron resonance radiography and fast neutron absorption spectroscopy. However, due to large transversal source-size (∼ mm) and long pulse duration (∼ ns) of traditional pulsed fast neutron sources, it is difficult to realize high contrast neutron imaging with high spatial resolution, and fine absorption spectrum. Here, we experimentally present a micro-size ultra-short pulsed neutron source by a table-top laser plasma wakefield electron accelerator driving photofission reaction in a thin metal converter. A fast neutron source with source-size of ∼500 µm and duration of ∼36 ps has been driven by a tens of MeV, collimated, micro-size electron beam via a hundred TW laser facility. This micro-size ultra-short pulsed neutron source has the potential to improve the energy resolution of fast neutron absorption spectrum dozens of times to e.g. ∼100 eV at 1.65 MeV, which could benefit for high quality fast neutron imaging and deep understanding theoretical model of neutron physics.

Keywords: High power laser; laser wakefield acceleration; photofission reaction; fast neutrons

1. INTRODUCTION
The laser-plasma accelerators have attracted significant interests over the last few decades, due to their high acceleration gradients and beam currents, thus not only enable GeV electron and hundred-MeV ion accelerators reducing to a length scale of centimeters, but can drive secondary radiation and particle sources with ultra-high brightness/flux. For example, laser plasma accelerating electrons/ions can induce photofission reactions and generate fast neutron source. Because of the uncharged property of neutron, it has different properties from charged particles or electromagnetic radiation when interacting with matters, which can result in obtaining complementary information. In recent decades, the neutron sources have been widely used in many fields, such as nuclear physics, biology, archaeology and medical science.

Comparing with traditional spallation and fusion neutron source, laser plasma accelerator driving neutron source has some advantages: compact, ultra-short pulse duration and ultra-high peak flux. This novel neutron source has great potential to further improve the quality of fast neutron resonance radiography (FNRR), fast neutron absorption spectroscopy (FNAS) and in laser-based neutrons experiment, a lot of efforts have been paid to realize high repetition rate, high flux and high yield neutron source. High yield and collimated neutron source (10^10 n/sr) can be generated via nuclear fusion and (p, n) reactions by high energy protons and deuterium ions deposited in a secondary target (named Pitcher Catcher scheme), but the neutron source has a long duration caused by the ion beam duration stretching when bombarding on the Catcher target. To optimize the neutron pulse duration, a new scheme was proposed to generate large charge energetic electron beams via a petawatt laser irradiating ultra-thin plastic targets. In this way, neutron source driven by the energetic electron beam has shorter pulse duration (∼100 ps), high yield (∼ 10^9 n/shot) and higher peak flux (> 10^{18} n/cm^2/s).
However, the electron beam accelerated from thin plastic target has large divergence angle (∼40°) which results in the neutron source size is larger than 1 cm. As for laser plasma wakefield acceleration (LWFA), whose electron beam has advantages in low divergence angle[38], femtosecond beam duration[39] and high stability[40] etc. This femtosecond collimated electron beam has also been utilized to generate neutron source with ultra-short duration (100s ps)[41], but the source size (∼5 mm) and neutron yield (10⁶ n/shot) are still needed to optimize. In addition, another table-top neutron source has micro-source-size (∼100s µm) via (D, D) fusion reaction driven by laser cluster Coulomb explosion[11], but this source has quasi-mono-energetic spectrum (2.45 MeV) and low yield (∼10⁶ n/shot) which are not conducive to the applications of FNRR and FNAS.

In this work, we proposed a method to measure the spatial intensity distribution of neutron source, and demonstrated experimentally the optimization of the neutron source size and pulse duration via large charge collimated electron beam from LWFA driving photofission reactions. A micro-size, ultra-short pulsed fast neutron source is obtained by optimizing the thin metal converter position to gas nozzle. This optimized neutron source is of great value to improve the imaging spatial resolution of FNRR and to realize finer FNAS.

2. EXPERIMENTAL SETUP

The experiment was performed at the Laboratory for Laser Plasma in Shanghai Jiao Tong University using the 100 TW laser system, a Ti: Sapphire laser with the central wavelength of 800 nm. In the experiment, the system delivered 3 J p-polarized pulse with duration of 45 fs (FWHM). The experiment setup is shown in Fig.1. The laser beam was focused by an f/4 off-axis parabolic mirror, and the intensity in the focal plane was close to Gaussian distribution with a radius w₀ ∼ 3.8 µm containing about 38% of the total laser power, i.e., ∼27 TW. Thus, the vacuum-focused laser intensity can reach up to 5.8 × 10¹⁹ W/cm², and the corresponding normalized vector potential a₀ is 4.9. The gas target was formed by using a 1.2 mm×10 mm supersonic gas jet, which can provide well-defined uniform nitrogen gas density profiles in the range of 3 × 10¹⁷ cm⁻³ to 2 × 10¹⁹ cm⁻³ by changing the gas stagnation pressure[42], based on the hydrodynamic calculations reported by Hosokai[43]. Electron beam bombards the DRZ phosphor screen (Gd2O2S:Tb) emitting fluorescence, which is detected by a 16-bit EM-CCD to get electron beam spot image (the DRZ phosphor screen is covered with 14 µm thickness Al film to block stray light). When the magnet is moved in, the electron beam angular distribution is recorded by a 20 cm×20 cm SR-type image plate (IP) which is covered by a 200 µm thickness Cu filter to block low energy electrons (E_k < 1 MeV). The electron beam charge is calculated as following: firstly, the IP is scanned by a Typhoon-7000 IP reader with the setup parameters of PMT 500 V, resolution 50 µm and L5; then the IP signal i.e. gray value is converted into PSL value by using the formula \[ PS_L = \left( \frac{g_{max}}{g_{min}} \right)^2 \frac{R_{min}}{R_{max}} h(V) \cdot 10^{L/2} \] [44], finally, the total charge for E_k > 1 MeV is calculated according to the response sensitivity of IP, and the response sensitivity is ∼0.007 PSL/electron which is nearly flat between 1 MeV and 40 MeV[45]. Moreover, the signal attenuation rate 25% is also taken into account[45], due to the fading time is about 8 mins which is the time of IP took out from vacuum chamber.

A stack of silver (Ag) plates with a total thickness of 1.6 cm was placed at the downstream of the gas jet. When the electron beam bombards the Ag target, the generated bremsstrahlung γ-rays would further induce photofission (γ, xn) reactions in Ag target, as shown in Fig. 1(a). Ag has two natural isotopes ¹⁰⁷Ag, ¹⁰⁹Ag with abundances of 51.8% and 48.2%, respectively. After the photofission reactions, the residual nuclei of ¹⁰⁷Ag and ¹⁰⁹Ag would be located at the nuclear ground state (radionuclides, ¹⁰⁶Ag and ¹⁰⁸Ag) and the nuclear excited state (isomers, ¹⁰⁶mAg and ¹⁰⁸mAg). Because the original generation position of neutron is same to the position of residual product of Ag nuclei, the distribution of residual products can reflect the neutron source distribution. The radionuclides ¹⁰⁶Ag and ¹⁰⁸Ag have relatively shorter half-lives about 23.9 mins and 2.4 mins, and they will release K-shell x-rays (∼21 keV) via internal conversion and positrons (hundreds keV to ∼2 MeV) via β⁺ decay[46]. However, the half-lives of isomers ¹⁰⁶mAg and ¹⁰⁸mAg are about 8.28 days and 438 years, which are difficult for acquiring neutron distribution in a short time. Here, we utilized the positrons and the K-shell

![Figure 1. Experimental setup. (a) The schematic diagram of photo-nuclear reactions for ¹⁰⁷Ag and ¹⁰⁹Ag atoms. (b) ¹⁰⁶Ag decay products, and the schematic diagram of measurement of neutron source spatial distribution.](image-url)
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x-rays from $^{106}$Ag to diagnose neutron source distribution, due to its half-life 23.9 mins is a little longer than the time $\sim$8 mins for taking out the Ag converter from vacuum chamber, and the products of $^{108}$Ag remained a little after nearly four half-lives. A MS-type IP was placed tightly on converters to measure the decay events distribution for ten mins, as shown in Fig. 1(b), then this IP was scanned by a Typhoon7000 IP reader with resolution of 25 $\mu$m.

3. RESULTS OF LWFA ELECTRON BEAMS

Figure 2. Experimental results of electron beam at plasma density of $3.68 \times 10^{19}$ cm$^{-3}$. (a) Electron beam angular distributions (PSL value). (b) Electron beam energy spectrum of continuous 10 shots. (c) Electron beam divergence angle of continuous 70 shots. (d) Electron beam charge.

In order to generate large charge and collimated energetic electron beam, we scan the nitrogen gas density. Due to the plasma bubble radius $R = \frac{\omega_{pe}}{\omega_{c}}$ and the laser self-focusing power $P_c \simeq 17 \frac{\omega_{pe}^2}{\omega_{c}^2}$ [GW], where $\omega_{pe} = \sqrt{4\pi n_c e^2/m_e}$ is plasma frequency and $n_c$ is critical density. A higher density plasma is usually required to match the small laser focal spot ($w_0 \sim R$) for maintaining laser intensity and overcoming quick defocus$^{[47]}$. Because the 27 TW tightly focused laser pulse is hard to self-focusing in low density plasma. When the plasma density increases to $3.68 \times 10^{19}$ cm$^{-3}$ corresponding to $P_c = 8$ TW, the optimized electron beam charge could be up to $\sim$20 nC and the divergence angle just $\sim 6^\circ$ (Figs. 2(a), 2(d)). The electron beam energy spectra of continuous 10 shots are shown in Fig. 2(b). It is fitted by using double temperature $T_e^1 = 1.19 \pm 0.19$ MeV, $T_e^2 = 12.88 \pm 2.41$ MeV, and the ratio of the total number of electrons in the two temperatures is $N_1/N_2 = 23.90 \pm 5.42$, here the error represents the standard deviation. The electron beam divergence angle of continuous 70 shots is shown in Fig. 2(c), the divergence angle at x and y direction is $7.0^\circ \pm 1.2^\circ$ and $6.1^\circ \pm 1.3^\circ$ respectively. Moreover, the electron beam charges are shown in Fig. 2(d), the average charge is $15.59 \pm 1.68$ nC. We have found that a large amount of electrons are ionization injected$^{[48]}$ into over ten plasma bubbles, which results in that the total beam charge can be increased about ten times higher than the usually LWFA, the details see in Ref$^{[49]}$.

4. RESULTS OF MICRO-SOURCE-SIZE NEUTRONS

Spatial distribution of neutron source. In order to acquire the neutron source spatial intensity distribution, the optimized electron beam (Figs. 2) is utilized to bombard the Ag stack which is composed with eight piece 200 $\mu$m silver plates and placed 5 mm away from the rear edge of gas nozzle. After the stack irradiated by twenty electron beams at shooting repetition rate of 0.025 Hz, these Ag plates become activated via photofission reaction. The spatial distribution of neutron source is deduced by measuring the distribution of activated products $^{106}$Ag in eight piece of silver plates. Due to the branch ratio of $\beta^+$ decay and internal conversion are 59.1% and 24.4% respectively, and the sensitive of MS-type IP to the positrons is about one order of magnitude higher than to the K-shell x-rays$^{[50,51]}$, so almost of signals recorded on IP are positrons.

The distributions of positrons in the eight Ag plates are shown in Fig. 3(a), and these pictures are line up from top to bottom along the electron beam propagation direction. According to the positron distribution on an Ag plate, the neutrons transverse distribution can be deduced, e.g., Fig. 3(b) which is from Fig. 3(a) P1. Therefore, the transverse size distribution of neutron source in different
Optimization of neutron source-size. Neutron source obtained with the above parameters of converter has a transversal size less than 3 mm (FWHM) and a longitudinal length $\sim700 \mu m$ (FWHM). To further optimize the neutron source-size, a thinner ($500 \mu m$) Ag converter is placed closer to the edge of gas nozzle without affecting the process of LWFA. The positron distributions measured from the front and back sides of the converter are shown in Fig. 4(a) and 4(b) respectively. The optimized neutron transversal source size is less than $500 \mu m$ in FWHM, which is fitted well with Gaussian distribution. The transversal size from the front side is slightly smaller than from the back. Moreover, the positron intensity measured from the back side is about 1.5 times higher than from the front side, thus the longitudinal source size can be approximately regarded as the target thickness ($500 \mu m$).

In order to acquire the pulsed neutron source duration and yield, a plastic scintillator detector is utilized to measure the neutrons time of flight (TOF) spectrum which is shown in Fig. 4(c), and its experimental layout is shown in Fig. 1. Due to the $\gamma$-ray flash from the electron beam bremsstrahlung is too strong, lead bricks are piled up around the detector to prevent the neutron signal from flooding in the $\gamma$-ray afterglow of scintillator. Considering the exponential decay of the long tail of the first dip in Fig. 4(c)\cite{52}, the neutrons energy spectrum is shown in Fig. 4(d). The photofission neutrons energy is mainly located in the range of hundreds keV to several MeV, which is belong to fast neutron source. Because the large difference in velocity of neutrons, the pulse duration of these fast neutrons would stretch after propagating a distance. The neutron pulse duration can be estimated by equation\cite{35} $\Delta t = 73 \cdot d[mm] \cdot (\frac{1}{\sqrt{E_{nl}[MeV]}} - \frac{1}{\sqrt{E_{nh}[MeV]}})[ps]$, where $d$ is the propagation distance (or the converter thickness), $E_{nl}$ and $E_{nh}$ is the neutron kinetic energy of low and high velocity in this pulse respectively. Therefore, the neutron original pulse duration is about 18.6 ps (FWHM) (for $E_{nl} = 0.40$ MeV, $E_{nh} = 2.83$ MeV), and the full pulse duration is about 36.0 ps (for $E_{nl} = 0.40$ MeV, $E_{nh} = 2.83$ MeV). The neutron yield has also been roughly estimated from the TOF spectrum. The scintillator detector has been calibrated by a Cf$^{252}$ fission source, and one ns-V corresponds to about 10 neutrons. The area of neutron signal is 5.38 ns-V, thus $\sim107$ neutrons have hit on the detector. The detector has a surface area of 0.01 m$^2$, and it is placed 1.5 m away from the neutron source. Considering the neutron source is uniformly distributed at 4$\pi$ solid angle, it’s total yield is $\sim3.0 \times 10^5$ per shot.

5. DISCUSSION

FNRR and FNAS has been widely used in security\cite{53}, industry\cite{54}, and special medical materials\cite{55}, et al., FNRR is an imaging method that exploits the characteristic cross-section structures of different isotopes in the energy range of fast neutron. When a inspected object is irradiated and it contains elements that possess sharp cross-section resonances, the transmitted FNAS will exhibit dips and peaks at specific energies which can reveal the elemental compositions and their distributions\cite{31,32}. However, due the fast neutron transversal source-size, e.g., spallation neutron source ($mm \sim cm$)\cite{21}, neutron source based on linear accelerator ($mm$)\cite{24,56}, the fast neutron radiography spatial resolution is usually limited to $\sim mm$. Here, the micro-size fast neutron source driven by LWFA could improve the spatial resolution to hundreds of $\mu m$. More significantly, the pulse duration of the LWFA based fast neutron is ultra-short and can be less than 100 ps, which has the potential to improve the art state of energy resolution ($E.R.$) of FNAS by an order of magnitude.
The energy resolution of FNAS is usually determined by three facts, including detector timing resolution, detection distance and neutron pulse duration. At present, the scintillator BaF$_2$:Y crystal$^{[57,58]}$ has realized a luminescence process with rise time $\sim 30$ ps and decay time $\sim 100$ ps, and it can distinguish the arrival time of radiation (i.e., timing resolution) within $\sim 12$ ps, which is sufficient for a 36 ps pulsed neutron source. Therefore, here mainly discuss the effects of detection distance and neutron pulse duration on the energy resolution of FNAS, as results shown in Fig.5. The farther the detection distance, the higher the energy resolution, e.g., for the case of 1 MeV energy and 1 ns duration ($E.R. = 27.5$ keV, 5.6 keV, 1.4 keV @ 1 m, 5 m, 20 m). And the higher the neutron energy, the lower the energy resolution, e.g., for the case of 5 m and 1 ns ($E.R. = 10.1$ keV, 52.8 keV, 114.8 keV @ 0.5 MeV, 1.5 MeV, 2.5 MeV). However, it is still too difficult for traditional fast neutron source with 1 ns pulse duration to acquire FNAS which can exhibit the finer structure of some resonance absorption peaks$^{[14,59]}$. For example, there is a resonance peak of $^{16}$O at $\sim 1.65$ MeV with typical FWHM about 5 keV which is from the theoretical calculation$^{[60]}$. Fortunately, the LWFA based neutron source (36 ps duration) has great advantage in accurate measurement of this kind of narrow absorption cross-sections, due to the $E.R.$ can reach $\sim 100$ eV @ 1.65 MeV and 20 m. Although the yield of ultra-short pulsed fast neutron source based on LWFAs is less than $10^6$ shots, it is also feasible to acquire the fine FNAS by accumulating enough shots, e.g. 100s shots.

![Figure 5. Energy resolutions for different neutron pulse duration (a) 1 ns; (b) 36 ps.](image)

6. CONCLUSION

In summary, we have presented a method in generating micro-size ultra-short pulsed neutron source via laser wakefield acceleration electron beam bombarding thin metal converter, and also a method in measuring this neutron source spatial distribution by using the positrons emitted from the activated silver stack converter. A large charge $\sim 20$ nC, tens of MeV and collimated electron beam has produced via a tightly focused $\sim 100$ TW laser pulse transversely matched in dense plasma. Then, an ultra-short ($\sim 36$ ps) fast neutron source with small source-size ($\sim 500$ $\mu$m) has acquired by utilizing this intense electron beam irradiates a thin silver converter. We have also prospected the application potential of this ultra-short neutron source in FNAS, it can optimize the current energy resolution dozens of times. This kind of LWFA based on table-top neutron source is of great value to acquire fine FNAS experimental data which is important to demonstrate the present theoretical model. Moreover, the micro-size ultra-short fast neutron source can play an important role in improving the spatial resolution and imaging contrast of FNRR.

7. ACKNOWLEDGEMENTS

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