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Efficient neutron generation from solid-nanoparticle explosions driven by DPSSL-pumped high-repetition rate femtosecond laser pulse

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Abstract. We propose novel neutron source using high-intensity laser based on the cluster fusion scheme. We developed DPSSL-pumped high-repetition-rate 20-TW laser system and solid nanoparticle target for neutron generation demonstration. In our neutron generation experiment, high-energy deuterons were generated from coulomb explosion of CD solid-nanoparticles and neutrons were generated by DD fusion reaction. Efficient and stable neutron generation was obtained by irradiating an intense femtosecond laser pulse of $>2\times10^{18}$ W/cm^2. A yield of $\sim10^5$ neutrons per shot was stably observed during 0.1-1 Hz continuous operation.

1. Introduction

Recent developments of high-intensity laser enable us to evolve a new type neutron source. A number of experiments [1-5] demonstrated the possibility of laser-driven fusion using pure D_2 or CD_4 clusters. In these works, multi-keV deuterium ions were generated by Coulomb explosion of a few nanometres clusters. Since the cross-section of deuterium-deuterium (DD) reaction reaches its maximum at 1750 keV with center-of-mass system, much higher ion energy is required for efficient neutron generation.

Features of the Coulomb explosion are that ion energy distribution function is proportional to the square root of its energy and the maximum energy is proportional to its radius [6,7]. Larger particles result in higher ion energy, although an intense laser irradiation is required for expelling electrons from the larger particles. We fabricated the solid density deuterated-polystyrene (CD) nanoparicles of 250 nm in diameter to obtain high ion energy of ~1 MeV. Stable neutron generation was demonstrated by irradiating 20-TW diode-pumped-solid-state-laser (DPSSL) to these solid nanoparticles.

2. Experimental setup

2.1. Laser system

In our laboratory, we have developed a DPSSL-pumped high-repetition-rate 20-TW laser (MATSU-1) and a pump laser KURE-1, a laser-diode-pumped Nd:glass laser system [8]. The KURE-1 is single longitudinal and transverse mode, nano-second pulse width, 10Hz repetition rate, diode-pumped green laser system based on thermally-edge-controlled zigzag slab amplifier techniques. Maximum output energy is 21.4 J and 12.7 J in 1053 nm and 527 nm, respectively. MATSU-1 consist of Ti:sapphire oscillator, pulse stretcher, acousto-optic programmable dispersive filter, regenerative amplifier, 1st main amplifier for 2 TW output, 2nd main amplifier for 20 TW output and vacuumed pulse compressor. The regenerative amplifier and the 1st amplifier are pumped by two diode-pumped Nd:YAG lasers. In the 1st amplifier, seed pulse output from the regenerative amplifier is amplified to 150 mJ with 6 pass amplification by 450 mJ pump energy. In the 2nd amplifier, seed pulse is boosted-up to 1.5 J by 4 pass amplification with 5 J pumping energy from KURE-1 laser. The seed pulse is compressed to typical 60 fs by the vacuumed pulse compressor with 80% of transmissivity. MATSU-1 generate 1.2 J (λ = 800 nm) with a pulse width 60 fs at 10 Hz. DPSSL is extremely stable at a longer life compared with conventional flash-lamp-pumped laser. In the focus spot of the MATSU-1 laser, 40 percent of the energy was focused into 8 μm diameter spot. Considering the laser transmission efficiency, the laser intensity on the target was $\sim 4\times10^{18}$ W/cm^2. The repetition rate was 0.1-1 Hz due to the limitation of data acquisition.

2.2. Target and injection system

We developed CD nanoparticles used as a target instead of gas clusters [9]. Figure 1(a) shows the SEM image of the nanoparticles which average size was 280 nm. The average size can be controlled with high precision between 150-700 nm. We, therefore, expect to give a certain amount of selectivity to the ion energy obtained by Coulomb explosion of these nanoparticles. Figure 1(b) shows the schematic view of the nanoparticle injection system. MATSU-1 enters from the direction perpendicular to the paper. Injection timing and number density of the nanoparticles were measured by the Mie scattering light intensity using He-Ne laser probe. The nanoparticles are injected to the MATSU-1 focus point at the center of interaction chamber. In this experiment, typical number density of injected nanoparticles was $\sim 10^9$ cm^{-3}.

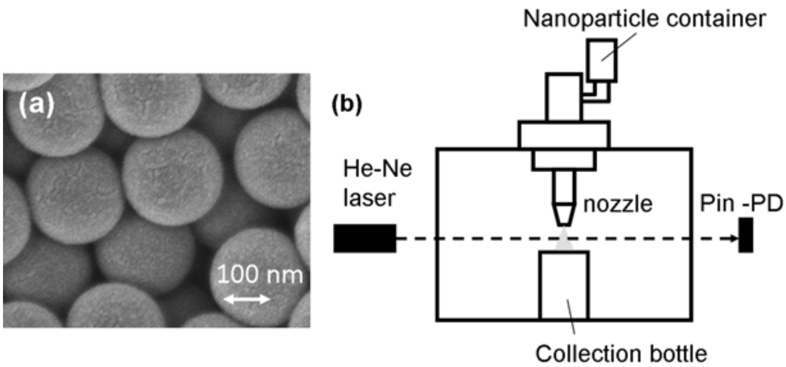

Figure 1. (a) SEM image of CD nanoparticles which average size was 250 nm. (b) Schematic view of the nanoparticle injection system.

2.3. Target and injection system

We have developed a Multichannel Time-of-flight system with Kinetic energy Analyzing Device (MT-KAD) to observe the ions of multispecies generated from relativistic laser plasma [10]. In this experiment, we used MT-KAD system to observe the ions generated from Coulomb explosion of CD nanoparticles. This system is composed of a ten-channel scintillation detector array and a permanent magnet that generates a magnetic field of ~0.09 T. The magnetic field and time-of-flight (TOF) information enables us to distinguish protons, deuterons, and stripped carbons. The layout of our detectors is shown in Fig. 2. The MT-KAD system constructed in the detector chamber and observed ions accelerated forward. Neutron detector, consisting of a plastic scintillator (BC420, 180 mm diameter, 100 mm long) coupled to a photomultiplier tube (H2431-50, Hamamatsu Photonics K.K.) was located outside the interaction chamber at distance of 140 cm from the laser focus point.

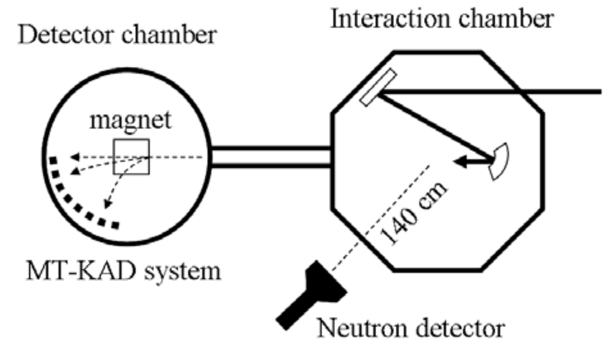

Figure 2. The layout of the detectors

3. Experimental setup

At first, we measured the deuterons generated by Coulomb explosion. Figure 3 shows the typical ion TOF signal of a single shot with CD nanoparticles. These signals were obtained by three of ten-channel detectors in detector chamber. Generation of high energy deuterons with energy up to 1.5 MeV was observed. On the other hand, no deuteron signal was observed in CH nanoparticles but only high-energy proton (up to 1.4 MeV) was observed. These observations clearly indicate that high-energy ions were generated by Coulomb explosions of solid-nanoparticles.

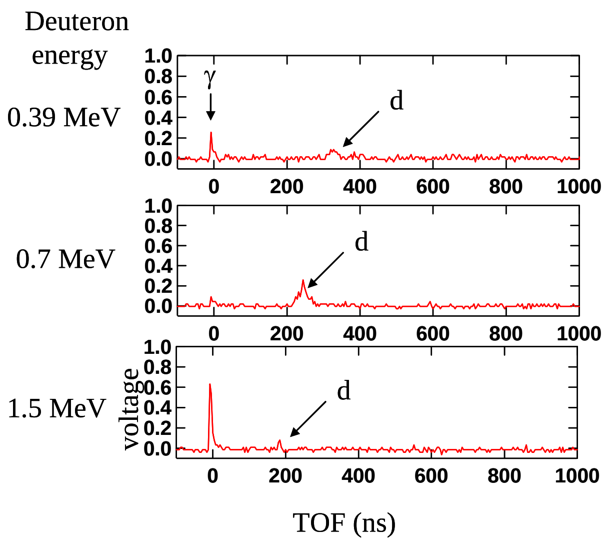

Figure 3. The typical ion TOF signal of a single shot

In the neutron generation experiment, we used a cylindrical CD plane, called “neutron booster”, in the interaction chamber. It was arranged around a nanoparticle injection nozzle to enhance the fusion reactions (See Fig.4(a)). High energy deuterium ions generated by Coulomb explosion might hit the plane and increase DD fusion reactions.

A typical signal of a neutron detector in the neutron generation experiment is shown in Fig.4(b). The signals due to the γ-ray and neutron bursts are easily resolvable. The relative delay with > 60 ns corresponds to the sum of the traveling time of deuterium inside the booster and the TOF of 2.45-MeV neutron to the detector. Assuming the neutron isotropic emission, the neutron yield was ~10^5 per shot. Such an efficient neutron generation was stably observed during continuous 100 shots (See Fig. 4(c)).

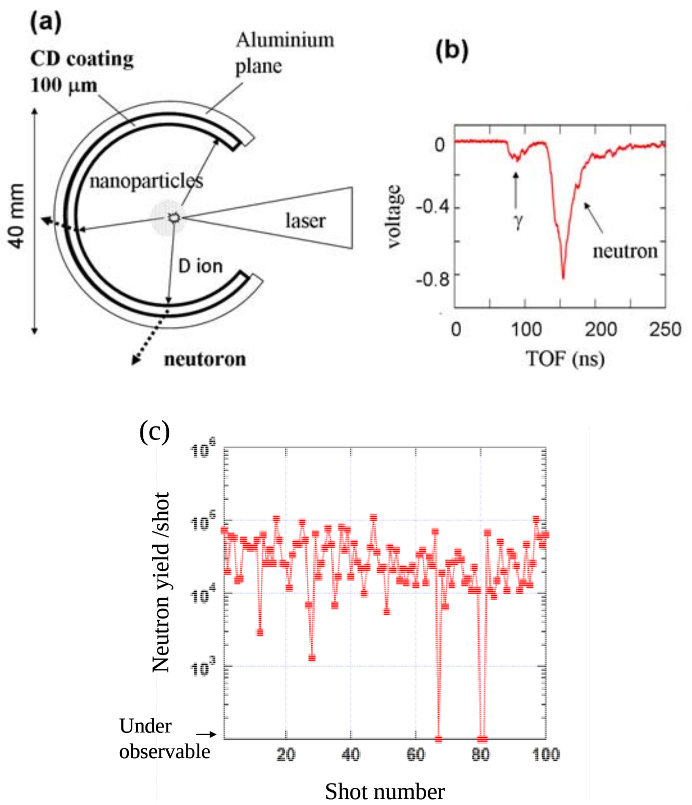

Figure 4. (a) Schematic view of the "neutron booster". (b) Single shot neutron TOF signal. (c) The history of neutron generation during continuous 100 shots.

4. Conclusion

Neutron generation experiment with 20-TW LD-pumped laser and CD nanoparticle was demonstrated. Energetic deuterium ions with energy up to 700 keV were observed. A yield of ~10^5 neutrons per shot was stably observed during 100 shots of 0.1-1 Hz continuous operation. This indicates that it may be possible to further enhance the neutron generation with an increase in laser energy. This demonstration will be expected to bring the progress of novel neutron source, which is characterized by a pulsed emission and point source, for many applications.

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