Laser ion acceleration and neutron source in short-pulse solid-nanoparticle interaction

K Nishihara, T Watari, K Matsukado, T Sekine, Y Takeuchi, M Takagi, N Satoh, T Kawashima and H Kan

1 Hamamatsu Photonics, K.K., 1820 Kurematsu, Hamamatsu 431-1202 Japan
2 Institute of Laser Engineering, Osaka University, Suita, Osaka 565-1801 Japan

E-mail: nishihara@ile.osaka-u.ac.jp

Abstract. We propose both an efficient neutron source and an extremely high energy proton source using solid CD and CH nano-particles, respectively, irradiated by an intense laser light. With a use of 3-d PIC simulations, we obtain an optimum CD radius for a neutron source, 250 nm and required laser field of $a = eE/m\omega c \approx 2$, which results in D-D reaction rate of $<\sigma v> = 2 \times 10^{-16}$ cm$^3$/s, corresponding to an effective deuteron temperature of 500 keV to 1MeV. Reduction of neutron yield by pre-expansion is discussed. In a range of $a \approx 100$, laser radiation pressure surrounding the particles accelerates electrons in the forward direction. Protons following the electrons become directional high energy, for example, proton energy of 450 MeV is obtained within 130 fs in CH particle interaction with 700 nm in radius. More than 10% of total protons in CH-particles are accelerated forward. Proton energy continuously increases with time and with the increase of particle size and the direction is also collimated with time.

1. Introduction

After the observation of nuclear fusion from the explosion of deuterium clusters heated with a compact, high-repetition-rate table-top laser [1], a number of experiments were performed to obtain neutrons and high energy protons using clusters and small particles (many references in Ref. [2]). If the laser intensity is high enough to expel all of electrons from the small particles, Coulomb explosion occurs and ion energy distribution function (EDF) becomes proportional to square root of the energy $dE/dN \propto \sqrt{E}$ up to its maximum value proportional to square of the particle radius $E_{\text{max}} \propto R_0^2$ [3]. Since D-D fusion cross section has its maximum value at the energy of a few MeV, high neutron yield can be obtained by choosing proper particle radius so that $E_{\text{max}}$ becomes a few MeV. There exist a critical laser intensity to expel electrons for a given particle radius. We performed 3d PIC simulations, using REMP[4], to obtain optimum conditions for a neutron source for solid CD nano-particles in a range of the normalized laser intensity of $a = eE/m\omega c = O(1)$.

The radiation pressure plays an essential role for proton acceleration at high intensity regime of $a = 100$ [5]. For CH particles comparable to a laser wavelength, laser light can penetrate into the particle due to both relativistic effect and its pressure. The radiation pressure accelerates efficiently electrons in the forward direction and high energy protons follows electrons. We show that protons following electrons become directional high energy and its energy continues to increase with time. It should be
mentioned that we have also observed experimentally the generation of stable neutrons and high energy protons using solid CD and CH nano-particles [6].

Simulation box size was $(120\lambda, 10\lambda, 10\lambda)$, where $\lambda=(c/f)$ is incident laser wavelength. A particle located at $20\lambda$ from x-boundary and the center in y-z plane was irradiated by a linear polarized Gaussian pulse with FWHM of $40f^1$ and duration of +/- 30 $f^1$. Initial electron density is given as $\omega_{pe}=6\omega$, namely electron plasma frequency is six times greater than the laser frequency.

2. Efficient neutron source and its conditions

2.1. Optimum conditions

We performed 3d-PIC simulations for particle sizes of 200 – 500 nm in diameter and laser intensities of $a=0.01$ to 10. The optimum conditions found among those parameters are CD particle with 500 nm in diameter and the normalized laser electric field of $a=eE/mc\omega=2$. Deuteron energy spectrum obtained is presented in Figure 1 with D-D fusion cross section, which shows that the deuteron energy spectrum has its peak near the energy corresponding to the maximum fusion cross section. The D-D reaction rates $<\sigma v>$ are estimated by averaging the cross section over the deuteron energy spectrum.

![Figure 1](image1.png)

**Figure 1.** Deuteron energy spectrum for 500 nm CD particle irradiated by a laser of $a=eE/mc\omega=2$ (dot) and cross section of D-D reaction (line).

![Figure 2](image2.png)

**Figure 2.** D-D reaction rate averaged over deuteron EDF of 500 nm CD irradiated by intensities of $a=1$, $a=2$, and $a=3$.

![Figure 3](image3.png)

**Figure 3.** D-D reaction rate (left) and energy distribution function (right) for CD particles with pre-expansion, cross (cyan); $R/R_0=2$, green (square); $R/R_0=4$, triangle (blue); $R/R_0=6$, and red (dot); without pre-expansion.
observed and are shown as function of time in Figure 2, for different $a$ of 1, 2 and 3. For the case of $a = 1$, the cross section is small, while the cross section decreases with time for $a = 3$. The decrease is due to the deuteron energy too large for D-D fusion reaction.

The estimated D-D reaction rate of $2 \times 10^{16} \text{cm}^3/\text{s}$ in neutron branch in D-D reaction corresponds to that of effective deuteron temperature of 500 keV to 1 MeV for a Maxwellian velocity distribution function.

2.2. Suppression of D-D reaction rate by pre-expansion due to pedestal

Pre-expansion due to pedestal or prepulse reduces ion energy. Reduction of D-D reaction rate is investigated by assuming initial density profile of a spherical isothermal expansion [7],

$$n(r) = n_0 \left( \frac{R_0}{R} \right)^2 \exp \left( -\left( \frac{r}{R} \right)^2 \right),$$

where $R/R_0$ is the ratio of the expanded radius to its initial value. As shown in Figure 3, the reduction is small for the case of $R/R_0 = 2$. This expansion may correspond roughly to the contrast ratio of $10^{-7}$ to $10^{-8}$ for 100 ps pedestal estimated from electron temperature scaling of $T_e = 6.0 \times 10^5$ MeV [8], where $T_e$ and $v_s$ are electron temperature and its thermal speed, respectively and assuming the expansion speed is given by ion sound speed [7]. However for $R/R_0 = 4$ and 6, the maximum energy and thus the reaction rate decreases very much as shown in Figure 3.

3. High energy directed proton source

Proton energy spectra and propagation direction are investigated for a laser with the normalized electric field of $a = 100$ interacting with CH particles with different sizes. Figure 4 shows a typical energy spectrum for a CH particle with 1.4 $\mu$m in diameter at time of $ft = 95$. It consists of three energy groups. Here we pay attention on the 1st group (hatched region), 386 MeV < $E$ and the peak energy at $E_{\text{peak}} = 415$ MeV indicated by arrow, since they are directed forward as shown by their solid angle distribution in Figure 5. The solid angle distribution at time $ft = 95$ becomes narrower than that at time $ft = 75$, it indicates that the acceleration direction is collimated with time. The radiation pressure accelerates efficiently electrons in the forward direction and high energy protons follows electrons and become directional high energy.

As shown blue squares in Figure 6, the ratio of the high energy protons to the total protons increases with the increase of the radius. For 1.4 $\mu$m CH, the high energy proton becomes greater than 10 % at $ft = 95$. It should be also mentioned that the 1st peak energy indicated by an arrow in Figure 4

![Figure 4](image_url) Proton energy distribution function at time $ft = 95$. There is a high energy group of 386 MeV < $E$ (shaded).

![Figure 5](image_url) Angle distribution of the high energy protons in Figure 4 ($E > 386$ MeV) at $ft = 75$ (blue) and 95 (red).
increases with the increase of the radius.

Figure 7 shows the 1st peak energy as functions of time for various CH particle sizes. It should be noted that the proton energy increases with time even after the laser pulse duration of 60 f\text{s} with 40 f\text{s} FWHM. It indicates that the protons follow the electrons continuously accelerated by the laser pulse, which may be similar to the unlimited acceleration observed for mass limited target [5]. The peak energy increases as the radius is larger as shown in Figure 7. These results indicate that directed relativistic protons of GeV can be obtained using larger particles even at this laser intensity.

4. Conclusion
Optimum CD nano-particle size and laser intensity for maximizing D-D reaction rate were obtained at 500 nm in diameter and laser of \(a = 2\). D-D reaction rate of \(<\sigma v> = 2\times10^{-16} \text{ cm}^3/\text{s}\), which corresponding to effective deuteron temperature of 500 keV to 1 MeV, can be obtained. We also investigated the suppression of D-D reaction by pre-expansion of the particles due to pedestal. The contrast ratio should be less than \(10^{-7}\) to \(-8\).

In radiation pressure dominant regime \((a = 100)\), protons following electrons become directional high energy of at least 450 MeV within 130 fs for CH particle with 1.4 \(\mu\text{m}\) in diameter. More than 10\% of total protons in the CH particles are accelerated forward. Proton energy increases with time and with the increase of the particle size, and the propagation direction is also collimated with time. These results indicate that relativistic (GeV) and collimated protons can be obtained at this laser intensity.

Acknowledgments
Simulations were performed on NEC SX-systems at the Cybermedia Centre of Osaka University.

References
[1] Ditmire T et al. 1999 Nature 398 489
[2] Daido H et al. 2012 Rept. Prog. Phys. 75 056401
[3] Nishihara K et al. 2001 Nucl. Instrum. Methods Phys. Res. A 464 98
[4] Esirkepov T 2001 Comput. Phys. Commun. 135 144
[5] Bulanov S 2010 Phys. Rev. Lett. 104 135003
[6] Watari T et al. 2013 This Proceeding (to be published)
[7] Murakami M and Basko M M 2006 Phys Plasmas 13 012105