Neutron Generation from deuterated methane Clusters with an Intense Femtosecond Laser

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1. Introduction

To consider the application of laser produced neutrons, there have been many studies to improve ion energy and ion current which can lead to higher neutron yield with different pulse parameters and target materials including solid targets, heavy water droplets [1], deuterium contained gas clusters[2,3]. For gas clusters, Coulomb explosion is main mechanism to accelerate ions, and by over-running effect, deuterium containing heteronuclear clusters is known to produce deuterons with higher energy compared to the homonuclear pure deuterium clusters [4]. The fusion reaction cross section between deuterons such as D + D → He^3 (0.82 MeV) + n (2.45 MeV) is highly dependent on deuteron energy, so we have used clusters of deuterated methane (CD4) to expect higher neutron yield.

2. Methods and Results

CD4 clusters are produced by a supersonic expansion with a nozzle assembly composed of two parts, a commercially available pulsed valve with a jet throat of 500 μm of 3 mm long with 10° half opening angle, which can control opening of gas thrust, and an additional conical nozzle with orifice of 500 μm, of 15 mm long and 5° half opening angle, which attachs to the primary nozzle securely. So the 3 mm output diameter of the cone defines the interaction length, and laser beam is focus 1.5 mm below the nozzle. The diameter of the clusters was measured by investigating Rayleigh scattering. The average cluster size in the flow was estimated to be about 5.4 nm at a backing pressure of 7 MPa.

The laser we used is a 10 Hz, Ti:sapphire, chirped pulse amplification laser delivering 220 mJ or 620 mJ of laser energy per pulse with 28 fs pulse width and wavelength of 800 nm. The laser output power is selectable by switching a final amplifier stage on or off. The high energy prepulse and ASE appeared before 0.2 nsec from main pulse were blocked with a fast Pockels cell. This laser beam was focused into cluster plume with a f /7 spherical mirror on a moving stage to change focal position in cluster plume. The beam waist size was 8 μm, resulting in a peak intensity of up to 4 x 10^{18} W/cm^2 or 1.1 x 10^{19} W/cm^2.

In order to analyze the energy distribution of the ions involved in the nuclear reaction, we use a microchannel plate (MCP) placed 1 m away from the plasma in perpendicular direction of laser beam propagation. In this ion TOF measurement scheme, we cannot separate ion signals of deuteron and carbon because a whole ion signal of carbon is collapsed with that of deuteron. But the high energy part of deuteron signal is free from carbon ion which has heavier mass than deuteron and arrives at MCP later. And deuteron with this higher energy region of spectrum contributes to fusion reaction strongly, so analysis of TOF spectrum is meaningful for CD4 clusters. To monitor the DD fusion we used a 12 cm diameter, 12 cm thick BC408 plastic scintillation detector placed 2 m away from the plasma, operating in single particle detection mode.

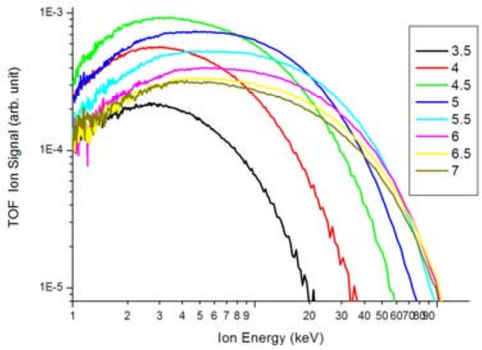

Fig. 1. Ion energy spectrum for various gas pressure with 22TW laser intensity (inset is gas pressure in MPa).

The maximum and average energies for homonuclear clusters are proportional to R_0^2 (R_0 : radius of cluster), and do not depend on the laser intensity. But for heteronuclear clusters, the final kinetic energies of the ions are determined both by energetic effects and by kinematic effects [4]. We measured ion distribution for a different cluster size by changing the gas pressure for 8 TW and 22 TW laser intensities to see that effect. For 8 TW laser intensity, ion energy and current are increasing dependently up to 4.5 MPa, but at higher pressure, the number of lower energy ions decreased and the number of higher energy ions increased. Above 5.5 MPa, The plasma channel seemed to start to shrink as the laser beam propagated into cluster plume, which led to higher laser intensity inside the plasma channel. So the plasma volume of laser interaction was decreased to limit the number of clusters in a plasma channel, which in turn suppressed increasing tendency of ion number. But laser intensity was still high enough to ionize big sized clusters, and as the cluster size increased, the kinematic effects were prominent, so ion energy kept increase up to 7 MPa. At 5.5 MPa, Maximum deuteron energy was ~20 keV and average deuteron energy was 7 keV. From the limitation of time resolution for the TOF detector at high energy region caused by interference of photoelectron signal, ion energy spectrum over 18 keV is not clear. The effect of increased laser energy to ion generation can be seen in Fig. 1. Maximum deuteron energy exceeded 100 keV and the average deuteron energy was 24 keV at 5.5 MPa. Though the total ion current did not increased much, ions got much higher energy than 8 TW laser intensity did.

The fusion reaction cross section for D-D fusion is given by [5]

$$(\overline{\sigma v})_{DD} = \frac{2.33\times10^{-14}}{T^{2/3}}\exp(-\frac{18.76}{T^{1/3}})cm^3 / \sec .$$

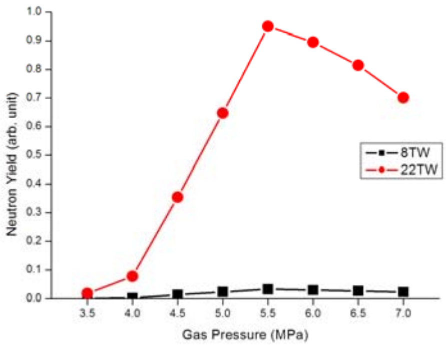

Fig. 2. Total neutron yield expected at various gas pressure (inset is laser intensity).

Figure 2 shows total neutron yield provided by summing of the data in Fig. 1. The neutron yield increases linearly to the pressure change until 5.5 MPa. But above this pressure the data shows discrepancy because of unclear ion TOF information. This result may be compared with the real values obtained from neutron detector. We detected neutron yield for 5.5 MPa with a scintillator operating in pulse counting mode for every 200 laser shots for each pressure and converted it to 4π. The measured neutron yield continuously increases to 7 MPa.

A very intensive x-ray was generated with 22 TW intensity laser, and the scintillator neutron detector was saturated to be insensitive for neutron. So we could not get neutron yield data for 22 TW, but from the estimation of ion TOF information, we can expect neutron yield of 2 x 10^5 at 7MPa.

As a result, if the signal of MCP is improved to give precisely time-resolved information, the TOF ion massspectrometry is very good tool to investigate fusion reaction expectation in laser produced plasma.

3. Conclusions

Heteronuclear clusters was found to be very efficient target material for high energy ion production with a femtosecond laser to be applicable for a compact neutron source. The optimum laser beam size was depended on laser intensity according to the kinematic effects. In this experiment deuterons with maximum ion energy of 100 keV, and the average ion energy of 24 keV were produced by a femtosecond laser. By comparing the relation of TOF ion signals for 8 TW and 22 TW intensity lasers with neutron yield measured for 8 TW, the neutron yield was estimated to be 2 x 105 per laser shot with 22 TW intensity laser by analysis of TOF ion spectrum.

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