Vol 17 No 6, June 2008
1674-1056/2008/17(06)/2124-06
Chinese Physics B
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Effect of laser spot size on fusion neutron yield in laser–deuterium cluster interactions*

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(Received 3 August 2007; revised manuscript received 5 December 2007)

The effect of the laser spot size on the neutron yield of table-top nuclear fusion from explosions of a femtosecond intense laser pulse heated deuterium clusters is investigated by using a simplified model, in which the cluster size distribution and the energy attenuation of the laser as it propagates through the cluster jet are taken into account. It has been found that there exists a proper laser spot size for the maximum fusion neutron yield for a given laser pulse and a specific deuterium gas cluster jet. The proper spot size, which is dependent on the laser parameters and the cluster jet parameters, has been calculated and compared with the available experimental data. A reasonable agreement between the calculated results and the published experimental results is found.

Keywords: clusters, femtosecond intense laser pulse, table-top laser driven nuclear fusion
PACC: 3640J, 5250J, 2588

1. Introduction

The interaction of femtosecond intense laser pulses with clusters has attracted much attention for more than a decade and a lot of important findings in experiment and theory have been reported, such as x-ray, energetic ion and electron production.[1−4] Perhaps one of the most remarkable findings is the observation of the intense femtosecond laser driven nuclear fusion from the explosions of deuterium clusters, i.e. the so-called table-top laser nuclear fusion, which would be an interesting possible neutron source.[5] Many correlative researches have been carried out experimentally and theoretically aiming at mainly increasing the neutron yield.[6−15] Now, it is well established that the fusion neutron yield is closely related to the energy and the total number of the deuterium ions. A higher laser intensity can fully strip all the electrons from the cluster of a larger size, and then can increase the kinetic energies of the deuteron ions ejected from the explosion of clusters. However, when the laser pulse energy is kept constant, increasing the laser intensity requires a decrease of the laser spot size, and as a result, the volume of the laser-cluster interaction is reduced as well. If the average deuterium atom density in the cluster jet is assumed to be uniform, the reduction of the volume of the interaction leads to the decrease of the total number of the energetic deuterium ions. Consequently, the fusion neutron yield would be limited. Hence, it is possible that there exists a proper laser spot size at which an optimum fusion neutron yield could be expected. However, the study of this problem is very complicated because the fusion neutron yield is related to many factors, such as the distribution of the cluster size in the cluster jet, the spatial and temporal intensity distributions of the laser pulse, and the energy attenuation of the laser pulse as it propagates through the cluster jet. In this paper, we use a simplified model to study the dependence of the fusion neutron yield in the laser–deuterium cluster interactions on the laser spot size within the cluster jet. In our model, the energy distribution of the deuterium ions in the laser-created plasma filament is calculated as in Ref.[16]. Under certain conditions, it has been found that with increasing laser spot size, the neutron yield increases until it reaches a peak value at a proper spot size, then the fusion neutron yield falls off with the further

*Project supported by the National Basic Research Program of China (Grant No 2006CB806000) and the National Natural Science Foundation of China (Grant No 10535070).
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increase of the laser spot size. The calculated results are compared with the available experimental data.

2. Modelling and methodology

The energetic deuterium ions ejected due to the explosions of the deuterium clusters, will collide with deuterium ions from the nearby deuterium clusters in the intense laser-created plasma filament. When the deuterium ion energy is high enough (greater than a few keV), the nuclear fusion D + D $\rightarrow$ He^3 + n can occur with a high probability, releasing a characteristic 2.45 MeV neutron.[5,6] In order to investigate the fusion neutron yield, we have to calculate the deuterium ion energy distribution including the effects of the cluster size distribution and the energy attenuation of the laser pulse. The method used to calculate the energy distribution of the deuterium ion is described in detail previously.[16] Considering that the experimentally measured cluster size distribution is best described by a log-normal distribution,[17] as in Ref.[8], we assume the cluster size distribution to be $f(n) = \exp[-(\ln n - \mu)^2/2w^2]/nw\sqrt{2\pi}$, where n is the cluster size in number of atoms per cluster ($n = 4\pi r^3\rho/3$, r is the cluster radius and ρ is the deuterium atom density in the cluster). The parameter μ and w are the mean and standard deviation of the logarithm of the cluster size, respectively. And w, which is proportional to the full width at half maximum of the distribution,[18] can be regarded as the cluster size distribution width. The average cluster size $\bar{n}$ is given by $\bar{n} = \int nf(n)\mathrm{d}n/\int f(n)\mathrm{d}n$. The laser-cluster interactions are divided into two regimes, i.e., the CVI (cluster vertical ionization) regime $\left(r < r_0^{(\mathrm{I})}\right)$, and the non-CVI regime $\left(r > r_0^{(\mathrm{I})}\right)$. Here, $r_0^{(\mathrm{I})}$, which is the so-called border radius, is determined through $r_0^{(\mathrm{I})}$ (nm) $= AI^{1/2}$,[12] where A is 3.0×10^{-8} (nm/(Wcm^{-2})$^{1/2}$) and I is the laser intensity in Wcm^{-2}. The laser pulse energy absorption by the gas jet is assumed to be equal to the total work done by the laser electric field in stripping off electrons from all the clusters in the laser-cluster interaction volume.[10] In the calculations of laser intensity repartition resulting from the pulse energy attenuation, the laser-cluster interaction volume is divided into a series of cylindrical segments along the laser propagation direction in which the local laser intensity is considered to be constant. The laser energy absorbed by the cluster of radius r can be written as $141\pi\rho^2e^2R/360\varepsilon_0$,[16] where R is equal to r^5 $\left(r < r_0^{(\mathrm{I})}\right)$, or $r^3r_0^{(\mathrm{I})2}$ $\left(r > r_0^{(\mathrm{I})}\right)$, ε_0 is the dielectric constant, and e is the electron charge. Then we can calculate the laser intensities in each segment along the laser propagation direction and obtain the average laser intensity in the interaction volume. Based on the calculated average laser intensity and the cluster size distribution, the deuterium ion energy distribution can be obtained. For the clusters of radius $r < r_0^{(\mathrm{I})}$, the deuterium ion energy distribution and the maximum ion energy from a single cluster are given as $F_1(E) \propto (E/\rho)^{1/2}$ and $E_{\max} = \dfrac{e^2\rho}{3\varepsilon_0}r^2$, respectively.[10] For the clusters with radius $r > r_0^{(\mathrm{I})}$, the ion energy distribution and the maximum ion energy from a single cluster can be written as $F_2(E) \propto (E/\rho_i)^{1/2}$ and $E_{\max} = \dfrac{e^2\rho_i}{3\varepsilon_0}r^2$. Here, we assume that the clusters partially ionized by the laser field have the uniform ion density of $\rho_i = \rho\dfrac{r_0^{(\mathrm{I})}}{r}$. The ion energy distribution from all the clusters is

$$F(E)\mathrm{d}E = F_1(E)\mathrm{d}E + F_2(E)\mathrm{d}E, \tag{1}$$

described by the contributions from the CVI part $F_1(E)\mathrm{d}E \propto \int_{n_E}^{n_0^{(\mathrm{I})}} f(n)\mathrm{d}n\sqrt{E}\mathrm{d}E$ and from the non-CVI part $F_2(E)\mathrm{d}E \propto \int_n^{\infty} f(n)\mathrm{d}n\left(\dfrac{n}{n_0^{(\mathrm{I})}}\right)^{1/6}\sqrt{E}\mathrm{d}E$, where $n_0^{(\mathrm{I})}$ and n_{E} are the sizes (in number of atoms per cluster) of the cluster with the border radius $r_0^{(\mathrm{I})}$ and of the cluster of which the Coulomb explosion will produce ions with the maximum kinetic energy E. This means that only the clusters with sizes equal to or larger than n_{E} can contribute to the energy distribution of the ions with energy E. Similarly, in the above expression n is equal to $\dfrac{4}{3}\pi\rho\left(\sqrt{E/(e^2\rho_i/3\varepsilon_0)}\right)^3$ $\left(n \geq n_0^{(\mathrm{I})}\right)$. The total number of the deuterium ions inside the plasma filament is given by $N = \int \rho_{\mathrm{av}}\mathrm{d}V$, where $\rho_{\mathrm{av}}$is the average deuterium ion density in the plasma filament and V is the volume of the plasma filament. The volume of the plasma filament depends on the laser spot size in the deuterium jet and the length of the filament. So the total neutron yield includes contributions from the deuterium-deuterium collisions occurring inside the plasma filament, termed "filament fusion", as well as the collisions between the energetic deuterium ions and the cold deuterium in the surrounding gas, which is termed "beam-target fusion".[8,19] For the beam target fusion (the moving ion hitting the stationary ion), the fusion cross-section

$\sigma(E)$ in barns (1 barns = $10^{-24}\,\mathrm{cm}^2$) as a function of the kinetic energy of the incident ion E in keV can be fitted by[20]

$$\sigma(E) = \left\{A_5 + [(A_4 - A_3E)^2 + 1]^{-1}A_2\right\} /E[\exp(A_1E^{-1/2}) - 1], \quad (2)$$

where the Duane coefficients A_1, A_2, A_3, A_4, and A_5 are 47.88, 482, 3.08×10^{-4}, 1.177 and 0 for the D-D fusion reaction, respectively. For the "filament fusion", the average fusion reactivity $\langle\sigma v\rangle$ is expressed as

$$\langle\sigma v\rangle = \iiint v\sigma(E)F(E_1)F(E_2)\mathrm{d}E_1\mathrm{d}E_2 \times \sin\theta\mathrm{d}\theta/2/\iint F(E_1)F(E_2)\mathrm{d}E_1\mathrm{d}E_2, \quad (3)$$

where v is the velocity of the incident ion. We set $E = E_1 + E_2 - 2\sqrt{E_1E_2}\cos\theta$, where θ is the angle of incidence between two colliding deuterium ions with the kinetic energies of E_1 and E_2, and $v^2 = {v_1}^2 + {v_2}^2 - 2v_1v_2\cos\theta$, where v_1 and v_2 are the velocities of the two colliding deuterium ions. The total fusion neutron yield can be estimated from the following expression[8]

$$Y = \frac{\tau}{2}\int \rho_{\mathrm{av}}^2\langle\sigma v\rangle\mathrm{d}V + N\int_0^{l/2}\rho_{\mathrm{av}}\langle\sigma\rangle\,\mathrm{d}l, \quad (4)$$

where τ is the disassembly time of the plasma filament, depending on the volume and the shape of the plasma as well as the average ion velocity, and l is the diameter of the cluster jet. The first term in expression (4) estimates the filament fusion neutron yield. The second term estimates the beam-target fusion neutron yield and $\langle\sigma\rangle = \int\sigma(E)F(E)\,\mathrm{d}(E)/\int F(E)\,\mathrm{d}(E)$ is the average fusion cross-section. The factor of 1/2 in the first term accounts for double counting of deuterium ions. In our calculations, we assume that the shape of the plasma filament and the deuterium ion number density in the plasma filament do not change with the variation of the laser spot size and the laser pulse energy.

3. Results and discussion

In our calculations, the shape of the plasma filament is assumed to be a cylinder with its diameter and length being approximately equal to the laser spot size d and the radial dimension of the cluster jet l ($\sim$2 mm), respectively. The disassembly time of the plasma filament τ is given by the laser spot size d divided by the average deuterium ion velocity v_{av}. The deuterium atom density in the cluster ρ is chosen to be $4.22 \times 10^{22}\,\mathrm{cm}^{-3}$.[8] The average deuterium ion density within the plasma filament ρ_{av}, which is equal to the average atom density in the cluster jet of $1.5 \times 10^{19}\,\mathrm{cm}^{-3}$, is assumed approximately uniform. First, we perform the calculations of the fusion neutron yield as a function of the laser spot size d under the typical experimental conditions that the laser pulse energy is 300 mJ, the laser pulse duration 60 fs, the wavelength 790 nm, the deuterium cluster jet with the average cluster size of 6.0 nm, and the cluster size distribution width 0.6. It is found that the variations of the filament fusion yield and the beam-target fusion yield with the laser spot size are the same. As an example, the dependence of the filament fusion neutron yield and average fusion reactivity on the laser spot size is shown in Fig.1 (in order to illustrate the different variation trends of both the filament fusion neutron yield and the average fusion reactivity against the laser spot size, they are normalized to their maximum values). It can be seen that with the increase of the laser spot size, the filament neutron yield increases rapidly and reaches a peak value at the spot size of 80 μm, then decreases slowly towards zero. The calculated results indicate that when the laser spot size is 80 μm, the average deuterium ion energy is 6.3 keV, the average fusion reactivity $\langle\sigma v\rangle$ is $3.3\times10^{-20}\,\mathrm{cm}^3\mathrm{s}^{-1}$ and the calculated maximum filament fusion yield is 4.6×10^3. As the spot size is set to 40 and 120 μm, the corresponding neutron yields are reduced to about 0.8×10^3 and 2.8×10^3, while the corresponding average deuterium ion energy and the average fusion reactivity are 6.7 keV and $4.5 \times 10^{-20}\,\mathrm{cm}^3\mathrm{s}^{-1}$, and 4.3 keV and $0.5 \times 10^{-20}\,\mathrm{cm}^3\mathrm{s}^{-1}$, respectively. From Fig.1, we can see that the average fusion reactivity keeps nearly constant with increasing laser spot size when the laser spot size is smaller than 60 μm. This is because before the spot size increases to 60 μm (corresponding to the laser intensity of $1.4 \times 10^{17}\,\mathrm{Wcm}^{-2}$), the laser intensity is high enough to completely strip the majority of the clusters in the jet. So the average deuterium ion energy and the average fusion reactivity are kept saturated. When the spot size is beyond 60 μm, with the increase of the spot size, the laser intensity will not be high enough to completely strip the majority of the clusters in the jet, and thus the average energy of the deuterium ions produced by the Coulomb explosions of deuterium clusters decreases. As a consequence,

the average fusion reactivity starts to fall off. However, the increase of the deuterium ion number in the plasma filament and the fusion time, as a result of the increase of the laser spot size, has compensated the decrease of the average fusion reactivity, so the fusion neutron yield does not decrease but continues to grow. This trend is held until the laser spot size increases to about 80 μm, i.e., the proper spot size. Beyond this proper spot size, the increases of the deuterium ion number and the fusion time are not large enough to compensate the decrease of the average fusion reactivity and the fusion neutron yield falls off with the increase of the spot size. Similarly, the total fusion neutron yield as a function of the laser spot size is shown in the inset in Fig.1. The maximum total fusion neutron yield of 5.7×10^3 is obtained at the proper spot size of 80 μm.

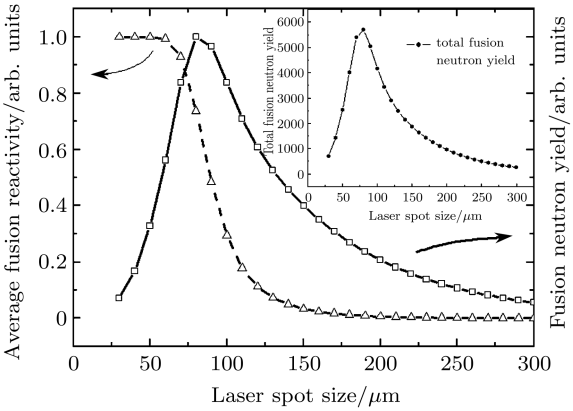


Fig.1. Dependence of the calculated filament fusion neutron yield and the average fusion reactivity on the laser spot size. The dependence of the total fusion neutron yield on the laser spot size is shown in the inset. In the calculations the laser energy $E_{\rm laser}$ = 300 mJ, the laser pulse duration Δt = 60 fs, the laser wavelength λ = 790 nm, the average cluster radius $\bar{r}$ = 6.0 nm, and the cluster size distribution width w = 0.6 are used.

In order to have a further insight into the concept of the proper laser spot size, we investigate the dependence of the proper spot size on the cluster size distribution and on the laser pulse based on the model and methodology described in Section 2. The calculated total fusion neutron yields as a function of the laser spot size for different cluster size distributions and for different laser pulses are shown in Fig.2. Figure 2 shows the total fusion neutron yield as a function of the laser spot size for different average cluster sizes $\bar{r}$ (a), cluster size distribution widths w (b), laser energies $E_{\rm laser}$ (c), and laser pulse durations Δt (d). The positions indicated by arrows in Fig.2 correspond to the proper spot sizes. For a given laser spot size, a larger neutron production may be achieved if the laser intensity (relevant to the laser energy and the pulse duration) and the cluster size (relevant to the average cluster size and the size distribution width) are increased correspondingly. As mentioned above, a higher laser intensity can make a larger cluster fully stripped, leading to a more energetic Coulomb explosion. As shown in Fig.2, the fusion neutron yield increases with the increase of the average cluster size, the cluster size distribution width and the laser energy, while decreases with the increase of the laser pulse duration. The following conclusions can be drawn from Fig.2. (A) For a given laser pulse, the larger the average cluster radius and the cluster size distribution width, the smaller the proper spot sizes should be. As shown in Figs.2(a) and (b), the proper spot sizes are 80, 110, and 140 μm for the average cluster radii of 6.0, 4.0, and 3.0 nm, respectively, while the proper spot sizes are 60, 80, and 90 μm for the cluster size distribution widths of 1.0, 0.6, and 0.4, respectively. With decreasing average cluster size, the saturated laser intensity (which is high enough to fully strip the majority of the clusters in the jet) decreases. Thus, for a smaller average cluster size, if the laser energy is kept constant, a large proper laser spot size is allowed to ensure a larger interaction volume, and then the optimum fusion neutron yield can be obtained. For a given average cluster size, a larger cluster size distribution width means that there are more large-sized clusters in the cluster jet. Consequently, similar to the dependence of the proper spot size on the cluster radius, the proper spot size increases as the cluster size distribution width decreases. (B) For a given cluster jet, the higher the laser energy and the shorter the laser pulse duration, the larger the proper spot size becomes. As shown in Figs.2(c) and (d), the proper spot sizes should be 60, 80, and 90 μm for the laser pulse energies 200, 300, and 400 mJ, respectively, while the proper spot sizes should be 70, 80, and 90 μm for the laser pulse durations 100, 60, and 30 fs, respectively. This result can be understood from the fact that for the cluster jet of a given cluster size distribution, the saturated laser intensity is kept constant, and as a consequence, the proper laser focus spot size is allowed to increase with the increase of the laser pulse energy or the decrease of the laser pulse duration.

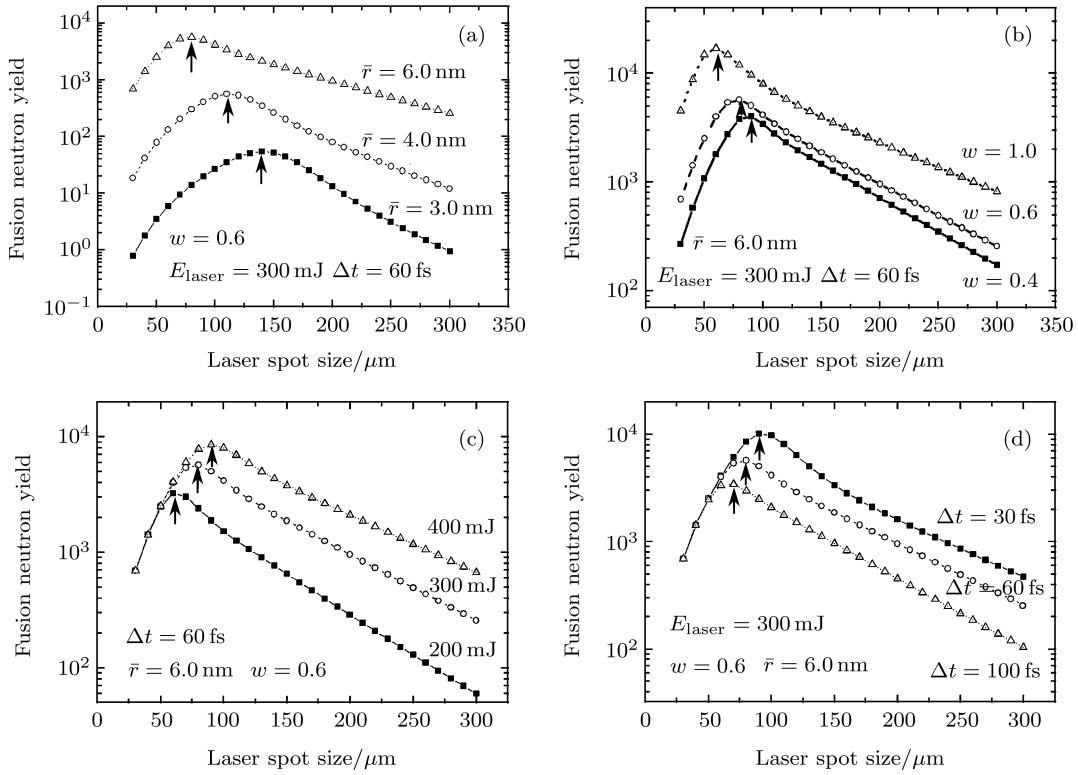


Fig.2. Dependence of the calculated total fusion neutron yield per shot on the laser spot size for different (a) average cluster sizes, (b) cluster size distribution widths, (c) laser pulse energies, and (d) laser pulse durations. The proper laser spot sizes corresponding to the maximum fusion neutron yields are indicated by arrows.

In order to compare our calculations with the available experimental data, the proper spot size is estimated under the experimental conditions described in Ref.[5]: the laser pulse energy is 120 mJ, the laser pulse duration 35 fs, and the average deuterium ion density $\rho_{\rm av}$ 1.5×10^{19} cm^{-3}. The cluster size distribution width is chosen to be 1.0.[6] Considering that the average deuterium ion energy is 7 keV derived from the TOF spectra,[6] the average cluster radius of 5.0 nm is used in our calculations. The calculated proper spot size is about 50 μm which is in agreement with the radial spot size of 40–80 μm estimated by Parks *et al*[10] from the experimental interferogram of the deuterium plasma, conducted to meet the maximum experimental neutron yield in Ref.[5]. However, our calculation gives a maximum total fusion neutron yield of about 4.1×10^3 which is by about a factor of 2.5 lower than the reported yield of 10^4 per shot.[5] This discrepancy of the fusion yield could result from the simplification of the present model and the experimental uncertainties. Since the laser pulse is Gaussian, the actual diameter of the plasma filament in the cluster jet is not uniform and is not necessarily equal to the laser spot size. Then, the cylindrical plasma filament assumed in the model will lead to an underestimation of the laser-cluster interaction volume in our calculations. Meanwhile, in the laser-cluster experiment the laser focal position in the gas jet is manipulated along the direction perpendicular to the nozzle axis so as to obtain the optimum neutron yield.[6] In this process, all the laser parameters and the cluster source parameters become well matched to produce the maximum neutron yield. However, in the present model the neutron yield is considered to be independent of the laser focus position under the assumption of a cylindrical plasma filament. Among other things, considering the measurement uncertainties of the cluster jet parameters, the laser parameters, as well as the neutron yield, the difference between the calculated results and that reported would not be significant under the given calculation conditions.

4. Conclusion

In conclusion, a survey of the impact of laser spot size on the neutron yield of table-top intense laser-driven nuclear fusion due to Coulomb explosions of

deuterium clusters have been demonstrated through calculations based on a simplified model. The proper laser spot sizes, connected with the optimum neutron yield, were estimated by varying the laser parameters together with the cluster parameters. Then the calculated results were compared with the available experimental data and a reasonable agreement was found. Although the laser-cluster interaction-induced nuclear fusion is very complex, the simplified model presents a straightforward physical picture for the effect of the laser spot size on the fusion neutron yield; and an estimate of the proper spot size in a specific table-top laser-driven nuclear fusion experiments is provided also.

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