Fusion neutron yield from high intensity laser-cluster interaction

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The fusion neutron yield from a compact neutron source is studied. Laser-irradiated deuterium clusters serve as a precursor of high-energy deuterium ions, which react with the walls of a fusion reaction chamber and produce copious amounts of neutrons in fusion reactions. The explosion of deuterium clusters with initial radius of 50–200 Å irradiated by a subpicosecond laser with intensity of 10^{16} W/cm^2 is examined theoretically. We studied the conversion efficiency of laser energy to ion kinetic energy, the mean and maximum ion kinetic energy, and ion energy distribution function by a molecular dynamics model. A yield of $\sim 10^5-10^6$ neutrons/J is obtainable for a peak laser intensity of $10^{16}-10^{17}$ W/cm^2 and clusters with an initial radius of 200–400 Å.
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Recent experiments[1–10] and theoretical simulations[9–14] demonstrated the possibility of laser-driven fusion employing deuterium clusters. Clusters are a unique form of matter with properties combining the best of solids and gases. Their application for fusion is motivated by several unique features, the most prominent of which are the efficient absorption of laser energy (approaching ~100%) and generation of high-energy ions. Fusion-based high-intensity laser-cluster interaction exploits the fact that laser-irradiated clusters explode under their internal pressure launching multi-keV ions, capable of driving fusion reactions.

Theoretical studies of cluster explosion have been done either analytically or through modeling. Most models adopt a hydrodynamic approach. In spite of its simplicity and overall correct picture of the cluster explosion, the accuracy of this approach is limited. The fusion reaction rate is extremely sensitive to the ion energy and, in general, to the ion energy distribution function (IEDF). Therefore the problem of calculating the neutron yield demands a different approach, namely a particle simulation model. Such an approach was undertaken in Ref. 14, where explosion of small (<50 Å) clusters was studied. We employ a state-of-the-art relativistic time-dependent three-dimensional (3D) particle-particle simulation model based upon following the electrons and ions trajectories[15–17] to study the neutron yield from fusion reactions due to exploding deuterium clusters in a virtual beam-target experiment. Previously, the model was used to study the interaction of a linearly polarized ultrashort pulse KrF laser with Xe clusters in the regime of ultrahigh intensities,[15] as well as the impact of the initial cluster radius[16] and laser wavelength[17] on cluster properties. We studied the temporal evolution of cluster heating and explosion, removal and recapture of electrons by the cluster, mean electron and ion energy, and electron and ion energy distribution function. The advantage of our molecular dynamics model is that it represents objects in 3D and acquires detailed 3D information about the particles, such as their trajectory, velocity, and energy distribution. For example, the kinetic energies of deuterium ions participating in fusion reactions can be calculated with high precision, which is paramount for computing the fusion reaction rate and neutron yield.

A schematic version of the fusion reaction chamber is shown in Fig. 1. The nozzle is located inside a cylindrical chamber. The vessel wall is coated with DT fuel or other deuterated material such as CD_2 to enhance the fusion reactivity. A hole in the cylinder allows the laser to irradiate clusters a few millimeters below the nozzle. The irradiated clusters are promptly ionized and a Coulomb explosion follows. High-energy deuterium ions born in the Coulomb explosion hit the deuterated vessel wall initiating fusion reactions. The separation of beam formation from the target is advantageous compared to fusion in the plasma volume since the interaction volume is larger.

Deuterium clusters $(D)_N$ with an initial radius of $R_0 = 50-200$ Å are irradiated by a subpicosecond laser with wavelength $\lambda = 800$ nm and peak intensity of $I_0 = 10^{16}$ W/cm^2. The laser pulse parameters are the same as in Ref. 16: the laser intensity pulse shape has a Gaussian profile $I(t) = I_0 \exp[-(t-t_0)^2/\tau^2]$ with parameters $t_0 = 200$ fs and $\tau = 75$ fs. The electromagnetic wave direction of propagation and the laser electric and magnetic fields are parallel to the y, x, and z axes, respectively, and the cluster is located at the origin of the coordinate system. Periodic boundary conditions are used as in Ref. 16. The number of deuterium atoms per cluster $N = (R_0/1.7)^3$ is calculated assuming that the atomic density equals that of liquid deuterium, which is $\rho = 0.05$ Å^{-3}.[14]

We performed simulations for deuterium clusters with different sizes, ranging from 50 to 200 Å. For clusters with an initial radius exceeding 200 Å, the number of particles is too large and leads to excessive computation time. Some of the most important properties of the cluster are shown in Fig. 2. The energy absorption per cluster E^{abs} increases with cluster size as it is with xenon clusters, following approximately $N^{3/2}$ dependence, comparable to the $N^{5/3}$ dependence observed for xenon.[16] Conservation of energy requires this absorbed energy to be distributed among various channels, such as optical field ionization, potential energy of the system, and kinetic energy transferred to the particles.[16] Part of

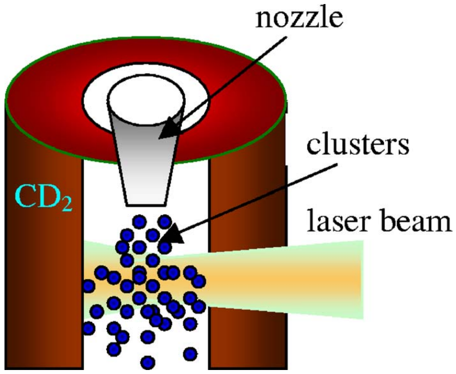


FIG. 1. (Color online) Schematic diagram of the reaction chamber. The target material is CD_2 with thickness 1 mm.

the latter goes as the kinetic energy of ions ($E_{\rm ion}^{\rm kin}$), which is also shown in the same figure. The conversion efficiency $\eta_{\rm ion}^{\rm kin}=E_{\rm ion}^{\rm kin}/E^{\rm abs}$, i.e., the fraction of absorbed energy converted into kinetic energy of ions, can be derived from Fig. 2. It is ~50% and shows a tendency to increase with cluster size.

The mean ion energy $\bar{E}_i$ versus the initial cluster radius is shown below. It increases with cluster size with a rate $N^{1/2}$. The maximum (cutoff) ion energy $E_{\max}$ for all cases considered is in agreement with the theoretical predictions; it is approximately 5/3 of the mean energy.[10,14] The ion energy distribution function $P(E)$ is of particular interest, since the fusion reaction cross section increases exponentially with the ion kinetic energy. A simple analytical formula for the IEDF is derived for the idealized situation of an exploding cluster consisting only of ions. The IEDF

$$P(E) \sim \frac{3}{2E_{\max}}\begin{cases}(E/E_{\max})^{1/2}, & E \le E_{\max},\\ 0, & E > E_{\max},\end{cases}$$

increases with energy, peaking at the maximum (cutoff) energy $E_{\max}$.[10,14] The IEDF at the end of the laser pulse, predicted by our simulation model, follows closely the analytical formula (Fig. 2). The discrepancy is most likely due to the small number of ions used in the simulations (a few hundred). In this particular case, simulations refer to the explosion of deuterium clusters with an initial radius of $R_0=200$ Å. The mean and maximum ion energies obtained from our model are $\bar{E}_i \cong 16$ keV and $E_{\max} \cong 25$ keV, respectively.

Our results for the mean and maximum ion energy can be compared with those based upon the hydrodynamic approach. In the latter the cluster explosion is described analytically as an expansion of a uniform sphere consisting only of positively charged ions. This approach assumes a naked cluster core and the absence of electrons, but in a more general version the electrons are included.[9,10,13] The cluster expansion is modeled by solving Newton's law for the motion of an ion at the cluster surface $Md^2R(t)/dt^2=Q(t)Z(t)/R^2(t)$, where R is the cluster radius, M is the ion mass, and $Q=NZ$ is the cluster charge.[13] The solution to this equation for a cluster with an initial radius R_0 gives the ion kinetic energy $E_{\rm ion}^{\rm kin}(t)=Q(t)Z(t)[1/R_0-1/R(t)] \rightarrow QZ/R_0$. The nanoplasma model, which is also a spatially averaged model, rep-

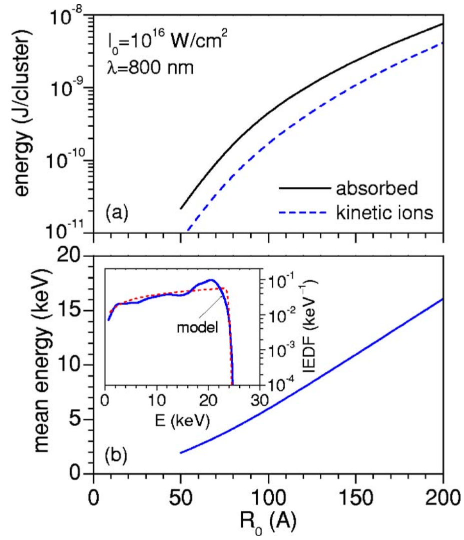


FIG. 2. (Color online) Absorbed energy per cluster (solid line) and energy converted into kinetic energy of ions (dashed line) vs initial cluster radius (a), and mean ion energy vs initial cluster radius (b). The inset in (b) shows the IEDF for $R_0=200$ Å. Peak laser intensity: $I_0=1\times10^{16}$ W/cm^2; wavelength: $\lambda=800$ nm; pulse duration: $T=400$ fs (150 laser cycles).

resents an improvement over the analytical approach by including the electron pressure in the right-hand side of the Newton's equation and solving it numerically.[18] Our simulations display a different power dependence of the mean ion energy versus the initial cluster radius. The power law obtained by fitting our results is $E_{\max} \sim R_0^{3/2} \sim N^{1/2}$, which is below the analytical upper limit (explosion of a naked cluster core, consisting only of ions), which scales as $E_{\max} \sim R_0^2 \sim N^{2/3}$.[2,4,9,10,13] The reason may be sought in the neutralizing background of electrons, which reduce the net (positive) charge of the cluster core, thus leading to somewhat smaller kinetic energies of the exploding deuterium ions.[10] However, a more fundamental consideration should be based on other factors, namely the energy absorption per cluster and the conversion efficiency to ion kinetic energy. Therefore calculation of the fusion reaction rate and neutron yield based on the simple analytical model may be overestimated.

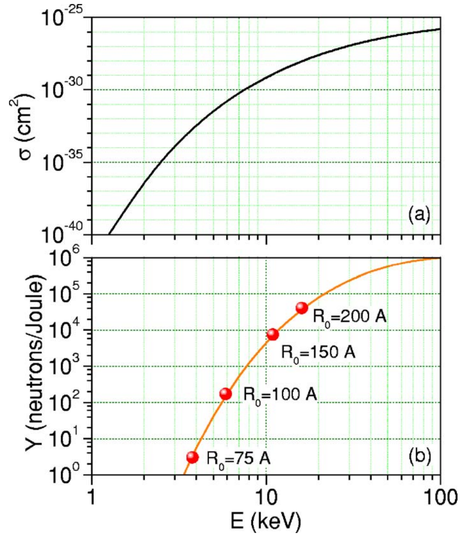
Having calculated the basic cluster parameters, we proceed with an estimate for the neutron yield, which is based on a beam-target interaction. The number of neutrons produced in fusion reactions is $Y \equiv N_n = N_{D^+}L/\lambda$, where N_{D^+} is the total number of deuterium ions, L is the stopping distance of D^+ in the target material, and $\lambda=1/\sigma(E)N_D$ is the reaction path length of deuterium ions in the target material with density N_D. The fusion reaction cross section

$\xrightarrow{50\%}$

$D+D \rightarrow He^3(0.82\ \mathrm{MeV})+n(2.45\ \mathrm{MeV})$ (Ref. 19) is plotted in Fig. 3(a). The number of ions can be calculated assuming that the driver laser energy is fully absorbed by the cluster (in Ref. 1, ~90% absorption was measured), which yields $N_{D^+}=\eta_{\rm ion}^{\rm kin}E_{\rm laser}/\bar{E}_i$. The total neutron yield

$$Y=\frac{\eta_{\rm ion}^{\rm kim}E_{\rm laser}}{\bar{E}}\sigma(\bar{E})N_D L$$

is plotted in Fig. 3(b) (solid line). For a typical cluster size of 200 Å the mean ion energy and conversion efficiency are



50%

FIG. 3. (Color online) Cross section for fusion reaction $D+D \rightarrow He^3+n$ (a), and neutron yield vs D^+ kinetic energy for laser energy $E_{laser}=1$ J and target with density $N_D \sim 2\times10^{22}$ cm^{-3} and thickness $L=1$ μm (b). Yield for clusters with an initial radius of 75, 100, 150, and 200 Å.

$\bar{E}_i \cong 16$ keV and $\eta_{ion}^{kin} \cong 0.5$, respectively (Fig. 2), and for laser energy $E_{laser}=1$ J, one gets $N_{D^+} \cong 2\times10^{14}$. The fusion cross section is $\sim 10^{-28}$ cm^2 and for a target with density $N_D \sim 2\times10^{22}$ cm^{-3} and $L=1$ μm the yield is $Y=4\times10^4$. The yield for clusters with different sizes is added to the plot in Fig. 3(b). As expected, the yield increases with the initial cluster radius. This increase is solely due to the increase of the mean ion energy with cluster size. From Fig. 3(b) one can conclude that a high neutron yield can be expected for deuterium ions with a kinetic energy exceeding ~ 10 keV, which can be obtained from exploding clusters with an initial radius of larger than 150 Å. Our model indicates that clusters with an initial radius of 200–400 Å are capable of providing a neutron yield of $\sim 10^5$ neutrons/J. Using large clusters, however, poses two problems. First, laser propagation effects can limit the penetration of high-intensity laser radiation to the region where clusters are formed. Experimental studies show that for clusters with an initial radius of 30 Å the neutron yield saturates and for larger clusters it starts to roll over.[2] Second, the laser may not fully penetrate the interior of large clusters due to shielding of the electric field by the plasma. The penetration depth is of the order of the skin depth, which is $\delta_s \approx 250$ Å.[11] Another possible explanation for the rollover effect was discussed in Ref. 10. The authors assumed that clusters with an initial radius larger than a critical one ($\sim$50–60 Å) are fully neutralized by the electron cloud and do not undergo a Coulomb explosion. However, the authors neglected the contribution of the hydrodynamics pressure, which is the main cluster explosion mechanism for relatively large clusters,[18] possibly because the electron temperature was underestimated by more than an order of magnitude.

We studied the impact of the laser intensity on the neutron yield. Such a study is relevant to clusters located off axis. An increase of the peak intensity from 10^{16} to 10^{17} W/cm^2 leads to a moderate increase of the mean ion energy, of the order of 10 %, consistent with the simulations in Ref. 14. Variation of the peak laser intensity leads to a slight change of the fusion yield, therefore clusters located off axis give fusion yields comparable with those on axis.

In conclusion, we studied the possibility of delivering a high neutron yield due to fusion reactions from energetic deuterium ions, obtained from laser-cluster interactions. Deuterium clusters mediate efficient conversion of laser energy into ion kinetic energy with an efficiency of $\sim$50%. The mean and maximum ion energy scale with a cluster radius as $\sim R_0^{3/2}$. The IEDF is close to that obtained analytically. The efficiency of the neutron production, $\sim 10^5 - 10^6$ neutrons/J, is of the same order of magnitude as in other D_2 cluster experiments [3×10^5 neutrons/J (Ref. 3)]. A high neutron yield from deuterium clusters is expected for peak laser intensity of $10^{16} - 10^{17}$ W/cm^2 and clusters with an initial radius of 200–400 Å.

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