Hot spot heating process estimate using a laser-accelerated quasi-Maxwellian deuteron beam

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Abstract

The hot spot heating process by an assumed deuteron beam is evaluated in order to estimate the contribution of the energy produced by the deuteron beam-target fusion to the heating process. The deuteron beam energy versus the number of deuterons is evaluated through the experimentally achieved proton beam energy distribution using the TRIDENT short pulse laser at the Los Alamos National Laboratory (LANL). The corresponding hot spot heating is then calculated using this assumed deuteron beam spectrum. The resulting first order heating dynamics is employed in the expanded "bonus" energy calculation, and a 12.73% extra energy from deuteron beam-target fusion was found with the assumed deuteron spectrum when $\rho r_b = 4.5$ g/cm^2 is considered, where ρ is the fuel density, and r_b is the ion beam focusing radius on the target. The results provide further insight into the contribution of the extra heat produced by deuteron beam-target fusion to the hot spot ignition process. A further analysis of how a converter foil using ultra-high-density cluster materials can help to achieve the yield requirements for ignition is presented.

Keywords: Bonus energy; Deuteron beam; Fast ignition; Hot spot; Inertial Confinement Fusion

INTRODUCTION

The achievement of laser intensities above 10^{18} Wcm^{-2} enabled the production of fast moving ions with kinetic energies approaching several tens or hundreds of MeV (Patel *et al.*, 2003; Robson *et al.*, 2007; Flippo *et al.*, 2008*b*). Ion beams with ultra-high energies and efficiencies provide new access to various advanced applications, including fast ignition (FI) of inertial confinement fusion (ICF) targets (Tabak *et al.*, 1994) with heavier ions, which is currently viewed as the preferred approach to achieve high gain ICF implosions for a laser fusion power plant.

The original relativistic electron beam approach proposed for FI operation suffers from problems with localized energy deposition and focusing. Protons offer better focusing by providing almost ballistic-like trajectories, but currently, the laser-to-ion converter foils used for proton ion generation give proton beam fluxes several orders of magnitude below the total fluxes required for practical FI (Snavely *et al.*, 2000; Fernández *et al.*, 2005). Special conical conversion

foil configurations are under study to help close this intensity gap (Flippo *et al.*, 2008*a*). Heavier ions, such as carbon, have been proposed and also studied to further improve focusing and ion yields, but much higher laser intensities needed for this approach will not be available in the immediate future (Fernández *et al.*, 2009).

Deuterons have been considered for FI as well (Bychenkov *et al.*, 2001; Shmatov, 2007; Naumova *et al.*, 2009; Tikhonchuk *et al.*, 2010). Our recent calculation has shown that deuterons would not only provide improved ballistic focusing, but also fuse with the target fuel (both D and T) as they slow down (Yang *et al.*, 2011*a*), providing a "bonus" energy gain. Depending on the target plasma conditions, this added fusion gain can feature a significant contribution (Shmatov 2004; Yang *et al.*, 2011*a*). For instance, our recent estimates have shown that an average 30% extra energy can be gained from deuterons with 1-MeV initial energy and 12% from deuterons with 3-MeV initial energy (Yang *et al.*, 2011*a*). Thus, if a high flux of deuterons can be achieved, deuteron beam driven FI could turn quite attractive. Various materials for the converter foil have been studied for deuteron beam generation. Some studies show that a deuteron beam (as well as a triton

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beam) can be generated by ponderomotive acceleration of deuterons (or tritons) in the overcritical plasma formed by the laser interaction with the ICF target itself (Naumova *et al.*, 2009; Tikhonchuk *et al.*, 2010). However, the ion flux obtained in that manner is not adequate for FI without a drastic increase in laser intensity well beyond that of current lasers (Fernández *et al.*, 2008; Naumova *et al.*, 2009). The converter foil approach overcomes the propagation instability issues involved in the direct coronal interaction (Deutsch, 2003), thus, it is considered to be the preferred method. A deuteron beam has been generated experimentally using a deuterated polymer layer coated on the substrate surface of a converter foil. However, the deuterated polymer contains a high density of carbon that is also accelerated, reducing the deuterium intensity and extraction efficiency (Nemoto *et al.*, 2001).

In our previous study (Yang *et al.*, 2011*a*), a novel cluster-based converter foil was proposed for deuteron beam generation. In this type of converter foil, deuterium is volumetrically loaded into the palladium lattice, and forms a condensed matter state — named "clusters" — in the palladium lattice defects. These clusters contain a hundred or so deuterium ions in a tightly bound almost metallic state. Palladium is much heavier than deuterium, thus unlike the carbon in the deuterated polymer, it has a much higher probability of being screened by the deuterons, meaning that deuterons will outrun palladium and take most of the energy with them. Moreover, volumetric loading offers a high total number of source deuterons. If all these deuterons can be utilized as in the relativistic transparent case (Henig *et al.*, 2009), this cluster converter foil has the potential to achieve the deuteron yield needed for hot spot ignition. In addition, the yield required for ignition is reduced for deuterons versus protons due to the "bonus" energy from the direct fusion between the deuteron beam and the D-T in the target. We previously presented a calculation to estimate the magnitude of this "bonus" energy gain under various deuteron energies and target temperatures (Yang *et al.*, 2011*a*). But that calculation used a first order approximation that assumed the deuterons heating of the hot spot occurs at certain defined energies into the hot spot at some prescribed temperatures as opposed to a continuous time heating profile. Hence, a more detailed calculation on hot spot heating is described here using a more realistic deuteron beam energy distribution and a continuous hot spot temperature rise. In this study, the deuteron beam energy distribution is estimated based on earlier measurements of proton beams generated by the conversion foil method using the TRIDENT petawatt pulse laser at LANL (Flippo *et al.*, 2010). The hot spot heating process by this assumed deuteron beam and first order heating dynamics is then employed in calculating the hot spot heating and the "bonus" energy. This study also provides further insight into how the energy produced by deuteron beam-target fusion can provide significant "extra" heating of the hot spot. A further analysis of how a converter foil using ultra-high-density cluster materials can help to achieve the yield requirements for ignition is presented.

DEUTERON BEAM ENERGY SPECTRUM ESTIMATE

When the intensity is sufficient, short-pulse laser interaction with solid foils have been shown in a number of laboratories to generate an electron beam that is typically accelerated to highly relativistic energies. A significant number of hot electrons propagate through the foil and emerge from rear surface (opposite side from the entering laser beam) to form a very high electrostatic field. This electrostatic field is sufficient to ionize atoms at the rear side of the converter foil (Pennington *et al.*, 2000; Murakami *et al.*, 2001; Bari *et al.*, 2010). This mechanism was termed target normal sheath acceleration (TNSA), which generally explains the acceleration process at the rear side of the target surface, and is a main mechanism of accelerating ions into very high energy. Some early experiments have shown that accelerated protons and deuterons could also originate from the front side (the side facing the laser) of the thin-film converter foil (Maksimchuk *et al.*, 2000, 2004; Nemoto *et al.*, 2001). This type of acceleration has been explained by a ponderomotive process. The laser's ponderomotive force can exert a pressure on the target electrons driving them away from regions of highest intensity into the target. The relatively heavy ions are unaffected by the laser fields directly, but respond to the electric field due to the electron displacement (Willingale *et al.*, 2011). When the laser pulse is circularly polarized, it quenches the fast electron generation, and accelerates ions by purely ponderomotive force, and then at moderate laser intensities the radiation pressure dominance is obtained. In this case, the ions accelerated ponderomotively can display specific feature such as high efficiency, large density and good collimation (Liseikina *et al.*, 2008). Further experiments have shown that by removing the contaminant layer on the converter foil surfaces, the heavier ions at the front and back sides can be used in unison to change and even increase the contributions of either side (Willingale *et al.*, 2011). These results suggest that depending on the parameters of both the target and the laser, ions at the front surface, within the foil (i.e., volumetric ions) and at the rear side can all be accelerated in the forward direction (laser light transport direction), although acceleration mechanism for ions in distinct regions exhibit different acceleration mechanisms.

To test the effect of our cluster concept, proof-of-principle shots with the cluster converter foils were recently performed on the TRIDENT 200 TW laser at LANL (Yang *et al.*, 2011*b*) The results showed that deuterium ions were extracted and accelerated to energies over 5 MeV. This estimate came out from the use of a titanium foil in the beam path prior to it impinging on the beam energy analyzer. According to stopping and range of ions in matter calculation, deuterons less than 5 MeV were blocked by a 100-μm Titanium foil

placed at the face of the ion energy analyzer. The purpose of this foil was to block carbon ions over 100 MeV in order to avoid their interference with deuterons) and up to about 10 MeV. This deuteron acceleration was achieved without attempting to remove any hydrocarbon contamination from the foil surface, thus a large amount of laser energy was lost in the acceleration of undesired carbon ions and protons (Yang *et al.*, 2011*b*). Therefore, the deuterons that were observed above 5 MeV could well have reached higher energies without this extraneous energy drain. As the D-clusters, i.e., the deuteron source, are located well inside the palladium volume rather than directly on the front and rear surface, these results, together with the previous finding of deuteron and proton acceleration from the front face of the foil noted above, suggest that ions beneath the front and rear surface can be accelerated when a suitable laser condition is fulfilled. Thus, concerns that the laser interaction mechanism might not provide good coupling to the unique D-clusters in the foil volume especially near the surfaces do not appear to be a major issue. Still, this is only a preliminary result and much more attention to this volumetric coupling deserves investigation.

The deuteron energy spectrum shown in Figure 1 was estimated by extrapolation of the proton energy spectrum achieved with TRIDENT short pulse 200-TW laser at LANL (Flippo *et al.*, 2008*b*, 2010). The proton energy and number were deconvoluted in a process termed radiochromic film imaging spectroscopy (Nurnberg *et al.*, 2009). The deuteron spectrum of Figure 1 extrapolates that result based on the following assumptions. First, according to the recent
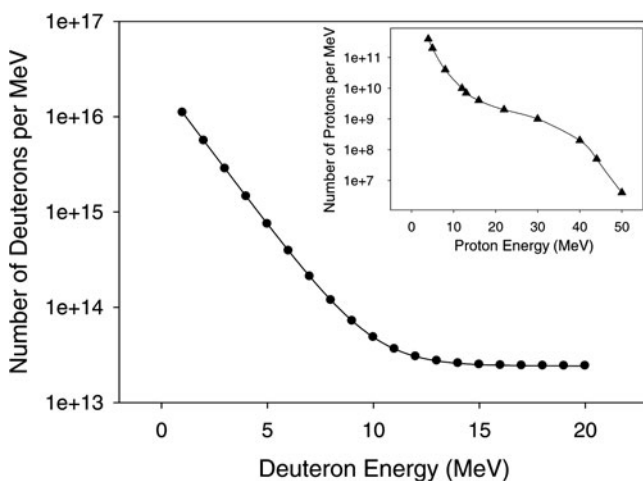
experiments, one can accelerate the deuterons to about the same energies as protons if protons are removed, or to about half their energy if the protons are still present (Willingale and *et al.*, 2011). However, to date, it is still very difficult to completely remove the hydrocarbon contaminant layer. Thus, we assume hydrocarbon contaminant layer has been significantly reduced from the deuterium converter foil, so deuterons will be effectively accelerated by the ideal electrostatic field arising from electron acceleration. Then the deuteron energy spectrum will have a shape that is similar to the measured proton energy spectrum, but with a slightly lower maximum energy. Second, as deuterons are mainly accelerated in the volume, the deuterium beam's high-energy cut-off will be shifted down further due to energy loss in the foil compared with the high energy protons that mainly arise from the rear side of the foil surface. Third, again due to volume loading, we assume deuterons have a higher source density and thus will have a higher yield at each energy level than protons that are generated from the surface layer and suffer a "depletion effect" (i.e., the source is depleted before the acceleration force decays) that limits their yield (Fernández *et al.*, 2008). Last, according to the proton beam energy distribution function, the number of protons in the high energy tail (from ca. 30 to 50 MeV) is several orders of magnitude less than those at the lower energy. Thus, we ignore the high energy tail and consider only an exponential shape as shown in Figure 1. The 20-MeV high-energy cut-off for deuterons is a rather conservative assumption due to the concern listed above. The total energy of the deuteron beam assumed in Figure 1 is 5.02×10^{16} MeV, which is slightly lower than the estimated ignition requirement that to ignite the fuel — about 10 kJ or 6.24×10^{16} MeV. This is so because it will be shown later that in some cases the hot spot can still be created with this estimated function.

Fig. 1. An estimated deuteron beam energy spectrum based on a proton beam energy spectrum (Inset) experimentally achieved from TRIDENT laser at LANL (Flippo *et al.*, 2008*b*, 2010). The X-axis represents the ion energy levels, and the y-axis represents the number of ions in a 1 MeV bin at each ion energy level. The deuteron beam energy spectrum has a shape similar to the proton beam but a lower high-energy cutoff. The yield of this deuteron beam is normalized to meet the ignition requirement for deuteron-driven FI of a DT ICF target ($\sim 10^{16}$ level). This yield is lower than what would be needed without the added "bonus" energy heating. This assumes that the volumetric deuterium loading with D-clusters enables very high yields compared to surface coated converter foils that suffer a "saturation" limit.

HOT SPOT HEATING AND THE BONUS ENERGY ESTIMATE

The parameters that affect hot spot heating process include the initial density and the temperature of the compressed fusion fuel just prior to its interaction with the FI ions or electron beam. Studies by Fernández *et al.* (2008) show that for high gain FI, the assembled fuel should be compressed to a mass density in the range $\rho = 300–500$ g/cm^3, in order to keep the required ignition energy and the fusion yield at manageably small levels. The initially compressed ICF target temperature is typically found to be about1 keV, while complete burn propagation requires that the hot spot reaches an average temperature ≥ 10 keV (Roth *et al.*, 2001; Hora *et al.*, 2011). Another key parameter that affects the hot spot heating process is the quality of the laser beam focusing which in turn determines the size of the hot spot. The radius of the hot spot should be large enough to prevent the fusion product alpha particles from escaping, but it shouldn't be too large, as more energy must be deposited in order to heat a

larger hot spot (Roth *et al.*, 2001; Hora *et al.*, 2011). According to Atzeni's (1999) model study, at $\rho r_b \approx 0.3$–0.6 g/cm^2 (r_b is ion beam focusing radius and ρ is the fusion fuel target density), the minimum igniter beam energy, power, and intensity required for FI are only weakly affected by the ion stopping range $\mathcal{R}$ over a reasonably wide interval $0.15 \leq \mathcal{R} \leq 1.2$ g/cm^2. Here $\mathcal{R} = \rho L$, and L is the hot spot length at the ignition ion beam transport direction. Then the optimal size can be conveniently stated in terms of $\mathcal{R}$ Too large an $\mathcal{R}$ yields a large hot spot volume, requiring extra hot spot energy to reach the ignition temperature, while a too small $\mathcal{R}$ yields too small a hot spot which is not able to induce burn propagation. An experimental setup is plotted in Figure 2 to further illustrate these parameters.

The deuterium energies and yield assumed in Figure 1 are used to estimate the hot spot heating process. The equation

$$S(E) \equiv \sum_k \kappa_k [<\sigma\upsilon(E)>_b]_{Ik}(E_f)_{Ik} / \left(\frac{dE}{dt}\right) \text{ (Eq. (2) in Yang}$$

et al., 2011*a*) was used to calculate the bonus energy during the ion deposition of each energy level, where $(\sigma\upsilon)_{Ik}$ is the fusion reactivity for the injected ion I of species k having atomic fraction κ_k in the target, $(E_f)_{Ik}$ is the corresponding energy released per fusion, E is the deuteron energy, and t is the time. Also, as discussed in Yang *et al.* (2011*a*), the bonus energy contribution from D-D fusion during the burn is orders of magnitude smaller than that from the D-T fusion portion, thus only the D-T part is considered here. $\rho r_b \approx 0.45$ or 0.6 g/cm^2 is assumed so that the D-T fusion product (helium 4) can be mostly stopped within this region. Moreover, a core plasma with single flat $\rho = 300$ g/cm^3 is assumed. This assumption simplifies the calculation and is thought to provide a reasonable first estimate of the hot spot behavior. The specific heat of the D-T fuel is assumed to be 115.8 MJ/(g × keV) (Frolov, 1998), and the total volume is calculated using equation $V = \pi \times r_b^2 \times$
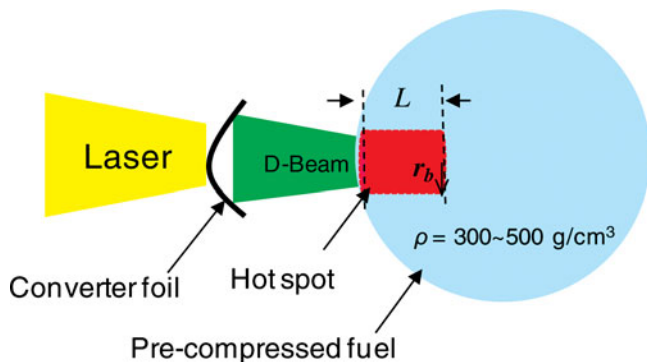

Fig. 2. (Color online) An illustration for the parameters L, r_b, and ρ in a setup of the FI experiment. L is the hot spot length at the ignition ion beam transport direction (Atzeni, 1999), and r_b is ion beam focusing radius. ρ represents the densities of both target and the hot spot as researchers have found that the density of the hot spot does not change significantly despite the significant increase of the temperature at the hot-spot region during the hot-spot formation (Honrubia *et al.*, 2009; Honrubia & Meyer-ter-Vehn, 2009).

L, where $L = \mathcal{R}/\rho$. We then know the heat capacity of the hot spot by assuming $\mathcal{R} = 1.2$ g/cm^2. In the calculation, a number of deuterons in a 1 MeV bin at each energy level are deposited as an energy "bunch" into the hot spot with hotter ions arriving at the target first. The hot spot temperature is calculated each time after one energy "bunch" is deposited by adding the incremental temperature due to each deposition to the temperature before the deposition. This first order calculation is not intended to give a precise description of the dynamic ignition process, but only to provide insight into how the bonus energy gained by the deuterium beam-target fusion contributes to the ignition of the hot spot (A computationally intensive three-dimensional simulation code evaluation would be needed to more accurately treat the detailed dynamics involved in this process). Results are used to evaluate the contribution of the "bonus" energy by comparing the total deuteron beam energy required for ignition with and without this added energy.

Figure 3 shows the hot spot heating process without (Fig. 3A) and with (Fig. 3B) considering the "bonus" energy, by assuming that the initial temperature of the D-T fuel is 1 keV. Under these conditions, the highest bonus energy gain occurs with lower energy deuterium ions in about the 3-MeV range. At first thought, the deuteron energy distribution with a very wide energy spread shown in Figure 1 would not appear to be very effective for this process since we aim at restricting the ion stopping within hot spot extension. However, the dynamic process during heating allows the lower energy ions to progressively penetrate into the target hot spot region once the higher energy component initiates heating. As discussed in previous study (Yang *et al.*, 2011*a*), when a deuteron beam is directed toward the D-T fuel, the higher energy deuterons arrive at the cold fuel in the hot spot region first with an energy appropriate for stopping in the desired volume, increasing its temperature. Then the lower energy deuterons arrive such that the elevated temperature allows good penetration despite the lower energy. They then produce a prominent fusion gain through beam-target reactions at the new, elevated temperature (Tikhonchuk *et al.*, 2010). Without the bonus energy and with the deuteron yield assumed in Figure 1, the highest temperature that the hot spot can eventually reach is 5.65 keV for $\rho r_b = 0.6$ g/cm^2, and 9.24 keV for $\rho r_b = 0.45$ g/cm^2, meaning that in both cases, the hot spot cannot reach required temperature (≥ 10 keV). The possible "bonus" energy was then calculated at each deposition, and was added back to the hot spot heating process at each deposition. The results are shown in Figure 3B. It can be seen that the ultimate temperature of case $\rho r_b = 0.45$ g/cm^2 is well above 10 keV, suggesting that the hot spot should be ignited with this assumed yield only when the bonus energy is considered. For the case of $\rho r_b = 0.6$ g/cm^2, the temperature also increases by up to 70% when compared with the no-bonus-energy condition. Both these results emphasize the advantage of the added "bonus" energy.

The above calculation is based on the assumption that all of the deuterons can be stopped in the hot spot (within
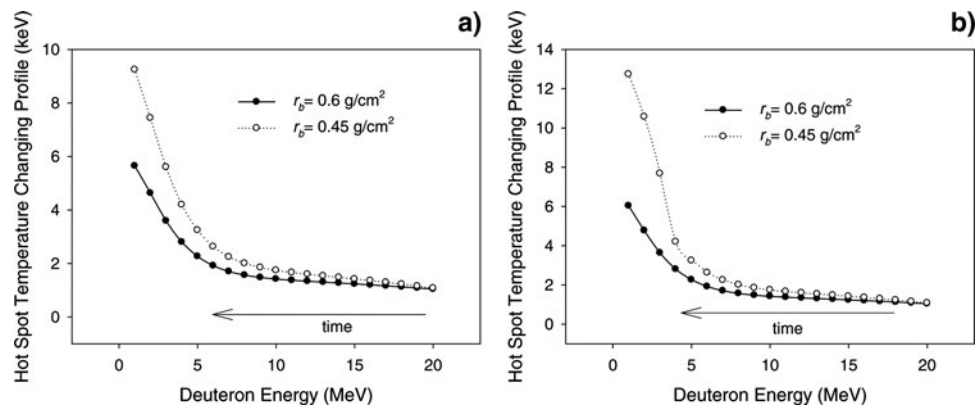
Fig. 3. Deuteron driven Hot spot heating process without (**a**) and with (**b**) the contribution from the bonus energy due to deuterium-beam-target fusion.

$\mathcal{R} = 1.2$ g/cm^2). According to our previous study (Yang *et al.*, 2011*a*), 10-MeV deuterons can be stopped within $\mathcal{R} = 1.2$ g/cm^2 when the hot spot temperature is below 5 keV, and 3-MeV deuterons (lower end of the spectrum) can be deposited within $\mathcal{R} = 1.2$ g/cm^2 when the hot spot temperature is below 10 keV, meaning that deuterons with energy in between 3 MeV and 10 MeV can be stopped within $\mathcal{R} = 1.2$ g/cm^2 when the hot spot temperature lies between 5 keV and 10 keV. Also, by expending our previous calculation (Yang *et al.*, 2011*b*) (results are not shown here), we know that deuterons with energy between 10 MeV and 20 MeV can all be stopped within $\mathcal{R} = 1.2$ g/cm^2 when the hot spot temperature remains below 3 keV. From Figure 2 we can see that all these conditions have been met during the hot spot heating, suggesting $\mathcal{R} = 1.2$ g/cm^2 is a valid assumption in this hot spot heating calculation.

To elaborate more on the contribution of the "bonus" energy achieved, the bonus energy achieved by deuterons of 1 MeV, 2 MeV, 3 MeV, and its percentage relative to the respective total deuteron-beam energies assumed are listed in Table 1. The total deuteron energy at each energy level is the product of the defined energy level and the number of deuterons at this energy level (see Fig. 1). The reason that we care only about this deuteron energy range is that according to our calculations (Yang *et al.*, 2011*a*), the bonus energy production is negligible when the deuteron energy is high and the hot spot temperature is low.

From Table 1, we see that at fixed R and ρ, the bonus energy increases with decreasing r_b. This is so because a smaller r_b gives a smaller hot spot volume and smaller heat capacity, thus the hot spot temperature rises faster at each deuteron energy level. Comparison of the current results with those in our previous study (Yang *et al.*, 2011*a*) shows that the "bonus" energy contribution from a more realistic deuteron spectrum used here is not as large, percentage-wise, as that from the previously assumed low energy (1 MeV to 3 MeV) mono-energetic deuterons. Still, the added energy, is significant, and remains an important contribution to the hot spot heating.

ACCELERATING ULTRA-HIGH-DENSITY DEUTERIUM CLUSTER MATERIAL BASED CONVERTER FOIL

Currently, the clusters in the materials we achieved experimentally have deuterium density exceeding 10^{24}/cm^3 (Miley & Yang, 2009; Miley *et al.*, 2010). However, the cluster sites presently occupy only about 0.1% of the volume of the host material, meaning the packing-fraction is relatively low (here packing fraction means clusters per cubic centimeter). In this case, the FI ignition requirement of 10^{18} Deuterons/cm^2 for about 1 mm^2 ion-beam focusing area (or the effective area of the converter foil) (Fernández *et al.*, 2008, 2009) would be achieved in a 1 μm thick target foil if 100% of the deuterons in the volume can be accelerated; alternately a thicker target foil would be needed if a smaller percentage of deuterons is accelerated. Nevertheless, the foil thickness cannot be arbitrarily increased, as with different laser parameters, such as contrast ratio and pulse duration, the acceleration process will be altered when using target

Table 1. *Bonus energy during hot spot heating process using first order hot spot heating estimation*

		Total deuteron beam energy at each deuteron energy level (MeV)	Bonus energy (MeV) for ρr_b(g/cm^2)	
			0.6	0.45
Deuteron energy (MeV)	1	1.10E + 16	2.64E + 15	3.30E + 15
	2	1.12E + 16	1.12E + 15	2.24E + 15
	3	8.53E + 15	4.27E + 14	8.53E + 14
	(~20)	5.02E + 16	4.19E + 15	6.39E + 15
Ratio of total bonus energy to the total deuteron beam energy assumed (%)			8.34	12.73

foils of different thickness (Maksimchuk *et al.*, 2000; Kaluza *et al.*, 2004; Ceccotti *et al.*, 2007). For lasers of different prepulse durations, an optimal thickness of the target exists for maximum proton cut-off energy (Kaluza *et al.*, 2004; Ceccotti *et al.*, 2007): when targets are thinner than the optimal thickness, ponderomotive acceleration dominates, and the rear side TNSA mechanism is suppressed due to the formation of a plasma density gradient at the rear side of the target, thus only the front side acceleration is active; for target thicknesses above the optimal value, protons are accelerated from both target surfaces with higher cutoff energies achieved from rear side acceleration (Kaluza *et al.*, 2004). Therefore, at longer prepulse duration, the maximum proton energies are achieved with thicker foils. As an example, the highest proton cut-off energy was achieved respectively from 2-µm-thick foil for prepulse duration of 0.5 ns and from ca. 8-µm-thick foil for prepulse duration of 2.5 ns. When the prepulse length is fixed, higher laser intensity gives higher maximum proton energy. For a high-contrast laser of constant energy, different pulse duration will produce different proton cutoff energy for the targets of certain thickness with the varied efficiency of the laser-plasma coupling and maximum obtainable electron temperature (Flacco *et al.*, 2010). Hence, by adjusting laser parameters, bulk accelerating deuterium cluster material of micron or sub-micron thickness is highly feasible.

When the TNSA sheath field is strong enough, it penetrates deeper into the target. In addition, high-intensity effect such as relativistic transparency can amplify acceleration from the bulk (Henig *et al.*, 2009). Maximizing both effects will finally determine the thickness of a deuterium laden target and should lead to significant volume acceleration. Currently, our goal is to find techniques to achieve 10 times more packing fraction in the converter foil material, which will provide a conservative deuteron-loading that would be advantageous in case the extraction percentage is not as high as hoped. In any case these estimates suggest that the present D-cluster foils are not far from what is needed for actual FI experiments and applications. Much more study is requested, however, to fully understand the acceleration process with clusters in order to accurately evaluate the potential for FI with this approach. Key development issues include the cluster volume fraction that can be achieved with nano-manufacturing of the base materials for the foils, the deuteron energy spectrum from such foils, and the deuteron extraction efficiencies.

SUMMARY

This study estimates the dynamics of the hot spot heating process in a pre-compressed D-T fuel by a high-energy deuteron beam. The deuteron beam spectrum was estimated according to an experimental proton beam energy function achieved using the TRIDENT short-pulse 200 TW laser. A "bonus" energy effect owing to beam-target fusion can provide a significant contribution to hot spot heating — with added hot

spot heating as high as 12.73% of the required total. Although these results are only a first estimate, they provide important insight into the possible significance of the bonus energy gained by the beam-target fusion to the hot spot heating. Future studies should give more detailed consideration to the stopping range changes during the heating process and temperature rise, but this will require rather elaborate simulation studies with a code such as LASNEX. In addition, the initial evaluation of our ultra-high-density deuterium cluster material indicates that with its volumetric loading this material has the potential to produce deuteron yields needed meeting the FI ignition requirement. Future effort is being devoted to methods for increasing the cluster packing fraction in the converter foil. Since the foil thickness is an important factor in the deuteron yield and energy spectrum, further studies of the optimum foil thickness are also underway. However, on the basis of the very preliminary TRIDENT experiments noted, plus these scoping calculations, this approach continues to appear as a potential contender to any effective FI.

ACKNOWLEDGMENT

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