IFE Target Design

Deuterium Cluster Target for Ultra-High Density Fusion

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Abstract

A radically new ICF target design is described that is designed to achieve ultra-high deuterium densities in implosions. This target is based on emerging technology for creating deuterium clusters with densities approaching $10^{24}/cm^3$ at room temperature in a Pd structure. Our initial studies of such clusters have relied on stress formation of dislocation sites in Pd thin films to the number of cluster sites per unit volume remains low. Here a new method employing nano-structuring of the Pd significantly increases the site density over the target volume. This in turn suggests that a sizable region of the compressed target deuterium can reach densities an order of magnitude higher than possible with prior target designs. This can significantly increase the fusion reaction burn density, hence the target burn-up efficiency.

D-CLUSTER CONVERTER FOIL FOR LASER-ACCELERATED DEUTERON BEAMS: TOWARDS DEUTERON-BEAM-DRIVEN FAST IGNITION

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A volumetrically-loaded ultra-high-density deuterium cluster material is described here for use as a deuteron beam source in laser matter interactions. Due to high volumetric loading, the material has potential to provide enough deuteron beam flux for the inertial confinement fusion (ICF) fuel ignition, avoiding depletion problem encountered by current proton-driven fast ignition (FI). In addition, accelerated deuterons can fuse with the ICF fuel (both D and T) to provide extra "bonus" energy gain, which further relaxes the laser-driver energy needed. Preliminary TRIDENT sub-Petawatt Laser experiments have provided some encouraging results showing that our cluster foils with a relative low packing fraction, can achieve a high yield of the accelerated deuterons even in the presence of an unwanted surface contaminant.

I. INTRODUCTION

To date, Fast Ignition approach (FI)[1] is being pursued as a way of reducing the laser energy required to ignite the inertial confinement fusion (ICF) fuel capsule, thereby achieving higher gain with less energy. In FI, the main fusion fuel target is first compressed with minimum heating, and then a separate short-pulse high-intensity laser ("Petawatt Laser") is fired onto the pre-compressed target, generating an intense particle beam (originally electrons) which is directed towards the fuel, creating a small "hot spot" in the center of the fuel. A relativistic electron beam though will have problems achieving localized energy deposition and focusing. Proton Fast Ignition[1] turns these problems into advantages with strongly localized energy deposition and better focusing through the use of ballistic trajectories,[2] but proton sources suffer from beam fluxes that may be two orders of magnitude below what is required for FI due to insufficient hydrogen in the contamination coating on the accelerating foil.[3]

Deuterons as well have previously been considered as an ignition source, but their achievable initial energy was considered to be too high (7 ~ 8 MeV) to form a desired hot spot.[4] However, some recent laser beam acceleration experiments on protons[5] suggest that the laser and target parameters can be adjusted to achieve ion beams within the desired range of initial energies and spectra with low $\Delta E/E$ for maximum use of the beam. This opens the door again to the consideration of deuteron FI. And, as already noted,[6] deuterons can fuse with the target fuel (both D and T) as they slow down in the target, providing a "bonus" energy gain. Depending on the target plasma conditions, this added fusion gain can be a considerable contribution.[7] A key issue then is the development of a laser-ion acceleration foil that can serve as a high yield deuteron source.

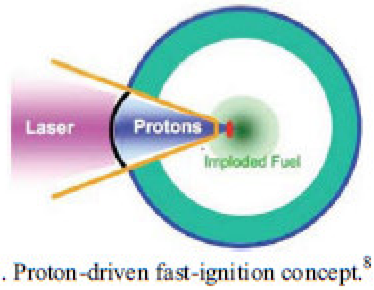

Fig. 1. Proton-driven fast-ignition concept.[8]

By analogy with the proton acceleration mechanism, the so-named Target Normal Sheath Acceleration (TNSA),[1] with the laser-ion acceleration foil scheme illustrated in Fig. 1, a thin layer of deuterated coating might be used to generate a deuteron beam. However, that approach would face the same flux depletion problems encountered in proton beam work to date. An alternative

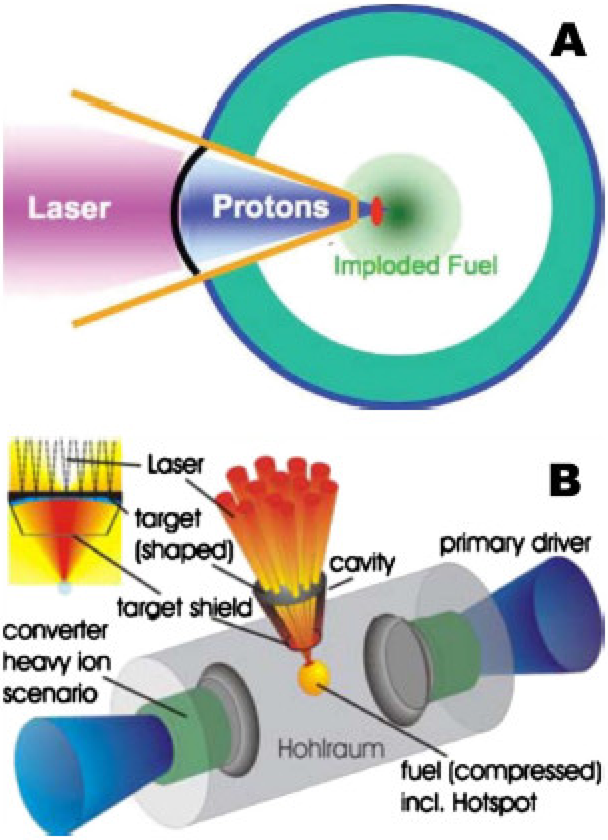

FIG. 1. (Color online) (a) Proton-driven fast ignition concept; proton created by the laser converter foil interaction continue in the conical insert to hit the center core of the fuel (Refs. 3 and 6). (b) Hohlraum-based proton FI concept for heavy ion beam driven fusion. Here the converter foil for the FI proton ion beam enters on the side of the hohlraum while the main heavy ion compression beams hit the tamper-converters on the ends (Refs. 5 and 6).

plasma.[21] For this reason, we focus on the enclosed converter foil approach here.

Creation of the deuteron ion beam can be done with a Petawatt laser hitting a converter foil much as employed for the proton concept shown in Fig. 1. Protons are typically obtained from a hydrogenous coating on the converter foil surface. Likewise, a deuterated coating could be used for deuteron beam generation. However, there appears to be a new option for the construction of the converter foil that could potentially improve the converter foil performance with a more volumetric-like loading of the hydrogen, or in the present case, deuterium.[22–26] This approach is based on recent experiments showing the existence of ultra high density deuterium "clusters" (D-cluster) in metal defects using temperature programmed desorption technique.[23–26] In related but somewhat different conditions, Badiei *et al*. found ultradense deuterium (or inverted Rydberg matter) at the surface of iron oxide.[27] These various experimental results suggest that deuterium can form condensed states in the material defects with densities as high as $10^{24}/\mathrm{cm}^3$. Now, further studies are needed to increase the packing faction [i.e., number per cubic centimeters (cm^3)] of clusters in the host material and thereby secure sufficient deuteron flux in FI. If the packing fraction can be increased by an order of magnitude more compared to the present results, the D-cluster materials could potentially be the basis for an improved converter foil design to achieve a deuteron fast igniter for ICF targets. Although the energy of the deuterons created in the Petawatt laser interaction needs considerable theoretical study and ultimately experiment demonstration, this potential, combined with the realization that the desired deuteron energies are predicted for proton experiments, encouraged us to reevaluate deuteron FI. In the present page, we focus an evaluation of the added energy released as the energetic deuterons interact with the target fuel ions. This added energy gain, although is an important feature, has not previously been evaluated. Thus, in this article, we use a modified energy multiplication factor F_c to quantify the bonus energy in terms of the added "hot spot" heating by beam-target fusion reaction.[18] The deuteron beam energy deposition range and time are also calculated to estimate the desired deuteron initial energy.

II. CALCULATION METHODS FOR THE MODIFIED ENERGY MULTIPLICATION FACTOR F_c AND THE TOTAL DEPOSITION ENERGY E_{total}

Earlier, Bathke and Miley *et al.*[18] calculated the fusion power generated by non-Maxwellian beam ions injected into various magnetically confined fusion fuel systems. Here we extend this technique to estimate the added fusion reactions obtained from injection of energetic deuterons into a compressed deuterium-tritium (DT) ICF target. The ratio between the fusion energy E_f produced and the ion energy input E_I to the plasma is termed the F value:[18]

$$F = n_T \frac{\int_{E_{\mathrm{th}}}^{E_I} S(E)\,dE}{E_I}. \tag{1}$$

Here E_I and E_{th} are, respectively, the average initial energy and the asymptotic (thermalized) energy of the injected single ion,[18,28,29]

$$S(E) = \sum_k \kappa_k [\langle \sigma v(E) \rangle_b]_{Ik} (E_f)_{Ik} \Big/ \left(\frac{dE}{dt}\right) \tag{2}$$

$$\frac{1}{n_T}\left(\frac{dE}{dt}\right) = -\frac{Z_I^2 e^4 m_e^{1/2} E \ln \Lambda}{3\pi (2\pi)^{1/2} \epsilon_0^2 m_I (kT)_e^{3/2}} \times \left[1 + \frac{3\sqrt{\pi} m_I^{3/2} (kT_e)^{3/2}}{4 m_k m_e^{1/2} E^{3/2}}\right] \tag{3}$$

where m_e is the mass of electron and m_I is the mass of the injected ion, both of which are in atomic mass unit (amu). $(\sigma v)_{Ik}$ 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, and T_e is the target electron temperature.[29] When substituting Eq. (3) to Eq. (1), we can see that the n_T in Eq. (3) cancels that in Eq. (1), and F is nearly independent of the target density (ρ). However, $\ln \Lambda$, the Coulomb logarithm, also enters through the T_e and

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(54) **METHOD OF USING DEUTERIUM-CLUSTER FOILS FOR AN INTENSE PULSED NEUTRON SOURCE**

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(60) Provisional application No. 60/920,659, filed on Mar. 29, 2007.

(51) **Int. Cl.**
H01J 49/06 (2006.01)
H01J 3/00 (2006.01)

(52) **U.S. Cl.**
USPC **376/108**; 376/109; 250/424

(58) **Field of Classification Search**
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See application file for complete search history.

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(Continued)

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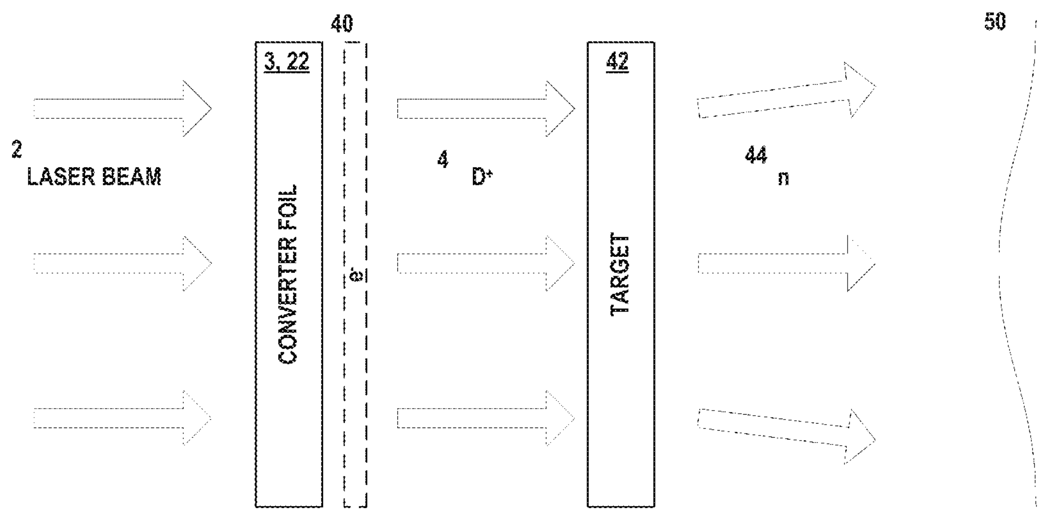
(57) **ABSTRACT**

A method is provided for producing neutrons, comprising: providing a converter foil comprising deuterium clusters; focusing a laser on the foil with power and energy sufficient to cause deuteron ions to separate from the foil; and striking a surface of a target with the deuteron ions from the converter foil with energy sufficient to cause neutron production by a reaction selected from the group consisting of D-D fusion, D-T fusion, D-metal nuclear spallation, and p-metal. A further method is provided for assembling a plurality of target assemblies for a target injector to be used in the previously mentioned manner. A further method is provided for producing neutrons, comprising: splitting a laser beam into a first beam and a second beam; striking a first surface of a target with the first beam, and an opposite second surface of the target with the second beam with energy sufficient to cause neutron production.

35 Claims, 8 Drawing Sheets



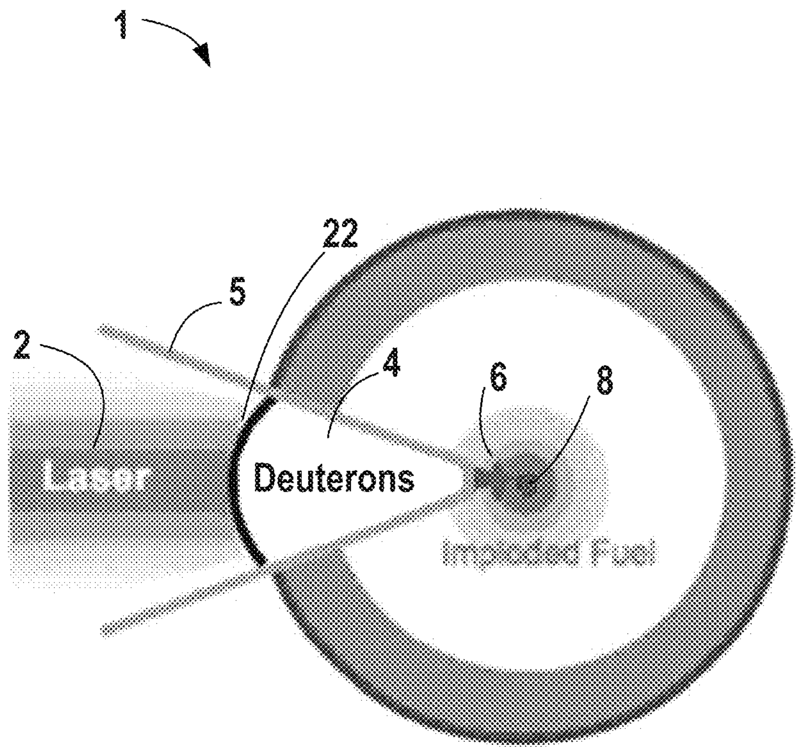


FIG. 3

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