An Energy Gain Estimation of Deuteron Beam Driven Fast Ignition

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ABSTRACT

here are a number of physics issues related to the traditional approach of using a petawatt laser to generate a relativistic electron beam for Fast Igniting inertial confinement fusion (ICF) target. One promising alternate approach is the laser generation of a proton beam. However, the total proton flux simply from water adsorption on the foil is too less to generate desired hot-spots. Here we propose to utilize a new "Deuterium Cluster "type structure for the laser interaction foil to generate an energetic deuteron beam as the fast igniter. The ultra high density deuterium in the cluster structure will promise much higher total flux for deuteron than for proton. Also, deuterons will serve very important dual purposes – the deuteron deposition in the target fuel will not only provide heating but also fuse with fuel as they slow down in the target. If the physics works as anticipated, the massive yield of deuterons generated from our cluster material through laser acceleration, should turn out to be the most efficient way of igniting the DT fuel, and making the dream of near-term commercialization of FI fusion more achievable.

Keywords: Fast Ignition, ICF, Deuterium, Deuteron

1 INTRODUCTION

Since the first laser driven inertial confinement fusion (ICF) experiment, the primary problems in making a practical ICF device remains building the laser of a required energy, and achieving energy breakeven. [1] In 1994, the Fast ignition (FI) concept was proposed to address this problem. The concept is to pre-compress the cold fuel and subsequently to ignite it with a separate short-pulse high-intensity laser or particle (electron or ion) pulse (Figure 1). [2-3].This approach will be able to reduce the required laser energy, relax the symmetry requirements for compression, and eventually increase the energy gain. [4] The relativistic electron beam approach has problems with focusing. Protons offer better focusing [5] but the foils (use adsorbed hydrogen) used for proton generation give two orders of magnitude below total flux than required for FI. [6] Other ions have been considered, e.g. C, but a practical solution for ion generation remains unsolved. [7]

Here we propose a deuteron (D)-beam based on our novel ultra-high-density D cluster electrode [8-10] for the laser conversion foil. D beams possess the advantages that other candidate driver ion beams, including efficient energy deposition in a small hot spot. Also, being heavier than protons, Ds are even more easily focused in a hot spot with a radius of a few microns? Most importantly, accelerated deuterons not only provide heating, but also fuse with the target fuel (both D and T) as they slow down in the target, providing a "bonus" energy gain.

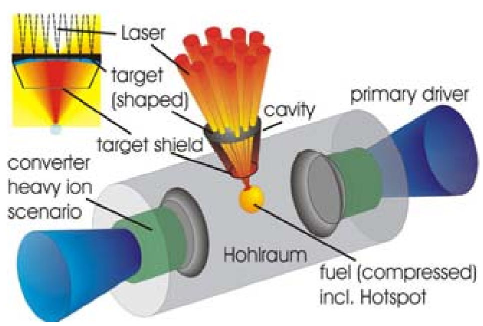

Figure 1 hohlraum-based proton FI concept. [2] [3]

2 ULTRA-HIGH-DENSITY DEUTERIUM CLUSTER MATERIAL AS A DEUTERON BEAM SOURCE

As discussed, a deuteron beam offers advantages as an FI beam source. The key issue is development of a suitable laser interaction foil containing high D densities. Previously, we observed ultra-high-density deuterium state (termed clusters) in a thin Palladium foil after it was electrochemically loaded and unloaded with H/D. [8-10] Based on a repetitive loading process, the metal lattice expands significantly to form dislocation defects (Fig. 2). The diameter of the dislocation defects is around 2 burgers factor, and their length varies, depending on film dimensions. They form a potential trap to form the ultra high density H/D clusters, as shown by previous experimental results. [8-9] Briefly, temperature programmed desorption (TPD) measurements suggest that the local loading ratio of hydrogen ([H]/ [Pd]) within the dislocation loops is 1.8. Both direct resistance measurements and SQUID analysis indicate H/D loaded sample is a type II superconductor. These results confirm the H/D clusters are in a condensed metal-like state with ultra high density.

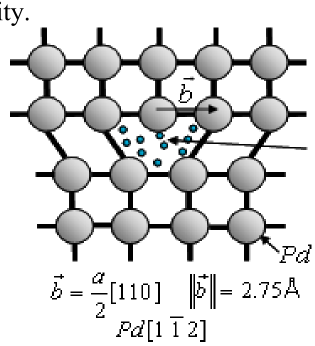

Figure 2 Scheme of the edge dislocation loops in Pd with condensed H/D.

By a rough calculation based on Loubeyre et al's theory, [11] molecular hydrogen at 180 GPa (local pressure of dislocation loops in Pd at ambient conditions) and 300K has a density > 2x1023/cm3, well above cryogenic hydrogen ice. In our case, H and D will first dissociate from H2/D2 before diffuse into Palladium foil. Kim [12] notes that D, as a boson, may form a Bose-Einstein like state due to the potential trap in a dislocation core under the local pressure of dislocation loops. Based on these theoretical estimations, the cluster may have even higher density than 1023/ cm3. The FI ignition requirement of 1018 D ion /cm2 for ~ 1 mm2 ion-beam target area is achieved if the cluster packing fraction in the foil exceeds 0.l in a 100-nm palladium foil. [13]. A lower packing fraction in palladium foil can be compensated by using a thicker foil thickness but the maximum thickness is limited by the accelerated D mean free path in the foil. Thus, in contract to current proton sources, present cluster type foils appear to meet the threshold flux needed for FI. Moreover, the packing fraction can potentially be further increased by advanced nano-material manufacture. [10]

3 THE ENERGY LEVEL OF LASER ACCELERATED DEUTERONS AT TRIDENT

Arrangements have been made for cluster foil experiments at the LANL TRIDENT laser. Various laser interactions foil type studies have been done there for several years so the techniques are well developed. The LANL Trident laser has a peak power of 200 TW delivering 100 J on target in 500 fs with a spot size smaller <12 m. 15- m flat-foil interaction foils with adsorbed hydrogen on the surface have been shown to produce proton beams with energies < 50 MeV with efficiencies ~5% using a laser intensity of only ~4 x1019 W/cm2. [13] Fig. 3A shows the proton energy distribution. While lower than protons, the improved slowing distance in the target would enable equivalent hot spot heating. The issue then is achieving the desired flux level, which hopefully our cluster targets can achieve. An estimated energy distribution for a deuteron beam generated by the interaction foil method is also included for reference. Moreover, LANL staff previously developed a method suitable for measurement of the energy of laser accelerated deuterons. [14] They used an interaction foil with a deuterated polystyrene layer deposited on the front side of the 6- m Mylar film (Fig 3B). Deuterons were detected by 10B(d,n)11C reactions in a reference boron plate detector. This method will be used in our proposed cluster test experiments.

4 ESTIMATION OF ADDED ENERGY GAIN OF DEUTERON BEAM DRIVEN FI

Earlier, Bathke and Miley et al. calculated the fusion power generated by non-Maxwellian beam ions injected into various magnetically confined fusion fuel systems. [15] Here we extend this technique to estimate the added fusion reactions obtained from injection of energetic D ions into a DT ICF target. The ratio between the fusion energy E_f produced and the energy input to the plasma E_I is termed the F value [14]: $F = C_1 n_T \frac{\int_{E_{th}}^{E_I} S(E)dE}{E_I}$, where C_1=4.39 × 10^7 $m_{iI}^{-1/2}$, E_I and E_{th} is respectively the average energy of injected single ion, and the asymptotic (thermalized) energy of the injected ion, $S(E) \equiv \sum_k \kappa_k [<\sigma\upsilon(E)>_b]_{Ik} (E_f)_{Ik} / \left(\frac{dE}{dt}\right)$

and $\left(\frac{dE}{dt}\right) = -nT \frac{2\times10^{-7}(Z_I e)^2 e^2 \ln\Lambda}{(E/m_I)^{1/2}} \left[\frac{1}{\sum_k \kappa_k m_k} + 0.75 \frac{\kappa_k Z_k}{m_e} \left(\frac{m_e E}{m_i T_e}\right)^{3/2} \right]$.

Here m_{iI} is the injected ion mass in amu; $(\sigma)_{Ik}$ is the fusion cross section for injected ion I with species κ_k having atomic fraction in the target and $(E_f)_{Ik}$ is the corresponding energy released per fusion. [16]

These equations show that F is essentially independent of n_T, but is a strong function of T_e and E_I. Also the F value saturates as $T_e \rightarrow \infty$. In Fig. 4, for D-T the peak F increases to ~3.8 at T_e = 50keV and approaches 3.9 as $T_e \rightarrow \infty$. Note that the F value gives the energy released in the fusion reaction carried by both fast neutrons and charged particles. However, for hot spot heating only the charged particles (e.g. DT alpha) contributes. Thus for D-T fusion (see Eq. 3) only 20% of fusion energy carried by alphas is useful for heating while for D-D fusion (see Eq. 4), about 63% is useful.

$${}_1^2D + {}_1^3T \rightarrow {}_2^4He(3.5MeV) + n^0(14.1MeV) \quad (3)$$

$$
\begin{aligned}
{}^2_1D + {}^2_1D &\rightarrow {}^3_1T(1.01MeV) + p(3.02MeV) \qquad 50\% \\
&\rightarrow {}^3_2He(0.82MeV) + n^0(2.45MeV) \qquad 50\%
\end{aligned} \qquad (4)
$$

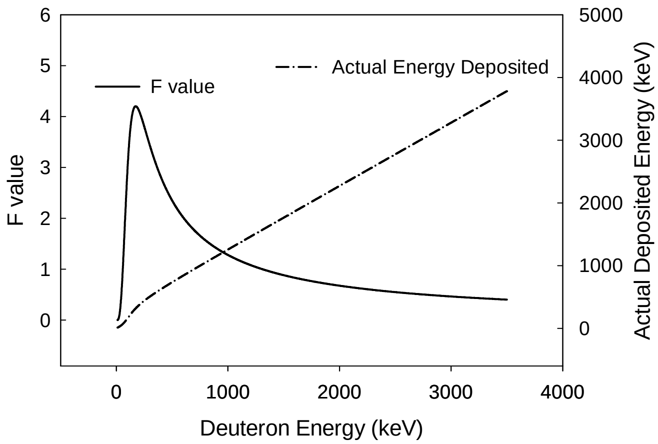

Figure 4. Energy multiplication factor F and actual deposited energy vs. deuteron injection energy for Te = 1keV in cold tritium and deuterium.

The F value primarily depends on the electron temperature (T_e) of the target fuel and the energy of the incident particles (E_I). For a hollow shell targets the center electrons can have very high temperature due to the explosive type implosion. However, with a cryogenic fueled target of interest here, and an ideal adiabatic compression, T_e approaches 1 keV just before the FI ion beam energy deposition. [13] The curve in Fig. 4 was calculated using $\ln\Lambda \sim 20$ for injection into a mirror reactor. However, for a laser confined plasma, $\ln\Lambda \sim 2$ suggesting the F value is roughly ten times of that for the curve T_e = 1keV with $\ln\Lambda \sim 20$ (not shown in the figure). The energy of the incident particles (E_I) is estimated from Fig. 3. Assuming a total ion energy of 10kJ (6.24 $\times 10^{16}$ MeV) is deposited into the hot spot [13] Then scaling the proton data of Fig. 3., a ~ 3.1 MeV deuteron beam of 2 $\times 10^{16}$ deuterons, is required. However, do to the added D fusion reaction, unlike protons, deuterons will deposit a total energy of $10(1+20\%F_{D\text{-}T}+63\%F_{D\text{-}D})$ kJ, which is ion energy (10kJ) plus beam target fusion energy ($10\times20\%F_{D\text{-}T}$ for D-T fusion and $10\times63\%F_{D\text{-}D}$ for D-D fusion). For D-T fusion, F is close to 1 when T_e = 1keV and $\ln\Lambda =\sim 2$. For D-D reactions, $F_{D\text{-}D}$ is ~ 0.1, thus are negligible compared to the D-T reaction. In conclusion, we obtain 20% extra energy from reaction heating on top of the ion deposition energy.

5 SUMMERY

These rough estimations clearly demonstrate that deuteron beam-driven FI offers important advances. Further, it appears that a practical deuterium beam can be generated using our ultra-high density deuterium clusters in the interaction foil. The extra beam-target-fusion gain can be used to relax the total flux of deuterons required, or alternately reduce the input laser energy needed. With either strategy the energy gain from the target is increased compared to proton driven FI. However, a more precise analysis is needed to fully explore this opportunity and to develop the basis for a target design to test the concept on NIF. For example, the F-value changes inversely with ion energy in the energy range of interest here.

A precise F-value calculation under various target temperature and ion beam energy is needed for beam-target fusion energy optimization. Also, in a 3D FI experiment, controlling the power of the compressing laser and the beam angles into the hohlraum will change the target T_e which must be adjusted and optimized to achieve maximum energy gain. Moreover, the deuteron beam deposition energy will affect the actual beam-target fusion gain. This deposition energy is dependent on the FI laser power, distance between deuteron source and target fuel, and the beam focus. Therefore a much more comprehensive calculation (vs. the rough first order calculation outlined above) is needed to realize a full 3D experimental design for maximum fusion gain.

In summary, first rough estimates indicate the deuteron-beam driven FI enjoys an important added energy production from deuteron fusions in the target as they slow down creating the desired hot spot. More detailed studies plus supporting interaction foil experiments of this promising D-ion FI approach are proposed here.

6 ACKNOWLEDGEMENTS

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7 REFERENCE

[1] D. Keefe, "Inertial Confinement Fusion," Annual Review of Nuclear and Particle Science **32** (1), 391-441 1982

[2] Atzeni S. et al Nucl. Fusion 42 L1 2002

[3] Roth M. et al Phys. Rev. Lett. 86 436 2001

[4] M. Tabak et al., Phys. Plasmas 1, 1626 1994

[5] Juan C. Fernández, Brian J. Albright, Kirk A. Flippo, Björn M. Hegelich,Thomas J. Kwan, Mark J. Schmitt, Lin Yin, Progress on Ion Based Fast Ignition, Journal of Physics: Conference Series 112 022051 2008

[6] Wilks S C, Langdon A B, Cowan T E, Roth M, Singh M, Hatchett S, Key M H, Pennington D, MacKinnon A and Snavely R A Phys. Plasmas 8 542 2001

[7] Fernández J C et al. Lasers & Part. Beams 23 267 2005; Cowan T E, et al. Phys. Rev. Lett. 92 2048012004; Snavely R A et alPhys. Rev. Lett. 85 2945 2000

[8] A Lipson, BJ Heuser, C Castano, G Miley, B

Lyakhov, A Mitin, Transport and magnetic anomalies below 70 K in a hydrogen-cycled Pd foil with a thermally grown oxide, Phys. Rev. B. 72 212507 2005

[9] AG Lipson, BJ Heuser, CH Castano, A Celik-Aktas, Observation of a low-field diamagnetic contribution to the magnetic susceptibility of deformed single crystal PdHx ($x \simeq 4.0\times10^{-4}$), Physics Letters A. 339 414-423 2005

[10] G. H. Miley and X. Yang, Deuterium Cluster Target for Ultra-High Density Fusion, Fusion Science and Technology, 56 (1), 395-400 2009

[11] P. Loubeyre, R. LeToullec, D. Hausermann, M. Hanfland, R. J. Hemley, H. K. Mao & L. W. Finger, X-ray diffraction and equation of state of hydrogen at megabar pressures, Nature 383, 702 – 704

[12] Yeong E. Kim, Theory of Bose–Einstein condensation mechanism for deuteron-induced nuclear reactions in micro/nano-scale metal grains and particles, Naturwissenschaften. 2009

[13] M. Roth et al., Phys. Rev. Lett. 86, 436 2001; M. Temporal, J. Honrubia, and S. Atzeni, Phys. Plasmas 9, 3098 2002

[14] K. Nemoto, A. Maksimchuk, S. Banerjee, K. Flippo, G. Mourou, D. Umstadter, and V. Yu. Bychenkov, Laser-triggered ion acceleration and table top isotope production, Appl. Phys. Lett. 78, 595 2001, DOI:10.1063/1.1343845

[15] Bathke, C., Towner, H. & Miley, G. H. Fusion Power by Non-Maxwell ian Ions in D-T, D-D, D-^{3}He, and p-^{11}B Systems. *Trans, Am. Nucl. Soc.,* **17,** 41-42 1973

[16] Miley, G. H. Fusion Energy Conversion, American Nuclear Society, Hinsdale, Illinois. 1976

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