Defense Threat Reduction Agency
8725 John J. Kingman Road, MS
6201 Fort Belvoir, VA 22060-6201

DTRA-TR-16-36

TECHNICAL REPORT

Novel Non-Destructive Identification of Nuclear Materials with an Ultra-Intense Laser Based Radiation Source

Distribution Statement A. Approved for public release; distribution is unlimited.

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Grant HDTRA1-08-1-0018

Richard R. Freeman

Prepared by:
The Ohio State University
Columbus, OH 43210

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A proposed technique for generating an intense point source of neutrons using an ultra-intense laser was investigated. The technique rested upon the successful generation of intense beams of deuterium ions from the rear of a thin target struck by laser of intensities on the order of 10^18 W/cm^2. An apparatus for the production of thin layers of heavy water ice on the back of the targets was conceived, designed and successfully demonstrated. The fast deuterium ion beam was made to strike a second target of Lithium, whereupon a large number (>10^8) of fast neutrons per laser shot were observed. Calculations combined with experimental results show that it is feasible, using current laser technology, to construct a portable, point source of high energy neutrons with a total yield of more than 10^12 neutrons/s.

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Neutron, Laser, Target Normal Sheath Acceleration, Ions

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement[*]

U.S. Customary Units	Multiply by → ← Divide by[†]	International Units
Length/Area/Volume		
inch (in)	2.54 × 10^{-2}	meter (m)
foot (ft)	3.048 × 10^{-1}	meter (m)
yard (yd)	9.144 × 10^{-1}	meter (m)
mile (mi, international)	1.609 344 × 10^{3}	meter (m)
mile (nmi, nautical, U.S.)	1.852 × 10^{3}	meter (m)
barn (b)	1 × 10^{-28}	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412 × 10^{-3}	cubic meter (m^3)
cubic foot (ft^3)	2.831 685 × 10^{-2}	cubic meter (m^3)
Mass/Density		
pound (lb)	4.535 924 × 10^{-1}	kilogram (kg)
unified atomic mass unit (amu)	1.660 539 × 10^{-27}	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846 × 10^{1}	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222	newton (N)
Energy/Work/Power		
electron volt (eV)	1.602 177 × 10^{-19}	joule (J)
erg	1 × 10^{-7}	joule (J)
kiloton (kt) (TNT equivalent)	4.184 × 10^{12}	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350 × 10^{3}	joule (J)
foot-pound-force (ft lbf)	1.355 818	joule (J)
calorie (cal) (thermochemical)	4.184	joule (J)
Pressure		
atmosphere (atm)	1.013 250 × 10^{5}	pascal (Pa)
pound force per square inch (psi)	6.984 757 × 10^{3}	pascal (Pa)
Temperature		
degree Fahrenheit (^{o}F)	[T(^{o}F) − 32]/1.8	degree Celsius (^{o}C)
degree Fahrenheit (^{o}F)	[T(^{o}F) + 459.67]/1.8	kelvin (K)
Radiation		
curie (Ci) [activity of radionuclides]	3.7 × 10^{10}	per second (s^{-1}) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760 × 10^{-4}	coulomb per kilogram (C kg^{-1})
rad [absorbed dose]	1 × 10^{-2}	joule per kilogram (J kg^{-1}) [gray (Gy)]
rem [equivalent and effective dose]	1 × 10^{-2}	joule per kilogram (J kg^{-1}) [sievert (Sv)]

[*] Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

[†] Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

2015-11-16

Final Report HDTRA1-08-1-0018

Novel non-destructive identification of nuclear materials with an ultra-intense laser based radiation source

A proposed technique for generating an intense point source of neutrons using an ultra-intense laser was investigated. The technique rested upon the successful generation of intense beams of deuterium ions from the rear of a thin target struck by laser of intensities on the order of 10^18 W/cm^2. An apparatus for the production of thin layers of heavy water ice on the back of the targets was conceived, designed and successfully demonstrated. The fast deuterium ion beam was made to strike a second target of Lithium, whereupon a large number (>10^8) of fast neutrons per laser shot were observed. Calculations combined with experimental results show that it is feasible, using current laser technology, to construct a portable, point source of high energy neutrons with a total yield of more than 10^12 neutrons/s.

Concept:

(1) The recently developed method for the acceleration of protons (or ions) from a target is based upon the "Target Normal Sheath Acceleration" (TNSA) mechanism. This mechanism is outlined in Figure 1

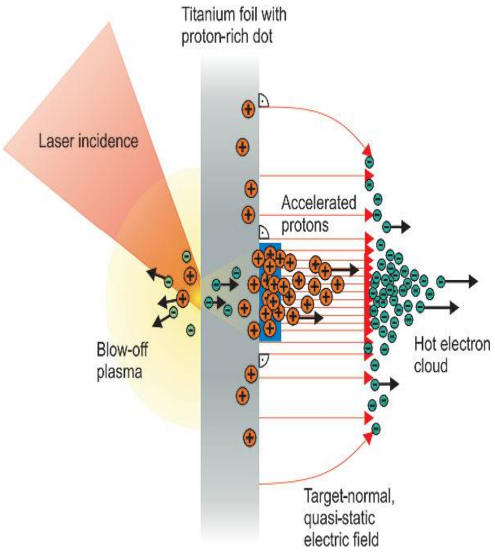


Figure 1 TNSA mechanism that generates ion beams with kinetic energies above 1 MeV

(2) The initial studies concentrated on characterizing the ion beam: We built an absolutely calibrated Thompson parabola ion spectrometer (Figure 2)

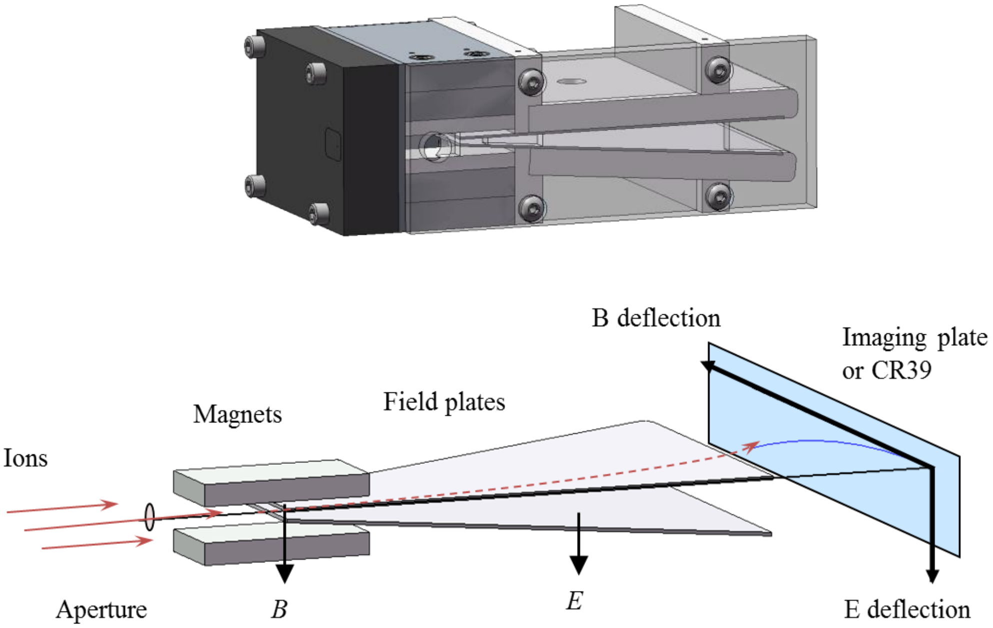


Figure 2 Thompson Parabola Ion spectrometer

(3) The historical problem with the use of TNSA to accelerate specific ions from the back of a target is that the spectrum is universally dominated by protons coming from water vapor and contaminants within the vacuum vessel (Figure 3).

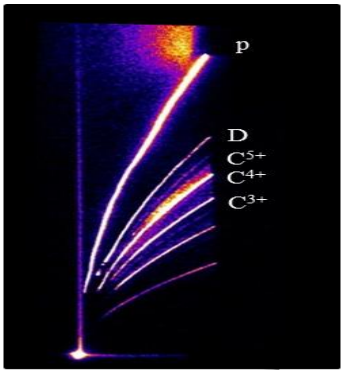


Figure 3 TNSA target with dueterated plastic on the back: The strong proton signal, which represents most of the laser energy, is pronounced. It is due to contaminants from the vacuum.

(4) Considerable time and effort was directed to defeating the ubiquitous proton contamination problem. Figure 4 shows the target configuration that was

successful. The actual target was a silicon wafer processed to have ultra thin regions (<1µm). The back was covered with heavy water ice just before the laser shot. The entire structure was enclosed in a shroud cooled to LN2 temperatures. Figure 5 shows the results: the deuterium ion line is isolated, with all the laser energy transferred to the deuterium ions.

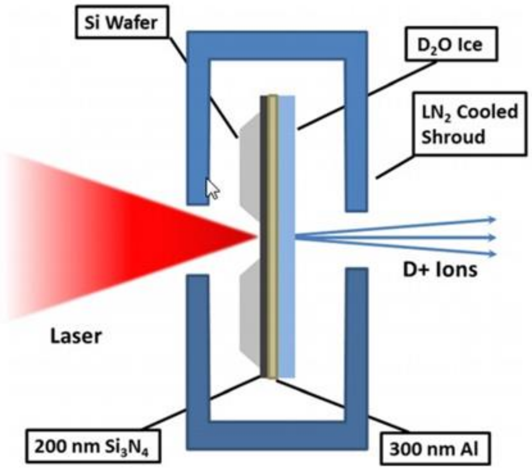


Figure 4 Target Schematic showing the heavy water ice on the back of the laser target

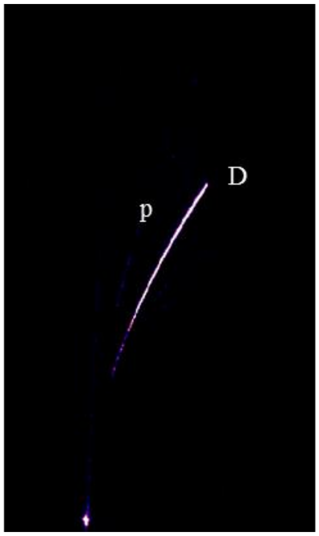
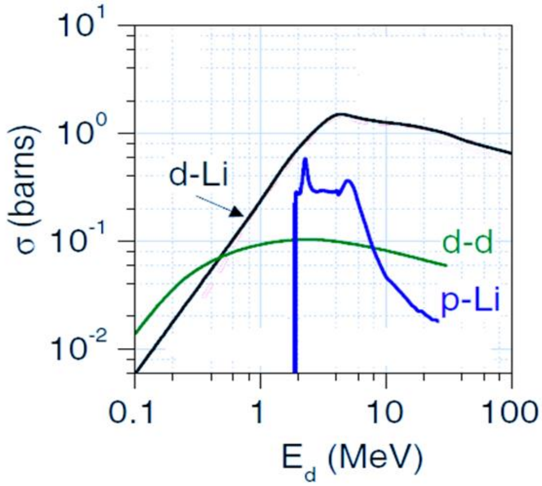


Figure 5 The Thomson Parabola ion spectrometer recording of the pure deuterium beam coming from the heavy water

(5) The resulting high energy deuterium beam is directed onto a subsequent Li target. The deuterium-Li interaction generates neutrons (Figure 6).



$$d + {}^{7}Li \rightarrow {}^{8}Be + n + 15MeV$$
$$d + {}^{7}Li \rightarrow {}^{7}Li + p + n + 15MeV$$

Figure 6 Cross-section for the generation of neutrons

(6) The experiment was carried out on the Ghost Laser and the University of Texas Petawatt Facility. Figure 7 is a schematic of the laser-target layout.

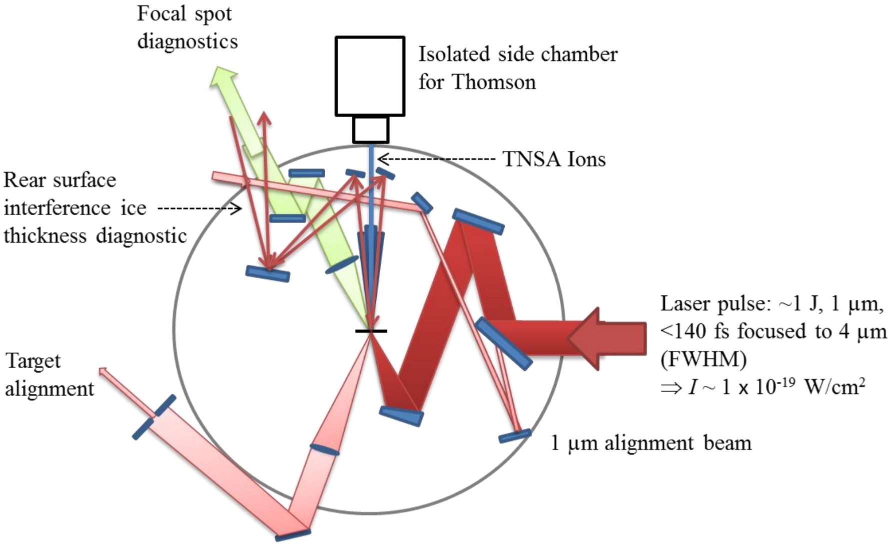


Figure 7Experimental Setup

(7) Neutrons were detected with Bubble Technology Industries (BTI) detectors. The high sensitivity detectors were capable of generating approximately 1bubble/80 neutrons of energy 1 MeV

Figure 8

Bubbles in detector from high energy neutrons

Conclusion:

This study has proven that a high intensity laser is capable of generating large numbers of high energy neutrons. Using our experimental data of the Ghost laser generating approximately 108 n/shot, that a state-of-the-art petawatt laser operating at 10 Hz, and a high rep-rated target, would be capable of generating over 1011 n/sec with energy greater than 1 MeV. These neutrons would have a duration of less than 1 psec, and be formed in a spot of approximately 10µm X 10µm X 10µm.

PAPERS

1. Design of and data reduction from compact Thomson parabola spectrometers

J. T. Morrison[1], C. Willis[1], R. R. Freeman[1] and L. Van Woerkom[1]

Rev. Sci. Instrum. **82**, 033506 (2011); http://dx.doi.org/10.1063/1.3556444

Thomson parabola spectrometers are used to characterize MeV ion beams produced in high intensity laser interactions. These spectrometers disperse multiple ion species according to their charge to mass ratio through the use of parallel electric and magnetic fields. Analytical solutions for ion deflection in electric and magnetic fields have been used to extract ion spectra with the assumption that fringing effects are negligible. Experimental space restrictions and dynamic range requirements necessitate designs that stress the analytical assumptions. Depending on design parameters, the error in the analytical assumption can be comparable to the energy resolution. Estimates are provided to approximate the error on the total ion deflection. A method for modeling ion trajectories including fringing effects is presented using software freely available or in common use. The magnetostatic fields are modeled in 3D, including material properties of nearby magnetic materials using RADIA. Electrostatic fields are modeled in 2D for a spectrometer implementing angled plates using the partial differential equation toolbox in MATLAB®. Using these models to calculate the ion trajectory allows for analysis of a Thomson parabola spectrometer with an arbitrary field configuration.

Acknowledgments:
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2. Front versus rear side light-ion acceleration from high-intensity laser–solid interactions

L Willingale[1], G M Petrov[2], A Maksimchuk[1], J Davis[2], R R Freeman[3], T Matsuoka[1], C D Murphy[3], V M Ovchinnikov[3], L Van Woerkom[3] and K Krushelnick[1]

2011 *Plasma Phys. Control. Fusion* 53 014011 doi:10.1088/0741-3335/53/1/014011

The source of ions accelerated from high-intensity laser interactions with thin foil targets is investigated by coating a deuterated plastic layer either on the front, rear or both surfaces of thin foil targets. The originating surface of the deuterons is therefore known and this method is used to assess the relative source contributions and maximum energies using a Thomson parabola spectrometer to obtain high-resolution light-ion spectra. Under these experimental conditions, laser intensity of (0.5–2.5) × 1019 W cm−2, pulse duration of 400 fs and target thickness of 6–13 µm, deuterons originating from the front surface can gain comparable maximum energies as those from the rear surface and spectra from either side can deviate from Maxwellian. Two-dimensional particle-in-cell simulations model the acceleration and show that any presence of a proton rich contamination layer over the surface is detrimental to the deuteron acceleration from the rear surface, whereas it is likely to be less influential on the front side acceleration mechanism.

Acknowledgments

This work was supported by the Defense Threat Reduction Agency (DTRA)

3. Selective deuteron production using target normal sheath acceleration

J. T. Morrison[1], M. Storm[1], E. Chowdhury[1], K. U. Akli[1], S. Feldman[2], C. Willis[1], R. L. Daskalova[1], T. Growden[1], P. Berger[1], T. Ditmire[2], L. Van Woerkom[1] and R. R. Freeman[1]

Phys. Plasmas **19**, 030707 (2012); http://dx.doi.org/10.1063/1.3695061

We report on the first successful demonstration of selective deuteron acceleration by the target normal sheath acceleration mechanism in which the normally overwhelming proton and carbon ion contaminant signals are suppressed by orders of magnitude relative to the deuteron signal. The deuterium ions originated from a layer of heavy ice that was deposited on to the rear surface of a 500 nm thick membrane of Si_3N_4 and Al. Our data show that the measured spectrum of ions produced by heavy ice targets is comprised of $\sim 99\%$ deuterium ions. With a laser pulse of approximately 0.5 J, 120 fs duration, and $\sim 5\times10^{18} W cm^{-2}$ mean intensity, the maximum recorded deuterium ion energy and yield normal to the target rear surface were 3.5 MeV and $1.2\times10^{12} sr^{-1}$, respectively.

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The authors thank Dr. Richard Stephens of General Atomics and Mr. Kent Ludwig of The Ohio State University for discussions on the deposition and metrology of heavy ice layers, and Mr. Jack Clifford of the University of Texas at Austin for his support in the fabrication of the cryogenic system. This work is sponsored under the auspices of United States Defense Threat Reduction Agency (DTRA) under award number HDTRA1–08-1–0018 and also is supported by the Department of Energy, National Nuclear Security Administration (NNSA) Grant Nos. DE-FC52–08NA28512 and DE-FG52–09NA29547, awarded to the Center for High Energy Density Science at The University of Texas at Austin.

4. Fast neutron production from lithium converters and laser driven protons

M. Storm[1], S. Jiang[1], D. Wertepny[1], C. Orban[1], J. Morrison[1], C. Willis[1], E. McCary[1], P. Belancourt[1], J. Snyder[1], E. Chowdhury[1], W. Bang[2], E. Gaul[2], G. Dyer[2], T. Ditmire[2], R. R. Freeman[1] and K. Akli[1]

Phys. Plasmas **20**, 053106 (2013); http://dx.doi.org/10.1063/1.4803648

Experiments to generate neutrons from the $^7Li(p,n)^7Be$ reaction with 60 J, 180 fs laser pulses have been performed at the Texas Petawatt Laser Facility at the University of Texas at Austin. The protons were accelerated from the rear surface of a thin target membrane using the target-normal-sheath-acceleration mechanism. The neutrons were generated in nuclear reactionscaused by the subsequent proton bombardment of a pure lithium foil of natural isotopic abundance. The neutron energy ranged up to 2.9 MeV. The total yield was estimated to be 1.6×10^7 neutrons per steradian. An extreme ultra-violet light camera, used to image the target rearsurface, correlated variations in the proton yield and peak energy to target rear surface ablation.Calculations using the hydrodynamics code *FLASH* indicated that the ablation resulted from a laser pre-pulse of prolonged intensity.
The ablation severely limited the proton acceleration andneutron yield.

Received 07 January 2013 **Accepted** 16 April 2013 **Published online** 22 May 2013

Acknowledgments:

This work was sponsored under the auspices of the United States Defense Threat Reduction Agency (DTRA) under Award No. HDTRA1-08-1-0018 and was also supported by the United States Department of Energy, National Nuclear Security Administration (NNSA) Grant Nos. DE-FC52-08NA28512 and DE-FG52-09NA29547, awarded to the Center for High Energy Density Science at the University of Texas at Austin.

THESIS

Morrison, John T.

Permalink: http://rave.ohiolink.edu/etdc/view?acc_num=osu1365523293

Year and Degree

2013, Doctor of Philosophy, Ohio State University, Physics.

Abstract

It has been known for more than a decade that surface contaminants from a thin foil will be accelerated to multi-MeV energies after irradiation with an ultra-intense laser. The versatility of an ion beam for the generation of neutrons can be improved by tailoring which ions are accelerated. Nominally, the dominant species accelerated is the lightest present on a target surface typically contaminated with hydrocarbons and water: protons. This work elucidates a method of in-situ cryogenic coating of heavy ice on ultra-intense laser targets and experimental confirmation of the dominant acceleration of ~MeV deuterons. 1D pseudo-Lagrangian calculations investigating the initial stages of ion acceleration with various levels of surface contamination are also presented.

The first successful demonstration of selective deuteron acceleration by target normal sheath acceleration (TNSA), in which the normally dominant contaminant proton and carbon ion signals are suppressed by orders of magnitude relative to the deuteron signals is reported. Using a laser pulse with 0.5 J, 120 fs duration, and ~5 x 10^{18}W/cm^2 mean intensity, the deuterons originating from a surface layer of heavy ice with energies up to 3.5 MeV comprised > 99% of the recorded ion signal.

The design, calibration, and implementation of a Thomson parabola spectrometer (TPS) to measure the target normal ion spectra is presented. In addition to estimations of the target coating and contamination rates, the effect of contamination thickness is modeled presented. Analytic calculations predicting characteristics of various neutron sources utilizing this deuteron source are presented.

...More

Committee

Linn Van Woerkom (Advisor)
Richard Freeman (Committee Member)
Richard Furnstahl (Committee Member)
Douglass Schumacher (Committee Member)

Subject Headings

Optics; Physics; Radiation

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8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, VA 22060-6201
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Center 8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, VA 22060-6201
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8725 John J. Kingman Road
Ft. Belvoir, VA 22060-6201
ATTN: Dave Petersen