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NUCLEAR FUSION EFFECTS INDUCED IN INTENSE LASER-GENERATED PLASMAS

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Abstract. Deutered polyethylene $(CD_2)_n$ thin and thick targets were irradiated in high vacuum by infrared laser pulses at 10^{15} W/cm^2 intensity. The high laser energy transferred to the polymer generates plasma, expanding in vacuum at supersonic velocity, accelerating hydrogen and carbon ions. Deuterium ions at kinetic energies above 4 MeV have been measured by using ion collectors and SiC detectors in time-of-flight configuration. At these energies the deuterium–deuterium collisions may induce over threshold fusion effects, in agreement with the high D−D cross-section values around 3 MeV energy.

At the first instants of the plasma generation, during which high temperature, density and ion acceleration occur, the D−D fusions occur as confirmed by the detection of mono-energetic protons and neutrons with a kinetic energy of 3.0 MeV and 2.5 MeV, respectively, produced by the nuclear reaction. The number of fusion events depends strongly on the experimental set-up, i.e. on the laser parameters (intensity, wavelength, focal spot dimension), target conditions (thickness, chemical composition, absorption coefficient, presence of secondary targets) and used geometry (incidence angle, laser spot, secondary target positions).

A number of D−D fusion events of the order of $10^{6\div 7}$ per laser shot has been measured.

Keywords: D−D fusion, plasma laser, D−D cross section, proton detection, neutron detection.

1. Introduction

The nuclear reactions between two nuclei of deuterons are generally accepted as playing crucial roles in recent observed nuclear processes and significant heat production in condensed matter. Independent measurements of the cross sections for these nuclear reactions have an important role and determine significant heat production from D−D nuclear reactions. By considering the possibility to achieve the D−D reaction through the injection into the plasma of deuterium ions, if results that the number of fusion events caused by the beam deuterons is too low to compensate for the energy expended on creating the plasma and the high energy ion beam, remains the possibility of increasing the efficiency of the D−D reaction. This can be done by using, directly or indirectly, the neutrons released in the D−D reaction [5].

As is well-known, in a deuterium plasma the D−D reaction can proceed along two paths having the same probability:

$$D^+D \rightarrow (T + 1.01\,\text{MeV}) + (p + 3.03\,\text{MeV}), \qquad (1)$$

$$D^+D \rightarrow ({}^3\text{He} + 0.82\,\text{MeV}) + (n + 2.45\,\text{MeV}). \qquad (2)$$

Intense pulsed lasers can be employed in the field of nuclear fusion in different ways, such as to increase the plasma temperature, to increase the electron density of the plasma, to ignite of fusion processes, or to accelerate ions inside the plasma. This is the reason why different lasers with different pulse durations, wavelengths, focalization methods and pulse energy can be utilized.

In our experiment a laser intensity of about 10^{15} W/cm^2 is used to irradiate in vacuum a deutered target producing a plasma from which deuterons are accelerated at energies above 3 MeV, as recently demonstrated [7]. These ions induce D−D nuclear fusion in the same target and in secondary targets, from which monochromatic protons and neutrons are generated.

2. Material and Methods

The iodine laser at Prague PALS laboratory was employed for the experiment; it provides 300 ps pulses at 1315 nm wavelength, 70 µm focused spot diameter and an energy of 500 J [3]. This laser has been used to irradiate thick and thin targets at normal incidence in high vacuum (10^{-6} mbar). Deutered polyethylene, $(CD_2)_n$, was used as thick (5 mm) and thin (5 µm) targets. The primary target irradiated by laser was a porous polymer acting as high absorbent laser radi-

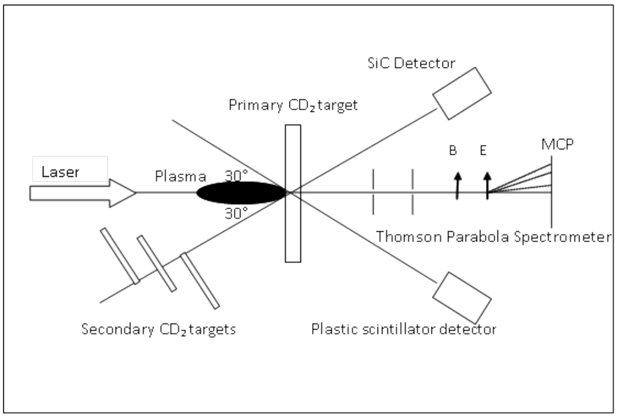

Figure 1. Sketch of the experimental set up.

ation; the secondary targets were three CD_2 polymers at high density and flat surface (each 1 cm radius). These secondary targets were placed at different distances and angles from the primary target, so as reported in the sketch of Fig. 1.

A SiC detector, a semiconductor with a 3.2 eV energetic gap, was fixed in forward direction, at 150° angle with respect to the incidence direction and at a distance of 102 cm, from primary target and at 115 cm, 127 cm and 141 cm from first, second and third secondary targets, respectively. It permits to detect ions with a low background signal due to its not-absorbent visible light emitted from plasma. Thus protons and deuterium ions emitted from primary and secondary targets, can be detected and their kinetic energy measured. SiC was employed in time-of-flight (TOF) configuration; its signal was acquired through a fast storage oscilloscope (20 GS/s) in order to measure the TOF of arriving ions and the corresponding kinetic energy of the produced protons, as in previous experiments [4].

A plastic scintillator NE102A has been used coupling it with a fast photomultiplier and a storage oscilloscope to detect MeV neutrons produced by the D−D neutron branch. The scintillator, having a density of $1.032\,\mathrm{g/cm^3}$, provides a fast response to gamma and neutrons, thanks to its 2.4 ns decay time and high detection efficiency (light output 65 % with respect to antracene medium). The scintillator was placed at a distance of 200 cm from the primary target and 216 cm, 238 cm and 242 cm from the first, second and third secondary targets, respectively. Its use was dedicated mainly to neutron energy measurements through TOF approach.

A Thomson parabola (TP) spectrometer is fixed along the normal direction to the target surface at about 2 m distance from the target. TP analyzes the plasma ion emission produced by thin targets ($\sim 1\,\mu$m in thickness) that is transimmetted by a narrow collimation constituted by two pinholes, the first 1 mm and the second 100 µm in diameter, respectively. A magnetic field of 0.2 T and an electric field of 3 kV are provided in order to produce the ions deflection.

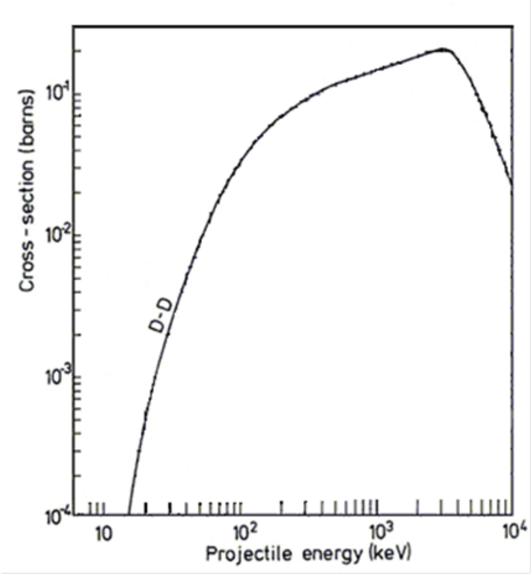

Figure 2. D−D cross section as a function of the deuterium energy.

The electric field is placed after the magnetic one it is realized using two parallel plates 8 cm long and 1 cm apart. The distance between the electric deflector plates and the shield containing the micro-channel plates (MCP) detector for the parabolas recording is 16.5 cm. A CCD camera, in remote control, captures, at high spatial resolution, the parabola images shown by MCP. OPERA-3D/TOSCA code [1] allows to simulate the ion trajectories starting from magnetostatic and electrostatic forces acting in the TP spectrometer so that simulation data can be compared with the experimental ones in order to have information about the charge/mass, charge states and ion kinetic energies.

3. Results

The D−D cross sections as a function of the deuterium energy, which permits to calculate the number of fusion events generating monocromatic protons and neutron branches carried out to calculate the number of monochromatic protons and neutrons, is reported in Fig. 2. The maximum cross section of 0.2 barns is obtained at 3.0 MeV incident deuterons.

The deuteron energy acquired in the laser-generated plasma has been measured by irradiating thick and thin CD_2i targets at normal incidence angle.

Figure 3 shows a typical example of SiC-TOF spectrum at 150° detection angle in forward direction obtained from a plasma generated by 5 µm deutered polyethylene target.

The SiC detector spectrum, placed at 102 cm distance from the target shows a narrow photopeak due to photons coming from plasma (start signal) and a narrow minor peak coming from electron Bremsstrahlung at about 10 ns.

Moreover, a structured and larger peak, due to the detection of fast and slower ions, extends

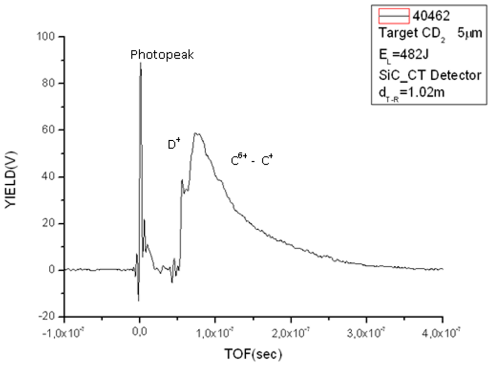

Figure 3. Typical example of SiC-TOF spectrum produced by the ions emitted from plasma generated in forward direction by 5 µm deutered polyethylene irradiated target; deuterium peak loceted at a TOF of 55 ns has an energy of 3.5 MeV.

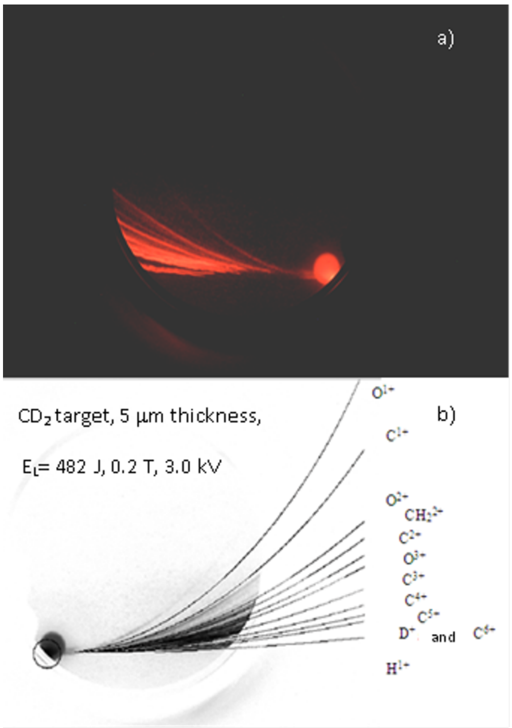

Figure 4. Typical TPS spectrum (a) and comparison with simulation data (b) reporting the parabolas for protons, deuterium carbon and contaminant oxygen ions; the maximum energy of 3.0 MeV and 3.5 MeV is evaluated for protons and deuterium respectively.

in times higher than 60 ns. The front peak, located at 55 ns, is due to fast deuterons detected at a kinetic energy of 3.5 MeV.

The deuteron energy measurement is confirmed also by TP analysis, for forward ion emission. A typical TP spectrum is reported in Fig. 4a together with the simulated plot (a) which permits the ion parabola recognition. It shows the parabolas relative to the detected ion species, charge states and kinetic energies coming from a laser irradiated thin deutered polyethylene foil.

The spectrum features protons, the six charge states of carbon ions, the deuterium parabola overlapped with C^{+6} parabola and the presence of oxygen contaminant ions. The maximum ion energy, measurable fron the distance between the center of the circle point (due to X-ray MCP detection) and the initial point of the parabola line, is 3.0 MeV and 3.5 MeV for protons and deuterium, respectively. The maximum energy for the carbon ions is of about 0.5 MeV per charge state.

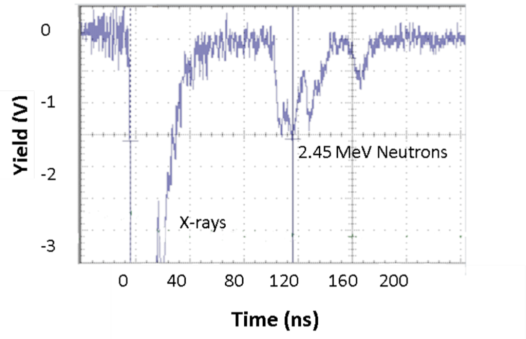

Figure 5. Typical TOF neutron spectrum obtained by the plastic scintillator reporting peaks at 2.5 MeV neutrons coming from the secondary targets.

The detection of protons and neutrons with the characteristic energy of 3.0 MeV and 2.45 MeV, respectively, was obtained by irradiating thick deutered polyethylene and by observing the SiC and the plastic scintillator spectra showing signals coming from the generation of protons and neutrons from the nuclear events. The scintillator spectrum relative to the neutrons detection is reported in Fig. 5. It shows a fast and very high photopeak, due to electron Bremsstrahlung in the primary target, followed by three lower peaks at different TOF times all corresponding to the 2.45 MeV neutrons emitted from the three secondary targets.

The fusion reaction yield, in terms of the number of fusion per incident D^+ ion produced along the ion track in the target, as a function of depth is given by

$$Y(x)\,\mathrm{d}x = \Phi_x N_\mathrm{D}\,\sigma(E(x))\,\mathrm{d}x\,, \tag{3}$$

where $Y(x)$ is the probability that a fusion will occur per unit length, Φ_x is the ion current, N_D is the density of deuterium atoms in the target, $\sigma(E(x))$ is the D$-$D fusion cross section as a function of the deuteron energy and $\mathrm{d}x$ is the distance along the deuteron track. The deuterium ions accelerated by the plasma penetrate in the CD_2 secondary target matter up to the range depth of the energetic particles. This can be calculated through SRIM code [8] that gives the energy loss per unit length in the target material $\mathrm{d}E(x)/\mathrm{d}x$ as a function of the depth. These data can be used to calculate the D^+ ion energy as a function of the depth travelled in the target as

$$E(x) = E_0 - \int_0^R \frac{\mathrm{d}E}{\mathrm{d}x}\,\mathrm{d}x \tag{4}$$

where E_0 is the initial accelerating energy assumed to be 3.5 MeV.

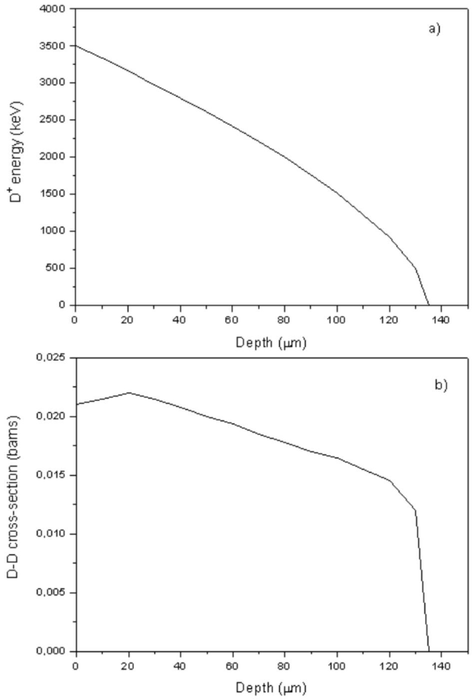

FIGURE 6. Plot of the deuterium energy (a) and of the D−D cross section (b) versus the polyethylene depth for 3.5 MeV D^+ ions impacting a CD_2 substrate.

Figure 6a reports the graph of deuterium energy versus the polyethylene depth for 3.5 MeV D^+ ions impacting a CD_2 substrate. The range is about 135 μm.

The total D−D cross section as a function of the depth can be calculated integrating the values over the deuterium ion range in the deutered polyethylene target through the equation

$$\sigma_{\mathrm{T}} = \int_0^R \sigma(E(x)\,\mathrm{d}x. \tag{5}$$

Equation 5 can be plotted as a function of the polyethylene depth, as represented in Fig. 6b, demonstrating that the cross section maintains its maximum value within the first 120 μm of surface layers.

The density of deuterium atoms can be calculated from the equation

$$N_D = 2\rho N_{\mathrm{A}}/M\,, \tag{6}$$

where ρ is the polyethylene density, N_{A} the Avogadro's number and M the CD_2 mass. The factor 2 is due to the presence of two deuterium atoms per carbon.

The total number of fusion processes can be calculated as

$$N_{\mathrm{F}} = \int_0^R Y(x)dx = \varPhi_x N_D \sigma_{\mathrm{T}}. \tag{7}$$

Thus, in order to evaluate N_{F}, three parameters must be known. The first parameter is the deuterium ion current, $\varPhi_x$, produced by the plasma developed from the primary target. IC measurements of ion currents from polyethylene laser irradiation have indicated that a total current of the order of 10 mA can be produced at time of the order of 10 μs. Assuming the mean charge state to be 2+ (carbon is present with charge states from 1+ up to 6+ but the lower charge states are more intense with respect to the higher ones) and that the deuterium ions represent only the 30 % of the total ions in the plasma, a current of about $\varPhi_x \simeq 10^{11}$ D^+ ions per laser shot can be estimated.

The evaluation of the second parameter concerns the target density: assuming the CD_2 polymer to have a density of $0.98\,\mathrm{g\,cm^{-3}}$, the atomic density is $N_{\mathrm{D}} = 7.4 \times 10^{22}\,\mathrm{cm^{-3}}$. Thus the deuterium atoms, for 120 μm deuterium range, correspond to $8.9 \times 10^{20}\,\mathrm{cm^{-2}}$. The surface of the three secondary targets irradiated by the primary deuterons is about $9.4\,\mathrm{cm^2}$, thus a total irradiation of about 8.4×10^{21} atoms is possible.

The third parameter is the D−D cross section which is about constant to $\sigma_{\mathrm{T}} = 0.018 \times 10^{-24}\,\mathrm{cm^2}$ in the first 120 μm depth, where the kinetic energy ranges between 3.5 MeV and about 1 MeV. These approximations permit to evaluate a total number of fusion processes N_{F} of about 1.5×10^7 per laser shot. A value comparable to other similar experiments performed with a laser-generated plasma [6, 2].

4. CONCLUSIONS

The measurements have determined, with an accuracy of the order of 15 %, the detection of 3.0 MeV protons and 2.5 MeV neutrons coming from the secondary targets irradiated by MeV deuterons accelerated by laser-generated plasma.

Proton detection occurs togheter fast deuterium ions, while neutron spectra show the coexistence of gamma-rays, as a consequence of the electron Bremsstrahlung. The preliminary evaluation of the number of fusion events per laser shot is of the order of 10^7. Further nuclear fusion events may occur in the primary target due to D−D collisions generated in plasma and increase the yield of monoenergetic protons and neutrons. Therefore the fusion event produces an energy emission of 3.27 MeV for the neutron production channel and of 4.03 MeV per the proton emission channel, the total number of events occurring in the three secondary targets corresponds to a nuclear energy generation of the order of 10 μJ per laser shot. Thus the laser energy conversion in nuclear event is low, considering that the used laser pulse is of about 500 J, and further investigations should be performed in order to increase this conversion factor.

The presented results highlight the importance of the laser induction of nuclear fusion events to develop nuclear energy without generation of dangerous radioactive species.

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