Laser-ion acceleration through controlled surface contamination

Bixue Hou, John A. Nees, Zhaohan He, George Petrov, Jack Davis et al.

Citation: Phys. Plasmas 18, 040702 (2011); doi: 10.1063/1.3574532
View online: http://dx.doi.org/10.1063/1.3574532
View Table of Contents: http://pop.aip.org/resource/1/PHPAEN/v18/i4
Published by the AIP Publishing LLC.

Additional information on Phys. Plasmas
Journal Homepage: http://pop.aip.org/
Journal Information: http://pop.aip.org/about/about_the_journal
Top downloads: http://pop.aip.org/features/most_downloaded
Information for Authors: http://pop.aip.org/authors

ADVERTISEMENT

Special Topic Section:
PHYSICS OF CANCER
Why cancer? Why physics?  View Articles Now
The use of short pulsed lasers to accelerate ions/protons is an active research field,\textsuperscript{1,2} one that may have many applications—such as the production of energetic neutrons.\textsuperscript{3–7} Neutron sources have numerous applications in the fields of radiography, tomography, materials analysis, and nuclear detection and can be produced through fusion reactions between light nuclei. Focused ultraintense lasers have been used to generate megaelectron volt deuterons capable of producing neutrons via D–D fusion: 

\[ D + D \rightarrow ^3\text{He}(0.8 \text{ MeV}) + n(2.45 \text{ MeV}). \]

Laser-driven neutron sources also exhibit small source size, which could improve the physics observed in previous attempts to accelerate laser-based sources are smaller and more cost-effective.

The motivation behind the present experiments is based on the physics observed in previous attempts to accelerate ions from solid targets. In those experiments,\textsuperscript{8} the ion signal produced from the interaction of intense laser pulses with the solid target was dominated by protons. This phenomenon is attributed to the presence of protons in the water and hydrocarbon residue\textsuperscript{9} on the target surface. A recent theoretical and experimental study provides new details on the specific role played by the contaminants.\textsuperscript{10} Under our experimental conditions (\(10^4 < 10^8\) J/cm\(^2\)), the contaminants completely dominate the energy absorption and ion acceleration. The most likely explanation for this phenomenon is that the ions residing on the target surface are “peeled off” one layer at a time, the outermost layer being accelerated first and the inner ones shielded from the space-charge field. This peculiarity of ion acceleration favors the contaminants, as they form the outer layer of atoms on the target surface. Among the contaminants, the protons, with the highest charge-to-mass-ratio, are more readily accelerated by the laser-induced fields than the heavier ions. As a result, the acceleration of all other ions is suppressed. The use of laser prepulse,\textsuperscript{11} target heating,\textsuperscript{12} or ion guns\textsuperscript{13} has enabled the removal of contaminant layers, but such techniques are often difficult to implement. Therefore, substitution of the contaminants with a desired species is a preferable means of obtaining energetic deuterons. In our research, this is tested by introduction of heavy water (\(D_2O\)) into the chamber to generate a new layer of \(D_2O\) before irradiation.

In this letter, we report on this very simple method of controlling laser-accelerated species from solid targets. We demonstrate acceleration of deuterons up to 75 keV from the surface of borosilicate glass (BK7) by placing a small quantity (1 ml) of heavy water inside the experimental chamber prior to pumping to generate a deuterated contamination layer on the target. Using the same technique with a deuterated-polystyrene-coated target also enhances deuteron yield by a factor of 3 to 5, while increasing the maximum energy of the generated deuterons to 140 keV. © 2011 American Institute of Physics. [doi:10.1063/1.3574532]
considered to be below the damage threshold of the glass. Using the same system configuration, 500 keV protons were previously produced along the target normal direction.

Ion spectra are measured with a Thomson parabola spectrometer along the target normal, which is equipped with a 50 μm metallic pinhole located 3.8 cm from the plasma. A 5 cm-long magnet pair following the pinhole provides a 1560 G magnetic field. The magnet pair is followed by a 2 cm-long electrode pair with a separation of 1 cm that provides an electric field of (3 ± 0.1) kV/cm to separate ion species. The parabolic traces of the ions are recorded on a CR39 plate located 8 cm from the exit of the electric field. The whole spectrometer is contained in a small secondary vacuum chamber, which is installed in the main target chamber. The larger chamber (40 l) is evacuated by a 250 l/min turbomolecular pump, while the spectrometer chamber is differentially pumped by a 70 l/min pump to avoid high-voltage breakdown initiated by ions generated in the high-repetition-rate laser target interaction.

We first generate energetic deuterons from a BK7 glass target, which is installed near the laser focus. The target position (z) is then optimized under vacuum by maximizing the second-harmonic light emitted from the plasma at low laser fluence. Opening the chamber, 1 ml of D₂O is placed on the floor of the chamber about 2 cm from the target surface. The D₂O is allowed to boil away under a pressure of 15 mbar during rough pumping, after which the turbo pumps are started. Fifteen minutes of further pumping leads to a pressure of 3 × 10⁻⁴ mbar in the main chamber. At this level, the CR39 plate in the spectrometer is exposed to the ions generated from ten shots without high voltage to record a reference signal and 100 shots with high voltage to disperse the ion species.

Figure 1(a) shows the scanned image of the developed CR39 plate. As with all images presented in this letter, these data are presented using a color lookup table applied to scanned gray values from 0 to 170. Many traces are apparent, all of which are identified from an analysis of the particle trajectories. In addition to native and contaminant ion species (H, B, C, and O ions), we clearly see a deuteron trace. Within the precision of our measurements, the traces of ¹⁰B⁺, ¹²C⁺, and ¹⁶O⁺ should overlap the deuteron trace. In order to rule out the contribution of these ions, the same experiment is repeated with a new BK7 target without dropping D₂O in the chamber (though with 83 shots). The scan from this experiment, shown in Fig. 1(b), exhibits very weak traces of ¹⁰B⁺ and ¹⁶O⁺ (not discernible in the scanned image) and no trace can be seen for the lower charge state of carbon, ¹²C⁺. Analysis of the data from the two runs shows that less than 5% contribution in the D⁺ trace can be attributed to ¹⁰B⁺ and ¹⁰O⁺. In Fig. 1(a), the signals of ¹¹B⁺ and ¹⁶O⁺ are weak, confirming the stated weakness in the production of ¹⁰B⁺ and ¹⁰O⁺ (particularly as ¹⁰B is the less abundant isotope by a ratio of 1:4). The spectrum extracted from this trace is shown in blue circle in Fig. 2. This shows that deuteron ions can be accelerated without the use of a deuterated target material, producing a considerable yield up to 75 keV.

The proton trace in Fig. 1(a) is found to be much weaker than that in Fig. 1(b), while the heavier ion traces are much more prominent. The proton trace in Fig. 1(a) is found to be much weaker than that in Fig. 1(b). The mass distribution of the ions is consistent with the expected distribution of the target material. The heavier ion traces are much more prominent than the proton traces, indicating a higher yield of heavier ions.

The spectrum extracted from this trace is shown in blue circle in Fig. 2. This shows that deuteron ions can be accelerated without the use of a deuterated target material, producing a considerable yield up to 75 keV.

![Image](https://via.placeholder.com/150)
stronger. The first observation indicates that the introduction of $D_2O$ reduces the acceleration of hydrogenic contaminants from the interaction. The second effect is a consequence of the reduction of the higher charge-to-mass-ratio species. It is also found that cleaning the glass target with $D_2O$ prior to installing it in the experimental chamber with the $D_2O$ evaporant provides only slight enhancement to the deuteron yield. The particular location of the $D_2O$ source on the target chamber floor has nearly no effect on the deuteron acceleration.

A second experiment confirms the enhancement of deuteron acceleration from a 2 $\mu$m-thick $CD$ film on BK7, modified by evaporating $D_2O$ in the chamber. Scanned images of the developed CR39 plates are shown in Fig. 3. Figure 3(a) shows the traces of ions accelerated from a coated glass disc in the absence of $D_2O$, while Fig. 3(b) shows those generated from the same target with $D_2O$ evaporated into the chamber. The indicated deuteron signal in Fig. 3(b) is greatly enhanced. The spectra for these two cases are shown in Fig. 2 (red triangles—without $D_2O$ and black squares—with $D_2O$), where the deuteron yield is seen to increase by three to five times. In these plates, ion counts in the high-energy portions of the $D^+$ spectra are subject to some uncertainty due to signal from scattered high-atomic-number ions. However, comparing the two spectra for $CD$-coated targets in Fig. 2, the evaporation of $D_2O$ in the chamber clearly enhances the maximum deuteron energy from 90 keV (red triangles) to 140 keV (black squares). Again we see that the introduction of $D_2O$ reduces proton flux while enhancing heavier ion acceleration, including that of deuterons.

There is another interesting contrast between ion spectra taken with (black squares) and without (blue circles) a $CD$ film, when $D_2O$ is added to the chamber. The introduction of the film is seen to increase energy at the expense of flux. This may be due to the efficacy of substituting the $D_2O$ contaminant on the surface of the different materials, as $CD$ is likely to have a contaminant layer with different characteristics from one on BK7.

To estimate the maximum deuteron energy, we adopted the blow-off model for the expanding plasma sheath in vacuum.\textsuperscript{16,17} The ion velocity is comparable to that of an ion’s sound speed $C_h = \sqrt{T_h/M}$, with $C_h \approx 511 (\sqrt{1 + 0.73T_{kT}} - 1)$ being the hot electron temperature in units of kilo electron volts, $I_{18}$ is the laser intensity in units of $10^{18}$ W/cm$^2$, and $M$ is the ion mass. In order to acquire full speed, the ion must traverse the plasma sheath—a length comparable to the Debye length $\lambda_D = \sqrt{T_h/(4\pi n_{cr}e^2)}$ of the hot expanding electrons at the critical density $n_{cr} \approx 1.3 \times 10^{21}$ cm$^{-3}$. If, however, the laser pulse duration $\tau_l$ is shorter than the time, $\tau_{SW} \approx 2\lambda_D/C_h$, that it takes an ion to traverse the plasma sheath, the ion energy must be scaled approximately by the ratio $\tau_l/\tau_{SW}$. A crude estimate of the maximum deuteron energy, $E_{D}^{\text{max}} \approx (1/2)MC_h^2(\tau_l/\tau_{SW})$, for $T_h = 500$ keV (corresponding to $I = 4 \times 10^{18}$ W/cm$^2$), $C_h \approx 5 \times 10^{8}$ cm/s, $\lambda_D \approx 0.2$ $\mu$m, and $\tau_l \approx 30$ fs, yields $E_{D}^{\text{max}} \approx 100$ keV, agreeing well with the experimental data.

The deuteron flux $F_D = N_{Df}/\delta\Omega$ is estimated from the total number of accelerated deuterons per shot, $N_D \approx (1/4)\pi D_{FWHM}^2 l_D p_D$ emitted into a solid angle of $\delta\Omega$ and multiplied by laser repetition frequency $f$. One expects the plasma sheath to deplete a “contaminant” layer of $D_2O$ with thickness of $\sim 2$ nm.\textsuperscript{10} We assume also that the deuterons are emitted in a solid angle of $\sim 1$ sr (observed in simulations). With conditions relevant to our experiments ($f = 500$ Hz, $D_{FWHM} = 1.5 \mu$m, $L_D = 2$ mm, and $p_D = 6 \times 10^{-2}$cm$^{-3}$), we get $N_D \approx 2 \times 10^8$ deuterons/shot and deuteron flux on the order of $F_D \approx 1 \times 10^{11}$ deuterons/sr/fs. This number is consistent with the experimental results in the case of BK7$ + CD + D_2O$, plotted in Fig. 2, for which the integrated data yields $F_D^{exp} \approx 2 \times 10^{11}$ deuterons/sr/fs.

We performed 2D particle in cell (PIC) simulations with conditions matching those of the experiments (Fig. 2). The BK7$ + CD + D_2O$ target was modeled as 1 $\mu$m Si$ + 2$ $\mu$m $CD + 2$ $\mu$m $D_2O$. The width of the targets is 10 $\mu$m and the incident angle of the laser with respect to the targets is $\theta = 51^\circ$. The laser radiation is linearly polarized and propagates in the $+x$ direction. Laser intensity profile $I(x,y) = I_0 \sin^2(\pi x/\tau_0)$ exp$(-y^2/R_0^2)$ with parameters $I = 4 \times 10^{18}$ W/cm$^2$, $R_0 = 0.9$ $\mu$m, and $\tau_0 = 2\tau_l = 60$ fs is used. The laser pulse energy $E_{\text{pulse}} = \pi R_0^2 I_0 \tau_l \approx 3$ mJ corresponds to that used in the experiments. The simulation box is a square with dimensions $12 \times 12$ $\mu$m$^2$, large enough to keep the particles inside during a simulation run, and the cell size is $10 \times 10$ nm$^2$. Particles and fields are advanced with a time step $\Delta t \approx 0.02$ fs and the total simulation time is 120 fs. The number of computational particles...
The electron density in the bulk of the target is \(1 \text{ eV}\). The charges of carbon and oxygen are assumed to be four. Particles, including ions, are mobile. They are initialized with ratios between electrons and ions have been introduced. All particles can leave the computational domain without reflection. The boundary conditions for particles are “open,” i.e., the particles can leave the computational domain without reflection. The calculated ion spectrum (dashed line) is in excellent agreement with experimental data and is nearly independent of Si layer thickness. The \(BK7 + CD\) target was simulated as \(1 \mu m \text{ Si} + 2 \mu m \text{ CD} + 2 \text{ nm H}_2\text{O}\), the latter being a thin (2 nm) contaminant layer of water vapor on top of the \(CD\) layer. The deuteron flux is about an order of magnitude lower compared to the previous case in which \(D_2O\) plays the role of contaminant. The simulations show that the protons of the \(H_2O\) layer strongly suppress the deuterons, both in flux and maximum energy, qualitatively in agreement with the experiments. Thus, these simulations confirm the hypothesis regarding the benefits of artificial contamination of deuterated polystyrene with \(D_2O\).

The scaling of the maximum deuteron energy and conversion efficiency with laser intensity can be evaluated qualitatively by following the general dependence on the hot electron temperature as well as maximum deuteron energy and conversion efficiency tend to increase linearly with laser intensity. Scaling up to higher laser intensity, in the relativistic regime, they transit to a sublinear increase, as evident from the formula for \(T_h\). The asymptotic scaling in the “high-intensity” (relativistic) regime is \(\sim (h_0 \lambda_0^2)^{1/2}\), which is roughly what is observed in the experiments and the simulations using ultrashort laser pulses.16

In conclusion, up to 75 keV deuterons are generated from \(BK7\) glass simply by placing heavy water inside the experimental chamber to introduce deuterium to the target surface. This procedure is also found to enhance the deuteron yield by three to five times from a \(2 \mu m\)-thick \(CD\) film on \(BK7\), the maximum energy of the generated deuterons also being increased. It is likely that this will provide a useful method for controlling accelerated species by evaporating liquids containing desirable elements in interaction chambers. It is possible that vapor can be introduced from a secondary chamber to enable selective contamination as well.

This work was supported by the Defense Threat Reduction Agency (DTRA), the Naval Research Laboratory (NRL), and a National Science Foundation Physics Frontier Center (FOCUS).