Production and Extraction of Protons by Solid Hydrogenated Targets via UV Laser Ablation

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Abstract

In this work we present the preliminary investigations about the production of proton beams by pulsed laser ablation of solid disks produced by compressed Titanium dihydride powder. The laser we used was an excimer KrF, operating at low intensity and ns pulse duration. The ion emission was analyzed by the time-of-flight technique using a Faraday cup as ion collector. We performed studies on the produced plasma for different laser fluence values and accelerating voltage. In free expansion mode we obtained protons and titanium ions having kinetic energy of some hundred of eV; by applying a post-accelerating voltage we obtained beams up to 15 keV.

Introduction

In the last years, new techniques to produce proton beams make use of the interaction between high power femtosecond laser pulses and thin metallic foils[1]. In contrast with other techniques, these give the advantage of obtaining highly collimated and energetic protons beams from the rear of the target surface, but require laser systems that, at the time of writing, aren't easy to setup. Depending on the laser parameters, two mechanisms seems to be responsible of this behavior: target normal sheath acceleration (TNSA)[2] and radiation pressure acceleration (RPA)[3]. Despite of the high quality beams obtained through TNSA and RPA systems, older and well known techniques, such as pulsed laser ablation (PLA), still play a fundamental role for applications, since the former have extremely high total costs of ownership.

It is widely known that the use of the PLA technique allows to easily obtain ions from solid targets, whose energy can be easily increased by applying post acceleration[4, 5]. Today it is possible to easily arrange laser beams at intensities of the order of $10^8 - 10^{10}$ W cm^{-2} and ns pulse duration that, interacting with solid matter in vacuum, produces hot plasmas[6] at high temperature and densities, of the order of tens of eV and 10^{17} electrons per cm^3[7] respectively. Thermal interactions, adiabatic expansion in vacuum and Coulomb interactions are responsible for the primary ions acceleration in plasma. By applying an extraction potential, it is possible to extract specific charged particles. This idea can be applied to plasmas of moderate density owing to their low electric conductivity. The percentage of ionized material obtained in laser ion sources (LIS) is not very high, with respect to the total ablated material, but sufficient to get ion beams of high intensity.

Nowadays, ion beams of moderate energy have a wide range of applications, from scientific to industrial ones. In this work, we present the preliminary results of a LIS performed for ions acceleration. The resulting protons beams could be utilized in various fields, for example as injector source for hadrontherapy applications [8].

Bearing in mind these considerations, we developed a simple but powerful ion source. In our homemade device we used an excimer laser to get PLA from compressed disks of TiH2 powder and a vacuum chamber in which we generated plasma and studied the inherent processes. By using a suitable Faraday cup, mounted in front of target, we characterized the collected beams.

Materials and methods

We used a Compex 205 KrF excimer laser operating at $\lambda = 248$ nm, $\tau = 23$ ns and maximum intensity of 600 mJ. Using a 15 cm focal distance lens, the laser beam has been focused on the target in a circular spot with average area of 0.05 mm^2 , obtaining a power irradiance of the order of 10^8 W cm^{-2}.

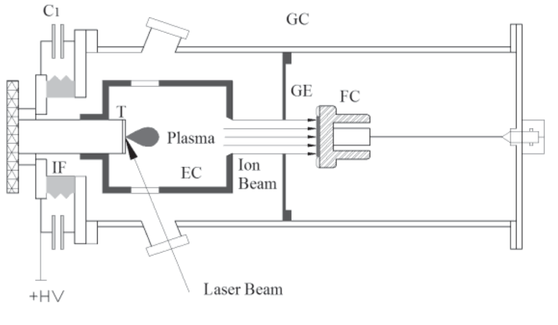


Figure 1: Sketch of the experimental setup

The vacuum compartment (10−6 mbar) consists of a plasma generation and acceleration chamber (GC) and a removable expansion chamber (EC), which allows an initial free expansion of the plasma before the ion extraction gap, as shown in Fig. 1. The target support (T) was mounted on the GC by an insulating flange (IF) and kept at an high positive volt- age, up to +15 kV in DC mode. Four 1 nF capacitors were connected between the T and the GC to stabilize the accelerating voltage during the fast ions extraction phase. The EC is an almost hermetic cylinder of a length (21 cm) sufficient to let the plasma expand freely and decrease its density. The EC was indispensable to avoid arcs versus ground. Moreover, the EC has an extremity (the one opposite to the target holder) drilled with a 1.5 cm diameter hole, necessary for the ions extraction from the plasma plume.

A grounded electrode (GE), placed in front of the EC at a distance of 3 cm, allows to generate an intense electric field. At the right end of the apparatus, there is a Faraday cup (FC, with a diameter of 7.7 cm) in order to collect and record the ion beams signals by a LeCroy WaveSurfer 422 200 MHz digital oscilloscope, connected to the FC through a 50 Ω characteristic impedance cable. The total fly length available for ions, from the target surface to the FC, is of 28.0 cm (21 cm of free expansion inside EC + 3 cm of acceleration between EC and GE + 4 cm between GE and FC).

The targets used in this work were solid disks obtained by compression of TiH_2 powder. The compression was made at a pressure of 10^4 kg cm^{-2} for 30 minutes. The choice of this particular type of target is justified from the fact that generally hydrogenated materials are good sources of protons and heavy ions [9, 10]; moreover, these powders are relatively cheap and widely available on the international market. Additionally, they could also have a high level of purity, that in our case is reported to be of 99 %.

Results

We irradiated the target with different laser fluence values (respectively 2, 4, 8 and 16 J cm^{-2}) and for different accelerating voltages, ranging from 0 V (free expansion) up to +15 kV in steps of 5 kV. The ion time of flight (TOF) signals collected by the FC and processed by the oscilloscope were analyzed by our team.

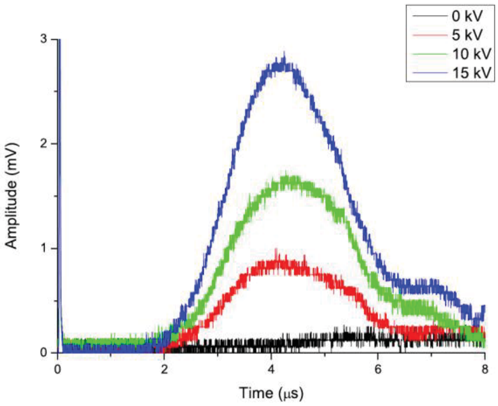


Figure 2: Detail of protons TOF signals at the fluence of 2 J/cm^2 , for different extraction voltages

In the free expansion case, the ions of the plasma plume were accelerated by different processes and the most important are: thermal interactions, photoionization, inverse bremsstrahlung and Coulomb interactions between plasma components. We obtained well defined and separate peaks for protons (Fig. 2) and Ti plasma (a convolution of Ti^{n+} ,H$^+$ and TiH^{n+}, shown in Fig. 3). Applying high positive voltages to the target holder T, these peaks increase in amplitude, denoting a better charge extraction. Protons are faster than any other plasma component since they have a smaller mass.

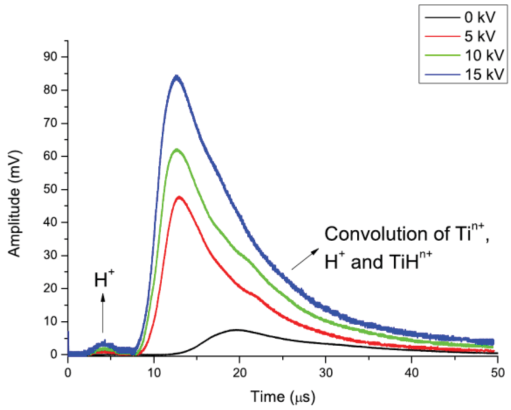
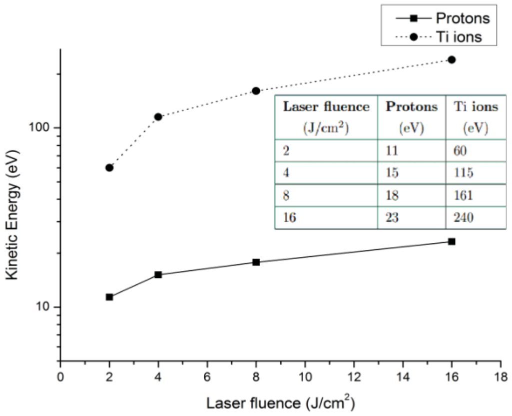


Figure 3: TOF signals at the fluence of 2 J/cm^2, for different extraction voltages

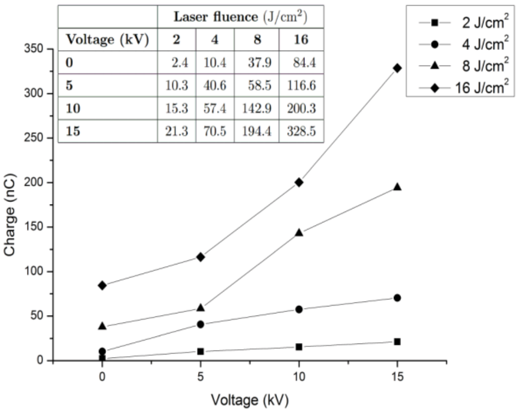
By TOF analysis, we were able to compute the average kinetic energy both for protons and Ti ions in free expansion. The results are presented in Fig. 4, where the curves are shown in logarithmic scale.



Laser fluence (J/cm^2)	Protons (eV)	Ti ions (eV)
2	11	60
4	15	115
8	18	161
16	23	240

Figure 4: Average protons and titanium ions kinetic energy (in logarithmic scale) as a function of the laser fluence

For what concerns the extracted charge, Fig. 5, we obtained values between 2 and 330 nC per laser shot, depending on the laser fluence and on the applied extracting voltage. Sensibly lower are the results for the charge of protons, Fig. 6. In Table 1 it is shown the number of extracted protons per pulse, depending on the laser fluence and on the extraction voltage.

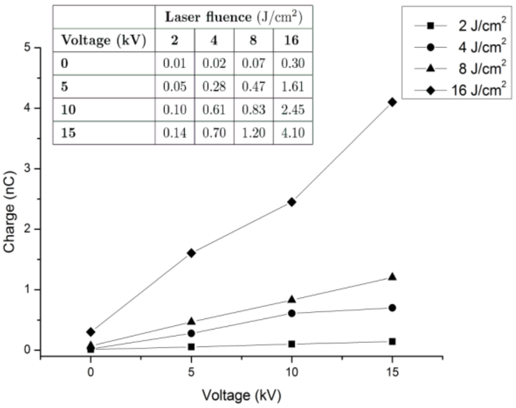


	Laser fluence (J/cm^2)			
Voltage (kV)	**2**	**4**	**8**	**16**
0	2.4	10.4	37.9	84.4
5	10.3	40.6	58.5	116.6
10	15.3	57.4	142.9	200.3
15	21.3	70.5	194.4	328.5

Figure 5: Total extracted charge as a function of the accelerating voltage for different values of the laser fluence

	Laser fluence (J/cm^2)			
kV	*2*	*4*	*8*	*16*
0	8.4E+07	1.5E+08	4.5E+08	1.9E+09
5	3.4E+08	1.7E+09	2.9E+09	1.0E+10
10	6.4E+08	3.8E+09	5.2E+09	1.5E+10
15	9.0E+08	4.4E+09	7.5E+09	2.6E+10

Table 1: Number of extracted protons per pulse, depending on the laser fluence and on the extraction voltage



	Laser fluence (J/cm^2)			
Voltage (kV)	**2**	**4**	**8**	**16**
0	0.01	0.02	0.07	0.30
5	0.05	0.28	0.47	1.61
10	0.10	0.61	0.83	2.45
15	0.14	0.70	1.20	4.10

Figure 6: Protons extracted charge as a function of the accelerating voltage for different values of the laser fluence

Looking at Fig. 3, for each value of extraction voltage it is possible to observe the occurrence of plasma peaks. All these slower peaks are the result of the convolution of different charge states of Ti ions present in the plasma plume (in our case, the principal charge state are 1+ [11, 12]) and we suppose also the presence of other components. In fact we expected that the extracted charge for protons and Ti ions should be sharply different from what it was obtained, according to the stoichiometry of the TiH_2 compound. For example, in free expansion at a laser fluence of 2 J cm^{-2} , the total charge obtained for pro- tons was 0.01 nC, while for Ti plasma was 2.32 nC. This behavior is confirmed also under the effect of accelerating voltages, so we suppose that, after the laser interaction with the target surface, clusters [13], protons and T i^{n+} ions are induced in the generated plasma. In our case, these clusters could be TiH^{n+} and, due to the limitations of our diagnostic system, we couldn't appreciate any difference with respect Ti^{n+} ions.

Conclusions

From this preliminary work, it is clear that TiH_2 solid disks are a promising proton source via excimer laser ablation. Accordingly, the use of these targets is very interesting not only using infrared PLA, as already shown in literature [9, 10], but also with the UV one. The study of the TOF signals collected by FC shows that it is possible to increase the proton extraction both increasing the laser fluence and the extraction voltage; but it reveals also a strange behavior for what concerns the extracted charge, if considered with respect to the target stoichiometry. We found a reasonable hypothesis to explain this, but the diagnostics used was not suitable for a proof of its correctness. Nevertheless, we obtained proton bunches with fluxes up to 10^{10}/pulse which represent a good result [9]. Further work will deserve more attention to the questions still open and the use of mass spectrometry could shed light on them.

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