Proton emission by TiH_2 laser ablation at different wavelengths

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Abstract

Ns-pulsed lasers operating in the electromagnetic regions from infrared to visible and to ultraviolet, with single pulse or repetition rate mode, were employed to produce non-equilibrium plasmas by ablating titanium hydrate targets.
The ion emission from the plasma was monitored through time-of-flight (TOF) measurements of emitted species, performed by using an ion collector (IC) placed along the normal to the target surface and a mass quadrupole spectrometer (MQS). Measurements demonstrated that for laser intensity ranging from 10^8 to 10^{11} W/cm^2 the ion kinetic energy and the ion yield are proportional to the pulse intensity and to the laser wavelength square.
Obtained results at three different wavelengths are compared and discussed.

Introduction

Laser ion source (LIS) is an interesting method to generate ions at high energy, high current and high charge states, on the basis of the laser generated plasma properties [1]. The high ion beam emission directionality along the target normal, high current density, high average charge state and ionization fraction are promising for a possible use as LIS. A special interest is devoted to the possible use of proton beams in nuclear physics, astrophysics, bio- medicine.
At low laser intensity the accelerated proton beams have maximum energies of about 100 eV but they can be post-accelerated by external electrical fields up to energies of the order of 100 keV and a total number of about 10^{10} protons/pulse [2].
At high laser intensities, a proton flux of about 10^9 protons/pulse can be accelerated at energies above 1MeV or more, without any post-acceleration [3]. To maximize the proton beam current, the choice of the best H-enriched material is challenging. Polymers, polymer foils (C_xH_y bonds) coupled to metal targets and metallic hydrides could be used to take advantage of the high hydrogen concentration.
In this work we focused on the ablation of a TiH_2 target, chosen for its stoichiometry and for the high electron density, that leads to a hot non-equilibrium plasma and consequently to energetic proton beams emission. Obtained results at three laser wavelengths are presented and discussed.

Materials and methods

A Compex 205 KrF excimer laser operating at a wavelength of 248 nm, with 23 ns pulse duration and maximum energy of 600 mJ, was employed at LEAS, Department of Physics and Mathematics, University of Salento. Using a 15 cm focal distance lens, a power irradiance of the order of 10^8Wcm^2 was obtained on a TiH_2 solid target mounted in a vacuum chamber at a pressure of 10^{-6} mbar.

A Q-switched Nd:YAG pulsed laser operating at 1064 nm and 532 nm (second harmonic) wavelengths, with 3 ns pulse duration, 1–150 mJ pulse energy, single shot or repetition rate (1–10 Hz) mode, was employed at the “Laboratory of plasma physics” at the University of Messina. The laser beam was focused, through a 35 cm focal lens placed in air, on the surface of the TiH_2 target placed inside a vacuum chamber at 10^{-6} mbar. The laser light passed through a thin window to the target, on which it produced a spot of about 1 mm^2 size. The target was mounted on a holder (externally vertically and angularly mobile) at an incidence angle of 45°. Fig. 1 shows a scheme of the experimental setup.

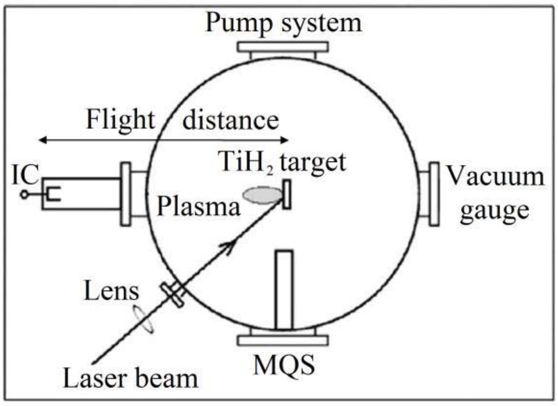

Fig. 1. A scheme of the experimental setup.

A Q-switched Nd:Yag pulsed laser operating at 1064 nm and 532 nm (second harmonic) wavelengths, with 9 ns pulse duration and 900 mJ maximum pulse energy, in single pulse or at a variable repetition rate from 1 up to 30 Hz, was employed at the INFN-LNS of Catania. The laser beam was focused, through a 50 cm focal lens placed in air, on the surface of the TiH_2 target placed inside a vacuum chamber at 10^{-6} mbar, with a spot size of 1 mm^2.

The employed target was a TiH_2 thick pill produced with Specac’s Atlas Manual Hydraulic Press. It is available at maximum in 10 ton load configuration. By a digital balance, 200 mg of TiH_2, in powder has been introduced inside a steel dies and covered with a pellet capsule. Successively, a protective safety shield has been closed in order to maintain constant the temperature and the pressure near a vessel. The upper bolster has been moved down and then, manually, the load has been adjusted. With the aim to manufacture metallic target 1 mm in thick, and 1 cm in diameter have been applied 8 ton of pressure for 18 minutes at room temperature and at environmental conditions of pressure and humidity.

An ion collector (IC), placed along the normal to the target surface, at 0° detection angle and 45° incidence angle, was used in time-of-flight (TOF) approach [4] at the three wavelengths.

A Pfeiffer Vacuum Prisma 200 mass quadrupole spectrometer (MQS), placed at 45° incidence angle, with an high sensitivity in the mass range 1-200 amu, mass resolution below 1 amu, was employed to detect plasma neutrals for several different targets as a function of the irradiation time.

Results

Fig. 2 reports a comparison between IC spectra obtained by irradiating TiH_2 at three different laser intensities, 10^8 W/cm^2, 3x10^9 W/cm^2 and 10^{10} W/cm^2 at laser wavelengths 248, 532 and 1064 nm, respectively.

The proton energy increases from about 15 eV at 248 nm wavelength and 10^8 W/cm^2 laser intensity (a), to about 105 eV at 532 nm wavelength and 3x10^9 W/cm^2 intensity (b), up to about 195 eV at 1064 nm wavelength and 10^{10} W/cm^2 intensity (c).

The proton peak, in fact, becomes faster increasing the laser intensity. Spectra obtained at 248 nm reports the IC detection of ions as emitted from plasma (0 kV) and as emitted submitting plasma ions to a post-acceleration produced by 15 kV voltage. Of course in this case protons assume a kinetic energy of 15 keV.

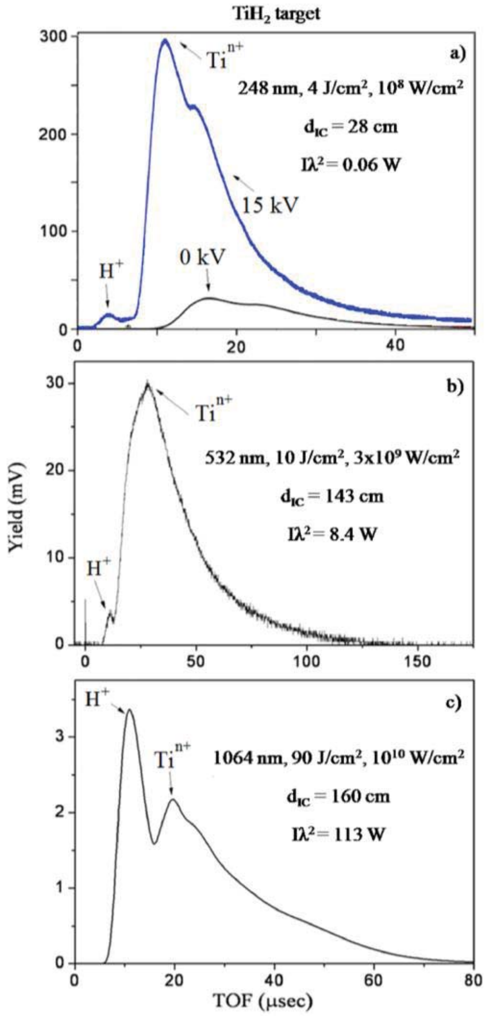

Fig. 2. A comparison between IC spectra obtained by irradiating TiH_2 at three different laser intensities.

The H^+/Ti^{n+} yield ratio increases from about 1.9×10^{-3} at 248 nm wavelength and 10^8 W/cm^2 laser intensity (a), to about 0.13 at 532 nm wavelength and 3×10^9 W/cm^2 intensity (b), up to about 1.62 at 1064 nm wavelength and 10^{10} W/cm^2 intensity (c).

The proton-to-titanium yield ratio, in fact, becomes higher increasing the laser intensity and the wavelength.

By using different laser intensities and by comparing the detected IC spectra, results indicate that the proton energy and the H^+/Ti^{n+} yield ratio both increase with the laser intensity and the laser wavelength, by using similar conditions of TiH_2 irradiation.

Fig. 3 indicates that the proton energy (a) and the H^+/Ti^{n+} yield ratio (b) are linearly proportional to $I\lambda^2$, where I is the laser intensity and λ the laser wavelength, in agreement with Ref. [5], i.e. the relative yield is proportional to the laser pulse power.

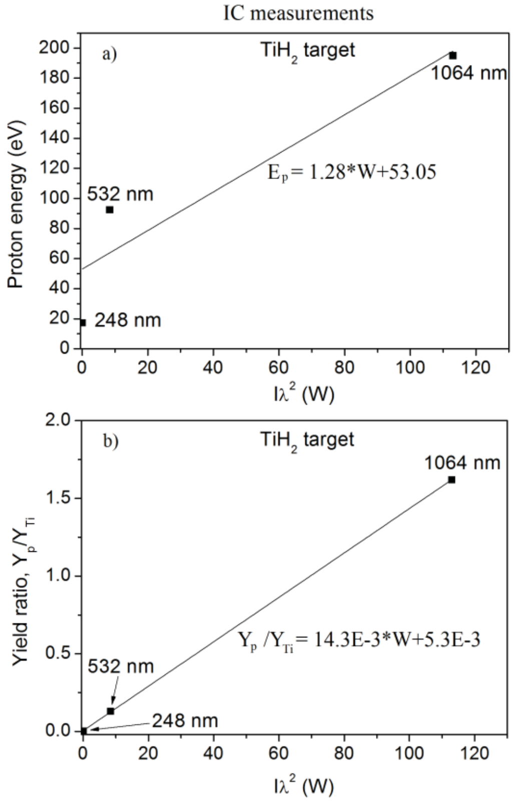

Fig. 3. The proton energy (a) and the H^+/Ti^{n+} yield ratio (b) as a function of $I\lambda^2$.

Experimental data can be fitted by a empirical linear relation between the proton energy E_p and the laser pulse power, W, according to the equation:

$$E_p = 1.28\,W + 53.05 \qquad (1)$$

Similarly, data relative to the yield ratio Yp/YTi and the laser pulse power are correlated by the linear equation:

$$Y_p/Y_{Ti} = 14.3\text{x}10^{-3}\,W + 5.3\text{x}10^{-3} \quad (2)$$

Fig. 4 shows MQS mass spectra comparison for titanium detection without and with laser ablation at 1064 nm, 180 mJ and 5 Hz repetition rate (a). The production of Ti, TiH, TiH_2, TiH_3, TiH_4 and TiH_5 was experimentally observed during the ablation process.

Fig. 4b reports a MQS time spectrum obtained during the laser ablation at 1064 nm, 180 mJ and 1 Hz repetition rate, confirming the formation of TiH_x chemical groups (x variable from 0 up to about 5).

The plasma produces different Ti-H molecules with high intensity of TiH_2 and TiH_3 species.

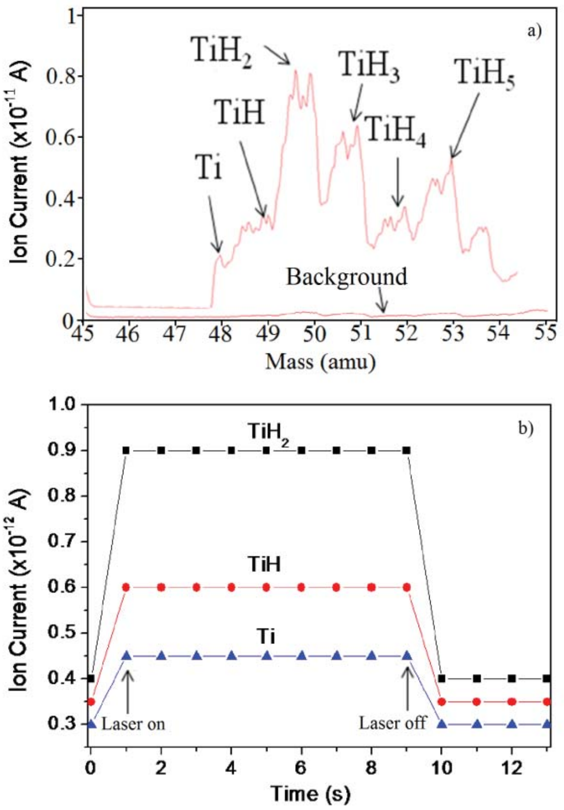

Fig. 4. MQS mass and time spectra for titanium detection.

Fig. 5 shows MQS spectra comparison for hydrogen detection without and with laser ablation at 1064 nm, 180 mJ and 5 Hz repetition rate (a).

An high production of H_2 was obtained with the ablation, as confirmed by the MQS time spectrum acquired at 1064 nm, 180 mJ and 1 Hz repetition rate and reported in Fig. 5b.

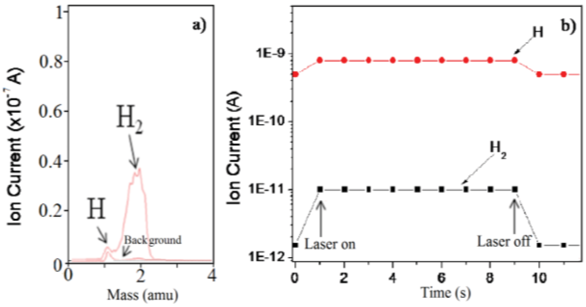

Fig. 5. MQS mass and time spectra for hydrogen detection.

This last result puts in evidence that the TiH_2 target could be employed as a very good hydrogen and proton source in a LIS system.

Discussion and conclusions

At the relatively low laser intensity employed in these experiments was possible to investigate the low energy proton beams generated by the laser matter interaction.

A special hydrogenated target such as TiH_2 allows the generation of plasma with peculiar properties, such as the temperature, density, fractional ionization and equivalent acceleration voltage responsible for the ion acceleration in the plasma. In this work a special interest is devoted to the dependence of the proton energy and yield from the laser parameter $I\lambda^2$. In fact from the literature [6-8] is known that the plasma electrons ponderomotive energy is dependent on this parameter. In this work a dependence also of the proton energy and yield from $I\lambda^2$ is shown.

In order to generate a proton beam from laser-generated plasmas, the use of hydrated titanium targets appears particularly interesting. In order to maximize the proton yield is possible to act on the laser parameters, such as intensity and wavelength, on the target hydrogen concentration, on the target structural composition (i.e. presence of nanostructures, which can control the laser light absorption coefficient) and on the target geometry. Various targets with proper geometries can allow to increase the proton energy, directivity and yield. Work in this direction is in progress and will be discussed in next papers.

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