

# Multi MeV protons, deuterons and carbon ions produced by the PALS laser system

Krása J<sup>1</sup>, Margarone D<sup>1</sup>, Velyhan A<sup>1</sup>, Pfeifer M<sup>1</sup>, Ullschmied J<sup>2</sup>, Klír D<sup>3</sup>, Řezáč K<sup>3</sup>

<sup>1</sup> Institute of Physics, ASCR, 182 21 Prague, Czech Republic, [krasa@fzu.cz](mailto:krasa@fzu.cz)

<sup>2</sup> Institute of Plasma Physics, ASCR, 180 21 Prague, Czech Republic

<sup>3</sup> Czech Technical University in Prague, 166 27 Prague, Czech Republic

## Abstract

Multi MeV ions and fusion neutrons were generated by focused radiation of the 3–TW Prague Asterix Laser System (PALS). The use of 8– $\mu\text{m}$  Al foil as XUV filter positioned in front of an ion collector allowed measuring currents of 4-MeV protons emitted behind a thin target in the forward direction. The proton energy of 4 MeV generated by a PALS laser irradiance  $I\lambda^2 \sim 5 \times 10^{16} \text{ W cm}^{-2} \mu\text{m}^2$  on target is nominally reachable for picosecond lasers when they deliver the intensity  $I\lambda^2 \sim 3 \times 10^{18} \text{ W cm}^{-2} \mu\text{m}^2$ . The enhanced maximum proton energy is favoured by a non-linear interaction of the laser beam with the pre-generated plasma. Non-linear processes also cause enhancement in the yield of fusion neutrons per focused laser energy from the  $\text{CD}_2$  plasma. The obtained results show that an equivalent neutron yield was reached by ps- and sub-ps laser beams for  $I\lambda^2 \sim 10^{19} \text{ W cm}^{-2} \mu\text{m}^2$ . The hampering influence of the electromagnetic pulse generated within the interaction chamber on diagnostics signals was eliminated.

## Introduction

Laser-production of plasmas is a promising technique not only in the field of ion and x-ray sources with a well characterized emission but also in the field of laser induced nuclear reactions and secondary particles generation. As in every new advanced technology there are a number of different constraints that must be overcome in order to progress. One of them is the electromagnetic pulse (EMP) which can be generated within the interaction chamber where the interaction of the high power laser with the target occurs [1]. Signals from plasma diagnostics can be strongly degraded and some item which is part of the electrical

equipment can be damaged by the EMP. Another difficult issue is the detection of multi MeV ions with the use of time-of-flight (TOF) detectors. The velocity of these ions being higher than  $1 \times 10^7 \text{ m/s}$  results in interference of an ion collector (IC) signal generated by them with a signal induced by XUV radiation which is generally produced within the target chamber for a time period of about 50 to 100 ns. A possible solution lies in extending the flight distance,  $L$ , between the target and the detector. Since the ion current decreases as  $L^{-3}$ , there is a limit for the distance given by the sensitivity of the signal-detection system. In this contribution we present methods of protection of diagnostics signals against their

degradation by the EMP and a separation of IC signals induced by fast ions from an XUV signal to obtain a clear cut evidence of production of multi MeV protons and other ions.

## Experimental arrangement

The 3-TW PALS laser system was operated at  $\lambda_0 = 1.35 \mu\text{m}$  [2]. 300-ps pulses irradiated Si,  $(\text{CD}_2)_n$  and graphite targets at  $0^\circ$  and  $30^\circ$  with respect to the target normal. The emission of ions was measured with the use of TOF ion collectors. Fusion neutrons were detected employing TOF detectors composed of a fast plastic scintillator and of a photomultiplier tube and their flux was measured with bubble dosimeters.

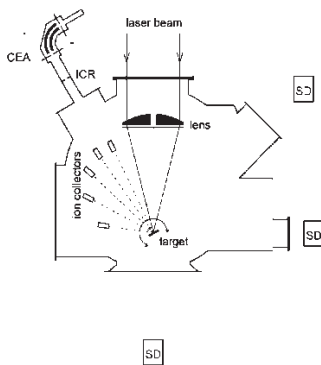


Fig. 1 Scheme of the experiment: CEA – cylindrical ion energy analyser or Thomson parabola spectrometer, ICR – ion ring collector, SD – scintillation detector. The bubble detectors were positioned inside and around the target chamber in various distances.

## Results and discussion

### Multi-MeV protons

Figure 2 shows a typical example of a strongly degraded ion collector signal by the EMP interference. The signal smoothing was not effective in separating the signals induced by XUV/soft X-ray radiation and multi-MeV carbon ions from the EMP one. Although the characteristics of this EMP are not accurately understood, its effect on diagnostics signals can be eliminated by inserting a delay unit between the IC output and the input of an oscilloscope. The 40-m length of the coaxial

cable allowed to separate the EMP pulse from the XUV and ion signals, as Fig. 3 shows. Since the intense XUV signal overlaps the fast proton signal in the TOF spectrum, as Fig. 3 shows, the IC was shielded with  $8\text{-}\mu\text{m}$  Al foil in order to cut off this plasma photopeak signal [3].

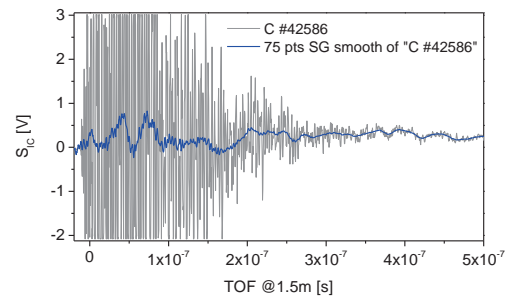


Fig. 2 Strong degradation of the ion collector signal by the electromagnetic pulse (EMP) interference.

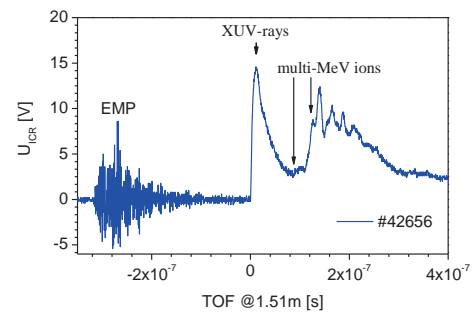


Fig. 3 Separation of the EMP from the ion collector signal using a delay unit. The  $(\text{CD}_2)_n$  target was exposed to the laser intensity of  $\sim 2 \times 10^{16} \text{ W/cm}^2$ .

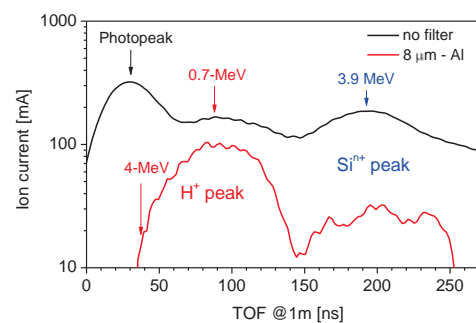


Fig. 4 TOF spectra of accelerated protons and Si ions emitted from the rear side of artificially hydrogenated  $17\text{-}\mu\text{m}$  Si single crystalline target irradiated by the laser intensity of  $\sim 2 \times 10^{16} \text{ W/cm}^2$  [5].

This technique was successfully applied in an experiment devoted to the forward acceleration of protons which were emitted from a rear side of a  $17\text{-}\mu\text{m}$  thin hydrogenated Si membrane [4].

This method allowed the exact determination of  $v_{MAX}$  by elimination of the XUV photopeak from the IC signal. It is evident that the fastest protons expand with of  $2.84 \times 10^7 \text{ m/s}$  ( $E_{MAX} \approx 4.2 \text{ MeV}$ ), which exceeds the expected value of  $1.3 \times 10^7 \text{ m/s}$  ( $E_{MAX} \approx 1 \text{ MeV}$ ) for the value  $I\lambda^2 = 3.6 \times 10^{16} \text{ W cm}^{-2} \mu\text{m}^2$ , as Fig. 5 shows [5]. Thus, for the corresponding effective target irradiance it holds  $I_{eff} \sim 55 \times I_0$ , where the target irradiance  $I_0$  is specified by the laser power divided by the focal spot area. The disagreement may lie in the self-focusing effect of the laser beam in the pre-generated plasma, as it was suggested in the case of generation of highly charged  $\text{Ta}^{q+}$  and  $\text{Au}^{q+}$  ions carrying the maximum charge state of  $\sim 50$  [6]. In this case it was estimated that the self-focusing increased the value of the target irradiance up to  $\sim 1 \times 10^{19} \text{ W/cm}^2$ .

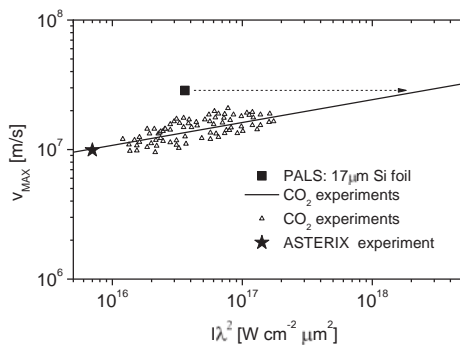


Fig. 5 Maximum proton velocity as a function of a similarity parameter  $I\lambda^2$ . Square stands for experiment performed with the PALS laser: emission from the rear surface of a 17- $\mu\text{m}$  Si target [5].

### $\gamma$ -rays and neutrons

The laser-plasma interaction gives rise to various secondary processes. One of them is the generation of MeV  $\gamma$ -rays, which are emitted similarly to the MeV bremsstrahlung from a solid target being struck by fast electrons. Their temperature was measured to be  $T_e \approx 0.9 \text{ MeV}$  when 200 mJ, 130 fs Ti:sapphire laser pulses irradiated various massive targets [9].

Figure 6 shows a scintillation detector's signal induced by  $\gamma$ -photons and neutrons emitted by  $\text{CD}_2$  plasma produced by  $I \sim 2 \times 10^{16} \text{ W/cm}^2$ . The detector was placed 221 cm far from the

target. It is evident that the EMP destroys the  $\gamma$ -signal when no shielding of the detector is applied. The best protection against the EMP is the use of Faraday cages for all detectors and oscilloscopes including uninterruptible power supplies that are connected with double-shielded coaxial cables. The signal without the EMP interference is shown in Fig. 7. The shielded scintillation detector was placed 320 cm away from a silicon foil target and was surrounded by an enclosure of lead bricks of 20 cm thickness towards the target and 5 cm on all other sides. In contrary to the femtosecond-experiments where over 2000 shots had to be accumulated to obtain a photon spectrum up to  $\sim 2.2 \text{ MeV}$  due to the low number of  $\gamma$  photons [9], the intensity of  $\gamma$ -rays in this PALS experiment was so high that only a single shot was needed to obtain high response amplitude, as Fig. 7 shows. The estimated energy of the detected  $\gamma$  photons is higher than  $\sim 1.5 \text{ MeV}$ .

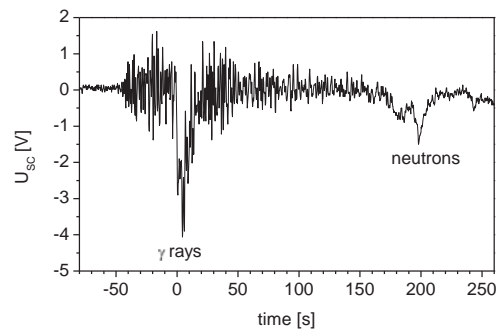


Fig. 6 Scintillation detector signal induced by fusion neutrons and  $\gamma$  radiation emitted from laser-produced  $\text{CD}_2$  plasma.

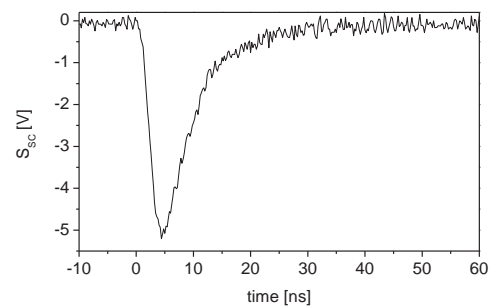


Fig. 7 Scintillation detector response to  $\gamma$  radiation generated with a single laser-pulse (627 J, 300 ps) focused onto a 10- $\mu\text{m}$  Si foil. The radiation penetrated 20-cm lead shielding.

The total flux of neutrons was measured with the use of bubble detectors that are sensitive only to neutrons. Fig. 8 shows a photo of one of irradiated detectors.

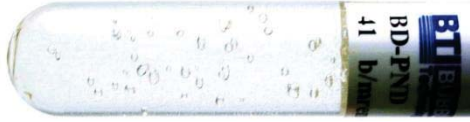


Fig. 8 Bubble detector exposed to 2.45-MeV neutrons emitted by  $CD_2$  plasma which was produced with a  $1.7 \times 10^{16} \text{ W cm}^{-2}$  intensity.

The maximum total yield of neutrons observed in this PALS experiment reached a value of  $2 \times 10^8$  neutrons per laser shot. The yields per laser energy,  $Y/E_L$ , obtained in other experiments and giving comparable value  $Y/E_L$  with the PALS one are presented in Table 1. It is evident that the PALS result belongs to a group of laser-plasma experiments with a higher efficiency of DD-neutron production. Two experiments [8, 9] giving similar values of  $1\text{--}10 \times 10^5$  neutrons/J also imply that the target irradiance of  $2 \times 10^{16} \text{ W/cm}^2$  deposited by the PALS laser induces non-linear effects enhancing the efficiency of neutron production.

Target thickness	$Y/E_L$ [n/J]	$E_L$ [J]	$\tau_L$ [ps]	$I_0$ [ $\text{W/cm}^2$ ]	Reference
60 $\mu\text{m}$	$1 \times 10^5$	400	1	$4 \times 10^{20}$	[8]
300 $\mu\text{m}$	$4 \times 10^5$	500	250	$2 \times 10^{16}$	PALS
400 $\mu\text{m}$	$1 \times 10^6$	6	0.3	$3 \times 10^{19}$	[9]

Table 1 Comparison of neutron yields per laser energy measured in various experiments [5].

## Conclusions

The irradiation of different targets by the same intensity of  $\sim 2 \times 10^{16} \text{ W/cm}^2$  delivered by the PALS laser resulted in generation of about 4-MeV protons, multi-MeV ions, fusion neutrons with a maximum yield of  $(1.7 \pm 0.3) \times 10^8$  neutrons/shot as well as of a very strong electromagnetic pulse. The PALS experiment has also shown that the "long-pulse" laser interaction does not depend only on the value of similarity parameter  $I\lambda^2$ , angle

of incidence, pulse duration and polarization, pre-pulse and target properties, uncertainties in the measurements, intensity assignments and random shot-to-shot fluctuations in the laser beam, but it is also significantly influenced by non-linear laser-plasma interaction. Just both the observed maximum proton energy and the neutron yield per energy already denote that these enhanced values could correspond to the self-focusing which causes the shrinking down of the laser beam spot diameter. Then the irradiance can reach a level of up to  $10^{19} \text{ W/cm}^2$  [6].

## Acknowledgement

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