Experimental study of proton acceleration from thin-foil on a table top Ti:Sapphire

I Sánchez, R Lera, J Ruda, JB Gonzalez, F Ruiz, D Lopez, A Ruiz-de la Cruz
Proton Laser Application S.L. (PLA), Av. Vilafranca del Penedés 11ª, 08734 (Barcelona), Spain. E-mail: i.sanchez@protonlaser.com.

Abstract. Table-top lasers of moderate energies (0.1- 0.5 J) are promising, cost-effective laser-driven sources of MeV-energy protons and ions accelerators, but many applications of laser-accelerated ion beams will not only require a low cost, compact system but also require operation at high repetition rates (>10 Hz).

This paper focus the effort to characterize and optimize proton acceleration processes using 3 TW/55 fs, table-top Ti:Sapphire (Ti:Sa) laser capable to operate at 10 Hz, with this intention the maximum proton energy obtained, in a single shot, was evaluated by irradiating a variety of flat targets, from thin film to sub-micrometric film membranes designed for our purposes in a high density target array.

The presented work is a previous stage and this study has the intention to be the prelude of the technological challenge, both in laser technology as well target design capable of operating at high repetition rates.

1. Introduction

Over recent years considerable effort has been made to develop laser-driven ion sources for multiple applications ranging from ion oncology [1] to proton radiography [2, 3, 4, 5]. Moreover, many applications of laser-accelerated ion beams will not only require a low cost, compact system, but also require operation at high repetition rates to achieve the necessary particle flux. e.g., radiation therapy [3], are demanding average flux which requires an elevated shot rate to accumulate useful levels of activity [6].

High intensity Ti:Sa lasers sources demonstrates that they not only occupy a smaller spatial, but they are able to operate at significantly higher repetition rates when compared to similar intensity Nd:Glass lasers [6,7]. Ti:Sa lasers are most likely to fulfill these requirements, hence experimental effort to characterize and optimize ion acceleration processes using femtosecond laser Ti:Sa sources is a crucial step towards many proof of principle experiments [8, 9].

Proton or ion acceleration with 10 Hz systems has been demonstrated at several laboratories [10, 11]. However, the actual shot rate normally is much lower due to restrictions in the target positioning which typically requires a mechanical precision of a few microns.

This is a real challenge that has not yet been solved and where we wanted to focus our efforts, in that sense this work presents an experimental study of laser-driven ion acceleration with micrometer and sub-
micrometer thick Al flat targets, the fabrication of these targets is another technological challenge because the repetition rate is determined by two factors, the pulse rate of the laser system and the time necessary to refresh the target [10-16].

The subjects to the present work are the follows: Firstly, we can point out the development of a compact table top Ti:Sa, low-cost, energy efficient, stable, ultra-high-intensity and ultra-short pulse laser with 10 Hz repetition rate. For this purpose, this paper reports the measurements of proton production using pulse duration of tens of femtoseconds ~55 fs and energies below 200 mJ. Optimum conditions for proton acceleration in terms of laser energy, contrast, target material and thickness have been characterized. Secondly, we employ large arrays of solid targets as the beginning for future high repetition processes, due to the complexity of the experiment here we show the single shot results, but the results obtained with our table-top laser could be demonstrated for accelerated protons and set high requirements on the laser and target properties.

2. Experimental setup

2.1. Laser system

Experiments was carried out employing a Chirped Pulse Amplification (CPA) Ti:Sa laser developed at Proton Laser Applications S.L (PLA) [12, 13]. The laser can deliver pulses energy up to 275 mJ (160 mJ on target surface) of energy with duration of 55 fs at a central wavelength of 780 nm. The scheme of the laser developed in this work is presented in Fig.1 and detailed in this section.

As the figure 1 shows, the front end consists of a commercial Ti:Sa oscillator (Venteon of Laser Quantum) that delivers 10-fs pulses with 80 MHz repetition frequency. Then the pulse passes through a stretcher which enlarges the pulse 10000 times. The stretcher employed was a single pass Öffner type [14] chosen due to its simplicity and its aberration low design [15], the mentioned stretcher comprised of one gold-coated reflecting diffraction grating (Horiba Jovin-Yvon) with a line density of 1200 lines/mm and 92 % reflectivity at 800 nm, tilted at 60° and a relay system of two spherical mirrors with a radius of curvature of 500 mm and -250 mm respectively. In order to compensate third order dispersion components due to the stretcher process it is required employ an external device, in our case it was used a programmable acousto-optic device (Dazzler of Fastlite) capable of shaping both the spectral intensity and phase of stretched pulse. At the end of the process the pulse duration of the stretched pulse was estimated to be more than 150 ps using a fast photodiode.

Afterwards, the remaining signal (6 nJ) is amplified first in a regenerative pre-amplifier which increase the energy to 1.5 mJ per pulse and achieve a beam diameter of 2 mm. As is shown in the figure, the active medium is a Ti:Sa crystal with rectangular end faces of 4 x 6 mm and 20 mm long. The pump laser of the regenerative amplifier is an Empower 15 of Spectra-Physics, which delivers 8 mJ and gaussian shaped beams of 200 ns at 100 Hz. Preceding the next amplifier, a Faraday isolator is included to prevent backreflected light from the following amplifiers.

Subsequently, a second three-pass pre-amplifier pumped at 532 nm by a Nd:YLF laser increased the energy to 30 mJ. This multipass amplifier is pumped by up to 200 mJ in 15 ns pulses at 100 Hz, this nanosecond laser deserves special mention because were designed to be used to pump this material and play a fundamental role to achieve a good performance at high repetition rates. It includes two diodes pumping chambers, PHS400 (manufactured in Monocrom S.L.) [12], loaded with Nd:YLF rods of 5 mm in diameter, there are disposed as a Master Oscillator Power Amplifier (MOPA) configuration. A KTP
crystal converted to a second harmonic the output energy at 527 nm and pump a three multipass configuration which contains a cylindrical Ti:Sa crystal 6 mm diameter x 15 mm length, water cooling. In order to compensate the action of the thermal lensing in this amplifier and improve the extraction efficiency, we implemented a telescope situated prior to the first pass which introduces divergence and compensate the converging effect induced by thermal lensing. The beam diameter obtained is 2.5 mm with 30 mJ of pulse energy.

Figure 1. a) Scheme of the table-top Ti:Sa laser developed at Proton Laser Applications S.L (PLA). A pulse oscillator sends a beam of a few femtoseconds that is stretched in time in a pulse stretcher. Then it enters a chain of amplification that starts with a regenerative amplifier that is followed by a first multipass amplifier and ends with a second multipass amplifier. The CPA chain ends with a compressor installed in a vacuum chamber.

After the first multipass amplifier the laser pulse is introduced into the final three-pass amplifier which is pumped with two 400 mJ, 532-nm Nd:YLF lasers and reaches uncompressed 275-mJ energy level. The amplifier is built in a multipass bow tie configuration with 3 passes. The Ti:Sa active medium is a plane-parallel crystal with 16 x 20 mm² rectangular facets and 20 mm length. The Crystal is cooled in cooper mount water cooling, which permits refrigerate the crystal at 15°C, to mitigate the effect of the thermal lensing, several approaches were used. First the seed beam was enlarged thanks to a telescope of low magnification introducing divergence, additionally, a convex mirror of radius of curvature -2000 mm had to be inserted before the last pass to increase the divergence of the laser and to prevent the beam from leaving the amplifier converging. The output beam had a diameter of 5.3 mm and 275 mJ energy per pulse are achieved using a total pump of 800 mJ.
In order to clean the pulse two saturable absorbers (SA) were inserted after the regenerative amplifier and the second before the final multi-pass amplifier. The contrast ratio of the amplified spontaneous (ASE) at a few ns was estimated to be $10^{-8}$ prior to the peak of the main pulse, and $10^{-6}$ of the peak pulse intensity at a few ps. These measurements were made by using a fast photodiode and oscilloscope. In ultra-intense lasers, the temporal quality of the pulses is of maximum importance, especially in applications such as particle acceleration. TW laser can be focused to a few microns and achieve a peak intensity more than $10^{18}$ W/cm², if the contrast at some point is less than six orders of magnitude, a preceding part of the pulse would present an intensity of at least $10^{12}$ W/cm², which can be enough to interact non-linearly with a material and generate plasma [10, 15].

Finally, the amplified pulse is guided to a compressor (63 % efficiency) with a standard configuration based on Treacy’s design [15] and covered inside a vacuum chamber. Consider the damage threshold of the holographic grating is about 300 mJ/cm², the beam was enlarged by a series of mirrors and a telescope to a diameter of 20 mm.

The pulse duration was measured with a Wizzler (Fastlite), which uses the third-order technique of self-referenced spectral interferometry [16]. A feedback loop can be set up between this device and the spectral shaper located before the regenerative amplifier to minimize the dispersion, especially third order, which was found to be the term which contributed the most to aberrations in the spectral phase. The pulse duration was determined to be 55 fs and the spectral bandwidth retrieved was 19 nm FWHM.

2.2. Interaction Chamber

The proton acceleration experiments take place in a vacuum chamber (20 mtorr) situated after the compressor (Fig. 2). A pulse coming from the compressor is p-polarized and is focused on a target at an incident angle of 30 º by using an f/1.3 off-axis parabola mirror (OAP). The spot diameter was measured with a CCD (WinCamD-UCD12 of Dataray) camera with an aspheric lens 0.57 μm effective pixel size, where we obtained the full width-half-maximum of the focal size of $5 \times 10$ μm². The parameters, which have routinely been achieved on the target for experiments, are listed in Table 1.

| Parameter                  | Variable unit | Value  |
|----------------------------|---------------|--------|
| Pulse duration             | $\tau_{\text{FWHM}}$ (fs) | 55     |
| Focal spot size            | $D_{\text{FWHM}}$ (μm)    | $5 \times 10$ |
| Energy on sample           | $E_L$ (J)      | 0.160  |
| Power on sample            | $P_L$ (TW)     | 3      |
| Contrast                   |                | $10^{-8}$ |

Focus alignment, which has a sensitivity of few micrometers, is controlled through a He:Ne laser coupled on the same optical path of the Ti:Sa beam [12, 13], a CCD camera imaging the systems, is placing along optical path of Ti:Sa laser beam and serves the dual purpose of laser focus diagnosis and precise positioning of the target.

The target holder formed by a framework with 16 windows to hold up the targets, these windows has a specific profile for tension the surface of the target and permits avoid variations from the exact focusing
position arising from target roughness or flatness. The holder, positioned at 30º of the incident beam, is moved by three motors enabling three freedom degrees with a positioning precision of 2.5 um. This configuration allows for testing several targets without breaking the vacuum condition.

![Figure 2](image)

**Figure 2.** a) Pictured in the image a schematic view of the interaction chamber and the disposition of the detectors employed in this experiment, behind the target holder there is a passive radiation detector (CR-39), and at the end of the flight tube there is a scintillator detector coupled by fiber to a photomultiplier tube (PMT). b) detailed view of the interaction chamber. In the first vacuum chamber a mirror steers the laser beam onto the OAP (off-axis parabola), which focuses the laser onto a target where the protons are generated.

According to the established theoretical models [18-20], the process acts as in the following: a high intensity laser impinges on the front surface of a thin foil, suddenly some electrons are directly accelerated by and penetrate the target. Most them spread and dissipates energy inside of it while the hot component of these electrons can reach the target rear side [20, 21]. Only the most energetic of these electrons can escape, leaving behind an electrostatic potential which generates an electric field that ionizes and accelerates surface ions in a process called Target Normal Sheath Acceleration (TNSA) [19-25].

### 2.3. Sample description

As mentioned previously, one of the bottleneck for a real laser-driven ion application are the rate sample supply system matched to the repetition rate of the driving laser. This is a field of technological research that is attracting a lot of attention, in our case we make a parallel research in collaboration with the Institute of Microelectronics of Barcelona (IMB-CNM (CSIC)), where a target array for high repetition rate, was designed [26].

For comparative reason, the experimental campaign was made with series (*Serie 1*) of different thickness Aluminum (Al) foils. This campaign allows us to find the optimal laser parameters in laser driven proton acceleration. A second campaign was made with a fabrication of sub-micrometric thin-layer conductive membranes embedded in a silicon wafer frame by using nano/micro-electro-mechanical-system
(N/MEMS), these samples are made by aluminum membranes supported by SiO$_2$ and are referred as Serie 2. A schematic structure of the samples is detailed in Figure 3.

Table 2. Sample description employed in this work, the samples are divided into two categories by composition (Serie 1 or 2), in which different thicknesses have been used.

| Samples | Composition   | Thickness $d$ (μm) |
|---------|---------------|---------------------|
| Serie 1 | Flat Al       | 0.8, 1.8, 2.5, 7.0  |
| Serie 2 | Flat Al +SiO$_2$ | 0.25, 0.5, 0.65, 1.0 |

The second method of fabrication of series 2 targets, not only permit us to tune membranes properties, such as thickness and material composition, further, it is potentially applicable on high repetition rate regime because this target array can load up in each 16 individual holder windows permitting a total of 256 targets available for experiments within one vacuum cycle. This work is focused on the laser development description for laser acceleration experiments, the target fabrication deserves a separate chapter which is detailed in the following references [26, 27].

2.4. Measurement and characterization techniques

The main diagnostic of multi-MeV proton acceleration was made by passive CR-39 nuclear track detectors and time of flight (TOF) measurements (see Fig 2).

Inside the same vacuum chamber, passive detectors such as 1 cm$^2$ CR-39 (Radosys) chips was placed in the direction behind the target. CR-39, allyl diglycol carbonate, is a plastic polymer, when an energetic proton arrives at the chip, it destroys the links between polymer chains through its range of penetration. However, these damaged tracks are not visible and the CR-39 must be post-treated with an etching process.
with a bath of 6.25M NaOH at 90°C for 4 hours. The energy of the particles can be inferred from the shape and size of the pits.

The other measurement technique was a Time-of-Flight (TOF) configuration formed by scintillator crystal. This device was situated at the end of the time of flight tube with a distance of 227 cm from the interaction chamber. The scintillator detector was coupled to a photomultiplier tube (PMT) which generates a signal that can be recorded with a high bandwidth oscilloscope. The number of ions and therefore the absolute proton spectral distribution can be inferred from the height of the signal created by the PMT which was previously calibrated, together with the CR-39, at the 3 MV cyclotron at the National Accelerator Center (CNA), Seville [20]. The particle detection adapted to our system was developed and calibrated by the research Institute for Molecular Imaging (I2M, Valencia), more information of the calibration work is reported in references [13, 28].

From these techniques is possible to obtain complete spectra of number of protons as a function of the accelerated energy. Moreover, TOF measurement technique gives on-line real-time information about the ion current shot-to-shot fluctuations as well as the maximum proton energy in real time, due to its simple and fast readout, can be used as a real-time diagnostic with high repetition rate lasers.

3. Results and Discussion

3.1. Target thickness and contrast influence

An intense collimated beam of high-energy protons is emitted normal to the rear surface of thin solid targets irradiated at 3 TW power, the beam profile at the focus (5 × 10 μm² FWHM) was measured directly with a camera. Up to 160 mJ of the laser is transferred to the sample with a peak intensity is $2 \times 10^{19}$ W/cm².

![Figure 4. Typical proton density distribution from time of flight measurements comparing different results varying the Al target thickness. The plot shows de number proton density as a function of accelerated energy for different target thickness: 0.8 μm (1.75 MeV), 1.8 μm (1.6 MeV), 2.5 μm (1.5 MeV), 7 μm (1.4 MeV).](image)

In order to observe the distribution of the protons generated in the interaction of the laser and the target the TOF and the scintillator were used as the principal detector simultaneously CR-39 chips were used as a secondary source of information.

The spectrum of the accelerated protons measured by the TOF for targets with different thicknesses is presented in Fig. 4. The energy spectra of the proton beams observed, typically with an exponential profile, has three main features: a large energy spread, a smooth decrease of particle number with energy and finally an abrupt “cutoff,” at a well-defined energy which we will term “maximum proton energy” in the following. This maximum proton energy is the quantity normally used to compare different experiments and determine experimental scaling laws for the acceleration process.

From these results we can obtain the maximum proton energy as a function of the target thickness. In this specific case, the maximum energy obtained with 0.8 μm reach 1.75 MeV, in the same graph we show the proton spectra obtained from 1.8 μm, 2.5 μm, and 7 μm Al thick.

With the objective to find the mechanism that can improve the maximum energy of the protons accelerated, it was measured the maximum proton energy for a variation of the thickness of the aluminum foil. Figure 5 shows the results achieved with different laser contrast. All the error bars were largely determined by the variation in maximum energy over multiple repeat data shots for each target thickness.

In that point we have to remark the importance of the contrast in the experiments, previous results in which we had a low contrast (< 10^-6) provided proton energies lower than with high contrast (10^-8) after introducing the saturable absorbers, the inclusion of these absorbers reduce the effect of the prepulse allowing to reach higher maximum energies and permitting the use of thinner targets, therefore it is evidence that for acceleration efficiency, contrast was an important parameter.

![Figure 5](image-url)

**Figure 5.** Maximum proton energy as a function of the flat Al target thickness, plot of measured data, color dots in blue correspond to high contrast experiments and black for low contrast conditions.
From the results obtained it has been shown that the energy maximum of proton accelerated via TNSA can be enhanced by using thinner targets and the proton acceleration depends strongly on the contrast of the laser. The comparison of our results with other experiments in scientist literature demonstrates that the proton energies observed in our experiments are consistent with theoretical scaling laws and previous empirical results [24, 25].

3.2. Proton acceleration with arrays of solid targets

Once we have the first campaign of proton acceleration, based on maximum proton energy from thin Al flat foil. Next step was to obtain the optimal laser-driven proton acceleration from the target Serie 2, based on MEMS fabrication, one of the scopes is to demonstrate the performance of targetry able to work at high repetition in vacuum.

In this stage same laser conditions described previously was performed using targets of Serie 2. The fabrication of these targets permits us to reduce the Al thicknesses until to 0.25 μm. Figure 6 shows the maximum proton energy as a function of Al thicknesses, comparing the different targets employed in this study, both Serie 1 and Serie 2.

![Figure 6. Maximum proton energy as a function of the flat Al target thicknesses.](image)

From the previous plot it is shown the increase of maximum proton acceleration with targets of series 2, hence it is clear that the deigned samples at Serie 2 match better with our laser system requirements and the results of preliminary experiments had shown the achievement of successful proton acceleration up to 2 MeV. Although this energy value is far from that necessary for the feasibility of laser-based proton accelerators, it is a very promising result and give us the importance of adapt the target composition and thicknesses to any specific laser-driven processes.

Another relevant question, on the contrary, we expected to reach the maximum proton energy with 0.25 μm thickness but the optimum value is achieved with 0.5 μm of Al thicknesses. How the acceleration varies in series 2, is still an open question and further investigation, including membrane composition,
focusing and laser parameters should be considered to fully understand these results. However, this study also demonstrates the existence of an optimum foil thickness and target design for reach maximum proton acceleration. Moreover, it has been shown that novel targets offer the possibility of improving the maximum energy and the number of individual targets per area have become manifest.

4. Conclusions

In this article we investigate laser-driven ion acceleration with micrometer and submicrometer Al flat targets and ultrashort 55 fs laser pulses with moderate energy (0.16 J) obtained from a Ti:Sa laser system. The main importance of our work resides in the successful operation of a compact, cost-effective laser ion accelerator. In that sense, the data obtained from planar foil targets demonstrate the effectiveness in proton acceleration with a table-top TW-class fs laser system capable of working at 10 Hz.

The improvement of contrast is an important contribution to the increase in proton energy since it enabled the use of thinner targets. The concept of contrast has low impact on the performance of the laser but can be very important to the efficiency of certain applications.

Also, we pay attention in the target and membranes properties, such as thickness for potential laser-plasma applications based on high repetition rate regime. The future research line is focused, from one hand to increase the laser pulse energy, and from the other, to develop more sophisticated target designs should improve the coupling and thus the acceleration results.

Laser-based proton accelerators are still at an early stage of evolution and major developments are necessary, hence experimental effort to characterize and optimize ion acceleration processes is a fundamental step towards achieving this objective and our system can be a valuable tool for studies the underlying physics of laser-plasma interactions as well as technical developments related to laser-based proton beams.

5. References

[1] Borghesi M, (2014). Laser-driven ion acceleration: State of the art and emerging mechanisms. Nucl Inst A, Vol. 740, 11.03.2014, pp.6–9.

[2] Green J.S, Robinson A. P. L, Booth N, Carroll D. C., Dance R. J., Gray R. J., MacLellan D. A, McKenna P, Murphy C. D., Rusby D, & Wilson L, (2014). High efficiency proton beam generation through target thickness control in femtosecond laser-plasma interactions. Appl. Phys. Lett. 104, 214101.

[3] Schardt, D. (2007) Heavy-Ion Therapy Collaboration. Tumor therapy with high-energy carbon ion beams. Nucl. Phys. A 787, 633.

[4] Schreiber, J., Bolton, P.R. & Parodi, K., (2016). “hands-on” laser-driven ion acceleration: A primer for laser-driven source development and potential applications. Rev Sci Ins, 87, 071101.

[5] Fourmaux, S. et al., (2013). Investigation of laser-driven proton acceleration using ultra-short, ultra-intense laser pulses. Physics of Plasmas, 20, 013110.

[6] Malka, V. Fritzler S, Lefebvre E, d’Humières E, Ferrand R, Grillon G, Albaret C, Meyroneine S, Chambaret JP, Antonetti A, Hulin D. (2004) Practicability of proton therapy using compact laser systems. Med. Phys. 31(6): 1587-92.
[7] Safronov, K. V. et al. (2009). Experimental study of the acceleration of protons emitted from thin foils irradiated by ultrahigh-contrast laser pulses. JETP Letters, 88(11), pp.716–719.

[8] Spencer I et al. (2003) Experimental study of proton emission from 60-fs, 200-mJ high-repetition-rate tabletop-laser pulses interacting with solid targets. Phys, Rev, E 67 046402.

[9] Rosinski, M. et al., (2016). Acceleration of protons in plasma produced from a thin plastic or aluminum target by a femtosecond laser. Journal of Instrumentation Vol 11, SN - 1748-0221N2.

[10] Daido H, Nishiuchi M, & Pirozhkov A.S, (2012). Review of laser-driven ion sources and their applications. Reports on progress in physics. Physical Society (Great Britain), 75(5), p.56401.

[11] T. Ceccotti, A. L evy, H. Popescu, F. R. eau, P. D'Oliveira, P. Monot, J. P. Geindre, E. Lefebvre, P. Martin, Proton acceleration with high-intensity ultrahigh-contrast laser pulses, Phys. Rev. Lett. 99 (2007) 185002.

[12] Matellanes, R. L. (2017). Thesis : Design and development of a high power high repetition rate ultrashort pulse laser for proton acceleration. University of Salamanca, Spain.

[13] Bellido P, Lera R, Seimetz M, Zaffino R. L., Vidal L, Soriano A, Rigla J. P, Moliner L, Iborra A, Conde P, Aguilar A, and Roso L, (2016) Characterization of protons accelerated from a 3 TW table-top laser system, JINST, 12 p. T05001, 2017.

[14] A. Öffner, U.S. patent 3,748,015 (1971).

[15] G. Cheriaux, B. Walker, L. F. Dimarco, P. Rousseau, F. Salin, and J. P. Chambaret, Aberration-free stretcher design for ultrashort-pulse amplification, Opt. Lett. 21, 414(416 (1996).

[16] E. B. Treacy, Optical pulse compression with diffraction gratings, IEEE J. Quantum Electron. 5 (9), 454 (1969).

[17] A. Trisorio, S. Grabielle, M. Divall, N. Forget, and C. P. Hauri, Self-referenced spectral interferometry for ultrashort infrared pulse characterization, Opt.Lett. 37, 2892–2894 (2012).

[18] Perego, C. et al., 2011. Extensive comparison among Target Normal Sheath Acceleration theoretical models. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 653(1), pp.89–93.

[19] Neely, D. et al., 2016. Appl. Phys. Lett. 89, 021502 (2006); doi: 10.1063/1.2220011.

[20] Maksimchuk, a et al., 2000. Forward ion acceleration in thin films driven by a high-intensity laser. Physical review letters, 84(18), pp.4108–11. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10990622.

[21] S. Fourmaux, S. Buffechoux, B. Albertazzi, D. Capelli, A. Levy, S. Gnedyuk, L. Lecherbourg, P. Lassonde, S. Payeur, P. Antici, H. Pepin, R. S. Marjoribanks, J. Fuchs, and J. C. Kieffer, Phys. Plasmas 20, 013110 (2013).

[22] Schnürer, M., 2011. Comparison of femtosecond laser-driven proton acceleration using nanometer and micrometer thick target foils. Laser and Particle Beams, 29(4), pp.437–446. Available at: http://dx.doi.org/10.1017/S0263034611000553.

[23] P. McKenna, F. Lindau, O. Lundh, D. Neely, A. Persson, and C.-G. Wahlstrom, High-intensity laser-driven proton acceleration: Influence of pulse contrast,Philosophical Transactions: Mathematical, Physical and Engineering Sciences 364, 711 (723 (2006).

[24] Kiefer, T., 2014. Investigation of the laser-based Target Normal Sheath Acceleration (TNSA) process for high-energy ions an analytical and numerical study.
[25] Fuchs, J. et al., 2006. Laser-driven proton scaling laws and new paths towards energy increase. Nature Physics, 2(1).

[26] Zaffino R. L., Sanchez I, Ruiz A, Seimetz M, Quirion D, Lera R, Bellido P, Benlloch JM, Lozano M, (2017) Wafer scale fabrication of high density targets array for stable generations of protons beams by laser-plasma interaction, J Phys Conf S (to be published).

[27] Zaffino R.L., Seimetz M., Quirión D, Ruiz A., Sánchez I., Mur P., Benlliure J., Martín L., Roso L., María J., Benlloch P, Lozano M, Pellegrini G, Preparation and characterization of micro-nano engineered targets for high-power laser experiments, Microelectronic Engineering, Vol 194, 2018, p.p 67-70, ISSN 0167-9317.

[28] Seimetz M, Bellido P, Soriano Asensi A, Conde Castellanos PE, Crespo Navarro E, González Martínez AJ, Hernández Hernández L,(2015). Calibration and Performance Tests of Detectors for Laser-Accelerated Protons. IEEE Transactions on Nuclear Science. 62(6):3216-3224.

Acknowledgements

The authors wish to thank the technical staff of the UPC2 Instituto de Microelectrónica de Barcelona IMB-CNM (CSIC), Spain, for their technical assistance in fabrication of the test samples, and to the Instituto de Instrumentación para Imagen Molecular (I3M) for the TOF design and calibration. This work has been partially supported by the Spanish Ministry for Economy and Competitiveness within the Retos-Colaboración, ref. RTC-2015-3278-1.