Development of a multi-shot experiment for proton acceleration

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Abstract. In this paper, we present a target system to produce protons from laser plasma interactions at high repetition rates. In order to increase the number of available shots needed for the foreseen application, the target system will help to improve the reproducibility and stability of the proton source. We describe the experiments that we will carry out with the 50 TW (1.2J, 25 fs, 10Hz) laser at the Laser Laboratory for Acceleration and Applications (L2A2) at the University of Santiago of Compostela to study the production of radioactive isotopes for medical imaging such as PET. We describe the multi-shot target that we have developed and the related diagnostic to characterize the focal spot and the relative distance between the target and the focus. The multi-shot target will permit the use of thin foils or nano-structured targets with repetition rates relevant to our high power laser system.

1. Introduction
Laser acceleration of ions by ultrashort high power laser system has been a topic of intense research over the last two decades [1, 2, 3]. The production of MeV ion bunches from the interaction of these laser pulses with solid targets is attractive for a wide range of applications such as ion beam therapy [4], fast ignition [5], radiography [6] and production of radio isotopes for nuclear medicine [7, 8].

The physical mechanisms behind the acceleration processes such as the Target Normal Sheath Acceleration (TNSA), Radiation Pressure Acceleration (RPA) and others are well established [3] and several proofs of principle exist. All of these mechanisms have limited efficiency and while some of these mechanisms have a favorable energy scaling for higher laser powers, the main bottleneck towards applications is the average power of the sources [9, 10]. The average power of the source is related to the energy of the ions produced on each shot and the number of shots per second that can be achieved. This last problem is directly related to the target system and the laser repetition rate to be used. A good target system for applications should solve the problem of reproducibility, stability of the source and the need for a large number of shots in the same target [11].
While high power laser systems can provide relatively high repetition rates ($\sim 0.5-10Hz$) there are only few examples of target systems that can sustain continuous operation of a proton source at relevant repetition rates [12, 13, 14, 15]. Most of the applications mentioned above require a stable proton source with high average power [11]. The advantages of having targets systems capable of sustaining the repetition rate of the laser are many, such as systematic studies, further optimization of the experimental parameters and ultimately the demonstration of the devised applications.

In this paper we describe the target system developed at the L2A2 facility at the University of Santiago of Compostela to produce ions from laser plasma interactions. The proposed target assembly provide an accurate positioning system of targets for repetition rates (0.1-10 Hz) relevant to high power laser systems for a large number of shots (>1000). The target system should also be capable to support different type of target materials such as thin foils or micron and nano-structured targets made with MEMS technology[17]. Such target system could be tested for the application of radio isotope production.

2. Experimental setup
For the ion acceleration experiment we will use a laser system (THALES ALPHA 10/XS) that has two Chirped Pulse Amplification (CPA) stages [16]. In the first stage the pulse is amplified to $E = 1 \text{ mJ}$ at 1 KHz and compressed to 35 fs where a Cross polarization wave (XPW) module [17, 18] is used to enhance the contrast of the pulse. The contrast achieved with this setup is larger than 10 orders of magnitude and will play an important role in the interaction with solid targets. After improving the contrast, the pulse goes through a second CPA amplification stage to reach a final energy of $E = 1.2 \text{ J}$ and after compression a temporal FWHM of 25 fs with a repetition rate of 10 Hz.

The compressor is connected to the experimental chamber through a 8 m vacuum beam line. The laser beam has a 50 mm diameter and enters into the experimental chamber parallel to a diode laser (Z-Laser, 40 mW, 685 nm) enlarged with a telescope to match the laser. We will refer to this beam as the alignment beam. Figure 1 shows the experimental setup. We use a $45^o$ Off Axis Parabola (OAP) with an reflective focal length of 89.28 mm (F/1.8) to produce a 4 $\mu m$
focal spot which corresponds to an intensity of $4 \times 10^{20}$ W/cm$^2$. A leak from one of the mirrors is frequency doubled with a BBO crystal to produce a probe beam which can be delayed from the main beam and that passes parallel to the target surface.

### 3. Target for multi-shot

The most important challenge for the design of the target system is to refresh the target material at the laser focus with the required accuracy and velocity to sustain a high repetition rate. Our target system consist of a positioning system, a holder for the targets and a diagnostic system to measure the focal spot and to align the target relative to the laser focus. The design of the system takes into account the experimental constrains of the laser focusing and the diagnostics of the interaction.

The positioning system is the most critical part because it must align the target in focus to achieve the highest intensity on target and keep the alignment for all the targets in the disk that holds the targets. The Rayleigh length defines the allowed error and in our case is 30 μm. The positioning system is made of an arrangement composed by one rotating stage (PiMicos, DT-65N) and two linear stages (PiMicos, PLS-85 and LS-110) all stacked in a single assembly as shown in Fig. 2(A). The rotating stage holds a disk where the target foils are located, and it can achieve a rotation speed of 15°/s in high vacuum. This stage is held by an L-shape piece to the first linear stage (S1) which controls the target position relative to the focal plane. This stage is attached on top of the second linear stage (S2) which is used to translate the disk and change the radius where the laser impacts.

We have designed different holders for the target system. The first one shown in Fig. 3(b) is a disk with 8 slots to hold up to 40 different targets in the disk. A second target made with a 3D printer can hold 9 slots each one with 6 targets (Fig.3(b)) and third holder will be used to hold 6” silicon wafer used in the construction of micro structured targets with the MEMS technology [14]. These micro structured targets have shown to enhance the energy absorption and the final energy of the accelerated protons [19, 20].
4. Diagnostic of the focus and target positioning

In order to characterize and to measure the spot size of the laser after the OAP we use a microscope objective (Mitutoyo, M Plan Apo NIR 50x) located behind the target in the axis defined by parabola and the visible alignment beam as shown in Figure 4.
Figure 5: Focal spot of the alignment beam for different magnifications/camera ($\beta$) resolutions.
(a) $\beta=3.62$, (b) $\beta=8.48$, (c) $\beta=8.52$ (d) $\beta=10.00$, (e) Calculated mean value for the focus: $15 \pm 2 \mu m$

We place the microscope objective and use the alignment laser described before to image the focal spot size with a linear stage with 0.05 $\mu m$ step size (Thorlabs, MTS25/M-Z8). Once the microscope objective is in place, we measure the spot size with a CMOS camera (5 Mpx, Mightex) for different magnifications, as shown in Figure 5. The measured spot size is $15 \pm 2 \mu m$ mean value for the alignment beam (Fig. 5(e)), which has larger divergence than the infrared beam. We make use of this setup to position the target surface in the best focus. We do this using two complementary techniques. The first one is imaging the rear side of the target and the other one is the speckle technique.

The first technique works in the following way: Once the laser spot size is characterized and the position of the microscope objective fixed to image the focus of the laser, we place the target holder in front of the laser and look at the rear side of targets using the microscope objective and a white LED light. As the incidence angle of the laser in the target is $45^\circ$, we only observe a line in focus in the camera. When the central part of the rear side image in the camera is in the objective focal plane as shown in Figure 6, that surface is at the position of the laser focus. Therefore we just need to use the motor S1 to move the target exactly by the width of the target disk to ensure that the laser focus matches the surface of the target facing the laser. We can use this technique to put in focus up to 10 targets places and record the motor positions for the best focus on target in each of these 10 targets. After we have done this we remove the microscope objective before the shots.
Figure 6: (a) Speckle image of the target on focus. (b) Speckle image of target 100 μm after focus. (c) Rear side image of a thin foil of copper used to test the technique at the best target position. (d) The same copper foil rear side when the target is off focus.

While this technique is enough to position the target on focus, we have verified that it matches with the best target position characterized with the speckle. Figure 6 shows the reflection of the alignment beam in the surface of the target. As the target approaches to the focus, the reflection of the alignment beam changes from a rough reflection (Fig. 6(b)) to a smooth reflection (Fig. 6(a)) on focus. The back lighting and the speckle techniques provide very similar positioning of the target at the laser focus. Both techniques have some advantages and problems and we use both complementary. The back lighting technique is useful to characterize the main laser focus but the microscope objective and the camera need to be removed before the high power laser can be used because of the required vacuum. On the other hand, the speckle technique uses a reflection which can be guided to a screen outside of the chamber.

In the Figure 7 an image of the target holder after the laser impact is shown. In each of the target position the laser destroy the target foil. The size of the damage is similar in all used positions which is an indication that the laser intensity has been the same in all of them.
Figure 7: Six targets after the impact with the laser pulse. The position of the motors for the beast focus on target is recorded for each site in the target, this way we guarantee the same intensities on target.

5. Conclusions
Proton acceleration from the interaction of solid targets with high power lasers using the TNSA scheme has been proven to produce ion beams with extraordinary features which could open new applications. In order to explore all these possible applications, it is necessary to design a source with high average power. Such source should have a target system which can work using the repetition rate available from the laser system. In this paper, we have introduced a multi-shot target and an alignment system which would allow us to have a large number of shots without opening the experimental chamber. The final objective is to obtain a multishot target to perform systematic studies and to improve the stability and reproducibility of the source. The rotating system presented here uses a rotating disk to accommodate > 1000 targets. Also we have verified that the backlighting and the speckle method coincide in the determination of the best overlap between the target and the laser focus which allow us to use them in different situations.

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