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Automated Delivery of Micro-fabricated Targets for Intense Laser Irradiation Experiments

--Manuscript Draft--

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Dear Editor,

Please find enclosed our manuscript entitled "*High Repetition-Rate Intense Laser Irradiation of Micro-fabricated Targets"* that we would like to be considered for publication in *JoVE*. This paper highlights a protocol for irradiating micro machined sub wavelength targets at a high repetition rate. We consider of value publishing these data in JoVE, as they bring on a solution for irradiation experiments requiring high statistics and fine scan of geometric attributes when in interaction with a high power laser. The techniques presented in this paper and demonstrated in video format will be highly useful for researchers working in the field of nuclear photonics.

The bulk of the procedure, experiments and writing of this manuscript were carried by all participants listed in the paper.

During the preparation and submission of this manuscript, we have been kindly assisted by Jialan Zhang & Lyndsay Troyer.
Thank you for your consideration of this manuscript. We look forward to hearing from you.

Sincerely yours,

Yonatan Gershuni
NePTUN – Nuclear Photonics at Tel Aviv University
P.I – Dr. Ishay Pomerantz

TITLE:

Automated Delivery of Microfabricated Targets for Intense Laser Irradiation Experiments

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KEYWORDS:
high intensity laser, thin foil irradiation, ion acceleration, MeV protons, laser target fabrication, target positioning

SUMMARY:
A protocol is presented for automated irradiation of thin gold foils with high intensity laser pulses. The protocol includes a step-by-step description of the micromachining target fabrication process and a detailed guide for how targets are brought to the laser's focus at a rate of 0.2 Hz.

ABSTRACT:
Described is an experimental procedure that enables high-power laser irradiation of microfabricated targets. Targets are brought to the laser focus by a closed feedback loop that operates between the target manipulator and a ranging sensor. The target fabrication process is explained in detail. Representative results of MeV-level proton beams generated by irradiation of 600 nm thick gold foils at a rate of 0.2 Hz are given. The method is compared with other replenishable target systems and the prospects of increasing the shot rates to above 10 Hz are discussed.

INTRODUCTION:

High-intensity laser irradiation of solid targets generates multiple forms of radiation. One of these is the emission of energetic ions with energies at the Mega electron-volt (MeV) level[1]. A compact source of MeV ions has potential for many applications, such as proton fast-ignition[2], proton radiography[3], ion radiotherapy[4], and neutron generation[5].

A major challenge in making laser-ion acceleration practical is the ability to position micrometer-scale targets accurately within the focus of the laser at a high rate. Few target delivery technologies were developed to answer this challenge. Most common are target systems based on micrometer-scale thick tapes. These targets are simple to replenish and may be easily positioned within the focus of the laser. Tape target has been made using VHS[6], copper[7], Mylar, and Kapton[8] tapes. The tape drive system typically consists of two motorized spools for winding and unwinding and two vertical pins placed between them to keep the tape in position[9]. The accuracy in positioning the tape surface is typically less than the Rayleigh range of the focusing beam. Another type of replenishable laser target is liquid sheets[10]. These targets are delivered rapidly to the interaction region and introduce a very low amount of debris. This system comprises a high-pressure syringe pump continuously supplied with liquid from a reservoir. Recently, novel cryogenic hydrogen jets[11] were established as means to deliver ultrathin, low-debris, replenishable targets.

The main drawback of all of these replenishable target systems is the limited choice of target materials and geometries, which are dictated by mechanical requirements such as strength, viscosity, and melting temperature.

Here, a system able to bring micromachined targets to the focus of a high intensity laser at a rate of 0.2 Hz is described. Micromachining offers a wide choice of target materials in versatile geometries[12]. The target positioning is performed by a closed-loop feedback between a commercial displacement sensor and a motorized manipulator.

The target delivery system was tested using a high-contrast, 20 TW laser system that delivers 25 fs-long laser pulses with 500 mJ on target. A review of the laser system's architecture is given in Porat et al.[13], and a technical description of the target system is given in Gershuni et al.[14]. This paper presents a detailed method for making and using this type of system and shows representative results of laser-ion acceleration from ultrathin gold foil targets.

The Thomson Parabola ion spectrometer (TPIS)[15,16] shown in **Figure 1** was used to record the energy spectra of the emitted ions. In a TPIS, accelerated ions pass through parallel electric and magnetic fields, which places them on parabolic trajectories in the focal plane. The parabolic curvature depends on the ion's charge-to-mass ratio, and the location along the trajectory is set by the ion's energy.

A BAS-TR imaging plate (IP)[17] positioned at the focal plane of the TPIS records the impinging ions. The IP is attached to a mechanical feedthrough to allow translation to a fresh area before each shot.

PROTOCOL:

1. Target fabrication

NOTE: **Figure 2** and **Figure 3** illustrate the fabrication process of freestanding gold foils.

1.1. Back Side

1.1.1. Use a 250 µm thick, 100 mm diameter, high-stress silicon wafer in a <111> crystal formation, coated on both sides with silicon nitride.

1.1.2. Clean the wafer using acetone, followed by isopropanol, and then spin coat a layer of SF9 resist to form an adhesive layer following the steps outlined in **Table 1**.

[Place **Table 1** here]

1.1.3. Bake the wafer at 180 °C for 5 min, then let it cool.

1.1.4. Spin-coat the wafer with an AZ4562 positive photoresist layer following the steps outlined in **Table 2**.

[Place **Table 2** here]

1.1.5. Photolithograph 1,000 µm x 1,000 µm square openings under vacuum, exposing the wafer in four cycles of 4 s each to a 400 nm UV lamp. Wait 25 s between cycles, so that the wafer is exposed to an overall fluence of 150 J/cm^2. Use an AZ726 developer to expose the silicon nitride, and a bath of dehydrated water to stop the process.

1.1.6. Use Reactive Ion Etcher (RIE) to remove the silicon nitride in the location of the squares.

1.1.7. Use an N-methyl-2-pyrrolidone (NMP) bath for 20 min to remove the residual resist and photoresist, producing a replica of the mask on the silicon nitride layer. Wash the wafer under fresh water and let dry.

1.1.8. Sink the wafer in a 30%, 90 °C, potassium hydroxide solution to etch the silicon through the square openings. Sink the wafer for 40 min for every 50 µm of silicon that needs to be etched. Because the etch rate in the <111> plane is much higher than in others, the potassium hydroxide reaches the bottom silicon nitride layer through the silicon bulk before etching any significant depth in the silicon nitride mask.

1.1.9. On the etched side of the wafer, use a physical vapor deposition machine (PVD)[18] to sputter a layer of a few hundred nanometers of gold on top of a ~10 nm thin film of adhesive titanium, nickel, or chrome. The sputtered gold layer will become the freestanding membrane target.

1.2. Front Side

1.2.1. For the front side, repeat steps 1.1.1–1.1.6 with a mask shaped as three concentric rings.

1.2.2. Use RIE to remove the silicon nitride where the rings are located, followed by an NMP bath to remove resist and photoresist leftovers.

1.2.3. Finally, to roughen the silicon rings, sink the wafer in nitric acid and in a solution of 0.04 M silver nitrate and 4 M hydrogen fluoride.

2. Alignment

NOTE: **Figure 4** shows the target irradiation setup.

2.1. Bring a first arbitrarily chosen target into view under a 100x magnification microscope.

2.2. Point a triangulation ranging sensor (e.g., MTI/MicroTrak 3 LTS 120-20)[19] to the roughened ring closest to the target, and record its displacement reading.

NOTE: The ranging sensor model used is not intended for high-vacuum applications. Different models, like the MTI-2100 from the same vendor, are compatible with low-outgassing applications.

2.3. While leaving the microscope in place, move the wafer away a known distance to clear the beam path.

2.4. Using two folding mirrors and the off-axis parabolic mirror (OAP), align the beam in low power into the field of view of the microscope.

2.5. Adjust these three mirrors to correct astigmatisms in the beam. The result should be a nearly diffraction-limited focal spot.

2.6. Block the laser beam and bring the target back to the focus of the microscope. Validate its position using the microscope and the ranging sensor's reading.

2.7. Move the microscope to a position in which it will be kept safe from laser light and debris.

3. Irradiation sequence and automated target positioning

3.1. Implement a closed-loop feedback between the focal axis manipulator of the target and the displacement sensor reading using software. Use the recorded value from protocol step 2.2 as the setpoint. The main PID[20] control sequence, prepared with LabView, is shown in **Figure 5**.

3.2. Once the closed-loop positioning has reached a desired tolerance distance from the setpoint, irradiate the target with a single high-power laser pulse.

3.3. Translate the IP using the mechanical feedthrough to a new position.

3.4. Repeat the irradiation sequence with the next target brought to focus by the software.

REPRESENTATIVE RESULTS:

This target delivery system was employed to accelerate ions from the back side of 600 nm thick gold foils. When irradiated with a normalized laser intensity of a_0 = 5.6, these ions were accelerated by the target normal sheath acceleration (TNSA) mechanism[21]. In TNSA, the lower-intensity light that preceded the main laser pulse ionized the front surface of the target foil. The ponderomotive force exerted by the main laser pulse drove hot electrons through the bulk matter. A charge separation on the back surface, induced by these electrons[22], created an extreme electrostatic gradient that accelerated ion contaminants in the target-normal direction. A time series of the target displacement along the focal axis is shown in **Figure 6**. The values are relative to the focal position setpoint. The green dots indicate when the target displacement was within a tolerance value of 1 µm from the setpoint; this is when a laser shot was taken.

Figure 7 shows TPIS traces from 14 consecutive irradiations of 600 nm thick gold foil targets. The energy spectrum derived from these traces is shown in **Figure 8**. The peak-to-peak stability of the maximum proton energy is within 10%.

FIGURE AND TABLE LEGENDS:

Figure 1: A technical layout of the Thomson parabola ion spectrometer.

Figure 2: A schematics sketch of the target wafer. The front side, showing 300 gold foil targets ordered in three concentric rings (left). The back, showing roughened fiducial rings positioned between the target foil locations (right).

Figure 3: An illustration of the wafer fabrication process.

Figure 4: A schematic layout (left) and photo (right) of the interaction chamber.

Figure 5: Target positioning PID LabView code (VI).

Figure 6: Target displacement during a shot sequence of 20 targets.

Figure 7: TPIS traces from 14 consecutive shots. The trajectories of ions and X-rays passing through the TPIS are illustrated.

Figure 8: Ion energy spectra derived from the 14 traces shown in Figure 7.

Figure 9: A TPIS trace recorded using a low dynamic range CCD imaging of a CsI(TI) scintillator.

Table 1: Resist spin coat steps.

Table 2: Photoresist spin coat steps.

Table 3: Comparison of different target types.

DISCUSSION:

With some variations, the target fabrication process described in this protocol is common (e.g., Zaffino et al.[23]). Here, one unique step that is critical to the operation of automatic positioning is the addition of nanometer-scale roughening in ring-shaped areas on the back of the wafer (step 1.2.3). The purpose of this step is to increase the diffused scattering of light incident on the wafer in those areas. The ranging sensor shines a low-power laser beam on the wafer, collects the scattered light, and determines its displacement by triangulation.

The data shown above were taken at a rate of one shot per 5 s, with the rate-limiting factor being the translation time of the IP. Shown here is a preliminary result of a simple, inexpensive, online readout method that will increase the shot duty cycle. Online readouts have been traditionally made using either microchannel plates[24] or plastic scintillators[25,26]. In the latter case, an expensive, image-intensified gated CCD was required to record the relatively low amount of scintillation light. The current system uses a simpler readout system based on a different scintillator material, Csl(Tl), which is bright enough to be recorded with an inexpensive, low dynamic range CCD. This choice of scintillator has been suggested and discussed by Pappalardo et al.[27].

Figure 9 shows a sample image of a TPIS trace taken with a low dynamic range CCD image of a Csl(Tl) scintillating screen. These traces were taken with a relatively large aperture, to produce a high quantity of scintillation light. Further study is required to identify the optimal settings in terms of signal-to-noise ratio and energy resolution.

The image shown in **Figure 8** was acquired using a 1.6 megapixel camera. At a 10 Hz rate and 8-bit pixel depth, the data stream would amount to about 130 Mbps. This data rate is supported by either a USB3 or GigE communication interface.

The mechanical stability of any replenishable laser target delivery system may be compromised by a higher delivery rate or by the higher impact induced by higher energy laser pulses. **Table 3** presents a comparison between this work and various other target delivery technologies. The performance of this system at higher shot rates and higher energy pulses will be investigated in the near future.

[Place **Table 3** here]

ACKNOWLEDGMENTS:

This work has been supported by the Israel Science Foundation, grant No. 1135/15 and by the Zuckerman STEM Leadership Program, Israel, which are gratefully acknowledged. We also acknowledge the support of the Pazy Foundation, Israel grant #27707241, and NSF-BSF grant No. 01025495.

DISCLOSURE:

The authors have no competing financial interests.

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photostimulable image plate detectors used as high-energy proton detectors. *Review of Scientific Instruments*. **79**, 73301 (2008).
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Figure 1

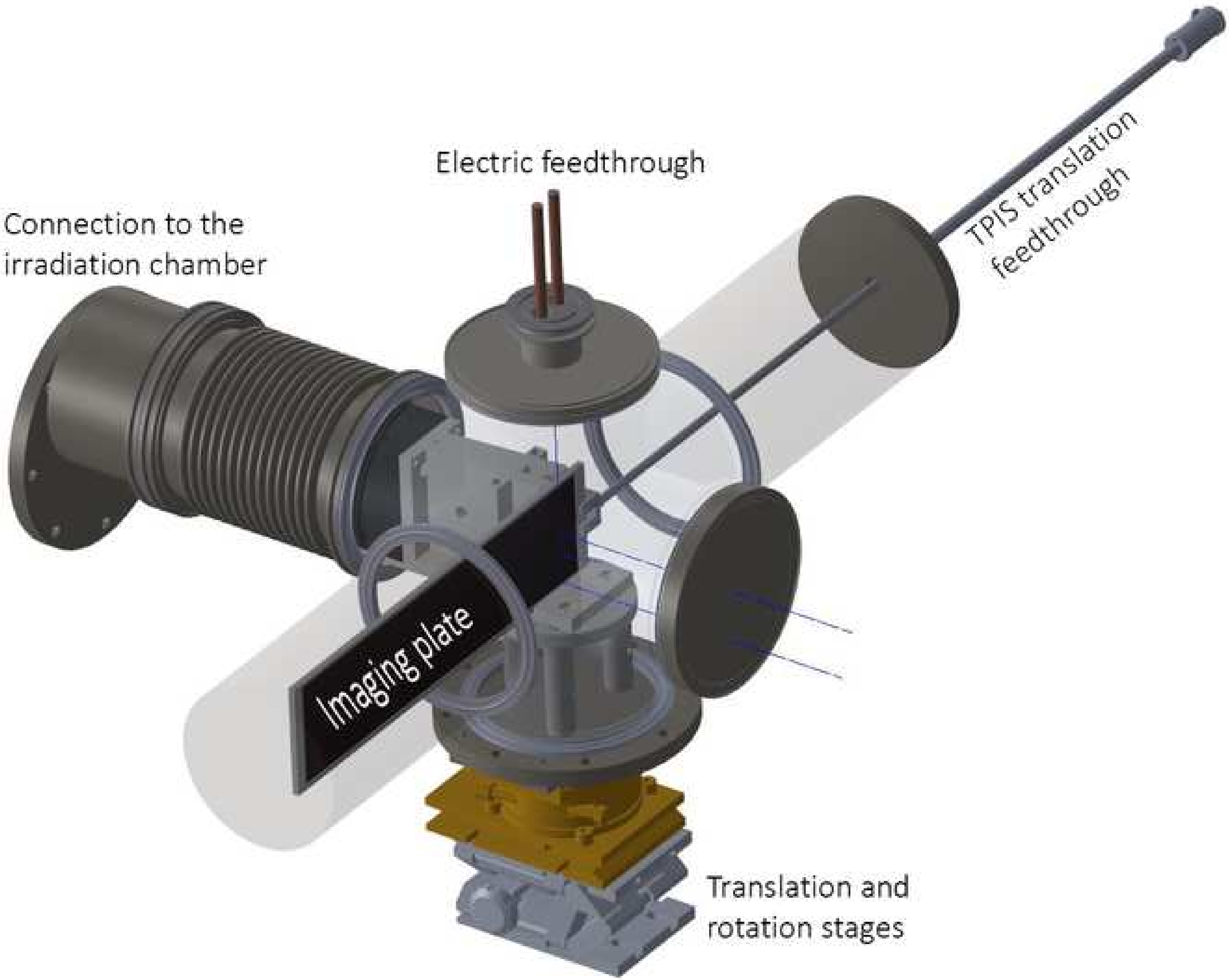

Electric feedthrough
Connection to the irradiation chamber
TPIS translation feedthrough
Imaging plate
Translation and rotation stages

Figure 2

Click here to access/download;Figure;Figure 2.tif

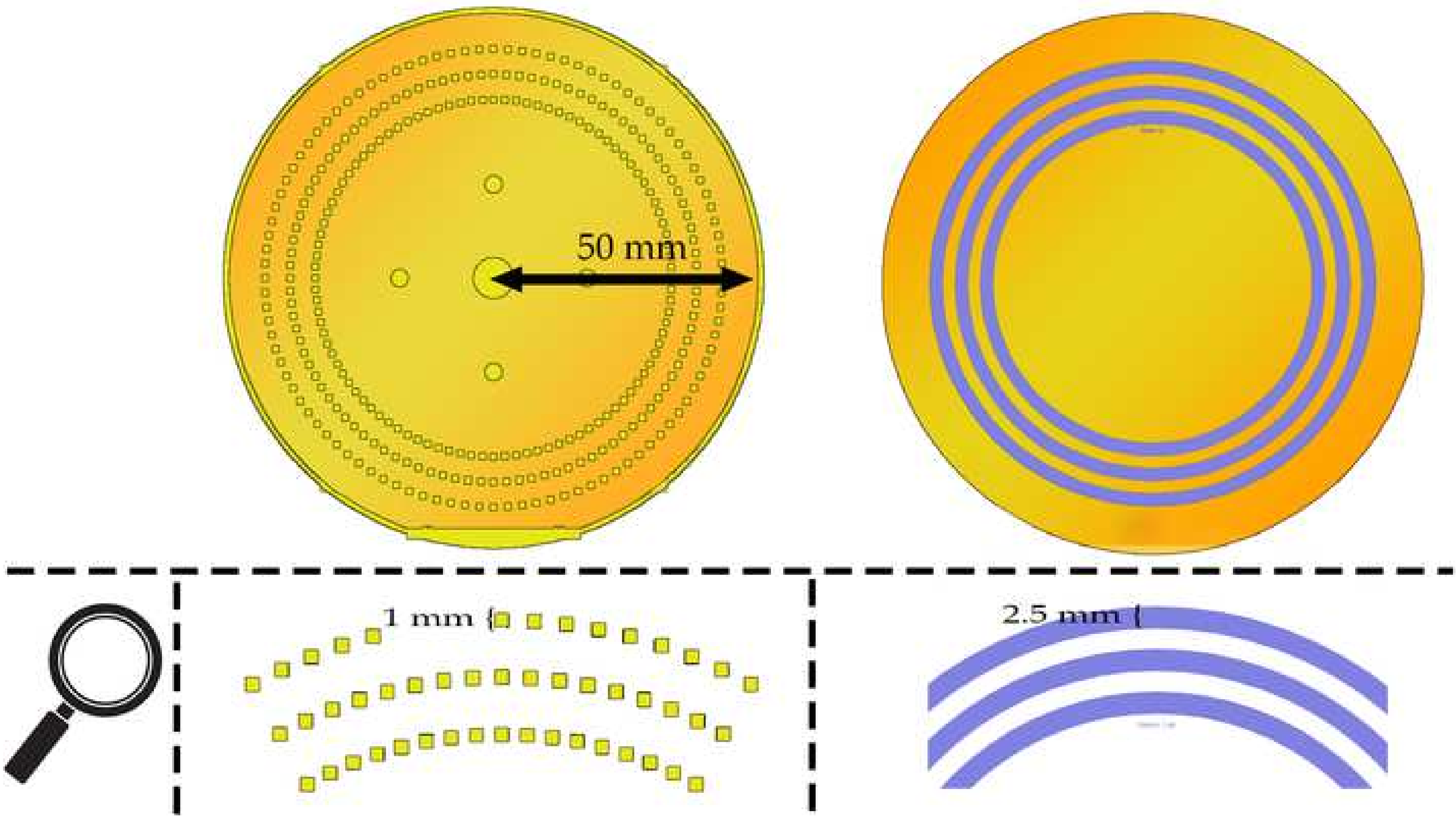


Figure 3

Click here to access/download;Figure;Figure 3.tif

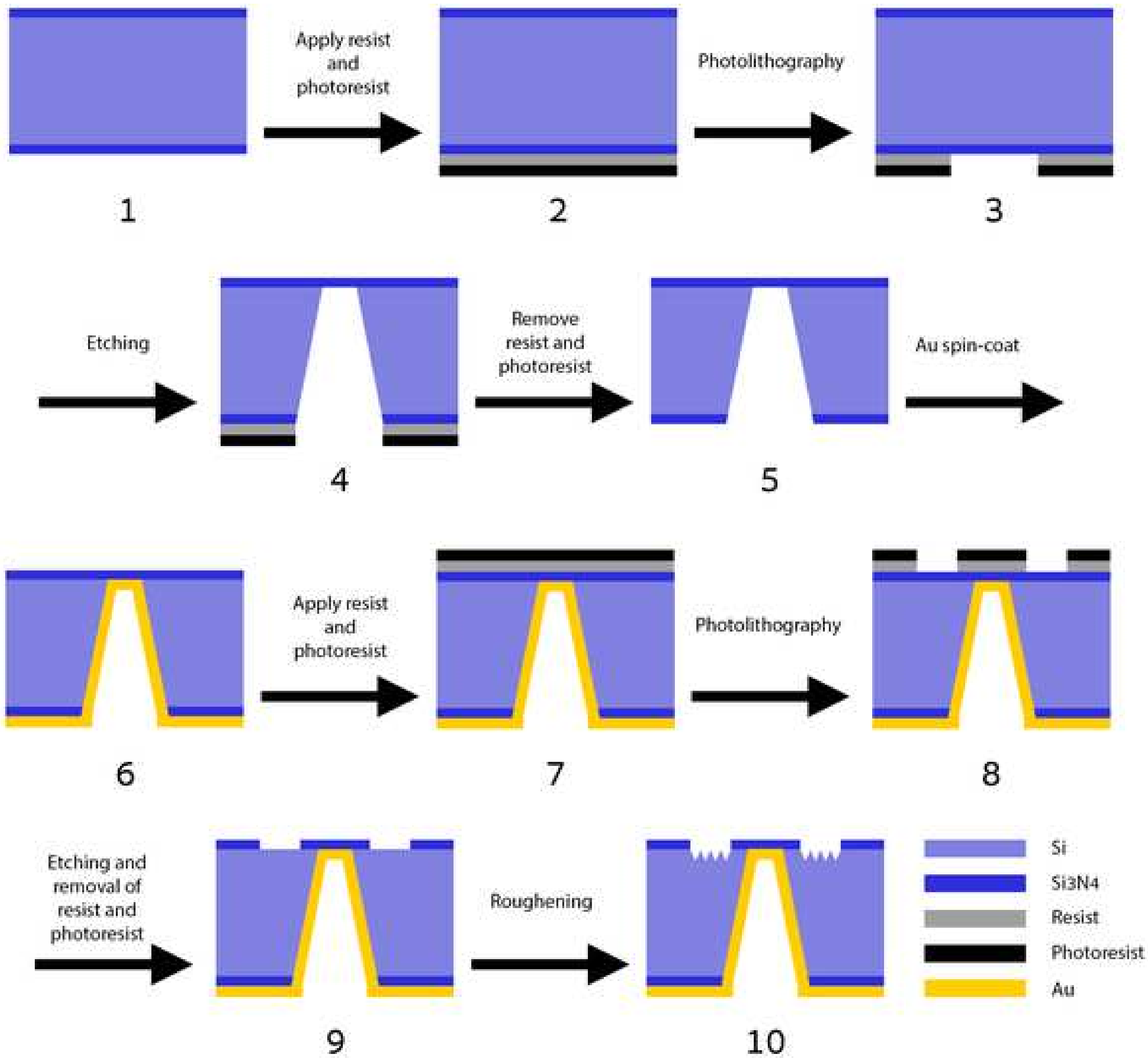


Figure 4 Click here to access/download;Figure;Figure 4.jpg

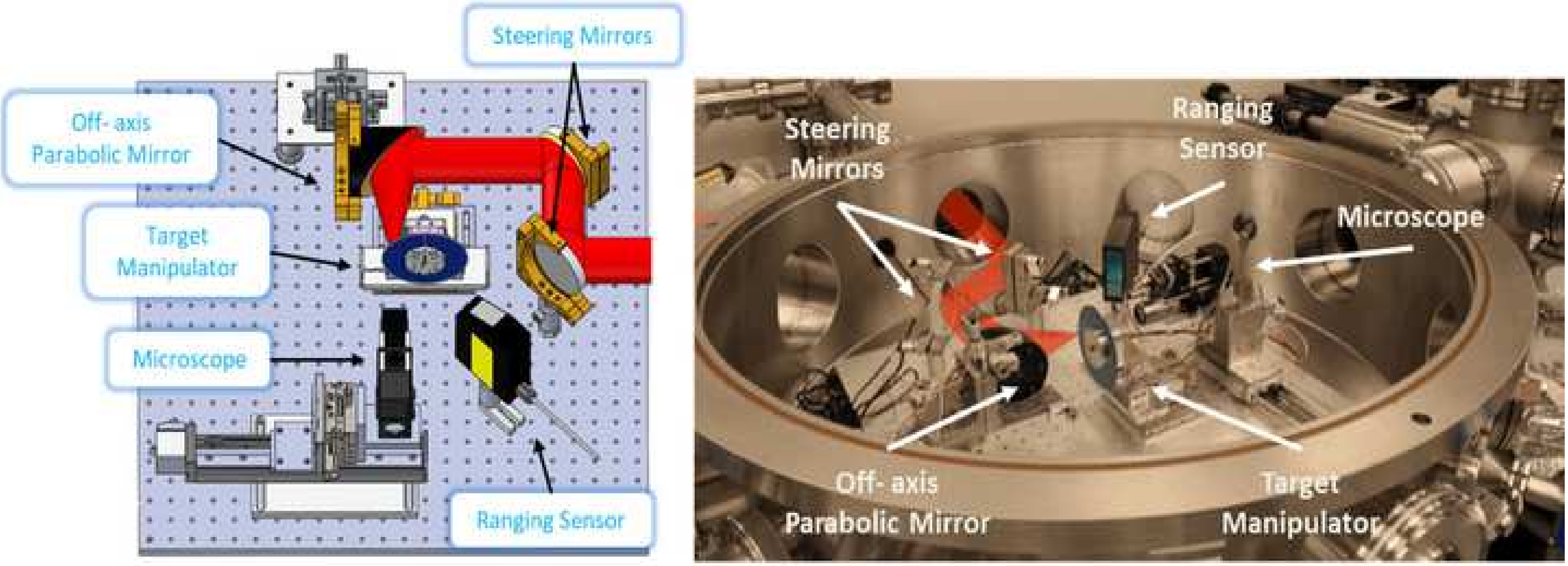


Figure 5

Click here to access/download;Figure;Figure 5.tif

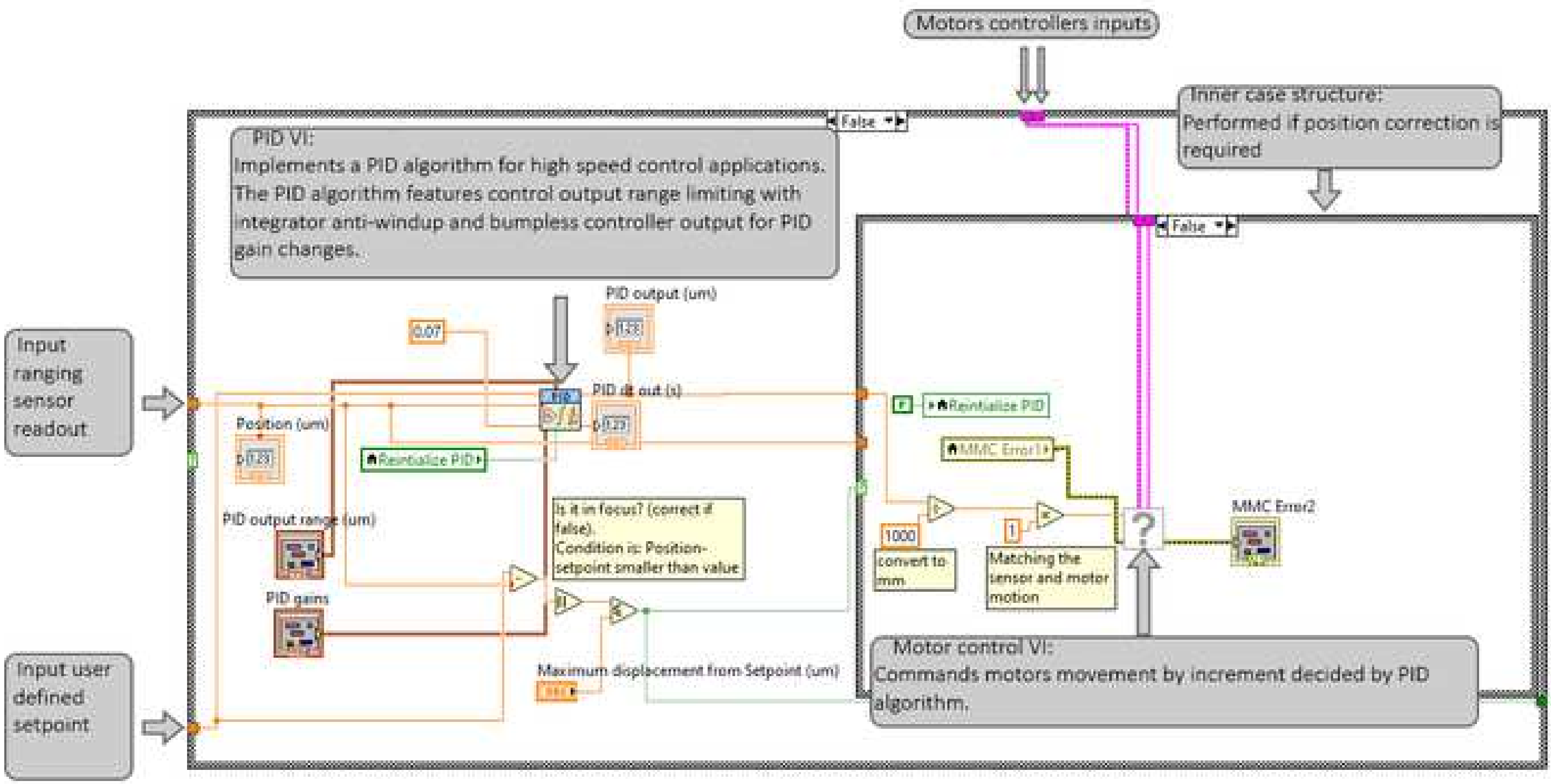
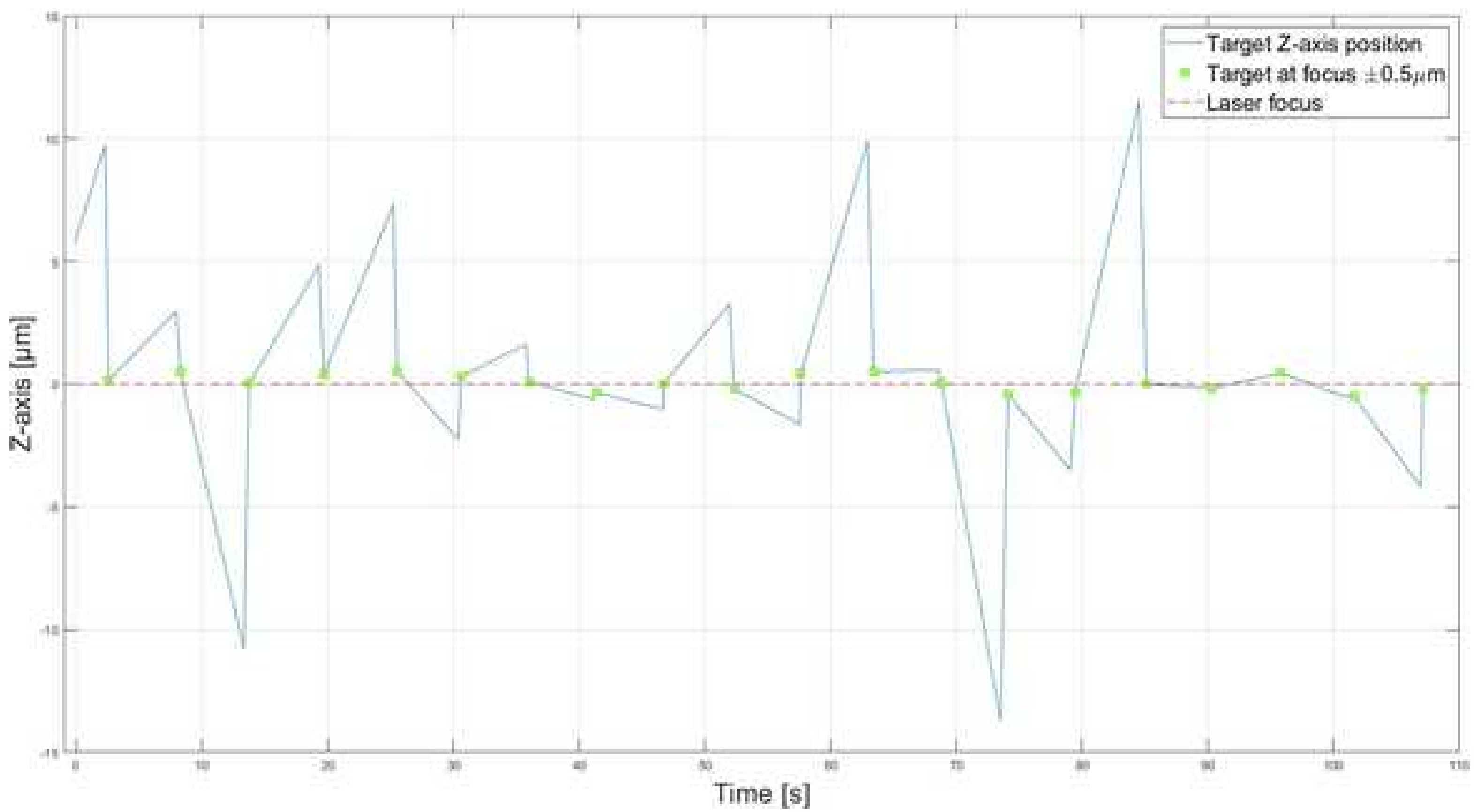


Figure 6



Target Z-axis position
Target at focus ±0.5μm
Laser focus
Z-axis [μm]
Time [s]

Figure 7

Click here to access/download;Figure;Figure 7.tif

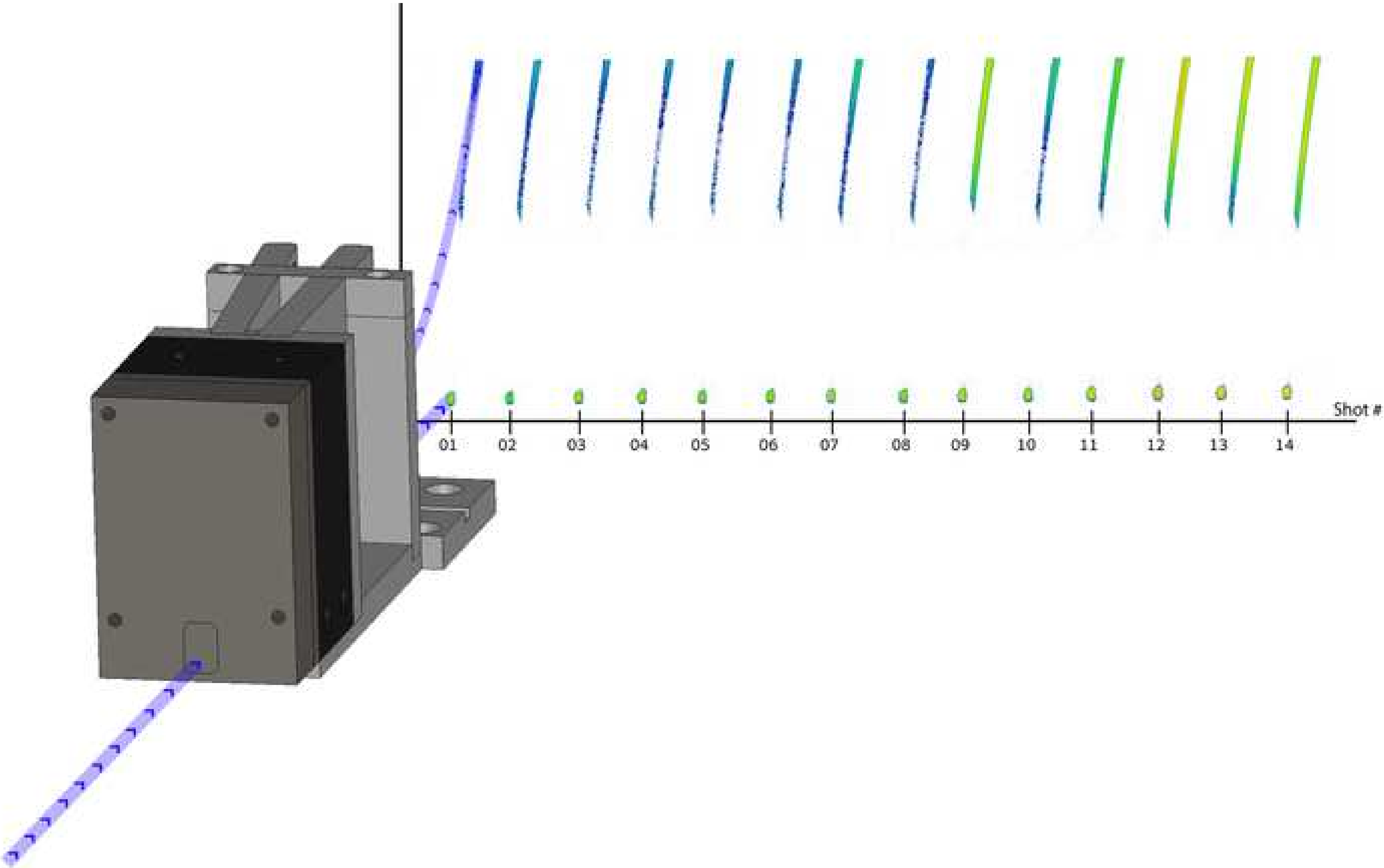


Figure 8

Click here to access/download;Figure;Figure 8.pdf

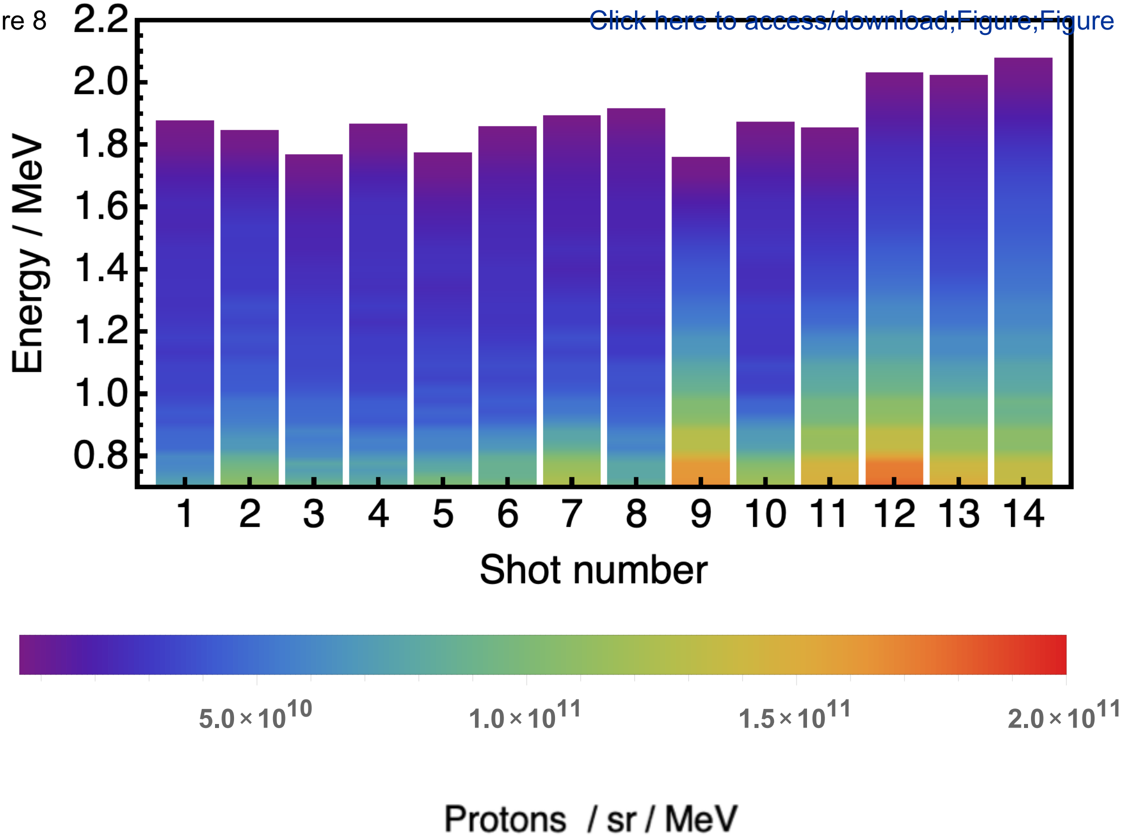
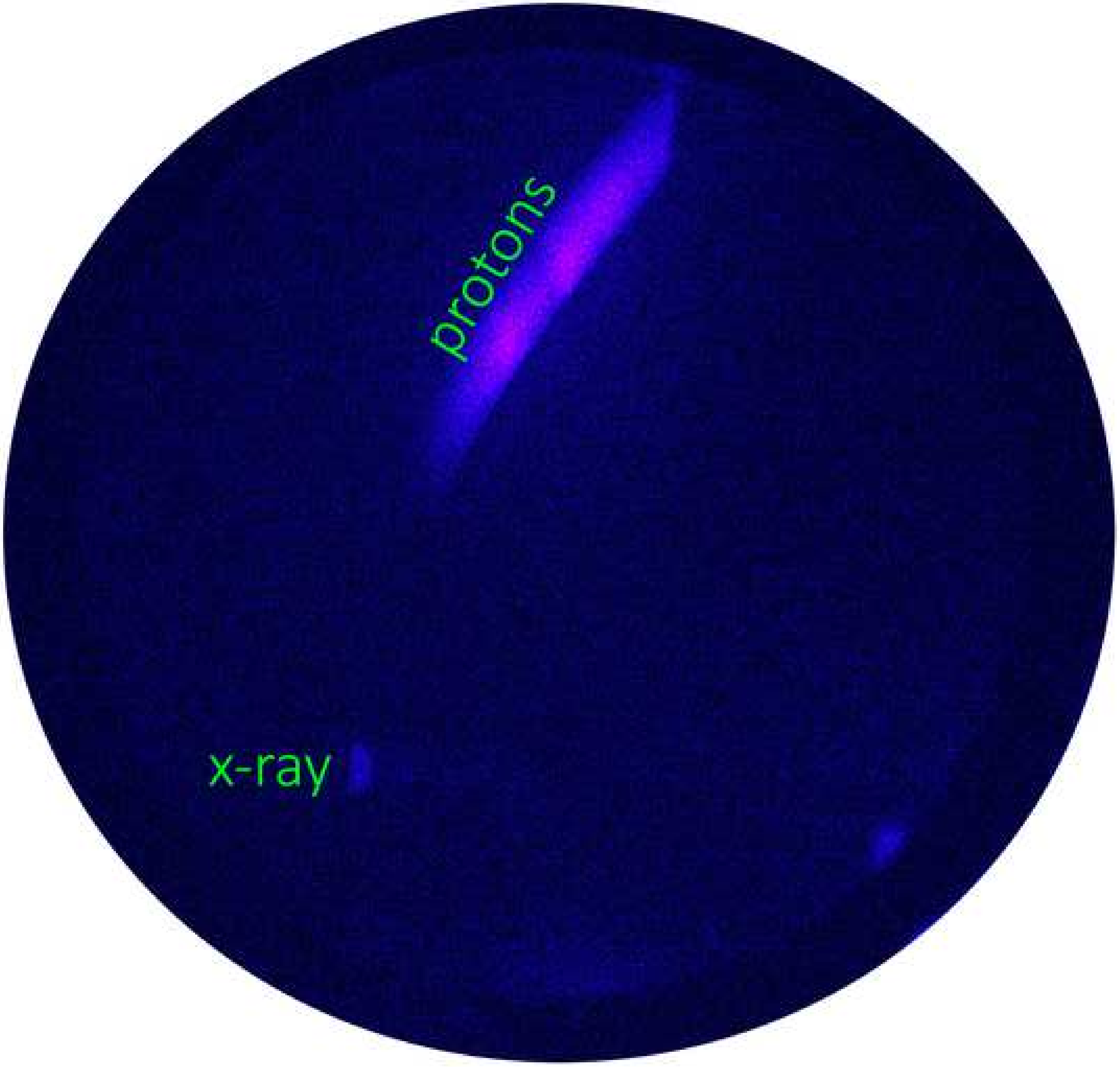


Figure 9

Click here to access/download;Figure;Figure 9.tif



Step	*v* [rps]	ramp [rps^2]	Duration [s]
1	500	500	10
2	4000	1000	45
3	0	1000	0

Table 2

Step	***v* [rps]**	**ramp [rps^2]**	**Duration [s]**
1	500	300	10
2	2000	1000	45
3	0	1000	0

Reference	**Target type**	**Materials**	**Thickness**
[6]	Tape	Mylar	15 µm
[10]	Liquid Sheet	Ethelyne Glycol	0.4 µm
[11]	Hydrogen Jet	H_2	20 µm
This work	Micro-machined Au foil	Au	0.6 µm

Repetition Rate	Laser Energy
0.2 Hz	5 J
1 kHz	0.011 J
1 Hz	600 J
0.2 Hz	0.5 J

Name of Material/Equipment	Company	Catalog Number	Comments/Description
76.2 x 127mm EFL 90° Protected Gold 100Å Off-Axis Parabolic Mirror	Edmund optics	35-535	
MicroTrak 3 LTS 120-20	MTI Instruments		
Ultrafast high power dielectric mirrors for 800 nm	Thorlabs		

Dear Dr Phillip Steindel,

Below is our detailed response to the reviewers' comments on the submission of our manuscript "High Repetition-Rate Intense Laser Irradiation of Micro-fabricated Targets".

We would like to express our gratitude for the constructive nature of their criticism.

Editorial comments:
General:
1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.
2. Please ensure that the manuscript is formatted according to JoVE guidelines–letter (8.5” x 11”) page size, 1-inch margins, 12 pt Calibri font throughout, all text aligned to the left margin, single spacing within paragraphs, and spaces between all paragraphs and protocol steps/substeps.
3. For in-text formatting, corresponding reference numbers should appear as numbered superscripts (without brackets) after the appropriate statement(s).

Keywords:
1. Please provide a separate ‘Keywords’ section with at least 6 key words or phrases.
Response: We added a keywords section.

Summary:
1. Please include a separate Summary section (before the abstract) that clearly describes the protocol and its applications in complete sentences between 10¬ and 50 words, e.g., “Here, we present a protocol to …

Response: We added a summary section.

Protocol:
1. For each protocol step/substep, please ensure you answer the “how” question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action. If revisions cause a step to have more than 2-3 actions and 4 sentences per step, please split into separate steps or substeps.

Response: We added these details to steps 1.1.2, 1.1.4, 1.1.7, 1.1.8 and 1.1.9.

Specific Protocol steps:
1. 1.1. Please provide more details about these steps; e.g., what are the parameters for sputtering in 1.1.9?

Response: We now indicate the specific sputtering process in 1.1.9 and give a general reference for the process of physical vapor deposition.

2. 3.1: Please provide more details about this software (possibly including code as supplemental information).

Response: We added Figure 5, which shows the schematics of the main closed loop controller, realized with LabView. The figure is referenced in the text:

The main PID control sequence, realized with LabView, is shown in Figure 5.

Figures:
1. Figure 5: Please use ‘s’ instead of ‘sec’. Please also ensure that ‘μ’ is not italicized.

Response: We applied these corrections.

2. Figure 6: Why is there an image of an instrument here? Please clarity in the legend.

Response: We show the instrument to guide the eye of a reader unfamiliar with Thomson Parabola spectrometers to the ion and x-ray trajectories. We added an explanation to the figure’s caption.

Discussion:
1. Please revise the Discussion to explicitly cover the following in detail in 3–6 paragraphs with citations:
a) Critical steps within the protocol
b) Any modifications and troubleshooting of the technique
c) Any limitations of the technique
d) The significance with respect to existing methods
e) Any future applications of the technique

Response: We added two paragraphs to the Discussion. One about the necessity of the nanometric roughening process and the other about the anticipated data-rates for an online readout.

Acknowledgment and Disclosures:
1. Please include a Disclosures section, providing information regarding the authors’ competing financial interests or other conflicts of interest. If authors have no competing financial interests, then a statement indicating no competing financial interests must be included.

Response: We added a statement indicating of no competing financial interest.

References:
1. Please format references as the following: [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. Source. Volume (Issue), FirstPage – LastPage (YEAR).] For more than 6 authors, list only the first author then et al.
2. Please do not abbreviate journal titles.

Response: We amended the bibliography to comply with JOVE format.
Table of Materials:
1. Please ensure the Table of Materials has information on all materials and equipment used, especially those mentioned in the Protocol.
Response: We uploaded an updated table of materials.

Reviewers' comments:
Reviewer #1:
Manuscript Summary:

The paper describes the fabrication and irradiation by an intense laser pulse of metallic thin layer targets in multi-shot sequential modality at a frequency of 0.2 Hz used to accelerate protons by the TNSA mechanism. The delivery of a fresh target at laser focus is assured by implementing a closed loop feedback between the target manipulator and the reading of a displacement sensor. Focusing fidelity between following shots is achieved with a variation of the peak-to-peak proton energy less of the 10%.

Major Concerns:
The development of applications based on the use of the radiation obtained by laser-ion acceleration requires both higher repetition rates (>>10Hz) and higher acceleration energies (>10MeV). In view of this, although the system presented brings the potential of fulfilling both conditions, we cannot agree on the use of the term "high repetition rate" working at 0.2 Hz, and ultra-intense laser pulse can nowadays produced at frequencies above 100 Hz. What is demonstrated here is the production of proton radiation by means of the TNSA mechanism in multi-shot modality as a proof of a concepts which is relevant towards the ability of working at high repetition rate.

Response: We replaced every referral to “high repetition rate target delivery” to “automated target delivery”, to include the title.

Alignment section:
Could you clarify better point 2.2? From fig. 1, it seems that the fiducial roughened rings are on the back side of the wafer and overlaps with the targets obtained on the front side, which is in contrast with what depicted in fig. 2 starting from step 8, from which one understood that each line of targets on the front wafer side is between two roughened ring on the back side. Then, could confirm that laser focusing is determined on the roughened ring?

Response: The reviewer noted that it will be difficult to the reader to see by-eye that the target foils and roughened rings do not overlap. We added a specific remark indicating that it is so to the figure’s caption.

In the final discussion it is missed a comparison of the results both in terms of energy and rep rate that could be achieved by the other methods presented in the introduction with that described here. Then, at higher pulse energy and repetition rate the mechanical stability of the silicon wafer could represent a concern. It would be interesting to include this point in the discussion of the prospects of increasing the frequency to 10 Hz.

Response: We added a comparison table of the various replenishable target delivery technologies discussed in this paper, in terms of the repetition rate and laser energy under which they were tested.

Minor Concerns:
Title: is there any reason to use capital letter for each word in the title?

Response: This capitalization matches the Journal’s formatting style

key words: why foil fabrication?

Response: We revised this keyword to “Laser-targets fabrication” which is a major focus in this manuscript.

Abstract: line 23: if challenging problems within a given phenomenon would impede their investigation we could stop working! Could you rephrase this? It is more like that up to know this issue impedes the development of applications based on the laser-ion acceleration.

Response: The sentence was rephrased to read:

“A major challenge in making laser-ion acceleration applicable..”

Reviewer #2:
Manuscript Summary:
The manuscript is definitively of interest for the laser plasma acceleration specialists since it reports on typical technological issues connected with target delivery and ion diagnostics using high repetition rate, high intensity lasers interacting with thin foils, thus it deserves publication in Journal of Visualized Experiments. However several improvements should be carried out, as suggested below.

Major Concerns:
1. A Section (or sub-section) describing the experimental setup (laser characteristics, laser, plasma and ion diagnostics in the vacuum chamber) is totally missing and should be added.

Response: We added the following sentence, specifying the laser characteristics:
“The target delivery system were tested using a high-contrast, 20 TW laser system which delivers 25 fs long laser-pulses with 500 mJ on-target. A review of the laser system’s architecture is given in Ref[13].”

We also moved the paragraph describing the Ion Diagnostics to the introduction section.

2. Fig.8 show a sort of "preliminary proton spectrum from a TP using a plastic scintillator as imagining detector, nevertheless no spectrum recorded with IP is shown, despite the fact this was the main geometry used in the experimental test (Fig.7 is based on it). A typical spectrum from the TP configuration using an IP should be added in Fig. 8. Furthermore, a comparison with the configuration using a plastic scintillator should be added in the text.

Response: The reviewer’s comment made us realize that the text in this section is unclear. All of the data presented in Figures 6 and 7 were taken using an Imaging Plate which was manually translated.

The discussion here deals with a future method to improve the shot-rate in a simple inexpensive online method: using a Cs(Tl) scintillator instead of the traditional Plastic scintillator used in other works. The purpose of the preliminary image in fig. 8 is to show that the trace is bright enough to be acquired using a cheap CCD (rather than expensive cameras used with plastic scintillators).

A detailed study of using this type of scintillator will be published in a follow up paper.

The section was revised to read:

“The data shown above were taken at a rate of one shot per 5 seconds, with the rate-limiting factor being the translation time of the IP. Here we show a preliminary result of a simple inexpensive online readout method which will eliminate this bottleneck to

increase the shot duty-cycle…. We realized a simpler readout system, based on a different scintillator material, Csl(Tl), which is bright enough to be recorded with an inexpensive, low dynamic range CCD."

3. The reference list is not adequate in some cases:
a) The reference on proton radiography [Cobble et al. 2002] is not the original one showing this technique for the first time [Borghesi et al., Plasma Phys. Control. Fusion 43 (2001) A267]. This should be corrected
b) The reference on cryogenic H targets used for ion acceleration [Gauthier, 2017] is not the proper one in terms of pioneering studies on this topic: [Garcia et al, Las. Part. Beams 32, 2014 , 56] and [Margarone et al, Phys. Rev. X 6, 041030, 2016]
c) Instead of ref 12 [Zaffino et al] which is very specific, it would be more appropriate to cite a review paper on targetry for high intensity laser-matter interaction as [Prencipe et al., High Power Laser Science and Engineering, (2017), Vol. 5]

Response: We revised the three references according to the reviewer's suggestion.
Minor Concerns:
1) Line 44: a comment on high vacuum compatibility of the commercial displacement sensor should be added

Response: We added the following footnote to step 2.2:

The ranging sensor model used in this work is not intended for high-vacuum applications. Different models, like the MTI-2100 from the same vendor, are compatible with low-outgassing applications.

2) Section "Protocol", Sub-section "target fabrication": the bullet point style should be changed with a flowing style

Response: We feel that the bullet point style is unpleasant in this context as well. However, we followed the JOVE formatting instructions which states:

> *The protocol must be a numbered list: step 1 followed by 1.1, followed by 1.1.1, etc. Each step should include 1−2 actions and contain 2−3 sentences. Use subheadings and substeps for clarity if there are discrete stages in the protocol.*

3) Line 128: probably a misprint when writing "600 um". It should be "600 nm"

Response: We corrected this misprint.

4) Line 156: a short comment on data transfer strategy at 10 Hz of a TPIS image should be added

Response: We added the following text to the discussion:

The image shown in Fig. 8 is was acquired using a 1.6 MP. At 10 Hz rate and 8 bit pixels, the data stream will correspond to about 130 Mbps. We note that although this rate is supported by an inexpensive USB3 communication interface, for long cable lengths a GigE interface may be preferable.