

Article

Automation of Target Delivery and Diagnostic Systems for High Repetition Rate Laser-Plasma Acceleration

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Abstract: Fast solid target delivery and plasma-ion detection systems have been designed and developed to be used in high intensity laser-matter interaction experiments. We report on recent progress in the development and testing of automated systems to refresh solid targets at a high repetition rate during high peak power laser operation (>1 Hz), along with ion diagnostics and corresponding data collection and real-time analysis methods implemented for future use in a plasma-based ion acceleration beamline for multidisciplinary user applications.

Keywords: high repetition rate target; ion acceleration; laser–plasma interaction

1. Introduction

The rapid development of high peak, high average power lasers led to the implementation of relatively compact experimental systems, capable of delivering laser energy on target with several tens of Joules at a high repetition rate (1–10 Hz) [1–5]. While the availability of ultrahigh intensity laser pulses has enabled investigation of new physical mechanisms in the field of laser plasma acceleration physics by means of proof-of-principle experiments in single-shot mode [6,7], societal applications (including medical ones) [8,9] require high repetition rate operation, which is very challenging in terms of target delivery systems and real-time detection of plasma radiation. In fact, the current bottleneck in such experiments is not represented by the laser operation mode, but rather by the development of suitable target and diagnostic systems capable of sustaining harsh laser-plasma experimental conditions, such as giant electromagnetic noise, ultrahigh dose rate ionizing radiation, and particle debris generated from the irradiated target [10–16]. Thus, new solutions for fast target delivery, detection, and data acquisition systems have to be developed in order to satisfy recent requirements for potential applications of laser plasma physics.

Recently, the TERESA (TEstbed for high REpetition-rate Sources of Accelerated particles) has been successfully used at ELI-Beamlines [17]. The mission of the project was to provide a developing and testing environment for novel solutions in target delivery and laser–plasma diagnostics at high repetition rates (up to 10 Hz). In this paper, we report on our progress in the development of target delivery and alignment solutions for high repetition rate laser operation, along with ion diagnostics, data acquisition, real-time

analysis methods, accurate control of vacuum, and alignment systems. The technologies described in this paper will be further tested at the ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) beamline to supply laser-accelerated ion beams to users carrying out research in various disciplines (physics, biology, chemistry, medicine, and material sciences) [18]. In Section 2, we discuss related experimental setups and operation modes. Target supply systems for thin solid films with fast target refreshing capability for operation up to 10 Hz, along with various diagnostics and related data acquisition systems, are presented in Sections 3 and 4. Conclusions and perspectives are outlined in Section 5.

2. Experimental Setup and Control

In general, good experimental conditions in laser-plasma interaction experiments require an optimal energy transfer between the incoming laser beam and the used target. Such a laser-plasma coupling efficiency is a key parameter to enhance the performance of a laser-plasma accelerator. This can be satisfied if both the laser beam focusing element, typically an Off-Axis Parabola (OAP), and the target positioner are handled carefully in order to place the target precisely into the position of the previously optimized focal spot (high encircled energy). The full procedure usually consists of three consecutive steps: (i) Definition and referencing of the interaction point position; (ii) OAP focal spot optimization and its positioning at the interaction point; (iii) Target alignment in 3D and its positioning at the interaction point.

Alignment procedures are typically available and well described in technical manuals at high power laser facilities. Low repetition rate laser beams, with a time interval between shots of several minutes, are typically focused and aligned on targets before each shot using a low power mode (unamplified version) of the laser beam. On the other hand, high repetition rate facilities require overall alignment of the target frames prior to the experimental run, due to the fact that the focus position must be optimized. Subsequently, all the targets must be pre-aligned before each irradiation sequence (at least few hundreds of shots) with high accuracy. Therefore, standard focal spot alignment procedure needs to be combined with a reliable target positioning system, which is capable of precise and repeatable operation, as described below. Naturally, overall pointing stability and vibration-free transport of the beam up to the focusing optics was ensured by careful engineering of both the mirror mounts and the vacuum systems, typically using decoupling between vacuum vessels and optical breadboard. Furthermore, additional potential unwanted effects, such as thermal lensing of optical components and slow laser beam drift, must be compensated.

The interaction point in the experimental chamber must be precisely defined since ion/plasma diagnostics and other experimental equipment (e.g., magnetic systems) are pointed at it, and it is considered a reference point for ideal observation of the laser-target interaction and further utilization of the accelerated particles.

The interaction point definition relies on the mechanical precision of the used components and is usually realized by placing a reference tip in the desired position. The tip is usually a conically sharpened (stainless steel) wire reaching a diameter of a few tens of micrometers. The alignment of different detectors with the interaction point itself is usually carried out using a small alignment laser beam (laser pointer perpendicularly attached to the detectors case front surface) propagating from the detectors towards the expected interaction point. This simple check ensures that the detector is oriented to the interaction point, and it has a clear view of the interaction. The intersection of the different detector alignment beams marks the interaction point where a reference tip is placed. Since the laser beam path in the experimental chamber was typically aligned horizontally (the beam axis is at the same height above the breadboard), the interaction point also remained at this defined height. Subsequently, the laser focal spot must be positioned in this point.

As soon as the interaction point is precisely defined and marked with a reference object, the monitoring system, consisting of a microscope objective with a given magnification, can be pre-aligned with the laser optical axis (the direction is given by the off-axis angle of

the OAP) and pointed at the reference object placed at the objective's working distance. The microscopic objective is then fixed, and the OAP focal spot is optimized and positioned onto the reference tip. The laser beam is centered onto the OAP reflective surface and the mirror is tilted vertically until the focal spot lies in the same horizontal plane as the axis of the beam inside the interaction chamber. Subsequently, the OAP is tilted in the horizontal plane to bring the focus close to the reference tip. As soon as the magnified focus becomes visible through the objective, the OAP optimization can start.

The monitoring system is moved towards and outwards of the incoming beam to evaluate the size and shape of the beam close to the focal point. One can achieve a small focal spot size with a large value of encircled energy (i.e., minimal wave front distortion and high laser intensity) on target only when the focusing OAP is properly optimized, which is evident from the circular shape of the converging and diverging beam in the proximity of the laser focus.

If the focal spot is not circular, the OAP alignment shall be optimized. The tip and tilt of the OAP are used while scanning the focal spot in the longitudinal direction. During this optimization, the focal spot moves away from the tip. This must be simultaneously compensated using the movement of the OAP holder since the focal spot follows the X, Y, Z movement of the OAP. This procedure is normally done manually step by step until the desired result is reached. As soon as a circular focal spot is achieved in front of and behind the focal plane, the transversal optimization ends. The monitoring system is then pointed back on the reference tip and the OAP is finally moved to place the focus (now a very small circle) onto the top of the reference tip. This ensures that the optimized focal spot sits in the interaction point. As the last step, the target is moved into the same position.

3. Target Delivery System

Modern systems, which are capable of delivering laser energy on target with several tens of Joules at high repetition rates (1–10 Hz) require at least several thousands of targets per hour since the target is destroyed after each laser shot. Moreover, there are strict technical requirements for the target system, such as fast target refreshing, positioning, and alignment. Currently, a wide range of targets has been developed for laser-plasma acceleration, such as thin solid foils, tapes [19], gas [20] or liquid jets [21,22], clusters [23], cryogenic targets [24,25], and liquid crystals [10,26]. Hereafter, we aim to address the need for high repetition rate planar thin target delivery as a continuous sheet of material (thin foil) that is refreshed by a motorized stage.

A picture of the planar target delivery systems (PTDS) used in our experimental tests is presented in Figure 1a. The main part of the device is modular to allow holding of various types of target frames. The system can accommodate 900 foil targets, with an average distance of 5 mm between neighboring positions. The foils are secured using a special frame system made of two metallic plates that hold the foils in between them. Both plates contain a matrix of conical holes of about 1 mm in diameter. The conical shape helps to avoid the shock wave propagation from one target to the neighbors, permitting use of all the available targets during the laser irradiation. Moreover, this design provides good protection of individual targets from excessive evaporation or overheating effects occurring during laser-target interaction, or contaminations from neighboring targets after the shot. The current modification of the system uses nine of these frame holders and is able to hold any kind of foil (metallic, semiconductor, or plastic targets) with a very broad range of possible thicknesses (from foils of few tens of nanometers to few hundreds of micrometers thick).

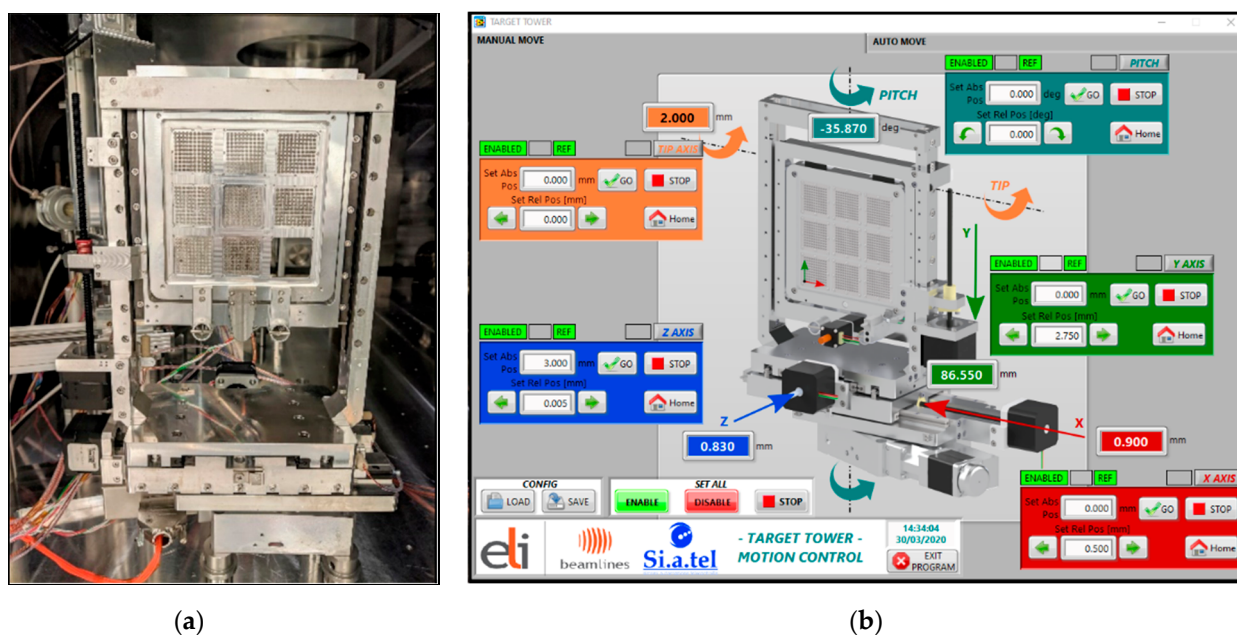


Figure 1. A picture of (a) the planar target delivery system and (b) the graphical user interface for control of the target system.

A motorized system of PTDS has five degrees of freedom (x, y, z, pitch, and tip) and allows the device to align and to hit each individual target at 1 Hz with an accuracy better than $10\ \mu\text{m}$ on each axis. To control the position of the device to avoid unwanted clashing with neighboring devices, each actuator is supplied with two linear limit switches to define the range of motion of the corresponding axis. The used motors are suitable for operation in a harsh environment where very strong electro-magnetic pulses (EMP), associated with high intensity laser-matter interaction, may affect the operation of electronics and high precision motorized systems. To reduce electrical discharge effects induced by laser-target interaction, the target holder is decoupled from the other metallic parts of the device with a polytetrafluoroethylene plate. The target holder itself is directly grounded to the vacuum chamber, thus the electrical conductor runs directly from the target plate to the ground.

The use of sophisticated optical systems imposes additional stringent requirements in terms of cleanliness levels of the vacuum systems. All PTDS parts, such as frames, motors, actuators, and limit switches, are made of high vacuum compatible materials. The connection cables are encased in copper braid with Kapton insulation to reduce the outgassing of particles detrimental to the vacuum system cleanliness.

A custom-made software is used for manual positioning of individual targets during the alignment phase and allows automatic refreshing of targets during a laser shot sequence. The graphical user interface shown in Figure 1b allows setting of either absolute or relative target positions, using five degrees of freedom with an accuracy of $5\ \mu\text{m}$ and recording an individual position of the target for the high repetition-rate laser shot sequence.

Accurate alignment of each individual target before the laser shot sequence is one of the most important parts of the experimental run preparation since the accurate positioning of the target into the laser focal plane heavily affects the laser-target interaction conditions and, consequently, the laser-plasma acceleration process.

The alignment procedure consists of several key steps to be followed: (i) defining the interaction point by placing a reference object (sharp pin) in the desired position; (ii) aligning a monitoring system that monitors the interaction point; (iii) fixing the monitoring system to use it as a reference for the next steps of target alignment; and (iv) removing the tip and placing the PTDS to allow its large metallic frame to be at the same position of the tip.

Once the frame is set according to the imaging system focal plane (typically with an accuracy of $10\text{--}20\ \mu\text{m}$), the alignment of each individual target includes recording of its

unique coordinates (x , y , and z , when the target is in focus). The other two coordinates (pitch and tip) are usually common for the whole target frame. Damaged or broken targets can be marked and automatically bypassed during the high repetition-rate laser shot sequence. Alignment of one frame with 100 targets generally takes about 10 min and usually can be done in advance.

Ultimately, the software provides a recorded table of target coordinates that is used for automatic target switch to the subsequent position by means of an external trigger sent by the laser system during the experimental run. It is crucial to prevent any hit of the target holder frame by the laser beam during the shot sequence. For this purpose, the control unit of the PTDS was equipped with a trigger input. The target swapping starts right after the incoming trigger is delivered with the laser shot. An output feedback signal indicates the completion of the target tower motion necessary to set the fresh target at the interaction point. A stable performance of the system at the repetition rate of 1 Hz is demonstrated in Figure 2. The PTDS starts motion right after the trigger (blue signal) associated with the laser shot. The finalization of alignment for the new target is indicated by the falling edge of the output feedback (orange signal) before the next laser pulse arrives.

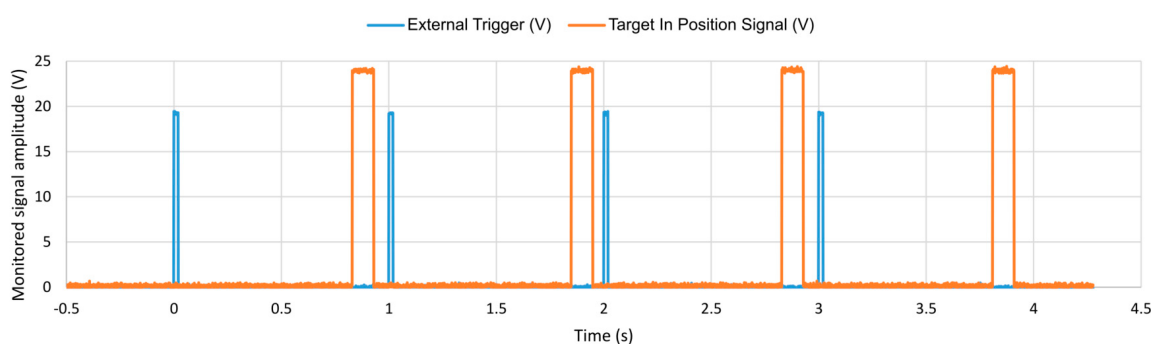


Figure 2. The sequence of four trigger signals (blue) at 1 Hz repetition rate initiating the motion of the following targets. The orange signal corresponds to a reference output confirming that the new target is in the aligned position.

The feedback output provides an estimated value of the potentially reachable target repetition rate during a laser shot sequence operation of about 1.25 Hz. Optical snapshots of the target positions were taken by means of the monitoring system during target renewal (see Figure 3). Monitoring system is supplied with LED placed on monitoring system to improve image quality. In this case, the target frame moves vertically from the upper to the lower target. The image becomes sharp after 800 ms since the target starts its motion, hence clearly indicating that a new target is set to the pre-aligned position and ready for the following shot. This observation is consistent with the feedback signal from the target tower. In fact, the monitoring system can hardly be used for the detection of a new target in the preset position, since image transfer from the camera and online analysis are demanding, with respect to data transfer infrastructure and computing power. Instead, analog feedback can be a reference for the data acquisition system. As a part of the control system, such a signal prevents potential damage of equipment by the laser beam during the target frame motion.

Another important property of the PTDS to be verified is the target position reproducibility when the targets are switching automatically. An accuracy test, with the aim of evaluating potential misalignment of different targets during a shot sequence, was performed using the target tower coupled with the imaging system.

Firstly, a set of targets was aligned, resulting in a table of target coordinates and a corresponding set of target snapshots taken by the imaging system. Then, the target renewal was simulated by a sequence of triggers with repetition rate of 1 Hz. Target snapshots were recorded once the target was in position. Comparing the respective images corresponding to the individual targets, the estimated misalignment was evaluated as less than 10 μm .

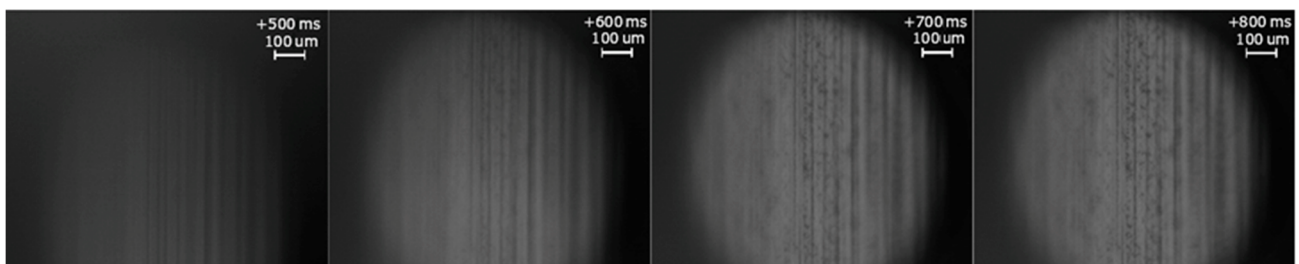
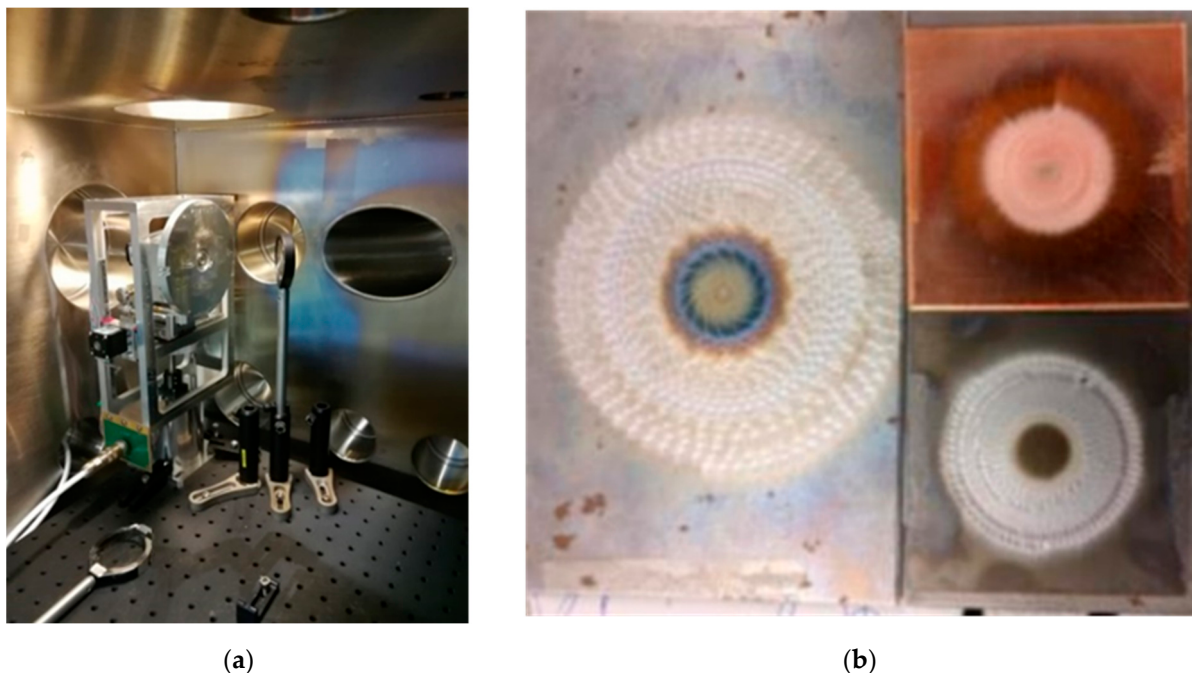


Figure 3. Imaging of the target switching process between two laser shots acquired with monitoring system.

The present configuration of the planar target delivery system demonstrates good ability of target refreshing at 1 Hz repetition rate in a real experimental run at TERESA target area [17]. The OAP with focal length of 330 mm ($\approx f/3.7$) allows to obtain a laser focal spot diameter of about $3.8 \mu\text{m}$ of full width at half maximum. All targets rastered before the laser firing can keep their position with a repeatability better than $10 \mu\text{m}$ over the whole laser shot sequence. During the operation of a 30-fs laser with 1 J energy on target (intensity around $5 \times 10^{19} \text{ W/cm}^2$), no substantial damage on individual target frames, nor EMP-related issues, nor nuclear activation were observed after a complete run of about 1000 shots.

Additionally, we have developed and tested a second type of fast target delivery system. The spiral tower is a concept of a target handling system, which allows work at high repetition rates (see Figure 4a). The device consists of a 1-cm-thick Al disk (10 cm diameter) where targets are fixed, a translation and a rotation stage for a motorized roto-translation movement, and two linear stages, one for tilt and one for z micrometer level adjustment. In addition, a linear stage allows adjustment of the height of the device according to the laser interaction point. Similar to the target tower described above, all parts of the device are made of vacuum compatible materials to avoid contamination inside the vacuum chamber.



(a)

(b)

Figure 4. Picture presents (a) the spiral tower, used at high repetition rate; and (b) examples of irradiated Fe, Cu, and Sn target plates with dimensions 50 by 50 mm. Left figure represents a zoomed picture of the irradiated area of Fe target showing a typical spiral shape.

Since the supporting disk is very thick, the device is used in experiments where only the backward plasma emission is of interest for the given experiment. Typically, the employed targets are mm-thick slabs. In contrast to the PTDS system, the number of interaction points is not fixed by the target holder. This device has been tested in single shot and at 1 and 10 Hz repetition rate, delivering thousands of shots continuously using the Bivoj laser (10 J max laser energy delivered in 5–10 ns pulse duration, working at the fundamental wavelength of 1032 nm) at the HiLASE laser center [5].

Dedicated software has been developed for motion control of the tower. It is possible to manually move every single motor or setting for a more complicated series of movements for multi-shot irradiation. A combination of translation and rotation allows the system to move in a spiral trajectory. Few irradiated targets are illustrated in Figure 4b, where the typical spiral shape is demonstrated. The distance between the subsequent interaction points on the target and the number of shots in the same position (if required by the user) can be preset according to the necessity of the experiment. The spiral tower demonstrated stable operation at repetition rates up to 10 Hz during the laser irradiation with stable ion shot-to-shot signal. It can be concluded that any displacement of the target in the direction of the laser propagation caused by the mechanics of the device, or non-ideal form of the target plate, was less than the Rayleigh length (typically 100 μm in this experiment at HiLASE) of the used optical system.

4. Data Acquisition System for High Repetition Rate Performance

Routine operation of PW-class laser-plasma experiments at high repetition rates would represent a new paradigm in terms of statistically relevant discoveries of new plasma acceleration regimes, investigation of complex effects, along with mitigation of laser-plasma instabilities to improve the stability of secondary sources (particles and radiation). This new scenario will require not only fast target delivery devices, but also fast diagnostics and data acquisition systems, along with real-time analysis tools allowing online characterization of laser-plasma generated secondary source parameters.

Online diagnostic systems for laser-generated ion beams at the TERESA and ELIMAIA beamlines are described in detail in [13,17,18], therefore, the following will mainly focus on recently developed and tested data acquisition systems and data analysis tools for high repetition rate operation (up to 10 Hz). Nevertheless, in terms of laser-plasma ion diagnostics, it is worth mentioning that one of the main challenges in the detection of laser-accelerated ions is the high-peak flux (10^{10} – 10^{12} ions/pulse) and the short bunch duration (0.1–1 ns), hence the very high dose-rates in a single pulse (around 10^9 Gy/s). Thus, innovative techniques and devices for beam characterization have been developed for the ELIMAIA beamline, since robust online diagnostics represents one of the crucial steps towards multidisciplinary applications of such non-conventional beams [18]. The main online ion diagnostic system is based on the time-of-flight (TOF) technique using diamond and silicon carbide detectors, as reported in the literature [12,13,27], which offers the possibility to monitor shot-by-shot the main ion beam features up to a repetition rate of 10 Hz. Another key ion diagnostic system is the widely used Thomson Parabola Spectrometer (TPS), which allows the detection of energy-resolved ion spectra while discriminating ions with different charge-to-mass ratios by means of combined use of electric and magnetic fields [28,29]. In high repetition rate TPS configuration, deflected ions are typically observed and amplified by means of a microchannel plate (MCP), and are sent to a phosphor screen, thus producing an image of the energy-resolved ion spectra subsequently recorded by a CCD camera. The acquisition of the raw CCD image is controlled by a trigger signal from the laser.

The use of a repetition rate of 1–10 Hz requires a data acquisition system (DAS) with the ability to measure and store a large amount of data. For this purpose, we have developed a data acquisition system based on commercially available oscilloscopes (Agilent Technologies, Santa Clara, CA, USA, DSO9064A; LECROY, Chestnut Ridge, NY, USA, WAVERUNNER 8404M and WAVERUNNER 8254), but with the capability of real-time

data transfer to the computer using standard TCP-IP communication over a local area network (LAN).

The DAS system was tested using all three oscilloscopes (with four active channels per device) operated simultaneously in one LAN. After successful triggering, data are acquired into the oscilloscope's memory. The dedicated NI Labview routine that follows the trigger status initiates the transfer of acquired data to the PC. During a test, the code allowed to count the data loss within a series of 200 subsequent triggers at different laser repetition frequencies, 1, 3.3, and 10 Hz (i.e., 1 s, 0.3 s, and 0.1 s), and various sampling rates per channel. Figure 5 depicts the data acquisition time for two extreme configurations: (a) delay between triggers of 1 s/1000 samples per channel; and (b) delay between triggers of 0.1 s/25,000 samples per channel. In the first case, a successful read of data happens in between two triggers without affecting the next measurement, while for the second configuration (where data loss is 29%), after few long data reads (longer than 10 Hz limit, as depicted by the orange line) a subsequent loss of data occurs. A summary of measured data losses for individual oscilloscopes is reported in Table 1.

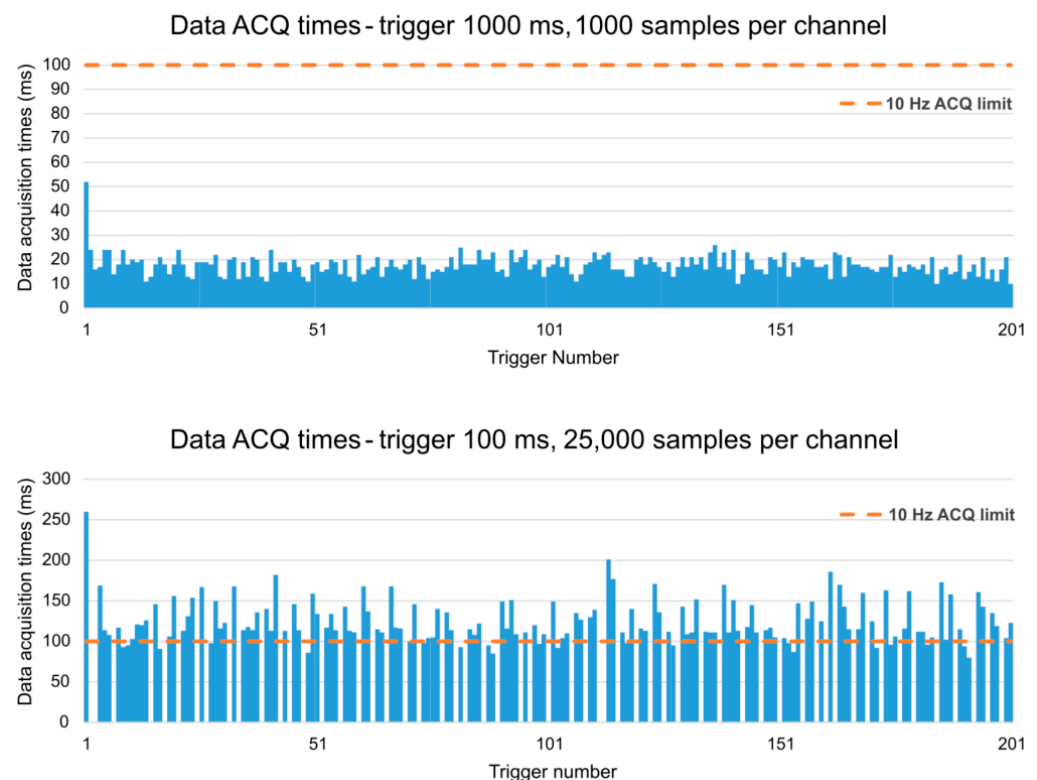


Figure 5. Example of data acquisition times for LeCroy Waverunner 8254: trigger delays of 1 s, 1000 samples per channel (top); trigger delays of 0.1 s, 25,000 samples per channel (bottom). The orange line shows the critical 10 Hz limit for data acquisition time.

Table 1. Measured data loss for a given trigger repetition rate and sampling rate. “X” corresponds to a non-tested configuration; “*” shows data acquisition (ACQ) read for four channels of equal length).

Agilent Technologies; DSO9064A					LECROY—WAVERUNNER 8404M					LECROY—WAVERUNNER 8254				
		Delays between Triggers					Delays between Triggers					Delays between Triggers		
		(ms)					(ms)					(ms)		
		1000	300	100			1000	300	100			1000	300	100
Samples per channel *	1000	0.0%	0.0%	0.8%	Samples per channel *	1000	0.0%	0.0%	0.3%	Samples per channel *	1000	0.0%	0.0%	0.0%
	5000	0.0%	0.0%	19.3%		5000	0.0%	0.0%	0.8%		5000	0.0%	0.0%	1.0%
	10,000	0.0%	0.0%	55.8%		10,000	0.0%	0.0%	6.5%		10,000	0.0%	0.0%	1.3%
	25,000	0.0%	1.5%	56.8%		25,000	0.0%	0.3%	17.8%		25,000	0.0%	0.0%	29.0%
	50,000	0.0%	12.8%	X		50,000	0.0%	1.8%	X		50,000	0.0%	1.8%	X
	100,000	1.0%	X	X		100,000	0.0%	X	X		100,000	0.0%	X	X

Data transfer rate from the oscilloscope to the PC depends mainly on the acquisition rate and the number of samples per channel. The oscilloscopes' transfer buffer and internal memory are independent. In case of overlapping between data transfer time and triggering time, there is still a possibility to transfer newly acquired data. However, inability to transfer data between neighboring triggers causes delay accumulation and after few repetitions leads to the loss of data acquired by the oscilloscope. A stable operation of the DAS with three parallel oscilloscopes (four channels per oscilloscope) can be easily achieved for 1 Hz laser repetition rates up to 50,000 samples per channel. On the other hand, operation at 10 Hz shows data loss, even acquiring 1000 samples per channel. However, a still reasonable performance of the DAS with the used oscilloscopes can be achieved even for 10,000 samples per channel and 10 Hz repetition rate (the observed data loss is about 6.5%).

To conclude, the chosen oscilloscopes demonstrate reasonable performance for data collection up to 3 Hz repetition rate. TOF diagnostics typically requires about 1000 samples to record all details of the ion beam spectrum. In case of high requirements to time-resolution (ultrafast ion signal), a relatively low repetition rate (around 1 Hz) is still acceptable in terms of overall data loss. Nevertheless, for application-based experiments, typically requiring a large number of shots, a compromise could be found by recording the ion spectra at a reduced repetition rate (e.g., an average signal acquired during 10 shots), even if the laser is operated at 10 Hz.

PW-class laser systems available at the ELI-Beamlines facility are characterized by high-repetition operating capability (1–10 Hz) that, in combination with suitable target delivery systems and laser-plasma diagnostic devices, provide unique possibilities for investigating new experimental regimes with high statistics. However, such a new scenario makes manual processing of raw data practically impossible. This also applies to typical laser-accelerated ion signals from various diagnostics, e.g., TOF detectors or TPS. In fact, any online analysis of a signal sequence would permit control of, *inter alia*, the uniformity and stability of TOF spectra that can be a crucial parameter for several applications of the measured particle beams [18]. Therefore, a special routine was developed using Python to perform TOF spectral analyses in real-time during an experiment. The script allows obtaining an average TOF signal based on the last N shots and, at the same time, calculates the standard deviation of the set, plotting the corresponding results (see Figure 6). The spectral changes over a certain time can be seen with high accuracy, and the overall stability can be tracked. This enables monitoring of the progress of the experiment and control of the process for possible errors or system breakdowns.

Real-time analysis of the obtained TPS images during an experiment was performed with specifically developed MATLAB-based graphical user interface (see Figure 7). At the initialization stage, it allows setting up the basic parameter of the used TPS geometry, such as the diameter of the pinhole, length of the electric and magnetic electrodes, distances between electrodes and camera, as well as particularly applied electrode fields strength, orientation, and scaling factor of the camera for the current experimental cycle. The routine can determine the appearance of the new experimental data continuously stored by TPS camera in the predefined folder, automatically start the procedure of their analysis, and save the calculated results.

At the first stage, the code performs a simulated trajectory of the particles inside the TPS device from the collimator down to the detector plane, according to the specified parameters. Furthermore, it controls the precision of the overlap between ion traces, detected with the TPS imaging system, and simulated traces of the ion species that are most commonly present in experiments with solid targets (e.g., protons and carbon ions with charge states from C^{+1} to C^{+6}). If necessary, the developed optimization toolkit corrects the preset parameters responsible for the position and orientation of ion traces in the image and removes possible artificial image noise caused by light scattered from the interior of the diagnostic device. The bulk of the code transforms the image in such a way that parabolic traces with different charge-to-mass ratios are converted into straight stripes, which in turn greatly simplifies the following data analysis.

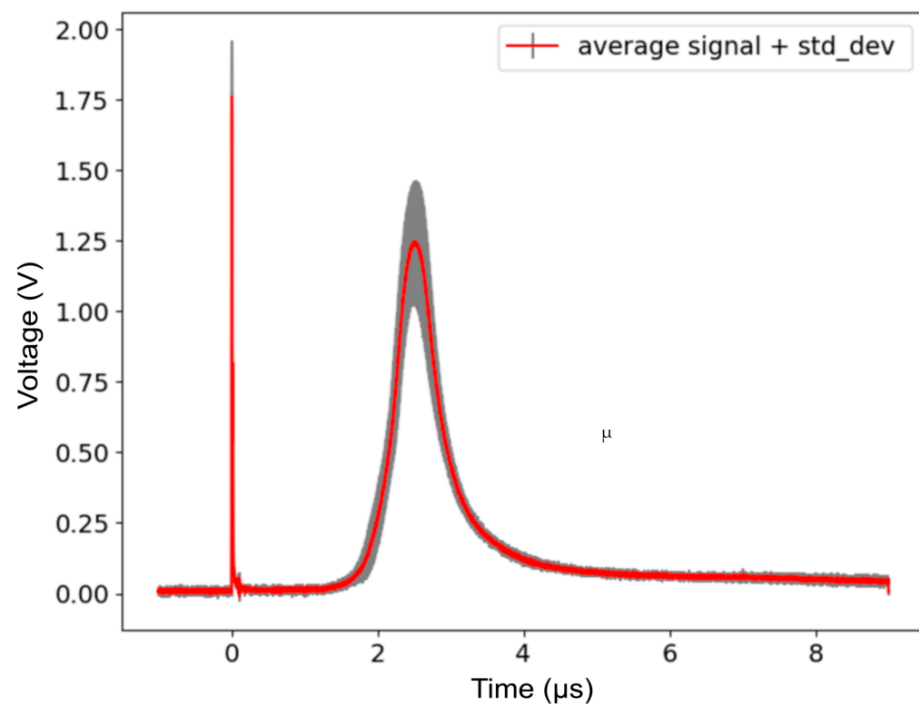


Figure 6. Average time-of-flight (TOF) spectrum and standard deviation calculated from 10 consequent signals recorded by a TOF diagnostic device when an Al target is irradiated with ns-class laser (4 J laser energy) at 10 Hz.

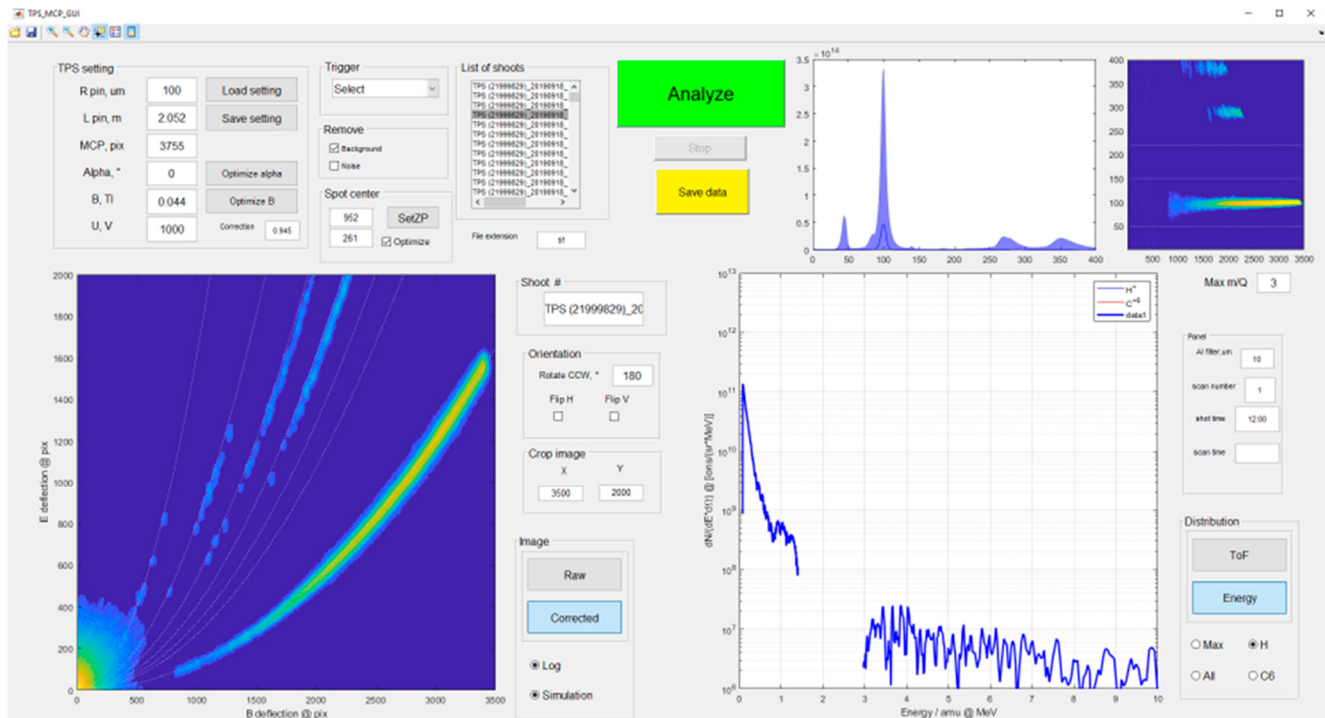


Figure 7. MATLAB-based graphical user interface used for analysis of the Thomson Parabola Spectrometer (TPS) images: (left GUI subfigure) example of the RAW image obtained by the TPS imaging system together with simulated ion traces; (right bottom GUI subfigure) corresponding ion energy distribution of the hydrogen ions as calculated by routine.

Ultimately, the automatically separated stripes representing individual ion species with defined charge-to-mass ratios are converted into corresponding ion energy distri-

butions, and subsequently raw data together with calculated energy spectra are plotted in a user interface windows for visual control. Storing of the calculated results enables provision of simple online statistics (maximum ion energies and their cumulative charge per shot) and control of the shot-to-shot stability in real-time. As a result, this routine can provide complete and quick information on the ion species and the underlying physical processes in the plasma for a shot sequence acquired at a repetition rate of 1 Hz.

5. Conclusions and Perspectives

Operation of high repetition rate, high peak power laser systems focused down to ultrahigh intensity onto solid targets is very beneficial for user experiments, and especially for multidisciplinary applications that require a large number of overall laser shots. In fact, large laser-plasma facilities, such as the ELI pillars, are entering user operations and promising to deliver experiments with high statistical accuracy. In fact, shot-to-shot instabilities are intrinsic features of laser-plasma interaction, thus obviously introducing large experimental uncertainties that can be reduced if experiments with a large number of shots are carried out using the high repetition rate capabilities of the newly available laser technologies at PW-level. This will allow investigation of novel and complex regimes of laser-plasma interaction of interest for fundamental science, as well as optimization of the production of laser-driven secondary sources, along with high average fluxes delivered onto the user sample.

The above-described target and diagnostic technological solutions, along with real-time data acquisition and analysis tools, were developed ad-hoc to be provided to future users of the recently installed ELIMAIA ion beamline at ELI Beamlines, which aims to operate at high repetition rate (1–10 Hz) [18]. These solutions were already successfully tested at 100TW-level [17] and will be further tested and optimized in upcoming commissioning experiments at 1PW-level. Further development is considered based on future beamline performance optimization and user requirements that will certainly aim at an even higher degree of automation.

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